FINAL REPORT



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# INVESTIGATION OF ELECTRICAL CURRENTS IN THE AURORAL IONOSPHERE

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A) Introduction

Under the support of NSG-6013 the following research was carried out:

1) Instrumentation designed, constructed and tested for successful auroral rocket flight 18:1004 launched from Andoya, Norway, February 6, 1977.
2) Instrumentation designed, constructed and tested for successful auroral rocket flight 18:1005 launched from Andoya, Norway, January 23, 1977.
3) Instrumentation designed, constructed and tested for flight aboard the Echo V mission scheduled for launch November 1979.

The instrumentation referred to under (1) and (2) consisted of energetic particle detectors, photometers and thermal ion detectors. For the Echo V mission, thermal ion detectors and energetic electron sensors will be provided.

Much of the analysis performed at the University of New Hampshire on the 18:1004 and 18:1005 data was done by L. Zanetti, Jr., who successfully completed his Ph.D. work on the project and was awarded the degree in May 1978. Dr. Zanetti's thesis is entitled "Convective Electric Field Measurements in an Auroral Plasma." He is currently employed at the Applied Physics Laboratory at Johns Hopkins University, Silver Spring, Maryland.

Work supported by the grant has resulted in five oral presentations at scientific meetings, one published paper, one paper accepted for publication, and one paper submitted for publication. As with all projects, they never end abruptly but slowly fade away; two more papers are in preparation for submission for publication in the near future. Moreover, the Echo V experiment has yet to be launched. These continuing efforts will be supported under the current grant NSG-6022.

B) Thesis

Convective Electric Field Measurements in an Auroral Plasma, Ph.D. Dissertation, L. Zanetti, Jr., University of New Hampshire, 1978.

C) Papers Presented at Scientific Meetings

The Relationship Between Field-Aligned Current Carried by Suprathermal Electrons, and the Auroral Arc, R. L. Arnoldy; Presented at Seattle IAGA Meeting, 1977, Seattle, Washington.

Auroral Electric Fields Inferred from Ion Convection Measurements, L. J. Zanetti, Jr. and R. L. Arnoldy; Presented Spring 1978 AGU, Miami Beach, Florida.

Rocket Measurements of Electric Fields and Currents Across the Harang Discontinuity, D. A. Behm, L. J. Cahill, Jr., R. L. Arnoldy and F. Primdahl; Presented Spring 1978 AGU, Miami Beach, Florida.

Electric Fields, Convective Flows and Currents Across the Harang Discontinuity, L. J. Cahill, Jr., D. A. Behm, R. L. Arnoldy and F. Primdahl; Presented at Innsbruck COSPAR Meeting 1978, Innsbruck, Austria.

Electric Fields and Ionospheric Currents in a Breakup Aurora, D. A. Behm, F. Primdahl, R. L. Arnoldy and L. J. Cahill, Jr.; Presented Fall 1978 AGU, San Francisco, California.

D) Published Paper

The Relationship Between Field-Aligned Current Carried by Suprathermal Electrons, and the Auroral Arc, R. L. Arnoldy, Geophysical Research Letters, 4, 407, 1977. (Copy enclosed.)

E) Paper Accepted for Publication

Ionospheric Electrical Currents in the Late-Evening Plasma Flow Reversal, D. A. Behm, F. Primdahl, L. J. Zanetti, Jr., R. L. Arnoldy and L. J. Cahill, Jr.; Accepted by the Journal of Geophysical Research, 1979. (Copy enclosed.)

F) Paper Submitted for Publication

Rocket Observations at the Edge of the Eastward Electrojet, L. J. Cahill, Jr., R. L. Arnoldy and W. W. L. Taylor; Submitted to Journal of Geophysical Research, 1978.

G) Papers in Preparation

Convective Electric Field Measurements in the Nightside Auroral Oval, L. J. Zanetti, Jr., R. L. Arnoldy, L. J. Cahill, Jr., D. A. Behm and R. A. Greenwald.

Floating Potential of an Electron Beam-Emitting Rocket in the Ionosphere, R. L. Arnoldy, B. M. Morgan, D. Meade and J. R. Winckler.

# IONOSPHERIC ELECTRICAL CURRENTS IN THE LATE EVENING PLASMA FLOW REVERSAL

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ABSTRACT

An instrumented sounding rocket was launched from Andøya, Norway in January 1977, in the late evening auroral oval. Its trajectory took it northward over a quiet auroral arc and over a region of plasma flow reversal. Horizontal currents were inferred from magnetic field measurements; they were also calculated from the measured electric field and conductivities derived from energetic particle influxes. South of the reversal region, the current density of the eastward electrojet was found to be ∿.1 A/m, while north of the reversal the current density was less than .05 A/m. The currents were enhanced in the arc. Current continuity considerations in the meridian plane implied downward field-aligned currents at the southern edge of the arc and upward field-aligned currents at the northern edge.

