

Signatures of equatorial plasma bubbles in VHF satellite scintillations and equatorial ionograms

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[1] Since their discovery in the 1970s, equatorial plasma bubbles (EPBs) have been invoked to explain the propagation of VHF signals on trans-equatorial circuits at night, and blamed for highly detrimental scintillation of VHF and GHz trans-ionospheric communications signals in equatorial regions. Over the last four decades, the properties of EPBs have been deduced by multiple techniques such as incoherent scatter radar, 630 nm airglow, depletions in GPS total electron content observations, VHF and GHz scintillations, and HF observations by ionosondes. The initiation and evolution of EPBs have by now been successfully modeled and a good understanding developed of the underlying physics. However, different communities tend to concentrate on a single observing technique, without regard to whether the different techniques provide a consistent physical picture. In contrast, this paper discusses two very different types of observations made on a night-by-night basis during the COPEX campaign of late 2002 in Brazil, namely, VHF scintillations and ionograms, and shows that the two methods of observation can provide a consistent interpretation of the properties of EPBs. For example, an EPB seen as an eastward drifting scintillation event can also be seen as an extra ionogram reflection trace that moves closer to and then away from the ionosonde site. The scintillations are attributed to strong gradients across the walls of an EPB, whereas the extra ionogram traces are attributed to oblique reflection of the ionosonde signals from the walls of the EPB.

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1. Introduction

[2] Historical scintillation observations and their physical interpretation in terms of equatorial plasma bubbles (EPBs) form the basis of the Scintillation Network Decision Aid (SCINDA), which is a real-time, data-driven communication outage forecast and alert system developed by the Air Force Research Laboratory (AFRL). Its purpose is to aid in the specification and prediction of satellite communication degradation due to ionospheric scintillation in the equatorial region (see, for example, *Basu and Groves* [2001] and *Caton et al.* [2004]).

[3] The purpose of this paper is to present EPB-based interpretations of scintillations of VHF satellite communica-

tion signals that were made under the umbrella of the SCINDA program, at the same time ensuring that the interpretations are consistent with observations of EPBs made in the HF band using collocated ionosondes.

[4] The VHF scintillation observations (at ~244 MHz) of satellite down-link communications were recorded at three locations in Brazil—Boa Vista, Alta Floresta, and Campo Grande—during the COPEX campaign of 2002 (September–December 2002). The solar activity was very high in 2002. Digisondes were deployed at Boa Vista, Cachimbo, and Campo Grande. VHF observations of the eastward drift motion of the EPBs were also made by AFRL at the three scintillation locations. For more on the COPEX campaign and its results, see, for example, *Reinisch et al.* [2004], *McNamara et al.* [2008], *Muella et al.* [2008], *Abdu et al.* [2009], *Sobral et al.* [2009], and *de Paula et al.* [2010]. The observing interval corresponds to the summer maximum of EPB occurrence for Brazil [*Sobral et al.*, 2002]. Scintillations at VHF frequencies are much more severe than those on GHz frequencies (as used by GPS satellites) (see, for example, *Fremouw et al.* [1978]). *Weber et al.* [1996] provide a description of earlier coordinated radio and optical measurements of the structure and dynamics of the post-sunset equatorial ionosphere at Agua Verde, Chile.

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The scintillations at GHz frequencies for one night during the COPEX campaign are discussed in some detail by *Carrano et al.* [2012].

[5] EPBs are generally created just after the post-sunset height rise of the F2 layer. A key property of EPBs is that they drift eastward throughout the night after formation. On rare occasions, they do drift westward, for example, if there was a storm or some other magnetic disturbance.

[6] As part of the SCINDA program, AFRL has developed procedures for real-time forecasting of scintillations on a VHF down-link to the east based on observations made at the same ground station on a VHF down-link to the west. The basic idea is that the EPBs causing the scintillations will drift from west to east so that scintillations seen to the west will appear at a later time on a VHF link to the east. However, this common scintillation scenario of observing satellites on fixed lines of sight (LOS) to the west and to the east has the limitation that EPBs seen as scintillation on the western LOS cannot be observed while they are drifting eastward between the two lines of sight. The gap between the ionospheric pierce points (IPPs) for the two LOS would typically be ~ 600 km, with an EPB taking just over an hour to move from one LOS to the other.

[7] Ionosondes are very useful instruments for studying both individual EPBs and their occurrence statistics. With an ionosonde at the SCINDA site, in particular, the EPBs can be detected in the gap between the two LOS. The papers by *Whalen* [1996, 1997, 1999, 2000] describe some of the earlier studies of EPBs as seen in equatorial ionograms.

[8] Section 2 of this paper describes the observational setup, with digisondes at three locations, and scintillation and drift measuring equipment at the same or nearby locations. Observations were made of VHF signals from two geostationary satellites: one over the Pacific Ocean and one over the Atlantic Ocean. The digisonde ionograms were investigated manually to determine if they contained any signatures of EPBs. The measurement and observed values of the drifts are discussed in section 3. Section 4 discusses the ionosonde signatures of EPBs and explains how these were defined and measured. A simple model of an EPB that is sufficiently complex to interpret both the scintillation and ionosonde observations of EPBs is presented in section 5. Section 6 presents case studies of the scintillations recorded on separate nights of the campaign, along with the corresponding ionosonde observations of EPBs. Section 7 discusses the derivation of drift velocities from the ionosonde observations and relates these velocities to velocities derived from the scintillations. The apparent decay of the scintillations and its relation to properties of EPBs are discussed in section 8. The longitudinal occurrence (along the magnetic equator) of EPBs seen on ionograms is discussed in section 9. Finally, section 10 summarizes the results of the analyses.

2. Observational Setup

[9] The VHF scintillation observations discussed in this paper were recorded at three locations—Boa Vista, Alta Floresta, and Campo Grande—during the COPEX campaign in Brazil. Digisondes were deployed at Boa Vista, Cachimbo, and Campo Grande [by Instituto Nacional de Pesquisas Espaciais (INPE)], so we were able to take advantage of the multiparameter information available from modern ionosondes. VHF observations of the eastward drift motion of the EPBs were made by AFRL at the three scintillation locations. The geosynchronous communications satellites were at longitudes of 266° (Pacific Ocean) and 337° (Atlantic Ocean).

[10] The locations of the observing sites are listed in Table 1.

[11] Cachimbo and Alta Floresta are close to each other on the magnetic equator. Boa Vista and Campo Grande are near the peaks of the equatorial anomaly and close to being magnetic conjugates.

[12] Figure 1 shows the locations of the COPEX observing sites, communications satellites, and ionospheric pierce points (IPPs). The digisondes at Sao Luis and Jicamarca are permanent installations.

[13] Tables 2–4 show the details of the IPP geometry for the three observing sites. Taking the altitude of the IPPs to be 350 km, the separations of the IPPs for Boa Vista, Alta Floresta, and Campo Grande are 640, 660, and 705 km.

[14] The largest difference between the elevation angles to the satellites was for Alta Floresta, for which they were 38.4° and 50.1° . This difference does not seem to be significant for the current analysis.

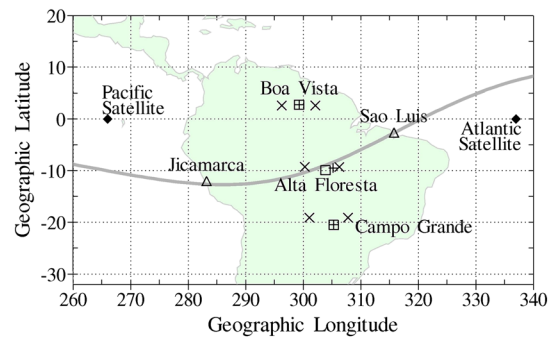


Figure 1. Locations of the COPEX observing sites (open squares), communications satellites, and ionospheric pierce points. The points to the east and west of the COPEX sites are the IPPs (X), which is where the lines of sight to the Pacific (western) and Atlantic (eastern) satellites pass through an altitude of 350 km. The ionosonde locations are indicated by the + signs. There are digisondes at Jicamarca and Sao Luis that are run on a routine basis.

