1. Introduction

In this work we present a summary of recent observations made of $E$ region field aligned irregularities at low latitudes, particularly those from the Jicamarca Radio Observatory (~1°N dip latitude) and those from the Piura VHF radar (~7°N dip latitude) both located in Peru. Although the observations at Jicamarca, under the magnetic equator, inside the equatorial electrojet (EEJ) region, started more than 40 years ago, there have been very few of them (few hundred hours a year) until the JULIA (Jicamarca unattended long-term investigations of the atmosphere) system started few years ago. Nowadays we are observing more than 4000 hours per year.

In the case of the Piura radar, which was originally conceived as a wind profiler, we have also started the $E$-region observations on campaign basis [Woodman et al., 1999; Chau and Woodman, 1999] by pointing perpendicular to the magnetic field, i.e., 14°N off vertical. Since January 2000, a special observing mode has been added to the normal operations of the Piura radar to get quasi continuous measurements of the $E$-region every 11 minutes [Chau et al., 2002].

It is important to mention that observations of $E$-region irregularities started during the International Geophysical Year (IGY) in 1957. At that time measurements were conducted using bistatic configurations shown in Figure 1. Measurements were conducted at the magnetic equator (over Huancayo), 5° North (over Trujillo), and 5° South (over Arequipa). The main conclusions relevant to this work are (a) $E$-region echoes were stronger during the day at the magnetic Equator and at 5°S; (b) $E$-region scatter signals at 5°N were weaker than those at the magnetic equator and 5°S, independent of season, and absent, most of the time, during the day [Cohen and Bowles, 1963]. The locations of the Jicamarca and Piura radars are indicated in the Figure 1 for reference.

First we will describe the different $E$ region observing modes currently available at Jicamarca including preliminary statistics based on JULIA observations. Then we describe the observations with the Piura radar along with recent statistics. Finally we summarize the main characteristics of the EEJ and Piura $E$ region irregularities, and different parameters that can be derived from those observations at Jicamarca and Piura.

2. Jicamarca $E$ region modes

The main operating mode at Jicamarca is the Incoherent Scatter Radar (ISR) mode that allows the measurements of densities, temperatures, compositions and drifts of the ionosphere [e.g., Farley, 1991; Kudeki et al., 1999]. Due to the presence of strong irregularities at $E$ region heights, i.e., EEJ [e.g., Farley, 1985], the ISR measurements are not possible at those heights. Given this limitation, in recent years, a number of observing modes has been implemented at Jicamarca to try to derive the state parameters of the ionosphere (e.g., density profiles, electric fields) from observing the $E$ region irregularities. These modes can be classified as (a) interferometer, (b) oblique, (c) bistatic, and (d) imaging modes.
2.1 Interferometer mode

Radar interferometry was pioneered by Farley et al., [1981] at Jicamarca and since then it has been applied to study most field-aligned irregularities at different latitudes. At Jicamarca, the north and south quarters are used for transmission while the East and West quarters are both used for reception independently. From the coherence, a measure of the width of irregularities is obtained, while the angle of arrival is obtained from the phase of the cross-correlation between receiving antennas. The main products of this mode are: (a) Signal-to-noise ratio (SNR), (b) Vertical drift (from Doppler velocity), and (c) Zonal drift from tracking the angle of arrival as a function of time [e.g., Kudeki et al., 1982]. In Figure 2, we show a typical example of measurements conducted almost continuously at nighttime. The poor range resolution is because F region irregularities are also being observed.

2.2 Oblique mode

The oblique mode observations were introduced by Balsley [1969] using the so-called mattress antennas at Jicamarca. The basic idea is to point with small antennas either to the East or West of the Jicamarca and then derived electric fields and neutral winds from the Doppler velocities measured at different ranges [e.g., Balsley, 1969; Balsley et al., 1976]. Recently the technique has been improved significantly. Using wide beams with small COCO antennas in addition to proper weighting functions, Hysell and Burcham [2000] have been able to obtain reasonable electric fields from the type II Doppler shifts. In addition, by using narrow beams with a relatively long array of Yagi antennas and with the help of a three-dimensional electrostatic model, zonal wind profiles at E-region heights could be obtained from the type II Doppler shift profiles [Hysell et al., 2002].

