RICE UNIVERSITY

THE DESIGN OF A ROCKET-BORNE
HIGH TIME RESOLUTION ELECTRON
DETECTOR

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

Thesis Director's signature;

[Signature]

Houston, Texas

May, 1970
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Instabilities operating in both the ionosphere and magnetosphere will produce an exponential growth of plasma waves. These waves could then act in resonance with precipitating auroral electrons at their local plasma and cyclotron frequencies (.5-10 MHz) to produce a modulation of the electron flux.

The design of a rocket-borne experiment to measure flux modulation of 4-8 keV auroral electrons in the previously unexplored frequency range of 10 kHz-10 MHz is described. The detector proposed for the experiment is a Johnston Laboratory MM-1 Electron Multiplier. A hemispherical electrostatic deflection system is used to provide large count-rates of the appropriate electrons, and to reduce the apparent modulation in the flux due to the spin stabilization of the rocket. An on-board spectral analysis of the signal is performed, and the frequency spectrum is telemetered to the receiving station.

Since the experiment is exploratory, the instrument is designed to measure only the amount and frequency of the occurring modulation.
I. INTRODUCTION

Beam-plasma instabilities operating in both the ionosphere and magnetosphere might provide energy to accelerate the precipitating auroral particles to their observed energies. Wave-particle coupling can then produce modulation of the electrons near the local plasma frequency (.5-10 MHz).

Modulation of greater than 5 keV electrons has been observed up to the 1 kHz frequency limit of the previously flown detectors. To date, no investigation has been performed to include higher frequencies of modulation, in particular, modulation near the cyclotron and plasma frequencies in the ionosphere (f_c ~ 1 MHz, f_p ~ 1.5 MHz). Identification of this modulation will provide insight into processes occurring in auroral phenomena.

The development of a High Time Resolution (HTR) experiment to measure the amount and frequency of auroral electron modulation is described herein. Due to its exploratory nature, certain compromises had to be made in the experiment's design. The single energy pass-band to be sampled is 4-8 keV, and the frequency range to be investigated is 40 kHz-10 MHz with 10 kHz resolution.
Before describing the development, however, a review of the previously observed modulation and possibly related instabilities is presented since these data are indicative of the types of processes occurring during the aurorae. These same processes may be responsible for the proposed higher frequency modulation.

A. Observations

The most obvious temporal variations are displayed by pulsating aurorae and flaming aurorae. Pulsating aurorae remain nearly constant in shape, but vary irregularly in brightness with periods from a minute to a few seconds; flaming aurorae are typified by waves of light moving from the base of the aurora upward in periods of less than a second. In addition to this variation in brightness, an aurora may also change its shape or move across the sky very rapidly.

As studies of the aurora became more sophisticated, more quantitative measurements were attempted. K. Anderson and Milton (1964), in high time resolution (HTR) studies of auroral events, observed bursts of bremsstrahlung X-rays produced by greater than 40 keV precipitating electrons. These bursts were characterized by periods on the order of $1/4$ second to a few seconds in period. The resolution of
their detector was 10 msec with $10^4$/sec count-rates. No substructure was seen in these bursts, which occurred in trains of less than three bursts; because of this lack of substructure, and because of the apparent similarity between this event and magnetic micropulsations, Anderson and Milton termed this phenomenon microbursts. Parks et al. (1966), McPherron et al. (1968), and Parks and Winckler (1969) have detected the correlation of 5-40 Hz micropulsations with microbursts.

The local time occurrence of pulsation phenomena, both in electron precipitation and in geomagnetic fluctuation, is shown in Table 1. Correlation has been observed between the two events for every time interval except that interval between 1500-2200 hours local time. During these 7 hours no significant particle bursts have been noted.

Restricting the discussion to fluctuation periods of less than 30 sec, the modulation observed can be divided into three categories: long period variations with periods of 1-30 seconds; microbursts having 1/4-1 second periods; and short bursts characterized by periods from 5 to 250 msec. No particle modulation faster than 1 kHz has been observed in auroral studies due to instrumental limitations. Table 2 lists the categories of modulation and the references to the observation. For completeness, a brief review of the observations is presented.
### TABLE 1: Local Time Occurrence of Temporal Events

<table>
<thead>
<tr>
<th>LOCAL TIME</th>
<th>PRECIPITATION EVENTS</th>
<th>GEOMAGNETIC EVENTS</th>
<th>CORRELATION REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 - 0200</td>
<td>Association with auroral breakup; 5-50 ms bursts (Parks et al., 1967; Evans 1967; Mozer and Bruston 1966; Mozer 1968); microbursts (Brown et al., 1965)</td>
<td>Irregular broadband noise bursts</td>
<td>Campbell and Matsushita (1962); Yanigahara (1963); Victor (1965)</td>
</tr>
<tr>
<td>0200 - 1000</td>
<td>5-10 sec (Brown et al., 1965; Barcus et al., 1966)</td>
<td>Irregular Pi 1 5-10 sec pulsations</td>
<td>McPherron et al. (1968)</td>
</tr>
<tr>
<td>0600 - 1400</td>
<td>Microbursts .25 sec (Anderson et al., 1966; Anderson and Milton 1964; Parks et al., 1967; Oliven et al., 1968; Venkatesan et al., 1968)</td>
<td>Magnetic impulses near noon 0600 - 0900 impulses VLF chorus</td>
<td>Milton et al. (1967); Parks and Winckler (1969); Oliven and Gurnett (1968)</td>
</tr>
<tr>
<td>1000 - 1500</td>
<td>20-30 sec (Parks et al., 1968); microbursts (Barcus et al., 1966)</td>
<td>Pc3 quasisinusoidal 15-40 sec</td>
<td>McPherron et al. (1968)</td>
</tr>
<tr>
<td>1500 - 2200</td>
<td>No significant variations observed</td>
<td>Pearl pulsations (Heacock 1963) Pi events (Heacock 1967) Micropulsations (McPherron et al., 1967)</td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Categories of Pulsations

<table>
<thead>
<tr>
<th>1 - 20 sec</th>
<th>1/4 - 1 sec</th>
<th>5 - 250 msec</th>
</tr>
</thead>
<tbody>
<tr>
<td>R  Mozer 1965</td>
<td>B  Anderson and Milton 1964</td>
<td>R  Mozer and Bruston 1966</td>
</tr>
<tr>
<td>B  Barcus et al., 1966</td>
<td>B  Parks et al., 1967</td>
<td>B  Parks et al., 1967</td>
</tr>
<tr>
<td>V  Cresswell and Davis 1966</td>
<td>R  Cummings et al., 1966</td>
<td>R  Evans 1967</td>
</tr>
<tr>
<td>B  Parks et al., 1968</td>
<td>B  Brown et al., 1965</td>
<td></td>
</tr>
<tr>
<td>B,S  Parks and Winckler 1969</td>
<td>B  Barcus et al., 1966</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S  Oliven et al., 1968</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B  Venkatesan et al., 1968</td>
<td></td>
</tr>
</tbody>
</table>

1. Energy ranges observed were usually > 10 keV for all observations except:

- Cresswell and Davis 1966 - 1-10 keV
- Cummings et al., 1966 - 10-100 keV
- Evans 1967 - 1-100 keV

NOTES:
- B = balloon
- R = rocket
- S = satellite
- V = visual
1. **1-30 Second Periodicities**

Brown *et al.* (1965) flew two balloons simultaneously at conjugate points and found no correspondence between the 5-10 sec events. One would expect some correspondence if the source of the modulation were in the equatorial region of the auroral field lines. However, with simultaneous flights separated by a north-south distance of 100 km, variations were observed to be in phase. An east-west separation of 150 km gave coincident bursts for 1/3 of the events.

Barcus *et al.* (1966) noticed a preferentially equatorward enhancement of 4-30 sec period bursts of greater than 25 keV electrons. In particular, modulation was observed for as long as three hours at $L = 5.5$ with no significant modulation at $L = 6.5$. This suggests that a local mechanism is operative rather than one located in the cusp region.

Parks *et al.* (1968) noticed that the 5-10 sec periodicities that occurred in early morning were associated with a soft energy spectrum; later in the morning, between 1000-1500 LT, periods of 20-30 sec were observed with a harder spectrum. In both instances, the scale size of the pulsations was often 100-150 km.
Parks and Winckler (1969) give results of spectral and coherence analyses of an event observed simultaneously in precipitated auroral electrons and in trapped electrons at 6.6 \( R_E \). Both microbursts and 10 sec period bursts were observed in precipitated electrons of energies greater than 20 keV and trapped electrons of energies greater than 50 keV. The coherence analyses imply that the precipitated modulated flux was not correlated with the trapped flux at 6.6 \( R_E \); however, there appeared to be a correspondence for six minutes at the beginning of the event. Despite the general lack of coherence (possibly due to the lack of conjugacy in the two observations, since the ATS 1 satellite was about 2000 km longitudinally away from conjugacy) the fact still remains that this modulation is not confined to precipitated electrons.

Parks and Winckler suggest that the acceleration and modulation processes (wave-particle coupling and plasma instabilities) are two distinct and separated phenomena, since greater than 40 keV electrons are often seen with no modulation. They propose that the acceleration mechanism operates continually with a sporadic modulation mechanism.

Visual observations in this range have been made by Cresswell and Davis (1966) and Johansen and Omholt (1966). Cresswell and Davis noticed a preferential enhancement of
pulsations on the equator-ward side of the aurora. Johansen and Omholt categorized the types of pulsations they observed into three classes which are best described by Figure 1 (taken from Johansen and Omholt, 1966). Classes A and B are rare events occurring most often near 2200 LT, whereas class C occurs most frequently near 0100 LT. The gradual decrease in amplitude over 5-8 pulses in class A led the authors to surmise: since the spacing of pulses was nearly equal to the total bounce time of the particles, the gradual decrease in intensity would be indicative of the loss of particles at each mirroring.

2. 1/4-1 Second Periodicities

As previously mentioned, Anderson and Milton (1964) observed x-ray microbursts with no substructure. These microbursts were seen in trains of no more than three pulses during intervals of 90 minutes. Since then, the morphology of microbursts has become better defined (Anderson et al., 1966). There are six classes of "microburst groupings":

a. Individual microbursts.

b. Double microbursts having spacing about one second between members of the pair, with the next pair occurring several seconds later.
Pulsation types observed by Johansen and Omholt (1966). Class A occurs infrequently with a peak occurrence rate at 2200 LT. Type B peaks at the same time as type A and is more frequently observed. Types C₁ and C₂ predominate near 0100 LT.
PULSATION TYPES (T~1 SEC)

FIG. 1
c. Multiple microbursts similar to doubles, but occurring in groups of three or four.
d. Comb events similar to multiples but containing 5-10 microbursts in about 5-10 seconds, the next comb event occurring 5-30 seconds later.
e. Swells similar to a comb envelope, consisting of smooth flux increases of about 5 seconds duration, the next swell occurring 5-30 seconds later.
f. Miscellaneous events which are perhaps unresolved microbursts.

Figure 2 shows examples of these variations.

These microbursts produced by greater than 20 keV electrons are observed most often in late morning and early afternoon. However, Anderson et al. (1966) point out that although no microbursts were observed during an optically pulsating aurora, there possibly was some modulation in electrons of less than 20 keV. The daytime microbursts tended to appear following nights of bright aurorae.

Other observations of microbursts are given in Table 2.
Figure 2: Classes of Microbursts
(K. Anderson et al., 1966)

a. Individual microbursts

b. Double microbursts having spacing about one second between members of the pair, with the next pair occurring several seconds later.

c. Multiple microbursts similar to doubles, but occurring in groups of three or four.

d. Comb events similar to multiples, but containing 5-10 microbursts in about 5-10 seconds, the next comb event occurring 5-30 seconds later.

e. Swells similar to a comb envelope, consisting of smooth flux increases of about 5 seconds duration, the next swell occurring 5-30 seconds later.

f. Miscellaneous events which are perhaps unresolved microbursts.
CLASSES OF MICROBURSTS

TAKEN FROM K. ANDERSON, ET AL., (1966)

FIG. 2
3. 5-250 mseconds Periodicities

Mozer and Bruston (1966) observed over 60 intensity variations with time scales of about 5 msec – 1 sec. The solid state detectors aboard the sounding rocket sampled electrons of energies from 65 keV to greater than 400 keV. Ground-based observations yielded general correlation, but did not show the detailed characteristics of the short time variations. This was probably due to the much larger angular view of the ground-based instrument, which tended to smear out any fine structure.