Table 1. Locations of Digisondes and Scintillation Stations

Station	Lat.	Lon.	Mag. Lat.	Observation
Boa Vista	2.8°N	60.7°W	12.9°N	Ionogram, VHF Scintillation, Drift
Cachimbo	9.5°S	54.8°W	0.4°N	Ionogram
Alta Floresta	9.9°S	56.1°W	0.4°N	VHF Scintillation, Drift
Campo Grande	20.5°S	54.7°W	10.6°S	Ionogram, VHF Scintillation, Drift

Table 2. Geometry of Ionospheric Pierce Points for Boa Vista (BV)

BV (2.8°N, 60.7°W)	Pacific (266°E)	Atlantic (337°E)
Elevation	44.4	46.3
Distance to IPP	329.9 km	310.8 km
Bearing to IPP	266.6	93.6
Latitude of IPP	+2.62	+2.62
Longitude of IPP	296.3	302.1
Separation of IPPs	639.5 km	

3. Observations of Eastward Drifts

Table 3. Geometry of Ionospheric Pierce Points for Alta Floresta (AF)

AF (9.9°S, 54.8°W)	Pacific (266°E)	Atlantic (337°E)
Elevation	38.4	50.1
Distance to IPP	402.4	273.1
Bearing to IPP	280.1	75.2
Latitude of IPP	−9.24	−9.27
Longitude of IPP	300.3	306.3
Separation of IPPs	660.0 km	

Table 4. Geometry of Ionospheric Pierce Points for Campo Grande (CG)

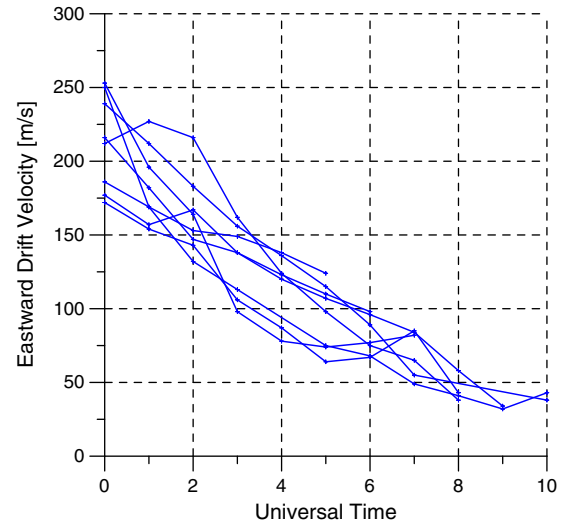
CG (20.5°S, 54.7°W)	Pacific (266°E)	Atlantic (337°E)
Elevation	34.0	46.9
Distance to IPP	466.5	303.6
Bearing to IPP	289.1	60.4
Latitude of IPP	−19.1	−19.1
Longitude of IPP	301.1	307.8
Separation of IPPs	704.8 km	

[15] *Muella et al.* [2008] analyzed the COPEX zonal drift velocities of the ionospheric irregularities (i.e., EPBs) that were measured using spaced GPS receivers. The average zonal velocities were found to be ~ 160 m/s for the first few hours (~ 20 to 22 LT), with a slow downward trend. After midnight, the velocities decreased to less than 100 m/s.

[16] The drift velocities at VHF were observed using equipment installed at the three sites by AFRL personnel. The drift velocities of the irregularities causing the VHF scintillations at each observing site were derived by correlating the signals received by a pair of antennas that were about 75 m apart and aligned magnetic east-west. There were two pairs of antennas at each site: one pair for the Pacific satellite and one for the Atlantic satellite. (These were geostationary satellites, so it is easier to reduce the observations than with moving GPS satellites.)

[17] Figure 2 shows the hourly median observed drift velocities for eight nights (which had the largest numbers of reliable observations) at Alta Floresta derived using the Pacific satellite.

[18] At 00 UT (~ 20 LT), the drift velocities are ~ 200 m/s, but these high values are the vector sum of the eastward drift and the large upward post-sunset drifts. The VHF drifts decay almost linearly (at ~ 20 m/s/h) until the observations basically cease at 10 UT (06 LT). This is in contrast to the GPS drift velocities [*Muella et al.*, 2008], which decay very slowly until midnight (04 UT). (We have no real explanation

**Figure 2.** Observed eastward hourly median VHF drift velocity for eight selected nights at Alta Floresta, Pacific satellite.

for the difference between the VHF and GPS drift velocities, but note that the VHF drifts are simpler to derive.) The Campo Grande VHF results were very similar to the Alta Floresta results of Figure 2. However, the Boa Vista velocities were systematically 50 to 75 m/s lower.

[19] Several of the curves in Figure 2 show a local increase in the drift velocity between ~ 04 and 07 UT (01–03 LT). The same feature was also seen in the observations of the Atlantic satellite, where it was more pronounced than for the Pacific satellite. It probably corresponds to a secondary post-midnight peak in EPB generation that we have observed in other studies.

4. Ionosonde Observations of EPBs

[20] The average values of the Boa Vista and Campo Grande foF2 (when they could be scaled) reached ~ 18 MHz between 00 and 04 UT (20–24 LT). The corresponding Cachimbo averages were ~ 10 MHz [*McNamara et al.*, 2008]. The strength of the GPS scintillations is directly proportional to the background electron density [*Whalen*, 2009]. *Aarons et al.* [1981] and *Basu and Groves* [2001] also concluded that GPS scintillations in the anomaly regions were higher than at the magnetic equator because of the differences in electron density. If the same applies to VHF scintillations, the scintillations would be lower at Cachimbo than at the two anomaly stations, since the ratio of the F2 peak densities is approximately $(10/18)^2 = 0.31$.

[21] For Boa Vista and Campo Grande ionograms, EPBs can be identified visually as basically horizontal patches of echoes that lie at approximately constant range and extend to the right of the main F2 trace (or where that trace would probably be if it were not obscured by the EPB traces). This rule is easy to apply for Boa Vista and Campo Grande, but the Cachimbo ionograms are a challenge because the EPB traces do not usually extend beyond the foF2 cusp.

[22] For convenience, we shall call the extra ionogram traces ionogram bubble traces (IBTs) so as to indicate their origin. The scintillation community describes an occurrence of scintillation as a bubble, but we prefer to use the descriptive

term “discrete scintillation event” (DSE), in parallel with the descriptive term IBT. Thus, DSE and IBT are the scintillation and ionogram manifestations of EPBs.

[23] Figure 3 shows a very clear example of an IBT at a virtual height of ~ 600 km on a Boa Vista ionogram during the COPEX campaign. Things are not always this clear. The confirmation that a trace is in fact an IBT can often be made only if the range of the trace changes with time (as the reflecting surface approaches or recedes from the ionosonde). Most of the extra echoes on the nighttime ionograms are oblique.

[24] The color changes of the IBT echoes with increasing frequency are mostly due to the changing lobe structure of the receive antenna array. On this particular night, the first indication that IBTs would appear later occurred at 23:00 UT ($\sim 19:00$ LT), in the form of blue traces parallel to the main traces at the low frequency end, like those in the 23:55 UT ionogram. The blue coding indicates that these echoes came from the NNE.

[25] The fact that these blue traces are parallel to the main trace suggests that the isodensity contours in the lower levels of the F2 layer have a corrugated shape, with reflections from multiple troughs. At these times, there is a locally generated EPB with its feet still in the lower altitudes of the F layer. The IBTs moved nearer in range until 01:20 UT, after which they moved to farther ranges.

[26] There may be multiple parallel IBTs in a given ionogram, corresponding to multiple reflection surfaces. These traces tend to move toward or away from the ionosonde in unison. When the IBTs first appear, they usually move downward and thus closer to the ionosonde. It is usually easier to note the onset of IBTs than their ending. The disappearance of the last IBT is often obfuscated by general spread F echoes common to equatorial nighttime ionograms.

[27] Figure 4 shows another illustrative example of IBTs at Boa Vista for day 305. There are now four IBTs. In general, all four traces moved closer to the ionosonde between 23:50 and 23:55 UT. The trace at ~ 750 km moved 50 km closer, while the trace at ~ 650 km moved ~ 30 km closer. Individual traces can usually be identified only for ~ 10 – 30 min. The drift velocity of an EPB can be derived from the changing ranges of a well-defined IBT, as discussed in section 7. This ionogram shows an extra trace above and parallel to the main F2 trace, which is again suggestive of a corrugated surface. The blue coloring of the “main” trace in Figure 4 indicates a fairly steep slope (16° or more) of the F2 layer, with heights decreasing toward the north. This suggests that the northern anomaly peak is equatorward of the station. There is also a depletion further to the east, i.e., at zenith angles larger than 16° , that produces a complete trace with ranges changing from ~ 400 to 600 km with increasing frequency. This is probably also the signature of an EPB, which reaches up to hmF2 and likely above that height. The large slope discussed above affects the appearance of these different traces.

