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THE HILAT MAGNETIC FIELD EXPERIMENT

Field-aligned "Birkeland" currents are associated with a variety of complicated plasma processes in the auroral ionosphere. The high sampling rate (20 vector samples per second) of the HILAT Magnetic Field Experiment, in combination with the other HILAT scientific instruments, will provide an opportunity to study the relationship of these currents with ionospheric scintillations, and their association with magnetospheric and interplanetary phenomena.

INTRODUCTION

At the beginning of this century, the Norwegian scientist, Kristian Birkeland, suggested that electric currents flowed into and away from the earth's polar regions along geomagnetic field lines.[1,2] Observations acquired from a variety of rocket and satellite experiments have absolutely confirmed the presence of the field-aligned "Birkeland" currents and have demonstrated their important role in coupling energy between interplanetary space and the lower atmosphere and ionosphere.

The transverse magnetic disturbances associated with Birkeland currents range from a few hundred to 1000 nanoteslas and are distributed over 100 to 500 km (approximately 1 to 5° of latitude), the nominal width of the auroral zone. The Birkeland current densities of these large-scale currents range from 1 to 5 microamperes per square meter and account for total currents of millions of amperes flowing into and away from the auroral zone when integrated over the surface area of the auroral zone (approximately 10^6 km^2).

These large-scale Birkeland currents flow in stable patterns that persist over a wide range of geomagnetic conditions (see Ref. 1, Fig. 9). On the morning side of the auroral oval, the Birkeland currents flow into the ionosphere on the high latitude side and away from the ionosphere at lower latitudes. This flow pattern is reversed on the afternoon side. The system of Birkeland currents on the high latitude side of the auroral zone has been referred to as the "Region 1" system and the low latitude side as the "Region 2" system.[3]

During the last few years, intense small-scale field-aligned currents have been discovered that are embedded in the large-scale Region 1/Region 2 Birkeland current system described above.[4] A principal objective of the HILAT program is to investigate small-scale features in the earth's ionosphere associated with plasma instabilities. The HILAT experiments were designed to provide the highest sampling rates possible in order to investigate those small-scale irregularities. The 20 vector samples per second provided by the HILAT Magnetic Field Experiment can detect Birkeland currents with spatial extent down to 400 meters. This experiment and some preliminary measurements of intense small-scale Birkeland currents from HILAT are described below.

INSTRUMENTATION

The Transit spacecraft that was converted to HILAT included a three-axis fluxgate magnetometer as part of the attitude determination system. A microprocessor was added to the existing Transit analog magnetometer, which substantially improved the resolution and sampling rate of magnetic field measurements. The Transit magnetometer was acquired from the Schonstedt Instrument Co. and installed on the spacecraft in the mid-1960's. The three magnetometer sensors are mounted separately on two of the solar panels and on the spacecraft body. The sensors mounted on the x and y solar panels (shown in Fig. 1 of the article by Potocki et al. in this issue) are aligned so as to minimize the magnetic fields produced by the electric currents flowing in the panels. In the polar regions of the earth, the x and y sensors are oriented nearly perpendicular to the geomagnetic field, and the z sensor (mounted on the body of the spacecraft) is oriented close to the main geomagnetic field. Consequently, the x and y sensors will be sensitive to magnetic disturbances associated with electric currents that flow along geomagnetic field lines into and away from the auroral region.[1,2] The z sensor measures approximately the total geomagnetic field in the polar regions.

The Transit analog magnetometer system used in the HILAT spacecraft is similar to the analog magnetometer on the APL-built 5E-1 satellite (1963-38C) that was launched into a circular polar orbit at an altitude of 1140 km on September 28, 1963. (Compare the HILAT spacecraft shown in Fig. 1 of Potocki et al. with the 5E-1 spacecraft shown in Fig. 2 of Ref. 5). Zmuda et al.[6,7] first confirmed the presence of auroral Birkeland currents by means of magnetic field data acquired by the 5E-1 attitude-determination magnetometer. Because of the limitations in the analog telemetry system used on the 5E-1 spacecraft and on subsequent Transit satellites, it was not possible to obtain consecutive samples from different magnetometer sensors in less than 82 seconds. When

