Analysis of Doppler Velocities of Equatorial Electrojet Type 1 Irregularities

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Abstract

Equatorial ionosphere observations using VHF radars show backscattered echoes from electron density irregularities in the equatorial electrojet (EEJ). The studies of the echoes have revealed distinct spectral signatures of two types of irregularities, named type 1 and type 2, explained by the modified two-stream and the gradient drift instabilities, respectively. Type 1 echo spectra normally presents a sharp peak centered at around 120 Hz for 50 MHz radars, which corresponds to a Doppler shift of about 360 m/s (close to the ion-acoustic speed). Several experiments have been done to investigate the EEJ irregularities in order to characterize its phenomenology using RESCO 50 MHz radar at the Brazilian sector. In the present work we summarize some characteristics of type 1 echoes based on power spectra of backscattered signals from 3-m EEJ plasma irregularities. We also show statistics of its occurrence in simultaneous height and time, including a velocity distribution analysis.

1. Introduction

At about 105 km of altitude in the equatorial E region and covering a latitudinal range of ±3º around the dip equator flows an intense electric current named equatorial electrojet (EEJ) [1]. It is driven by the E region dynamo [2]. Studies of the equatorial ionosphere using VHF radars have shown echoes backscattered from plasma irregularities in the EEJ. Spectral studies of such echoes showed two distinct spectral signatures for the observed irregularities. And they were labeled type 1 and type 2, accordingly. Nowadays, they are also known for their theory of development as modified two-stream [3,4] and gradient drift instabilities [5], respectively.

Type 1 echoes are characterized by a narrow spectra with high amplitude predominantly localized in the upper portion of the EEJ. These echoes are observed under strong enough electrojet conditions, when the plasma was found to be unstable if the relative drift between ions and electrons exceed the ion-acoustic speed [6]. On magnetically quiet days type 1 echoes are expected to appear between 10h and 13h LT, or when the phase velocities reach the ion-acoustic speed [1]. On magnetically disturbed days, due to energy deposition of the magnetic disturbance, it may be more produced [7].

The theory of this instability shows that it is applied to waves propagating in a cone of angle φ, given by:

\[ V_d \cdot \cos \theta = C_s (1 + \psi) \]  

where \( V_d \) is the relative velocity between electrons and ions, \( C_s \) is the ion-acoustic speed (approximately 360 m/s), given by:

\[ C_s = \left( \frac{k(T_e + T_i)}{2m_i} \right)^{\frac{1}{2}} \]

where \( k \) is the Boltzmann’s constant, \( T_e \) and \( T_i \) are the ion and electron temperatures and \( m_i \) the ion mass. The anisotropy factor \( \psi \) is given by:

\[ \psi = \frac{v_e \cdot v_i}{\Omega_e \cdot \Omega_i} \left( \frac{\sin^2 \alpha + \frac{\Omega_e^2}{\Omega_i^2} \cos^2 \alpha}{v_e^2} \right) \]

where \( \alpha \) is the angle between the wave and the magnetic field, \( \Omega \) and \( \Omega \) are the collision rate and gyrofrequencies for the electrons and ions. The cone is centered on the relative drift direction, and from Eq. (1) we see that for the instability to operate the component of the relative drift velocity in the direction of the wave must exceed the ion-acoustic speed. The amount that the ion-acoustic speed must be exceeded depends on \( \phi \) and hence on the propagation direction with respect to the magnetic field (\( \alpha \)). This is the reason why electrostatic waves generated by this mechanism usually propagates normal to the magnetic field and why the difference of velocities is close to the ion-acoustic speed [8]. VHF radar observations at Jicamarca show that...
during intense daytime electrojet streaming, type 1 echoes are mostly observed in a narrow range between 103 and 107 km [2]. When viewed at vertical incidence, an asymmetry is often seen between downward and upward moving type 1 waves, both in time and space. During daytime, upward moving type 1 irregularities are more frequently observed and occur over a larger range of altitudes than the downward traveling irregularities. In the lower part of the scattering region, below about 103 km, the spectra are considerably narrower, having smaller Doppler shifts, and are much less variable in time. The downward type 1 waves are more common at night and are observed over a larger altitude range than the upgoing type 1 waves. Therefore the up-down type 1 asymmetry reverses from day to night. This asymmetry is also more pronounced during nighttime [2]. In addition to the asymmetry observed at vertical incidence, an east-west asymmetry of backscatter power from echoes at oblique beam positions is also a common feature [9]. Reference [10] argued that the source of those asymmetries could be explained by kilometer-size structures breaking down to become tilted with holes moving obliquely up and westward while blobs are moving obliquely down and westward.