[28] Only a minority of ionograms show resolved IBTs. Figure 5 is somewhat more typical. The previous ionograms in fact showed discrete IBTs, which evolved into the less discrete and more complexly structured patches present at 23:40 UT.

[29] The earliest IBTs for the day 299–329 analysis interval occurred at 22:40 UT (Boa Vista), 22:30 UT (Cachimbo), and 22:35 UT (Campo Grande), which is $\sim 18:30$ LT. The median start times were 23:10 UT, 22:55 UT, and 23:00 UT, but the distributions of start time were rather broad. The ending times were very broadly distributed. On some nights, the IBTs disappeared and then reappeared. The spread in the onset times probably arises from the fact that the EPBs giving rise

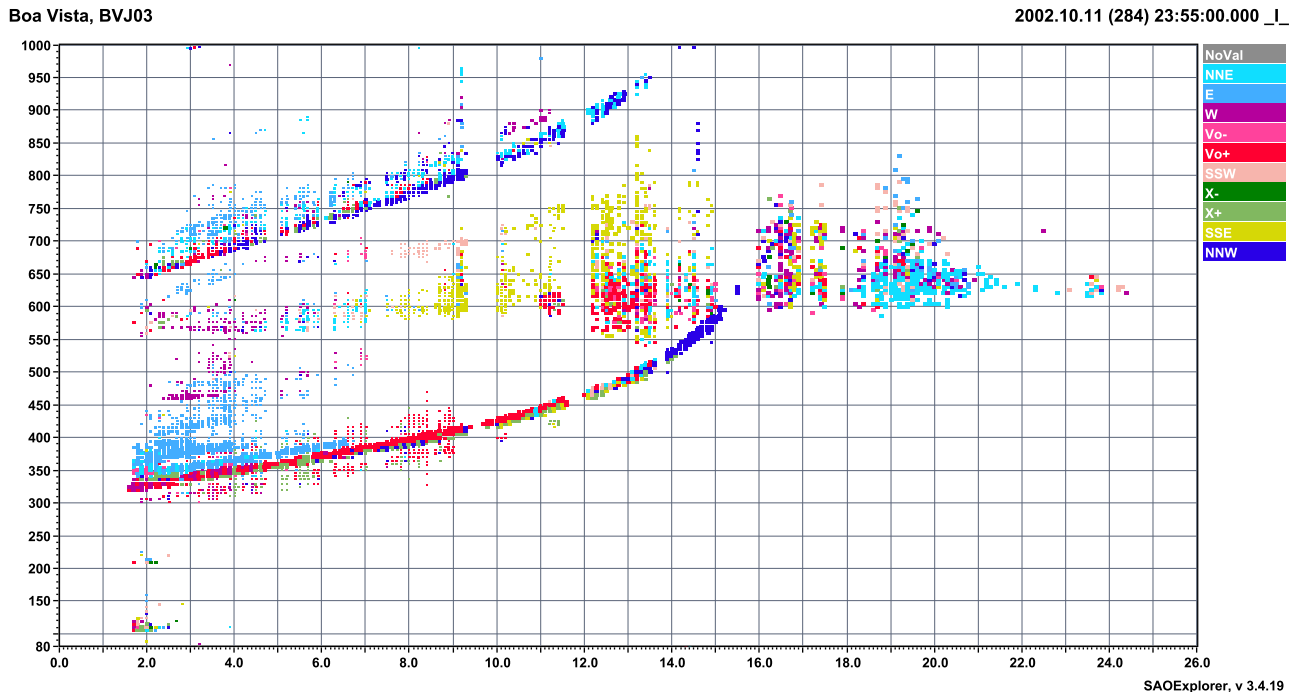


Figure 3. Boa Vista day 284, 23:55 UT ($\sim 19:55$ LT) ionogram showing ionogram bubble traces attributed to an EPB.

Boa Vista, BVJ03

2002.11.01 (305) 23:55:00.000 _I_

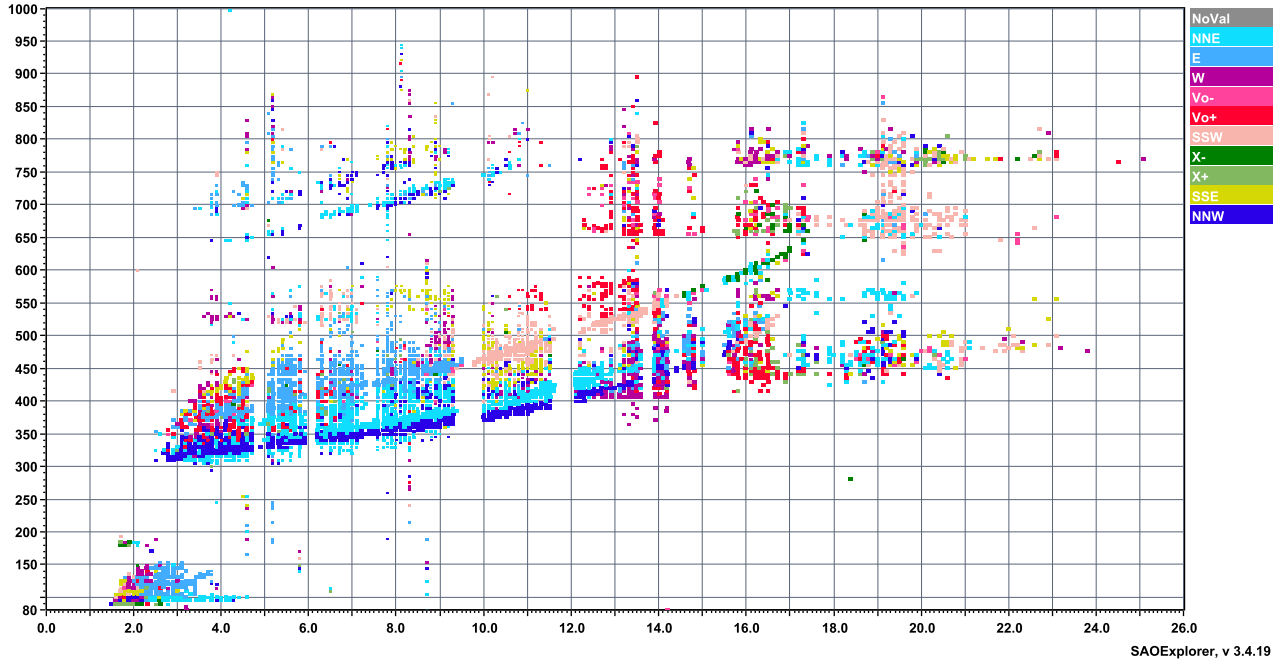


Figure 4. Boa Vista day 305, 23:55 UT ($\sim 19:55$ LT) ionogram showing ionogram bubble traces attributed to an EPB.

