The Lowering of the EEJ Backscattering Region Based on Coherent Radar Soundings in the Brazilian Sector

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Abstract

In the present paper we present a new feature of the equatorial electrojet observed in the Brazilian sector based on the RESCO coherent radar observations. The center height of the scattering region of the equatorial electrojet is observed to systematically decrease in altitude along the years. It has been observed through VHF radar soundings at São Luís (2.3° S, 44.2° W). This feature is discussed in terms of the displacement of the dip equator from the radar site due to the long term variations in the Earth magnetic field, which can be detected by measurements using ground magnetometers at the radar site. The math tolls used to infer the center height is presented and all different aspects of the equatorial electrojet are present and discussed in terms of established concepts and theories.

Introduction

The equatorial electrojet (EEJ) is an electric current that flows in the height region from about 90 to 120 km (at ionospheric E region), covering a latitudinal range of $\pm 3^\circ$ around the dip equator (Forbes, 1981). It is driven by the E region dynamo electric field (Fejer e Kelley, 1980) and plays an important role in the development of the plasma irregularities of the equatorial ionosphere-thermosphere system. Among them, its polarization electric field drives plasma instabilities which can scatter electromagnetic waves in the VHF frequency range, which are detected by VHF coherent radar like RESCO. Figure 1 shows vertical profiles of polarization electric field (blues line), Hall-to-Pedersen ionospheric conductivity ratio (red line) and resulting EEJ current (green line). Since radar echoes are backscattered by EEJ plasma irregularities drove mainly by electric field, this graph gives us the height region where radar echoes come from at the E-Region heights. Sounding observations of the equatorial ionospheric E region using VHF radars have shown backscattered echoes from electron density irregularities in the EEJ in several sectors, such as the Peruvian sector (Cohen e Bowles, 1967; Balsley, 1969; Cohen, 1973; Fejer, Farley *et al.*, 1975; Farley, 1985), the Indian sector (Prakash, Gupta *et al.*, 1971; Reddy e Devasia, 1981; Somayajulu, 1991), and the Brazilian sector (Abdu, Denardini *et al.*, 2002; Abdu, Denardini *et al.*, 2003; De Paula e Hysell, 2004; Denardini, Abdu *et al.*, 2004; Denardini, Abdu *et al.*, 2005). These echoes contain Doppler shifted frequency components due to the drift of the irregularities, which

present distinct spectral signatures called type 1 and type 2 spectra (Figure 2). Spectrum type 1 is produced by irregularities generated by the modified two-stream plasma instability process (Buneman, 1963; Farley, 1963); while type 2 is originated from the gradient drift instability mechanism (Rogister e D'angelo, 1970).

Fig. 1 - Polarization electric field, Hall-to-Pedersen ionospheric conductivity ratio and the resulting EEJ current polarization electric field at E-Region.

Fig. 2 - Typical EEJ irregularities spectral signatures identifies by the RESCO radar at São Luís.

Despite these several studies on the EEJ, none of them revealed the lowering of the back-scattering region observed in our analysis. Moreover, due to displacement of the dip equator away to the radar site we had the unique opportunity to scan horizontally the EEJ with VHF radar. Of course, there is day-to-day variability in the EEJ as well as seasonal and many other dependencies like magnetic disturbances, and it is not neglected here. In the following we present and discuss this EEJ feature of lowering the region that is backscattering echoes from such plasma instabilities in the Brazilian sector based on the RESCO radar observations. When discussing EEJ characteristics in terms of the magnetic activity, the K_p index was used. When it reached values above 3⁺ at any time during the corresponding day, it was classified as disturbed. In this compilation we have selected several days from 2002 to 2004, which will be classified when necessary.

Equipments Description and Data Analysis

Radar System Description

The RESCO (which is an acronym for *Radar de ESpalhamento COerente*, in English Coherent Scatter Radar) 50 MHz coherent backscatter radar is sensitive to field aligned plasma irregularities of 3-meter scale size. The operations started in 1998 at the São Luís Space Observatory - OESLZ (2.3° S, 44.2° W), very close to the dip equator in Brazil. It is operated with the beam tilted 30° westward or eastward from vertical or even vertical, in the E-W plane (Figure 3). The estimated theoretical beam width is 7.4°. The height range set for EEJ observations is from about 80 to 120 km. The radar is operated at a peak power of 40 kW, with the pulse width set to 20 μs and inter-pulse period 1 ms to avoid ambiguity in the echo detection. The backscattered signals are sampled at 20 μs, which corresponds to range sampling at 3 km in the oblique direction that corresponds ~2.6 km in terms of height. Each echo is divided into 16 sampling gates, which correspond to 16 height samples. For more detailed information about this radar system see, for example, Abdu, Denardini et al. (2002) and Denardini, Abdu et al. (2004).

