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ANALYSIS OF ELECTRON RETARDING POTENTIAL ANALYZER MEASUREMENTS --ETC(U)

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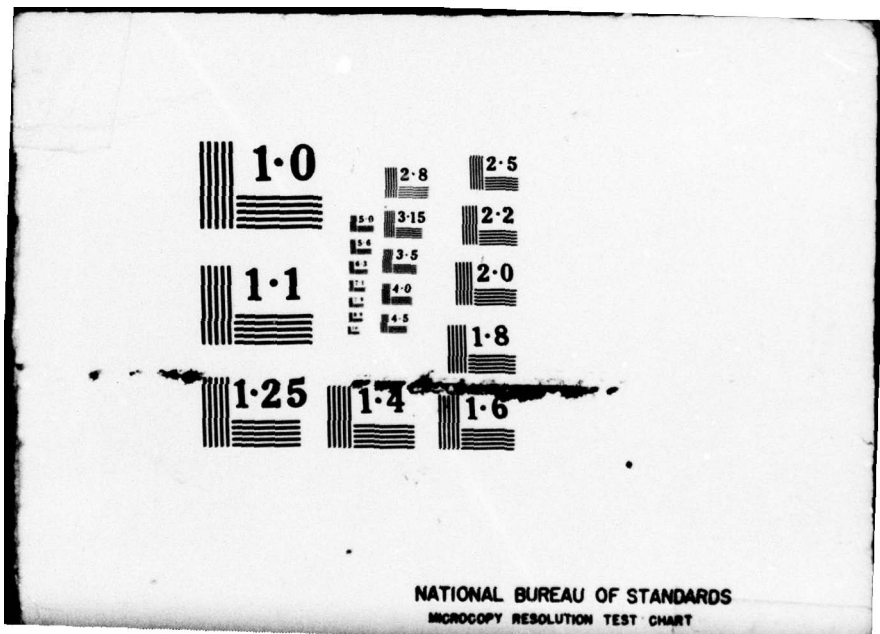
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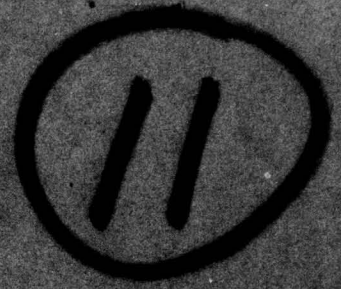


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**ANALYSIS OF ELECTRON RETARDING POTENTIAL  
ANALYZER MEASUREMENTS OF VEHICLE SKIN  
POTENTIAL IN THE PRECEDE EXPERIMENT**

Fritz Bien

Aerodyne Research, Inc.  
Bedford Research Park  
Bedford, Massachusetts 01730

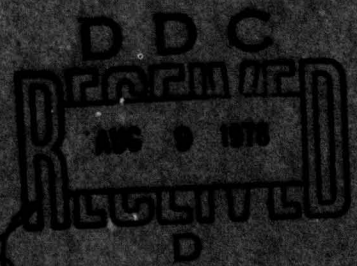
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AIR FORCE GEOPHYSICS LABORATORY  
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apogee (120 km) to a decent altitude of approximately 80 km providing a total of 90 pulses of the 2.5 kV 0.8 ampere electron beam over a period of 180 seconds. A rocketborne retarding potential analyzer provided a measure of the vehicle potential due to a net positive charge build up on the electron emitting payload. A steady-state vehicle potential of less than 30 volts was indicated at apogee with substantially smaller values at lower altitudes. Langmuir probe theory is shown to accurately model the altitude dependent steady-state vehicle potential.

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## 1. INTRODUCTION

EXCEDE is an experimental program designed to study auroral processes using a rocketborne electron accelerator operating in the altitude range 80 to 140 km. The primary scientific interest is the investigation of the detailed production and loss processes of various excited electron and vibrational states resulting in optical and infrared emission as energetic primary electrons and their secondary and all subsequent generation electrons are stopped in the atmosphere. In artificial auroral experiments, the dosing conditions of: electron energy and power, deposition volume, deposition altitude and dosing duration are parameters that may be controlled and monitored. In natural aurora, these excitation conditions must be inferred and the observed atmospheric emissions typically are effects integrated over a range of conditions (electron energy, electron-flux density, altitude, and dosing time). Observations of these integral effects make interpretation of optical/infrared emissions in terms of basic production and loss processes exceedingly complex. At present, considerable uncertainty exists in the interpretation of auroral optical and infrared emissions including such a well-studied feature as the auroral green line, O(<sup>1</sup>S) 5577A emission (Slanger and Black, 1973; Rees and Luckey, 1974; Shepherd, 1974).

The primary objective of the EXCEDE program is to: determine the mechanisms in which energetic electrons partition energy as they are stopped in the atmosphere, follow the chemical reactions of electron induced ionized and excited species and observe the ultraviolet, optical and infrared emissions induced directly by electron impact as well as the emissions induced by a series of consecutive chemical reactions.

Other artificial auroral experiments using rocketborne accelerators providing energetic electron beams of several kilowatts include the launch described by Hess et al. (1971) and Davis et al. (1971) and the more recent results reported from the joint Franco-Soviet ARAKS (Artificial Radiation and Auroras between Kerguelen and the Soviet Union) Program (Cambou et al., 1975). These experiments, designed to study the geomagnetic field orientation, conjugate point locations, conjugate reflection of energetic electrons and particle drift rates, utilized apogees in excess of

several hundred kilometers. In contrast to these other artificial auroral studies the EXCEDE experiments are conducted in the denser atmosphere at altitudes of 80 to 120 km to confine the electron excited atmosphere to the vicinity of the payload.

A feasibility study (O'Neil et al., 1973) indicated that 3 kW (3 kV, 1 ampere) electron beams deposited in the 100 to 120 km altitude range provided selected optical and infrared time dependent radiance profiles readily measured by both rocket and ground based photometric and radiometric sensors. Specific infrared emissions of interest include electron induced NO radiation at 2.7 to 5.4 microns as well as CO<sub>2</sub> and NO<sup>+</sup> radiation at 4.3 microns. The present report summarizes the rocketborne retarding potential analyzer measurements of the PRECEDE launch and infers an altitude dependent steady state vehicle potential for the electron emitting vehicle.