These rapid variations are discussed by Mozer (1968). All occurred near local midnight and no corresponding variations were seen in the proton flux. Some of the events were observed only in the greater than 65 keV detector; others were seen only in the greater than 400 keV detector. Mozer notes that sometimes the lower energy electrons showed the greatest fluctuation, unlike the observation of Barcus et al. (1966) where the fluctuation was more pronounced in the higher energy electrons.

An upper limit of the distance to the source is estimated to be less than 1 \( R_E \) due to the lack of noticeable dispersion in arrival time of the electrons in the various energy channels. Mozer suggests that a combination of spatial and temporal effects is the cause, i.e., there is
a source that moves in space and produces a constant modulation in time. This explanation, however, implies that statistically one should observe the higher energy electrons first; this is not the case.

Evans (1967) noticed a 10 Hz temporal variation in electrons in the 1-120 keV range. The more energetic electrons, as noted by Barcus et al. (1966), had a greater fluctuation than the lower energy electrons. The events were simultaneous in all of the four energy channels (8, 16, 60 and 120 keV) except that the 8 keV channel showed an arrival time consistently .015 sec earlier than that noted by the 60 keV channel. This early arrival of lower energy particles suggests that either the 8 keV particles are affected earlier or are generated earlier than the higher energy electrons. Due to the simultaneity of the 16 keV and 120 keV events, and due to the time resolution of detection (.01 seconds), the source of the pulsations is estimated to be closer than 1200 km. Since the rocket moved roughly one gyroradius per variation time, spatial effects were ruled out.

During this flight, Evans also observed a strong monoenergetic flux of electrons at 5-6 keV. Similar fluxes have been seen by Westerlund (1967) and Albert (1967). Evans suggests that the mechanism which is operating arises
from a beam-plasma instability as described by Stix (1964). As will be discussed later, a sufficiently monoenergetic beam of electrons traveling through a plasma immersed in a magnetic field can produce an instability which allows the exponential growth of various modes of plasma waves. Certain resonances occur between the electrons and the waves (e.g., resonances at the plasma frequency, gyrofrequency, and their harmonics); this can lead to the rapid stochastic acceleration of favored electrons. When the transfer of energy from the wave to the electrons exceeds the growth rate of the wave, the wave is damped and the cycle begins again. This sequence of events may occur on time scales of \(0.1\) sec (Evans 1967). Perkins (1968) shows that such an instability can produce stochastic acceleration of monoenergetic electrons to 40-100 keV on a time scale of \(0.01\) sec. The observed monoenergetic fluxes exhibit a finite spread in energy. Bird and Schmidt (1969) discuss how small this spread must be in order for an instability to be produced in the magnetosphere. This will be treated later.

Certain salient features are apparent in the above observations. First and most obvious, there are rapid variations in the electron flux in the auroral region. These variations have been observed to the high frequency limit of the previously used detectors. Second, the longer term
variations seem to suggest a correspondence to a magnetospheric substorm (Parks et al., 1968; McPherron et al., 1968; Parks et al., 1966). Third, the more rapid variations occur near breakup and are suggestive of a modulation mechanism operative within 1000 km of the auroral region. In the next section, applicable types of instabilities and waves and the possible occurrence of higher frequency modulation will be briefly discussed.

B. Plasma Waves and Instabilities

Any sufficiently dense gas is capable of transmitting acoustical waves due to short range collisions. In a plasma, additional waves can propagate as a result of the stronger, longer range effects of the electrostatic interactions of the ions and electrons. Table 3 reviews the various plasma waves and their corresponding applicable frequency ranges. There are four independent modes of plasma wave propagation parallel to a magnetic field: ion waves, electron waves, right-handed polarized waves, and left-handed polarized waves. The first two modes are longitudinal and the last two are transverse.

The mechanism that allows the bunching of electrons in the plasma can be visualized by considering a longitudinal plane wave propagating in a plasma in the +x direction (Figure 3). In the frame of reference of the
TABLE 3:
Waves in a Cold, Anisotropic Plasma

Propagation Along $\vec{B}$:

- **longitudinal waves**: $\omega^2 \gg \omega_{p+}^2$ electron waves
  
  $\omega^2 \ll \omega_{p-}^2 \ll k\omega_{-}$ ion waves
  
  $\omega^2 \ll k^2\omega_{-}^2 \ll \omega_{p-}^2$
  
  $(\omega_{\pm}^2 \approx$ thermal velocity)

- **transverse waves**: $\omega \ll \omega_{c+} \ll \omega_{c-}$ Alfvén waves
  
  $\omega \gg \omega_{c+}$
  
  $\left\{ \begin{array}{l}
  \text{Right circ polarized (ordinary wave, including Whistlers)} \\
  \text{L circ polarized (extraordinary wave)}
  \end{array} \right.$

Propagation Transverse to $\vec{B}$:

- **longitudinal waves**: $\omega \ll \omega_{c+} \ll \omega_{c-}$ magnetosonic waves

- **transverse waves**: ordinary mode (unaffected by $B$)
  
  extraordinary mode

**Notes:**

- $\omega_{c+} = \text{electron}$
  
  $\omega_{c-} = \text{ion}$
  
  cyclotron frequency

- $\omega_{p+} = \text{ion}$
  
  plasma frequency
Figure 3: LONGITUDINAL PLANE WAVE PROPAGATING IN + X DIRECTION.

Electrons traveling near the phase velocity of the wave will see an oscillating electric field. In regions of positive $E$, electrons will be decelerated; in regions of negative $E$, electrons will be accelerated. Electrons with the proper relative velocity $V_x$ will be bunched at every other node.
\[ V_x = (V_x - V_p) \]

**ELECTRON MODULATION**

**FIG. 3**
wave, the electric field is given as \( \vec{E} = E_0 \hat{x} \cos kx \).

For electrons having velocity \( v_x \) sufficiently near the phase velocity of the wave \( v_p \), longitudinal oscillations occur. Electrons in the region of positive \( \vec{E} \) will be decelerated and the electrons in the region of negative \( \vec{E} \) will be accelerated, providing modulation of the velocity of these electrons. There will be a tendency for the electrons to be bunched at every other node.

Lockwood (1963) discusses another example of bunching occurring at the cyclotron harmonics in the topside ionosphere due to plasma excitation by fixed frequency sounding satellites.

The modulation in both of these cases is indicative of plasma waves originating from some source mechanism and propagating down the field lines into auroral regions. The source, as previously mentioned, is thought to be some plasma instability fed by the plasma free energy, which creates the rapid growth of plasma waves.

There are four chief sources of energy responsible for the growth of instabilities:

1. Expansion energy which is the energy available as a plasma expands.

2. Kinetic drifts such as particle beams and field aligned currents.
3. Anisotropies in the distribution function such as found in mirror confinements where \( \mathbf{v} \parallel \mathbf{B} \) (electron velocity \( \parallel \) to \( \mathbf{B} \)) is zero at the mirror point. As the distribution relaxes toward isotropy, energy is available.

4. Magnetic energy where the energy is provided by a relaxation in the field strength.

Due to the observed double humped velocity distributions in auroral zone electrons, and the evidence for a field aligned current above aurora (Cloutier et al., 1970; Zmuda et al., 1966), the instabilities operating probably receive their energy from these kinetic drifts.

The pertinent instabilities are briefly described:

1. Two stream instability

A longitudinal electromagnetic wave propagating through a normal Maxwellian plasma will gain energy from electrons with velocities slightly greater than the phase velocity of the wave \( v_p \), and will lose energy to the electrons traveling slightly slower than \( v_p \). If there is a negative slope in the velocity distribution at \( v_p \), then there are more particles slightly slower than \( v_p \). Landau damping then occurs, as the wave gives up energy to the particles. However, if a positive slope can be introduced
at \( v_p \), the situation will be reversed and the plasma will pump energy into the wave; this positive slope can be obtained by superimposing on the primary distribution a beam of plasma having a velocity \( v \) greater than \( v_{th} \) (Buneman 1959), where \( v_{th} \) is the thermal velocity of the ambient Maxwellian plasma (Figure 4).

The observations of the monoenergetic fluxes between 5-10 keV provide evidence of the existence of this double humped distribution in auroral events. Furthermore, evidence of field aligned currents have been observed by satellite (Zmuda et al., 1966) and by sounding rocket (Cloutier et al., 1970). This current could also give rise to a two stream instability (Dessler and Jaggi, 1969).

These instabilities have been studied in the laboratory with large beam currents (.01-10 amps) and large magnetic fields (typically 2000 gauss). The beam-plasma interaction is greatly increased (Fainberg, 1962) by the fact that self modulation of the beam occurs; this leads to coherent interaction between particles in the beam and the plasma.

2. Cyclotron Instabilities

The cyclotron motion of particles can couple to the electrostatic waves associated with oscillations in a homogeneous, anisotropic plasma. This results in cyclotron
The one dimensional velocity distribution $f(v_x)$ contains two maxima. For a wave with phase velocity $v_p$ occurring on a negative slope, wave damping occurs. For $v_p$ on the positive slope of the second maximum, wave amplification will occur.
FIG. 4
TWO-STREAM VELOCITY DISTRIBUTION
instabilities. The wave modes that can propagate include the electron-ion, ion-ion and electron-electron longitudinal modes. In the first mode, the motion of the electrons along the magnetic field is in resonance with the ion Larmor motion; the remaining modes involve the motion of only one particle type. This type of instability operating in the magnetosphere is discussed by Hruska (1966).

3. Loss Cone Instability

The loss cone instability exists in a mirror system where a humped particle velocity distribution arises from the loss of particles in the loss cone. This situation gives rise to a local minimum in the Maxwellian distribution of velocities, producing instabilities analogous to the two stream instability. At low plasma densities, the characteristic frequencies of waves generated by this instability are multiples of the ion Larmor frequency.

Bird and Schmidt (1969) considered the case of a two stream instability occurring in the magnetosphere. The effects of two different distribution functions, each containing a loss cone, were considered for the approximation $\omega_p >> \omega_c$. The first function was a monotonic, isotropic distribution, and the second was an isotropic double-humped distribution. The conditions for stability in transverse
waves propagating in the magnetosphere were determined and are summarized below:

**Distribution 1:** RH mode stable for $\omega$ greater than $\omega_{c-}$.  
LH mode stable for $\omega$ greater than $\omega_{c+}$.  
Whistler mode can be unstable.  
Magnetosonic mode can be unstable.  
Ion cyclotron mode can be unstable.

**Distribution 2:** Whistler mode in cyclotron resonance with electrons at the peak of the secondary hump can become unstable if the secondary hump is sufficiently monoenergetic.

The instabilities in the first distribution depend upon the mirror ratio and the particular parameters of the distribution. In the second distribution, Bird and Schmidt employed an exponential energy spectrum $N(E) = N_0 E^{-5/2}$ with data from OGO 3 supplied by Frank (1967). Their results indicate that only damping will occur. The growth rate of the instability is a strong function of the beam's spread in energy, and the calculations indicate that the observed beam is not sufficiently monoenergetic to produce an instability. Perhaps the observed beam was once more monoenergetic, and after having produced an instability, increased in width.
Perkins (1969) employed the same type distribution as in case two of Bird and Schmidt, but applied it to the topside ionosphere at night. He considered waves with frequencies near the upper hybrid resonance in regions where \( \omega_p \) is near or greater than \( \omega_c \), since plasma waves are most unstable when \( \omega_p = \omega_c \). Perkins points out that the existence of a loss cone does not significantly change growth rates of the instabilities, since it is largely the monoenergetic character of the secondary hump that determines the growth rate. His results show that most wave amplification occurs when \( k \parallel \ll k_\perp \) where \( k \) is the propagation vector. Cyclotron modes are stable and whistler modes can be unstable only when \( \omega_p >\omega_c \). Near the ionosphere \( \omega_p \sim \omega_c \) and therefore whistlers are stable.

