

# Equatorial range spread F echoes from coherent backscatter, and irregularity growth processes, from conjugate point digital ionograms

M. A. Abdu,<sup>1</sup> I. S. Batista,<sup>1</sup> B. W. Reinisch,<sup>2</sup> J. W. MacDougall,<sup>3</sup> E. A. Kherani,<sup>1</sup> and J. H. A. Sobral<sup>1</sup>

Received 25 February 2012; revised 21 September 2012; accepted 18 October 2012; published 12 December 2012.

[1] Radio wave returns from spread F plasma structures as received by ionosondes can originate from total/specular reflection, partial reflection or coherent backscattering. The dominant mechanism to account for the spread F traces in equatorial ionograms is still an open question. Depending upon the precise mechanism, ionosondes are sensitive to irregularity scale sizes of tens of meters to several tens/hundreds of kilometers. In this paper we analyze signatures of range spreading F layer traces in Digisonde ionograms, taken at Fortaleza (3.9°S, 38.45°W, dip: −9°) and Sao Luis (2.33 S, 44.2W, dip angle: −0.5°), and at a dip equatorial site Cachimbo (9.5°S, 54.8°W, dip: −4.2°) and at its two conjugate sites Bova Vista (02.8°N, 60.7°W, dip: 22.0°) and Campo Grande (20.5 S, 54.7 W, dip −22.3°) in Brazil, to determine the dominant process/mechanism of echo returns from the irregularity structures. A significant component of the ESF trace structures is found to be consistent with the echoes originating from coherent backscattering at field line perpendicular directions. The degree of range spreading of the echoes is found to increase linearly with the top frequency of the echo trace, which is shown to be a more precise indicator of the irregularity strength. Further, the irregularity strength exhibits a significant increase from the equator toward the EIA crests, as well as a strong asymmetry between the conjugate sites.

**Citation:** Abdu, M. A., I. S. Batista, B. W. Reinisch, J. W. MacDougall, E. A. Kherani, and J. H. A. Sobral (2012), Equatorial range spread F echoes from coherent backscatter, and irregularity growth processes, from conjugate point digital ionograms, *Radio Sci.*, 47, RS6003, doi:10.1029/2012RS005002.

## 1. Introduction

[2] Plasma irregularities of the nighttime ionospheric F region are known to be magnetic field aligned density structures with wide ranging transverse scale sizes (spanning several orders of magnitudes) that are responsive to diagnostics by diverse types of radio, optical, and in situ observational devices. Ionosonde observation identifies them as diffuse echoes in the ionograms constituting spread in the F layer traces, in range and frequency, generally known as ‘spread F’. Both the range and frequency types of the spread F traces have been the subjects of extensive investigations at middle, low and equatorial latitudes during the last several decades. Over the equatorial latitudes the most widely

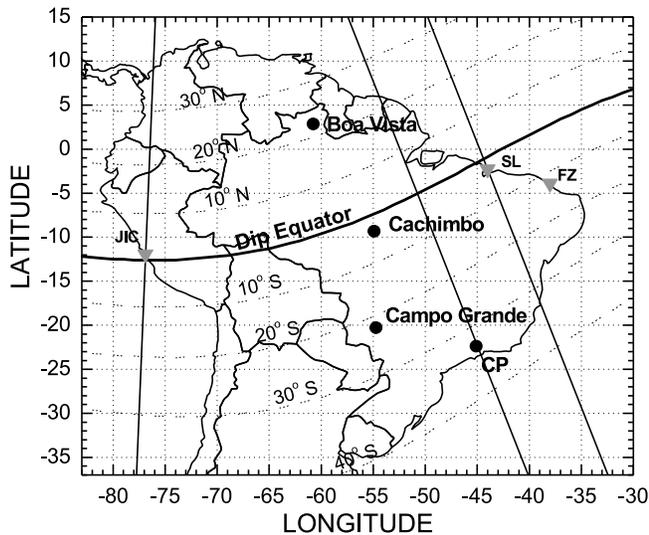
investigated class is the range type spread F and the generic name, the equatorial spread F (ESF), is now used to represent the composite of the equatorial nighttime F region plasma structuring that span from meter to several hundred kilometer scale sizes. A recurring question remains to be the one concerning the bandwidth of the irregularity structure scale sizes required for interpreting the ionogram spread F traces, which inevitably should invoke mechanisms for radio signal returns from the irregularities. The considered mechanisms include total reflection from over dense structures [e.g., King, 1970; Bowman, 1990; Wright *et al.*, 1996, and references therein] [see also Reinisch *et al.*, 2004; Carrasco and Batista, 2012] to partial reflection or Rayleigh scattering from small size irregularities [Booker and Wells, 1938; Booker and Ferguson, 1978], and to Bragg backscattering (or coherent scattering) by plasma density fluctuations with scale size of  $\lambda/2$ ,  $\lambda$  being the radio wavelength. The Bragg scattering principle, applied to scatter echoes from ionospheric irregularities diagnosed by coherent backscatter radars, has been widely discussed in the literature [e.g., Schlegel, 1996]. Depending upon the detailed features that can be identified in well-resolved spread F traces one or more of the above mechanisms can be invoked for interpreting them. For example, the midlatitude spread F traces often appear to be superposition of unresolved F layer traces

<sup>1</sup>Instituto Nacional de Pesquisas Espaciais, São Jose dos Campos, Brazil.

<sup>2</sup>Lowell Digisonde International, LLC, Lowell, Massachusetts, USA.

<sup>3</sup>Department of Electrical Engineering, University of Western Ontario, London, Ontario, Canada.

Corresponding author: M. A. Abdu, Instituto Nacional de Pesquisas Espaciais, Ave. dos Astronautas 1758, Jd da Granja, 12245970, São Jose dos Campos, Brazil. (maabdu@dae.inpe.br)



**Figure 1.** The Digisonde sites used in this study. The sites are: SL (Sao Luis), Fz (Fortaleza), and Cachimbo, Boa Vista and Campo Grande constituting the COPEX (Conjugate Point Experiment) sites.

