DC polarization electric field, current density, and plasma density measurements in the daytime equatorial electrojet

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Abstract. Measurements of the vector DC electric field, current density, and plasma number density were gathered in the daytime equatorial electrojet on a sounding rocket launched from Alcântara, Brazil. The data set provides a self-consistent picture of the electrodynamics of the daytime electrojet, permitting a detailed comparison of the altitude profiles of the vertical component of the DC electric field, E_{vert} , the current density, J , and the plasma number density, N_e . Good agreement in the upper electrojet region between both the magnitude and the profile of the plasma drifts, calculated independently from E_{vert}/B and J_{zonal}/qN_e , demonstrates that the equatorial electrojet is a Hall current consisting of electron motion driven by a vertical DC electric field. The data support the basic Cowling conductivity ideas of electron flow at the dip equator within a narrow conducting layer in which the ions are at rest.

Overview, Launch Conditions, and Instruments

In the Guarú Campaign, a series of NASA rockets were launched to study the electrodynamics of the equatorial electrojet [see Pfaff et al., *this issue*]. Excellent data were returned from three rocket experiments which each revealed vertical DC electric fields that peak near 105 km within the electrojet, coincident with where the observed current density is also maximum. In this paper, we present results from one of these rockets with the aim of providing, insofar as possible, a complete electrodynamic picture of the daytime equatorial electrojet based on a "snapshot" of data gathered by the rocket-borne probes.

On September 21, 1994, the ground-based magnetometer at Alcântara, Brazil revealed a strong positive deflection in the ΔH component, as shown in Figure 1. The data show variations with periods of about an hour and amplitudes of roughly ± 15 nT about a mean peak excursion of about 100 nT. Magnetometer data from an off-equator station (Vassouras, mag. lat. $\sim 20^\circ$) also showed a large ΔH excursion of approximately 60-70 nT, implying that an extended Sq current system was present. Coincident with these observations, the CUPRI radar observed strong VHF backscatter echoes throughout the morning in the lower electrojet, 95-105 km [Swartz, personal communication, 1994]. No high altitude (106-110 km) echoes associated with primary two-stream wave excitations were observed.

With these electrojet conditions evidenced in the ground-based observations, NASA rocket 21.111 was launched at 10:56:00 L.T. (13:56:00 U.T.) from Alcântara, Brazil, along an azimuth in the magnetic east direction. The payload achieved an apogee of

120.2 km approximately 3 minutes later, and returned good data from all of its instruments. At the time of apogee, the ground magnetometer ΔH deflection was 105 nT.

The rocket payload was equipped with double probes of different lengths to measure the DC and wave electric fields, a high precision, three-axis flux-gate magnetometer to determine the current density, and a plasma frequency probe to measure the electron density. A set of spaced receivers was included to measure the wavelength and phase velocity of the plasma waves.

After exiting the lower atmosphere, the attitude control system oriented the spin axis to within 1 degree of the magnetic field direction. As shown in Figure 2, the spin plane, where the double probes gather their most reliable measurements, was thus perpendicular to the magnetic field and co-planar with the plane containing the electric fields [see Pfaff, 1991]. A gyroscope provided attitude data with an accuracy of 1 degree.

Measurements

DC Electric Field. Electric field data from two perpendicular double probes gathered near apogee (120 km) are shown in the spacecraft frame in Figure 3. The large sine waves occur at the spin period of roughly 2s. Gathered with 4.4 cm diameter spherical sensors separated along 5.5 m and 3.0 m baselines, these fields represent the measured potentials divided by their respective boomlengths. The electric field magnitudes are the same in the two panels indicating that the potentials scale linearly with boomlength and that valid fields have been measured. Notice that the two components differ in phase by 90° as

Figure 1. INPE magnetometer ΔH deflection at Alcântara, Brazil on September 21, 1994. Local Time = U.T. - 3 hours.

Figure 2. Payload orientation with the spin plane, which contain the double probes, perpendicular to the magnetic field direction.

expected from perpendicular, spinning probes. The data also depict small "sun notches" twice per spin, which are due to photoelectron current asymmetries which occur when one sphere is in the shadow of the payload and the other is in sunlight.

