Studies of the EEJ Intensity Correlated with the Fluctuations in AE Activity (Transients in 3-meter Irregularity Power and Local Time Dependence) Using the RESCO 50 MHz VHF Coherent Radar and Magnetometers Data.

Clezio M. Denardini, National Institute for Space Research
Mangalathayil A. Abdu, National Institute for Space Research
José H. A. Sobral, National Institute for Space Research

This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

Abstract

We have analyzed the data collected during an observational campaign of the equatorial electrojet (EEJ) plasma irregularities using 50 MHz coherent back-scatter radar operated at São Luís, Brazil. We have selected a disturbed 3-day period for the present analysis. A correlative analysis of the auroral electrojet indices and radar and magnetometer data are carried out to investigate the diverse characteristics of the responses of the EEJ and its instabilities processes to the disturbance zonal electric fields that penetrate to equatorial latitudes during auroral disturbance. Large degree of day-to-day variability in the EEJ current intensity, 3-meter echo powers were observed. Among the outstanding results of this analysis are the following findings: (a) the observed EEJ current and 3-meter irregularity response phases to the intensification/decay phases of an auroral sub-storm event agree with the prediction by the existing models; (b) the phase relationship of the EEJ response versus AE intensification is altered/inverted under the presence of a ring current (D_{st}) development; and (c) the amplitude of the EEJ response show clear local time dependence being maximum around noon. These results are presented and discussed.

Introduction

The equatorial electrojet (EEJ) current that flows at about 105 km in the equatorial ionospheric E-region has been intensively studied since its discovery by Sidney Chapman (1951) based on study of magnetometer data over Huancayo. The characteristics of the plasma instabilities of the EEJ and the resulting plasma irregularities have been investigated extensively using VHF radars and rocket born experiments that have clarified many outstanding features of the dynamics and morphology of these irregularities (see for example, Cohen et al., 1962; Balsley, 1966; Balsley and Woodman, 1969; Fejer et al., 1975; Farley, 1985; Reddy, 1981; Prakash et al., 1971; Pfaff et al., 1987). Theoretical considerations on the plasma instabilities and the electrodynamics of the EEJ can be found in Matsushita (1951); Farley (1963); Buneman (1963); Fejer and Kelley (1980); Forbes (1981); Kudeki et al. (1985); Fejer (1996). The most basic features of these plasma irregularities are: (a) they are essentially fluctuations in the local plasma density; (b) they are elongated parallel to the magnetic field; (c) they propagate as plasma waves in direction perpendicular to the magnetic field and opposite to the EEJ flow direction; (d) they have been observed during day and night time, except during sunrise and sunset.

The EEJ and its instabilities are known to present significant short-term variability. A high degree of day-to-day variability in the EEJ strength and instability spectral features have been observed in the Brazilian sector as shown in a preliminary analysis of the initial data from a 50 MHz radar that has become operational at São Luís (Abdu et al., 2002). It is not clear though if such variability is a distinct characteristic of the Brazilian longitude sector as compared to other longitudes. The purpose of this study is to analyze the data set selected during the campaign of December 1999 aiming at further clarification of the characteristics of the EEJ variability as function of auroral electrojet activity (auroral indices, Rostoker, 1972) and ring current intensity (in some case) as against that arising from local disturbance sources (possibly from neutral atmospheric dynamics). The selected 3-day period (11-13 Dec.) was marked by moderate auroral electrojet (sub-storm like) intensification events. The data on Range-Time-Intensity maps were obtained from the 50 MHz coherent back-scatter radar that became operational at the magnetic equatorial site, São Luís (2.33° S, 44.2° W, dip: -0.5 °) in Brazil, in 1998. The data presented and discussed here were taken using the radar beam pointed at 30° westward of the zenith.

Several investigations concerning the EEJ responses to auroral disturbances have been conducted both in terms of the current variability as also in terms of the plasma irregularity dynamics (see, for example, Fejer et al., 1976; Gonzales et al., 1979; Reddy et al., 1979; Abdu et al., 2003). Studies of electric field penetration from the auroral region to the equatorial region using other techniques have been made during the last decades (for example, Nishida et al., 1966; Kikuchi et al. 1978; Fukushima, 1989; Abdu et al., 1991; Sastri et al., 1993; Fejer and Scherliess, 1997; Abdu et al., 1998).