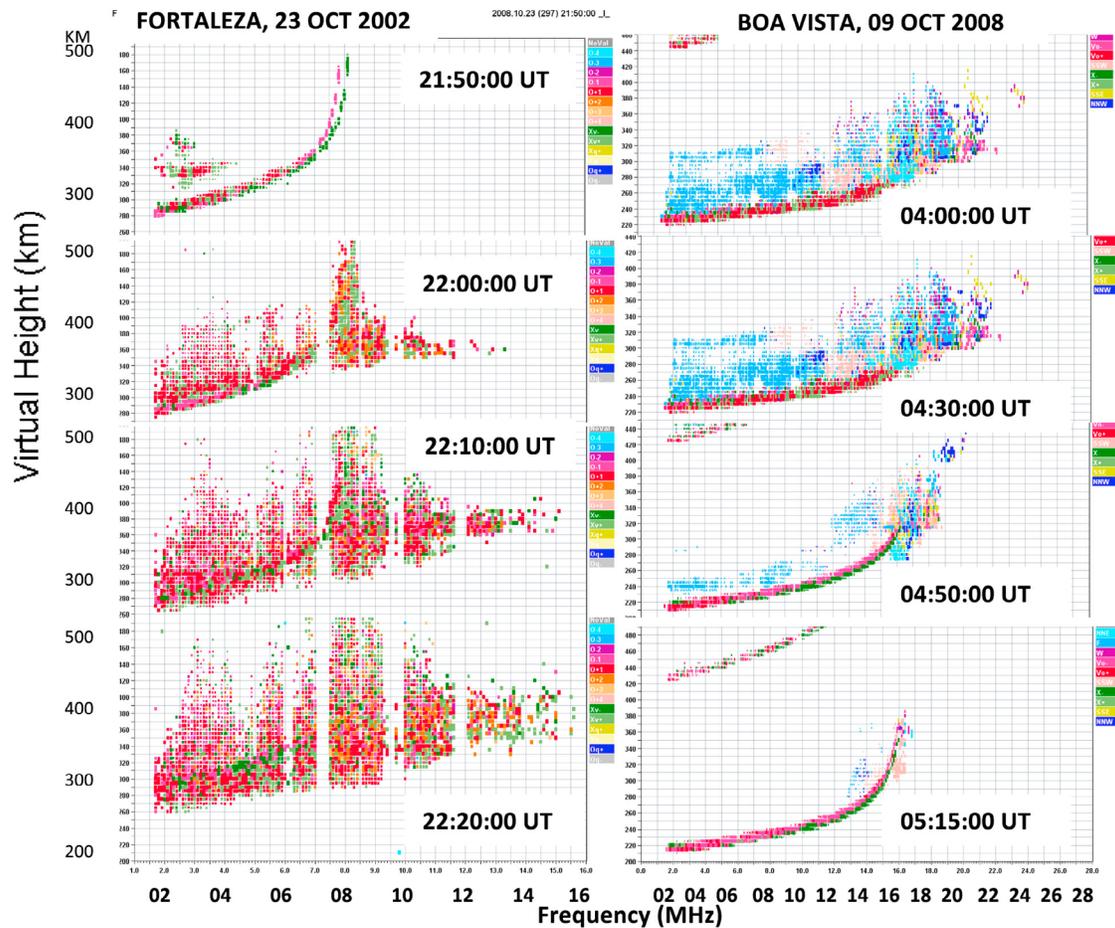
arising from total reflection in oblique direction coming from surfaces of undulations with strong horizontal gradient in dense plasma. There have been suggestions in the literature [e.g., King, 1970; Wright *et al.*, 1996] favoring the total reflection processes as responsible also for the spread F traces in the equatorial ionograms. This question, however, appears to be far from being resolved as new results from moderns digital ionosonde do show strong evidence of the dominating presence of coherent backscatter echoes constituting the major features of spread F traces over equatorial latitudes. Sales *et al.* [1996] showed from ray tracing simulations that Digisonde HF rays returning from spread F/plasma depletion irregularities encountered perpendicularity with the earth's magnetic field. Based on the ionograms recorded at dip equatorial and conjugate sites in Brazil we present here evidence showing that the major characteristics of the spread F trace development during an instability process are compatible with the process of coherent backscattering of the radio waves, even when multiple unresolved traces that could be originating from total reflection process at oblique angles could be present. The Digisonde ionogram spread F trace echoes interpreted in terms of coherent backscattering reveal the nature of the irregularity cascading process during the growth phase of an ESF instability. The present results further show that the ESF irregularity strength as measured by the top frequency of the spread F trace increases from the equatorial anomaly trough to the crest latitude. The irregularity strength exhibits also significant asymmetry between the low latitude conjugate ends of a magnetic field line.

## 2. Results

[3] The results presented in this paper were obtained from several Digisondes operated at the Brazilian sites shown in Figure 1. Figure 2 shows some examples of the ionograms to illustrate how the echo range spreading in the F layer trace