The sun notches also provide independent attitude information. Since this rocket was launched on the equinox, a few degrees from the geographic equator, and near local noon, the sun was nearly overhead during the flight and hence the notches occur near to that part of the spin cycle when each boom pair rotated through the vertical direction. Since the ambient and $\mathbf{V} \times \mathbf{B}$ electric fields (due to the horizontal motion of the payload, discussed below) were almost entirely in the vertical direction when the payload was near apogee, the sun notches appear near the extrema of the spin modulated electric fields in Figure 3.

The largest contribution to the electric field measurements on a spacecraft moving through the equatorial ionosphere is that due to the $\mathbf{V} \times \mathbf{B}$ fields created by the motion of the payload across the Earth's ambient magnetic field, where $\mathbf{V}$ is the rocket velocity in the earth-fixed frame and $\mathbf{B}$ is the ambient magnetic field. The contributions due to $\mathbf{V} \times \mathbf{B}$ are shown by the dotted lines in Figure 3 and represent the fields that would have been measured if no ambient (i.e., geophysical) electric fields were present. Our next step is to subtract these $\mathbf{V} \times \mathbf{B}$ fields from the measurements and rotate the resulting components from the spacecraft frame into a more meaningful coordinate system in order to better interpret the results. Based on measurements and theory, we make the assumption that $\mathbf{E} \cdot \mathbf{B} = 0$ for the DC electric fields that concern us here. After these calculations are carried out, the fields are rotated into geomagnetic coordinates and the results for the downleg are plotted vs. altitude in Figure 4 (a,b).

Notice immediately in the electric field data in Figure 4 that there is a large DC electric field in the vertical direction and that this peaks near 105 km with a value of approximately 10 mV/m. This is the polarization electric field that drives the electrojet current. The value of the electric field is about 2.5 mV/m at apogee which is consistent with satellite measurements at higher altitudes of the Sq dynamo electric field for this local time [Maynard et al., 1988]. The electric field in the lower electrojet region (90-104 km) is also non-zero and represents vertically oriented potential differences sustained in this region. Unfortunately, the lower altitude electric field data were

contaminated with wake effects, so it is difficult to interpret the data in this altitude region, as we discuss further on below.

The zonal component, E_{zonal} , is approximately 1 mV/m eastward at apogee. Although the direction of this component agrees with that of the expected, daytime zonal Sq electric field, its value is larger than average values of 0.3 mV/m inferred from incoherent scatter measurements at higher altitudes [Fejer et al., 1979]. It is also somewhat larger than the daytime zonal electric fields deduced from phase velocity measurements of backscatter echoes near 150 km [Kudeki and Fawcett, 1993]. Average measurements of the vertical ion plasma drift (corresponding to the zonal electric field) gathered by satellite probes at this local time [Coley and Heelis, 1989] correspond more closely to the zonal electric field value that we report here. In general, despite possible errors in the measurement (see discussion below), in contrast to the vertical component, the measured zonal electric field component in the daytime electrojet is small and eastward above 104 km. Larger variations are observed in the lower electrojet created by gradient drift-driven perturbations.

Errors in the electric field measurement vary with altitude as they are a strong function of both the ambient plasma and neutral number densities. The largest source of error is wake effects which occur as each sphere rotates through the trailing velocity cone of the payload once per spin. Such effects are significant since the payload was aligned in the north-south direction and the rocket was launched along an eastward trajectory. In other words, the same payload orientation (Figure 2) which enables the zonal and vertical electric fields to both be determined within the spin plane also enhances the wake effects that would otherwise be minimized for a vertically oriented payload. These wake-induced perturbations are worse for shorter boom systems and could be alleviated in future missions with longer booms.

At this stage in the analysis, we estimate that the errors associated with the DC electric fields shown in Figure 4(a,b) are ± 0.5 mV/m above 105 km, increasing to values possibly as large as ± 3 mV/m at 100 km. In this presentation, we have removed the sun notches discussed above. The data have also been smoothed using averaging and detrending techniques to reveal the slowly varying component of the electric field components.