The main points of the EEJ variability discussed in this paper concern: (1) 3-meter irregularity development/ decay depending in the phase of the transient changes in the AE; and (2) local time dependence of EEJ response to penetration electric field under AE activity.

Data Acquisition and Analysis

The back-scattered 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 carrier wave is removed passing the two resulting signals through a 50 kHz low pass filter. 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 1024 pulses for each sampled range gate. The data processing done for each range gate consisted in an off-line FFT analysis of 1024 data points which resulted in the spectral distribution of the Doppler frequencies contained in the returned signal for each range gate. For December 1999 radar data, the time resolution between each set of 1024 pulses is 6 seconds and the aliasing frequency for each spectrum is 500 Hz (1500 m/s) with ~ 1 Hz (~ 3 m/s) of frequency resolution. By integrating incoherently in time 10 subsequent spectra we were able to obtain an averaged 1-minute resolution spectrogram per range gate. Then, by integrating in frequency each spectrogram 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.

Results and Discussion

Transients in 3-meter irregularity power and EEJ intensity correlated with the fluctuations in AE activity:

We present, in the Figure 1, the results for the selected three disturbed days. For each day the top panel shows 1-minute resolution auroral indices and the hourly ring current index D_{st}. The D_{st} provide a good indication of the magnetic disturbance over low latitude, while the auroral indices in general would represent the degree of variability in the magnetospheric source of the disturbance electric field that penetrate to the equatorial altitudes. The middle panel shows the magnetic field H component variations (that is, ?H variation with respect to the midnight value of H-component) over Jicamarca - JIC (12? S, 76.9? W, dip: 1?) in Peru, and Vassouras - VSS (22.4? S, 43.7? W, dip: -34?), in Brazil. The Jicamarca station was chosen for equatorial magnetogram because we did not have magnetograms available for this campaign from São Luís. It should be noted that the H component variations from these two stations located in separate longitude sectors will not be adequate to determine the quiet time EEJ current strength. But the longitude separation is small enough to yield the correct magnitude of the disturbed EEJ current fluctuations for this longitude sector as has been shown by Abdu et al. (2003). Thus, the disturbance effect shown on the middle panels of each graph was obtained by subtracting the disturbance ?H variations over Vassouras from that of Jicamarca ($?H_{JIC}$ - $?H_{vas}$). The bottom panel shows the RTI map obtained by the radar. The fluctuations in penetration electric field represented by the auroral indices can be correlated with simultaneous enhancements observed in the echo power in the RTI maps. We call the attention of the readers to the fact that each RTI maps presented in this paper has different power scale due to day-to-day variation of the EEJ itself. Each power scale was chosen based on the maximum power received during the day. It may be noted further all the plots are in Universal Time - UT.

The three disturbed days are marked by several episodes of AE intensification and decay that are characteristics of sub-storms, while the D_{st} increase that characterizes a magnetic storm event occurred only on 13 December. On December 11th an AE intensification (of ~200 nT) had onset at 12 UT (09 LT) which coincided with a minor increase in the 3-meter echo at the start of the RTI map on this day. The event that had duration of ~4 hours was structured by series of short-lived enhancements and decay phases. The more notable of them are identified by the arrows 'a', 'b', 'c', and 'd' that have associated with them corresponding structures in the H-component and the 3-meter echo power. The AE increases of relatively larger amplitude ('b' and 'c') produce correspondingly larger amplitudes of H increases and 3-meter irregularity power as compared the relatively weaker AE increases ('a' and 'd') that produced much weaker effects in both. It may be noted further that the larger AE increases caused also significant broadening of the irregularity echo region. It may be verified further that the decreasing phase of the AE indices that followed each of these increases produced corresponding decrease in the H-component and 3-meter echo power. This behavior suggests that AE increases (decreases) in theses cases were associated with prompt penetration of disturbance electric field (PP electric field) to equatorial latitude of eastward (westward) polarity that caused generation (decay) of 3-meter irregularities and enhancement (decay) in H-component. The PP electric field polarity relationship to AE activity phases presented in these cases are in good agreement with the plasma convection model results published by Spiro et al. (1988) and Fejer et al. (1990). This and other existing models predict for the daytime conditions eastward (westward) polarity PP electric field over low latitudes corresponding to an increase (decrease) in polar cap potential drop representing the growth (decay) phase of the AE activity. The relationship between the magnitude of the PP electric field observed over the equator with that of the causative AE intensification/polar cap potential drop is not clear from the existing models, however. The dependence of the EEJ response to AE intensification on the local ionospheric conductivity variations will be addressed in this paper.

