RADIO SCIENCE, VOL. 39, RS1014, doi:10.1029/2003RS002914, 2004

The São Luís 30 MHz coherent scatter ionospheric radar: System description and initial results

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Received 16 May 2003; revised 20 October 2003; accepted 9 December 2003; published 24 February 2004.

[1] A new 30 MHz coherent scatter ionospheric radar has been operating at the equatorial station at São Luís (2.33°S, 44°W, dip latitude 1.3°S), Brazil, since December 2000. This VHF radar has a peak power of only 8 kW but uses long coded pulses and a high PRF with coherent integration to achieve good sensitivity. Two side-by-side square antenna arrays composed of 16 5-element Yagi antennas directed vertically are used for transmission and reception. This radar measures the backscattered signals from E and F region ionospheric irregularities. In the standard operational mode, the irregularity intensity, as well as the vertical and zonal velocities using Doppler analysis and interferometry, respectively, are determined. We initially present a brief description of the radar system, signal characteristics and data processing, followed by some of the initial observations. Electrojet echoes ranged from about 94 to 108 km in altitude with the strongest echoes coming from about 104 km and with an uplift to about 110 km occurring in the late afternoon. Echoes from the valley region (150 km echoes) were strong, quasi-periodic with periods of about 10 to 15 minutes, and had the necklace shape observed at others sites. F region bottom-type, bottomside, and topside (plumes) spread F layers were observed at night. The large-scale topside F region plumes, moving eastward and upward, reached altitudes of about 1,400 km and were preceded by bottom-type layers around 400 km altitude that were moving westward. The characteristics of the echoes were similar to those observed by the JULIA radar at Jicamaca, Peru. However, some differences in the behavior of the echoes between the two sites were noted. *INDEX TERMS:* 2403 Ionosphere: Active experiments; 2415 Ionosphere: Equatorial ionosphere; 2439 Ionosphere: Ionospheric irregularities; *KEYWORDS:* ionospheric irregularities, VHF coherent radar, 150 km echoes

Citation: de Paula, E. R., and D. L. Hysell (2004), The São Luís 30 MHz coherent scatter ionospheric radar: System description and initial results, *Radio Sci.*, *39*, RS1014, doi:10.1029/2003RS002914.

1. Introduction

[2] The coherent scatter radar is a powerful instrument for probing ionospheric irregularities. Ionospheric E and F region irregularity characteristics have been studied using HF radars [*Blanc et al.*, 1996; *Farges et al.*, 1999; *Haldoupis*, 1996; *Tsunoda*, 1994] and VHF radar [*Balsley*, 1969; *Fejer et al.*, 1975a, 1975b; *Farley et al.*, 1970; *Patra et al.*, 1995; *Tsunoda and Ecklund*, 2000; *Swartz*, 1997; *Hysell et al.*, 1997; *Hysell and Burcham*, 1998, 2002; *Abdu et al.*, 2002]. Irregularities and electric fields in the equatorial electrojet have been studied extensively by several authors [e.g., *Balsley*, 1973; *Fejer et al.*, 1975a, 1975b; *Fejer and Kelley*, 1980; *Kudeki et al.*, 1982; *Farley*, 1985; *Pfaff et al.*, 1987; *Swartz and Farley*, 1994; *Ragharavao et al.*, 2002] and since their discovery by *Balsley* [1964], the so-called 150 km echoes have also been studied by many researchers [*Royrvik*, 1982; *Kudeki and Fawcett*, 1993; *Blanc et al.*, 1996; *Hysell et al.*, 1997; *Tsunoda*, 1994; *Farges et al.*, 1999; *Tsunoda and Ecklund*, 2000]. As they affect telecommunication and navigation systems, plasma irregularities associated with equatorial spread F phenomena have been studied intently for many years [*Farley et*

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al., 1970; *Woodman and La Hoz*, 1976; *Sobral et al.*, 1980; *Kelley*, 1985; *Fejer*, 1997; *Fejer et al.*, 1999; *Aarons*, 1999; *Hysell and Burcham*, 1998, 2002; *Abdu et al.*, 2000; *Abdu*, 2001; *Musman et al.*, 1997]. In the past, spread F studies at Jicamarca were made episodically. However, the JULIA radar at Jicamarca now facilitates long-term studies of the irregularities [*Hysell and Burcham*, 1998, 2002], their climatological behavior, and their prediction. A similar capability was sought in Brazil. A coherent 30 MHz scatter radar operating at the low end of the VHF band was built at INPE, São José dos Campos, Brazil, in collaboration with Clemson University. The system is conceptually similar to that of JULIA radar at Jicamarca [*Hysell and Burcham*, 1998]. On December 2000, when the average 10.7 cm solar flux was 168.2, the radar was installed and has been operated almost continuously at the equatorial station at São Luís, a site with large magnetic declination (about 20°W) and a high incidence of ionospheric irregularities. This radar also has the capability of long-term equatorial studies of electrojet, 150 km echoes and spread F in the Brazilian sector, which has been undertaken to further investigate longitudinal differences in their morphology, occurrence, climatology, and persistence. In the following sections we give a brief description of our radar system and then present some of our initial results.

2. System and Data Processing Description

[3] The radar is constituted basically of a pulse former, a driver amplifier, 2 transmitters, 2 double-conversion analog receivers, a T/R switch, and two arrays of 16 Yagi antennas arranged in side-by-side "square-to" magnetic north arrays located on a magnetic E-W axis and with 5/8 wavelength element separation. Table 1 shows the radar parameters for the three main modes of operation.

Table 1. Radar Parameters for the Three Main Modes of Operation

	Electrojet	150 km Echo	Spread F
Baud length	1 km	1 km	2.5 km
Code length	13 bits	28 bits	28 bits
IPP	600 km	600 km	1400 km
Duty cycle	2.17%	4.67%	4.46%
Nominal number of coherent integrations	1	16	1

[4] Information about the radar system, the antenna configuration, and the radar measurements can be found at the URL http://200.241.80.42. Figure 1 shows a map of South America with the dip equator line and the radar location. The half-power full beam width of the transmitting array is approximately 10 degrees in the equatorial plane. Coded pulses are generated by a digital pulse former. Data acquisition is performed with an analog-to-digital converter capable of sampling up to 4 quadrature receiver outputs simultaneously with 12 bit precision at a rate of about 400 ksamples/sec/receiver. Both the pulse generator and data acquisition systems are contained within and controlled by a PC server running Linux. Data are written to helical scan tape and also processed and distributed through the worldwide web in real time. The radar has Doppler and interferometry capabilities for measuring line-of-sight and cross-beam drifts.