## Introduction

In January, 1977, a sounding rocket, launched from Andøya, Norway, (69.3° N, 16.0° E geographic; 66.5° N invariant magnetic latitude) traversed a region, in the late evening auroral oval, where the plasma flow reversed from westward to eastward. Such plasma flow reversal, often called the Harang discontinuity, has been observed previously through Barium ion drift, electric field observations and radar doppler measurements (Wescott et al., 1969; Maynard, 1974; Wedde et al. 1977). In earlier reports on this rocket flight we described the precipitating electron flux and its relation to an auroral arc in the southern part of the flow reversal (Arnoldy, 1977) and the flow reversal itself as simultaneously observed by electric double-probes on the rocket and by the Stare radar (Cahill et al., 1978b). In this report we describe horizontal ionospheric currents, flowing near the flow reversal, as inferred from ground and rocket magnetic observations and as calculated from derived ionospheric conductivities and the observed electric field.

## Instruments and Trajectory

The instrumentation, which included several magnetometers, electric field double-probes and curved plate electrostatic analyzers, has been described in earlier reports (Cahill et al., 1978b; Arnoldy and Lewis, 1977). Two magnetometers were flown to detect the east-west component of the horizontal ionospheric currents. A proton precession magnetometer provided total field magnitude measurements once each second with an accuracy, limited by vehicle noise, of ∿ 10 nanotesla (nT). A three component fluxgate magnetometer was also flown to supplement the PPM measurements and to evaluate the fluxgate as a possible replacement for the PPM on future flights. Three perpendicular component measurements were sampled about 360 times each second with a resolution of 30 nT. Only the field magnitude, obtained by combining the three components, was used in this report. Both instruments were sensitive, as described below, to changes in the north-south and vertical field components observed as the rocket penetrated east-west current layers.

The magnetic fields produced by the horizontal current layers were of order 100 nT, and horizontal (except near the layer edges), while the earth's field at Andøya was about 55,000 nT and only 12° from vertical. Magnetic north was 10° west of geographic north. An eastward (or westward) flowing horizontal current layer produced a northward (or southward) magnetic field (X) directly below the layer. Such a field made a contribution to the total field magnitude of X sin 12° (20.8 nT when X was 100 nT). This contribution changed sign as the rocket climbed to the top side of the current layer. A northward or southward flowing current layer produced an eastward or westward magnetic field also of order 100 nT, but perpendicular to the earth's field. The total field magnitude increased in this case by only about 0.1 nT, an undetectable change.

The electric field double-probes provided measurements of the north and east electric field components with an accuracy of ± 5mV/m (Cahill et al., 1978a). Electron flux measurements, between a few eV and 22 keV, were available with energy resolution of 10% and a flux resolution of $10^5$ ($cm^2$ s ster keV)$^1$. Using multiple detectors, distribution functions were measured every 5 seconds of flight time (Arnoldy and Lewis, 1977).

The rocket was launched at 1918:06 UT (~2200 MLT) on 23 January 1977. The flight lasted 470 s, reached 221 km peak altitude and travelled 213 km downrange on geographic azimuth 345°. The spin rate was 3.9 Hz and there was a precession of 3.24° half angle with period 58.55 s.

## Observations

A positive magnetic bay (40 nT) in the northward geographic component, an upward vertical component (20 nT) and almost zero disturbance in the east-ward geographic component existed at launch, as shown in Figure 1, while a quiet auroral arc was visible in the north. Observers at the Stare radar reported a westward plasma flow over Andøya and an eastward flow about 100 km further north; the conditions were right for flight over the Harang discontinuity (Cahill et al., 1978b).

The magnetic signature of penetration through an eastward electrojet is shown in Figure 2. The proton precession magnetometer record is shown on top and the fluxgate record at the bottom. Similar reference fields have been subtracted in each case to emphasize the changes due to penetrating the current layers. Between 90 and 120 km on the upleg, a sudden 50 nT decrease in $\Delta B$ was apparent in both records. There were several other smaller features ($\sim$ 10 nT) in each record, presumably not due to ambient magnetic field changes since there were no correlations between the two records. Between 120 and 90 km on the downleg there was no field decrease that could be attributed to a possible westward electrojet current layer. The 50 nT change in $\Delta B$ corresponded to a 50/sin 12° = 240 nT change in the X component. For an infinite current sheet one half of this, 120 nT, would be observed on the ground below. The $\Delta X$ = 240 nT change in the horizontal component through the current layer corresponded to a sheet current strength of $\Delta X/\mu_0 \sim 0.19$ A/m.