Fig. 3 - Geometry of the RESCO radar oblique soundings in the presence of a descending movement of the plasma irregularities (V_y), superposed to its natural daily westward displacement (V_y').

Radar Data Description

Daily radar data analysis produces one spectrogram per sampled height, which consists of a contour map of Doppler frequency versus local time with a color-coding used to indicate the power spectral density. Integration in the Doppler frequency for each spectrogram results in time-variations of the total echo power for a specific range gate. Arranging all resulting echo power time-variation in a graph of height (gate) versus time produces a daily Range-Time-Intensity (RTI) map.

Magnetometer Data Description

Diurnal variation of the EEJ strength and dip angle variation are also monitored at the OESLZ using two fluxgate ground-based magnetometers. One of them is set to measure the horizontal component (H), the vertical component (Z) and the variation of the declination (D) of the Earth magnetic field. The other is set to sample the three components Earth magnetic field orientated geographically: northward (X), eastward (Y) and vertical (Z). Both magnetometers sample the magnetic field at about one measurement per second. For determining the dip angle variation we have used the measurement of the magnetic field components orientated geographically. And, in order to avoid the diurnal variation of the magnetic field components caused by induced current of the EEJ and/or external sources, we have only taken the local midnight value of the dip to get the long term trend in the dip variation.

Math Tools for Radar Data Analysis

The current RESCO data processing uses Least Squares Fitting Method (Levenberg, 1944; Marquardt, 1963; Press e Rybicki, 1989) to fit Gaussians and white noise to the vertical profiles (for RTI maps) or to the power spectra (for spectrograms). In case of Doppler power spectra of irregularities we use the sum of two Gaussians (each one representing one type of irregularity). The aliasing frequency is obtained from the Fast Fourier Transform (FFT) of the chosen set of consecutive received EEJ echoes. The frequency resolution (normally about 1 Hz) depends upon the aliasing frequency and the number of consecutive echoes. In case of power profiles from the RTI map we fit a single Gaussian. The limiting range height is obtained by the height range used during the soundings, and the height resolution is based on the range sampling. As the data processing for both cases is similar, in the following we will describe the math processing for power spectra. For processing the power profiles in RTI map, just assume one Gaussian instead of two. All the processing is made based on the assumption that each spectrum is described by a S distribution in function of the frequency, given by:

$$S(f) = \frac{P_1}{s_1 \sqrt{2\pi}} \exp \left[-\frac{(f - f_{d1})^2}{2s_1^2} \right] + \frac{P_2}{s_2 \sqrt{2\pi}} \exp \left[-\frac{(f - f_{d2})^2}{2s_2^2} \right] + P_N \quad (1)$$

where P_N , P_i , s_i and f_{di} are the noise level, spectral power, spectral width and Doppler frequency, respectively. The i index indicates the type of the described irregularity: type 1 ($i=1$) or type 2 ($i=2$). Therefore, the Maximum Likelihood Estimate (MLE) is used for nonlinear fitting of the 7 Gaussian parameters of each spectrum, $a = (f_{d1}, f_{d2}, s_1, s_2, P_1, P_2, P_N)$. The fitting method is based on finding the

parameters $\mathbf{a}$ that maximize the probability function $P(y_1 \dots y_n | \mathbf{a})$ of obtaining the data set $\mathbf{y} = (y_1 \dots y_n)$, i.e., it is a problem of finding the parameters $\mathbf{a}$ that minimize the square sum of residual errors between the observational data set $\mathbf{y}$ and the corresponding Gaussians $S(f)$ that describes the data set, considering the uncertainty s_i related to each point y_i . Eq. (2), named objective function, describes mathematically the above statement.

