RICE UNIVERSITY

MEASUREMENT OF LOW-ENERGY AURORAL PARTICLES

by

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ABSTRACT

MEASUREMENT OF LOW-ENERGY AURORAL PARTICLES

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A measurement of the flux and pitch-angle distribution of low-energy auroral particles (electrons and protons with $E < 4$ kev) at rocket altitudes may not coincide with the primary fluxes and angular distribution at the top of the atmosphere due to factors affecting these quantities. Several of these factors are discussed, including energy loss, pitch-angle altering processes, secondary electron fluxes, and rocket shadowing effects.

A rocket-borne auroral experiment, now being prepared, is designed to determine a quantitative relationship between incident particles producing an auroral arc and any field-aligned current system associated with the arc. A description is given of the design and calibration of the electron-proton detectors in the payload which will measure the energy range 0.5 to 20 kev in seven intervals. A brief description of the other payload instruments is also given.
TABLE OF CONTENTS

I  INTRODUCTION 1

II  CONSIDERATIONS FOR A ROCKET-BORNE MEASUREMENT OF AURORAL PARTICLES

A. AURORAL ELECTRONS
   1. Range and Energy Loss 3
   2. Energy Loss and Flux Attenuation Calculations Including Scattering 7
   3. Secondary Electrons 10
   4. Pitch-Angle Altering Processes 13
   5. Payload Shadowing Effects 19

B. AURORAL PROTONS
   1. Range 22
   2. Corrections to Proton Flux Measurements 24
   3. Pitch-Angle Altering and Payload Shadowing 28

III  CONCLUSIONS 29

IV  DESIGN AND CALIBRATION OF THE LOW ENERGY ELECTRON AND PROTON DETECTORS

A. DESIGN 31

B. ANGULAR RESPONSE CALIBRATION 34
V OTHER PAYLOAD INSTRUMENTATION

A. MAGNETOMETER 40
B. SOLID-STATE DETECTOR 42
C. GEIGER-MUELLER DETECTOR 44
D. HIGH TIME RESOLUTION DETECTOR 44

ACKNOWLEDGEMENTS 45

REFERENCES 46
I. INTRODUCTION

A rocket-borne experiment is now being prepared at Rice University to measure electron and proton fluxes in an auroral arc and to determine a quantitative relationship of these fluxes to any field-aligned currents associated with the arc.

The aim of the auroral particles experiments in the payload is to determine the energy spectrum of electrons and protons in the energy range 0.5 to 20 kev and the fluxes at higher energy. The success in determining this energy spectrum is limited by three factors: 1) a number of instruments of the same and different types are needed to cover a wide energy range and yet yield a differential spectrum, 2) the difficulty in completely separating spatial and temporal effects because of rocket and arc motion and, 3) due to energy loss and scattering, a measurement of low-energy particles and their pitch-angle distributions at rocket altitudes may not coincide with the fluxes and pitch-angle distributions above the atmosphere.
This thesis discusses the last factor; specifically that energy loss places a lower limit on the energy of primary particles that are observable at a given altitude and that pitch-angle altering processes may significantly alter an incident pitch-angle distribution.

A description of the design and calibration of the Channeltron proton-electron detectors as well as a brief description of the other instruments in the payload (hereafter referred to as N/T-1) is also included.
II. CONSIDERATIONS IN A ROCKET-BORNE MEASUREMENT
OF AURORAL PARTICLES

A. Auroral Electrons

1. Range and Energy loss

During the quiet or pre-break-up evening phase of auroral activity the precipitating electrons occur mainly in the energy range 1 to 10 kev and it has been found that a substantial portion of the upward field-aligned current associated with an arc is carried by electrons in the energy range 2 to 18 kev (Vondrak, 1970). Because these electrons continuously lose energy while penetrating the atmosphere an energy spectrum made by a rocket measurement (up to ~200 km) does not correspond exactly to the spectrum at the top of the atmosphere.

A rocket-borne particle detector at a given altitude can make measurements of primary particles only as low as $E_{\text{min}}$, that energy particle whose range corresponds to the mass traversed from the top of the atmosphere to that altitude. We can get an idea of this minimum penetration energy and how it varies with pitch-angle by considering the empirical range
relation

\[ R_0 = a E_0^n \]

where \( R_0 \) = range of particle with energy \( E_0 \).

For electrons in air, Grün (1957) gives the values

\[ a = 4.57 \times 10^{-6} \]

\[ n = 1.75 \]

giving \( R_0 \) in g/cm\(^2\) for \( E_0 \) in kev.

A particle penetrating from the top of the atmosphere to a given altitude traverses an amount of mass, \( \ell \) (g/cm\(^2\)), which depends on its initial pitch-angle and how the scattering collisions it suffers affect this pitch-angle. The minimum penetration energy to altitude \( z \) is given by

\[ E_{\text{min}}(z) = \exp \left[ \frac{1}{n} \ln \left( \frac{\ell_z}{a} \right) \right] \]

where, \( \ell_z \), the atmospheric depth including the adiabatic motion of the particle is

\[ \ell_z = \int_0^{z_0} \rho_z \sec \left[ \arcsin \left\{ \frac{(R_E + z_0)^3}{(R_E + z)^3} \right\} \sin^2 \alpha_0 \right] \frac{1}{2} \, dz \]

\[ \rho_z = \text{density at altitude } z \]

(U.S. Standard Atmosphere, 1962)

\[ R_E = \text{radius of Earth} \]

\[ z_0 = \text{top of the atmosphere (400 km)} \]

\[ \alpha_0 = \text{pitch-angle at } z_0 \]
The density, \( \rho_z \), which enters the calculation of \( \ell_z \) is also a function of the seasonal variations in the atmosphere and the sunspot cycle; however, the effect of these density variations on the penetration altitude is less than that of scattering or straggling. The penetration altitude of an electron of 0.5 kev energy will vary only by several kilometers depending on the model atmosphere used. For higher energy electrons the variation will be even less.