The electric field measurements, shown as the top panel of Figure 3, have been reported by Cahill et al. (1978b); a brief review follows. South of the auroral arc a strong northward electric field produced a westward plasma flow and an eastward (Hall current) electrojet. The field decreased over the arc, decreased again north of the arc and rotated to an eastward direction (northward plasma flow). Recovering north of this, the field rotated to the south (eastward plasma flow). A sudden increase to over 50 mV/m at 300 seconds was followed by a direction shift to southeast, an oscillation with 6 s period, and a gradual decrease in magnitude. An eastward electric field (northward plasma flow) is not normally associated with plasma flow reversal in the Harang discontinuity. It is possible that the weak eastward field is a transient feature associated with counterclockwise flow around an auroral loop observed east of the trajectory (Cahill et al., 1978b).

Electron measurements on this flight have also been reported earlier (Arnoldy, 1977). Briefly, as shown in Figure 4, there were intense, $10^9$ (cm$^2$ s ster keV)$^1$, electron fluxes with energies of a few hundred eV over and near the arc (130-160 s), in the plasma flow reversal region (200-210 s) and in the eastward plasma flow region (250-280 s). Electrons of keV energies were observed only directly over the arc. The electric field magnitude, inverted, is also shown. Note that the field is low when the 0.3 keV flux is high.

## Calculations

The east, $J_E$, and north, $J_N$, components of the horizontal, vertically integrated, current density were calculated (Anderson and Vondrak, 1975; Evans et al., 1977; Cahill et al., 1978a). The electron flux and energy spectrum were used, with models of the ionosphere, to calculate electron densities (Rees, 1963). Height-integrated Hall and Pedersen conductivities, shown in Figure 3, were obtained from the electron densities and model collision frequencies. In turn, the conductivities and measured north and east electric field components, $E_N$ and $E_E$, yielded north and east ionospheric current components, $J_N$ and $J_E$.

The height integrated conductivities were about 2 Siemens(S) (1 S = 1 mho) in the westward plasma flow region, south of the auroral arc. The Hall conductivity increased to 20 S over the arc while the Pedersen conductivity went to 32 S. North of the arc the calculated conductivities remained below 2 S. Since the northward electric field was high in the strong westward plasma flow, south of the arc, there was a moderate calculated current density there, ∿ 0.1 A/m for the eastward component and ∿.05 A/m for the northward component. The current densities increased dramatically in the auroral arc, to ∿ 0.5 A/m east and ∿ 0.4 A/m north. North of the arc, including the strong eastward plasma flow from 240 to 300 sec, the calculated current density components were less than 0.05 A/m.

The Joule power dissipation by horizontal ionospheric current flowing in the direction of $\vec{E}$ was also calculated (Evans et al., 1977). The Joule power density is compared, in Figure 3, with the power deposited in the same column of the ionosphere by precipitating electrons. The Joule power was ∿ 3 $mW/m^2$ column (1 $mW/m^2$ = 1 $erg/cm^2$ s) in the eastward electrojet south of the arc, principally due to the northward current component. Over the arc the Joule dissipation increased to ∿ 8 $mW/m^2$ column, while north of the arc the power was less than 1 $mW/m^2$ column. The precipitating electron power was less than 1 $mW/m^2$, except over the arc where it rose to 7 $mW/m^2$.

## Discussion

We have two measurements of the magnetic field due to the eastward electrojet current. The northward component at Andøya is 40 nT and the northward component just below the current layer is 120 nT. For a very broad current sheet the full 120 nT should be seen at ground level. The section of the eastward electrojet penetrated by the rocket must, therefore, be of limited width, north-south. At Andøya the vertical component is -20 nT indicating the center of the eastward electrojet is south of Andøya.

An east-west band current of 0.19 A/m strength (inferred from the rocket measurements) approximately 150 km south of the launch site would explain the 40 nT horizontal disturbance and the -20 nT vertical disturbance observed at the ground. The height integrated current density derived from the rocket magnetometer measurement is 0.19 A/m while the eastward current density calculated in the eastward electrojet, 20 km south of the arc but 25 km north of the rocket electrojet penetration, is ∿ 0.1 A/m. The calculated current is 50% less than that derived from the magnetometer measurements. This may be due to variations in current density at the two different locations but may also be caused by uncertainties in the modeling procedures used to calculate the current. Considering the uncertainties in various models used we estimate the possible error in the conductivities to be less than ±50%. Since the errors in the electric field are smaller the calculated currents may also be in error by as much as ±50%.

The currents were calculated assuming that the neutral winds were negligible. No neutral wind measurements were available during the flight, however observed neutral winds in the auroral zone during geomagnetically quiet or moderately disturbed times ($Kp \lesssim 3$) have been found by Brekke et al. (1973) to be generally less than or on the order of 100 m/s. Neutral winds of this magnitude, if they were present, would add an effective electric field vector to the observed electric field vector of no more than 5 mV/m. The effects of neutral winds on the calculated currents would be small except in the reversal region where the measured electric field is small.

The lack of a westward electrojet as observed by the magnetometers on the downward leg agrees with the calculations. A very weak, 0.02 - 0.04 A/m, calculated westward component is present below the rocket from 250 to 300 s. With the electric field direction change to southeast the calculated currents become southward, 0.02 to 0.04 A/m.