## 2. PRECEDE EXPERIMENT

This initial launch in the EXCEDE program of artificial auroral experiments was designated PRECEDE. The PRECEDE launch vehicle was a Nike Hydac Rocket (EX 407.41-1) instrumented with a 2 kW (2.5 kV, 0.8 A) electron accelerator launched at 10:20:00 UT on 17 October 1974 from White Sands Missile Range. This flight was an engineering test of the electron accelerator to be subsequently used on the heavily instrumented follow-on experiments. The electron accelerator consisted of three modules with separate high voltage supplies and tungsten filaments directly heated to approximately 2800°K by a common filament supply. A square wave oscillator operating at 0.5 Hz synchronously pulsed the high voltage supplies. The accelerator high voltage supplies powered by silver cell batteries were each current limited to approximately 0.5 amperes to avoid catastrophic failure in the event of arcing or momentary short circuit operation during launch. The electron source was initiated at 95 km on payload ascent and continued through apogee (120 km) to a descent altitude of approximately 80 km, operating for an interval of 180 sec. The payload was launched from north to south so that the electron beam was deposited along the geomagnetic field above the payload (Figs. 1 and 2). The trajectory for the PRECEDE launch was in the plane of the magnetic declination, 12° east, and the Tiff optical station was located to observe the payload along the magnetic field at approximately 100 km during payload descent. In this configuration the electron deposition volume, constrained along the magnetic field, presents a minimal source size for the photometric and spectrographic instruments located at the Tiff optical station. Stations at Denver and Cloudcroft contained various camera systems to record the electron-induced atmospheric luminescence with viewing aspects arranged to image radiance along the magnetic field and record the size of electron-excited atmosphere. On board measurements included monitors of electron-beam voltage and current and a retarding potential analyzer to determine particle flux and vehicle potential.

Figure 3, a montage of PRECEDE photographs from Denver optical site (see Fig. 1) is an illustration of the overall dimensions of the electron beam as a function of altitude. In Fig. 4 is given in greater spatial detail: the electron-beam energy

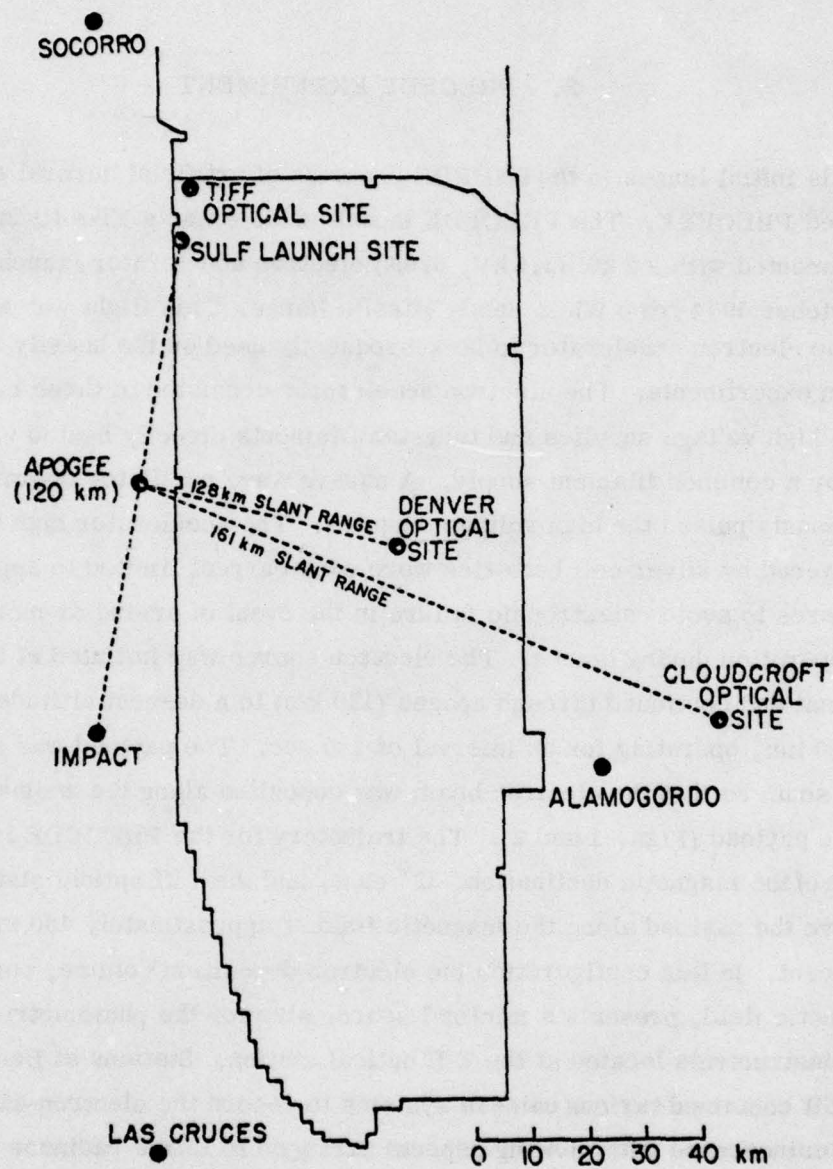


Figure 1. White Sands Missile Range, New Mexico Indicating the Trajectory of the PRECEDE Launch and the Location of the Three Optical Ground Stations.