[5] The radar makes use of two relatively low-power solid-state transmitters generating about 4 kW of peak power each but with maximum duty cycle close to 15%. By implementing long coded pulses sequences and operating with a high pulse repetition frequency and incorporating coherent integration, we are able to sustain relatively high average power levels nonetheless. The system was designed to operate at 29.795 MHz, just above the amateur 10 m band. This allowed us to use commercially available Yagi antennas and other components. Note also that the backscatter intensity from field aligned irregularities generally grows with increasing wavelength faster than does the background sky noise at VHF frequencies, affording an increase sensitivity for a 30 MHz coherent scatter radar compared to one operating at 50 MHz, for example. This principle does not hold for irregularities directly generated by Farley Buneman instabilities [*Fejer and Kelley*, 1980]; however, type 1 electrojet irregularities remain sufficiently strong at 5 m wavelengths to be detected.

[6] The radar has been operating on a routine basis since April 2001, sampling the E and valley regions in the daytime and the F region at night. Outstanding features of the accumulated database will be discussed in publications to follow.

3. First Observations

[7] In this section we present mainly the first radar results for the December 25–29, 2000 campaign. A substorm occurred within this period, but those observations will be presented in details elsewhere. Note that, at São Luís, UT = LT + 3h.

3.1. Electrojet Echoes

[8] Since our initial campaign from December 25 to 29, 2000, intense electrojet echoes were routinely observed from about 12:00 to 21:00 UT with an uplift in the afternoon on some days but without significant day-to-day variations otherwise, except during one peculiar event during a substorm period discussed briefly below. Figure 2 shows an example of the electrojet echoes in RTI format for December 25, 2000. The electrojet echoes range from about 94 to 108 km with the strongest echoes coming from about 104 km altitude. In the late afternoon,

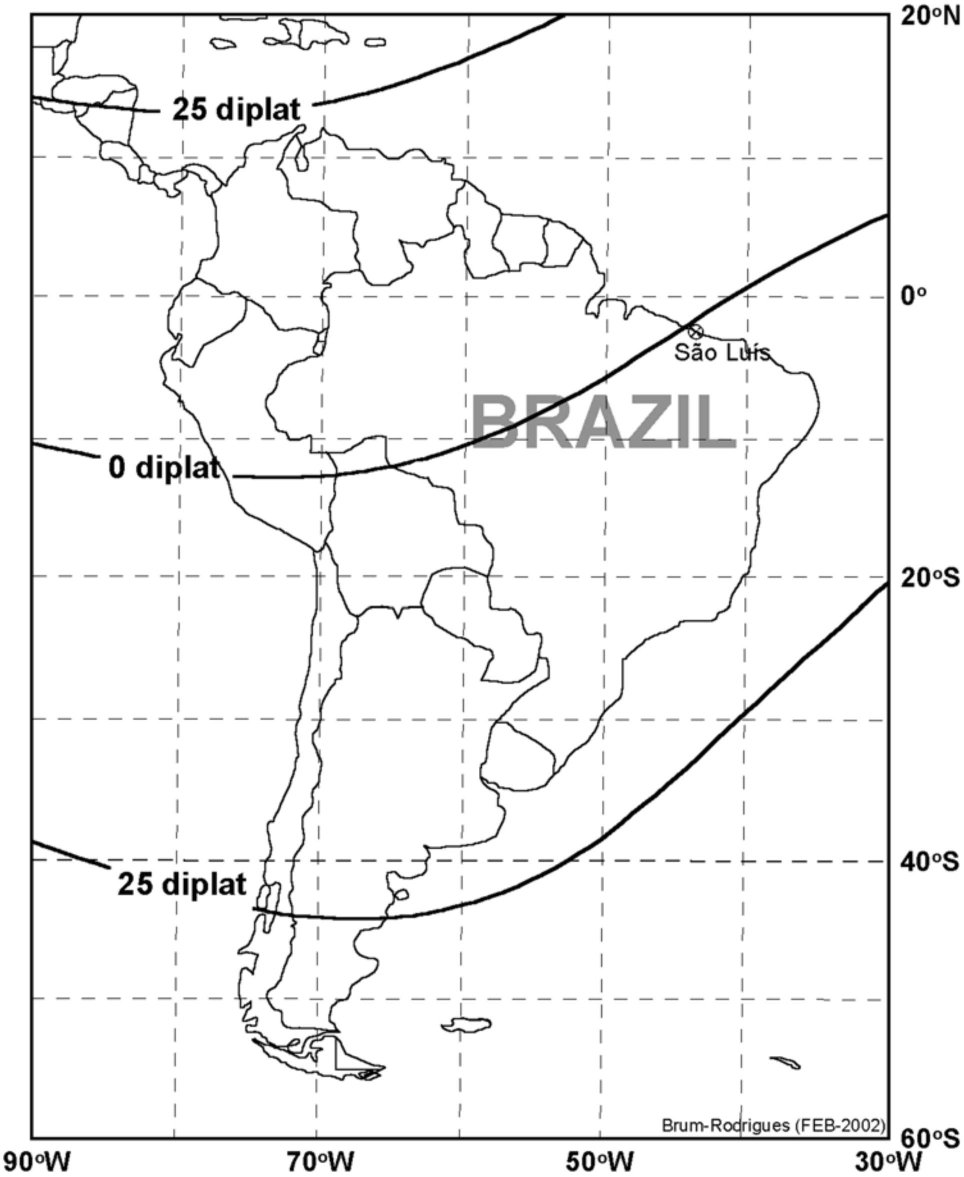

Figure 1. South America map showing the São Luís radar location.

the region of most intense echoes ascended to about 110 km and covered a larger altitudinal range. Figure 3 shows the power spectra of the electroject echoes in an altitude range from 95 to 104 km. In this figure the Doppler spectra are plotted against a velocity axis, the spectral shading is total relative power and the sidebars are peak relative power. The spectra are dominated by broad type II components, but also show some evidence of narrowly peaked type I components at the spectral wings near the ion acoustic velocity. In contrast to observations made at 50 MHz [*Fejer et al.*, 1975a], we find that distinct type I echoes do not appear by themselves in the 30 MHz coherent scatter data but instead are manifested as steep shoulders of type II spectra.

[9] The afternoon uplift of the electrojet echoes, which cover a broad range of altitudes, was also observed during campaigns at São Luís by *Abdu et al.* [2002] using a 50 MHz coherent radar located nearby and is a common feature of electrojet echoes observed at Jicamarca [e.g., *Fejer et al.*, 1975b] and elsewhere.