In addition to those features, St. Maurice et al. [6] explained some cases where type 1 phase velocities exceed the isothermal ion-acoustic speed (when \( T_i = T_e \)), 360 m/s. They included electron thermal fluctuations in the theoretical treatment of this instability. These electron thermal fluctuations are caused by electron heating and cooling effects related to the wave dynamics. When the electron thermal fluctuations are included in the calculations the derived instability threshold speeds match the upper limit reached by the observations. Those higher velocities are called non-isothermal ion-acoustic speed.

2. Methodology and Experimental Description

The 50 MHz RESCO radar is located at the Brazilian equatorial region at 2.51° south, 44.27° west, -0.5° dip latitude. The COCO (coaxial-collinear) antenna array consists of 32 strings of 24 dipoles separated by a half wavelength, totaling 768 dipoles. The array is configured so that the antenna beam can be steered electronically between the vertical and one oblique direction (±30° zenith angle) or between two oblique directions. The theoretical beam widths are ~7° in E-W and ~3° in N-S planes and the transmitter peak power is ~40 kW.

The radar is usually set for EEJ sounding. The inter-pulse period (IPP) of transmission is usually set to 1 ms. The time delay (TD) between transmission and reception is set to 600 or 620 µs. The observations have been made using a pulse width (PW) of 20 µs that corresponds to 3 km height resolutions using the vertical beam or 2.6 km when the radar beam is oblique. The radar data acquisition system samples the echoes so that the height coverage is between around 80 and 120 km.

The backscattered echo received by the antenna array is amplified before passing through two phase-coherent detectors that provide in-phase and quadrature signals containing the Doppler frequency and power information. The phase detected signals are sampled in 16 range gates and stored in a sequential binary format. The signals are grouped in sets corresponding to 256 or 512 pulses (NP) for each sampled range gates. The data processing consisted in an off-line spectral analysis using Fast Fourier Transform (FFT) for each range gate of NP data points which resulted in the spectral distribution of the Doppler frequencies contained in the returned signal for each range gate. For the periods of analysis, the time resolution between each set of NP pulses is 12 s and the aliasing frequency for each spectrum is 500 Hz with ~ 2 Hz (NP=512) or ~ 4 Hz (NP=256) of frequency resolution. Then, by integrating each spectrogram in frequency, we obtained the total power received from each height, and the time variation of the total power in all the range gates is used for plotting the daily Range Time Intensity (RTI) maps.

The Doppler spectrum of the echoes is a composite of both type 1 and type 2 irregularities present inside the sampled radar volume. Assuming that the experimental spectra can be decomposed in various Gaussian spectra the spectral decomposition technique involves fitting the sum of two Gaussian curves to the spectrum. Each Gaussian (related to one specific irregularity type) is characterized by three parameters: center of frequency distribution (corresponding to Doppler shift), spectral power density and spectral width. After inverting the curves, the six statistical moments (three to each irregularity type) are evaluated. Gaussians with spectral power smaller than 5% of the maximum spectral power for the whole day are discarded to avoid eventual bad fitting related-problems.

The analysis was performed using data collected from the westward radar beam during some magnetic quiet days in 2002. The data set was separated into three season groups: solstice D (November, December and January), solstice J (May, June and July), and equinoctials M and S (February, March, April, August, September and October) months. We have selected 15 days on J, 18 from M and S, and 38 on D months. We carried two distinct analysis related to type 1 irregularities: statistical analysis of occurrence in simultaneous height and time and a study of the distribution of velocities.