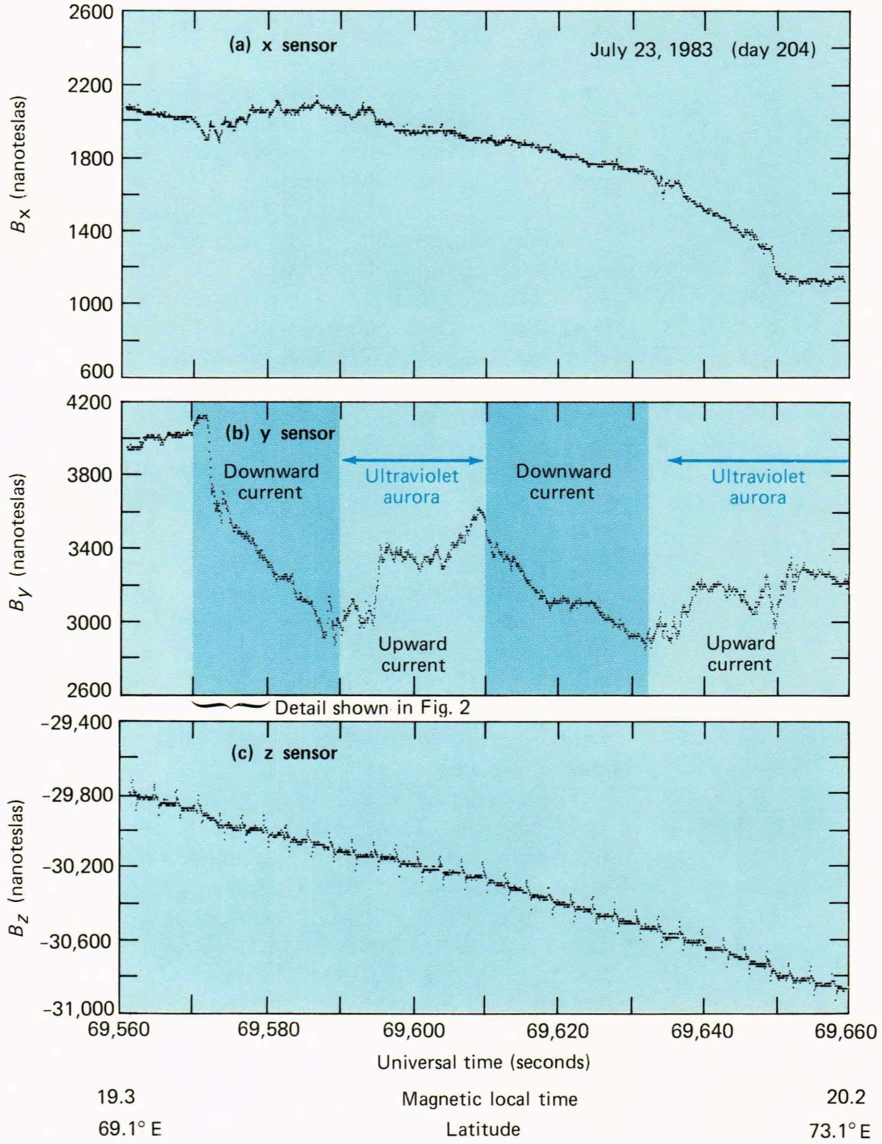

Figure 1 — A 100 second segment of magnetic field data acquired by HILAT over the dusk side of the auroral zone on July 23, 1983, from (a) the x sensor (aligned close to the north-south geomagnetic direction), (b) the y sensor (aligned close to the east-west geomagnetic direction), and (c) the z sensor (aligned close to the main geomagnetic field at this time). This is a detail of the full-orbit data shown in Fig. 4 of the article by Fremouw and Wittwer in this issue.

the telemetry commutator was "locked on" a given magnetometer axis, a magnetic field sample could be obtained in 0.314 second with a resolution of approximately 20 nanoteslas.[6,7]

A signal processor designed around the RCA 1802 microprocessor was included in the HILAT Magnetic Field Experiment. It digitizes the analog outputs of the three orthogonal axes of the fluxgate magnetometer (each of which provides a range of ±2.75 volts output for a ±55,000 nanotesla magnetic field input) to a 13 bit resolution, which provides a magnetic field resolution of 13.4 nanoteslas. With a data compression differencing scheme, the HILAT magnetometer processor provides 20 vector magnetic field samples per second with a telemetry data rate of only 348 bits per second. (Without the processor, the required data rate would be 780 bits per second.) This is accomplished by computing difference values between successive samples (in a given sensor) and retaining the four least significant bits (plus sign) of the differences. The format of the telemetered data is a full 13 bit sample followed by nine 5-bit "difference values." In this manner, 10 samples were transmitted for each sensor in a 0.5 second period (producing the 20 vector samples per second). The full-resolution magnetic field values are recovered by data processing techniques on the ground. The characteristics of the Magnetic Field Experiment are summarized in Table 1.