and the top frequency of the received spread F echoes evolve with time in successive ionograms. These echoes arise either from irregularities at the bottom side (or inside) of a growing plasma bubble structure, or that of a decaying bubble, as seen by the Digisonde. In the left panels that illustrate a growth phase of a spread F trace over Fortaleza (3.9°S, 38.45°W, dip angle:  $-9^\circ$ ), the echo trace started at 2150 UT (1918 LT). We note in the subsequent ionograms that the echo spread range steadily increased from around 60 km at 2150 UT to around 200 km at 2220 UT when the corresponding top frequency of the spread F trace (fop) increased from around 4 MHz to 15 MHz. An exactly opposite trend is evident in the ionograms on the right panels that illustrate the decay phase of a spread F trace over Boa Vista (02.8°N, 60.7°W, dip angle:  $22.0^\circ$ ). If the signal returns originate from coherent backscattering by irregularities having scale sizes half the wavelength of the probing radio waves, then the fop would represent the smallest scale size of the evolving/cascading irregularities. Thus it is interesting to see that as the irregularity scale size becomes smaller in successive ionograms (indicated by the increase in fop) the range spread from larger scale size irregularities (at smaller frequencies, that is,  $f < \text{fop}$ ) increases. It is our present understanding that the plasma bubble development by the Rayleigh-Taylor mechanism, operating on larger-scale structures, is accompanied by simultaneous generation of smaller scale structures by cascading process through secondary instability mechanisms operating at the steepening density gradients regions of the larger scale structures [e.g., Haerendel, 1973]. Thus we expect to observe a broadening of the irregularity spatial spectrum, that is, the cascading smaller scale sizes dominating with time during the growth phase of a bubble event. The result in Figure 2 appears to be consistent with this picture and therefore suggests that the process of coherent backscattering is indeed the dominant mechanism in this case responsible for the formation of spread F traces in the ionograms recorded by the Digisonde. It has been observed that spread F trace with these characteristics occur regularly in addition to whatever unresolved traces (often oblique traces) from total reflection that may also be present, as discussed in the literature.

[4] Having seen the qualitative relationship between the top frequency of the spread F trace (fop) and the degree of range spreading (RSF) we will examine below in further detail the consequences of such a relationship for the use of the parameter fop for quantifying the RSF intensity in ionograms. Figure 3a shows the local time variation of the monthly mean spread F range (in km) plotted for a one-year period, from July 2002 to June 2003, over Sao Luis, Brazil (2.33 S, 44.2W, dip angle:  $-0.5^\circ$ ). To obtain the monthly mean spread F range, we first generated an average spread F range (ASR) for each ionogram by considering the SR (Spread Range) at all the frequencies of that ionogram. This value is then used to obtain the mean spread range at a given local time for the entire month, which we call monthly mean spread range (MMSR) calculated at 15-min resolution (the ionogram cadence). Correspondingly we calculated also the monthly mean fop values (MMfop). The MMSR plots of Figure 3a clearly brings out the well-known characteristics of the local time and monthly/seasonal behavior of the range spread F irregularity occurrence over Brazil for the period of



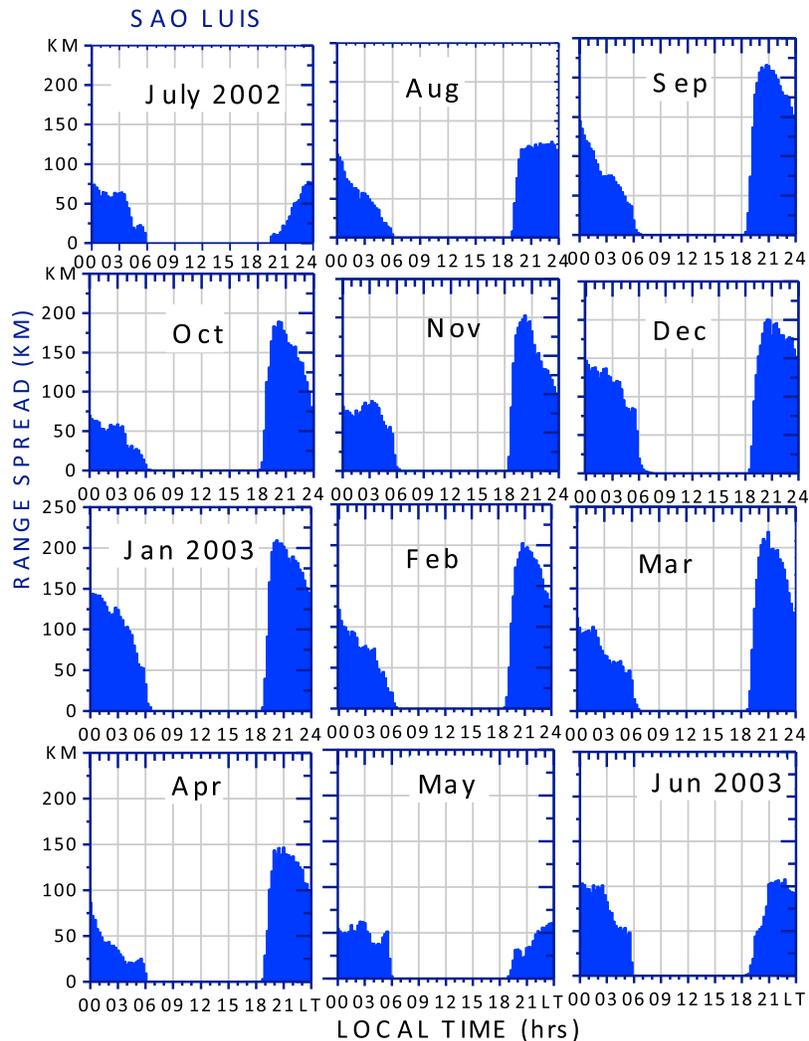
**Figure 2.** (left) Ionograms from the DPS-4 over Fortaleza illustrating the initiation and growth of the spread F trace at successive 10 min interval starting at 2150 UT (1918 LT). The top frequency of the spread F trace (fop) varied from 4 MHz at 2150 UT to 16 MHz at 2220 UT and the spread range correspondingly increased from approximately 60 km to 200 km. (right) The recovery of an event over Boa Vista.

2002–2003 which is close to a solar maximum epoch. We notice that the post sunset spread F starts near 19 LT and peaks near 20 LT or a little later in all months, and its peak intensity (that is, the peak spread F range) is strongest during the months running from September to March. This is similar to the previously published results for Fortaleza, a nearby location [see, e.g., *Abdu et al.*, 1992]. Figure 3b shows the corresponding temporal distribution of the MMfop over Sao Luis. The outstanding features in the monthly mean local time variations of the two parameters are strikingly similar in the two figures, which would suggest the possibility, to be discussed later, of using the parameter fop for quantifying the intensity of a range spread F event. From observations over Jicamarca it has been shown [*Rastogi*, 1978] that the range spread F occurrence is closely correlated with VHF radar plumes produced by coherent backscatter from 3-m scale size irregularities associated with plasma bubbles.