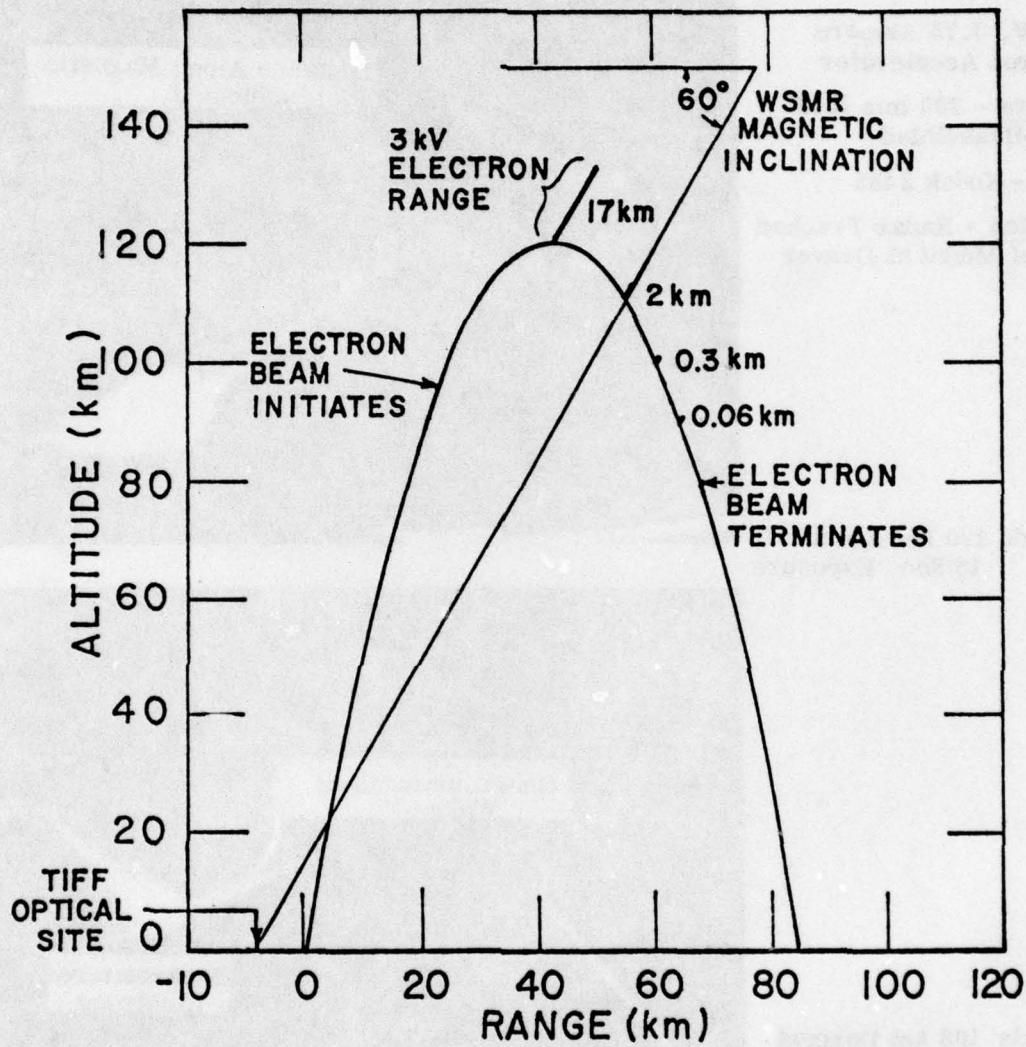


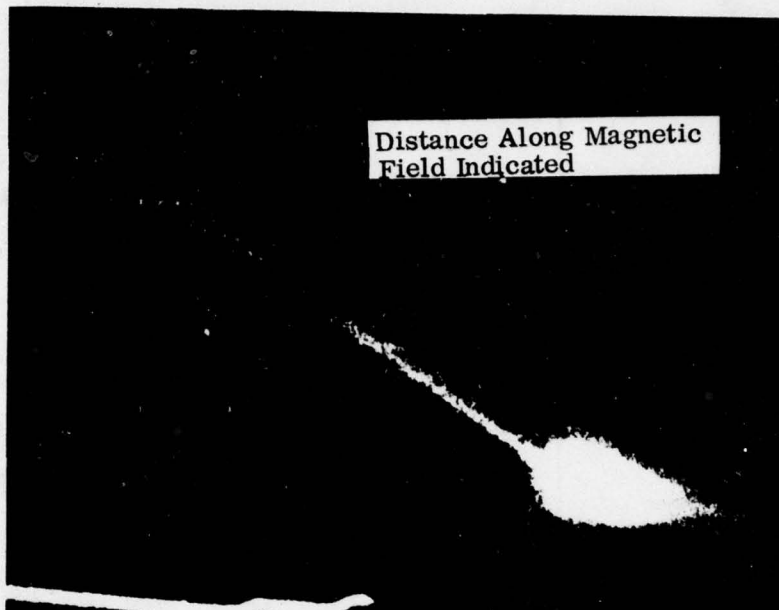
Figure 2. Flight Profile of the PRECEDE Launch Indicating the Calculated Practical Range of a 3 kV Electron Along the Magnetic Field and the Viewing Aspect of the Image Intensified Spectrograph and the Two-Color Telephotometer Located at the Tiff Optical Site.

2.5 kV, 0.75 Ampere  
Electron Accelerator

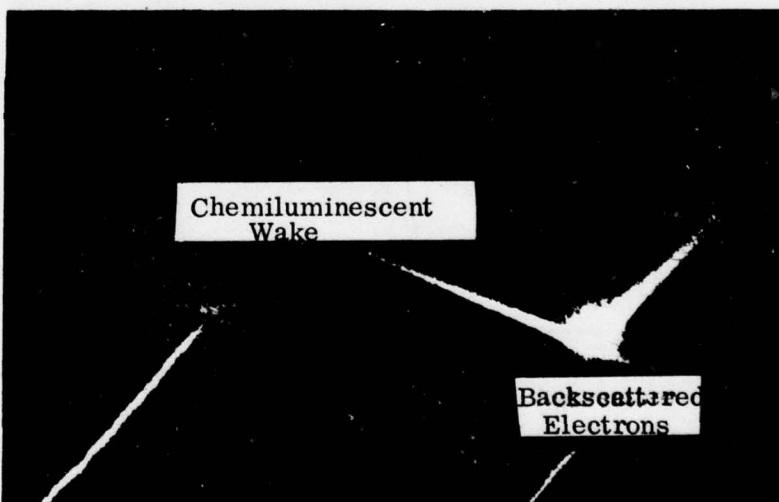
Camera - 300 mm f0.9  
Delft-Hasselblad

Film - Kodak 2485

Location - Radar Tracked  
Optical Mount at Denver  
Site



Altitude 120 km Ascent  
16 Sec. Exposure



Altitude 108 km Descent  
5 Sec. Exposure



Altitude 102 km Descent  
2 Sec. Exposure  
Beam Length 0.4 km

Figure 3. Photographs Taken By TIC, Inc., of Bedford, MA From the Denver Optical Site.