MAGNETIC DISTURBANCES AND FIELD-ALIGNED CURRENTS

The density and flow direction of Birkeland currents associated with magnetic disturbances, $\delta\mathbf{B}$, are determined from the relationship

$$\mathbf{J} = \frac{1}{\mu_0} \nabla \times \delta\mathbf{B} \quad . \qquad (1)$$

Table 1 — HILAT Magnetic Field Experiment summary.

Range	±55,000 nanoteslas
Resolution	13.4 nanoteslas (13 bits)
Sampling rate	20 vector samples/second
Anti-aliasing filter	10-hertz low-pass
Data rate	348 bits/second (using RCA 1802-based on-board data processor)

Note: Schonstedt fluxgate aspect magnetometer provided in Transit spacecraft; data processor added in HILAT experiment.

The magnetic disturbances associated with Birkeland currents occur predominantly in the geomagnetic east-west direction (B_y) so that

$$J_{\parallel} = J_z = \frac{1}{\mu_0} \frac{\partial}{\partial x} B_y \,, \tag{2}$$

where x is directed toward the north, y toward the east, and z is positive downward and parallel to the main geomagnetic field. The Birkeland current, $J_{\parallel}$, is uniform in the east-west (y) direction; (i.e., the Birkeland current sheets are aligned in the east-west direction and are "infinite").

Since $\mu_0 = 4\pi \times 10^{-7}$ henry/ meter,

$$J_{\parallel} = 8 \times 10^{-4} \frac{\partial B_y}{\partial x} \text{ A/m}^2 \,, \tag{3}$$

where B_y is in nanoteslas and x is in meters.

Since the speed of the HILAT spacecraft is approximately 8 km/second,

$$J_{\parallel} = \frac{1}{\mu_0} \left(\frac{\partial x}{\partial t}\right)^{-1} \frac{\partial B_y}{\partial t} = 0.1 \frac{\partial B_y}{\partial t} \ \mu\text{A/m}^2 \,, \tag{4}$$

where $\partial B_y / \partial t$ is in nanoteslas per second.

DATA

Figure 1 shows a 100 second segment of data acquired with the HILAT Magnetic Field Experiment between 1919:20 and 1921:00 UT on July 23, 1983. This is a portion of the data shown in Fig. 4 of the article by Fremouw and Wittwer in this issue. The top panel shows the magnetic field in nanoteslas measured by the x sensor, the middle panel by the y sensor, and the bottom panel by the z sensor. For these data, HILAT crossed the auroral zone near dusk (at approximately 2000 magnetic local time). The y sensor was aligned close to the geomagnetic east-west direction, and the disturbances shown in the middle panel of Fig. 1 are associated with a complicated system of Birkeland currents that HILAT passed through. The x sensor is oriented close to the geomagnetic north-south direction at this time and shows relatively few disturbances associated with the Birkeland currents. The z sensor is aligned along HILAT's vertical axis, which is close to the alignment of the main geomagnetic field in the polar regions. Consequently, the z sensor measures nearly the total geomagnetic field (approximately 30,000 nanoteslas, from the data in Fig. 1c). Since the z sensor is mounted directly on the body of the spacecraft, it is subjected to magnetic noise produced by the spacecraft. The periodic disturbance (with about a 3 second period and a 200 nanotesla peak-to-peak amplitude) shown in Fig. 1c is caused by the mirror scan motor of the Auroral Ionospheric Mapper (see the article by Schenkel and Ogorzalek in this issue).

The large-scale negative gradient observed in the transverse y sensor in Fig. 1b between 69,570 and 69,590 seconds UT can be associated with a downward-flowing Birkeland current that has a density of about 5.6 microamperes per square meter and is 160 km wide. Complicated small-scale features are superimposed on this large-scale gradient. The largest small-scale gradient occurs at the edge of the large gradient (near 69,572 seconds); details of this are shown in Fig. 2.

The y sensor magnetic field measurements shown in Fig. 1b also show a large-scale positive gradient from about 69,590 to 69,610 seconds, a negative gradient from 69,610 to 69,632 seconds, and a positive gradient from 69,632 seconds to the end of the plot. These gradients are interpreted as being caused by a system of large-scale Birkeland currents with flow directions as indicated in Fig. 1b. Also noted in Fig. 1b are the locations of ultraviolet auroral forms observed with the Auroral Ionospheric Mapper instrument and shown in Fig. 3. The ultraviolet auroras occur in the regions of upward-flowing Birkeland currents; this is consistent with the fact that downward-flowing energetic electrons are the current carriers and also produce the auroras.