The electric fields, corresponding plasma flow velocities and calculated horizontal current vectors are shown in a summary view, Figure 5. The weakening of the electric field and of the plasma velocity over the arc is apparent as well as the reversal of the flow velocity north of the arc. The largest current densities, over 0.5 A/m to the northeast, are associated with the arc. Unlike earlier flights over quiet arcs, in this case the calculated eastward electrojet current is intensified in the arc (Evans et al., 1977; Cahill et al., 1978a) . This is principally because the conductivities increase by a factor of 10 over this arc but only by a factor of 3 or 4 over the earlier arcs.

The total current in the arc is about 4 kA, and the payload flies by it at a distance of about 25 km. The peak magnetic disturbance in the total field at the rocket is then expected to be of the order of 30 nT which should be detectable by the on-board magnetometers. However, the disturbance increases and decreases gradually over a substantial part of the trajectory, so with the modeling technique used in reducing the magnetometer data the disturbance may not be discernable. The lack of evidence of the line-current in the magnetometer measurements could, of course, also be due to errors in the ionospheric modeling procedure leading to a calculated arc current that is too large. As estimated earlier the errors may be as large as $\pm 50\%$.

The electric field was almost constant during the first part of the flight from 83 s to 116 s, directed $\sim 6°$ west of geographic north. During this time interval the Andøya horizontal magnetic perturbation was also constant and directed towards $\sim 4°$ west of geographic north or, within the measurement uncertainties, parallel to the dc electric field. With calculated height-integrated Hall and Pedersen conductivities of $\sim 1$ S in this region the northward Pedersen current should have rotated the horizontal magnetic disturbance 45° to the west. The missing Pedersen current magnetic field component at ground level confirms Vasyliunas' (1970) suggestion that the magnetic fields from the field-aligned currents and the Pedersen currents are confined in regions above the ionosphere. The northward current must be part of a solenoidal current system where current flows down in a field-aligned east-west sheet, then north horizontally, then up in a field-aligned sheet.

Assuming homogeneity along the auroral arc (east-west), then changes in the northward current density imply field-aligned currents in order to satisfy current continuity (Evans et al., 1977; Cahill et al., 1978a). The increase from 0.03 A/m at 90 sec to 1.0 A/m at 120 s indicates a downward field-aligned current sheet, 20 km thick, with integrated current density .07 A/m. In similar fashion a 0.2 A/m downward sheet is implied in the southern part of the arc and a 0.3 A/m upward sheet in the northern part.

We are completing a study of field-aligned currents measured by several techniques during this flight: net electron fluxes (from a few eV to 22 keV); ion drift measurement and measurements of changes in the east-west magnetic component when passing through possible field-aligned current sheets. There appear to be some discrepancies between the field-aligned currents measured by the several techniques and between the measured currents and the currents inferred, as above, from the calculated northward current density. A more thorough evaluation of the field-aligned currents will be presented later.