Figure 1 shows values of \( E_{\text{min}} \) for various altitudes with several initial pitch-angles and neglecting pitch-angle changes due to scattering.

The energy loss, \( \Delta E_0 \), of a particle of energy \( E_0 \) penetrating to an altitude \( z \) can also be calculated from the above relation,

\[
\Delta E_0 = E_0 - \exp \left[ \frac{1}{n} \ln \left( \frac{R_0 - \ell_z}{a} \right) \right]
\]

where \( \Delta E_0 < E_0 \) for \( \ell_z < R_0 \) and \( \Delta E_0 = E_0 \) for \( R_0 = \ell_z \). We also have

\[
R_0 = a \, E_0^n
\]

\[
R_0 = \exp \left[ \ln a + n \ln E_0 \right]
\]

\[
\Delta E_0 = E_0 - \exp \left[ \frac{1}{n} \ln \left( \frac{\exp \left[ \ln a + n \ln E_0 \right] - \ell_z}{a} \right) \right]
\]
The minimum penetration energy for electrons with initial pitch-angles, $\alpha_0$, at 400 km.

**Figure 1** The minimum penetration energy for electrons with initial pitch-angles, $\alpha_0$, at 400 km.
where again \( l_z \) includes the effect of the adiabatic motion of the particle.

Plots of energy loss versus initial electron energy are shown for altitudes of 180 km and 220 km in Figure 2a and 2b. It can be seen that at energies up to about 3 keV the particles at large pitch-angles are much more attenuated than the ones at smaller pitch-angles. Thus, this energy attenuation affects the pitch-angle distribution (depending on how much of the flux is below \(~3~keV\)) as well as the energy spectrum. A detector at 180 km and looking at \( \alpha = 0^\circ \) with an energy passband of 1 to 2 keV sees particles which where incident at the top of the atmosphere with \( 1.25 < E_o < 2.15 \) keV.
Figure 2a  Energy loss for electrons penetrating to 180 km with initial pitch-angle $\alpha_0$ at 400 km.
Figure 2b Energy loss for electrons penetrating to 220 km with initial pitch-angle $\alpha_0$ at 400 km.
2. Energy Loss and Flux Attenuation Calculations Including Scattering

Using a Monte Carlo method, Maeda (1965) has calculated energy loss and flux attenuation for electrons of 2.5, 5, 10, and 20 kev. His calculations included electron scattering and energy loss as a function of energy and the calculations were done for the cases of straggling (fluctuations of the energy loss about some mean value) and no-straggling.

Ranges and penetration altitudes of the above energies for particles of 0° pitch-angle are shown below

<table>
<thead>
<tr>
<th>E₀ (kev)</th>
<th>r₀ (g/cm²)</th>
<th>Z₀ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>2.76 x 10⁻⁵</td>
<td>118.0</td>
</tr>
<tr>
<td>5</td>
<td>8.79 x 10⁻⁵</td>
<td>107.1</td>
</tr>
<tr>
<td>10</td>
<td>2.91 x 10⁻⁴</td>
<td>100.2</td>
</tr>
<tr>
<td>20</td>
<td>9.82 x 10⁻⁴</td>
<td>93.2</td>
</tr>
</tbody>
</table>

Figure 3 (a-d) shows how the relative intensity of a monoenergetic beam varies with altitude for both vertical and isotropic incidence for four electron energies. From 3a we can see that at 152 km between 80% and 95% of the incident flux of 2.5 kev electrons is present depending on the incident distribution.
Figure 3 The relative flux intensity at various altitudes for electrons of four energies. \( r \) is the range in g/cm² of electrons with energy \( E_0 \).
A rocket measurement at this altitude will then measure more than 80% of the incident flux of all electrons with $E_{0} > 2.5$ kev.

Not only is the flux attenuated but the particles lose energy as they penetrate. If $E_{0}$ is the initial particle energy then the initial energy flux, $E_{0}$, is

$$E_{0} = \xi_{0} F_{0}$$

where $F_{0}$ is the initial particle flux. The relative energy loss at an altitude is then given by

$$\frac{\xi(z)}{\xi_{0}} = \left( \frac{I_{0}}{I(z)} \right) \left( \frac{E(z)}{E_{0}} \right)$$

where $E(z)/E_{0}$ is the relative energy flux. Figure 4 shows the relative intensity and energy flux for 2.5 kev electrons. Electrons of lower energies will experience similar energy decreases but at higher altitudes.

The loss of energy by auroral particles means that a monoenergetic beam incident at the top of the atmosphere will be measured at a lower altitude with a spread of energy with a maximum $\xi_{max} < \xi_{0}$.
Figure 4  Relative intensities and energy fluxes for electrons of energy $\xi_0 = 2.5$ kev at various altitudes.
Figure 5 shows the relative differential energy spectra calculated by Maeda for monoenergetic electrons with initial energy $E_0$. For electrons with lower energies the spectra have almost identical shape for each value of the parameter $x = r/r_0$, where $r_0 (g/cm^2)$ is the range of the particle, corresponding to an altitude.

Maeda has also calculated the backscatter coefficient (fraction which backscatter to the top of the atmosphere) versus energy for vertical and isotropic incidence (Figure 6). The backscatter coefficient falls off for $E < 10$ kev because broadening in the energy distribution increases the number of low energy electrons. The energies are so low for some that they are unable to leave the atmosphere even though they are backscattered. Maeda's calculations did not take into account the electron's adiabatic motion (but did consider the particle's pitch-angle) so the backscatter coefficient does not include any particles which have mirrored for the case of isotropic injection.