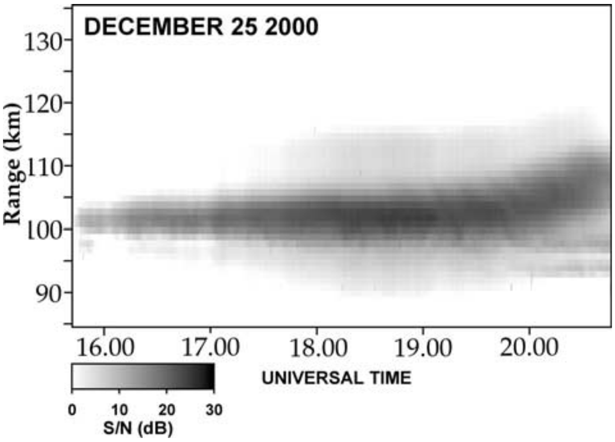

Figure 2. RTI electrojet echoes for December 25, 2000 (UT = LT + 3).

[10] On one occasion on December 27 during a substorm period in the campaign, daytime echoes were detected at apparent altitudes between 110 and 140 km. Figure 4 shows the RTI and the vertical velocity plots for this event. The spectra of the echoes were narrower than the type II spectra seen in the electrojet, and their Doppler shifts, which were initially positive, then zero, and then negative, were inconsistent with the electrojet echoes received simultaneously. Sounding rocket data presented by *Prakash et al.* [1971, 1972] may have indicated the occurrence of small-scale (1–15 m) irregularities up to about 140 km altitude during the daytime. According to theoretical calculations by *Fejer et al.* [1975b], however, we should not expect the equatorial E region to be unstable above about 115 km during the day because of the damping effect of recombination. They suggest that only at night, when the recombination becomes negligible, can radar signals be scattered from

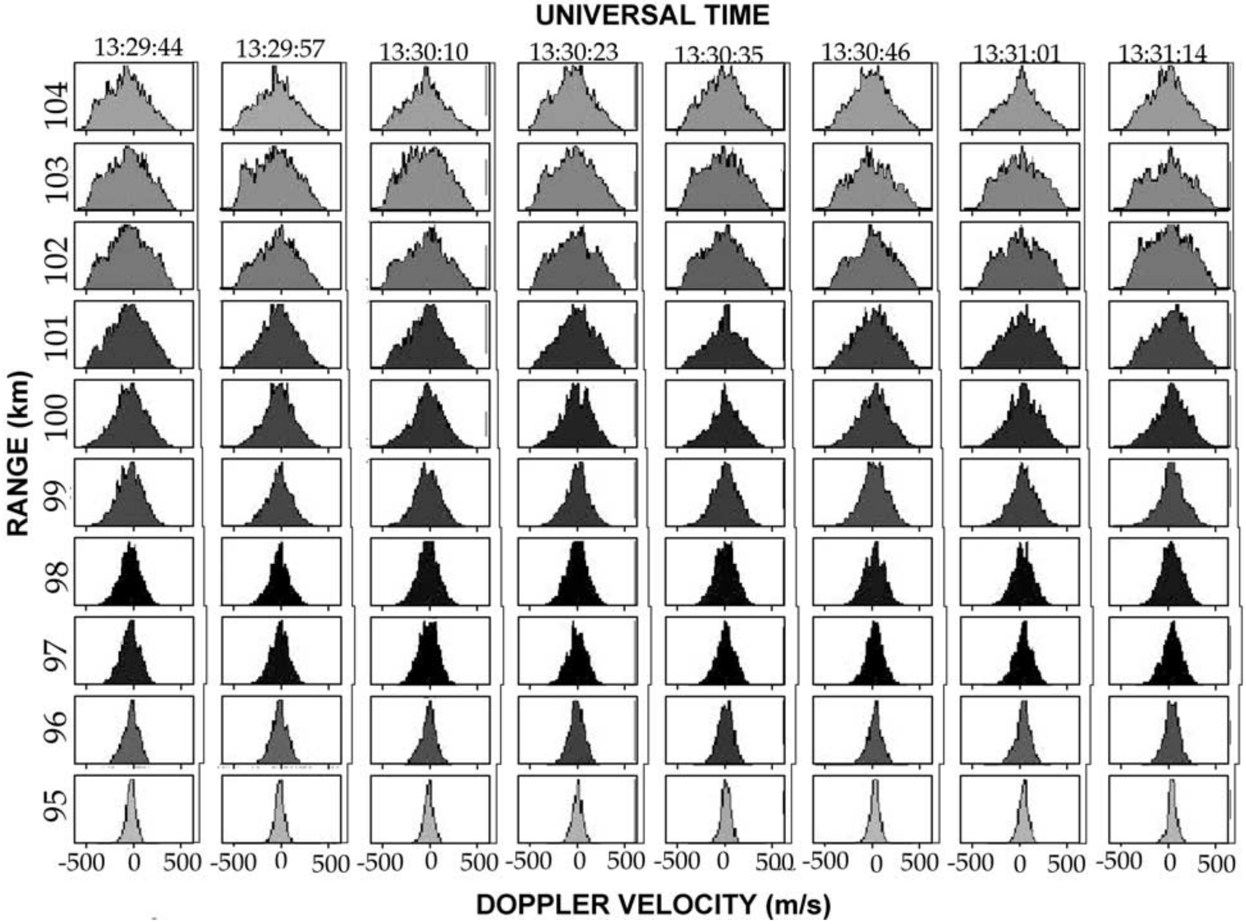

Figure 3. Power spectrum for the electrojet for December 25, 2000.

thin layers extending up to 130 km. However, the presence of echoes at about 110 km from 16:10 to 16:30 UT (with a gap around 16:20 UT) and some patches at 16:15 UT at 135–142 km and around 16:30 UT at 125–135 km in Figure 4 indicates the presence of irregularities even above 115 km till 142 km. As these echoes are anomalous we suggest that they are induced by the substorm. The other echoes coming from regular spaced ranges in Figure 4 are due to the coding sidelobes and they are down by 22–23 dB compared to the maximum power on the S/N scale.

3.2. 150 km Echoes

[11] The so-called 150 km echoes were observed every day during the campaign period and during many sounding days after December 2000. Figure 5 shows 150 km echoes for December 26 and 28, 2000, along with electrojet echoes at lower altitudes. These quasi-periodic echoes, with periods varying between 10 to 15 minutes, appeared at about 12:00 UT around 165 km altitude, fell to about 145 km at local noon, moved gradually upward to around 160 km in the afternoon, and then disappeared at about 17:00 UT, presenting the necklace shape observed at others sites. Figure 6 presents the spectral analysis of the echoes in the altitude range of 146 to 155 km. The characteristic narrowness of the spectra permits us to determine their Doppler shift very accurately. Figure 7 shows another example of 150 km RTI and electrojet echoes from 12:00 to 17:00 UT for August 14, 2002. The 150 km echoes disappeared completely when the E region begins to uplift around 17:00 UT. In this figure, E region range sidelobes due to pulse coding are also observed.