The time scale for wave-particle interactions during the stochastic acceleration of particles in the monoenergetic beam is on the order of .01 seconds (Perkins 1969); this same time scale applies for many auroral electron bursts.

Ionospheric instabilities are attractive to consider because of the inferences made by Evans (1967) and Mozer and Bruston (1966). The measurements of Fejer and Calvert (1964) and Calvert and Van Zandt (1966) of excitation of cyclotron and plasma resonances by topside sounding satellites are indicative of certain plasma waves in the ionosphere.
Magnetospheric instabilities are suggested by Kennel and Petschek (1966) and Kennel (1968) to produce pitch angle diffusion of trapped electrons into the loss cone.
II. METHODS OF OBSERVATION

Since aurorae exhibit visual pulsations in brightness, an obvious method of observation of high frequency modulation is ground-based photometric studies. This involves comparatively little expense and apparatus. However, the visual components of the auroral display are a result of the excitation of the atmospheric molecules by collisions with low energy secondary electrons. It is unlikely that the secondary electrons will preserve the modulation of the energetic primaries since collisions may occur anywhere on the primary electron's gyro-orbit. Even if the production of secondaries were in phase with the primaries, the dispersion in interaction time of these secondaries with atmospheric molecules would be much greater than a microsecond. Furthermore, the most intense emissions occurring are produced by forbidden transitions which have characteristic lifetimes on the order of $1/2$ sec. The random decay of such a system of particles will follow a Poisson distribution with a characteristic spread in time on the order of .7 seconds. In order to produce at least 1% variation in intensity, the shortest modulation observable is on the order of .1 sec. Observations made by Cresswell and Davis (1966) with an image orthicon television system and photometers revealed pulsations with this periodicity.
Since allowed transitions do occur and their lifetimes are typically $10^{-8}$ seconds, intensity variations near a megahertz would be possible, but for this to occur, the modulation must be retained by the secondaries.

Another method of observation would be the detection of electromagnetic emissions arising from some natural cause associated with the auroral display. This leads to difficulties in determining the exact nature of the signal. For example, cyclotron radiation does not require the bunching of electrons to produce cyclotron emission since any distribution of identical, charged particles gyrating in a constant magnetic field will produce radiation at the gyrofrequency and its harmonics.

A tendency for 12 and 18 MHz noise to occur before a sudden commencement event has been noted by Hower and Dunlap (1966). An association between the 18 MHz noise and the occurrence of echoes from irregularities along the field lines was also evident. This association may be interpreted to be scattering of man-made signals instead of naturally produced noise; however, a distinct difference in the diurnal variation of the two events argues to the contrary.

This arrangement of ground-based observations is not suitable for the primary means of investigation. As support data for the primary experiment, however, the monitoring of
the short-wave spectrum for the duration of the experiment is recommended.

Another emission process is Bremsstrahlung X-ray production by primary electron bombardment. Bremsstrahlung is the radiation emitted due to energetic charged particles colliding with relatively colder, more massive atmospheric particles; the high energy particles are decelerated in the process, and consequently emit radiation. In a local region where bunched electrons interact with the atmosphere, the radiation should be pulsed, indicative of this bunching. A suitable X-ray detector flown on a rocket or balloon is able to look over a wide region. If there is any spatial dispersion of the bunching, the modulation will be averaged out, due to the large sampling area of the detector. Coherent pulsations could not be observed from the Bremsstrahlung emission region if this layer were sufficiently thick. In order to observe 10 MHz pulsations in X-ray intensity, the layer in which the emissions occur must be less than 30 m thick. This is not the case, since electrons in the energy range of 10-100 keV can penetrate into the atmosphere much greater than this distance. Although most X-rays are produced by greater than 40 keV electrons, there have been measurements of X-rays produced by electrons from 1-10 keV by Ulwick et al. (1967).
Rockets are ideal for the purpose of direct detection of the primary precipitating particles. Whereas balloons are limited to about 40 km in altitude, sounding rockets can achieve the appropriate altitude of over 100 km. The rocket-borne instrumentation must be designed to withstand the acceleration and vibration occurring during burn.
III. EXPERIMENTAL SITUATION

Figure 5 shows a block diagram of the design of the rocket-borne experiment. The source consists of electrons and protons having an energy spectrum similar to Figure 6. The electron flux is normally $10^{-10}$ times greater than the proton flux. Since the electrons are lighter and therefore more responsive to forces than the protons, they are more likely to contain bunching. A selector must transmit the appropriate electrons and reject protons. Since most of the energy of the precipitating particles is carried by the lower energy electrons which produce the visual aurora, it is interesting to look in this energy range. Modulation might occur in the monoenergetic fluxes of electrons which have been observed at various energies between 5 and 10 keV (Evans, 1967; Albert, 1967; Westerlund, 1967). To select electrons of this energy, an energy/charge selector such as a curved plate electrostatic analyzer is to be used.

The selected electrons are detected by some detector with a time resolution of $\sim 10^{-9}$ sec. The signal is amplified and suitably processed by a spectrum analyzer capable of measuring the modulation spectrum at frequencies from 40 kHz-10 MHz with 10 kHz resolution.
Figure 5: EXPERIMENTAL DESIGN

The design can be represented in block diagram as shown.

Figure 6: TYPICAL AURORAL ENERGY SPECTRA FOR PROTONS AND ELECTRONS

Electron data are taken from Westerlund (1968) and proton data from Whalen and McDiarmid (1969).
EXPERIMENTAL DESIGN

FIG. 5

- DETECTOR
- SELECTOR
- TRANSMITTER
- ANALYZER
- RECEIVER

SOURCE
TYPICAL AURORAL ENERGY SPECTRA

FIG. 6
The total output current of the detector is also monitored and this signal plus the output of the spectrum analyzer drive a standard subcarrier which modulates the transmitter.

Each of these components will be discussed in more detail.
VI. SELECTOR

A. Type

Since there is no quantitative measure of the amount of electron modulation occurring, an estimate of \(\sim 0-20\%\) modulation of the total flux is made. Only an unusually efficient mechanism could be expected to modulate all of the electrons. An estimate of twenty percent is made as an arbitrary upper limit of the modulation. The lower limit is set by the necessity that the particle count-rate must be sufficiently high to provide meaningful statistics in the fast time intervals to be investigated. This requires that at least \(10^9\) electrons/sec must be incident on the detector in order to detect modulation as low as 1%. An IBC II aurora could provide fluxes of \(10^8-10^9\) electrons per sec-\(cm^{-2}\)-ster-keV (Westerlund, 1968; Cloutier et al., 1970). A selector with a sufficiently large geometric factor will transmit this flux to give the required count-rate. Hemispherical plate analyzers are suitable to provide large count-rates, since these deflection systems offer a larger angular field of view than the commonly used cylindrical systems. The electrostatic potential between the plates is proportional to \(1/r\) producing Keplerian motion of electrons through the system. Thus an electron of the appropriate energy will orbit in the plane containing its original
trajectory and the center of curvature of the plates. It will exit the hemispheres diametrically opposite its point of entry. This produces a large angular field of view along one axis (α, Figure 7; 2Δα, Figure 8a), allowing many pitch angles φ to be sampled simultaneously. As a consequence of this, any information concerning the pitch angle distribution is lost.

B. Spin Modulation

The instrument will be flown on a spin stabilized Nike-Tomahawk sounding rocket. An apparent modulation in the detected anisotropic flux will be produced at the rocket's spin frequency (~6 Hz). However, the hemispherical system's sensitivity to a wide range of pitch angles will reduce the amount of modulation produced by the spin. The effect of this slow modulation can be estimated by considering a set of hemispheres that transmits all electrons entering its aperture from its angular field of view. The t = 0 configuration of the hemispheres mounted on the rocket is shown in Figure 8. The angle ε(t) is given as

\[ \varepsilon(t) = \arcsin \left[ \cos \omega_s \cos \Delta \alpha \sin \lambda_0 + \cos \lambda_0 \sin \Delta \alpha \right] \]

which is the time varying angle the line NP makes with the plane perpendicular to \( \vec{B} \) containing NM. NP represents the extreme limit of the 2Δα acceptance angle. It generates a cone of revolution about \( \vec{w}_s \) with a half angle of 90° - Δα. As the acceptance fan rotates, electrons of pitch angles...
Figure 7: ANGLES $\alpha$ AND $\theta$

Figure 8: $t = 0$ CONFIGURATION OF HEMISPHERICAL DEFLECTION SYSTEM ON ROCKET

a shows the configuration on the rocket.
b shows the geometric configuration of rocket and angular field of deflection system to the field line B.
FIG. 7

ANGLES $\alpha$ AND $\theta$
FIG. 8
SUPPRESSION OF SPIN MODULATION:

\( t=0 \) CONFIGURATION

\( \vec{B} \) = MAGNETIC FIELD
\( \vec{\omega}_s \) = SPIN AXIS OF ROCKET
\( \lambda_0 = \lambda(0) \) = ANGLE BETWEEN \( \vec{B} \) AND \( \vec{\omega}_s \)
\( \lambda(t) \) = TIME VARYING ANGLE BETWEEN LINE O-L AND PLANE \( \perp \vec{B} \)

\( 2\Delta \alpha \) = ACCEPTANCE FAN OF HEMISPHERES

\( \varepsilon(t) \) = TIME VARYING ANGLE BETWEEN LINE NP AND PLANE \( \perp \vec{B} \)

\( \varphi \) = PITCH ANGLE
\[ 90^\circ - \varepsilon(t) + F(\lambda_0, \Delta \theta, \Delta \alpha, t) < \varphi < 90^\circ - \varepsilon(t) + 2\Delta \alpha + F(\lambda_0, \Delta \theta, \Delta \alpha, t) \]

are accepted without attenuation by the deflection system. \( F(\lambda_0, \Delta \theta, \Delta \alpha, t) \) is a correction function arising from the fact that at times other than \( t = n\pi/\omega_s \), the \( \alpha \) axis is no longer coplanar with the \( \varphi \) axis. The various pitch angles enter the system, then, from a solid angle with \( \theta \neq 0^\circ \). This non-zero \( \theta \) decreases the spread of pitch angles since \( \Delta \theta < \Delta \alpha \).

Assuming a pitch angle distribution as determined by Vondrak et al. (1969) and shown in Figure 9,

\[
j(\text{electrons/sec-cm}^2\text{-ster-keV}) = \begin{cases} (3.72 - .031 \varphi) \times 10^8 & 0^\circ < |\varphi| < 90^\circ \\ (1.28 - .006 \varphi) \times 10^8 & 90^\circ < |\varphi| < 180^\circ \end{cases}
\]

Then \( C(t) = \frac{\text{counts}}{\text{sec-keV}} \)

\[
C(t) = \int_{\pi/2 - \Delta \theta}^{\pi/2 + \Delta \theta} \sin \theta' \, d\theta' \int_{\pi/2 - \varepsilon(t) + 2\Delta \alpha + F}^{\pi/2 - \varepsilon(t)} A \sin(\varepsilon(t) + \varphi) \, j(\varphi) \, d\varphi
\]

where \( A \) is the aperture area and \( \sin(\varepsilon(t) + \varphi) \) takes into account the decrease in \( A \) due to oblique incidence. In arbitrary units of counts/sec \( N_0 \), for the particular case of \( \lambda_0 = 30^\circ \), \( \Delta \alpha = 75^\circ \), and \( \Delta \theta = 25^\circ \), the extreme limits
Figure 9: PITCH ANGLE DISTRIBUTION

(Vondrak et al., 1970)

Solid lines are least squares $E^{-1}$ fit.
FIG. 9

PITCH-ANGLE DISTRIBUTION

COUNT RATE (counts/sec)

FLUX (10^8 cm^-2 sec^-1 ster^-1 keV^-1)
of \( N(t) \) are:

\[
N(0) = 1.7 N_0 \\
N(\pi/w_3) = 1.0 N_0
\]

Thus the rate of change of the count-rate due to spin modulation is on the order of \( \frac{7 N_0}{1/12 \text{ sec}} \) or \( 8.4 \frac{N_0}{\text{sec}} \).