[5] Figure 4 shows a plot of the MMSR against the MMfop over Sao Luis for the same one-year period 2002–2003 as that of the Figures 3a and 3b. The near linear dependence between the two parameters is consistent with the result presented in Figures 3a and 3b, which therefore reinforces the possibility that the intensity of a range spread

F event (or plasma bubble event) can be quantified in terms of the measured fop value. We want to point out here that the fop is a specific frequency which can be read precisely from an ionogram whereas the spread range (SR) in an ionogram can vary significantly with the sounding frequency so that some degree of uncertainty in the value determined as the ASR is expected to be present. This fact might explain in part the degree of scatter of the points in Figure 4. Based on above facts, the parameter fop turns out to be a more reliable indicator of the spread F intensity than is the (until now used) spread range index that can vary considerably with the frequency in the ionogram.

[6] For a better evaluation of the significance and consequences of these results we analyzed additional data collected by Digisondes operated at magnetically conjugate sites during the COPEX (Conjugate Point Equatorial Experiment) campaign conducted in Brazil during the October–December 2002 period. (Some results from the COPEX campaign can be found in *Abdu et al.* [2009], *Batista et al.* [2008], and *Sobral et al.* [2009]). Figures 5a, 5b, and 5c show, respectively, the results of the analysis for the dip equatorial site Cachimbo – CX (9.5°S, 54.8°W; dip: –4.25°), the northern conjugate site Boa Vista – BV (02.8°N, 60.7°W;

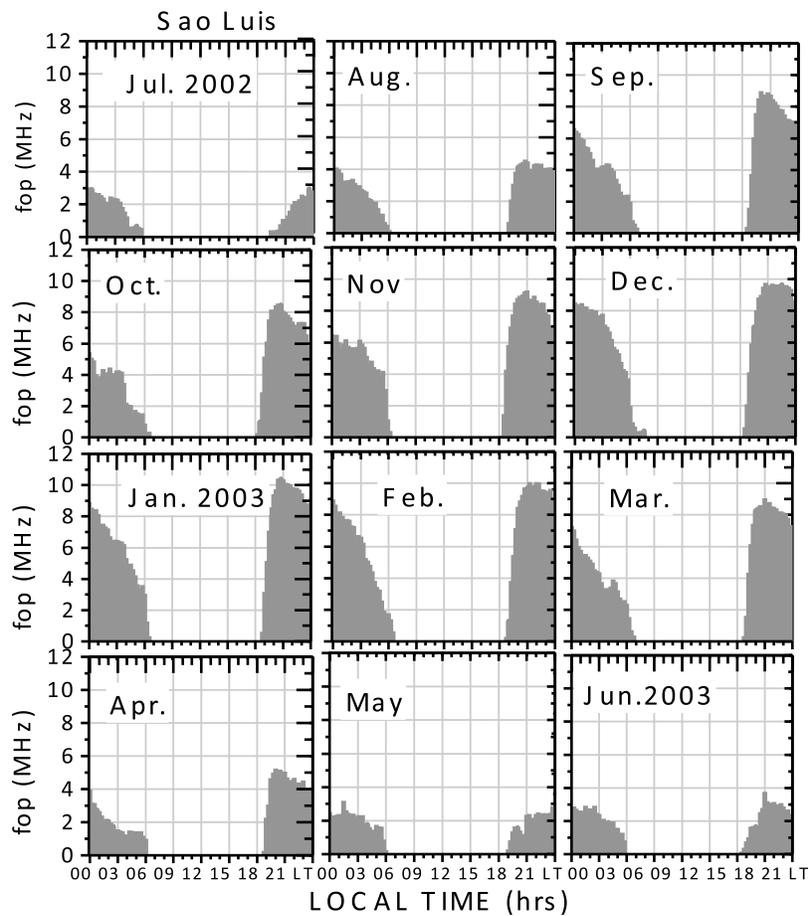


**Figure 3a.** Local time variation of the monthly mean spread range (MMSR) in km plotted for a one-year period, from July 2002 to June 2003, over Sao Luis, Brazil (2.33°S, 44.2°W, dip angle:  $-0.5^\circ$ ).

dip:  $22^\circ$ ), and the southern conjugate site Campo Grande – CG (20.44°S; 54.64°W; dip:  $-22.31^\circ$ ). Exactly identical antenna configuration was used at all the three sites. The points plotted are the individual values of the Spread Range (ASR) versus the top frequency registered in the Spread F traces corresponding to each of the ionograms taken at 5-min cadence. We note large degree of scatter of the points in these plots which is caused mainly by the uncertainty (mentioned before) in the estimation of the frequency averaged spread range (ASR) specific to a trace in each ionogram. However, the similar positive linear relationship between the two parameters (that is, the ASR and fop) that is consistently evident for all the three stations strengthens the existence of such a relationship. It is interesting to note that the fop values at Cachimbo, the dip equatorial site, are significantly smaller than those at the low latitude/conjugate sites. While the maximum fop at Cachimbo (CX) is near 15 MHz the corresponding maxima at the conjugate sites are near or above 28 MHz (the programmed upper limit of the Digisonde’s frequency sweep) where in fact the points tend to crowd. In this context it needs to be remembered

that the F layer critical frequency foF2 (proportional to  $\sqrt{N_m F2}$ ) has smaller values at the equatorial anomaly (EIA) trough location, CX in this case, than at the EIA sub-crest locations BV and CG. The implications of this will be discussed later.