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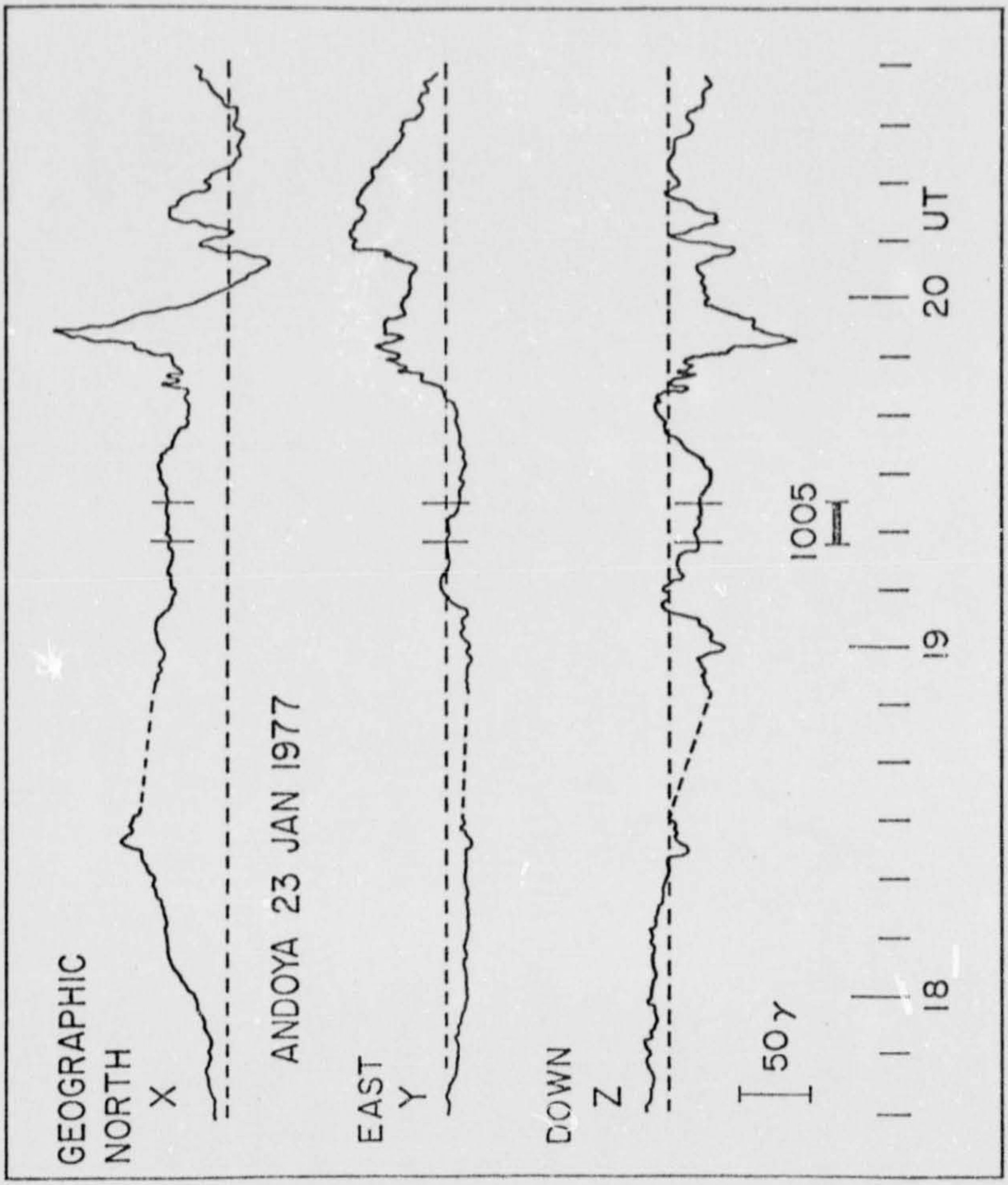
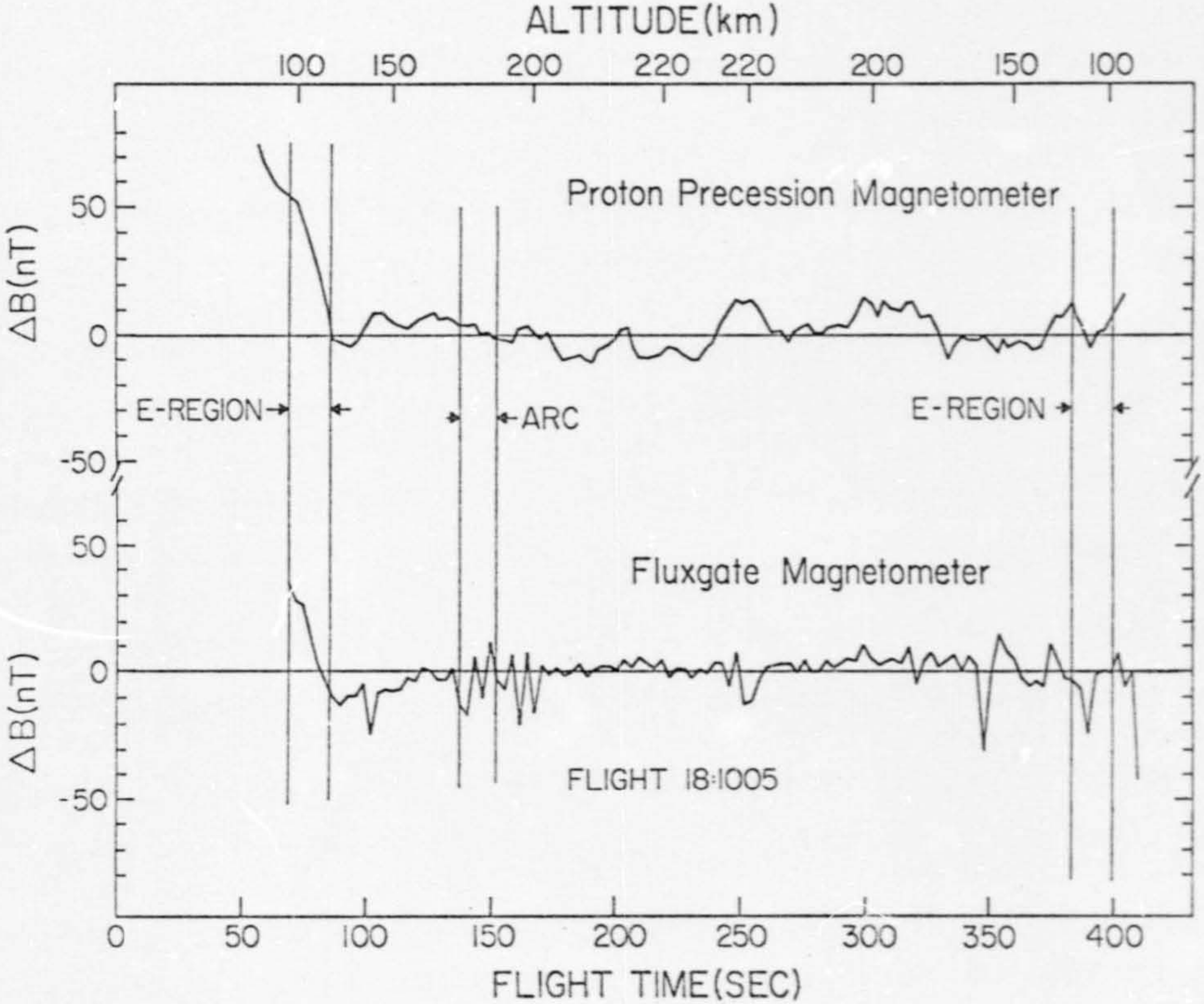
# FIGURE CAPTIONS