The net effect of energy loss, then, is to decrease the number flux of measured particles and to alter the energy spectrum especially at low energy ($E \leq 4$ kev) and large pitch-angles.
**Figure 6** Backscatter coefficients for electrons for vertical and isotropic incidence.
Figure 5 The energy spectrum at various altitudes for a monoenergetic electron beam incident at the top of the atmosphere.
3. Secondary Electrons

Primary auroral electrons ionize the atmospheric constituents in inelastic collisions causing ejection of secondary electrons. Many auroral features, including the green and red lines of atomic oxygen, 5577 Å and 6300 Å, are excited by these secondary electrons. A rocket-borne measurement to determine the total flux of precipitated electrons, in order to determine the total field-aligned current, must then distinguish between these secondaries and the primary particles at low energies (~0 to 1 kev).

Rees (1969a) has calculated a differential spectrum for secondary electrons from a primary spectrum measured by Hoffman (1969), Figure 7. The dip in the theoretical spectrum at 2.5 ev is caused by vibrational excitation of the metastable levels of atomic oxygen.

Measurements of secondary electrons have been made by a number of experimenters, and their spectra, as reported by Pfister (1967), are shown in Figure 8. The general shape of the measured spectra agree quite well even though the measurements were made at altitudes from 105 to 250 km. The noticeable differences
Figure 7  The theoretical spectrum (left) of secondary electrons produced by the primary spectrum (right) measured by Hoffman (1969)
Figure 8  Measured auroral secondary electron spectra, Pfister (1967).

Ogilvie et al., ~250 km, weak diffuse aurora
Heikkila and Matthews, 125-145 km, nighttime absorption event
Doering, stable post break-up
between these measured spectra and the theoretical one are: 1) the lack of structure below 20 ev and, 2) the excess of electrons at energies greater than ~100 ev.

The theoretical secondary electron spectrum falls off very rapidly for \( E > 25 \) ev and there appears to be no interaction that produces secondary electrons with the energies needed to give the measured spectra (Rees et al., 1969b). Rees (1969a) has concluded that the region \( 50 \text{ ev} < E < 100 \text{ ev} \) may include both primary and secondary electrons; the combination producing the measured spectra.

Any measurement designed to distinguish between the primary and secondary spectra must take into account the fact that the primary spectrum has been degraded in energy at altitudes where secondary production is significant; that is, any experiment measuring secondary electrons must, of necessity, measure a primary spectrum that is degraded in energy (especially \( E < 1 \) kev). It then appears that the best altitude for a measurement of this type (\( E < 0.5 \) kev) is somewhere between 200 and 300 km. The production rate of secondaries in this altitude range
varies from \(\sim 1/20\) to \(\sim 1/100\) (from 200 km to 300 km) of that at 150 km, so that there are measureable amounts of secondaries and the primary spectrum is degraded in energy significantly only below \(\sim 1\) kev.
4. Pitch-Angle Altering Processes

The pitch-angle distribution measured at rocket altitudes may reflect pitch-angle altering processes occurring both above and below this altitude. Local electric field acceleration will alter the distribution for \( \alpha = 0^\circ \) to \( 90^\circ \) if the electric field is above the measurement altitude and the magnetic field produced by the auroral electrojet may sufficiently distort the geomagnetic field to cause alteration of the pitch-angle distribution.

The effect of the auroral electrojet on precipitated electrons has been studied by Maehlum and O'Brien (1968). They have found that long period oscillations (50 to 300 sec) in auroral structure may occur due to particle-atmosphere interactions if the current driving electric field is sufficiently strong and the gradient in the pitch-angle distribution of the ionizing electrons is steep near the boundary of the "loss cone."

The auroral electrojet is enhanced in the region of the precipitation due to increased ionization. Thus, a westward flowing electrojet produces a magnetic field which increases the total field at
the northern boundary of the region of precipitation raising the mirror altitudes of the electrons while the decreased field at the southern boundary lowers mirror altitudes. If the gradient in pitch-angle distribution is steep near the boundary of the "loss cone" this raising of mirror altitudes will effectively shut off ionization in the northern region and increase it near the southern boundary.

The effect of the electrojet on mirror altitudes can be determined by considering a typical current of $5 \times 10^4$ amps flowing westward at an altitude of 120 km. $\Delta B$, the component of the electrojet magnetic field along $\vec{B}_G$, the geomagnetic field, is plotted versus altitude along a field line 20 km from the electrojet in Figure 9. South of the electrojet $\Delta B$ is opposite in direction to $\vec{B}_G$ and north of the electrojet $\Delta B$ is in the same direction as $\vec{B}_G$.

The mirror altitudes of particles in adiabatic motion about the field lines are given by

$$B_G(h_m) = B_G(h)/\sin^2 \alpha$$

where $B_G(h_m)$ = field strength at mirror altitude
Figure 9  The $\Delta B$ parallel to the Earth's magnetic field at a distance of 20 km from an electrojet of $5 \times 10^2$ amps at 120 km altitude.
\[ B_g(h) = \text{field strength at altitude } h \]
\[ \alpha = \text{pitch-angle at altitude } h \]

If we consider particles of various pitch-angles at 200 km we see that, due to the electrojet, particles of certain pitch-angles will have their mirror altitudes lowered. The effect is greatest for particles with pitch-angles normally mirroring near 120 km (e.g., a particle with 80° pitch-angle at 200 km normally mirrors at ~120 km) as shown in Figure 10. The magnitude of \( \Delta h \) depends on the strength of the electrojet and the north-south distance from it; the width of the pitch-angle range for which \( \Delta h \) is appreciable depends on the distance from the electrojet; and, the \( \alpha \) with \( \Delta h \) a maximum depends on the altitude of the electrojet.