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3. Results

Fig. 1 presents the results of occurrences (%) of type 1 echoes for (a) solstice D, (b) solstice J and (c) equinoxials M and S months. The D months (Fig. 1a) clearly shows the occurrence of type 1 echoes is well localized. The echoes seem to occur after 15h LT in around 10% of the days. As our analysis does not use data after 18h LT, it is not possible to determine precisely the local time that the type 1 echoes stopped to be observed. The statistics also reveals the preferential height distributing between 95 and 110 km. There are some occurrences of echoes between 9h30 and 15h30, but having less statistical significance then those at the end of the day. Fig. 1b shows the occurrences of type 1 echoes for J months having no clear pattern of the occurrences; despite some significant occurrences in all heights are evident. However, it can be seen that the echoes appear preferably in the upper portion of the EEJ, between 105 and 110 km. Moreover, the echoes seem to be constraint to the period before 15h LT, with some few occurrences higher than 20 % lather then this hour. The interesting feature is that the region where the J months detected a few observations is the same one where D months showed maximum occurrences. Fig. 1c presents the occurrences of type 1 echoes for equinoxial M and S months. The figure shows echoes in all heights and times with no clear tendency. It has a region of significant occurrences after 15h30 LT as well as D months, but the region of highest occurrences is before 12h30 LT.

Fig. 2 presents the distribution of occurrences (%) of the ion-acoustic speed (m/s) deduced from type 1 echoes for (a) solstice D, (b) solstice J and (c) equinoxial M and S months using data acquired in 2002 with the RESCO westward radar beam. The D months (Fig. 2a) shows one distribution of velocities centered on 360 m/s and another one on 430 m/s. The distribution on 360 m/s sharply decays moving away from the peak and the second distribution (around 430 m/s) decays slower. The second distribution still seems to decay faster to slower velocities, but not can be said about upper velocities distribution since they are to close to the upper limit of Doppler velocities scale. Fig. 2b shows the distribution of type 1 velocities for J months. Despite the same pattern on D months is seen in the J months, there are some distinct features. The number of occurrences of velocities in the 360±10 m/s range is higher. Also, the curve distribution centered in 360 m/s decays faster in J than D months. Fig. 2c presents the distribution of velocities for equinoxial M and S months. It is still shown the same pattern, a peak around 360 m/s and second distribution on the upper velocities. However, the second center of distribution around 430 m/s is not clearly defined. Actually, it seems the occurrence of velocities ranging between 385 and 440 m/s is almost constant around 4%. However, the curve of upper velocities distribution clear shows decay in the upper scale side not seen in the previous ones. It is also pointed out that the worst statistics for velocities in the range 360±10 m/s was obtained in the equinoxial M and S months, being approximately 4% of the occurrences.

4. Discussions

The results on Fig. 1 showed that the EEJ type 1 echoes have a seasonal behavior in time and space. Neutral winds are known to affect the EEJ current as well as the zonal electric field and shown a seasonal dependence [11]. Therefore, a seasonal dependence of the occurrence of type 1 echoes can be attributed to neutral wind. The statistical behavior in height and time of type 1 echoes on equinoxial M and S, and solstice J months are not clearly detected, but on solstice D months it is. This result could be caused by the different number of days in each data set, as we have used 38 days on D, 18 from M and S, and 15 on J months. D months clearly show that the echoes have a well-localized occurrence after 15h LT in the height range from 95 to 110 km. Unfortunately our analysis does not use data after 18h LT because the RESCO radar operations is usually schedule to stop at that time. Hence, very few can be said about Doppler velocities observations distribution around sunset. The authors would like to stress there is no other published result, which shows similar statistical occurrence of those echoes between 15h LT and sunset, to the best of their knowledge. This result seems to show that the EEJ strength on D months is higher on the afternoon than on the morning, i.e., there is an average behavior of type 1 Doppler velocities related to a seasonal variation superposed to its day-to-day variability.