[12] The observed 150 km echo periods, altitude range, and shape are similar to those reported by *Kudeki and Fawcett* [1993], using Jicamarca data, and by *Tsunoda and Ecklund* [2000], who used a 49.92 MHz radar located on the island of Pohnpei in the Micronesia during January 1997, and with the general description of 150 km echoes characteristics from *Ragharavao et al.* [2002]. *Kudeki and Fawcett* [1993] showed that the phase velocity of such 150 km echoes are proportional to the electrojet current and provide a good estimate of the zonal electric field in the ionosphere. This hypothesis was supported by *Woodman and Villanueva* [1995] using incoherent scatter radar experiments. The 150 km echoes are from the valley region of the ionosphere where there is a very low ionization, no obvious sources of free energy for irregularity generation and no gradients in the plasma density, electric fields, currents and neutral winds of substantial intensity. Although some suggestion for their

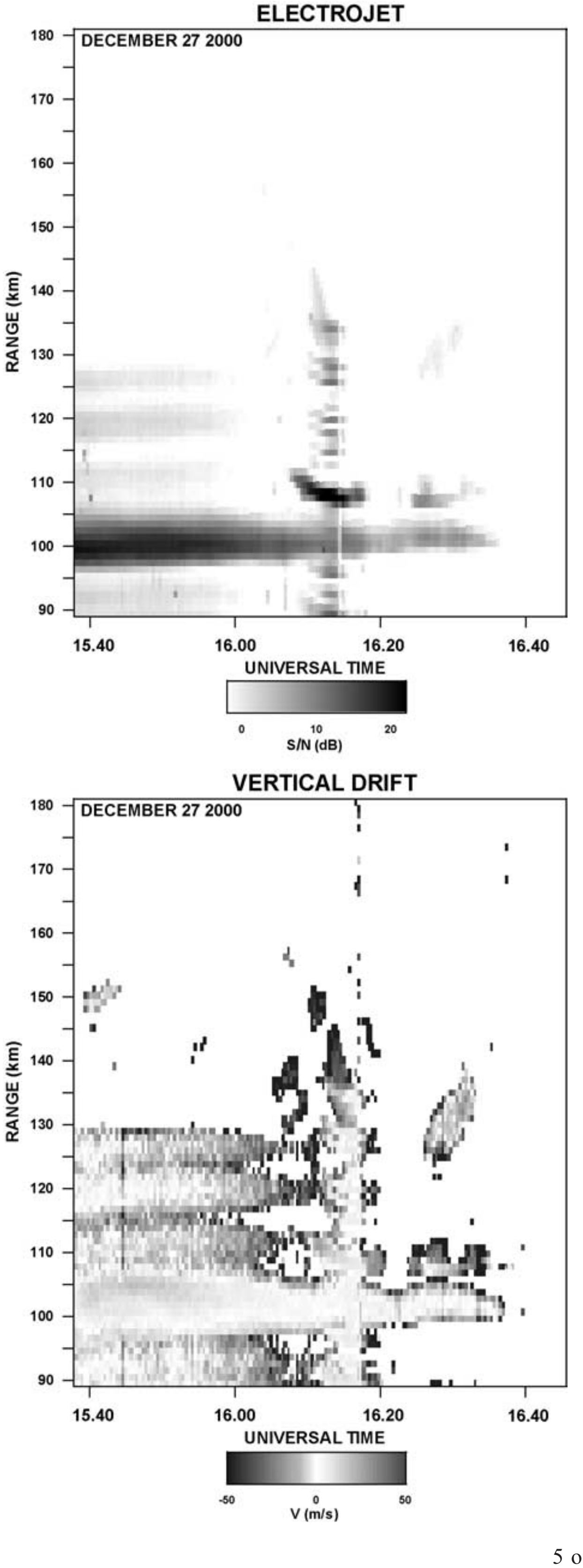

Figure 4. Electrojet RTI echoes and their vertical drift velocities for December 27, 2000. See color version of this figure at back of this issue.