This variation of count-rate corresponds to an electron density variation of \( \sim 0.14\% \) during the time of analysis for a particular frequency. The variation would be considerably accentuated if a directional deflection system were used, and would interfere with the signal detection. Knowledge of the pitch angle distribution is therefore sacrificed in the initial exploratory experiment, and the parameters to be measured are the frequency and the amount of modulation. Once a value can be determined for these characteristics, future designs will emphasize the structure of the phenomenon.

C. Geometric Factor

It is necessary to relate the output of this instrument in \( N \) counts/sec to the input flux \( j(\Omega,E) \) in electrons/sec-cm\(^2\)-keV, where \( \Omega \) is the solid angle defining the local direction of the particle flux and \( E \) is the energy.
per particle of the flux. This relation is a function of the geometry of the plates and is termed the geometric factor $g(\Omega, E)$ in cm$^2$. The general definition of the geometric factor can be written as

$$N = \int \int j(\Omega, E) g(\Omega, E) \, d\Omega dE$$

where $N$ is the output of the instrument in counts/second, and the integration is performed over all $\Omega$ and $E$. If certain assumptions are made about $j(\Omega, E)$, this integration can be simplified by the removal of $j(\Omega, E)$ from the integral. For instance, if $j(\Omega, E)$ were an isotropic, energy independent beam of particles $j$, then

$$N = j \int \int g(\Omega, E) \, d\Omega dE = Gj$$

where $G$ is the total integrated geometric factor in cm$^2$-ster-keV for this particular flux $j$. Since $g(\Omega, E)$ is a function of the geometry of the system, it is possible, although considerably involved, to determine an accurate value of $g(\Omega, E)$ through purely theoretical considerations. An estimate can be made under certain approximations, but the determination of the geometric factor is best performed by experimental methods.
The Appendix treats the case of two concentric hemispherical shells with the separation between shells small compared to their mean radius of curvature. The method used in the Appendix to obtain a first order estimate of the geometric factor assumes circular electron orbits (Paolini and Theodoridis, 1967). However, where Paolini and Theodoridis derived an expression for the locus of centers of orbits for each point of incidence in the aperture, the Appendix derives an expression for the aperture area available for transmission of particles having centers of orbit at point \((x,y)\) for all available \((x,y)\). Thus each point \((x,y)\) has an associated transmission coefficient, and integration over all \((x,y)\) yields the total integrated geometric factor. Figure 10 shows the shape of the locus of centers of orbits as derived in the Appendix. \(x\) and \(y\) are related to the electron energy and lateral angle of incidence \((\theta)\), respectively, and a transformation from \(g(x,y)\) to \(g(E,\Omega)\) is then performed to obtain the geometric factor.

The relation

\[
N = \frac{8}{9} \frac{\Delta R^3}{r_o} E_o d j
\]

is derived in the Appendix for an isotropic, energy
Figure 10:  LOCUS OF CENTERS FOR ALLOWED ORBITS,

\[ \Delta R / r_o \ll 1 \]

An electron having center of orbit \((x,y)\) has available for entrance that part of the aperture denoted by \(A\). \(A\) is determined for each \((x,y)\) and represents the geometric factor. The locus of centers is shown to be symmetric about the center of curvature of the plates.
LOCUS OF CENTERS FOR ALLOWED ORBITS, $\Delta R/r_0 \ll 1$

FIG. 10
independent flux of electrons $j$, under the approximations

$$\frac{AR}{r_o} \ll 1 \quad , \quad d < r_o$$

where $AR$ is the plate separation, $r_o$ is the mean radius of curvature, $d$ is the aperture length, and $E_o$ is the passband center energy. The approximation of $AR/r_o \ll 1$ is valid up to $AR/r_o \sim 1/4$. When the device is adjusted to permit a maximum transmission of 8 keV electrons (i.e., $E_o = 8$ keV) this gives a value of $G = 2.3 \text{ cm}^2\text{-ster-keV}$ for $AR/r_o = 1/4$, $r_o = 6 \text{ cm}$, and $d = 3.5 \text{ cm}$. The energy passband of the plates is given as $\Delta R/2r_o$, yielding a 1 keV FWHM passband centered at $E_o = 8 \text{ keV}$. The FWHM lateral angular field of view ($2\Delta \theta$, Figure 7) is given as $\Delta R/r_o \sim 14^\circ$.

Figure 11 shows the locus of centers of orbits when $\Delta R/r_o \sim 1/2$. The locus is elongated in the $y(\theta)$ direction and is no longer symmetric about either axis. The energy passband is relatively unaffected, except that since elliptical orbits are now considered, the center energy $E_o$ varies with angle $\theta$. The corresponding transmission curve in $\theta$ and $E$ is similar to that in Figure 12. The lines in the figure represent contours of constant transmission, increasing in value toward the origin.
Figure 11: LOCUS OF CENTERS FOR $\Delta R/r_o \sim 1/2$

As $\Delta R/r_o$ increases, the asymmetry of the locus of centers is pronounced. The center energy of transmission depends upon the angle of incidence.

Figure 12: TRANSMISSION CONTOURS

The locus of centers in Figure 11 can be represented by a contoured transmission curve. The lines in the area represent contours of constant transmission. $y$ is replaced by $\theta$ and $x$ by $E$. 
LOCUS OF CENTERS FOR $\Delta R_{k}, \sim \bar{V}$

Fig. 11
TRANSMISSION CONTOURS

FIG. 12
The geometric factor must be accurately known since a relation between the incoming and outgoing flux is necessary. This determination of G must be accomplished experimentally. The procedure involves measuring the output of the device as a function of all independent variables with a suitable detector such as a Faraday cup. These variables are the energy and the two angles comprising the solid angle (see Figure 7).

Since the total integrated geometric factor G is a function of the same parameters as the flux $j(\Omega, E)$, it is desirable to use the type of flux expected in the aurora to calibrate the instrument. This flux is rather difficult to simulate in the laboratory; it is easier to apply superposition principles and use a monoenergetic, unidirectional, homogeneous beam of electrons covering the entire entrance aperture. The energy and angle of incidence ($\alpha$ and $\theta$) can be adjusted to provide a complete distribution which can be properly integrated to obtain the particular G. It is noted that transmission is relatively independent of $\alpha$ because of symmetry. The calibration consists then, of first measuring the transmission coefficient for the range of $\alpha$. After this curve has been obtained, the transmission coefficient at some reference $\alpha$ is measured for each E and $\theta$. This can be represented by a matrix of $\{E, \theta\}$. Integration over all the elements yields the response of the instrument.
to an isotropic, energy independent flux for the reference \( \alpha \). Summation over \( \alpha \) yields the total response to this type of flux. By the selection of the appropriate weighting function for each term in the matrix, the response to various flux distributions can be obtained.

For a more rigorous calibration, \( \alpha \) is included in the matrix; that is, transmission grids of \( \theta \) and \( \alpha \) for each \( E \) are constructed and properly integrated.

D. Initial Calibration

The testing of a set of concentric hemispherical deflection plates (inner radius 4 cm, outer radius 6 cm) was initiated by exposing the aperture to a wide unidirectional beam of monoenergetic electrons. The transmitted beam was detected by a Johnston MM1 Electron Multiplier. The system was rotated about both axes and the relative transmission was measured for various energies to determine limits on angular view. The results for electrons of energy \( E_0 = 7 \) keV are shown in Figure 13 and Figure 14.

The transmission curve for various \( \theta \)'s (Figure 13) has a FWHM of \( \sim 20^\circ \). The dashed curve in Figure 14 represents the decrease in the aperture area as \( \alpha \) is varied. The bars are data points taken for \( \theta = 0^\circ, E = E_0 \), and follow the \( \cos \alpha \) curve for \( \alpha > 0^\circ \). For \( \alpha < 0^\circ \) the bars fall below
this curve, but display the same shape. It is possible that the input beam was obstructed or deflected in the configuration where $\alpha < 0^\circ$. The energy passbands for various unidirectional fluxes are shown in Figure 15.

These preliminary curves were necessary for the design of the aperture in the rocket skin and for the positional mounting of the instrument behind that aperture.

More extensive calibration will be performed on the total flight assembly of deflection plates, electron multiplier, and suitably packaged preamplifier.

E. Energy Spectrum

In order to measure the energy spectrum of the electrons, the voltages on the plates can be switched to correspond to a different center energy. If one set of plates were used, its aperture width would be on the order of the detector's diameter, 3 cm. Balanced voltages applied to each of these plates, necessary to allow passage of 1-10 keV electrons, are typically from $\pm 1$ keV to $\pm 10$ keV. Rapid switching of voltages this high is difficult and the probability of arcing is great. A more viable situation is the arrangement of several smaller sets of concentric hemispheres. The necessary voltages are considerably reduced, facilitating switching, but then the geometric
Figure 13: DEFLECTION SYSTEM: RELATIVE TRANSMISSION AS FUNCTION OF $\theta$

Transmission curve as a function of $\theta$. $\alpha = 0^\circ$ and electron energy $E = E_0 = 7$ keV. FWHM $\approx 20^\circ$.

Figure 14: DEFLECTION SYSTEM: RELATIVE TRANSMISSION AS FUNCTION OF $\alpha$.

Transmission curve as a function of $\alpha$. $\theta = 0^\circ$ and $E = E_0 = 7$ keV. The data points follow the shape of the $\cos \alpha$ curve representing the decrease in area due to oblique incidence. The asymmetry of the data points could be a result of beam deflection when $\alpha < 0^\circ$.

Figure 15: DEFLECTION SYSTEM: RELATIVE TRANSMISSION AS FUNCTION OF ENERGY FOR VARIOUS $\theta$.

Transmission curves as a function of energy $E$. $\alpha = 0^\circ$ and $\theta$ was changed. The effect of the asymmetry of the locus in Figure 11 is evident.
DEFLECTION SYSTEM

RELATIVE TRANSMISSION AS FUNCTION OF $\theta$

FIG. 13
DEFLECTION SYSTEM:

RELATIVE TRANSMISSION AS FUNCTION OF $\alpha$

FIG. 14
DEFLECTION SYSTEM

RELATIVE TRANSMISSION AS FUNCTION OF ENERGY FOR VARIOUS $\theta$

FIG. 15
factor for each energy channel is reduced by a factor of 10 or more. An arrangement combining both of these ideas compromises the situation by utilizing only two sets of hemispheres. This requires lower voltages than those necessary for just one set, yet the geometric factor for each energy channel is still large enough for the measurements. Figure 16 illustrates this configuration.

The largest of these copper hemispheres to be used is 12 cm in diameter. There are four plates, the inner set separated from the outer set by 3 mm. In both cases \( \frac{AR}{r_0} = 0.4 \).

The original design intention was to switch the deflection system through the electron energy range of 1-10 keV in 1 keV steps. It is desirable to sample all energy bands in the same spatial location, yet to switch through ten channels requires a finite amount of time. This places an upper limit on the time for one complete cycle of switching. A lower limit is set by the time required for the spectrum analyzer to scan its frequency range (1/6 sec). Several frequency spectra should be made of each energy channel, implying that perhaps 1 second would be a minimum time of operation for each channel. Ten such channels extend the switching time through 1-10 keV to approximately 10 seconds, during which time the rocket will have moved about 10 km. Since the width of an auroral arc is of this order,
The deflection system to be used in the experiment consists of two sets of hemispheres as shown. The radii are 6, 4, 3.7, and 2.5 cm, yielding $\Delta R/R_0 = .4$ in both cases.
TWO SETS OF CONCENTRIC HEMISPHERES
only one energy sweep is possible while over a visible arc. If the spectrum analyzer were not limited in frequency sweep rate by the telemetry (see page 59), the measurement of the energy spectrum would be feasible.