1. Andøya magnetogram. X is the north, Y the east and Z the vertical (down) component. The vertical lines indicate launch and re-entry times. The dashed portion of each trace represents a time period when the trace was lost due to interference.
2. Magnetic field magnitude measurements. Reference fields have been subtracted from the measured fields. The zero-levels are arbitary.
3. Measured electric field, calculated conductivities, calculated horizontal currents, and power dissipated by electrons and by Joule heating. The electric field and horizontal current components are given with reference to magnetic north and east.
4. Electron directional intensities at .3 keV and 3.0 keV. The higher energy electrons are seen only over the arc (137 s to 152 s). The electric field magnitude is shown with inverted scale at right.
5. Summary plot of electric field, plasma convection velocity, and calculated horizontal currents. The shaded region denotes the location of the arc. The trajectory has been projected to 110 km, therefore the time scale on the left is not linear. Scales for the three quantities are given at the bottom.


ANDOYA 23 JAN 1977
GEOGRAPHIC NORTH X
EAST Y
DOWN Z
50γ
1005
18
19
20 UT



ALTITUDE(km)
100 150 200 220 220 200 150 100
Proton Precession Magnetometer
ΔB(nT)
50
0
-50
E-REGION
ARC
E-REGION
Fluxgate Magnetometer
FLIGHT 18:1005
0 50 100 150 200 250 300 350 400
FLIGHT TIME(SEC)