It is interesting to note that the decrease of the echo power associated with the AE decay phase that followed the increase 'd' appears to last beyond the almost total recovery of the AE activity at ~16 UT. The continuing absence of 3-meter echoes until ~18 UT might be arising from neutral atmospheric dynamics that must have caused a weak EEJ over São Luís. We could not verify this fact due to the lack of magnetogram data for this site. This situation seems to characterize most part this day, as judged from the from RTI map during the pre-noon hours showing the 3-meter echo power being generated only because of the enhanced AE activity. Later in the afternoon the normal (quiet time) 3-meter irregularity generation seems to have resumed after 18 UT (15 LT), under favorable neutral dynamical conditions.

On 12 December (the middle graph) also the EEJ intensity appears to be generally weak with transient increases occurring due to AE intensifications. The AE intensification at 13 UT (10 LT) identified as 'e' has produced significant enhancement of 3-meter echoes with small effect on the H component. The subsequent AE intensifications identified as 'f', 'g', 'h' and 'i' have produced significantly larger effects on the EEJ current with moderate enhancements in the 3-meter echo power. The rapid AE intensification that occurred near midday (at ~16 UT/13 LT) seems to have produced the most intense but shorter duration responses in the 3-meter echo power and in the magnetic field H component. The response of the H component to AE fluctuations appear to get weaker at local times far separated from local midday. The phase relationship between the 3-meter echo intensification/ decay (or the H-component increase/decrease) and the power suggesting the role of eastward electric field associated with these AE increases in contrast to such features in AE that caused westward electric field on the two previous days.

The variations in the AE index and disturbance H-component during 10-17 UT of Figure 1 are shown blown out in Figure 2 for a more detailed examination of the correlation between the two parameters. In the lower panel of this figure the disturbance H component variation on 13 December over Jicamarca is compared with that of 14 December taken as reference quiet day curve. We note that the EEJ intensity is weaker on the 13th relative to that of 14th as to be expected under the possible influence of a disturbance dynamo electric field (see for example, Mazaudier et al., 1990). These curves may not represent the absolute values of the H variation of EEJ over Jicamarca due to the use of Vassouras data to generate these difference curves as explained before. The possibility exists that the westward electric field of 13th might be arising from the ongoing ring current activity as well. In any case the main points of the comparison between the AE and the ?H variation can be noted as follows: (a) an initial increase in ?H that occurred around 11 UT (08 LT) seems to be produced by an eastward PP electric filed caused by the rapid increase of AE as was the case during the events of the previous days; and (b) during the other two events of AE intensification, starting at the vertical lines near 14 UT and 15 UT, the ?H responds with an opposite/ambiguous phase relationship. This latter point and the related aspect of the 3-meter irregularity generation discussed above appear to be important questions to be recognized in the study of EEJ response to PP electric fields associated with AE activity.