In Figure 3, we show typical spectrograms of oblique observations using wide beams (top row) and narrow beams (bottom row). A two-Gaussian function is fitted to the
measured spectra in order to separate the type I and type II contributions. Type I Doppler shifts are indicated with yellow curves, while type II with black curves.

2.3 Bistatic mode

The bistatic mode was developed by Hysell and Chau [2001] using small antenna modules for transmission and reception. The transmitting array was located ~200 km south of Jicamarca (Paracas) while the receiving system was located at Jicamarca. On reception two orthogonal polarizations were used in order to measure the Faraday rotation of the signal due to the changes in density in the connecting path. In this case, we took advantage of the strong EEJ echoes as targets for sampling the E region ionosphere. In Figure 4, we show the preliminary density profiles obtained with this technique. For comparison a density profile from a rocket measurement is also shown (left). The first observations were conducted just few days for testing. Continuous measurements are scheduled to start by the end of 2003.

![Figure 2. Example of interferometry measurements of nighttime E-region irregularities over Jicamarca, SNR, vertical drift, and zonal drift.](image)

2.4 Imaging mode

Radar imaging is an extension of radar interferometry and was first introduced by Kudeki and Süerüçü [1991] to study the E region irregularities. Since then, the technique has been improved significantly and is now being used successfully to study E and F region irregularities at Jicamarca [e.g., Hysell and Chau, 2002; Hysell and Woodman, 1997]. The technique makes use of many receiving antennas. At Jicamarca 6 antennas with non-redundant spacing have been used to study the field-aligned irregularities. Since magnetic field is almost horizontal, only a two-dimensional approach is needed (East-West vs.
altitude). In Figure 5 there is an example of the typical range-time intensity (RTI) plot, used by most radars, of nighttime E region irregularities (left) and an image for the time indicated by the vertical red line (right). The image shows the structures inside the illuminated beam. Doppler velocity is color coded where pure colors represent very narrow spectral widths (red: away from the radar, green: around zero, blue: towards the radar) while whitish colors represent very wide spectral widths. The intensity is proportional to the SNR. This is a new way of looking at irregularities, so major efforts are being conducted to improve the understanding of the scattering mechanisms and to extract state parameters (e.g., winds, electric fields).

![Figure 3](image)

Figure 3. Examples of spectrograms from oblique observations of EEJ using wide beams (top) and narrow beams (bottom). The type I and type II Doppler shifts are indicated with yellow and black curves, respectively.

3. JULIA observations

As we mentioned in the Introduction, the observations of field-aligned irregularities, E-region irregularities in particular, are being performed more frequently at Jicamarca by using small transmitter units and small antenna arrays (JULIA concept). Figure 6, shows an example of the latest observing modes using the JULIA system. Between 1830 and 0600 E and F region irregularities are observed in interferometer mode (range scale on the left). Using the range scale on the right, oblique modes are used between 0600 and 0900 and between 1600 and 1830 using narrow (top) and wide (bottom) beams. Between 0900 and 1600 a narrow oblique beam mode (top) is used for observing the EEJ, while the main Jicamarca antenna is used for observing the 150-km echoes [e.g., Kudeki and Fawcett, 1993] (bottom).

Besides getting the day-to-day as well as seasonal variability of these irregularities, the main products of these observations can be summarized as follows: vertical and zonal...
drifts at $E$ and $F$ regions heights between 1830 and 0600 LT, $E$-region zonal wind profiles and electric fields between 0600 and 1830. These observations started in 1996, and since then we have been increasing the number of observing hours every year. In 2002, we have observed close to 5000 hours on these JULIA modes.

Figure 4. Examples of $E$-region density profiles obtained with a bistatic system (right). The left panel shows one of the few density profiles measured with rockets (from Pfaff et al. [1987]).