Boa Vista, BVJ03

2002.11.20 (324) 23:40:00.000 _I_

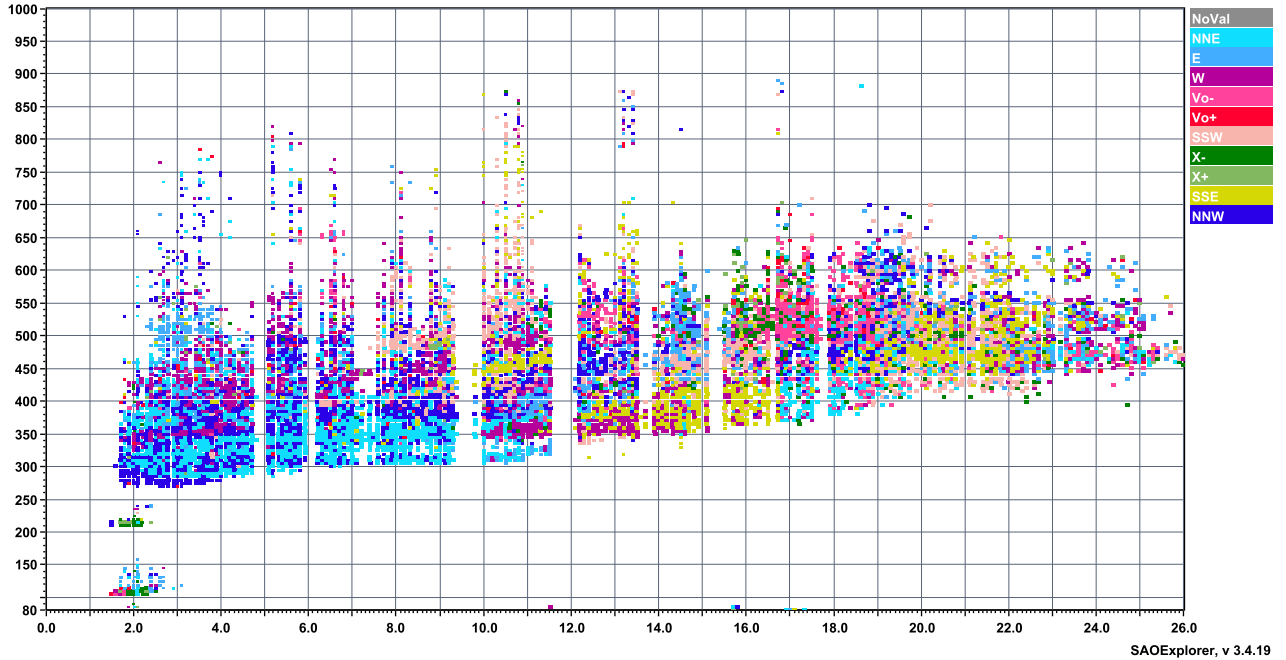


Figure 5. Boa Vista day 324, 23:40 UT ($\sim 19:40$ LT) ionogram showing ionogram bubble traces attributed to an EPB.

to the IBTs could have been produced anywhere in the quite large field of view of the ionosonde.

5. A Simple Model of an EPB

[30] An EPB is a 3-D electron density depletion in the equatorial F2 region. For discussion purposes, we need to

define the longitudinal width of the bottom of the EPB. To do this, we follow the plots given by *Comberiate and Paxton* [2010], and assign an average width of 3° . Because the 3-D shape of an EPB is not simple (see, for example, *Takahashi et al.* [2001] and *Yao and Makela* [2007]), we adopt a model that includes just the essential features.

[31] Figure 6 illustrates the longitudinal cross section of a simple model of an EPB that will be used to interpret the IBTs and DSEs. In line with observations made over the years, the top of the model EPB is tilted to the west.

[32] From the point of view of scintillations, the key features of an EPB are the strong electron density gradients across the walls of the EPB since these lead to meter-scale irregularities that scatter the VHF signals (Bragg scattering at $\lambda/2$) (see, for example, *Vijayakumar and Pasricha* [1997]). *Sales et al.* [1996] alternatively explained the observed echo traces resulting from a plasma depletion (EPB) in terms of coherent scatter of the HF waves from the irregularities at the walls of the bubble.

[33] From the point of view of the IBTs, the key features of the EPBs are the walls at the base of the F2 layer. These are illustrated in Figure 6 as smoothly curved, but the presence of multiple IBTs on the same ionogram suggests that they in fact have vertical structure. The extension of the IBTs to frequencies exceeding 25 MHz suggests that scattering is involved, not simple reflection, but the model is meant to be simple.

[34] As an EPB drifts to the east toward the ionosonde/VHF receiver, the western wall of the EPB will move across the LOS to the (western) satellite, followed by the eastern wall, and scintillations will occur. The fact that scintillations continue while the gap between the walls moves across the LOS indicates the presence of fine structure within the actual bubble, contrary to our simple model.

[35] The IBTs will start out at longer range and then move nearer to the normal F2 trace or closer to the ionosonde. This is consistent with reflections from the base of the western wall. (*Sales et al.* [1996] determined that the reflection occurs from within the EPBs, but we defer to our simple model.) When the EPB passes overhead, the IBT will lie on top of the normal F2 trace and will not be identified as a separate feature of the ionogram. As the EPB drifts to the east away from the ionosonde/VHF receiver, IBTs would be created by reflection from the base of the eastern wall.

[36] Because of the westward tilt, the EPBs crossing the western VHF LOS could be aligned almost parallel to the LOS. If this is true, the scintillations would cease once the western wall has crossed the LOS. On the other hand, the eastern LOS could cut through multiple EPBs, and there would be a smaller chance of having no scintillations. A

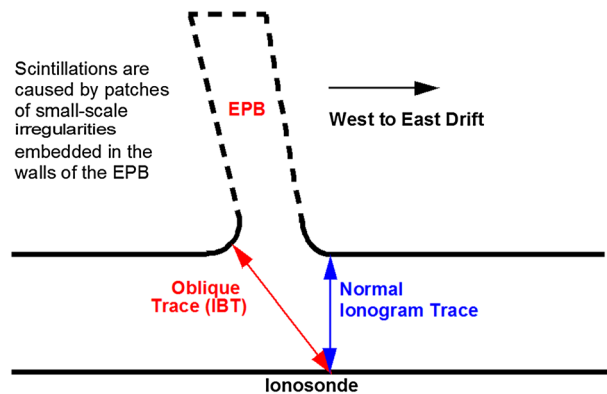


Figure 6. Simple model of an EPB used to interpret the ionogram bubble traces and the temporal occurrence of scintillation of satellite communications signals.

similar effect has been seen in optical observations at several equatorial sites, which show an enhancement of spatial contrast when viewing to the west nearly parallel to the plume walls, and a corresponding reduction in contrast when viewing to the east along LOS more perpendicular to tilted plumes. In particular, historical optical data sets that AFRL has collected from Ascension Island and Carmen Alto, Chile, which are situated to either side of the COPEX region of study, commonly show this effect.

6. Observations of VHF Scintillations

6.1. Overview of Section

[37] Recall that observations of the VHF scintillations and the eastward drift of the EPBs were made at Alta Floresta near the magnetic equator and at Boa Vista and Campo Grande near the anomaly peaks. This section illustrates and interprets the observations in terms of multiple case studies.

[38] The strength of the scintillations is expressed in terms of the S4 index, which is defined as the normalized standard deviation of the received signal power intensity expressed as follows [*Yeh and Liu*, 1982]:

$$S4^2 = [\langle I^2 \rangle - \langle I \rangle^2] / \langle I \rangle^2$$

[39] where I is the signal power. The scintillation events discussed here were predominantly for strong scattering (saturated – $S4 = 1.0$). We have not analyzed any observations recorded under more moderate conditions.

[40] The COPEX campaign nominally ran from September to December 2002. However, because we wanted nights for which both VHF scintillation and ionosonde observations were available, we analyzed the data for the nights of 299/300 to 329/330, except for 304/305 and 307/308 to 315/316 for which there was either no scintillation data or no ionograms. No scintillations were observed at any site for the night of 306/307, and no ionogram showed any IBTs. In general, scintillations and IBTs occurred together. However, there were intervals that had IBTs and no scintillations, and vice versa. There were usually no IBTs present as $S4$ decreased at the end of a night.

[41] The vertical geometry of a scintillation receiver and two communications satellites is illustrated in Figure 7. For a particular EPB drifting in from the far west, scintillations will occur first on the western LOS. The EPB will then pass into the gap between the two LOS, and neither LOS will be

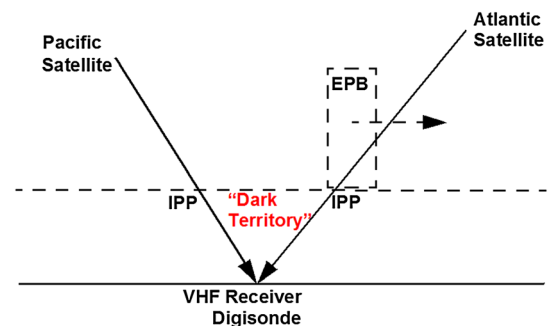


Figure 7. Sketch of the lines of sight to the two communications satellites.

affected. After about 75 min, scintillations will start up on the eastern LOS as the EPB passes across it. No scintillations will be observed once the EPB has crossed the eastern LOS. The continued occurrence of scintillations on the two links is an indication of a train of EPBs drifting eastward across the SCINDA observing site or developing within the digisonde observation region.