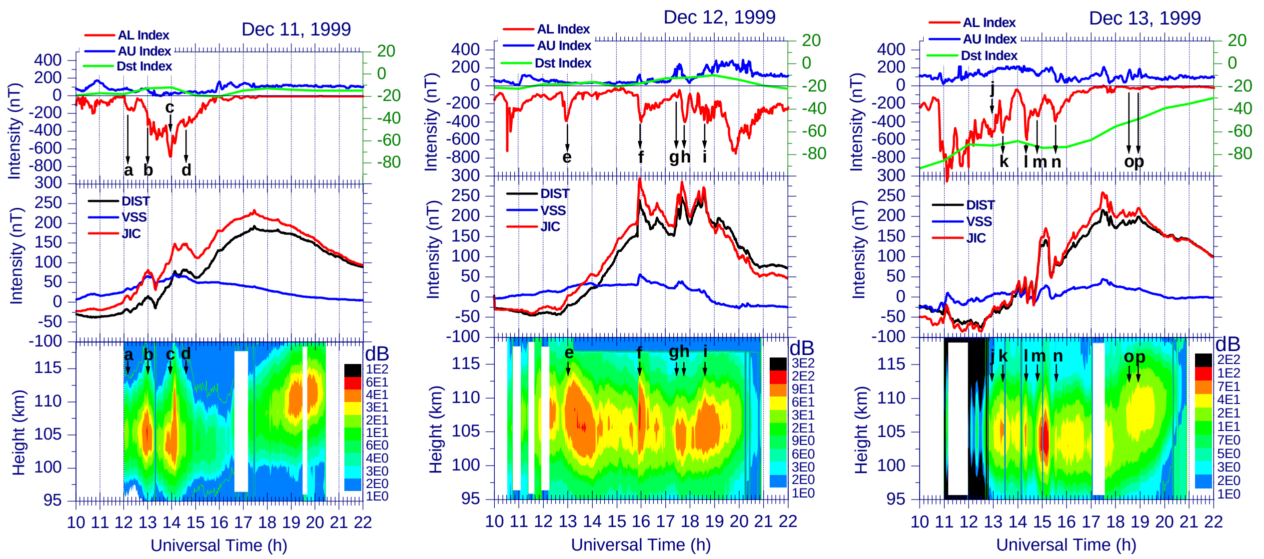

Figure 1 - Range Time Intensity (RTI) maps from selected three disturbed days: December 11th, 12th and 13th, from the RESCO 50 MHz coherent radar (bottom panel). On the top panel of each graph is shown the variation of the auroral indices AU (blue line) and AL (red line) referred to the left axis scale and the variation of the ring current index Dst (green line) referred to the right axis scale. The middle panel shows the variation of the horizontal component of the Earth's magnetic field (? H) over Vassouras (blue line) and that over Jicamarca (red line). The black line represents the disturbance effect obtained by the difference between the ? H components over Jicamarca and Vassouras.

AE activity on this day is very similar to that discussed for the events of 11 December.

The characteristics of the response to the AE activity on 13 December (the right most graph) presents significantly more complexity due to a magnetic storm of moderate intensity with D_{st} decrease of ~ -90 nT that dominated the morning hours of this day. A dawn-dusk disturbance dynamo electric field (Blanc and Richmond, 1980; Scherliess and Fejer 1997; Abdu et al., 1997) in combination with a possible westward electric field associated with the gradual but structured recovery of the AE activity seems to be responsible for the less than normal H component and the inhibition of 3-meter irregularities until ~13 UT (10 LT) on this day. Near midday the amplitudes of the responses in H component and in 3-meter echo power are more enhanced than at other local times (with the exception of the response feature observed near 1730 UT). There is indication that the polarity of the PP electric field, associated with the AE increase/decrease phases, which is expected to be eastward/westward directed, as was seen on the two previous days seems to get reversed when a D_{st} associated (or other) sources of a westward electric field is also present as seems to be the case on this day. This point can be checked by comparing the response in H component and 3-meter echo power to the AE features identified as 'j', 'k', 'l' 'm' and 'n' on this day with similar correlated features on the two previous days. For example the decrease in AE starting at these identified points seems to have caused increases in 3-meter echo

Local time dependence of EEJ response to AE activity:

It was stated above that the amplitude of the EEJ response as observed in Figures 1 and 2 show significant dependence on local time. This point is addressed in detail below.

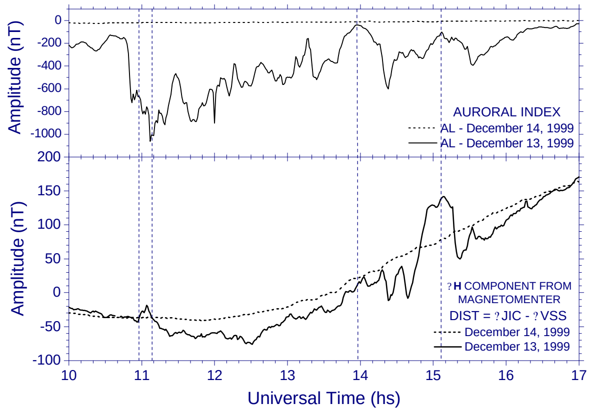

Figure 2 - Evolution of the sub-storm sequence represented by auroral index (top panel), which took place on December 13th, 1999 (continuous line), related to the disturbance H-component magnetic field variation over Jicamarca (bottom panel). The dashed line represents the H-component variation on 14th December 1999 taken as a reference quiet day.