[7] A comparison of the linear fit lines of Figures 5a, 5b, and 5c are presented in Figure 6. We note some interesting contrasts in the slopes of the linear trends between the equatorial and the conjugate sites on the one hand, and that between the two conjugate sites on the other. As the spread range increases (above approximately 60 km), for a given values of the SR the fop is significantly larger at the low latitude sites than at the equatorial site. Larger fop signifies smaller irregularity scale sizes responsible for the coherent backscatter, and therefore more intense cascading of the irregularities, within the detection sensitivity of the Digisonde. This result would therefore imply that the intensity of a spread F irregularity event increases as we approach the EIA crest, as compared to its intensity at the EIA trough. Based on the same reasoning we conclude from Figure 6 that for the COPEX campaign period the irregularity strength

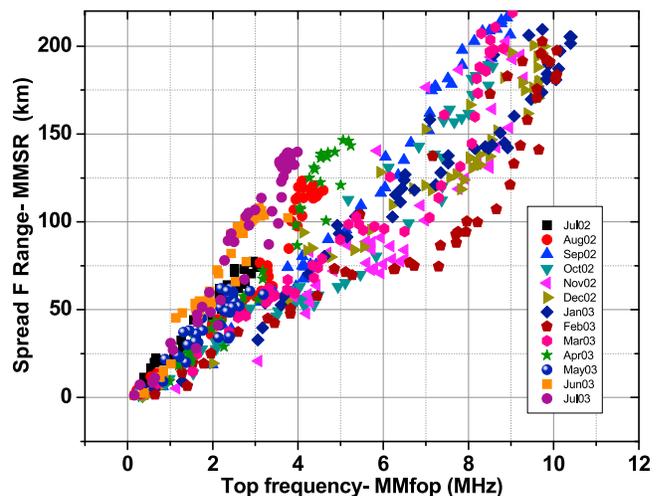


**Figure 3b.** Local time variation of the monthly mean fop (MMfop) values (the fop being the top frequency of the range spread F trace) plotted for a one-year period, from July 2002 to June 2003, over Sao Luis, Brazil.

over the southern crest (near Campo Grande) is systematically higher than over the northern crest (near Boa Vista), that is, there is a significant asymmetry in the irregularity strength between the two conjugate sites.

### 3. Discussion and Conclusions

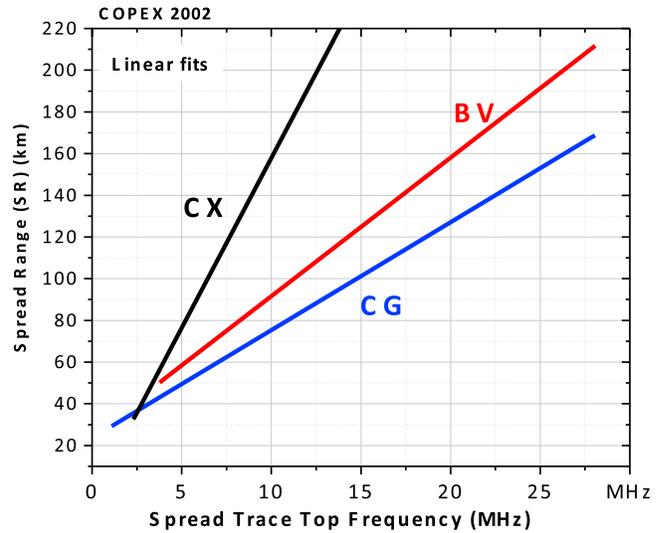
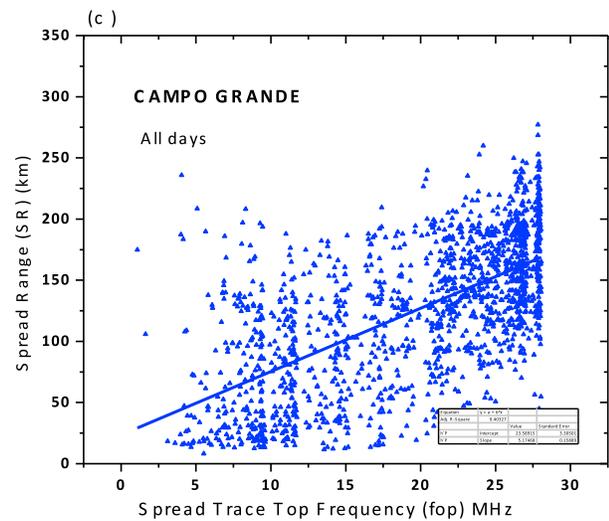
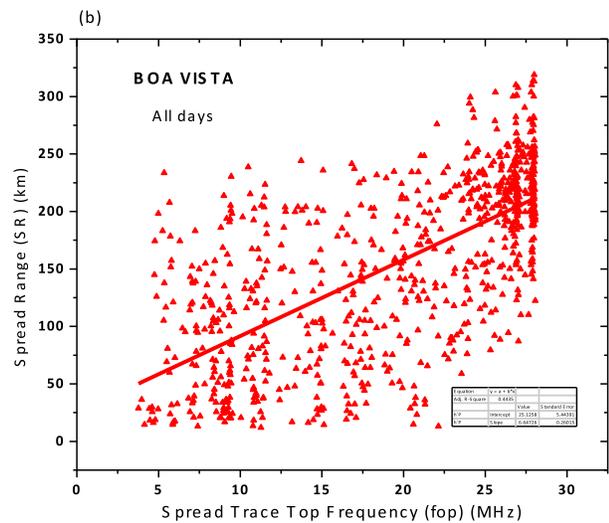
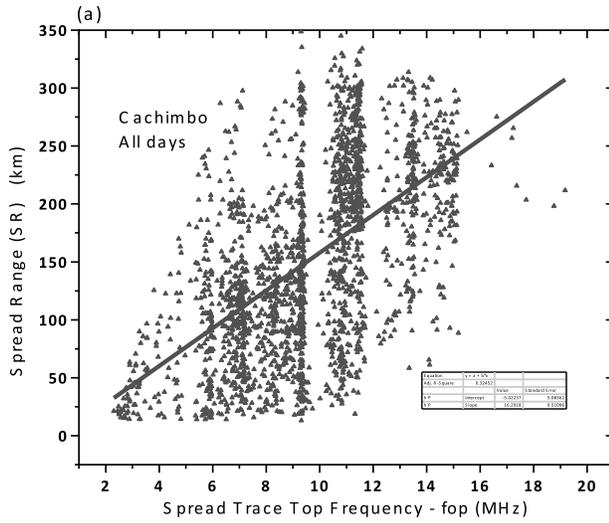
[8] There have been discussions in the literature concerning the total/specular reflection from wave modulated electron density surfaces as being responsible for the ionogram spread F traces over equatorial- and midlatitudes. In this perspective the equatorial range spread F traces have been attributed to the presence of multiple traces, made up of unresolved replica of the main F trace [see, e.g., King, 1970; Reinisch et al., 2004; Wright et al., 1996; Tsunoda, 2010]. Such explanation could be uniquely valid for midlatitude locations where field line orthogonal echoes are not observable by ionosonde usually operated with vertically directed broad antenna lobes (even with their large beam widths). Over equatorial locations where field line perpendicularity condition for the antenna beam and the received signals is possible, it turns out that we need to consider echoes from coherent backscatter mechanism as the dominant component of the range spread F traces in ionograms as