Figure 2 shows a 20 second segment of data from the y sensor shown in Fig. 1b. An arbitrary constant has been subtracted from all the values. The negative gradient (approximately 330 nanoteslas in 0.3 second) near 69,572 seconds can be explained by a downward-flowing Birkeland current with a density of 100 microamperes per square meter and a spatial extent of about 4 km. This current is 20 times higher in density than the large-scale current in which it is embedded. Both currents flow into the ionosphere and could be carried by upward-flowing thermal electrons from the ionosphere. The existence of intense, small-scale Birkeland currents has been observed before, but their flow directions were directed away from the ionosphere. The intense upward-flowing currents are consistent with the suggestion that beams (or filaments) of energetic electrons, produced by some unknown acceleration mechanism above the ionosphere, are focused into the ionosphere. We be-

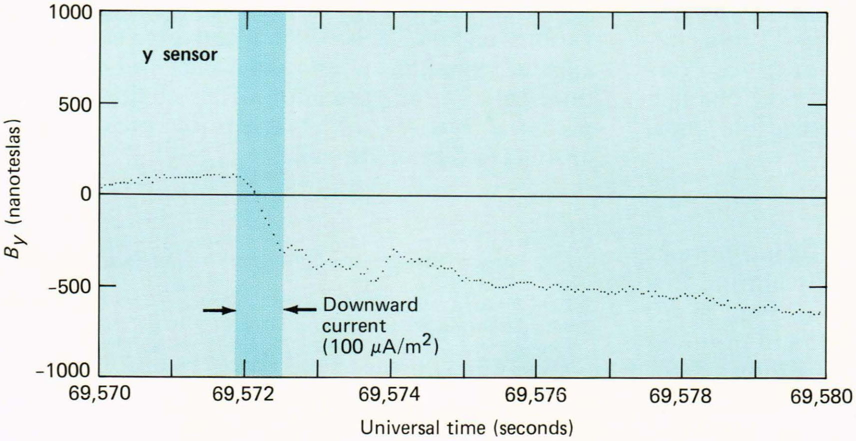

Figure 2 — A 20 second detail of the magnetic field data from the y sensor shown in Fig. 1b. The details provided by the 20 sample per second data rate become very apparent in this plot.

lieve that the intense downward-flowing current filaments discovered by the HILAT Magnetic Field Experiment are important to an understanding of the generation mechanisms of Birkeland currents and the influence that ionospheric conductivity has on them. These filament currents may also have an important relationship to ionospheric plasma instabilities.

Details of field-aligned currents associated with ultraviolet auroral forms are shown in Fig. 3. In this figure, the magnetic perturbations measured by the transverse y sensor shown in Fig. 1b have been superimposed on a detail of the ultraviolet image shown on the cover of this issue. Figure 3 shows a longer (210 second) segment of magnetic field data than is shown in Fig. 1b. An artificial baseline (determined from a fifth-order polynomial fit to the undisturbed data segment) has been subtracted from the magnetic field observations. The horizontal line in the middle of the image in Fig. 3 is the magnetic field disturbance baseline and is also the orbital track of HILAT over its two-dimensional image. The in situ magnetic field observations were made at an altitude of approximately 800 km, and the ultraviolet images are believed to be produced at an altitude of 100 km. A correction must be made for this inclination of the earth's magnetic field in order to map in situ observations at HILAT's altitude down along field lines to the altitude of the ultraviolet emissions. The relatively low altitude of HILAT eliminates geomagnetic field line mapping as a difficult problem (as in the case for high-altitude spacecraft), and this correction was applied to the data in Fig. 3.

The ultraviolet auroral feature in Fig. 3 is an enlargement of the fork-shaped form shown in the global image on the cover. This detail appears between Iceland and the coast of Greenland on the cover image and has been rotated by 90° in Fig. 3. The individual image pixels, which measure approximately 5 by 24 km, can be recognized in this enlargement.