[42] Scintillations generated to the west will not be observed while the EPB is drifting across the gap (labeled “dark territory”) between the two IPPs. However, their presence would be indicated by the presence of IBTs on the digisonde ionograms.

6.2. Case Study 1: Days 302/303

[43] Figure 8 shows the temporal variation of the VHF scintillation index for the links to the west (Pacific) and east (Atlantic) communications satellites for the night of 302/303. The blue traces correspond to the scintillations, while the thick green lines indicate the presence of IBTs on the ionograms (which were all processed manually). The times are all UT, with times on the next day being incremented by 24. Local time is ~ 4 h behind UT for all three sites. The scintillation index saturates at 1.0, and the definition loses meaning above that. The indices for Alta Floresta and Boa Vista have been offset by 2 and 4 for clarity of the plots.

[44] The IBTs (thick green lines) and scintillations (DSEs) on the eastern LOS start almost simultaneously. Note that the DSEs that first cross an LOS are associated with the youngest EPBs. The EPBs age as they drift eastward. The median onset times of scintillations for the eastern LOS were 22:50 UT (Boa Vista), 22:45 UT (Alta Floresta), and 23:00 UT (Campo Grande). The spread in onset times at each site is too large to determine if the differences between sites are significant.

[45] Figure 8 was chosen for discussion mainly because of the isolated peak in the S4 observations on the Pacific link at 27:00 UT (for Boa Vista and Campo Grande; $\sim 26:45$ for Alta Floresta). This same isolated peak shows up on the Atlantic link at $\sim 28:15$ UT, 75 min later. Since the IPPs are separated by ~ 640 km, the EPB giving rise to the

scintillations must have had an effective easterly drift speed of ~ 512 km/h or ~ 142 m/s. Recall that section 3 showed that the drift velocities actually decrease after their original post-sunset onset, so the 142 m/s velocity is just an average value.

[46] It is generally difficult to associate a particular scintillation peak with particular IBTs, since we cannot tell where an EPB lies in the field of view of the ionosonde. However, this isolated peak offers a consistent interpretation. There was an IBT on the ionograms that moved to shorter ranges at all three sites between 26:40 and 27:35 UT. The ionogram color code for the lower frequency part of the IBT indicated that the IBT echoes were coming from the west, which is as expected. This IBT corresponds to the 27:00 UT scintillation peak on the Pacific LOS, as the EPB moves to the east and closer to the ionosonde. For the 27:35 UT ionogram, the ionosonde would be basically looking up into the EPB.

[47] Likewise, there was an IBT present on the ionograms that moved to longer ranges between 27:55 and 28:25 UT, lifting off the main trace and eventually disappearing (the amplitudes of the echoes decreased to zero) from the ionograms. This IBT corresponds to the 28:15 UT scintillation peak on the Atlantic LOS, again as the EPB moves to the east, but this time further from the ionosonde. The ionogram color code for the lower frequency part of the IBT indicated that the IBT echoes were coming from the NNE, which is again as expected.

[48] IBTs with increasing ranges that did not appear in the next ionogram were also seen, for example, from 02:35 to 03:15 UT on the night of 304/305, and also at Campo Grande between 00:00 and 00:25 UT, and between 01:15 and 01:45 UT on the night of 329/230. These IBTs are from reflections in the north. It is interesting to note, however, that IBTs reflected from the western wall usually appear at longer ranges than those reflected from the eastern wall. This feature was also reported by *Sales et al.* [1996] for a southern anomaly digisonde site. There are always exceptions, of course. An IBT on the Campo Grande ionogram of day 320 moved to longer ranges between 01:25 and 02:45 UT, finally disappearing at the unusually long range of 900 km. This EPB does not seem to have passed overhead of the ionosonde.

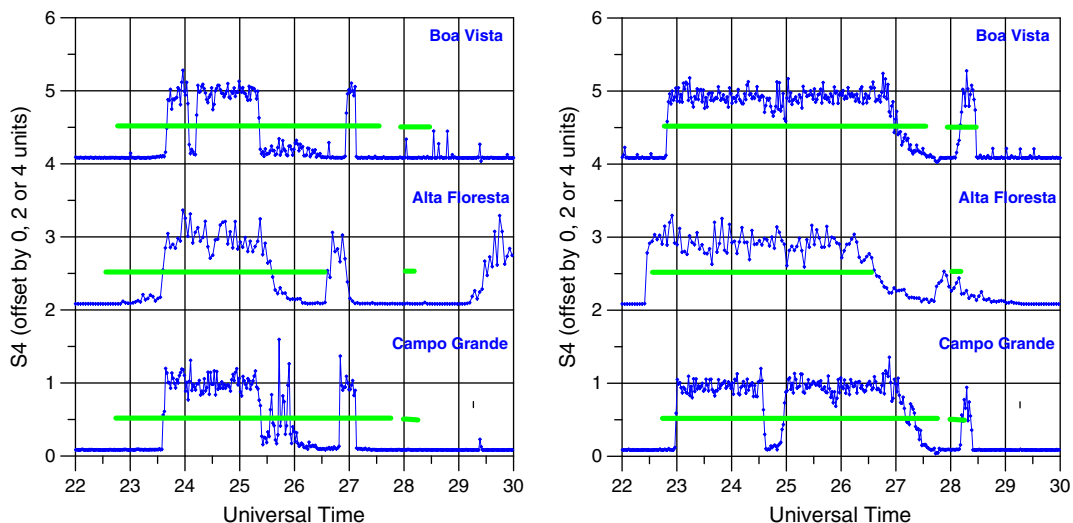


Figure 8. (left) Days 302/303: Offset VHF scintillation index for observations of the Pacific Ocean satellite. (right) Days 302/303: Offset VHF scintillation index for observations of the Atlantic Ocean satellite.

[49] The scintillation observations for the eastern LOS in Figure 8 show a gap in the Campo Grande record at 24:30 UT. The restart of scintillations at 25:00 UT corresponds to the onset of scintillations at 23:30 UT on the western LOS, after an eastward drift that lasted 1.5 h.

[50] The narrowest DSEs lasted between 15 and 30 min. For a 30 min DSE, which is more typical than the shorter 15 min DSEs, a drift speed of 512 km/h would yield an approximate width of the EPB of 256 km, or $\sim 2.5^\circ$. Narrow DSEs are seen only very rarely on the eastern LOS. This is consistent with westward tilt of the bubbles, which precludes observations of single EPBs aligned with the tilt when looking east.

[51] It is not always possible to associate EPBs crossing the western and eastern LOS because the scintillations on the eastern LOS tend to be more continuous than those on the western LOS. One possible explanation of this feature is as follows. The EPBs seen on the eastern LOS are always at least ~ 75 min older (if we are tracking an individual bubble) than they were when they passed across the western LOS, and may have diffused horizontally and become broader. The decrease of the drift velocity with time (Figure 2) would also lead to a concatenation of the train of EPBs.

6.3. Case Study 2: Days 329/330

[52] Figure 9 shows the temporal variation of the VHF scintillation index for the night of 329/330. This is another carefully chosen case that allows features to be tracked from the western LOS to the eastern LOS.

[53] For Boa Vista, the scintillations started on the eastern LOS at 23:10 UT ($\sim 19:10$ LT), as did the IBTs on the Boa Vista ionograms. The scintillations started to decay at $\sim 25:30$ UT and reappeared at $\sim 26:15$ UT. On the western LOS, the scintillations started at 25:00 UT, so we can attribute the scintillations on the eastern LOS at $\sim 26:15$ UT to the same EPB that caused the 25:00 UT scintillations on the western LOS, delayed by a drift time of 75 min. Similar arguments can be applied to the Alta Floresta and Campo Grande observations.

[54] Note that the ionograms continued to exhibit IBTs at all three digisonde sites during the dropout of the scintillations. This would seem to be a simple viewing effect. The LOS are precisely defined and isolated in space. On the other hand, the digisondes have a conical field of view that has a half angle of at least 15° that would cover a large part of the sky and potentially encompass several EPBs. Consequently several EPBs could be contributing to the presence of IBTs.

[55] Figure 9 also shows that the third scintillation peak on the Pacific LOS does not have sharp edges for Boa Vista and Campo Grande. One interpretation of this feature is that it corresponds to an older EPB for which the gradients across the bubble walls have been decreased by diffusion so that they do not cause strong scintillation.