**Figure 4.** The monthly mean values of the fop (MMfop) in MHz plotted against the corresponding monthly mean of the spread F range (MMSR) in km over Sao Luis for July 2002 to June 2003.

the present results and earlier results by *Sales et al.* [1996] demonstrate.

[9] The linear increase of spread range (SR) with increasing top frequency of the returned echoes (fop) is an

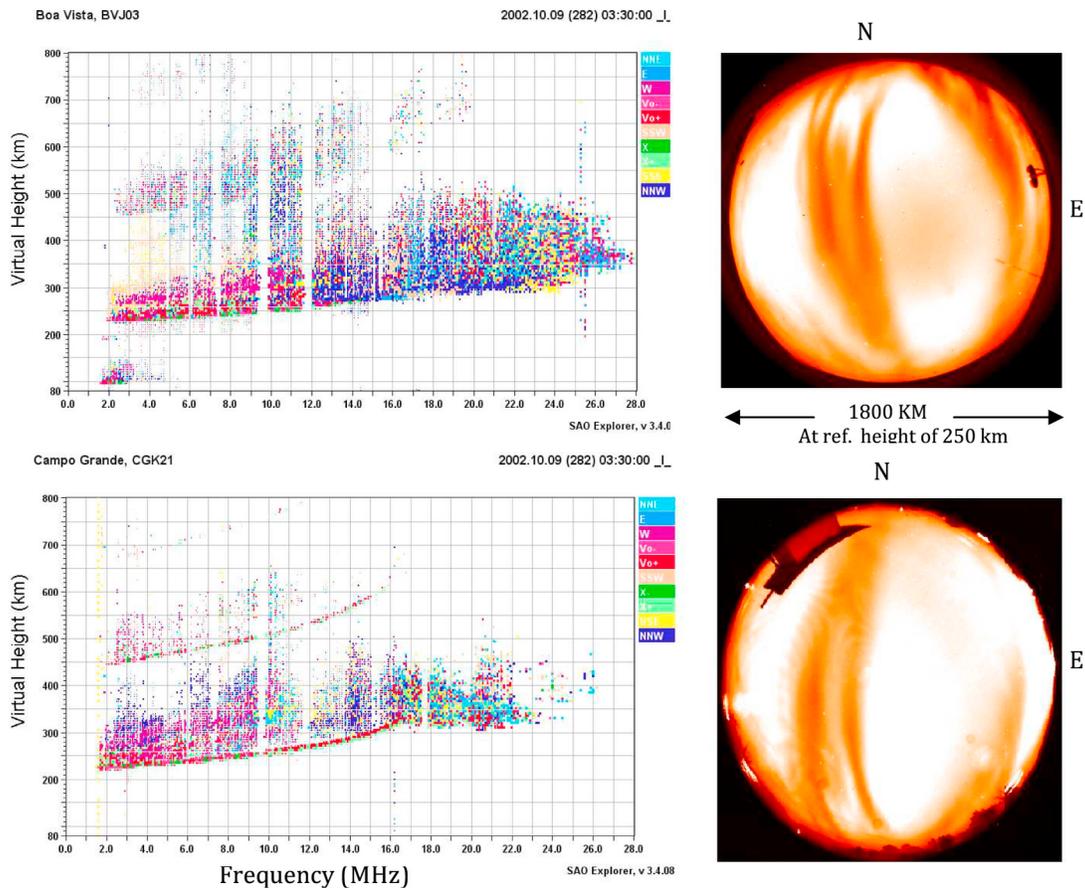


**Figure 6.** The linear fit lines of Figures 5a, 5b, and 5c all plotted together for comparison.

indication that the strength of the larger scale irregularities (for  $f < f_{op}$ ) increases with increase in  $f_{op}$ . This may be seen, alternatively, in terms of the angular extension of the echoes received in a plane orthogonal to the magnetic field steadily increasing as the echo producing irregularity scale size decreases. This is compatible with the visualization that in the course of spread F/plasma bubble instability growth, secondary irregularities develop by a cascading process at the steepening gradient regions of the developing plasma depletions whose interior/bottom edge is diagnosed by the Digisonde signals. The lower limit of the irregularity sizes (for example, a 20 MHz upper limit of the  $f_{op}$  would correspond to 7.5 m as the lower limit of the scale size) as seen by the Digisonde does not necessarily mean that irregularities of even smaller sizes do not exist. It only means that the Digisonde may not be sensitive enough to see them when they exist, or it does not transmit at high enough frequencies (in fact from VHF radar measurement it is known that they often/always exist during spread F/plasma bubble events).