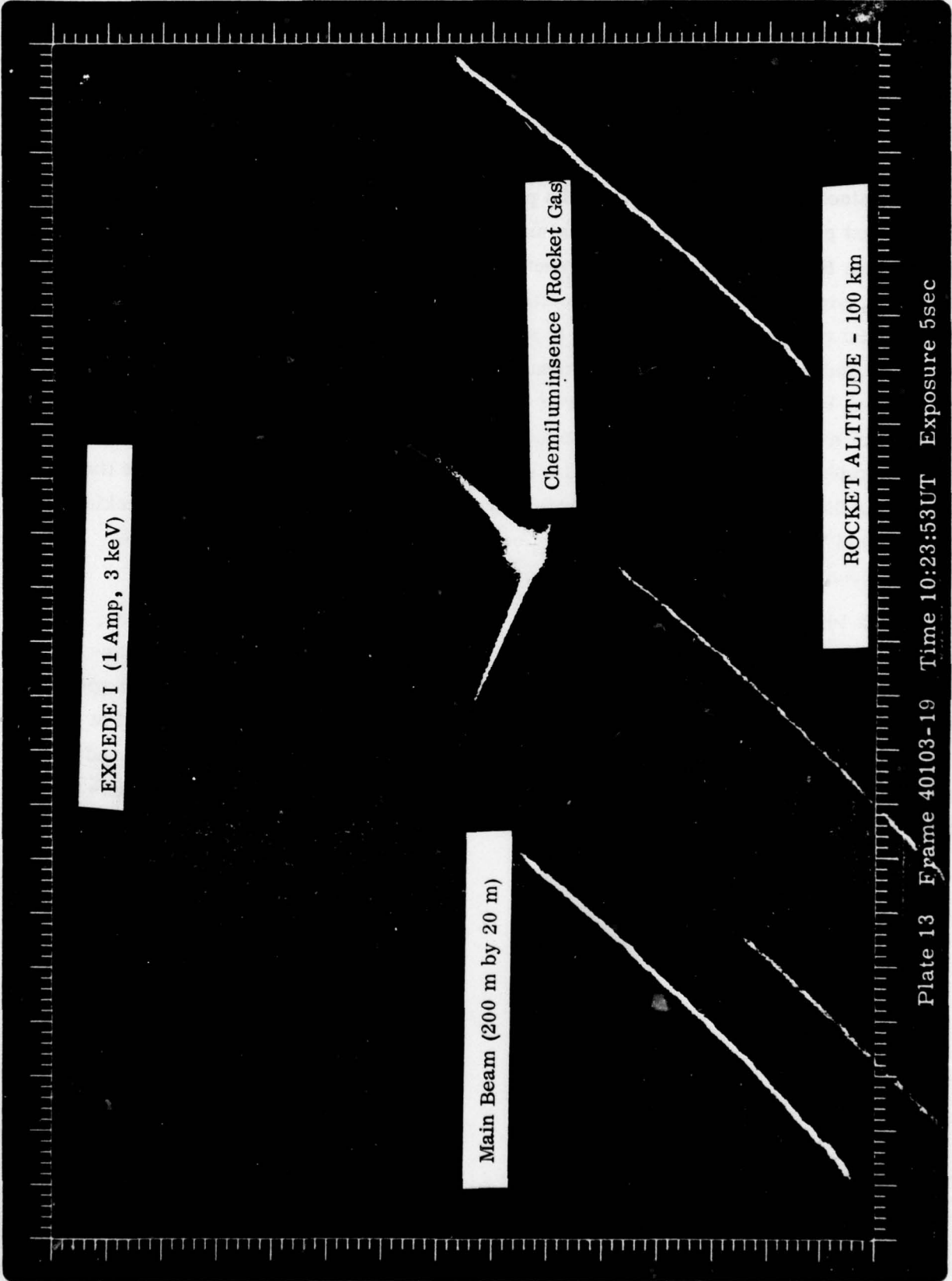


Plate 13 Frame 40103-19 Time 10:23:53UT Exposure 5sec

Figure 4. Atmospheric Emission Induced By the PRECEDE Accelerator Recorded By an Image Orithicon at the Cloudcroft Optical Site.

deposited above the payload along the magnetic field, the relatively faint electron-beam luminescence below the payload due to back-scattered electrons, and a bright chemiluminescent wake tangential to the payload trajectory believed to be due to residual rocket propellants (aluminum or aluminum compounds) outgassing from the smoldering Hydac rocket engine and reacting with atmospheric atomic oxygen.

Figure 4, provided by the Cloudcroft optical station, was taken with an image orthicon system and represents an integration of several seconds. All three optical ground stations used radar controlled instrument mounts which located and tracked the payload within 1-arc min for the duration of the experiment. The precise tracking of the optical mounts allow the ground-based imaging systems, an image intensified spectrograph and the television and film cameras, to effectively utilize exposure times as long as 20 sec. For the spatial resolution of the imaging systems and the tracking precision of the optical mounts, effective exposure times were determined by the shutter-open period rather than by the focal-plane image smear.