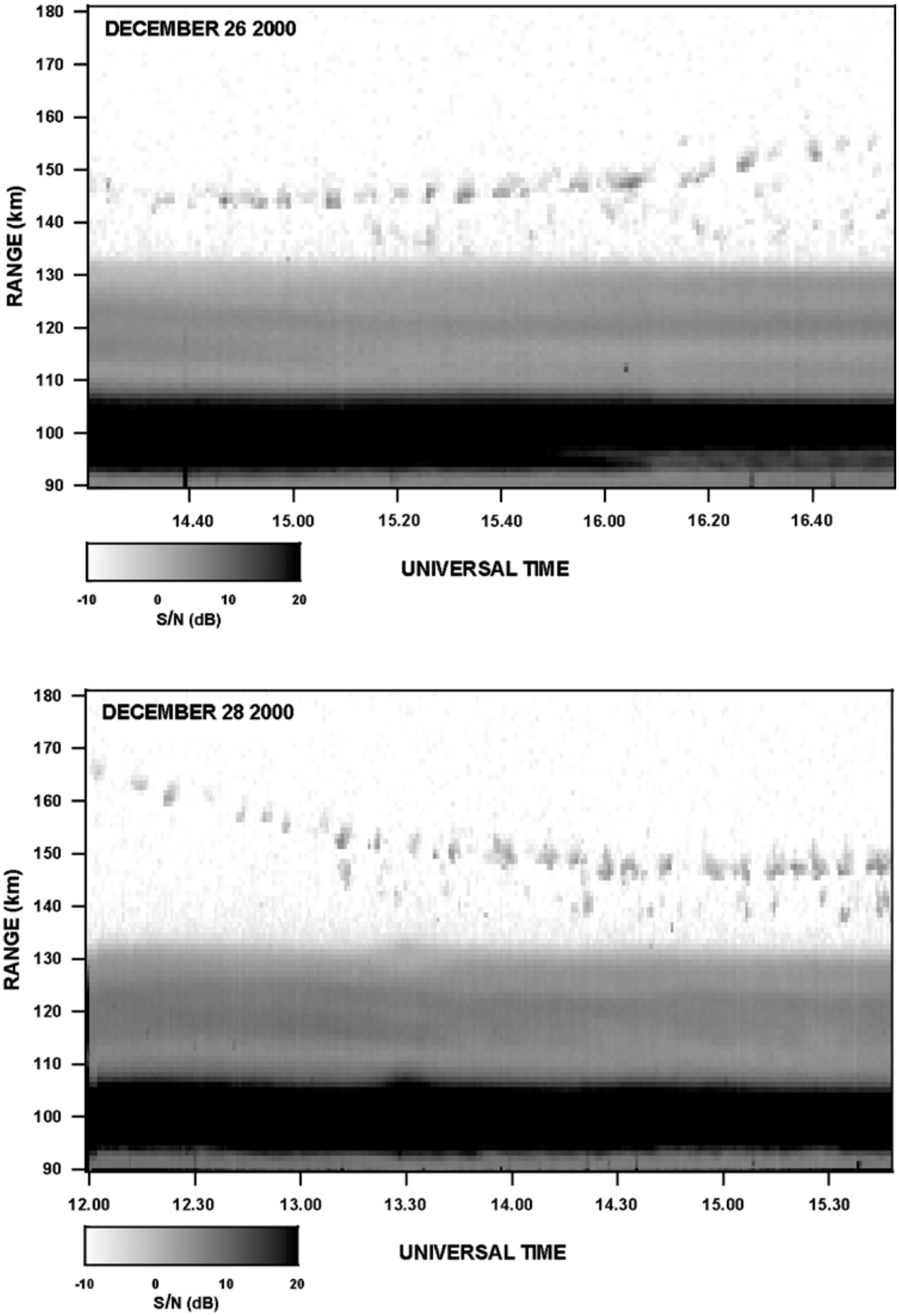

Figure 5. RTI 150 km echoes for December 26 and 28, 2000.

generation mechanism have been proposed in terms of gravity waves [*Royrvik*, 1982; *Kudeki and Fawcett*, 1993] or polarization electric fields at the electrojet altitude mapped to 150 km altitudes [*Tsunoda*, 1994], the cause of the 150 km irregularities remains unknown. *Ragharavao et al.* [2002] suggest that more 150 km observations are needed to elucidate their characteristics related to seasons, solar flux, winds, and any other geo-

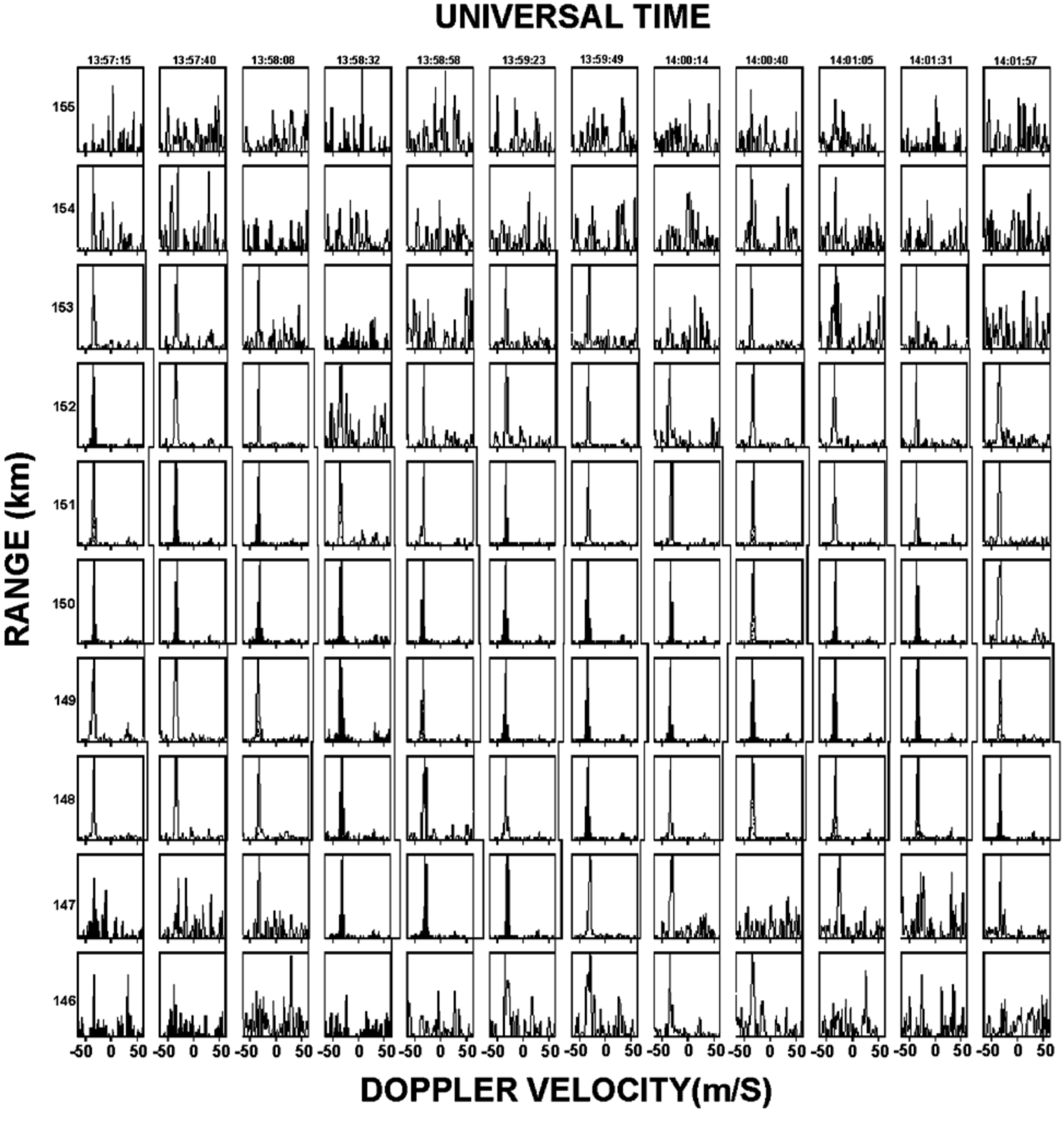

Figure 6. Power spectrum for the 150 km echoes for December 28, 2000.

physical parameters. Long term observations of 150 km echoes have been performed at São Luís as an effort to study the behavior of the ionospheric electric field.