Since particles in this range of pitch-angles with depressed \( h_m \) will mirror at lower than normal altitudes less will be backscattered than normal and one might expect to see this effect in the pitch-angle distribution measured at 200 km. However, because particles in this pitch-angle range mirror only after many scattering collisions and because the depression of \( h_m \) occurs over a narrow range of pitch-angles, this effect, in general, would be difficult to observe.
Figure 10 The change in mirror altitude for electrons 20 km south of a westward flowing electrojet of $5 \times 10^4$ amps at 120 km altitude. Pitch-angles are those at 200 km.
Electrostatic fields in the upper ionosphere with components parallel to the Earth's magnetic field lines can accelerate precipitating particles in this direction and thus lower their mirror points. We can see the effect of an accelerating potential, \( V \), by considering a particle's magnetic moment

\[
\mu = \frac{E_\perp}{B} = \text{constant of the motion}
\]

\[
= \frac{E_T}{B} \sin^2 \alpha
\]

where \( E_\perp \) is the energy perpendicular to \( B \) and \( E_T \) is the total energy of the particle. Since \( \mu \) remains constant for the motion we can write

\[
\frac{E_0 \sin^2 \alpha_0}{B_0} = \frac{E_h \sin^2 \alpha_h}{B_h} \quad \text{and} \quad E_h = E_0 + V
\]

where \( E_0 \), \( \alpha_0 \), and \( B_0 \) are the quantities at the altitude of the electrostatic layer and \( E_h \), \( \alpha_h \), and \( B_h \) are the quantities at the altitude of measurement. For particles mirroring at the altitude of the electrostatic layer \( \alpha_0 = \pi/2 \) and then at the altitude of measurement

\[
\sin^2 \alpha_h = \frac{B_h}{B_0} (1 - \frac{V}{E_h})
\]
Then \( \alpha_h \) is the maximum pitch-angle observable at this altitude and will be less than \( \pi/2 \).

Albert and Lindstrom (1971) have found evidence in measured pitch-angle distributions that parallel components of electrostatic fields (electrostatic double layers) exist in the Earth's ionosphere at altitudes greater than 250 km. Specifically the data suggest that: 1) the mirror points are lowered by the presence of electrostatic double layers in the ionosphere thereby causing additional electron precipitation and producing a 'void' region of \( \alpha \approx 80^\circ \) above which no precipitating particles are seen, and, 2) particles seen in the region \( 80^\circ < \alpha < 90^\circ \) are transient populations of precipitated electrons which are scattered by the atmosphere and are trapped between their magnetic mirror points and the region of the ionospheric double layers.

For electrons of auroral energies Coulomb scattering is primarily through small angles (Chappell, 1968); however, in penetrating to rocket altitudes (\( \sim 200 \) km) electrons of this energy
will undergo between 10 and 100 collisions, thus, the initial pitch-angle distribution may be considerably altered.

From the calculation on diffusion of auroral electrons in the atmosphere Maeda (1965) has calculated the effect of pitch-angle scattering on a vertically incident monoenergetic beam of electrons. Figure 11 shows the relative intensity/steradian plotted against the non-dimensional parameter \( x = r/r_0 \) (\( r_0 \) is the range of an electron with energy \( E_0 \); see Figure 3 for altitudes corresponding to various values of \( x \)). Considering an incident energy of \( E_0 = 2.5 \) kev we see from Figure 11 that at \( x = 0.1 \) (corresponding to 180 km) the intensity at 0° is about 80% and the intensity at 30° is about 15% of the incident intensity at 0°. For higher energies and for higher altitudes the beam spreading will be even less. At 200 km altitude, higher energy electrons (\( E > 5 \) kev) will retain their initial pitch-angle distribution except for very large pitch-angles.
Figure 11 The relative intensity/steradian vs. altitude for a monoenergetic, vertically incident electron beam ($\theta$ is measured from the magnetic field direction). $x = r/r_0$, where $r_0$ is the range of the particle with energy $E_0$ (see Figure 3).
5. Payload Shadowing Effects

In order to accurately measure the complete pitch-angle distribution of auroral particles it is necessary for the particle detectors to have a large pitch-angle coverage. For narrow-field detectors a complete coverage of $0^\circ < \alpha < 180^\circ$ is obtained only for the case where the detectors "look" at $45^\circ$ and $135^\circ$ to the rocket spin axis, and this axis is inclined $45^\circ$ to the magnetic field direction. But even for this case we may not measure the entire pitch-angle distribution since particles of certain energies and $\alpha$'s have trajectories which intersect the rocket before they reach the detector. These particles are thus not counted and are said to be "shadowed".

The shadowing effect of the payload for a given energy particle depends only on the location (lengthwise) of the particle detectors, the diameter of the payload, and $\theta_B$, the angle of the rocket spin axis with the magnetic field. The N/T-1 payloads have a diameter of 23 cm and the low energy electron-proton detectors are situated 178 cm = L from the nose cone and 485 cm = L' from the end of the Tomahawk stage which remains attached throughout the flight. The angle $\theta_B$ will ideally be $45^\circ$ as the rocket passes over the arc.
We can visualize the effect of payload shadowing by assuming the particle's trajectory in a magnetic field to lie on a cylindrical surface of radius $a_c$, the particle's gyroradius. For particles detected the spin axis of the payload is then tangent to this cylinder at the appropriate angle $\theta_B$ and the payload intersects a portion of it as shown in Figure 12. Considering particles of one energy it can be seen that there will be a range of $\alpha$'s giving trajectories passing through this region and thus not reaching the detector.

Calculation of the "shadowing" effect involves determining $z_i$, the projection of the length of the intersected region in the magnetic field direction. The maximum pitch-angle of a particle that can reach the detector is then

$$\alpha_{\text{max}} = \arccos \left( \frac{z_i}{z} \right).$$

For higher energy particles ($a_c \gg L$) the intersected region will extend from the end of the payload to the detector, and

$$z_i = L \cos \theta.$$

For lower energies the intersected length is less
Figure 12 The effect of payload shadowing on the trajectory of a particle with pitch-angle near $90^\circ$. 
than \( L \) and we have

\[
z_i = a_c \cot \theta_B \sin \left( \arccos \left( 1 - \frac{r}{a_c} \right) \right)
\]

where \( r = \) radius of payload.