$$c^2 \equiv \sum_{i=1}^N \frac{[y_i - S(f_i; P_1, f_{d1}, \mathbf{s}_1, P_2, f_{d2}, \mathbf{s}_2, P_N)]^2}{s_i} \quad (2)$$

Here, N is the number of frequency beams in the power spectrum, y_i is the observed spectral amplitude for a given frequency and all the other parameters have been introduced before. In cases when the data variance is too high curve fitting algorithm can provide results not satisfactory enough. In such cases we integrate incoherently several consecutive spectra to reduce high variances. The incoherent integration reduces the variance of the noise (s_N^2) and better defines the power spectra without change the mean values of signal (P) nor the spectral noise (P_N) power densities (Fukao, 1989). Mathematically, the unitary ratio s_N/P_N from a single spectrum decays with the inverse of the square root of the number of incoherent integrations ($NICH$), i.e., s_N becomes $P_N/(NICH)^{1/2}$. Another math tool used to increase the accuracy of the fitting method is constraining the search for Gaussian parameters. It means to impose boundaries in the parameters domain, which can not be crossed during the search. This is made imposing penalties to the objective function when the method assumes unrealistic physical values (Bard, 1974), like adding the following term.

$$V_j = \frac{a_j}{h_j(P_1, f_{d1}, \mathbf{s}_1, P_2, f_{d2}, \mathbf{s}_2, P_N)} \quad (3)$$

Here, a_j is the weight of the function and h_j is penalty function for each Gaussian parameter. Such function should be positive in the valid region of search, decrease rapidly as the search approach of the prohibited region, and be negative when the method crosses the boundary.

Results and Discussion

After several years of VHF radar sounding the EEJ, we have observed that the center height of the EEJ backscattering region have been systematically lowering along the years. Figure 4 shows a series of RTI maps taken as samples of daily RTI in consecutive years. Height scale is not the same in all graphs, but it is notable the center of the EEJ backscattering region (EJC) have been lowering in altitudes along the years. Using the math tool described before we were able to determine the thickness of the EEJ backscattering region (EJT) and the EJC mean values for the selected days. The results are summarized in Table 1.

Tab. 1 - Range height and mean height of the center of the EEJ backscattering region

Date	Mean EJT (km)	Mean EJC (km)
28-01-2002	5.53	101.4
05-11-2002	5.48	101.3
29-08-2003	4.44	101.0
17-11-2003	4.50	99.9
11-02-2004	4.53	99.6
19-11-2004	4.78	99.3

Others features that can be notes in these RTI maps are the rising of the EJC in the afternoon and the appearance of a scattering region at higher altitude than the normal EEJ at that day in the evening. Both features have been reported and discussed by the RESCO team (Abdu, Denardini *et al.*, 2002; Denardini, Abdu *et al.*, 2005; Denardini, Abdu *et al.*, 2006) and were not considered when obtaining the center of the EEJ backscattering region. In the present work we will only address the

observed lowering in the EJC. However, analyzing the EEJ backscattering region is not easy, because the two types of EEJ plasma irregularities that compose the scattering region have different mechanism of generation. Thus, it is important to determine which type of plasma irregularities dominates the power spectrum in as a function of time and height. Regarding the height distribution, Denardini, Abdu *et al* (2004) have shown that irregularity type 2 are more frequently observed in the lower backscattering region while type 1 are observed mainly in the upper part, as shown in Figure 5.

Fig. 5 - Height distribution of irregularities type 1 (Red bars) and type 2 (Green bars) detected by the RESCO radar during quiet (a) and disturbed (b) period in 2003, constrained between 8h and 10h LT.

This figure shows a histogram of height distribution of irregularities type 1 and type 2 detected by the RESCO radar during quiet and disturbed period in 2003, covering about 100 days of the year. These histograms represent the typical behavior of the height distribution observed at the radar site and show the clear dominance of irregularity type 2 in the bottom part of the scattering regions of the EEJ as well as show the almost complete disappearance of type 1 irregularity during magnetically disturbed periods, except for some cases not shown here. This interesting dominance of type 2 is not only in height but also in time. Figure 6 is similar to Figure 5, and also covers about 100 days in 2002. It shows the diurnal occurrence of irregularities type 1 and type 2 per range height for radar soundings during the quiet days in 2002. These graphs cover the heights from 99 to 111 km, with ~2.6 km of height resolution, center at the height indicated in the upper right corner of each graph. The vertical scale in the occurrence plots of the type 1 irregularity ranges from 0 to 4 % of days, while the same scale for the type 2 irregularities ranges from 0 to 35 % of days. It is also clear that irregularities type 1 are more often observed in the morning and afternoon rather than around midday, while irregularities type 2 are frequently observed during the whole day with a clear maximum in the evening period, when they dominate the power spectrum. The dominance of irregularities type 2 during the morning and the evening hours is not surprising because type 1 irregularities need strong electric fields to be generated, which are often achieved around midday. So, it was expected type 1 irregularities to dominate the spectrum around local midday. The observations in the Brazilian sector contradict the theories and other observations in different sectors, however. Figure 6