3.3. Equatorial Spread F

[13] Observations of F region plasma irregularities at São Luís are presented in Figures 8 and 9for December 25, 26 and 27, 2000, respectively. The range specific bursts at 15 minutes interval are due to one digisonde operating nearby. On December 25 and 26, there were bottom-type layers [*Hysell and Burcham*, 1998, 2002] confined to altitudes around 400 km from about 22:30 to 23:50 UT (Dec. 25) and 22:15 UT to 23:20 UT (Dec. 26). After this time, large-scale radar plumes developed,

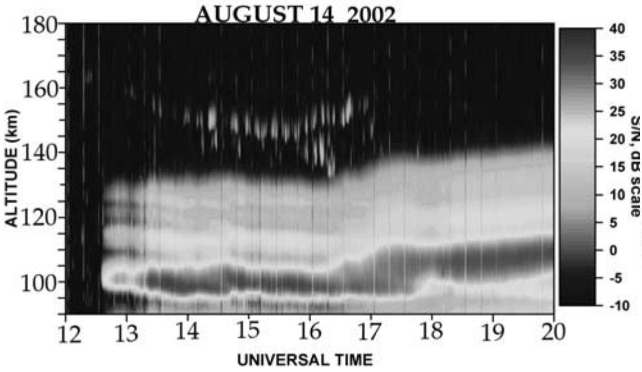

Figure 7. RTI 150 km and electrojet echoes for August 14, 2002. See color version of this figure at back of this issue.

reaching to about 800 km in altitude. Later, the topside plumes transformed into bottomside layers that were more structured than the bottom-type ones. On December 27 (see Figure 9 where besides RTI there are also

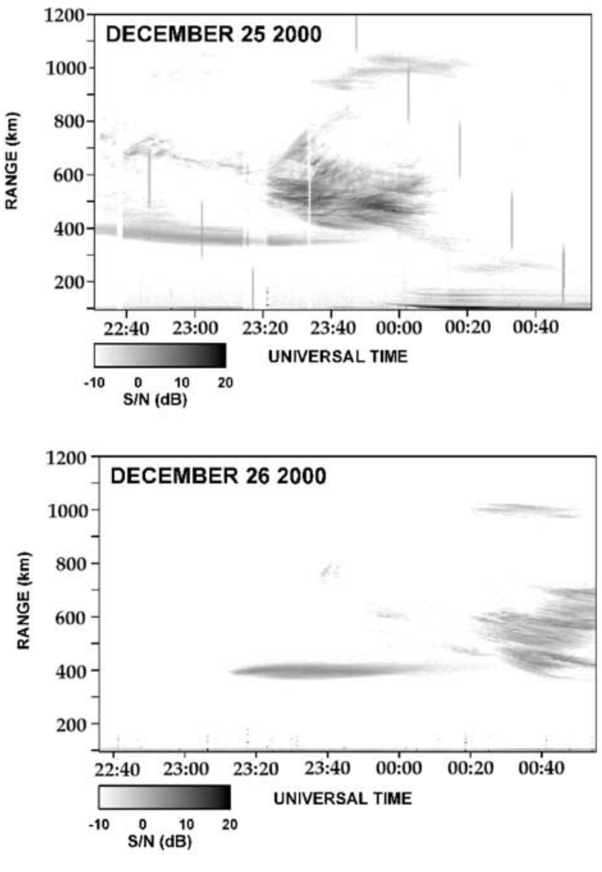

Figure 8. RTI of F region echoes for December 25 and 26, 2000.

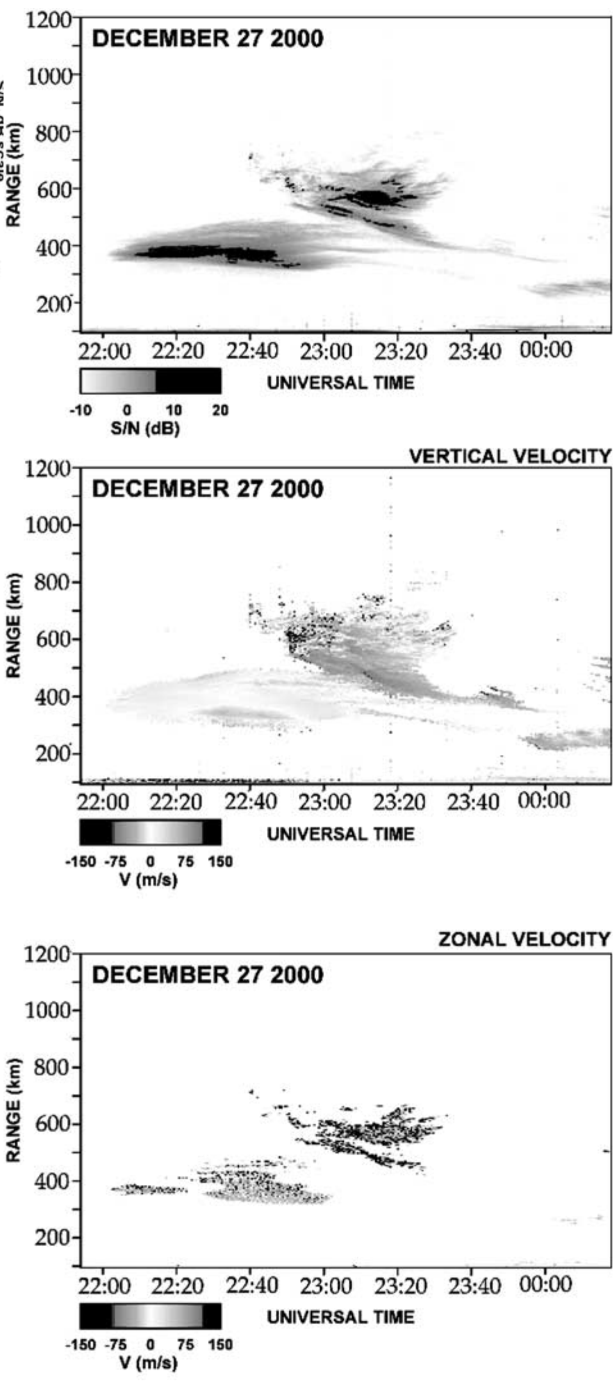

Figure 9. RTI of F region echoes and their vertical (positive upward) and zonal drifts (positive eastward) for December 27, 2000. See color version of this figure at back of this issue.