The maximum pitch-angles observable for electrons at various particle energies are shown in Figure 13. These were calculated for \( a_c \) at 200 km (\( B = 0.500 \) gauss) and for dimensions of the N/T-1 payload. It should be noted that at \( \theta_B = 30^\circ \) the pitch-angle coverage is \( 15^\circ \) to \( 75^\circ \) and \( 105^\circ \) to \( 165^\circ \) and the effect of shadowing cannot be observed.
Figure 13 The maximum pitch-angle observable for the electron detectors on the N/T-1 payload. The dashed curves are the result of the longer section of rocket below the detectors.
B. Auroral Protons

1. Range

Energy loss by protons penetrating to a given altitudes is actually less than that of electrons of the same energy for altitudes greater than 130 km. Thus, at an altitude above this, the minimum proton energy observable is less than the minimum observable electron energy.

We can get an idea of this minimum penetrating energy using the empirical range relation

\[ R = k E_o^n \]

where \( E_o \) is the energy of the proton and \( R \) is the range. The values of the constants have been determined by Cook, Jones, and Jorgenson (1953) for \( E_o \leq 76.5 \) kev, and in air

\[ k = 4.22 \times 10^{-6} \]

\[ n = .73 \]

\[ R = \text{range in g/cm}^2 \]

The minimum energy needed to penetrate to a given altitude is then

\[ E_{min} = \exp \left[ \frac{1}{n} \ln \left( \frac{\lambda_h}{k} \right) \right] \]
where $l_h$ is the mass traversed, $g/cm^2$, in going from the top of the atmosphere to altitude $h$.

The minimum penetration energy for various altitudes is shown in Figure 14 for protons with pitch angle $\alpha = 0^\circ$. The mass traversed, $l_h$, was calculated starting at 400 km and integrating to $h$. It was assumed that the pitch-angle was unaltered by scattering or charge exchange processes. For an altitude of 200 km the minimum observable energy is 0.1 kev for $\alpha = 0^\circ$; thus, it would not be possible to detect protons of this energy at greater pitch-angles since these would have traversed more mass.
Figure 14  The minimum penetration for protons with $\alpha_o = 0^\circ$ at 400 km.
2. Corrections to Proton Flux Measurements

Although visual auroral forms are normally sharply defined in north-south extent (10's of km) the hydrogen emission region is much more diffuse and typically extends ~ 3° in latitude (~300 km). The reason for this dispersion is that the proton path, because of charge-exchange collisions, is not as well constrained to field lines as are precipitated electrons. If a proton spiraling along a magnetic field line with an appreciable pitch-angle captures an electron at an altitude of several hundred kilometers it may travel as a neutral hydrogen atom across the field lines for a distance of a hundred or more kilometers, depending on altitude (see Figure 15).

The spatial distribution of auroral protons and hydrogen atoms has been calculated by Davidson (1965) using a Monte Carlo method. The path length before charge exchange for the incoming protons was randomized as well as the azimuthal angle of the neutral hydrogen atom after the collision. The trajectory was thus followed through successive neutralizing and ionizing collisions.
Figure 15 Schematic drawing showing proton beam dispersion as neutral hydrogen atoms.
The most effective charge exchange mechanism in the upper atmosphere for protons with $E < 30$ kev is

$$H^+ + O \rightarrow H + O^+$$

with the cross section increasing for decreasing proton energy. Hydrogen atoms lose electrons in ionizing collisions and through charge-exchange but charge-exchange is not likely at altitudes of several hundred km since the abundances of positive ions are low. At 300 km, for example, the hydrogen atom has a mean free path of $\sim 300$ km before it is ionized again. Thus the fraction of the incident proton beam which charge-exchanges at high altitudes is spread rather far initially and relatively little spreading occurs at lower altitudes. A proton at altitudes of less than 180 km will generally make less than one complete orbit before electron capture. Thus the motion below this altitude is constrained to the field lines and can be regarded as that of a particle with less than one electronic charge.
Figures 16 a and b show Davidson's results for 10 kev protons with an isotropic injection pitch-angle distribution and one proportional to $(\sin \alpha)^{-1}$ at two altitudes. The beam spreading was found to be relatively insensitive to energy from 5 kev to 20 kev.

These graphs show spreading for injection along one field line and are thus not representative of an extended arc. For an arc of essentially infinite east-west extent the total flux $(H + H^+)$ is constant at one altitude along a line of magnetic latitude. Normalizing Davidson's results for this situation gives a total flux of $H + H^+$ at 200 km between 0.1 and 0.2 of the incident proton flux depending on the assumed arc thickness (10 or 20 km).

In a particle measurement to determine the total field aligned currents carried by auroral particles we must take the beam spreading of the proton flux into account if the only region in which we observe statistically significant counts is over the arc.
Figure 16a The number of protons and H atoms/cm$^2$ crossing altitudes of 307 km (dashed) and 200 km (solid) for an isotropic injection pitch-angle distribution.

Figure 16b The number of protons and H atoms/cm$^2$ crossing altitudes of 307 km (dashed) and 200 km (solid) for an injection pitch-angle distribution proportional to $(\sin \alpha)^{-1}$. 
At the altitude of a rocket measurement a fraction of the total incident protons will be H atoms and these will not be counted by detectors using electrostatic energy analyzers. Thus we must know the ratio of protons at an altitude to the total incident flux.