An alternative is to switch only two energy channels, 4-6 keV and 6-8 keV. This requires the use of four vacuum tubes in the switching circuit which take up more room onboard than allotted to the experiment. For this reason, it was decided to completely forego an energy spectrum measurement, and to operate both sets of plates simultaneously obtaining one constant energy passband from nominally 4 to 8 keV.

It has been shown that the hemispherical system will aid in selecting the appropriate particles, in providing large count-rates, and in decreasing the effect of spin modulation which could be a factor influencing the detected signal. However, will the expected particle bunching be transmitted? Secondary electrons will be produced when the primaries impact the walls of the plates. If the rate of secondary production is high enough, and the secondaries reach the exit of the system, they might contaminate the signal. This is not too likely, since each secondary is produced with less than 100 eV of kinetic energy, while the field within the plates is about 3000 V/cm. Under these
conditions an electron produced on the outer plate is accelerated to the inner plate in about 1 nsec, during which time it will have moved no more than 1/2 cm parallel to the plates. Therefore, the detection of secondary electrons produced in the system is negligible.
V. **DETECTOR**
   
   A. **Types**

   The detection of the output signal from the selector requires a device that amplifies all incident electrons on a large surface area. This means that the detector must respond to impulses faster than $10^{-7}$ seconds in order to detect modulation at 10 MHz. There are several detectors that meet these requirements: solid state detectors, scintillation counters, and electron multipliers all achieve the desired time resolution and have large surface areas for ample geometric factors.

   A solid state detector produces pulse heights that are proportional to the particle energy. The typical minimum energy required for particle detection is 50 keV. Even if 10 keV electrons could be detected, the low gain ($10^3$) at this energy leaves the signal vulnerable to contamination by noise. For reasons discussed later, it is advantageous for the detector to produce a constant pulse height with respect to energy. Therefore, a solid state detector is not the most suitable instrument to use.

   A scintillation counter consists of either an organic or inorganic crystal, or organic liquid, coupled to a photomultiplier. Organic scintillators offer a fast response time on the order of $10^{-9}$ seconds; this time is also characteristic of many photomultipliers.

   The advantage of using an electron multiplier is that no window coated with scintillating material is necessary. Therefore lower energy electrons can be directly detected, dispensing with the intermediate step of light production. Furthermore, the pulse height produced by a scintillation counter, like that of the solid state
detector, is dependent upon the energy of the initial charged particle. The photomultiplier is also fragile and not easily adaptable to a rocket environment of high acceleration and vibration. However, the greatest objection to the use of a photomultiplier is its sensitivity to light. Since a visual aurora will be occurring during the experiment, efficient light shielding must be designed to obtain only particle data.

An electron multiplier is more rugged, simpler, and less sensitive to light than the photomultiplier. The particular type used in this investigation is the Johnston Laboratory Focused Mesh Electron Multiplier (MML). Its surface area is 9.6 cm$^2$; its gain is typically $10^6$ at 3500 volts bias; its rise time is 3 nsec. It is flight tested and withstands temperatures up to 400°C in vacuum. The internal noise produced is approximately one count/sec at $10^6$ gain.

The multiplier consists of 20 copper-berillium dynodes, each separated by a resistance of 1 megohm. Each dynode consists of hundreds of raised surfaces and holes for electron passage. The dynodes are arranged so that the raised surfaces are underneath the holes in the dynode above it (Figure 17). In this way, efficient transmission of the secondary electrons is obtained.

The multiplier must be tested in various modes of operation to determine its performance with respect to the design criteria. The output vs input current of the multiplier must be determined as a function of energy, bias voltage, and angle and point of incidence. Furthermore, a pulse height distribution must be known since the expected signal will consist of few pulses per
Electrons are constrained by the electrostatic field to pass through the nearest hole in the dynode as shown by the dotted lines in the figure.
LONGITUDINAL SECTION OF MM-1 ELECTRON MULTIPLIER

FIG. 17
analysis time. The range of the pulse heights will determine whether it is necessary to make allowance for this variance prior to input into the spectrum analyzer. In order to perform these tests, a suitable source of electrons is utilized.

B. Calibration Source

In laboratory testing, the auroral source must be simulated in order to calibrate the experimental instrument. The laboratory source must be capable of:

1. Producing a wide electron beam ~ $20 \text{ cm}^2$
2. Producing beam current densities up to $10^{-9} \text{ amp/cm}^2$
3. Modulating 0-100% of the beam up to 10 MHz
4. Producing energies from 0-10 keV

These criteria were met by two different electron sources: an ultraviolet stimulated gun and a hot tungsten filament gun. The ultraviolet (uv) gun consisted of a gold-plated emission surface mounted above several equally spaced aluminum acceleration rings. Each ring was separated by a resistance, forming a resistance chain from ground to the high negative voltage emission plate. The uv lights were mounted between a control grid and the emission plate to decrease the amount of uv radiation incident on the acceleration rings. The ideal configuration would have exposed only the emission surface to the uv, thereby rendering all of the photoelectrons produced under the control of the grid.

The amount of modulation was varied by applying a dc bias voltage on the control grid and changing the amplitude of a superimposed time varying voltage. When
this time varying voltage is sinusoidal, \( V = V_0 \cos \omega_0 t \), the beam current \( i \) is given as

\[
i = i_0 (1 + m \cos \omega_0 t)
\]

The modulation coefficient \( m \) is determined by calibrating the beam current as a function of the grid voltage.

Any photoelectrons produced between the grid and ground provide an ambient background beam current. Thus there exists a maximum value of the percent of modulation which is less than 100\%. The configuration used gave almost complete modulation (95\%).

The energy was varied by changing the potential of the emitting surface. Current densities ranged from 0 - \( 10^{-10} \) amps/cm\(^2\). High frequency modulation of the beam was produced, but there was an extraneous modulation due to an inherent 10 kHz oscillation in the uv intensity. This modulation had the effect of turning the beam gradually on and off at .1 msec intervals, thereby interfering with the spectrum analysis which lasts for .16 msec for each frequency. For this reason, it was decided to change electron sources.

The tungsten filament consisted of a series of wires forming a grid with a linear density of 1 wire/cm. The filament was mounted with the same accelerating rings and control grid that were used with the uv gun. A battery produced a filament current of \( \sim 4 \) amps. This arrangement satisfied all the criteria and no appreciable problems were encountered.

The beams produced by each source were calibrated
by means of a Faraday cup mounted adjacent to the multiplier. By moving the multiplier out of the beam and the Faraday cup into it, the beam current incident on the multiplier was determined.

C. **Response of MM1**

1. **DC Measurements**

Experimental dc measurements are discussed as output current vs input current as a function of:

a. **Energy** - Figure 13 shows there is no significant variation in gain ($i_{out}/i_{in}$) with electron energies from 4 - 8 keV. There is no departure from a flat response within ± 5% over this energy range. As desired in the design, electrons of all energies sampled will be weighted equally.

b. **Bias voltage** - Typical gain curves are shown in Figure 19. The multiplier will saturate and be degraded when an output current of more than 1 microamp exists for a length of time on the order of minutes. For long term use and optimum stability, the manufacturer advises that the output be kept below this value. This corresponds to an operating bias voltage between 2300 V and 3000 V for the expected auroral input currents of $< 10^{-10}$ amps. However, for flight use, where no long term use of the multiplier is planned, it might be appropriate to exceed 1 microamp output. No tests have yet been performed to verify the manufacturer's statement.

c. **Time** - It was noticed that the gain decreased over a period of time as shown in Figure 19. This is apparently due to contamination of the multiplier surfaces.
Figure 18: GAIN vs ENERGY

The range of energies from 4 – 8 keV results in constant gain.

Figure 19: GAIN CURVES

Gain decrease over time was due to contamination of multiplier surface by diffusion pump oil. Reactivation of the MML was performed by Johnston Laboratories in January, 1969.
GAIN VS ENERGY

FIG. 18
CURRENT GAIN

GAIN CURVES AT DIFFERENT TIMES

FIG. 19

GAIN OF MM-1

VOLTAGE ACROSS MULTIPLIER IN KV

10^2

10^3

10^4

10^5

AUG. 16, 1968

OCT. 20, 1968

DEC. 2, 1968
by diffusion pump oil, and reactivation was performed by Johnston Laboratories. Several conditions degrade the gain of the multiplier:

1) Exposure to Atmosphere
2) Organic Contaminants
3) Beam saturation such that the anode current exceeds 1 μamp.

Figure 20 shows the curves of the secondary electron coefficient $\delta$ obtained by Laurenson and Koch (1965) for a 93% copper – 2% berillium strip 2.5 cm wide and .2 mm thick. The secondary electron collector was a 12.5 cm diameter copper hemisphere. Curve a shows $\delta$ for a clean strip (from the manufacturer); curve b shows $\delta$ after the 100 hour exposure of the strip to the atmosphere. If there were 20 stages of such strips, this degradation would correspond to a drop in gain by a factor of 15. This lower value of $\delta$ after atmospheric exposure is attributed to the adsorption of water vapor onto the strip.

Figure 21 shows two MM1 gain curves taken at Rice. Curve a was taken prior to storage of the multiplier in a dessicated container of Houston air; curve b was taken 7 days later. Subsequent curves verified that the gain had dropped by a factor of 2.5.

Other contamination may occur by the formation of organic films created by the interaction of electrons with organic molecules such as pump diffusion oil (Ennos 1954). Laurenson and Koch deposited a polymer film on a copper-berillium plate and then baked it off by ion bombardment in a glow discharge in an argon atmosphere (Holland 1958) of $10^{-2}$ torr at 2 keV and 10 μamp. This bombardment
Figure 20: DEGRADATION DUE TO ATMOSPHERIC EXPOSURE (Laurenson and Koch 1965)

Curves of secondary electron emission coefficient $\delta$ of a Cu-Be strip before and after exposure to atmosphere for 100 hours. The decrease represents a factor of 15 in gain loss over 20 such stages.

Figure 21: MULTIPLIER DEGREDATION

Gain curves of the MML taken at Rice. The gain dropped after a 7 day storage of the multiplier in a dessicated container.

Figure 22: EFFECT OF REACTIVATION (Laurenson and Koch 1965)

A polymer film was allowed to contaminate the Cu-Be strip. Reactivation consisted of a 5 minute ion bombardment in a glow discharge in an argon atmosphere at .01 torr. The increase in $\delta$ after reactivation is interpreted as the result of improper initial oxidation of the target surface.
DEGRADATION DUE TO ATMOSPHERIC EXPOSURE

FIG. 20
MULTIPLIER DEGRADATION

FIG. 21
Figure 22: Effect of reactivation on secondary electron emission coefficient.

- Reactivated
- Contaminated

Secondary electron emission coefficient (%) vs. voltage (V)

EFFECT OF REACTIVATION

FIG. 22
lasted for five minutes and then the target's secondary electron coefficient was remeasured. Figure 22 shows that the resulting $\delta$ was higher than the $\delta$ obtained from the originally clean target. Laurenson and Koch believe this improvement in due to improper initial oxidation of the target surface. The bombardment of the Cu-Be surface with water vapor ions to oxidize the Be is suggested for reactivation.

The degradation due to saturation is cumulative; that is, the gain is decreased permanently after the output current is restored to normal ranges. This saturation could be the efficient formation of polymers on the latter dynodes due to the high currents.