The analysis of Fig. 2 reveals that the velocities distribution of type 1 irregularities shows very similar behavior in all periods of the year. It have a distribution centered on 360 m/s (the isothermal ion-acoustic speed), sharply decaying as it moves away from the peak, and a second distribution with a smoother decay. The distribution around the peak, from 350-370 m/s (117-123 Hz) could be attributed to interference from the first harmonic of the power supply system, 120 Hz (since the fundamental frequency is 60 Hz). However we do not believe that it is the case, as we would expect to obtain a distribution around the isothermal ion-acoustic speed (360 m/s) and due to the shielding system. The second distribution for D and J months seems to be centered on around 420-435 m/s (140-145 Hz), where there is no possible effect of interference. On equinoxial M and S months, the second distribution is located in the range 385-440 m/s with almost continuous occurrences. This
distribution still shows the occurrence decaying just after 440 m/s. It seems that the velocities on equinoctial periods are smaller than on any one of the solstices since the occurrence of non-isothermal ion-acoustic speeds (445-450 m/s), are 3.5% against 4.25% on D or J months.

Fig.1 - Statistics of occurrences of type 1 echoes (%) of type 1 echoes for (a) solstice D, (b) solstice J and (c) equinoctial M and S months using the RESCO radar west beam data set on 2002.
Fig. 2 – Distribution of occurrences (%) of the ion-acoustic speed (m/s) deduced from type 1 echoes for (a) solstice D, (b) solstice J and (c) equinoctial M and S months using the RESCO radar west beam data set on 2002.
5. Conclusions

In the present work, we have summarized some statistical characteristics of type 1 echoes based on power spectra of backscattered signals from 3m EEJ plasma irregularities. We also show a statistics of its occurrence in height and time, including a velocity distribution analysis. The analysis was performed using data collected from the RESCO westward radar beam during magnetic quiet days in 2002. The data set was separated in three season groups: solstice D (November, December and January), solstice J (May, June and July), and equinoctials M and S (February, March, April, August, September and October) months. We carried out two distinct analysis related to type 1 irregularities: statistical analysis of occurrence in simultaneous height and time and a study of the velocity distribution.

The first analysis showed that there no clear statistical tendency to type 1 echoes appear in certain height nor time in equinoctial M and S, and solstice J months. However, there is some tendency in solstice D months. The echoes are well-localized after 15h LT in the range height from 95 to 110 km. This result seems to show that the EEJ strength on D months is higher on the afternoon than on the morning, i. e. there is an average behavior of type 1 Doppler velocities related to a seasonal variation superposed to its day-to-day variability.

The analysis on the Doppler velocity distributions of type 1 plasma irregularities resulted in a very similar behavior in all periods of the year. It revealed a one distribution centered on 360 m/s (the isothermal ion-acoustic speed), sharply decaying as it moves away from the peak, and a second distribution with a smoother decay. The second distribution for D and J months seems to be centered on around 420-435 m/s (140-145 Hz), what could be seen as non-isothermal ion-acoustic speeds. On equinoctial M and S months, the second distribution is located in the range 385-440 m/s with almost continuous occurrences. Finally, the analysis seems to show that the velocities on equinoctial periods are smaller than on solstices.


References

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30 October to 02 November 2007

Abstract Book
1020 h – 1140 h Session IRS: Ionospheric Remote Sensing and Propagation
Convener: Bertram Arbesser-Rastburg (ESA-ESTEC, The Netherlands)

1020 h – 1040 h: Paper IRS.1 “Analysis of Doppler Velocities of Equatorial Electrojet Type 1 Irregularities”
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1040 h – 1100 h: Paper IRS.2 “Analysis of Sporadic-E Layers During Disturbed Periods Based on Ionosonde Data and Magnetometer Signature of Induced Currents”
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1100 h – 1120 h: Paper IRS.3 “Counter Electrojet Characteristics Obtained from Radar and Magnetometers: Cases Study in the Brazilian Sector”
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1120 h – 1140 h: Paper IRS.4 “Ionosphere Error Analysis Tools”
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