Earlier in the morning and later in the afternoon the ionospheric conductivity is lower than its value around midday, when the solar zenith angle dependent ionization rate is high. The effect of the ionospheric conductivity on the EEJ response to a PP electric field is characterized in Figure 3. This figure presents a scatter plot of the amplitude of the disturbance effect in the magnetic field H component against the auroral index for 12 December 1999. We calculated the amplitude of the disturbance effect by subtracting the 1-minute time resolution disturbance effect from its 2-hour running averaged values. The left panel contains data from midday hours (from 10 to 14 LT) and the right panel contains data from morning and evening hours (before 10 and after 14 LT).

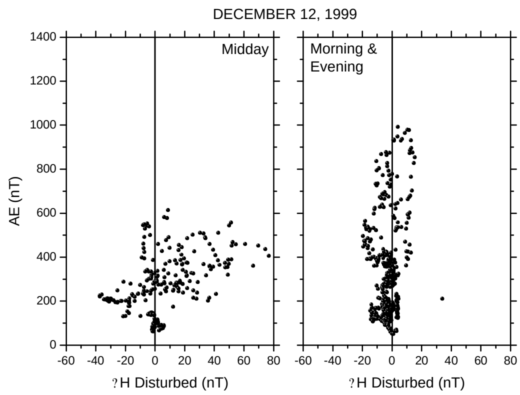

Figure 3 - Scatter plots of the amplitude of the disturbance effect from magnetometer data against the auroral index, for December 12th, 1999. The left panel contains data from midday hours (from 10 to 14 LT) and the right panel contains data from morning and evening hours (before 10 and after 14 LT).

The data corresponding to hours centered around the local noon shown in the left panel indicates that a perturbation in the AE index ranging from 50 nT to 600 nT could produce equatorial ?H variation ranging from -40 nT to +80 nT. On the other hand a significantly larger amplitude of AE variation, ranging from 50 nT to 1000 nT, on the right panel produces ?H variation of only ±20 nT during earlier and later hours. This is a strong indication that in the morning and evening hours even large disturbances can have a very small influence in the equatorial electrojet. It should be pointed out that this results does not suggest any local time dependence of the PP electric field by itself rather it points out that for a given PP electric field present over the equator the EEJ response has a strong local time dependence apparently controlled by the solar zenith angle dependent E layer electron density/conductivity

Conclusions

This work intends to demonstrate the diversity of phenomena in the EEJ and the large variability of the EEJ current strength and irregularity power at the Brazilian longitude sector. Indeed, a quantitative work is in progress and some aspects discussed here can be better checked when this ongoing work gets completed. However, the present work gives us a good idea of some important aspects of the EEJ during disturbed conditions.
Large degree of short-term variability of the EEJ was observed during the observational period. During periods of sub-storm like auroral electrojet intensification the transient changes in the EEJ are clearly correlated with the variations in the AE indices. Intensification in the AE produces, in general, an enhancement in the EEJ current intensity and 3-meter plasma instabilities, which can be attributed to the prompt penetration to equatorial latitude of magnetospheric disturbance electric field of eastward polarity. The recovery phase of the AE intensification was associated with a decrease of the EEJ effects due to a PP electric field of westward polarity. These phase relationship between the AE activity and EEJ effects are in good agreement with previous results and the predictions by the existing global models. However, as a new result, it is found that in the presence of ring current development such phase relationship become ambiguous or even inverted in some cases. The amplitude of the EEJ response, in terms of the current intensity and 3-meter irregularity power, is found to be local time dependent, having largest amplitudes near noon and lower amplitudes during the morning and afternoon hours. These results showed the influence of ionospheric conductivity on the EEJ response to disturbance electric filed, and do not in any way suggest a local time variation pattern for the disturbance electric field by itself.

Acknowledgments

This work was supported by FAPESP (Fundação de Amparo a Pesquisa de Estado de São Paulo) through thematic project grant no. 99/00437. Support received through CNPq (Conselho Nacional de Pesquisa e Desenvolvimento) grants nos. 520185/95-1 and 522919/96-0 is also acknowledged. C. M. D. wishes to thank FAPESP for the financial support to his doctoral degree program through the project n° 98/16156-8.