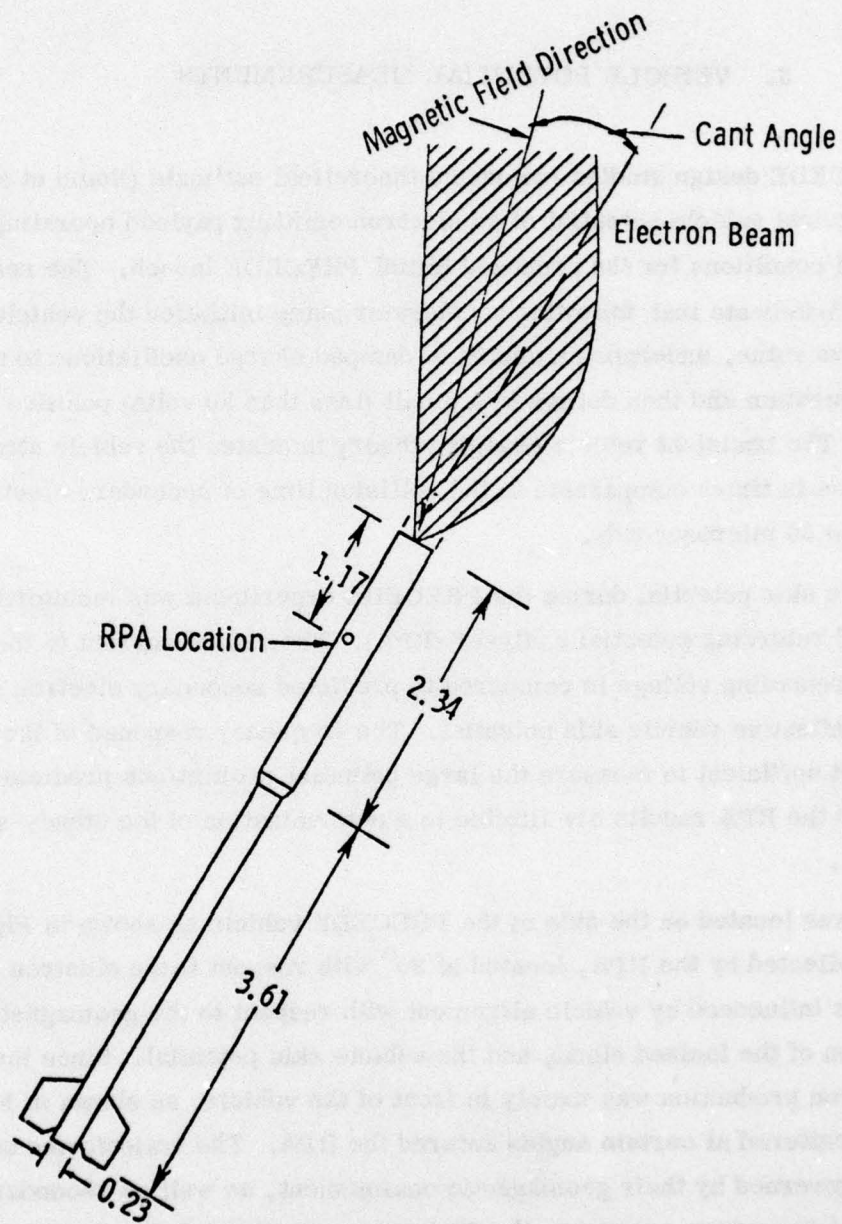
The PRECEDE launch trajectory was configured such that the electron beam, originating from the nose of the payload, was deposited above the vehicle along the magnetic field without the use of an attitude control system. The nominal pitch angle ranged from 0 to 40° during the experiment and was 25° for the case represented in Fig. 4. The dimensions of electron range and radial scatter indicated in Fig. 3 and 4 are in good agreement with the experimental results of Grün (1957) and the calculations of Berger et al. (1970, 1974), respectively.

### 3. VEHICLE POTENTIAL MEASUREMENTS

Initial EXCEDE design studies included a theoretical estimate (Baum et al., 1975) of the time dependent vehicle potential of an electron emitting payload operating under the experimental conditions for the proposed initial PRECEDE launch. The results of Baum et al. (1975) indicate that following accelerator pulse initiation the vehicle charges to a large positive value, undergoes a series of damped charge oscillations to account for electron momentum and then decays to a small (less than 30 volts) positive steady-state potential. The transient vehicle charging theory indicates the vehicle attains a steady-state value in times comparable to the collision time of secondary electrons, on the order of 10 to 50 microseconds.

The vehicle skin potential during the PRECEDE experiment was monitored using an onboard retarding potential analyser (RPA). The return current to the RPA as a function of retarding voltage is compared to predicted secondary electron spectra to obtain an effective vehicle skin potential. The frequency response of the instrument was not sufficient to measure the large potential oscillations predicted theoretically and the RPA results are limited to a determination of the steady-state vehicle potential.

The RPA was located on the side of the PRECEDE vehicle as shown in Fig. 5. The electrons collected by the RPA, located at  $90^\circ$  with respect to the electron beam accelerator, was influenced by vehicle alignment with respect to the geomagnetic field, the location of the ionized cloud, and the vehicle skin potential. Since the secondary electron production was mainly in front of the vehicle, as shown in Fig. 5, only electrons scattered at certain angles entered the RPA. The trajectories of these electrons were governed by their geomagnetic confinement, as well as secondary collisions. The total return current to the RPA was approximately the fraction of RPA area to the total vehicle skin area. The dimensions of the electron accelerator payload and vehicle are shown in Fig. 5. The effective collecting area of the payload presented to the returning electrons varied with vehicle orientation and electron energy.



**Figure 5. Location of the Retarding Potential Analyzer on the PR<sub>h</sub>CEDE Vehicle. The Dimensions Are Given in Meters.**

A typical RPA data frame is shown in Fig. 6. The retarding voltage was stepped through a sequence of 14, 0, -17, -33, 0, -120, and -550 volts in two second intervals equivalent to the electron beam pulse period. A retarding potential of -1960 volts was also used, but failed to operate reliably. The nominal 16 second RPA data frame represents an altitude increment of approximately 10 km at 100 km and 7 km at 110 km in the PRECEDE trajectory.

A 5 volt accelerator grid was placed in front of the retarding grid to ensure collection of electrons in the vicinity of the RPA. The entrance aperture of the RPA was  $3.5 \text{ cm}^2$  and the instrument design allowed acceptance of electrons as much as 80 degrees from normal.

Figure 6 indicates the RPA dynamic range extended to currents as low as  $10^{-10}$  amps. This collection current infers ambient electron densities as low as  $10^2 \text{ cm}^{-3}$  were measurable. However, RPA currents were not detectable when the electron accelerator was turned off during the PRECEDE experiment, even when a positive 14 volts was placed on the retarding grid. It is speculated the inability to measure ambient atmospheric electron densities is due to the vehicle orientation with respect to the geomagnetic field and the possibility of a slight negative charge on the vehicle skin, built-up after the electron accelerator was turned off.