These effects dictate certain cleanliness requirements which must be met if optimum operation is desired. During the final testing and waiting before launch, the multiplier must not be exposed to atmosphere any more than necessary. The pre-launch conditions must be such that as little contamination as possible will occur. There are several means of accomplishing this requirement. The rocket's interior can be purged with one atmosphere of dry nitrogen (or an inert gas such as argon), or the HTR system can be isolated from the rest of the payload by a suitable enclosure allowing the system to be either at a vacuum or in an atmosphere as mentioned above.

d. Point of Incidence - The configuration of the two sets of hemispheres directs the transmission from the inner plates toward the edge of the multiplier. If there is a decrease in surface sensitivity toward the edges, the signal from this energy channel would not be amplified as much as that from the outer plates. Since both energy
channels will be operating simultaneously, discrimination against the lower energy electrons, which are transmitted by the inner set of plates, would occur.

An attempt was made to measure the surface response of the multiplier. The electron beam was restricted to a small area (~1 cm²) by passage through an aperture placed directly above the multiplier surface. The surface response along two axes was measured for a constant beam current as shown in figure 23a. The multiplier used was not new and had suffered pump oil contamination. Repeating the measurements with a clean multiplier confirmed the conjecture that Figure 23a was not representative; Figure 23b shows this measurement along one axis of the new multiplier. For a clean multiplier, then, the surface response is adequate to meet the design criteria.

e. Angle of Incidence - Since electrons orbiting through the hemispheres will exit the system at various angles, it is recommended that the response of the multiplier to beams of various degrees of incidence be observed. As yet, however, this has not been done.

The response of the multiplier to light is insignificant. There is a response to uv, but this is a very small one. When using the uv stimulated gun, the output of the multiplier due to uncalibrated uv incidence was ~10⁻¹⁰ amps at a gain of 10⁵. Proper shielding of exposed surfaces from auroral uv is recommended to reduce the production of photoelectrons.
Figure 23: SURFACE RESPONSE,
a. Degraded Multiplier
b. New Multiplier

a shows the surface response of a degraded MM1 to a constant, small diameter electron beam. The dashed curve represents one axis and the solid curve represents the response along the perpendicular axis.

b shows the response along one axis of a newly opened MM1. The output falls off by less than a factor of two toward the edges.
A. DEGRADED MULTIPLIER

B. NEW MULTIPLIER

SURFACE RESPONSE

FIG. 23
2. **AC Measurements**

The electron beam was modulated up to 10 MHz with a pulse generator ac coupled to the control grid. The amount of modulation could be varied by a dc bias placed on the grid and by varying the pulse amplitude. The circuit is shown in Figure 24. There were considerable noise problems at frequencies above 5 MHz, but modulation of the beam up to this frequency was detected by the multiplier. More quantitative work is now being performed with the multiplier coupled to a spectrum analyzer. A modulation factor as small as 2% has been observed for a beam of electrons producing a count-rate of $10^9$/sec. The results of these preliminary tests are discussed with the description of the spectrum analyzer (page 55).

3. **Pulse Height Analysis**

Integration of the signal output of the multiplier is performed to reduce the noise level. An accurate measure of the number of pulses per integration time requires a minimum of variation in the height of the individual pulses from the multiplier.

Defining the gain of the multiplier $G_i$ for a particular particle $i$ as the charge out/charge in,

$$Q_i/q_i,$$

the pulse height is $G_i q_i/C$ where $C$ is the anode capacitance of the multiplier. Many factors influence the value of $G_i$: factors such as where the primary particles impact the
Figure 24: MODULATION CIRCUIT FOR ELECTRON GUN
MODULATION CIRCUIT

FIG. 24
surface, the particle type, the particle energy (minimal for this detector), the accelerating fields, surface characteristics, etc.

The anticipated count-rate \( r(t) \) can be represented to vary as

\[
r(t) = \bar{r} (1 + m\cos\omega_0 t)
\]

where \( m \) is the modulation factor defining the percent of modulation, \( \bar{r} \) is the average count-rate, and \( \omega_0 \) is the signal frequency. This corresponds to an average signal current out of the multiplier \( \bar{I}(t) \)

\[
\bar{I}(t) = \bar{G} q r(t)
\]

where \( \bar{G} \) is the average gain.

Integration over a time interval \( T = t_2 - t_1 \) yields the average charge in this time interval,

\[
\bar{Q} = \int_{t_1}^{t_2} \bar{I}(t) \, dt
\]

\[
\bar{Q} = \bar{G} q \bar{r} \left( T + \frac{m}{2\omega_0} \sin\omega_0 T \cdot \cos\omega_0 \frac{t_1 + t_2}{2} \right)
\]

If \( \omega_0 T \ll 1 \),

\[
\bar{Q} = \bar{G} q \bar{r} T (1 + mA)
\]

where

\[
A = \cos\omega_0 \frac{t_1 + t_2}{2}.
\]
The variation of the average charge depends upon the statistical variations in $G_i$ and $r$, plus the signal strength $m$. In order for this value of $\bar{Q}$ to be representative of any particle density fluctuations arising from $m$, the statistical variations must be sufficiently small. The expected charge in time $T$ can be written as

$$\bar{Q} \pm f_Q = (\bar{G} \pm f_G)(\bar{r} \pm f_r)(1 + mA) T q$$

where $f_G$ and $f_r$ represent the fractional standard deviation due to the two noise sources considered. The noise arising from the random fluctuations in $r$ will follow a Poisson distribution and can be determined theoretically. The noise produced by the variation in $G_i$, however, must be determined experimentally by means of a pulse height analysis. These two variances are the major noise sources and set a definite lower limit to the value of $m$ that can be distinguished as signal.

A pulse height analysis was performed using a monoenergetic beam of electrons produced by the uv stimulated electron gun. The signal from the multiplier was amplified by an ORTEC 410 Linear Amplifier and then fed into a 128-channel Pulse Height Analyzer (PHA). The circuit is shown in Figure 25. The results are summarized in Table 4, and a typical pulse height distribution is shown in Figure 26. From Table 4 it can be seen that a typical value of the fractional standard deviation $f_G = \sigma/G$ was from .3 to .6 in all valid measurements. The data for the curves with bias voltage 4000 v are not reliable, as the first 7 channels
Figure 25: PULSE HEIGHT ANALYSIS: MM1 CIRCUIT

Figure 26: TYPICAL PULSE HEIGHT SPECTRUM

Typical spectrum for 1 keV electrons. The standard deviation $\sigma$ is seen to be large.
PULSE HEIGHT ANALYSIS:
MM-1 CIRCUIT

FIG. 25
TABLE 4:

Fractional Standard Deviation of
Pulse Height Distribution

<table>
<thead>
<tr>
<th>BIAS VOLTAGE</th>
<th>GAIN</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>0.65 x 10^7</td>
<td>0.73</td>
<td>0.59</td>
<td>0.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>4500</td>
<td>2 x 10^7</td>
<td>0.47</td>
<td>0.51</td>
<td>0.57</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>4600</td>
<td>2.5 x 10^7</td>
<td>0.51</td>
<td></td>
<td></td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>4700</td>
<td>3 x 10^7</td>
<td>0.34</td>
<td>0.51</td>
<td>0.41</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>4800</td>
<td>3.5 x 10^7</td>
<td>0.50</td>
<td></td>
<td></td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>4900</td>
<td>4.2 x 10^7</td>
<td>0.31</td>
<td>0.47</td>
<td>0.31</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>4.7 x 10^7</td>
<td></td>
<td></td>
<td></td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>
of the pulse height analyzer were attenuated and therefore the positive slope of the distribution was not fully counted. These measurements were taken in the 4000-5000 \( V \) bias range of the multiplier, corresponding to gains from \( 0.65 \times 10^7 \) to \( 5 \times 10^7 \). The expected range of operation during flight is from 2000-3000 \( V \). There appeared to be a slight decrease in the fractional standard deviation as the bias voltage increased, but this is possibly due to the loss of the tail of the distribution occurring past channel 128. Assuming that the fractional standard deviation would still fall in this range for lower bias voltages, an estimate of the variation in total charge per time \( T \) can be made.

For any sampling of particles, the pulse heights should follow the parent distribution. The integration essentially takes the average charge of each time interval \( T \), consisting of \( rT \) pulses. If, for the moment, \( rT \) is assumed to equal some mean value \( \bar{T} \) with no Poisson variation, a characteristic value of the pulse height variation can be calculated. Each group of \( \bar{T} \) pulses will have an output charge

\[ Q = \sum_i Q_i = \bar{T} \sum_i G_i q_i \]

that falls close to the true mean output charge \( \bar{Q} \) of the parent distribution. It is this distribution of the total charge of \( \bar{T} \) pulses about the parent mean that is of significance, representing the error in measurement of
Due to only the pulse height spread. The standard deviation of the total charges, $\sigma_m$, about the true mean $GqT$ is given as

$$\sigma_m = \frac{\sigma}{\sqrt{T}}$$

where $\sigma$ is the standard deviation of the parent distribution. The fractional error is

$$\frac{\sigma_m}{G}$$

so that assuming

$$\frac{\sigma}{G} = 1/2$$

$$\frac{\sigma_m}{G} = \frac{1}{(2\sqrt{T})}$$

The spectrum analyzer described in section VI has a bandwidth of 10 kHz and sweeps through 10 MHz in .16 sec. This corresponds to a time of .16 msec during which each frequency is analyzed. If the integration time is $T$, there will be

$$\frac{.16 \times 10^{-3}}{T}$$

integrations sampled, each containing $\bar{F}T$ pulses. Statistically, the variation caused by the pulse height fluctuations will be reduced by a factor of

$$\left[ \frac{T}{.16 \times 10^{-3}} \right]^{1/2}$$

so that the total fractional error due to pulse height variation $f_g$ is now given as
\begin{align*}
  f_g &= \sigma_m/\bar{G} \left[ \frac{T}{0.16 \times 10^{-3}} \right]^{1/2} \\
  f_g &= \frac{1}{2} \left[ \frac{6 \times 10^3}{\bar{r}} \right]^{1/2}
\end{align*}

which is independent of the integration time.

If \( \bar{r} = 10^9/\text{sec} \),

\[ f_g = 0.12\% \]

This source of noise is therefore negligible for the expected count-rates.

The other major noise source is the variation of \( rT \) due to the random arrival times of the electrons. Assuming no pulse height variation, one sampling of \( rT \) particles will differ from the mean value \( \bar{r}T \) with a standard deviation

\[ \sigma = \sqrt{\bar{r}T} \]

The fractional error is

\[ \sigma/\bar{r}T = \frac{1}{\sqrt{\bar{r}T}} \]

The total fractional error \( f_r \) is given by

\[ f_r = \left[ \frac{6 \times 10^3}{\bar{r}} \right]^{1/2} \]

Again, for \( \bar{r} = 10^9/\text{sec} \),

\[ f_r = 0.25\% \]
This Poisson noise is also not significant for this count-rate. However, it begins to become important for count-rates near $10^7$/sec.

The results of preliminary tests performed with the spectrum analyzer are given in Section VI for count-rates of $\bar{r} = 10^9$/sec.
VI. ANALYZER

The signal output from the detector prior to amplification is from 1 µvolt to 1 mV depending upon the multiplier gain. Each pulse from a single incident particle will have a width of about 5 nsec. The actual instrumentation that can reduce this signal to a frequency spectrum is shown in block diagram in Figure 27. The signal is amplified, integrated, and then mixed with a variable oscillator which sweeps linearly (within 1%) from 30-40 MHz with a sweep frequency of 6 Hz. This frequency is limited to a maximum value of about 14 Hz due to the limited response of the telemetry (see page 59).

The resultant output frequencies of the mixer are the carrier frequency $f_s(t)$ of 30-40 MHz range, the original signal frequency $f_0$, and the two side frequencies $f_s(t) \pm f_0$. When $f_s(t) - f_0 = 30 \pm 0.015$ MHz, the signal is passed through a 30 MHz Intermediate Frequency Amplifier with a temperature stabilized 3 dB bandwidth of 30 kHz. The time during the sweep at which this ~30 MHz output signal occurs corresponds to the original signal frequency $f_0$. This superheterodyning has stepped the signal up in frequency to provide a greater separation between the image frequency and the signal. An image frequency of $60 + f_i$ MHz will produce a 30 MHz sideband when $f_s(t) = 30 + f_i$ MHz. This will also be passed by the IF. However, integration of the signal prior to input into the analyzer will significantly attenuate frequencies this high.
Figure 27: HTR BLOCK DIAGRAM
The 30 ± .015 MHz signal is next heterodyned with a 29.5 MHz oscillator and passed through a 500 kHz IF with a temperature stabilized 6 db bandwidth of 10 KHz. The signal is subsequently compressed in a logarithmic amplifier and converted to a 0-5 volt output.