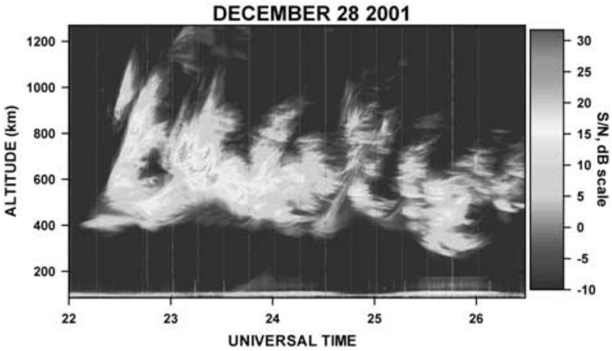

Figure 10. RTI of F region echoes for December 28, 2001. See color version of this figure at back of this issue.

zonal and vertical irregularity velocities) a bottom-type layer was present from 22:00 to 23:15 UT, and radar plumes extending up to about 800 km appeared at 22:40 UT with about one hour duration. The average 10.7 cm solar flux for December 2000 was 168.2 and still in the increasing phase of the solar cycle. The bottom-type layer moved slowly upward and westward, while the plumes after this time had upward and downward drifting portions and a predominant eastward drift of about 150 m/s. This radar-derived zonal drift measurement is comparable to that one calculated using the cross-correlation method [*Kil et al.*, 2000; *de Paula et al.*, 2002] from magnetic east-west spaced GPS receivers at this site. This GPS method is sensitive to the drifts plasma irregularities with ~400 m wavelengths, whereas the coherent scatter radar detects irregularities with 5 m wavelengths. Another example of F region plumes (RTI) during high solar flux (F10.7 cm solar flux was 254.6) that reached about 1,400 km of altitude for December 28, 2001 is shown in the Figure 10. Many vertical quasi-periodic structures can been observed at this RTI plot with very strong echoes coming from about 22:30 to 24:00 UT.

[14] According to *Hysell and Burcham* [1998], the bottom-type layers move westward, probably driven by the E region dynamo, and are often precursors of the plumes that, during magnetically quiet periods, move eastward under the influence of the F region dynamo.

[15] The irregularities observed with the VHF radar over São Luís depicted in Figures 8, 9, and 10 have very similar characteristics compared to the irregularities detected by the JULIA radar at Jicamarca [see, e.g., *Hysell and Burcham*, 1998, Figure 1]. However, RTI plots similar to their Figure 4 showing bottomside layers with regular, closely-spaced, quasi-periodic depletions ascending from them through the F peak have not been observed at São Luís. This is likely due to the rather broad beamwidth of the São Luís radar which prevents the detection of detailed irregularity structure in the zonal direction. In the future we plan to increase the number of antenna modules and receivers deployed at São Luís and to implement radar imaging strategies so as to be able to detect this structure. Our broad beam will permit us to image entire plume structures at once, something that is not presently possible at Jicamarca.

[16] Longitudinal differences in irregularity morphology, occurrence, climatology, and persistence may nevertheless exist, something that was pointed out by *Batista et al.* [1986]. For example, no spread F was observed at Jicamarca on December 26 and 27, 2000. Uncovering these differences demands long-term campaigns of simultaneous measurements with the JULIA and São Luís radars.

4. Summary

[17] In this paper, initial results from the São Luís, Brazil, VHF coherent scatter radar were presented. A short description of the radar hardware, antenna array, and data processing was given, and then observations of electrojet, 150 km and F region irregularities were presented. The electrojet was observed on all days, with the strongest echoes coming from about 104 km in altitude from about 12:00 UT to 20:00–21:00 UT. There is a tendency for the electrojet to reach higher altitude (about 110 km) in the last hours of the afternoon and with a larger altitudinal range, a fact corroborated by INPE's 50 MHz coherent radar also in operation at São Luís [*Abdu et al.*, 2002]. The presence of regularly range spaced daytime echoes around 110–130 km and below 100 km are due to coding sidelobes. During the daytime, clear 150 km echoes were observed on all days with the necklace shape and with the same altitude range and periodicity observed at others sites. They had quasi-periodic behavior with periodicity between 10 to 15 minutes, appeared at about 165 km altitude in the morning (12:00 UT), fell to about 145 km altitude at local noon, and rose again to about 160 km at 17:00–18:00 UT. As mentioned previously, some theories in terms of gravity waves or polarization electric fields have been proposed to explain the origin of 150 km daytime irregularities, but the physical mechanism for their existence is not well established.

[18] The nighttime F region exhibited bottom-type layers moving westward and confined in altitude. These were precursors of topside layers (plumes) appearing at about 22:00 UT that reached altitudes of about 1,400 km, moved eastward, and persisted for about one hour. These in turn were followed by thin bottomside layers at lower altitudes that were ultimately damped by collisions with the neutral atmosphere. Jicamarca JULIA radar data from December 26 and 27, 2000 did not show irregularities, evidencing the longitudinal differences between the Peruvian and Brazilian sectors. The F region plumes at

both sites have similar behaviour except that the São Luís RTI echoes were more diffuse probably due to its broader antenna beamwidth. As the VHF radar at São Luís is located in a position where the magnetic declination is high (about 20°W), and as it is possible to perform routinely measurements with it, it is well suited to perform long term studies of the E and F region equatorial ionospheric irregularities for climatological, prediction and longitudinal studies. Such studies have been underway since December 2000. Complementary data from digisonde, magnetometer, scintillation GPS receivers, and TEC meter can also be available at São Luís observatory.

[19] **Acknowledgments.** This São Luís radar was developed and installed with the support of FAPESP under process 99/00026-0 at INPE and NSF grant ATM-0080338 to Clemson University. E. R de Paula was partially supported by CNPq under process 502223/91-0. The authors are grateful to Lázaro P. de Camargo and Francisco P. V. Mesquita for helping the radar construction, to Acácio C. Neto and his team at São Luís for the radar operation and maintenance, to Dr. Esfhan A. Kherani, Fabiano S. Rodrigues and Alexandre C. Jardim for the radar data processing, and to Drs. M. A. Abdu, B. G. Fejer and K. N. Iyer for fruitful discussions.