The RPA current is the integral of all electrons having energy greater than the retarding potential. Thus, accounting for the 5 volt accelerating potential, a -17 volt retarding potential would be a sum of all electrons having energy of greater than 12 volts, etc. In the absence of a negative vehicle skin potential, the retarding voltages of +14 and 0 volts should show the same return current. This was indeed borne out by the RPA data. Similarly, if the vehicle potential was above 28 volts, the RPA current at -33 volts retarding potential would be equal to the 0 volt RPA electron current. This condition was not met even at apogee, indicating that the vehicle skin potential at no time exceeded 28 volts steady-state.

A spin modulation was presented on most of the RPA data and was most prominent at large retarding potentials. The current modulation was caused by the asymmetrical area of the RPA projected across the geomagnetic field and the electron excited atmosphere as the vehicle spun. The RPA was also shielded by the vehicle

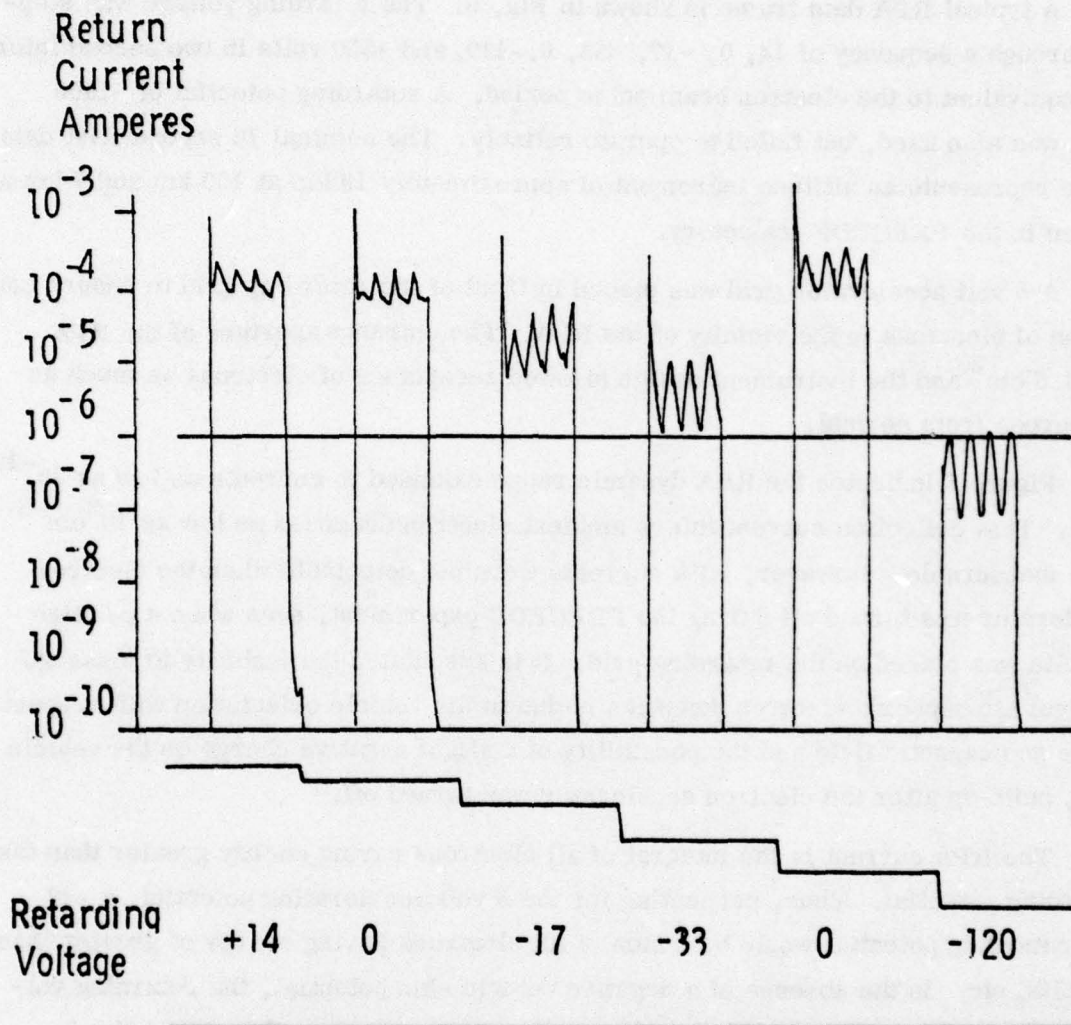


Figure 6. Return Current Collected by the Retarding Potential Analyzer at Various Retarding Voltages in the 112 to 116 km Altitude Range During Payload Ascent. Each Retarding Potential Was Applied for Two Seconds Equivalent to the Period of the Pulsed Accelerator Which Was Square Wave Modulated at 0.5 Hz.

from the highly excited atmosphere during one half of its spin, limiting collection electrons to a small angular distribution of scattered secondary electrons.

In order to obtain a vehicle skin potential from the RPA returns, a simplified model of the electron energy spectra was used. Here it was assumed that once the secondary electrons were formed, they traveled in a gyrating path around the geomagnetic field until they entered the RPA. The geometric orientation of the RPA was, thus, convoluted with the angular dependence of the secondary electron production spectra and the orientation of the electron beam. From this convolution the electron flux was derived for several vehicle orientations as a function of electron energy. The electron flux was then integrated as a function of effective retarding potential on the RPA for a primary electron of a given initial trajectory. Finally, a Monte Carlo technique was used to account for  $30^\circ$  divergence angle in the electron beam emanating from the accelerator and the probability of secondary electron production of a given energy and scattering angle. A mean size of one thermal electron Larmor radius was used as a sample grid size in the calculation. The energy distribution of the electrons collected by the RPA was determined by the angular orientation of the vehicle axis with the geomagnetic field and the orientation of the sensor with respect to the roll axis. Both the total integrated secondary electron current and the relative energy dependence of the electron current changed with orientation of the roll axis. In the absence of a simple roll dependence for the electron flux incident on the RPA, a maximum return current was assumed at all retarding potentials presumably equivalent to the peak values of the spin modulated currents of Fig. 6. Based on the laboratory measurements of Opal et al., (1971), the integrated cross-section for the production of secondary electrons by a 3 kV primary is shown in Fig. 7. The cross-section was in turn combined with the geometric factors to determine the electron flux at the RPA for various retarding voltages.