Figure 17 (Eather, 1967) shows that for proton energies of less than 300 kev 90% equilibrium is reached for altitudes less than 250 km. For a measurement below this altitude we can assume that equilibrium has been reached for protons of auroral energies and correct the measured fluxes using the appropriate equilibrium fraction, also shown in Figure 17.
Figure 17 The equilibrium fraction $H^+/H$ vs. proton energy and the altitude for 90% equilibrium vs. energy.
3. Pitch-Angle Altering and Payload Shadowing

An electrostatic field which accelerates electrons in the direction of $\mathbf{B}$ would have the effect on protons of reducing the flux at lower altitudes (by raising the "mirror" points) and reducing the proton's energy, especially for those with small pitch-angles. There would be no 'void' region in the proton pitch-angle distribution.

If there are significantly lower fluxes of auroral protons compared to electrons, any effects of pitch-angle altering processes will be more difficult to observe in the proton pitch-angle distribution.

Payload shadowing effects for protons are not as pronounced as those for electrons because of the larger proton gyro-radius for equivalent energy. Shadowing occurs for pitch-angles between $89.5^\circ$ and $90.5^\circ$ for the N/T-1 payload for protons with $E$ greater than 0.1 kev.
III CONCLUSIONS

The considerations for a rocket-borne measurement of auroral particles discussed in Section II can be applied to the N/T-1 payload experiments to get an idea of the expected measurements. The payload contains proton-electron detectors to measure the fluxes of both incident and backscattered particles in seven energy intervals from 0.5 to 20 kev. The ideal trajectory of the rocket will place the payload over an arc at apogee (~200 km) with an angle of 45° between the spin axis and the geomagnetic field direction.

The minimum energy for electrons to penetrate to 200 km altitude is ~0.5 kev for α= 0°. Thus a large number of particles observed by the lowest energy passband (0.5 to 1.0 kev) electron detector will be those which were incident at the top of the atmosphere with energies from ~1.0 to ~1.5 kev and have lost energy through collisions. The energy loss and flux attenuation of electrons with E > 5 kev is very small and the pitch-angle distribution should be that of the incident particles (except for large pitch-angles).

The payload does not contain an electron detector suitable for measuring the spectrum of secondary electrons (energy range 50 ev to ~500 ev). The ideal altitude for making a measurement to distinguish between the primary and secondary particles is ~240 km.
The angular response of the electron detectors is about 4° FWHM so that structure in the pitch-angle distribution smaller than this is not observable with our instrument. The rocket shadowing effect should be observable if the angle \( \theta_B \) is about 45°.

The minimum energy for protons penetrating to 200 km is \( \sim 0.1 \) kev so that protons measured by even the lowest energy proton detector have not lost much energy. Because of dispersion as neutral H atoms and the equilibrium number of H atoms, the fluxes of protons at 200 km are expected to be much lower than the incident fluxes.
IV DESIGN AND CALIBRATION OF THE LOW ENERGY ELECTRON AND PROTON DETECTORS

A. Design

The detection of particles with $E < 50$ keV requires a device with little or no window thickness. An appropriate detector is the Bendix "C"-type Channeltron, a windowless electron multiplier. The Channeltron consists of a C-shaped hollow glass tube with a highly resistive coating on the inside ($\approx 10^9 \Omega$). With the aperture end at ground, a bias voltage (typically +3500 volts) applied at the end of the tube produces an electric field which accelerates secondary electrons produced by the incident particle. These secondaries in turn produce more secondaries upon striking the wall, resulting in a total particle gain of $\approx 10^8$.

Although the Channeltron is suitable for detecting even very low energy particles ($E < 100$ ev) the output from the detector provides no energy information about the incident particle. Determination of the flux at a certain energy is accomplished by the use of cylindrical curved-plate analyzers placed before the detector. The energy of the particles reaching the
detector is

\[ E_0 = \frac{V q}{2 \ln \left( r_2 / r_1 \right)} \]

where \( V \) is the voltage between the plates, \( q \) is the charge of the particle, and \( r_1 \) and \( r_2 \) are the inner and outer radii, respectively, of the plates.

A schematic drawing of a detector unit (consisting of an electron and proton detector) is shown in Figure 18. Because of the finite spacing between the plates and the size of the Channeltron aperture, particles with \( E \) slightly different from \( E_0 \) will also be able to reach the detector for a given \( V \). The width of this energy passband depends on the spacing, \( (r_2 - r_1) \), and the arc length of the plates and placement of the Channeltron detector. The angular response of the instrument is determined by the shape and placement of the aperture.

The N/T-1 payload will carry 14 such units; 7 units "looking" at 45° to the rocket's spin axis and 7 units at 135° to the spin axis. Each group of 7 units will cover the energy range 0.5 to 20 kev for electrons and protons in the following seven intervals
Figure 18 A schematic drawing of the N/T-1 Channeltron proton-electron detectors.
<table>
<thead>
<tr>
<th>Unit Number</th>
<th>Center Plate Voltage</th>
<th>Energy Passband</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67.5 v</td>
<td>0.5-1.0 kev</td>
</tr>
<tr>
<td>2</td>
<td>125 v</td>
<td>1.0-2.0 kev</td>
</tr>
<tr>
<td>3</td>
<td>250 v</td>
<td>2.0-4.0 kev</td>
</tr>
<tr>
<td>4</td>
<td>250 v</td>
<td>4.0-6.0 kev</td>
</tr>
<tr>
<td>5</td>
<td>250 v</td>
<td>6.0-8.0 kev</td>
</tr>
<tr>
<td>6</td>
<td>250 v</td>
<td>8.0-10 kev</td>
</tr>
<tr>
<td>7</td>
<td>1250 v</td>
<td>10-20 kev</td>
</tr>
</tbody>
</table>

The center plate voltage on each unit remains constant throughout the flight.
B. Angular Response Calibration

Calibration of the Channeltron detectors consists of determining the response of the instrument for various energy particles at various angles of incidence with respect to the entrance aperture.