6.4. Case Study 3: Days 319/320

[56] Figure 10 shows the temporal variation of the VHF scintillation index for the night of 319/320.

[57] The Boa Vista scintillations for 319/320 started up on the eastern LOS at $\sim 22:55$ UT ($\sim 19:00$ LT), in step with the IBTs (green bars). They started up just before 24:00 UT (19:45 LT) on the western LOS, which is 0.75 h later in local time than on the eastern LOS. This is an indication that the first EPBs of the night are not all created at the same LT at different longitudes.

[58] The buildup again at $\sim 25:30$ UT of the scintillations on the eastern LOS corresponds to the onset of scintillations on the western LOS at $\sim 24:00$ UT, with a drift time of ~ 1.5 to 1.75 h. The S4 index on the Atlantic LOS at Boa Vista and Campo Grande decreases to lower values after $\sim 26:15$ UT. This decrease is discussed in section 8.

6.5. Case Study 4: Days 305/306

[59] Figure 11 shows the temporal variation of the VHF scintillation index for the night of 305/306.

[60] The scintillations on the Pacific LOS for the night of 305/306 are some of the most abundant for the analysis interval, with a long train of EPBs coming from the west. The Atlantic scintillations started up at $\sim 23:00$ UT (19 LT at the

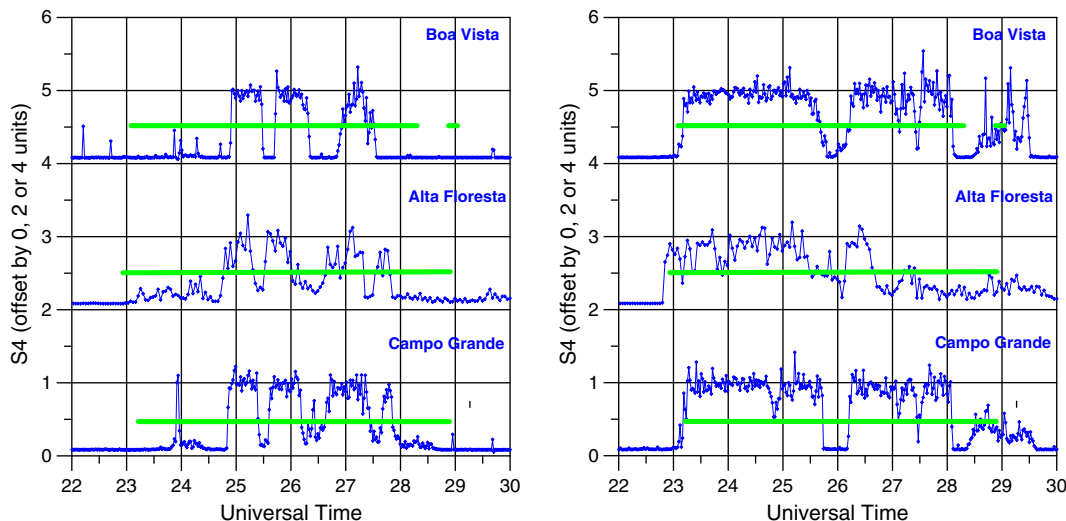


Figure 9. (left) Days 329/330: Offset VHF scintillation index for observations of the Pacific Ocean satellite. (right) Days 329/330: Offset VHF scintillation index for observations of the Atlantic Ocean satellite.

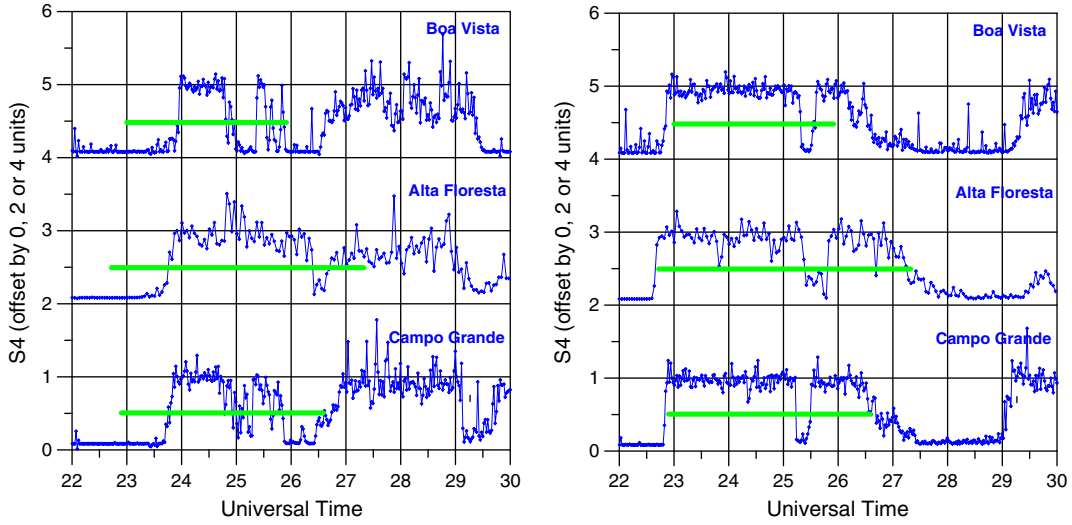


Figure 10. (left) Days 319/320: Offset VHF scintillation index for observations of the Pacific Ocean satellite. (right) Days 319/320: Offset VHF scintillation index for observations of the Atlantic Ocean satellite.

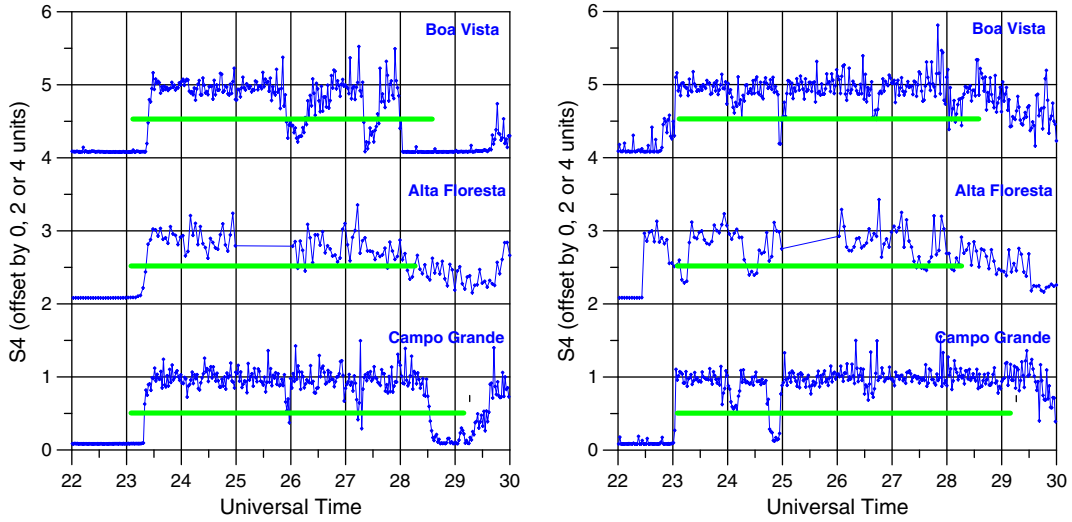


Figure 11. (left) Days 305/306: Offset VHF scintillation index for observations of the Pacific Ocean satellite. (right) Days 305/306: Offset VHF scintillation index for observations of the Atlantic Ocean satellite.

observing sites; a little later in LT at the IPP), while the Pacific scintillations started at $\sim 23:20$ UT. If the scintillations start at the same LT, the difference in UT would correspond to the separation of the IPPs, which is ~ 660 km, 6° in longitude, and ~ 24 min.

[61] The sudden decrease of S4 for the Campo Grande eastern LOS at 24:45 UT does not correspond to any feature of the scintillations on the western LOS.

6.6. Case Study 5: Days 324/325

[62] Figure 12 shows the temporal variation of the VHF scintillation index for the night of 324/325.