The integrated production cross-section of Fig. 7 was convoluted with the RPA returns from the PRECEDE experiment (see Fig. 6) and with altitude to produce an estimated vehicle skin potential. The effects of change in altitude and change in pitch angle of the vehicle with respect to the geomagnetic field, between retarding potential measurements, were considered in the calculation of the vehicle skin potential. The

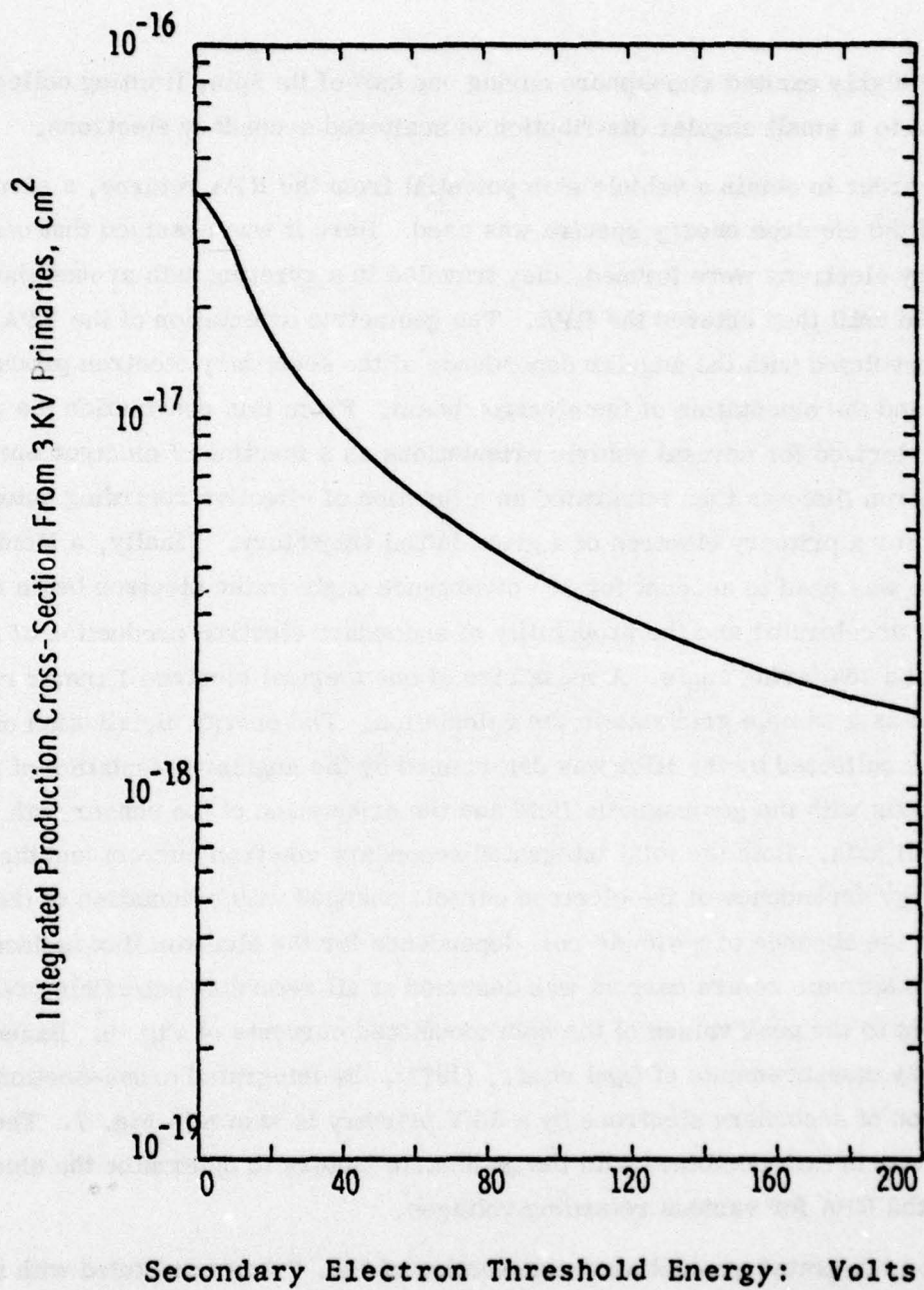


Figure 7. Integral Cross Sections for the Production By 2.5 kV Primary Electrons of Secondary Electrons With Energy Greater Than the Threshold Indicated.

resulting vehicle potential as a function of altitude is known in Fig. 8. The horizontal error bars represent the altitude extent over which a particular set of RPA readings were taken. The vertical error bars are due to the variations in current introduced by the spin modulation of the RPA. The maximum skin potential during the experiment was approximately 27 volts at apogee. Slightly larger vehicle potentials were observed on the descent trajectory compared to the equivalent upleg altitude. This asymmetry is presumably due to the greater payload velocity across of the geomagnetic field during descent which causes shorter electron beam dose times for each given volume element. The result of which would be smaller electron densities and thus a slightly larger vehicle potential.

A theoretical steady-state vehicle potential may be estimated by using Langmuir probe theory together with steady-state electron concentrations associated with the electron beam ionized cloud. In the steady-state case, it is assumed a vehicle to plasma potential is established to provide an electron return current to the payload equivalent to the accelerator current. The return current to the vehicle skin, which must balance the outgoing current is given by:

$$I_r = I = n_e u_e e A_v \quad , \quad (1)$$

where  $n_e$  is the number density of electrons near the vehicle,  $u_e$  is the drift velocity toward the vehicle,  $e$  the electron charge, and  $A_v$  is the area of the vehicle skin. At the altitudes of interest, the electron mean free path varies from several centimeters to several meters, much larger than the Debye length.