Current density. A high precision, three-axis flux-gate magnetometer was built specifically for this experiment and was extended at the end of a 1.3 m rigid, fiberglass boom. The data were digitized on-board using a 16-bit analog-to-digital converter for which the least significant bit corresponded to ± 1.5 nT. The payload was designed to minimize spurious magnetic signals and

Figure 3. Examples of raw data from the 5.5 m and 3.0 m electric field detectors from the apogee region (near 120 km).

Figure 4. Zonal (a) and vertical (b) electric field profiles for the downleg. Current density (c) determined from the vertical gradient in the measured magnetic field data. Plasma number density (d) determined from the plasma frequency probe. The thin solid lines in (c) and (d) represent empirical fits to these data.

was calibrated in the NASA/Goddard Space Flight Center Magnetic Test Facility. Using Ampère's law, $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$, and assuming no vertical currents, the derivative of the magnitude of the magnetic field with respect to altitude is determined. (Here, $\mathbf{J}$ is the current density and μ_0 is the permeability of free space.) The computed current density consists of the magnetic zonal component, J_{zonal} , and is plotted in Figure 4(c).

The current density profile peaks at 8 A/km^2 near 105 km. This altitude is slightly lower than that corresponding to the peaks of the current density profiles observed off the coast of Peru [e.g., Maynard, 1967; Richmond, 1973] and India [e.g., Maynard and Cahill, 1965; Sampath and Sastry, 1979]. The magnitude of the current density is consistent with the ground ΔH magnetometer deflection of 105 nT, as shown by Richmond [1973] and Sampath and Sastry [1979] for similar data sets.

Plasma Density. The plasma number density was measured using a plasma frequency probe which locks onto a parallel resonance corresponding to the upper hybrid frequency [Jensen and Baker, 1992]. Since the magnetic field is known, the electron gyro frequency is easily determined, yielding the plasma frequency from which the electron number density is obtained. The data are shown in Figure 4(d) and reveal a peak near 104 km of $1.3 \times 10^5 \text{ cm}^{-3}$, which is consistent with other daytime equatorial observations and with simultaneous measurements from a nearby ionosonde in São Luis (Abdu, personal communication, 1994). The variations below 105 km are due to the gradient-drift driven km-scale structures. The small negative gradient of the plasma density between 104 and 107 km is a real effect and has been noted in other data sets [e.g., Pfaff et al., 1987]. The instrument lost "lock" at approximately 97 km on the downleg. Data (not shown) from a Langmuir probe corroborate these measurements and extend this profile to lower altitudes.

Discussion

The simultaneous measurements of the DC electric field, current density, and plasma number density permit a detailed investigation of the electrodynamics of the daytime equatorial electrojet and an opportunity to test the long held Cowling conductivity theory concerning the electrojet formation. Notice immediately in Figure 4 that the vertical electric field peaks

where the electrojet current is maximum at 105 km. Since the current density is a function of the plasma number density, a more relevant comparison is of the electron drift velocity associated with each profile.

Drift Velocity Comparisons. The drift velocity, V_d , of a plasma population of equal number of electrons and ions in thermal equilibrium is given by:

$$V_d = V_i - V_e = J/qN_e \quad (1)$$

in which V_i and V_e are the ion and electron drift velocities and q is the electronic charge. This profile has been calculated as a function of altitude in which we have fit empirical smooth functions to the current density and plasma number density represented by the thin lines in Figures 4(c) and 4(d). The results are shown by the solid line in Figure 5 and show a peak velocity

Figure 5. Comparisons of the drift velocity using the current density and plasma number density (solid line) and that from the E_{vert}/B measurements (dotted line).

of 370 m/s at 105 km. The drift velocity can also be independently calculated from $\mathbf{E} \times \mathbf{B}$ motion using the electric field measurements. Assuming that the ions are at rest (i.e., $\mathbf{V}_i = 0$) and ignoring the small zonal electric field contribution, the horizontal electron drift is simply

$$V_d = V_e = E_{\text{vert}}/B \quad (2)$$

This profile is shown in Figure 5 by the dotted line, and peaks at 390 m/s at roughly 104.5 km. Since we have fit the electric field profile with a smooth function, the actual peak altitude may vary somewhat, particularly since the data is modulated by the km scale plasma instability electric field structures.