References

Abdu, M. A., J. H. A. Sobral, E. R. de Paula, and I. S. Batista, *Magnetospheric disturbance effects on equatorial ionization anomaly (EIA): an overview*. **Journal of Atmospheric and Solar-Terrestrial Physics**, v. 53, n. 8, p. 757-771, 1991.

Abdu, M. A., J. H. Sastri, H. Luhr, H. Tachihara, T. Kitamura, N. B. Trivedi, and J. H. A. Sobral, *DP 2 electric field fluctuations in the dusk-time dip equatorial ionosphere*. **Geophysical Research Letters**, n. 25, n. 9, p. 1511-1514, May 1998.

Abdu, M. A., J. H. Sastri, J. MacDougall, I. S. Batista, and J. H. A. Sobral, *Equatorial disturbance dynamo electric field longitudinal structure and spread F: a case study from GUARA/EITS campaigns.* **Geophysical Research Letters**, v. 24, n. 13, p. 1707-1710, July 1997.

Abdu, M. A., C. M. Denardini, J. H. A. Sobral, I. S. Batista, P. Muralikrishna, and E. R. de Paula, *Equatorial electrojet irregularities investigations using a 50 MHz back-scatter radar and a Digisonde at São Luís: Some initial results*. **Journal of Atmospheric and Solar-Terrestrial Physics**, v. 64, n.12-14, p. 1425-1434, 2002.

Abdu, M. A., C. M. Denardini, J. H. A. Sobral, I. S. Batista, P. Muralikrishna, K. N. Iyer, O. Veliz, and E. R. de Paula, *Equatorial electrojet 3-m irregularity dynamics during magnetic disturbances over Brazil: results from the new VHF radar at São Luís*. **Journal of Atmospheric and Solar-Terrestrial Physics**, in press, 2003.

Balsley, B. B., *Evidence of the nighttime current reversal in the equatorial electrojet*. **Annales de Géophysique**, v. 22, fasc. 3, p. 406-470, 1966.

Balsley, B. B., and R. F. Woodman, *On the control of the F-region velocity by the E-region electric field: experimental evidence*. **Journal of Atmospheric and Terrestrial Physics**, v. 31, p. 865-867,1969.

Blanc, M., and A. D. Richmond, *The ionospheric disturbance dynamo*. **Journal of Geophysical Research**, v. 85, p. 1669-1686, 1980.

Buneman, O., *Excitation of field aligned sound waves by electron streams*. **Physical Review Letters**, v. 10, n.7, p. 285-287, Apr. 1963.

Chapman, S., *The Equatorial electrojet as detected from the abnormal electric current distribution above Huancayo, Peru and elsewhere*. **Archives Fur Meteorology, Geophysics And Bioclimatologie**, A 44, p. 368-390, 1651.

Cohen, R., K. L. Bowles, and W. Calvert, *On the nature of equatorial slant sporadic E*. **Journal of Geophysical Research**, v. 67, n. A3, p. 965-972, Mar. 1962.

Farley, D. T., *A plasma instability resulting in field aligned irregularities in the ionosphere*. **Journal of Geophysical Research**, v. 68, n. A22, p. 6083-6097, Nov. 1963.

Farley, D. T., *Theory of equatorial electrojet plasma waves - new developments and current status*. **Journal of Atmospheric and Terrestrial Physics**, v. 47, p. 729-744, 1985.

Fejer, B. G., *Natural ionospheric plasma waves*. In: Kohl, H., R. Rüster, K. Schleger (Eds.) ***Modern ionospheric Science***, Max–Plank Institute for Aeronomy, Katlenburg-Lindau: Germany, 1996. Chap. 8, p. 216-273.

Fejer, B. G., and L. Scherliess, *Empirical models of storm time equatorial zonal electric fields*. **Journal of Geophysical Research**, v. 102, p. 24047-24056, 1997.

Fejer, B. G, and M. C. Kelley, *Ionospheric Irregularities*. **Reviews of Geophysics and Space Physics**, v. 18, n. 2, p. 401-454, May 1980.

Fejer, B. G., D. T. Farley, B. B. Balsley, and R. F. Woodman, *Oblique VHF radar spectral studies of the equatorial electrojet*. **Journal of Geophysical Research**, v. 80, n. A10, p. 1307-1312, Apr. 1975.