[10] Further evidence supporting the coherent backscatter nature of the echo returns is the significant asymmetry in the echo strength ( $f_{op}$ ) between the conjugate sites. Such an asymmetry is evident when we compare in Figure 6 the  $f_{op}$  values at CG and BV for a given SR value. For example, at a value of the SR = 100 km the  $f_{op}$  is near 11 MHz at BV whereas it is near 15 MHz at CG, the asymmetry tending to increase with increasing SR. This asymmetry means that the irregularities of scale sizes of a few tens of meters or less (e.g., 10 m at 15 MHz) are not magnetic field line mapped between the conjugate sites. A striking example of a specific

**Figure 5.**  $f_{op}$  values in MHz versus the corresponding spread range in km (ASR labeled as SR) from 5-min ionograms over (a) Cachimbo, near dip equator, (b) Boa Vista, the northern conjugate site, and (c) Campo Grande, the southern conjugate site, during the COPEX–2002 campaign in Brazil. A linear fit line is also shown. Note that the  $f_{op}$  values are truncated at the 28 MHz in Figures 5a and 5b which is the upper limit of the DPS-4 frequency sweep.



**Figure 7.** Illustrative ionograms over (top left) Boa Vista and (bottom left) Campo Grande. (right) The simultaneous all-sky images on the night of 9 October 2002 [from *Abdu et al.*, 2009]. The North-South elongated streaks are the footprints, in the airglow emission region, of the magnetic field aligned plasma bubbles/depletions. The North is to the top and the East to the right. The horizontal extension of the all sky imager field of view projected at 250 km height is also shown (as 1800 km).

case of the symmetry/asymmetry situation is illustrated in Figure 7, which shows the Digisonde ionograms from the northern and southern conjugate sites together with the corresponding all-sky images of the OI 630 nm emission at the growth phase of an ESF/plasma bubble event during the COPEX campaign [*Abdu et al.*, 2009]. The all-sky images show north-south/magnetic field aligned airglow emission depletions that are the footprints of the plasma bubbles just below the F layer peak height and that have transverse (east-west) scale sizes of tens to hundreds of kilometers. These structures indicate perfect symmetry between the north and south conjugate points (as was shown also by *Otsuka et al.* [2002]), which means that the large scale polarization electric fields that drive them map along the entire field lines between the conjugate sites. In contrast, the ionogram spread F traces appear highly asymmetric, the fop and SR values being significantly larger for the northern site (BV) than for the southern site (CG). From theoretical considerations [*Farley*, 1959] an electric field with scale size of the order of a kilometer and more should be mapped along the field line connecting the conjugate Digisonde sites (around 2000 km apart). Therefore if the SF traces in the ionograms were to originate from total reflections for which the first Fresnel zone size (for the HF) is a few kilometers, we should expect

symmetry in the shape of the spread F trace between the conjugate sites, contrary to what is observed. The strong asymmetry seen in the spread F traces in Figure 7 is likely caused by decameter size irregularities that do not map all the way to the conjugate point.

[11] Once the ASR and fop represent the basic characteristics of the spread F trace and the (apparently linear) relationship between them is identified as being inherent with the process of coherent backscattering, it is worth examining their possible use to evaluate the intensity of a specific spread F event. As pointed out before, the ASR averages the range spread over all the frequencies of the spread F echo trace and therefore its value, determined with some difficulty, can be more uncertain compared to that of the fop, which is a specific frequency that can be read precisely and directly from ionograms. We may therefore examine further the possibility of using the fop as an index to evaluate the intensity of a spread F event. A comparison of the range spread F traces in ionograms over Jicamarca with simultaneous ROTI parameter (rate of TEC change index determined for GPS TEC fluctuations) was presented by *Li et al.* [2011]. An examination of their Figures 1 and 2 shows that the ROTI value is larger when fop is large; in fact the ROTI was absent when the fop had smaller values. This

relationship appears interesting even though it is based on a limited data sample. On this basis the result in Figure 6 showing that the fop values at the northern and southern conjugate sites (BV and CG, both close to the EIA crests) are significantly larger than over those at the EIA trough location Cachimbo, is very important. It shows that the ROTI parameter and therefore the GPS signal scintillation can be more intense at equatorial anomaly crest locations than over the equatorial trough. Such results, e.g., stronger GPS scintillation near the EIA crest than in the trough, have been confirmed by recent studies on GPS scintillation in the Brazilian and Indian sectors [see, e.g., Muella et al., 2008; de Paula et al., 2003; Rama Rao et al., 2006]. In particular, Muella et al. [2008] have shown from analysis of COPEX data that the GPS scintillation is significantly more intense over BV and CG than over CX during the same period as that of the results of Figure 6. Thus we note here that there is great potential for the use of the parameter fop for a more quantitative investigation of the spread F spatial and temporal variabilities than it has been possible so far.

[12] The main conclusions of this study may be stated as follows: The range spread echoes in equatorial ionograms originate predominantly from the coherent backscatter mechanism, even when unresolved traces caused by total reflection are potentially coexisting. The echo range spread increases with the top frequency of the backscattered echo trace, which would suggest that the process of irregularity cascading that characterizes a spread F instability growth phase, is generally at work based on the entire data sample. The diurnal and seasonal distribution patterns of the range spread F occurrence as seen in the monthly mean spread range (MMSR) parameter are very similar to that seen in the MMfop parameter, which is also consistent with the statistical linear relationship between them. The fop is, however, a more reliable indicator of the strength of a spread F event, and therefore of a related scintillation event. It also exhibits latitudinal variation characterized by lower values at the EIA trough and higher values at the crests in much the same way as does the GPS UHF scintillation distribution. Based on the analysis of the fop during the COPEX period it turns out that strong asymmetry between low latitude conjugate locations may exist in the strength of the decimeter size irregularities, and consequently also in the related UHF scintillations. The fop parameter pertaining to the spread F trace appears to be a better index to represent the spread F intensity than is the presently used range spread F index.

[13] **Acknowledgments.** M.A.A. acknowledges support from CNPq through grants 300883/2008-0. B.W.R. was in part supported by AF grant FA8718-06-C-0072. Logistical support for the operations of the instruments at the conjugate sites (Campo Grande, Cachimbo, and Boa Vista) was provided by the Brazilian Aeronautic Ministry's Instituto Tecnológico de Aeronautica (CTA), which is thankfully acknowledged.