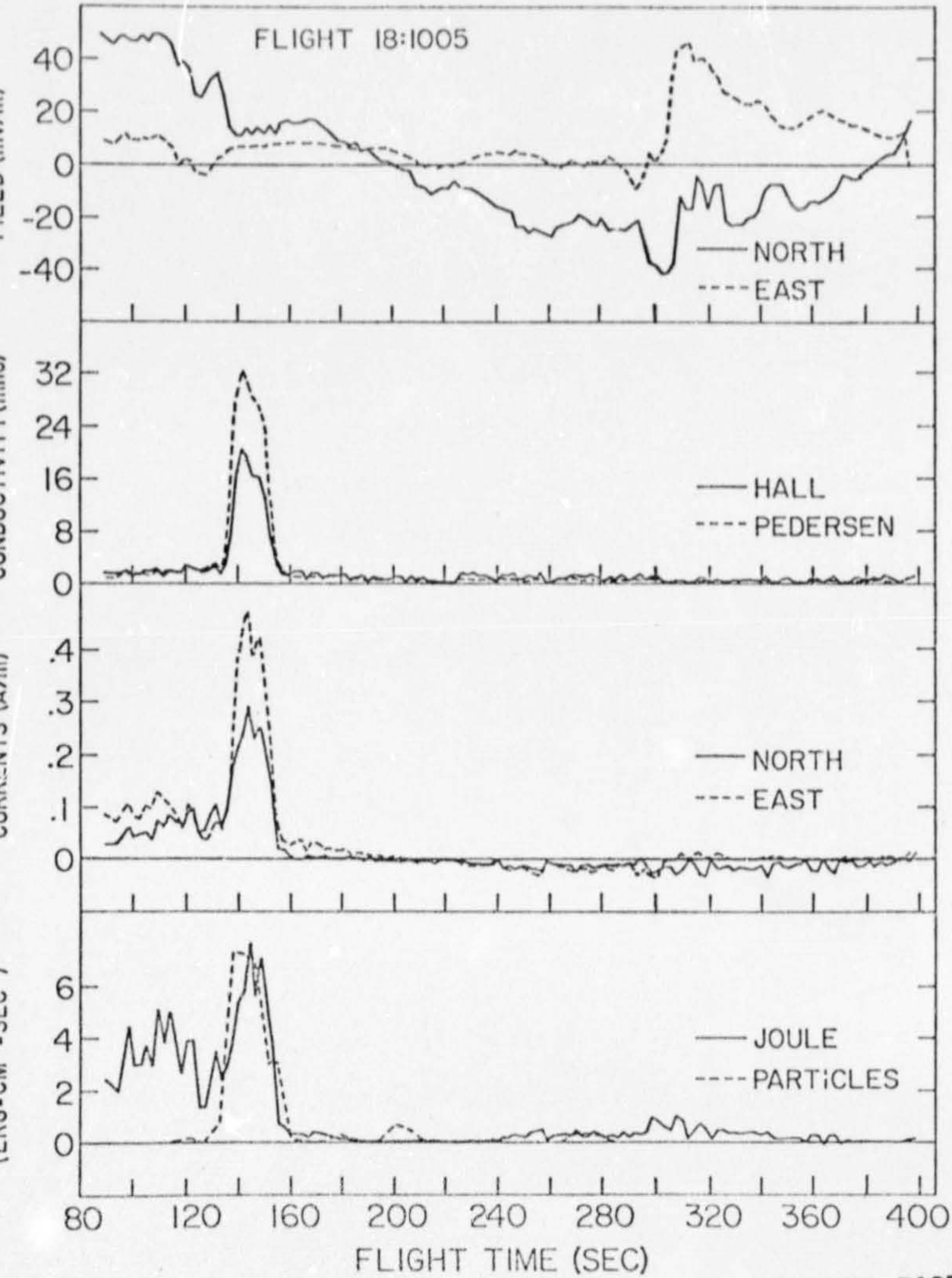



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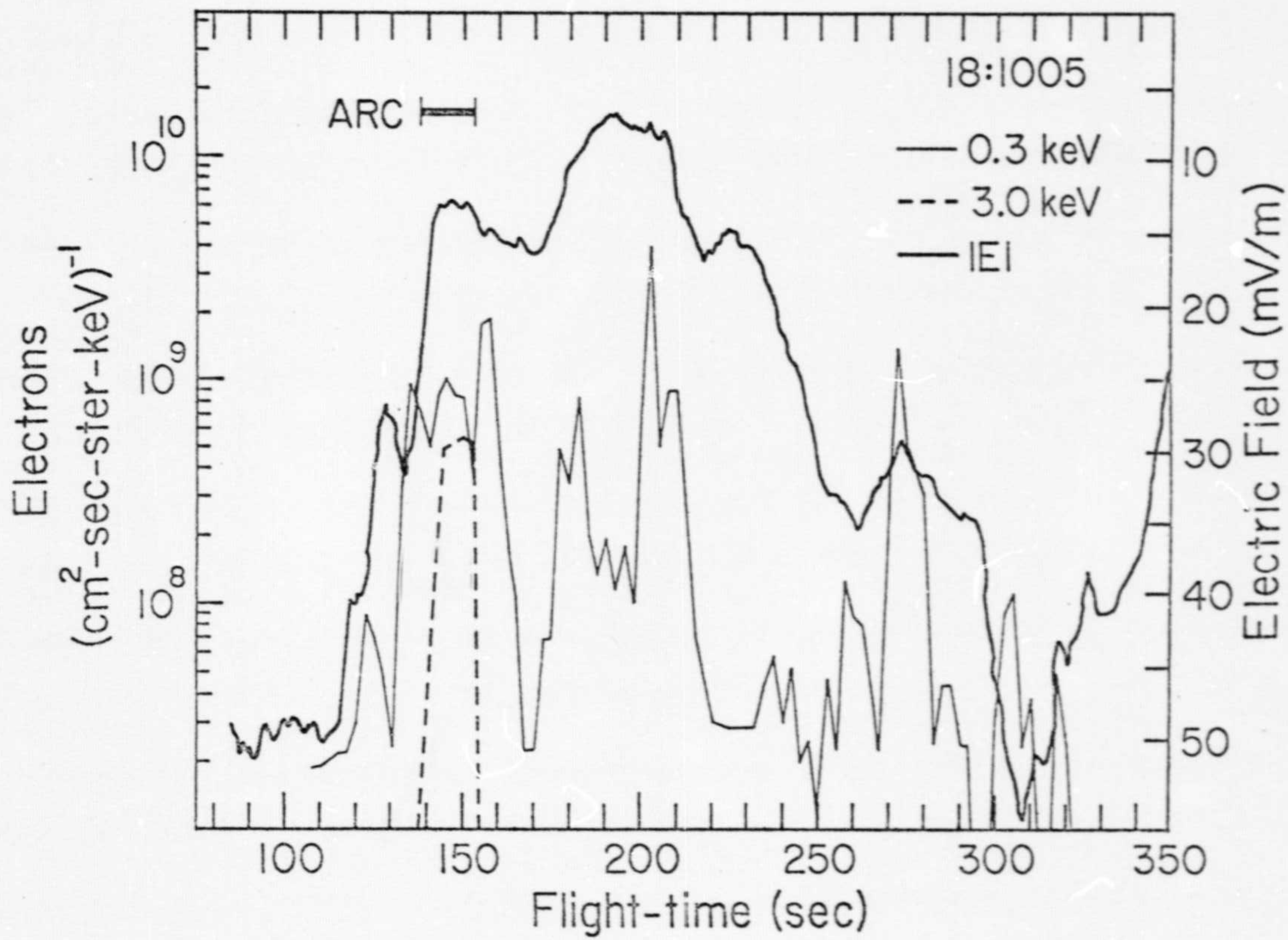
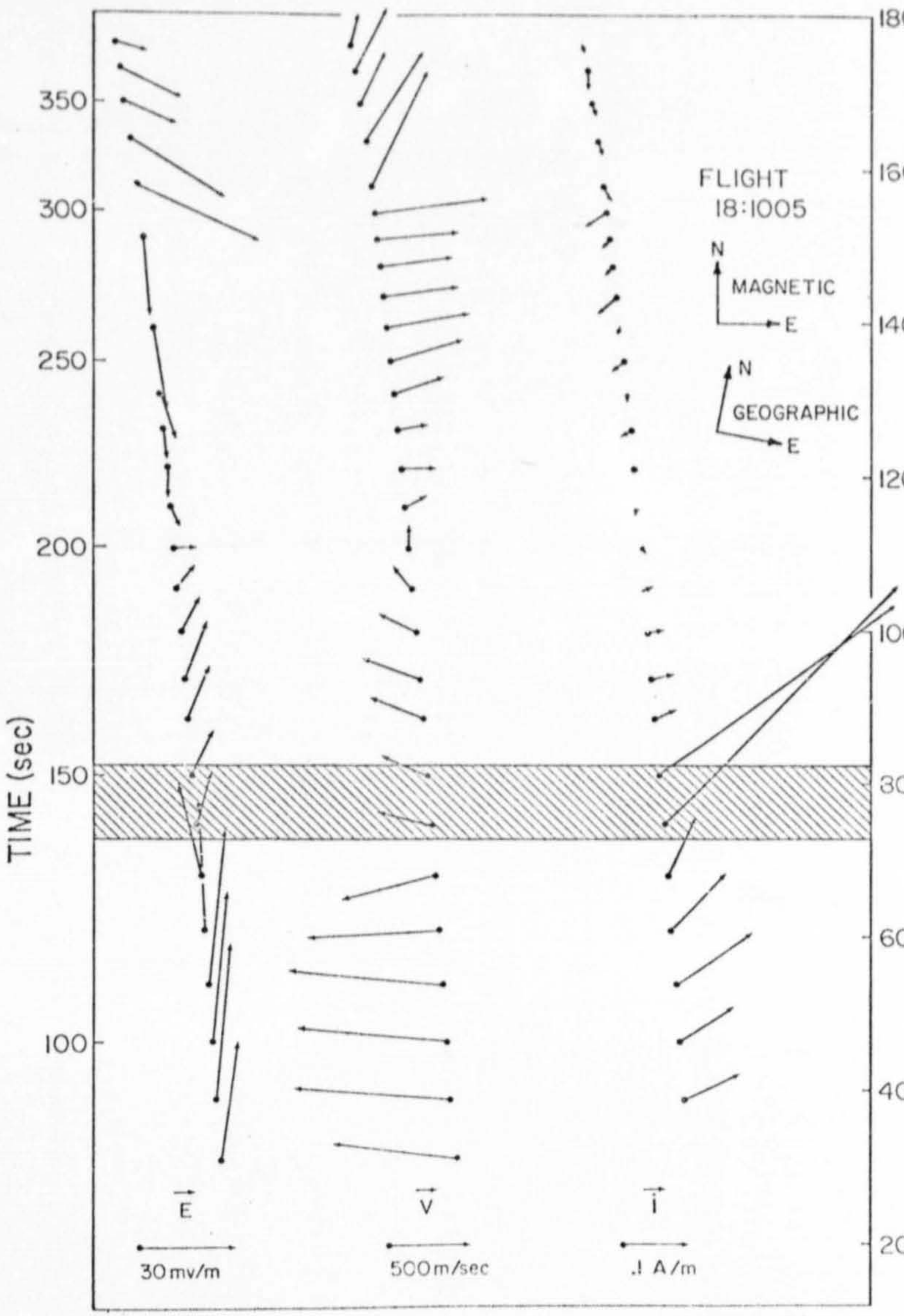
Fig. 3



ARC
18:1005
0.3 keV
3.0 keV
|E|
Electrons $(cm^2-sec-ster-keV)^{-1}$
$10^{10}$
$10^9$
$10^8$
Electric Field (mV/m)
10
20
30
40
50
100
150
200
250
300
350
Flight-time (sec)



FLIGHT
18:1005
N
MAGNETIC
E
N
GEOGRAPHIC
E
TIME (sec)
RANGE (km)
350
300
250
200
150
100
180
160
140
120
100
80
60
40
20
E
V
I
30 mv/m
500 m/sec
.1 A/m




Fig. 5