A. **Integration of Signal**

To eliminate noise due to the individual particle pulses, an integration of the signal is performed prior to input into the analyzer. This integration smooths out the statistical fluctuations of the pulses and emphasizes frequencies that are less than the reciprocal of the time constant of integration $T$. Frequencies on the order of $T^{-1}$ will begin to be attenuated in amplitude. Ideally, the integration time constant could be swept in phase with the variable oscillator of the spectrum analyzer, thus holding $f_s(t)T(t)$ constant, where $f_s(t)$ is the frequency of the variable oscillator. This process would attenuate the high frequency noise except during analysis of the upper end of the frequency spectrum where $T(t)$ is less than $10^{-7}$ seconds. The high frequency noise would thereby be present only during analysis of this upper frequency range instead of being present over the whole spectrum. To phase a variable integration circuit over three decades of frequencies is difficult. It might be sufficient to simply set $T$ at an intermediate value of 250 nsec, attenuating much of the noise and at the same time, providing no more than -6db attenuation of signals greater than 3 MHz. If the amount of attenuation is known and taken into account, and if the signal is not destroyed, this is a much easier and simpler method of
integration. Tests during the calibration will show if this system is appropriate.

B. Testing

The spectrum analyzer was calibrated over the 1 - 10 MHz frequency range. The output amplitude vs the input peak-to-peak amplitude of a 3 MHz sinusoidal signal is shown in Figure 28a. The logarithmic amplifier of Figure 27 was designed to produce a logarithmic response for output voltages in the range of 1 - 5 volts; Figure 28a verifies this. Upon plotting the same points on a log-log graph as in Figure 28b, the output response is seen to be a straight line with a slope of about 2 in the 50 - 500 mvolt output range. This curve was used as the calibration curve, and the data discussed below fit this curve in this range of voltages.

To test the operation of the integrated system of the analyzer and the MM1, a modulated beam of electrons was directed onto the multiplier. The beam was modulated as previously described (page 46), and the modulation coefficient m was calculated for various modulating voltages. The graphs of analyzer output amplitude at f_Q vs m for different i_Q are shown in Figure 29. The data points are connected by a least squares fit, and the slopes of the log-log curves are 1.95 and 1.98; these curves fit the calibration curve in this voltage range. The lowest m corresponds to the noise level and constitutes a lower limit of detection. This noise level is higher than that predicted for such countrates. This could have been caused by other noise sources in either the analyzer or surrounding
Figure 28: CALIBRATION OF SPECTRUM ANALYZER

a. Semi-log plot shows logarithmic response for 1.3-6 volts output.
b. Log-log plot shows power law response $V_o \propto V_i^2$ for 50-500 mvolts output.

Figure 29: SIGNAL CALIBRATION OF SPECTRUM ANALYZER.

A modulated electron beam with known values of m, the modulation coefficient, was detected by the MML; the signal was fed into the spectrum analyzer and the output amplitude was plotted for different values of m. The curves for two different beam currents are shown to match curve 28b.
SPECTRUM ANALYZER:
CALIBRATION AT 3 MHZ

FIG. 28b.
SIGNAL CALIBRATION OF
SPECTRUM ANALYZER

FIG. 29
equipment. The possibility of rf noise from the pulse
generator used to modulate the beam is not ruled out; however,
none was noticed at the time. The important result from
these preliminary studies is that it is feasible to detect
very low level modulation in realistic count-rates. More
complete measurements are currently underway, where $F$, $T$, 
and $f_0$ are varied as well as $m$. 
VII. **NIKE-TOMAHAWK PAYLOAD**

The HTR instrument will be flown in a Nike-Tomahawk sounding rocket from an as yet undetermined launch site. The primary goal of the flight is to measure possible field aligned currents flowing above an aurora. The instrumentation on-board is shown in Figure 30 and includes the following:

1. A Cesium-vapor magnetometer to measure the direction and scalar magnitude of the magnetic field.
2. A Lunar Aspect Sensor to measure the angle between the rocket spin axis and the moon.
3. GM detectors to measure the flux of energetic electrons (greater than 40 keV) and protons (greater than 500 keV) over all pitch angles.
4. Solid State Detectors to measure the flux of auroral protons in three output passbands: 50-100 keV, 100-500 keV, and 500-5000 keV.
5. 28 Channeltron Detectors to measure the energy spectrum of auroral electrons and protons over all pitch angles. 14 Detectors, 7 looking up the field lines and 7 looking down the field lines, are utilized for electrons; the same arrangement exists for measurement of protons. The energy passbands are to be .5-1 keV, 2-4 keV, 4-6 keV, 6-8 keV, 8-10 keV, and 10-15 keV.
6. High Time Resolution instrument to measure high frequency modulation in the 4-8 keV electron flux.

A block diagram is shown in Figure 31.
Figure 30: NIKE-TOMAHAWK PAYLOAD

Figure 31: PAYLOAD BLOCK DIAGRAM
PAYLOAD BLOCK DIAGRAM

FIG. 31
The overall experimental design dictates certain criteria for launch conditions:

1. Rocket must pass over a stable, visible arc at an altitude greater than 130 km.
2. Rocket trajectory must be within 30° normal to the arc.
3. Rocket spin axis must be 35°–55° from the local field.
4. Moon must be more than half full and greater than 15° above the horizon.
5. Sun must be more than 15° below the horizon.
VIII. **TELEMETRY**

Due to the large sampling rates and the presence of a large number of digital signals on-board, an FM/FM telemetry system is not adequate for data handling on this flight. Instead, a hybrid PCM-FM/FM system has been developed to accommodate the various signals. Figure 32a shows the frequency spectrum of the various subcarriers, and Figure 32b shows a block diagram of the on-board telemetry system.

The HTR 0-5 volt output signal frequency modulates a standard IRIG subcarrier centered at 93 kHz. The maximum frequency deviation of this subcarrier is 15% or 14 kHz, yielding a bandwidth of 28 kHz permitting separation from the other subcarriers (see Figure 32a). The bandwidth limits the modulation frequency to less than 14 kHz for transmission of the major sidebands. This maximum modulation frequency of the subcarrier, plus the bandwidth of the second IF (10 kHz) in the spectrum analyzer, limits the sweep frequency of the analyzer to less than 14 Hz.
Figure 32: TELEMETRY

a. Frequency spectrum of the various subcarriers. The HTR system modulates a standard IRIG subcarrier centered at 93 kHz with a band width of 28 kHz.

b. Block diagram of the telemetry system.
FIG. 32 a

POWER

MODULATION

SPECTRUM

PCM
HTR
VCO
MAGNETOMETER

2
46.8
79
107
125
250

FREQUENCY IN KHZ

FIG. 32 b

HTR DETECTOR
93 KHZ VCO

MAGNETOMETER
125-250 KHZ

MIXER

PCM ENCODER
57.6 KHZ

6 POLE FILTER
46.8 KHZ

TELEMETRY:
SPECTRUM AND BLOCK DIAGRAM

XMITTER 240.2 MHz
IX. DATA REDUCTION AND ANALYSIS

The signal received will be passed through a
discriminator and the raw data recorded on a strip-chart.
The data contained on the chart will include flux measure-
ments, power supply voltages, a frequency spectrum every 1/6
second, and a time calibration marker.

Recurrent frequency spikes above the noise level
are subject to investigation by a thorough correlation
analysis. Some recurrent spikes might be due to certain loc-
al noise events, and possible causes must be taken into
account. Some high frequency (MHz) noise will be produced
in the magnetometer, but testing during payload integration
will show if there is any interference. The spin modulation
may also produce some recurrent effect.

Analysis will reveal whether any observed spikes
are indicative of particle bunching.
X. CONCLUDING REMARKS

The testing performed on the HTR system indicates that the instrument meets the design requirements. The multiplier has a time resolution of 5 nsec, produces an output pulse independent of input electron energy, and is rugged enough to withstand a rocket environment.

The hemispherical deflection system is in the preliminary stage of testing. The initial results indicate that it does possess the desired characteristics of a large geometric factor and a wide angular view. The system has been integrated with the multiplier and observed to perform adequately. Future packaging of the two instruments will allow the interior of the hemispheres to be filled with argon to eliminate contamination of the multiplier. More sophisticated calibration of the integrated system in a payload unit will allow determination of the geometric factor.

The bread-board circuit of the spectrum analyzer functions satisfactorily. Input signals as low as 5 μvolts in amplitude can be detected over the frequency range of 40 kHz - 10 MHz. The multiplier has been used as an input device to the analyzer, and 2% modulation of a laboratory electron flux of $10^9$/sec-cm$^2$ has been detected. The ambient noise limiting the low level response of the analyzer is apparently not due to the inherent particle fluctuations in the flux. The concept of the measurement of low level modulation by the means proposed in this experiment is valid.

Much further testing must be carried out before the
design is labelled as completely satisfactory. Certain features of the design work against themselves; for example, the wide energy passband, which helps to create large countrates, may also lower the modulation coefficient if modulation occurs in a very small energy interval. However, if modulation is occurring over the whole energy passband, destructive interference of the modulation may occur due to the dispersion in arrival times of the various energy electrons.

All systems must be integrated together to test interfaces and the performance of the overall design. Assembled testing such as vibration tests, spin tests, vacuum temperature stability tests, cross-talk with other experiments, etc. must be performed.

Compromises have been made in the original experimental concepts in order to meet physical limitations. Future investigations, no longer as exploratory as this one, can become more specialized in design.

The HTR instrument will fly on the first Nike-Tomahawk payload in the series to be launched in November, 1970.
XI. **ACKNOWLEDGEMENTS**

I wish to especially thank Dr. H.R. Anderson, my thesis advisor, and Dr. R.J. Spiger without whose concern and help this thesis might have been longer in coming. Mr. Delbert Oehme, because of his many helpful discussions, deserves much appreciation.

Thanks are also extended to many friends, and especially to Ruth Parks, who typed at all hours in order to help.

Most of all, appreciation goes to Pat, my wife, who endured much for a long time.

The Nike-Tomahawk rockets have been funded by NASA contract NAS 6-1667. Development of the instrumentation has been supported by NASA SRT grant NGR 44-006-012.
APPENDIX

Consider two concentric hemispherical shells having radii $r_1$ and $r_2$ and a potential difference between them chosen so that an electron of kinetic energy $E_0$ entering the middle of the aperture at normal incidence travels in a great circle. In general, if fringing is neglected, when an electron $P(E, \omega)$ of energy $E$ enters the aperture at any point from a solid angle of $\Omega$, it travels in an ellipse which has one focus at the origin (the center of curvature of the shells). This is seen by noting that the electric field between the plates is proportional to $1/r^2$, which means that the force experienced by an electron between the plates is proportional to $-1/r^2$; this negative $r^{-2}$ dependence results in Keplerian motion, and the orbit is an ellipse if the eccentricity $e$ is such that $0 < e < 1$ (i.e., the total energy $W = E + U$ is negative).

In this treatment, the ellipses are approximated by circles with centers displaced from the origin. To test this approximation, a calculation of $a - b$ ($a =$ semi-major axis; $b =$ semi-minor axis) is advantageous (Paolini and Theodoridis 1967).
\[ a - b = \frac{M}{1-e^2} - \frac{M}{\sqrt{1-e^2}} \]  
\[ = a \left(1 - \sqrt{1-e^2}\right) \]

for \(e\) max, \(a - b\) is max.