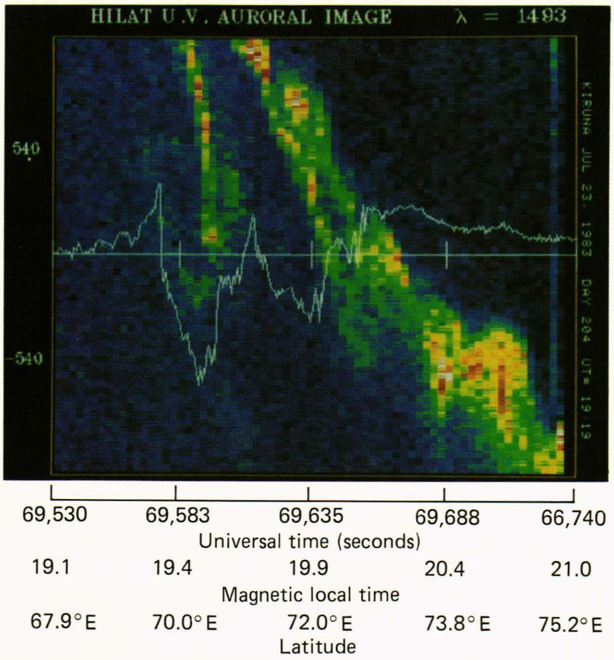

Figure 3 — A detail of the ultraviolet auroral image provided by the Auroral Ionospheric Mapper (the global view is shown on the cover of this issue) with the trace of magnetic field data acquired by the y sensor superimposed. A correction has been made in order to map the magnetic field measurement, made at HILAT's 800 km altitude, down along the geomagnetic field lines to the 100 km altitude of the auroral emissions. The aurora is located in regions of positive magnetic field gradient, which indicates regions of upward-flowing Birkeland currents (because of downward-flowing "auroral" electrons).

A negative gradient in the magnetic field variation shown in Fig. 3 indicates the presence of a field-aligned current flowing into the ionosphere, and a positive gradient indicates the presence of an upward-flowing current (as is also shown in Figs. 1 and 2). The magnetic field observations provide only a one-dimensional "slice" through the two-dimensional ultraviolet image, but the two upward-flowing field-aligned currents (indicated by the two large-scale positive magnetic field gradients) are spatially coincident with the two ultraviolet auroral forms. The downward-flowing field-aligned current (indicated by the two negative gradients) is located in regions where there is an absence of auroral forms.

This is consistent with the fact that the downward-flowing currents are carried by upward-flowing electrons and that the upward-flowing currents are carried by downward-flowing "auroral" electrons that have sufficient energies to cause the ultraviolet emission.

SUMMARY

It is now known that large-scale Birkeland currents that flow into and away from earth's auroral and polar regions comprise a permanent element in the circuit connecting interplanetary space and the lower ionosphere. The Birkeland currents are associated with a wide variety of auroral phenomena including visual, ultraviolet, and radar forms, ionospheric currents, and ionospheric plasma instabilities. Ionospheric scintillations, auroral kilometric radiation, micropulsations, and electrostatic ion cyclotron waves have already been associated with Birkeland currents.[8]

The unique complement of instruments on HILAT will provide the first opportunity to study the direct relationship between small-scale Birkeland currents and ionospheric scintillations from the same spacecraft. These studies will address the precise role that Birkeland currents play in ionospheric plasma instabilities associated with scintillations. The presence of these currents may not be sufficient to cause instabilities but are the Birkeland currents the primary energy source for the growth of these instabilities? Are the various regions of Birkeland currents, such as the auroral region, cusp, and polar cap, to be regarded differently in the generation of instabilities? We expect the HILAT observations to provide some answers to these questions.

REFERENCES

[1] T. A. Potemra, "Magnetospheric Currents," *Johns Hopkins APL Tech. Dig.* **4**, 276 (1983).

[2] T. A. Potemra, "Studies of Auroral Field-Aligned Currents with Magsat," *Johns Hopkins APL Tech. Dig.* **1**, 228 (1980).

[3] T. Iijima and T. A. Potemra, "The Amplitude Distribution of Field-Aligned Currents at Northern High Latitudes Observed by TRIAD," *J. Geophys. Res.* **81**, 2165 (1976).

[4] W. J. Burke, "Electric Fields and Currents Observed by S3-2 in the Vicinity of Discrete Arcs," in *Magnetospheric Currents,* T. A. Potemra, ed., Geophysical Monograph 28, American Geophysical Union, pp. 294 (1983).

[5] D. J. Williams and A. M. Smith, "Daytime Trapped Electron Intensities at High Latitudes at 1100 Kilometers," *J. Geophys. Res.* **70**, 541 (1965).

[6] A. J. Zmuda, J. H. Martin, and F. T. Heuring, "Transverse Magnetic Disturbance at 1100 Kilometers in the Auroral Regions," *J. Geophys. Res.* **71**, 5033 (1966).

[7] A. J. Zmuda, F. T. Heuring, and J. H. Martin, "Dayside Magnetic Disturbances at 1100 Kilometers in the Auroral Oval, " *J. Geophys. Res.* **72**, 1115 (1967).

[8] T. A. Potemra, "Birkeland Currents: Present Understanding and Some Remaining Questions," *High Latitude Plasma Physics,* B. Hultguist and T. Hagfors (eds.), Plenum Publishing Co., pp. 335-353 (1983).

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