[63] Whereas some nights show abundant scintillations for both satellites (and make scintillation forecasting trivial), the night of 324/325 shows only about 2 h of scintillations on the Atlantic LOS, and virtually none on the Pacific LOS. The scintillations on the Atlantic LOS are consistent with the occurrence of IBTs, so the scintillation observations

can be taken as valid. There is no real evidence of DSEs having drifted from the west to the east (and appearing after the locally generated DSEs had terminated). On this night, therefore, the EPBs observed were probably mostly created in the field of view of the ionosonde, and not to the west of the Pacific LOS. This would make forecasts based on EPBs crossing the Pacific LOS largely unsuccessful.

[64] The scintillations on the Pacific LOS are highest for Alta Floresta and Campo Grande, and smallest for Boa Vista. A similar situation holds for the nights of 301/302 and 316/317 (not shown in this paper). A possible interpretation is that the lower drift speed at Boa Vista (see section 3) results in less efficient irregularity generation. Also, asymmetry of electron densities across the magnetic equator can cause differences in scintillation strength. Although the EPBs and other large-scale features follow flux tubes and map across the equator, scintillation-scale irregularities are generated locally.

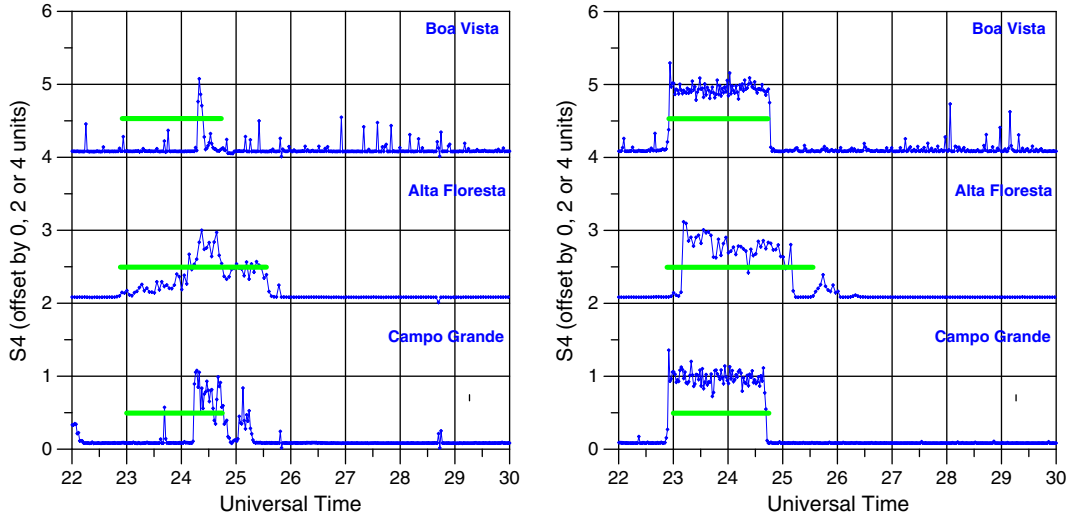


Figure 12. (left) Days 324/325: Offset VHF scintillation index for observations of the Pacific Ocean satellite. (right) Days 324/325: Offset VHF scintillation index for observations of the Atlantic Ocean satellite.

7. Drift Velocities Derived from the IBTs

[65] As mentioned in section 6, the average horizontal drift velocity derived from the LOS crossings for the narrow scintillation peak in Figure 8 (for the night of 302/303) was ~ 512 km/h or ~ 142 m/s. The spaced-receiver measured drift velocity between 03 and 04 UT for this night was ~ 110 – 120 m/s. This second technique showed that the drift velocity actually decreases during the night.

[66] A third estimate of the eastward drift velocity can be derived using the range of an IBT as it drifts from west to east (toward and then away from the ionosonde), although this is often an uncertain procedure because the IBTs are inherently spread in range. It is also not easy to find a single EPB that can be tracked as it crosses over the ionosonde. There are often several overlapping EPBs, none of which seems to go through the zenith. For the case discussed here, the slant range (read as the virtual height on the ionogram) of the leading edge of the IBT was measured at a constant frequency of 16 MHz (foF2 was ~ 20 MHz).

[67] Figure 13 illustrates the drift of an IBT derived from observations of the slant range for the Boa Vista ionograms between 02:45 UT and 04:25 UT on day 303. The horizontal range of the IBT is derived from the slant range and the virtual height of the main F2 trace at $\sim 03:35$ UT. The IBT was indistinguishable from the normal F2 trace between 03:30 and 03:45 UT, when the EPB was overhead and the ionosonde was looking into the EPB.

[68] The early movement toward the ionosonde (and reflection from the west wall of the EPB) yielded an eastward drift velocity of ~ 540 km/h (~ 150 m/s), while the later slower movement away from the ionosonde (and reflection from the east wall of the EPB) yielded a velocity of ~ 415 km/h (~ 115 m/s).

[69] The different drift velocities derived from the three types of measurement are considered to be consistent, given that the different drift velocities correspond to different and not well-defined features of the EPB.

[70] There were many opportunities to calculate the drift velocity corresponding to an IBT, but the process is intensely manual, so only a few cases were investigated. A second case

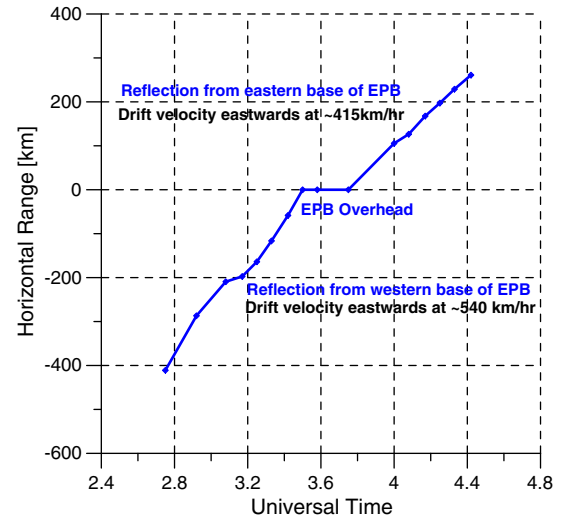


Figure 13. Horizontal range and drift velocity of an IBT tracked through the overhead position, night of 302/303, Boa Vista

considered was for Campo Grande, day 302. The drift speed for a retreating IBT between 04 and 05 UT was nearly constant (as in Figure 13), at ~ 250 km/h or 69 m/s. This value is consistent with the 04 UT hourly value of 79 m/s derived from the spaced antennas for the same night. The scintillations started to decay when the IBT vanished at 05:10 UT. (In the interests of paper length, we have not considered here the drifts measured directly by the digisondes. In fact, the “Directograms” generated by the digisonde gives the drift velocity as the slope of the echo pattern. See Reinisch *et al.* [2009], their Figure 10, and references therein.)

8. Rate of Decrease of S4

[71] Many of the Atlantic S4 curves follow an exponential decrease toward the end of the plotted observing period (06 UT; 02 LT). Although this looks like a decay, the most

likely interpretation is that the LOS traverses a shorter and shorter section of the EPB as the EPB drifts across the LOS, thereby encountering fewer and fewer sources of scintillation.

[72] The “decay” time constants have been derived manually for several cases by plotting $\ln(S4)$ versus time, modeling the decay as $\exp(-t/\tau)$. Figure 14 shows the exponential decay of S4 with time for Boa Vista for the night of 302/303. At 26.8 UT (when the decay started), the EPBs would have been ~ 3 h old. (The S4 observations were shown in Figure 8.)

[73] For this case, the time constant was ~ 21 min. It was ~ 48 min for Alta Floresta and ~ 17 min for Campo Grande. Note that the manual determination of the time constant is approximate. Note also that these time constants apply to the last EPB(s) to cross the eastern LOS for that night. The decay of earlier EPBs would often be masked by younger EPBs arriving from the west. The 324/325 scintillations (Figure 12) from the apparently isolated EPB that crosses the Atlantic LOS basically just cut off—there is no gradual decay.

[74] There were six nights with usable decays at all three sites at the end of the scintillations on the eastern LOS for the night. The median time constants were 21, 47, and 28 min for Boa Vista, Alta Floresta, and Campo Grande. Thus, the time constants were similar for the two anomaly locations and about twice as long at the equatorial site. The determination of the time constants was relatively uncertain for Alta Floresta because the S4 index did not always saturate (and thus define a clear start time for the decay).

[75] In general, the Pacific observations tend to cut off quickly, and not decay slowly. We attribute this difference between the two LOS to the fact that the EPBs are tipped to the west and are aligned more closely with the slope of the Pacific LOS than the Atlantic LOS.