Figure 5. Example of nighttime $E$-region irregularities (a) RTI and (b) Image cut for the time indicated with the vertical red line. The image represents the structures inside the beam where the velocity has been color-coded. The intensity of the colors is proportional to the SNR.

Figure 7 show the occurrence statistics of nighttime $E$-region irregularities for 2002 as function of time of the day, and day of the year. The number of events (days) used to get these statistics are indicated below. Between February and March there were not too many observations. Although we need more years to derive strong conclusions, it appears that the nighttime equatorial $E$-region irregularities occur more frequently during the local summer and before sunrise.
Figure 6. Example of JULIA observing mode (see text for details).

Figure 7. Statistical occurrence of nighttime $E$-region irregularities in 2002 as function of time of the day and day of the year. The number of events used for each period is indicated below.

4. Piura $E$ region observations

Piura $E$ region observations started in 1991. Since then intermittent measurements have been conducted on campaign basis. Figure 8 shows an example of SNR, Doppler velocity, and spectral width measurements. The main results derived from these intermittent observations are that Piura $E$ region irregularities [Woodman et al., 1999]: 
- Are characterized by type II echoes, i.e., generated by a gradient drift instability.
- Occur mainly at night.
- Occur in two distinct ranges, the upper echoes and lower echoes. Upper echoes present a patchy structure, wide spectral width and positive Doppler shift. Lower echoes are more continuous, have narrow spectral width and their Doppler velocities vary around zero.

Figure 8. Example of nighttime E-region observations over Piura. SNR, Doppler velocity, and spectral width.

From the continuous measurements, we are able to obtain important statistics about these echoes. For example, in Figure 9 we show the percentage of occurrence of these echoes for the last three years for the upper (top) and lower (bottom) echoes as function of season and time of the day. It is clear that these echoes occur mainly at night. Moreover, as in the case of mid-latitude E-region echoes, at Piura the occurrence is higher during the summer (southern hemisphere). Note that Piura is located in the northern magnetic hemisphere but in the southern geographic hemisphere.

In addition, we are trying to derive electric fields and meridional winds from the Doppler information. The Doppler is basically a combination of the projected meridional wind and the \( E \times B \) drifts. At lower altitudes where collisions dominate, the Doppler will be
mainly given by the meridional wind. On the other hand, at higher altitudes (above 105 km) the Doppler is given by the $\mathbf{E} \times \mathbf{B}$ drift. In Figure 10 we show the mean Doppler shifts for the upper and lower region for different seasons. In the upper region, the Doppler velocity is consistently positive (i.e., towards the radar) consistent with the $\mathbf{E} \times \mathbf{B}$ drifts measured at Jicamarca. The lower region Doppler velocities show a predominant annual variability [Chau et al., 2002]. We expect to improve these crude estimates with proper modeling and compare them to other independent measurements.

Figure 9. Percentage of occurrence of Piura $E$-region echoes for the upper and lower echoes between January 2000 and May 2003.

5. Summary

Observations are being carried out very frequently of $E$ region irregularities under the EEJ region (Jicamarca) and outside the EEJ region (Piura). The main characteristics of the EEJ echoes are:

- They occur during day and night, but are stronger during the day.
- Spectral characteristics are of type I (very narrow spectra and high Doppler velocities) and type II (wide spectra) echoes.
- They are stronger and more frequent during the summer, based on 2002 observations. Piura echoes are also more frequent and stronger during local summer but they occur mainly at night and present only type 2 echoes.

As we pointed out, a major effort is being placed to derive ionospheric parameters at $E$ region heights from the observations of these irregularities. Among other parameters currently under development, from Jicamarca EEJ echoes it is possible to get (a) zonal wind profiles, (b) electric fields, (c) density profiles, and perhaps (d) temperatures. Moreover, EEj echoes could be used for wireless communications purposes (see Sarango et al. this issue)
The main parameters that could be obtained from Piura E region measurements are (a) nighttime meridional winds from lower echoes, (b) nighttime electric fields from upper echoes.

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Figure 10. Doppler velocity statistics from Piura E region echoes for the upper and lower echoes between January 2000 and May 2003.

Bibliography


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