A uniform electron beam of 6 inches diameter and variable energy was used for the calibration. The energy of the beam was set at a particular value and counts from the detector were accumulated for 60 milliseconds for a certain angular position. The detector was then "stepped" to a new position and another 60 millisecond count made. This was done until the entire angular response region was covered for each energy.

The detector positioning was done automatically by the SDS 92 computer which also recorded the counts at each position and monitored the beam flux each time the energy was set to a new value. Generally, the positioning in the $\theta$ direction went from $-20^\circ$ to $+20^\circ$ in $0.4^\circ$ increments and in the $\varphi$ direction from $-15^\circ$ to $+15^\circ$ in $1.0^\circ$ increments. This angular stepping gives 3,131 accumulations for each energy.

Contour plots of typical electron and proton detector responses are shown in Figure 19.
Figure 19 Relative response for particles of 1.5 kev for the unit with energy passband 1.0 to 2.0 kev.
The proton detector response was measured using an electron beam with the center plate voltage reversed. The plots show relative response for an energy of 1.5 kev in the 1.0 to 2.0 kev unit.

From this calibration data we wish to determine a quantity which will relate the incident particle flux to the detector count rate. We can write \( R \), the detector count rate, as

\[
R = \int \int r(\Omega, E) \ d\Omega \ dE
\]

(1)

where \( r(\Omega, E) = \text{particles/sec-ster-kev} \) is the count rate in a particular direction at a particular energy. We can also write the relation of the count rate to the incident flux

\[
R = \int \int g(\Omega, E) \ N(\Omega, E) \ d\Omega \ dE
\]

(2)

where \( g(\Omega, E) \) is the directional geometric factor \( (\text{cm}^2) \) and \( N(\Omega, E) \) is the particle flux in a particular direction and energy \( (\text{particles/cm}^2\cdot\text{ster-sec-kev}) \). Then

\[
r(\Omega, E) \ d\Omega \ dE = g(\Omega, E) \ N(\Omega, E) \ d\Omega \ dE
\]

(3)
During the calibration we can assume a beam which is monoenergetic within \( dE \) and unidirectional within \( d\Omega \); then our count rate at one position is

\[
T(\Omega, E) = r(\Omega, E) \, d\Omega \, dE \tag{4}
\]

\[
= \text{total counts in one accumulation} \over 60 \text{ milliseconds}
\]

and the flux is related to the Faraday cup current by

\[
\frac{I}{eA} = N(\Omega, E) \, d\Omega \, dE \tag{5}
\]

where \( I_0 \) is the Faraday cup current, \( A \) is the cup area, and \( e \) is the electronic charge. Substituting (4) and (5) into (3) yields

\[
g(\Omega, E) = \frac{r(\Omega, E) \, d\Omega \, dE}{N(\Omega, E) \, d\Omega \, dE} = \frac{T(\Omega, E)}{I_0/eA} \cdot
\]

A somewhat more useful quantity, \( G(E) \), the energy geometric factor is given by

\[
G(E) = \int g(\Omega, E) \, d\Omega
\]

\[
= \int \frac{T(\Omega, E)}{I_0/eA} \, d\Omega
\]
or, for small angular steps,

\[ G(E) = \frac{eA}{I_0} \sum_{\theta} \sum_{\varphi} T(\theta, \varphi, E) \Delta \theta \Delta \varphi, \]

and

\[ G(E) = \frac{eA}{I_0} \frac{T_s}{\tau} \eta(\Delta \theta \Delta \varphi) \]

where

- \( T_s = \) sum of counts of all accumulations for one energy
- \( \tau = \) accumulation time (60 milliseconds)
- \( \eta = \) number of accumulations
- \( \Delta \theta = \theta \) increment between accumulations
- \( \Delta \varphi = \varphi \) increment between accumulations.

\( G(E) \) is more useful for calculations involving an isotropic flux since

\[ N(\Omega, E) = N(E) \] for an isotropic flux

and the count rate is given by

\[ T = \int G(E) N(E) \, dE. \]

The energy geometric factors for the 28 detectors are plotted versus energy in Figures 20 and 21. The four sets of curves represent 550 calculations of
Figure 20: The energy geometric factors, $G(E)$, for the proton-electron detectors, (down-looking detectors)
Figure 21 The energy geometric factors, G(E), for the proton-electron detectors.
G(E) made on the SDS 92 computer from a total 1.6 million data words (each word represents the total count for one accumulation period).

As mentioned previously the calibration data for the proton detectors was obtained by reversing the polarity of the center plate voltage of the detector and proceeding as for the electron detectors. The G(E)'s for the proton detectors plotted in Figures 20 and 21 do not take into account the ratio of the Channeltron efficiency for protons to the efficiency for electrons, $\varepsilon(E)$;

$$\varepsilon(E) = \frac{\varepsilon(E^+_O)}{\varepsilon(E^-_O)}.$$  

Assuming the efficiency of the curved plate analyzers is the same for both protons and electrons we must multiply the proton geometric factors by $\varepsilon(E)$ to get the correct values.