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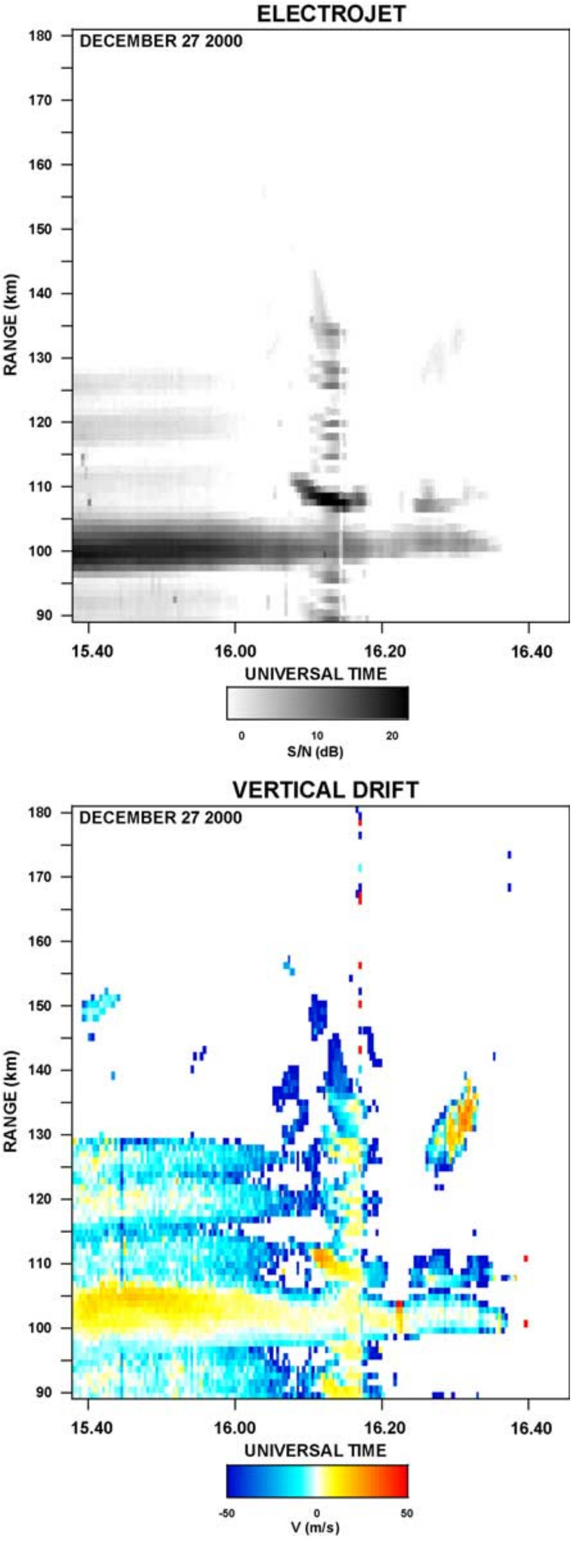

Figure 4. Electrojet RTI echoes and their vertical drift velocities for December 27, 2000.

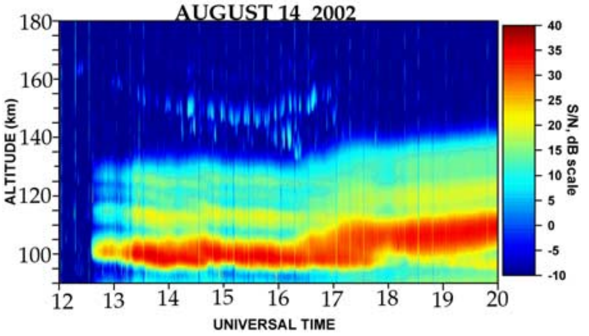

Figure 7. RTI 150 km and electrojet echoes for August 14, 2002.

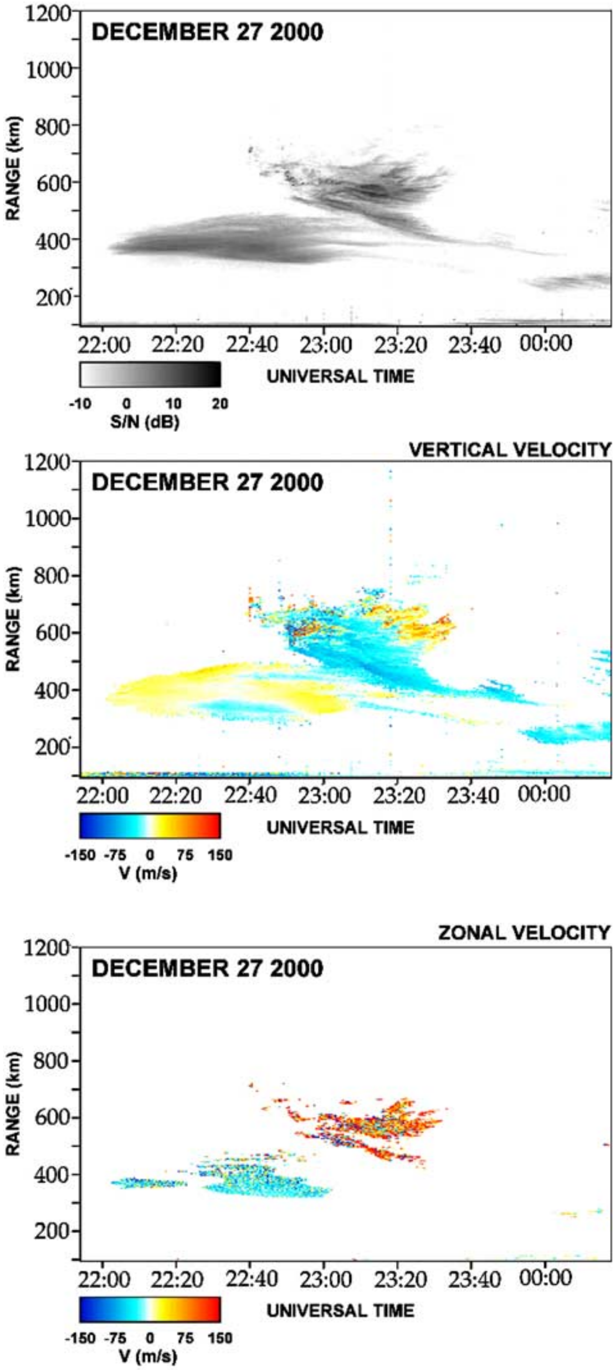

Figure 9. RTI of F region echoes and their vertical (positive upward) and zonal drifts (positive eastward) for December 27, 2000.

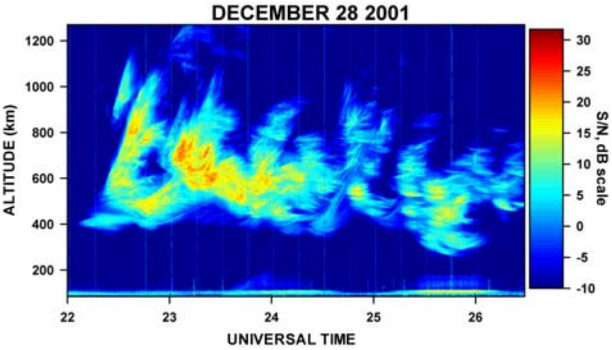

Figure 10. RTI of F region echoes for December 28, 2001.