Max \(e \approx \sin \theta\)

\[ = a - b \approx a(1 - \cos \theta) \]

\[ \approx \frac{a \theta^2}{2} \]

taking \(a \approx r_o\)

\[ a - b \approx \frac{r_o \theta^2}{2} \]

as will be shown later

\[ \theta_{\text{max}} \approx \frac{\Delta R}{r^2} \]

\[ = a - b \approx \frac{\Delta R^2}{2r_o} \]

So if \(\Delta R \ll r_o\), the conditions for this approximation are good. Furthermore, this is the only limit necessary for the rest of this analysis.
Next we can proceed to find out something about the allowed orbits and the locus of their centers*. The first thing to find is the relation of $y_O$ to $x$, $y_O$ being the maximum $y$ for a given $x$.

In Figure 33, $y_O$ is shown for an arbitrary $x$. Also in the figure,

- $nAR$ = distance from $r_1$ to the entry point for the orbit tangent to outer plate at $I$ and intersecting the inner plate at the exit.
- $r_c$ = orbit radius.
- $(x,y)$ = center coordinates from origin $O$.
- $r = \sqrt{x^2 + y^2}$.
- $I$ = point of tangency of orbit and outer shell.
- $r_t = \sqrt{r_c^2 - y_o^2}$.

First $nAR$ is found in terms of $x$:

\[ r_t = r_1 + x \]

from the triangle on the right

\[ r_t - nAR + x = r_1 \]

from the triangle on the left

Thus, $nAR = 2x$.

Next $y_O$ is found in terms of $x, r_1, r_2$.

\[ IO = r_c + r = r_2 \]

\[ r_t = nAR + r_1 - x \]

* Allowed orbits are those which do not hit the walls.
Figure 33: $y_0$ FOR ARBITRARY $x$.

$y_0(x)$ is the maximum $y$ for a given $x$. An electron whose center is $(x, y_0)$ will follow the orbit drawn; the orbit is tangent to the outer hemisphere at $I$ and exits the system just grazing the inner hemisphere. Thus there is only one allowed orbit for a point containing a $y_0$. 
These two equations imply

\[ y_0 \sim \Delta R \sqrt{1 - \frac{2x}{\Delta R}}. \]

Three approximations were used, all of which are equivalent to \( \Delta R \ll r_0 \):

1) \[ \frac{y_0^2}{(r_1 + x)^2} \ll 1 \sim \left(\frac{\Delta R}{r_0}\right)^2 \ll 1 \]

2) \[ \frac{\Delta R^2}{r_2^2} \left(1 - \frac{2x}{\Delta R}\right) \ll 1 \sim \left(\frac{\Delta R}{r_0}\right)^2 \ll 1 \]

3) \[ \sqrt{\frac{r_1 + x}{r_2}} \sim 1 \sim 1 \sim 1 \]

So as long as \( \Delta R \ll r_0 \), the approximations are valid.

Also seen from Figure 33 is

\[ \tan \theta_0 = \frac{y_0}{r_c} \sim \frac{y_0}{r_0} \]

The maximum value for \( y_0 \) occurs when \( x = 0 \) which implies \( y_0^m = \Delta R \). Since \( \tan \theta_0^m = \frac{\Delta R}{r_0} \ll 1 \), it follows that

\[ \theta_0^m = \frac{\Delta R}{r_0}. \]
To summarize what has been found:

1) \( n \Delta R = 2x \)

2) \( y_o = \Delta R \sqrt{1 - \frac{2x}{\Delta R}} \)

3) \( \theta_o = \frac{\Delta R}{r_o} \)

The first two results define the locus of centers of orbits. This locus is shown to be symmetric in Figure 34 (for this approximation) about the axes. Since this symmetry exists, we need consider only one quadrant, in particular, the second.

Turning to this quadrant then, we wish to determine the "entry area" seen by each incoming electron \( P(x,y) \) with center of orbit coordinates \( (x,y) \). The "entry area" is defined as the area on the aperture which allows an electron to travel unimpeded between the shells and exit the system. It can be perhaps best visualized by Figures 34 and 35.

Figure 34 shows \( A \), the radial length allowing transmission. Figure 35 shows the aperture of the shells looking along the \( y \) axis. The sensitive surface area of the detector is shown and the corresponding "entry area" (shaded) is diametrically opposite. This figure assumes the detector is flush against the plates, but it can be separated a small distance away without destroying the argument.
Figure 34: LOCUS OF CENTERS FOR ALLOWED ORBITS, 

\[ \frac{\Delta R}{r_0} \ll 1 \]

A is the radial length allowing transmission for an electron whose center of orbit is \((x, y)\). Each point has an associated A which corresponds to the geometric factor. 

\[ z + A + n\Delta R = \Delta R. \]

Figure 35: ENTRY AND EXIT AREAS

The figure shows the aperture of the shells looking along the y axis. The shaded areas represent an entry area and its corresponding exit area.
FOR ALLOWED ORBITS, $\Delta R/\delta \ll 1$
ENTRY AND EXIT AREAS

FIG. 35
Assuming \( d \ll r_o \),

\[ A \cdot d = "\text{entry area}" \]

where \( d = \text{diameter of detector's active surface} \).

\[ \Delta R - n\Delta R - z = A \]

but \( n\Delta R = 2x \)

therefore \( A = \Delta R - 2x - z \)

where \( z \) is shown in Figure 34.

To find \( z \), these two geometric identities are used along with the definition of \( r_t \):

\[ r + r_o = r_2 \]

\[ r_t + z + x = r_2 \]

The solution under the approximation of \( \Delta R \ll r_o \) is

\[ z = r - x + \frac{y^2}{2r_c} \]

which reduces to in first order

\[ A = \Delta R - x - r \]

So the "entry area" for \( P(x,y) \) can be approximated by

\[ A \cdot d = \left( \Delta R - x - \sqrt{x^2 + y^2} \right) \cdot d \]
We are now in a position to relate the Geometric Factor to the above. Let

\[ j(E, \Omega) = \text{particles per cm}^2\text{-sec-keV-ster} \]

\[ G(E, \Omega) = \text{cm}^2, \text{the Geometric Factor} \]

\[ N = \text{counts per sec registered by detector} \]

\[ d\Omega = \sin \theta d\theta d\alpha \]

\[ = -\cos \theta d\theta d\alpha \]

\[ N = \int \int j(E, \Omega) G(E, \Omega) dE d\Omega \]

\[ G(E, \Omega) \text{ is dependent purely on the type of system we have, and } j(E, \Omega) \text{ is independent of that system. A·d corresponds to } G(x, y) \text{ and all that is necessary is to transform } G(x, y) \text{ to } G(E, \Omega). \text{ We now look for the relations between } x \text{ and } E \text{ and } y \text{ and } \Omega. \]

For the case of spherical plates

\[ y = y(\theta) \]

\[ x = x(E). \]

It has already been shown that

\[ \theta \sim \frac{y}{r_0} \Rightarrow r_0 \theta \sim y \]

so \[ y \sim \theta r_0. \]
Since the orbit of the electron is an ellipse with one focus at the origin, \( x = er_0 \) from analytic geometry. So we need only to find \( e \), the eccentricity of the orbit.

\[
e = \left(1 + \frac{2EL^2}{mk^2}\right)^{\frac{1}{2}}
\]

Taking \( E = E_0 + \Delta E \) where \( \Delta E \) is positive and \( L^2 = 2mr_0^2E_0 \), we get

\[
e = \frac{\Delta E}{E_0}
\]

which implies \( x \approx \frac{\Delta E}{E_0} r_0 \).

So now transform:

\[
G(x,y) = \left(\Delta R - x - \sqrt{y^2 + x^2}\right) d
\]

\[
\Rightarrow G(E,\Omega) = \left[\Delta R - \frac{E - E_0}{E_0} r_0 - \left(\theta^2 r_0^2 + \frac{(E - E_0)^2}{E_0^2} r_0^2\right)^{\frac{1}{2}}\right] d
\]

\[
G(E,\Omega) = \left[\Delta R - \frac{E - E_0}{E_0} r_0 - r_0\left(\theta^2 + \frac{(E - E_0)^2}{E_0^2}\right)^{\frac{1}{2}}\right] d
\]
also, \[ Y_o = \Delta R \left( 1 - \frac{2x}{\Delta R} \right)^{\frac{3}{2}} \]

\[ \theta_o r_o = \Delta R \left( 1 - \frac{2(E - E_o)}{E_o} \frac{r_o}{\Delta R} \right)^{\frac{1}{2}} \]

\[ \theta_o = \frac{\Delta R}{r_o} \left( 1 - \frac{2(E - E_o)}{E_o} \frac{r_o}{\Delta R} \right)^{\frac{1}{2}} \]

and \[ x_m = \frac{\Delta R}{2} \], where \( x_m \) = maximum \( x \).

\[ E_m = \left( \frac{\Delta R}{2r_o} + 1 \right) E_o \]

Thus we have \( G(E, \Omega) \) and the integration limits for finding the total count-rate due to all \( E \) and all \( \Omega \). If the count-rate for electrons of energy spread \( \Delta E \) is desired, merely changing the limits of integration over \( dE \) is required.

The geometric factor \( G(E, \Omega) \) is diminished for small angles of incidence as is seen in Figure 36. So,

\[ N = - \iiint j(E, \Omega) G(E, \Omega) \cos^2 \theta \sin \theta d\theta d\phi dE \]

where the extra \( \cos \theta \) is due to the same effect illustrated in Figure 36.

\[ \text{effective length} = ds \sin \alpha \]
Assuming azimuthal symmetry for \( j(E, \Omega) \), i.e., \( j(E, \Omega) \rightarrow j(E, \theta) \), and knowing that \( G(E, \Omega) \rightarrow G(E, \theta) \), we can perform the integration over \( d\alpha \) immediately:

\[
\int_{0}^{\pi} \sin \alpha d\alpha = 2 \int_{0}^{\pi/2} \sin \alpha d\alpha = 2
\]

\[
N = -2 \iint j(E, \theta) G(E, \theta) \cos^2 \theta d\theta dE
\]

Since \( \theta \ll 1 \), the \( \cos^2 \theta \) can be set equal to 1.

\[
N = -2 \iint j(E, \theta) G(E, \theta) d\theta dE
\]

or \( N = -8 \iint j(E, \theta) \left[ \Delta R - \frac{E - E_0}{E_0} r_0 - r_0 \left( \theta^2 + \frac{(E - E_0)^2}{E_0^2} \right) \right] d\theta dE \)

where

\[
\theta(E) = \frac{\Delta R}{r_0} \left( 1 - \frac{2(E - E_0)}{E_0} \right) \frac{r_0}{\Delta R}, \quad (E - E_0) > 0.
\]

This is the count-rate of the detector. The factor of 4 is due to the taking of only one quadrant. The total count-rate over all \( E \) and \( \theta \) is found by letting the upper limit of integration over \( E \) go to \( E_m = \left( 1 + \frac{\Delta R}{2r_0} \right) E_0 \).
Upon integration for the total count-rate, assuming \( j \) isotropic and independent of \( E \):

\[
N = \frac{8\Delta R^3 E_0 j d}{9r_o^2} + \frac{9r_o^2}{2} 
\]

But \( E_0 = \frac{K}{2r_o} \).

And \( K = \frac{qVr_1r_2}{\Delta R} \), where \( q \) = charge of electron.

Therefore \( E_0 = \frac{qVr_1r_2}{2\Delta Rr_o} = \frac{qVr_o}{2\Delta R} \).

\[
N = \frac{+4}{9} \frac{\Delta R^2}{r_o^2} j d q V 
\]

Typical values for such a system are:

\[
\begin{align*}
r_o &= 5 \text{ cm} \\
qV &= 2 \text{ keV implying } E_0 = 8 \text{ keV} \\
d &= 3.5 \text{ cm} \\
\Delta R &= 0.5 \text{ cm} \\
\frac{\Delta R}{r_o} &= 0.1
\end{align*}
\]

These give \( N = \frac{1}{9} j \). So if we have an isotropic \( j \) (constant over all energies), the count-rate is on the order of \( .11 \ j \).
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