## References

Abdu, M. A., I. S. Batista, and J. H. A. Sobral (1992), A new aspect of magnetic declination control on equatorial spread F and F region dynamo, *J. Geophys. Res.*, *97*(A10), 14,897–14,904, doi:10.1029/92JA00826.

- Abdu, M. A., I. S. Batista, B. W. Reinisch, J. R. de Souza, J. H. A. Sobral, T. R. Pedersen, A. F. Medeiros, N. J. Schuch, E. R. de Paula, and K. M. Groves (2009), Conjugate Point Equatorial Experiment (COPEX) campaign in Brazil: Electrodynamics highlights on spread F development conditions and day-to-day variability, *J. Geophys. Res.*, *114*, A04308, doi:10.1029/2008JA013749.
- Batista, I. S., M. A. Abdu, A. J. Carrasco, B. W. Reinisch, E. R. Paula, N. J. Schuch, and F. Bertoni (2008), Equatorial spread F and sporadic E-layer connections during the Brazilian Conjugate Point equatorial Experiment (COPEX), *J. Atmos. Sol. Terr. Phys.*, *70*, 1133–1143, doi:10.1016/j.jastp.2008.01.007.
- Booker, H. G., and J. A. Ferguson (1978), A theoretical model for equatorial ionosphere spread F echoes in the HF and VHF bands, *J. Atmos. Terr. Phys.*, *40*, 803–829, doi:10.1016/0021-9169(78)90032-6.
- Booker, H. G., and H. W. Wells (1938), Scattering of radio waves in the F region of ionosphere, *J. Geophys. Res.*, *43*, 249–256, doi:10.1029/TE043i003p00249.
- Bowman, G. G. (1990), A review of some recent work on mid-latitude spread F occurrence as detected by ionosondes, *J. Geomagn. Geoelectr.*, *42*, 109–138, doi:10.5636/jgg.42.109.
- Carrasco, A. J., and I. S. Batista (2012), Estimation of the initial amplitude of plasma bubble seed perturbation from ionograms, *Radio Sci.*, *47*, RS2008, doi:10.1029/2011RS004862.
- de Paula, E. R., F. S. Rodrigues, K. N. Iyer, I. J. Kantor, M. A. Abdu, P. M. Kintner, B. M. Ledvina, and H. Kil (2003), Equatorial anomaly effects on GPS scintillations in Brazil, *Adv. Space Res.*, *31*, 749–754, doi:10.1016/S0273-1177(03)00048-6.
- Farley, D. T., Jr. (1959), A theory of electrostatic fields in a horizontally stratified ionosphere subject to a vertical magnetic field, *J. Geophys. Res.*, *64*, 1225–1233, doi:10.1029/JZ064i009p01225.
- Haerendel, G. (1973), Theory of equatorial spread F, report, Max-Planck Inst. für Phys. und Astrophys, Munich, Germany.
- King, G. A. M. (1970), Spread F on ionograms, *J. Atmos. Terr. Phys.*, *32*, 209–212, doi:10.1016/0021-9169(70)90192-3.
- Li, G., B. Ning, M. A. Abdu, X. Yue, L. Liu, W. Wan, and L. Hu (2011), On the occurrence of post midnight equatorial F region irregularities during the June solstice, *J. Geophys. Res.*, *116*, A04318, doi:10.1029/2010JA016056.
- Muella, M. T. A. H., E. R. de Paula, I. J. Kantor, I. S. Batista, J. H. A. Sobral, M. A. Abdu, P. M. Kintner, K. M. Groves, and P. F. Smorigo (2008), GPS L-band scintillations and ionospheric irregularity zonal drifts inferred at equatorial and low-latitude regions, *J. Atmos. Sol. Terr. Phys.*, *70*, 1261–1272.
- Otsuka, Y., K. Shiokawa, T. Ogawa, and P. Wilkinson (2002), Geomagnetic conjugate observations of equatorial airglow depletions, *Geophys. Res. Lett.*, *29*(15), 1753, doi:10.1029/2002GL015347.
- Rama Rao, P. V. S., S. Gopi Krishna, K. Niranjan, and D. S. V. V. D. Prasad (2006), Study of spatial and temporal characteristics of L-band scintillations over the Indian low latitude region and their possible effects on GPS navigation, *Ann. Geophys.*, *24*, 1567–1580, doi:10.5194/angeo-24-1567-2006.
- Rastogi, R. G. (1978), On the equatorial spread F, *Proc. Indiana Acad. Sci.*, *87A*, 116–131.
- Reinisch, B. W., M. Abdu, I. Batista, G. S. Sales, G. Khmyrov, T. A. Bullett, J. Chau, and V. Rios (2004), Multistation Digisonde observations of equatorial spread F in South America, *Ann. Geophys.*, *22*, 3145–3153, doi:10.5194/angeo-22-3145-2004.
- Sales, G. S., B. W. Reinisch, J. L. Scali, C. Dozois, T. W. Bullett, E. J. Weber, and P. Ning (1996), Spread-F and the structure of equatorial ionization depletions in the southern anomaly region, *J. Geophys. Res.*, *101*, 26,819–26,827, doi:10.1029/96JA01946.
- Schlegel, K. (1996), Coherent backscatter from ionospheric E-region plasma irregularities, *J. Atmos. Terr. Phys.*, *58*(8–9), 933–941, doi:10.1016/0021-9169(95)00124-7.
- Sobral, J. H. A., et al. (2009), Ionospheric zonal velocities at conjugate points over Brazil during the COPEX campaign: Experimental observations and theoretical validations, *J. Geophys. Res.*, *114*, A04309, doi:10.1029/2008JA013896.
- Tsunoda, R. T. (2010), On equatorial spread F: Establishing a seeding hypothesis, *J. Geophys. Res.*, *115*, A12303, doi:10.1029/2010JA015564.
- Wright, J. W., P. E. Argo, and M. L. V. Pitteway (1996), On the radiophysics and geophysics of ionogram spread F, *Radio Sci.*, *31*(2), 349–366, doi:10.1029/95RS03104.