A measurement of the absolute Channeltron efficiency, as a function of energy, for both protons and electrons has been published by Egidi et. al. (1969). They state errors of $\approx 20\%$ in their values of both efficiencies resulting in considerable error in the value of $\varepsilon(E)$. The main source of error is the difficulty in determining the beam current density which must be $\sim 10^{-14}$ amp/cm$^2$ to give count rates from a bare Channeltron of $\sim 10^4$/sec.
In order to determine a much better value of $\epsilon(E)$ a proton source has been constructed and is being tested. The source is capable of producing a total beam current of up to $10^{-9}$ amp/cm$^2$ with the energy of the particles variable from 0 to 10 kev. An Einzel lens is used to control the cross sectional area of the beam. The determination of $\epsilon(E)$ will be made using a Channeltron detector and an electrostatic analyzer so that the beam current density can be increased to $\sim 10^{-11}$ amp/cm$^2$, which is more accurately measurable and still gives count rates of $\sim 10^4$/sec. The geometric factor for a given direction and energy, $g(\Omega_o,E_o)$, will be measured for both protons and electrons giving

$$
\epsilon(E_o) = \frac{g(\Omega_o,E_o)^+}{g(\Omega_o,E_o)^-}
$$

where the subscripts refer to geometric factors measured with electrons or protons.
OTHER PAYLOAD INSTRUMENTATION

The basic objective of the N/T-1 payload experiments is to measure field-aligned currents above the auroral zone and to simultaneously measure the flux of precipitating auroral particles while an auroral arc is present. It is hoped that from these measurements a quantitative relationship of field-aligned currents to the precipitated particles will be determined.

A view of the payload instrumentation is shown in Figure 22.

A. Magnetometer

Magnetic disturbances observed on the ground when arcs are present overhead are due mainly to horizontal ionospheric currents. In order to measure field-aligned currents it is necessary to make in situ measurements of the magnetic field using a rocket or satellite.

Currents flowing along the field lines produce mainly a directional change of the total magnetic field with no appreciable change in its magnitude thus making a vector measurement of the field necessary. A transverse disturbance field of 100\gamma results in a \Delta B of \sim0.1\gamma and a change in field direction of \sim0.1^\circ.
Figure 22 The N/T-1 payload.
A magnetometer with such directional sensitivity has been successfully flown to measure the ionospheric current system of the Solar Quiet daily magnetic variation, $S_q$, (Cloutier and Haymes, 1968) and field-aligned currents above an auroral arc (Park, 1971).

The magnetometer is a cesium vapor sensor of the optical pumping type. A single bias coil placed at approximately a right angle to the vehicle spin axis produces a modulation at the spin rate from which the angle between the rocket's spin axis and the magnetic field and a reference angle (obtained from the lunar aspect sensor) specifies the field vector in the vehicle coordinate system. A knowledge of the vehicle aspect allows the components of the field change to be calculated in a geographic coordinate system. The complete details of the analysis are given in Park (1971).
B. **Solid-State Detector**

The measurement of proton fluxes in the energy range 50 kev to 2.0 Mev is made with a solid-state detector. The system consists of a silicon surface barrier detector and a collimator housing an electron rejecting "broom" magnet. A section view of the detector and housing is shown in Figure 23. Two units are mounted in the payload at 45° and 135° to the rocket's spin axis.

The detector is a pre-mounted device manufactured by ORTEC with a depletion depth of 100µ for a bias voltage of 31 v. The output is connected to an ORTEC 109A pre-amplifier and the output of that goes to four level detectors whose thresholds correspond to 50 kev, 100 kev, 500 kev, and 2.0 Mev, the overflow threshold level. The output of each level detector goes to a one-shot and is transformer coupled to the PCM telemetry system. A block diagram of the system is shown in Figure 24. Outputs from the three channels are for protons with

1) \(50 \text{ kev} < E < 2.0 \text{ Mev}\)

2) \(100 \text{ kev} < E < 2.0 \text{ Mev}\)

3) \(500 \text{ kev} < E < 2.0 \text{ Mev}\)
Figure 23  Section view of the solid-state detector unit.
Figure 24 Schematic drawing of the solid-state detector electronics.
A plot of energy-loss for protons is shown in Figure 25. The dead layer correction is for the front gold layer of ~40 μg/cm² thickness.

The geometric factor of the detector, G, relates particle flux, N, to counting rate R.

\[ R \text{ (counts/sec)} = G \text{ (cm}^2\text{-ster)} \times N \text{ (particles/sec-cm}^2\text{-ster)} \]

Because of cylindrical symmetry,

\[
G = \varepsilon \int_0^\infty \int_0^{\pi/2} A \sin \theta \, d\theta \, d\varphi \\
= 2\pi A \varepsilon \int_0^{\pi/2} \sin \theta \, d\theta \\
= 2\pi A \varepsilon \left(1 - \cos \theta\right) \\
\]

\( A = \text{active area of detector} = 0.843 \text{ cm}^2 \)

\( \varepsilon = \text{efficiency} \approx 1.0 \)

\( \theta = \text{viewing half-angle} = 10^\circ \)

\[
G = 0.793 \text{ cm}^2\text{ster} \]
Figure 25 Energy loss for protons in 100μ silicon detector. Dead layer thickness is 40 μg/cm² of gold.
C. Geiger-Mueller Detectors

The two GM tubes mounted at 45° and 135° to the rocket's spin axis will measure electrons with \( E > 50 \) kev and protons with \( E > 500 \) kev. The detectors are thin window 6213 tubes manufactured by EON. A typical response versus energy curve is shown in Figure 26. The collimator has a full opening of 18.8° and the active area of the detector is \( 7.93 \times 10^{-2} \) cm\(^2\) giving a geometric factor of

\[
G = 6.47 \times 10^{-3} \text{ cm}^2\text{-ster.}
\]

D. High Time Resolution Detector

The HTR detector is designed to detect modulations as low as 2% in the precipitated electron flux with frequencies from 40 kHz to 10 MHz in the energy range 4 to 8 kev. The instrument consists of two sets of hemispherical electrostatic analyzers and a Johnston Laboratory MM-1 electron multiplier. Spectral analysis of the signal is performed on-board and the frequency spectrum is telemetered separately on a standard IRIG subcarrier. A complete description of the design and operation is given by Loewenstein (1970).
Figure 26  The relative response as a function of electron energy for an EON 6213 Geiger tube. The window thickness is 2 to 4 mg/cm² of mica.
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