shows that irregularities type 2 seems to dominate the power spectrum the whole day. This tricky but important result need accurate measurements to be confirmed and will not be addressed in the present work, indeed. The important point we would like to stress here is that the irregularities type 2 is the dominant type during the whole day and whole heights in the Brazilian sector.

Fig. 6 - Daily occurrence of irregularities type 1 (a) and type 2 (b) at 99.96 km (violet), 102.55 km (dark yellow), 105.15 km (olive), 107.75km (blue), and 110.34 km (red) heights for radar soundings during the quiet days in 2002.

Finally, we can assume for the present analysis the backscattering regions of the EEJ is basically formed by irregularities type 2. The development of irregularities type 2 depends upon the electron density gradient and the ambient electric field to be anti-parallel (Fejer e Kelley, 1980). Electron density profiles (not shown here) obtained from a digital ionospheric sounder located at the OESLZ revealed that during all the radar soundings the backscattering region was located below the E-Region density peak, i. e., in a region of upward electron density gradient. Also, we have selected normal EEJ condition and the Doppler shift seen on the spectrograms obtained for the selected days indicated that the polarization electric field is upward. Therefore, the condition for type 2 plasma irregularities to develop was always established. Based on this EEJ characteristics and assumptions above, the lowering of the EEJ scattering region can be attributed to a lowering in either the region of favorable gradient density and/or the region of stronger electric fields. Since we saw no clear descending in the electron density profiles obtained from the ionograms (not shown here), we assume that the region of favorable electric fields is descending. Also, such descending of the center height of the EEJ backscattering region is well correlated with the increasing in dip angle at the radar site measured by ground-based magnetometer (Figure 7).

Fig. 7 - Dip angle variation derived from magnetometer measurements at São Luís - MA (2.3° S, 44.2° W).

When the radar start operates in 1998 the dip angle at the OESLZ was about -0.5° . Nowadays, the dip angle at the radar site is near -5.4° . It means that the center of the radar beam is standing away from the EEJ region. Denardini (2007) had presented a magnetic field aligned integrated conductivity model in which he verified the height region of higher Cowling conductivities around the equatorial E region descent as we depart from the center of the magnetic equator. He attributed the descent of this higher Cowling conductivity region to the integration along the magnetic field line, because the magnetic intensity decays with the square power to the cosine of the co-latitude in a dipolar representation. As a result, equatorial phenomena like the EEJ current, which is directly related to the field aligned integrated Cowling conductivity, will be observed at lower altitudes if sounded close apart from the magnetic equator in comparison with soundings at the dip equator. Figure 8 illustrates the EEJ bulk format showing a field aligned shape that could explain the lowering of the EEJ backscattering region based on coherent radars soundings in the Brazilian sector.

Fig. 8 - Illustration of a vertical radar beam passing through the equatorial electrojet bulk close to the dip equator.

Conclusions

There has been observed through coherent radars soundings a lowering in the center of the EEJ back-scattering region along the years. A tentative explanation to this lowering was presented in terms of an effect due to a lowering the region of favorable electric fields anti-

parallel to the density gradient, which in turn is due to the displacement of the dip equator from the radar site. The discussion was based on the evidences that irregularity type 2 clear dominate all heights (mainly in the bottom part) of the scattering regions of the EEJ during the whole day with a clear maximum in the evening period. We have also seen in the Brazilian sector irregularities that type 1 are more often observed in the morning and afternoon rather than around midday, which contradict the theories and other observations in different sectors. Another feature regarding type 1 irregularity is their almost complete disappearance during magnetically disturbed periods.

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