Fejer, B. G., D. T. Farley, B. B. Balsley and R. F. Woodman, *Radar studies of anomalous velocity reversals in the equatorial ionosphere*. **Journal of Geophysical Research**, v. 81, p. 4621, 1976.

Fejer, B. G., R. W. Spiro, R. A. Wolf, and J. C. Foster, *Latitudinal variations of perturbation electric fields during magnetically disturbed periods: 1986 SUNDIAL observations and model results*. **Annales Geophysicae**, v. 8, n 6, p. 441-454, 1990.

Forbes, J. M. *The equatorial electrojet*. **Reviews of Geophysics and Space Physics**, v. 19, n. 3, p. 469-504, Aug. 1981.

Fukushima, N., *Contribution to geomagnetic Sq-field and equatorial electrojet from the day/night asymmetry of ionospheric current under dawn-to-dusk electric field of magnetospheric origin*. **Pure and Applied Geophysics**, v. 131, n. 3, p. 437-446, 1989.

Gonzales, S. A., M. C. Kelley, B. G. Fejer, J. F. Vickrey, and R. F. Woodman, *Equatorial electric fields during magnetically disturbed conditions 2. Implications of simultaneous auroral and equatorial measurements*. **Journal of Geophysics Research**, v. 84, n. A10, p. 5803-5812, Out. 1979.

Kikuchi, T., T. Araki, H. Maeda, and K. Maekawa, *Transmission of polar electric fields to equator*. **Nature**, v. 273, n. 5664, p. 650-651, 1978.

Kudeki, E., D. T. Farley, and B. G. Fejer, *Theory of spectral asymmetries and nonlinear currents in the equatorial electrojet*. **Journal of Geophysical Research**, v. 90, n. A1, p. 429-436, 1985.

Matsushita, S. *Intense E_s ionization near the magnetic equator*. **Journal of Geomagnetism and Geoelectricity**, v. 3, p. 44, 1951.

Mazaudier, C., and S. V. Venkateswaran, *Delayed ionospheric effects of the geomagnetic storm of March 22, 1979 studied by the sixth coordinated data analysis workshop (CDAW-6)*. **Annales Geophysicae**, v. 8, p. 511-518, 1990.

Nishida, A., N. Iwasaki, and T. Nagata, *The origin of fluctuations in the equatorial electrojet; a new type of geomagnetic variation*. **Annales de Geóphysique**, t. 22, fasc. 3, p. 478-484, 1966.

Prakash, S., S. P. Gupta, B. H. Subbaraya, and C. L. Jain, *Electrostatic plasma instabilities in the equatorial electrojet*. **Nature**, v. 233, p. 56, 1971.

Pfaff, R. F., M. C. Kelley, E. Kudeki, B. G. Fejer, and K. D. Baker, *Electric field and plasma density measurements in the strongly driven daytime equatorial electrojet. 1. The unstable layer and the gradient drift waves*. **Journal of Geophysical Research**, v. 92, n. A12, p. 13578-13596, Dec. 1987.

Reddy, C. A. *The equatorial electrojet: a review of the ionospheric and geomagnetic aspects*. **Journal of Atmospheric and Terrestrial Physics**, v. 43, n. 5/6, p. 557-571, 1981.

Reddy, C. A., C. V. Devesia, and V. V. Somayajulu, *Global scale electron dynamic coupling of auroral and equatorial dynamo region on quiet days*. **Advance in Space Exploration COSPAR Symposium Sciences**, v. 8, Pergamon Press, London, 1979.

Rostoker, G. *Geomagnetic indices*. **Reviews of Geophysics and Space Physics**, v. 10, n. 4, p. 935-950, Nov. 1972.

Sastri, J. H., J. V. S. V. Rao, and K. B. Ramesh, *Penetration of polar electric field to the nightside dip equator at times of geomagnetic sudden commencements*. **Journal of Geophysics Research**, v. 98, n. A10, p. 17517-17523, Oct. 1993.

Scherliess, L., and B. G. Fejer, *Strom time dependence of equatorial disturbance dynamo zonal electric field*. **Journal of Geophysics Research**, v. 102, p. 24037, 1997.

Spiro, R. W., R. A. Wolf, and B. G. Fejer, *Penetration of high-latitude electric field effects to low latitudes during SUNDIAL 1984*. **Annales Geophysicae**, v. 6, p. 39-50, 1988.