For the upper electrojet region (> 104 km), notice not only the similarity of the profiles with altitude, but also that the two drift velocities peak with approximately the same magnitude. The good agreement of the two drift velocities support the view that the electric field is driving a Hall current of electrons in accordance with (1) and (2). The slight departures above the peak may be due to uncertainties in producing the smoothed profiles and from vertical currents ignored in computing the curl of $\mathbf{B}$. In the lower electrojet (< 104 km), the curves do not agree as well. Although it is not unreasonable for vertical electric fields to be sustained at lower altitudes at the equator, the exponential decrease in plasma density results in far fewer current carriers. Wake effects may have altered the electric field data in the lower electrojet. Such effects would not hamper the magnetic field measurements or the current density profile.

Finally, the measured plasma drift velocities are supported by the fact that neither the *in-situ* wave measurements (not shown) nor the CUPRI radar data (not shown) reveal any evidence for primary two-stream waves above 105 km in the region where such waves are known to be excited by strong electrojet currents. The electron drift threshold for this instability at 105 km at the equator is roughly 1.2 times the acoustic velocity [e.g., Fejer and Kelley, 1980]. Since this threshold is about 430 m/sec, the measured drift velocities are consistent with the lack of evidence of two-stream waves and the conclusion that the electron drift speed was below the two-stream instability threshold.

Cowling Conductivity. Ionospheric currents may be represented by $\mathbf{J} = \underline{\sigma} \cdot \mathbf{E}$, where $\underline{\sigma}$ is the conductivity tensor which is highly anisotropic due to the influence of the Earth's magnetic field. For cases where the magnetic field is strictly horizontal (i.e., dip angle = 0) and vertical currents are assumed to be zero (because of the small, finite height of the conducting strip), it is straightforward to show [e.g., Kelley, 1989]:

$$J_{\text{zonal}} = (\sigma_H^2/\sigma_P + \sigma_P) E_{\text{zonal}} = \sigma_C E_{\text{zonal}} \quad (3)$$

and

$$E_{\text{vert}} = -(\sigma_H/\sigma_P) E_{\text{zonal}} \quad (4)$$

where σ_H and σ_P are the Hall and Pedersen conductivities and have their usual definitions [e.g., Kelley, 1989], and σ_C is the Cowling conductivity. The Cowling conductivity may be viewed as an enhancement of the Pedersen conductivity.

Inserting an E_{zonal} value of 0.3 mV/m into (4) yields a polarization field of about 11 mV/m peaking near 100 km. Thus, the measured ambient E_{zonal} of about ~1 mV/m at apogee would yield an unrealistically large E_{vert} . Although possibly explained by measurement uncertainties, it is also likely that quasi-global

values of E_{zonal} should be used in (4) and not specific, local ones. The peak altitude of the vertical electric field predicted by (4) occurs about 5 km lower than the observed peak altitude of ~105 km, for reasonable collision frequencies [e.g., Forbes, 1981]. Similar discrepancies between current density peak altitudes and those predicted by (4) have been studied by several authors [e.g., Forbes, 1981; Stening, 1985]. The fact that the independently-derived electron drift profiles driven by the measured vertical electric field and the measured current density (Figure 5) both disagree with the altitude profile predicted by (4) further underscores the limitations of the simple theory.

A more complete analysis of the DC electric field, current density, and plasma number density must include neutral winds, vertical currents, and global electrodynamic considerations. Since the measured DC polarization electric field is consistent with the measured current and plasma number density and since the measured zonal and vertical electric field components follow the general response predicted by (4), we conclude that the Cowling conductivity at the dip equator is a viable explanation for the creation of the equatorial electrojet.

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