[76] It is interesting to consider if there is any ionogram signature that could correspond to the (apparent) decay stage of the S4 index. In fact, there seems to be no such

signature—the most common situation is for there to be no more IBTs. This is consistent with the EPBs moving out of the field of view.

9. Longitudinal Dependence of IBTs

[77] Climatological studies of IBTs would be very useful for planning the deployment of scintillation equipment because of the high correlation between VHF scintillation and the occurrence of IBTs. Climatological studies of other aspects of EPBs could also be useful for planning purposes. For example, *Sobral et al.* [2002] determined the climatology of EPBs over Brazil (actually at Cachoeira-Paulista) using 630 nm airglow observations. Likewise, *Seemala and Valladares* [2011] determined the climatology of depletions in total electron content (TEC) over South America, which are clearly related to EPBs.

[78] As part of the present study, we have determined the existence of EPBs (as indicated by the presence of IBTs in the ionograms) for Jicamarca, Cachimbo, and Sao Luis on each night in October 2002 (actually for 30 nights from 278/279 through 307/308; there were no Sao Luis ionograms for six nights). The corresponding EPB counts for the Jicamarca, Cachimbo, and Sao Luis ionograms for October 2002 are compared in Tables 5 and 6.

[79] The occurrences of EPBs at Sao Luis and Cachimbo are obviously highly correlated. An EPB at Sao Luis would successfully indicate the presence of an EPB on the same night at Cachimbo on 18/19 = 95% of nights. On five nights, there were no EPBs at either Sao Luis or Cachimbo.

[80] An EPB at Cachimbo would successfully indicate the presence of an EPB at Jicamarca on 16/25 = 64% of nights.

[81] The occurrence percentages of EPBs for the three sites (Sao Luis, Cachimbo, and Jicamarca) are 19/24 = 79%, 25/30 = 83%, and 18/30 = 60%. This westward decrease of the occurrence probability of EPBs is consistent with the westward decrease of the occurrence rate of TEC depletions found by *Seemala and Valladares* [2011] for the same season (but low solar activity: 2008). From a statistical study of ionosonde data, *Abdu et al.* [1998] showed a westward decrease of the spread F occurrence; while using DMSP and ROCSAT-1 observations, *Burke et al.* [2004] also found significantly fewer occurrences of EPBs than expected near the west coast of South America.

10. Summary and Discussion

[82] The primary aim of this paper was to present and interpret observations of scintillations of VHF satellite communication signals received at equatorial locations, in terms of the

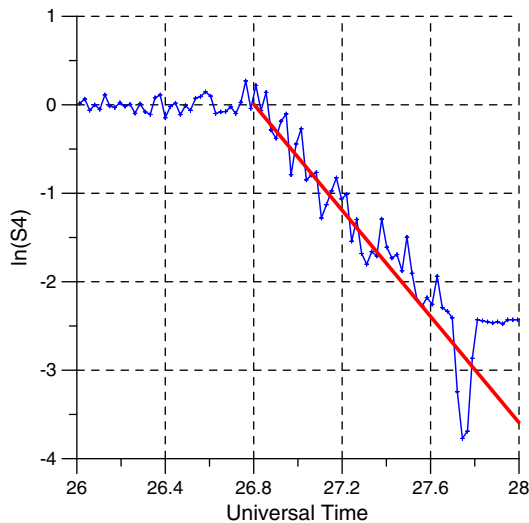


Figure 14. Days 302/303: Logarithmic decrease with time of the VHF scintillation index for Boa Vista observations of the geostationary satellite to the east (Atlantic)

Table 5. Numbers of Nights with EPBs at Sao Luis and Cachimbo

$n = 24$	Sao Luis EPB	Sao Luis No EPB
Cachimbo EPB	18	0
Cachimbo No EPB	1	5

Table 6. Numbers of Night with EPBs at Cachimbo and Jicamarca

	Cachimbo EPB	Cachimbo No EPB
Jicamarca EPB	16	2
Jicamarca No EPB	9	3

known properties of EPBs. A secondary aim was to ensure that the interpretations were consistent with features seen on corresponding equatorial ionograms.

[83] The occurrence of discrete scintillation events (DSE) has been shown to be highly correlated with the presence on ionograms of extra traces that we have called ionogram bubble traces (IBTs). IBTs are the ionogram signature of EPBs, just as DSEs are the satellite communications signature of EPBs. In our simple model, scintillations occur as the walls of an EPB cross the lines of sight (LOS) to the geostationary communications satellites. The IBTs correspond to “reflection” of the digisonde signals from the walls of the EPB and move to different ranges as the EPB moves generally eastward across the digisonde’s field of view. Five case studies were used to compare individual DSEs and IBTs in detail.

[84] The eastward drift velocity of an EPB can be obtained (1) by direct observation using an antenna array, (2) by the time a DSE takes to move from the LOS to the Pacific satellite over to the LOS to the Atlantic satellite, and (3) from the rate of change of the slant range to an IBT that can be identified and tracked for a sufficiently long time. For the night of 302/303 (case study 1; Boa Vista), for example, the direct drift measurements showed an initial velocity of ~ 200 m/s followed by a deceleration of ~ 20 m/s/h. The average drift velocity derived by following a DSE as it drifted between the lines of site was ~ 140 m/s (~ 500 km/h). For the early hours of UT day 303, an IBT drifted toward the digisonde at ~ 540 km/h (~ 150 m/s), and later away from the ionosonde at the lower velocity of ~ 415 km/h (~ 115 m/s). The different drift velocities derived from the three types of measurement are considered to be consistent, given that the different drift velocities correspond to different and not well-defined features of the EPB.

[85] The scintillation patterns for the Pacific LOS usually show much more structure than those on the Atlantic LOS. This is consistent with westward tilt of the EPB, which precludes observations of single EPBs aligned with the tilt when looking east.

[86] The decay with time of the S4 index for different DSEs, especially for the Atlantic LOS, has been interpreted in terms of the LOS traversing a shorter and shorter section of the EPB as the EPB drifts across the LOS, thereby encountering fewer and fewer sources of scintillation.

[87] Since the VHF scintillations are so highly correlated with the presence of EPBs on ionograms, we have extended our analysis of IBTs to include other ionosonde sites in South America (Sao Luis and Jicamarca), thus providing a general picture of when and where VHF scintillations could be expected to interfere with satellite communications. The occurrence rates for IBTs (i.e., EPBs as seen on ionograms) were found to decrease to the west, in line with several earlier studies. The IBT occurrence rates would provide a planning tool for deploying scintillation networks such as SCINDA.

[88] Real-time observations of equatorial ionograms do not seem to be necessary for the successful forecasting of scintillations if scintillation receivers are already deployed, at least for the case of near-vertical-incidence soundings. However, a low-elevation HF backscatter sounding system could be employed to detect EPBs and scintillation regions at long ranges over regions with no ground station coverage.

The HF signatures would not be as directly applicable to the operational problem of monitoring ionospheric scintillation, in that they do not measure scintillation directly, but the close correspondence of HF IBTs and actual scintillation regions suggests that remote sensing of scintillation regions by long-range HF radar would provide useful scintillation forecasts.

[89] VHF scintillations in a region could also be inferred from observations of VHF propagation on transequatorial circuits, which relies on ducted propagation along EPBs (see, for example, *Heron and McNamara* [1979] and *Platt and Dyson* [1989]). VHF reception would confirm the presence of an EPB, which would in turn indicate the likelihood of VHF scintillations.

[90] **Acknowledgments.** The COPEX campaign was conducted by the Brazilian National Institute for Space Research (INPE) in collaboration with the Brazilian Air Force and the U.S. Air Force Research Laboratory (AFRL). The digisondes at Boa Vista, Cachimbo, and Campo Grande were built and deployed by the University of Massachusetts Lowell. The scintillation amplitude and drift equipment was developed and deployed by personnel from AFRL. The COPEX ionograms were displayed using SAO Explorer (<http://ulcar.uml.edu/SAO-X/SAO-X.html>). The ionograms can also be viewed at <http://umlcar.uml.edu/DIDBase/>, but with less resolution and flexibility.

[91] We thank Bodo Reinisch for helpful discussions. T.R.P. was partially supported by the Air Force Office of Scientific Research.

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