If the secondary electrons in the vicinity of the vehicle are not greatly depleted, their number density can be approximated by the steady-state concentration,

$$n_e(0) \approx [P(0)/\alpha(0)]^{1/2} \quad , \quad (2)$$

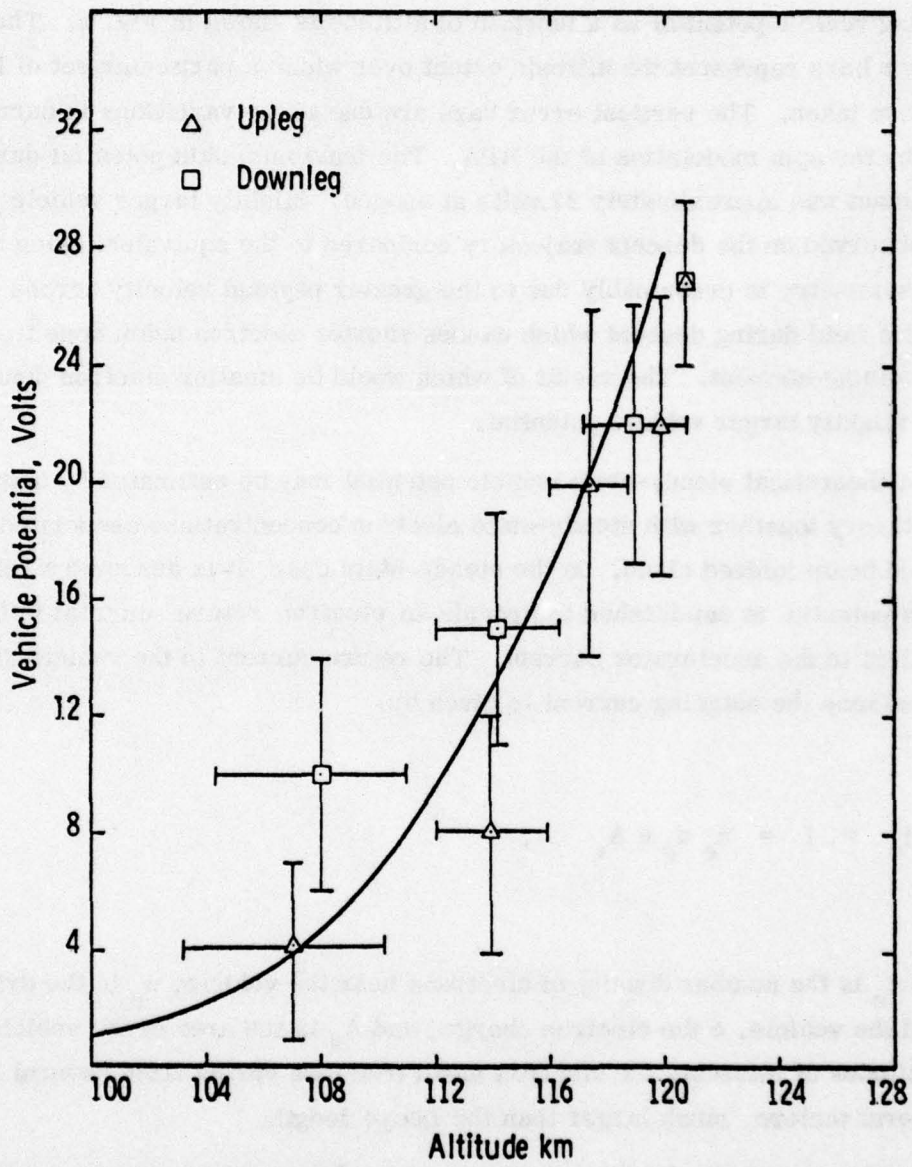


Figure 8. The Vehicle Potential Inferred From the RPA Measurements and the Potential Estimated Assuming Steady-State Langmuir Probe Theory.

where  $P(0)$  is the ionization rate near the skin of the vehicle, and  $\alpha(0)$  is the electron recombination rate in the same region. The production rate  $P(0)$  can be approximated by the empirical relationship,

$$P(0) \approx 1.86 \times 10^{-3} nIV^{-5/2} \text{ cm}^{-3} \text{ sec}^{-1}, \quad (3)$$

by fitting to laboratory data by Grun (1957) with magnetic field confinement described by Berger et al., (1970, 1974). Here,  $V$  is the electron beam voltage in kV and  $I$  its current in amperes. The atmospheric density,  $n$ , in  $\text{cm}^{-3}$ , is taken to be mainly  $N_2$ . Clearly, corrections for ionization cross-section for O and  $O_2$  should be made if an accurate number is to be obtained. However, these corrections are not considered significant compared to errors introduced in the effects of orientation and the assumptions of homogeneity of the electron beam source.

The recombination rate near the vehicle,  $\alpha(0)$ , is assumed to be  $1 \times 10^{-7} \text{ cm}^3 / \text{sec}$ , comparable to the  $\text{NO}^+$  recombination rate at  $T_e \approx 0.5 \text{ eV}$  (Huang et al., 1975) and typical of ion recombination rates observed in the upper atmosphere. Thus, the electron density in the vicinity of the vehicle is

$$n_e(0) \approx 136 V^{-5/4} I^{1/2} n^{1/2} \text{ cm}^{-3}. \quad (4)$$

In the 100 to 120 km altitude range, atmospheric number density varies between  $10^{13}$  and  $5 \times 10^{11} \text{ cm}^{-3}$ . Thus, the electron mean free path is at all times much greater than the Debye sheath at steady-state. The vehicle skin, if perfectly conducting, would behave much like a Langmuir probe (Langmuir and Compton, 1931). The return current, using Langmuir's solution for the case when the probe potential is larger than a few tenths of a volt, is

$$I_r = \left( \frac{n_e \langle c_e \rangle}{4} \right) \left( 1 + \frac{2e\phi_v}{kT_e} \right)^{1/2} eA_v, \quad (5)$$

where  $\langle c_e \rangle$  is the mean thermal speed of the electrons,  $\phi_v$  is the vehicle potential,  $k$  Boltzmann's constant, and  $T_e$  is the plasma temperature.

Solving for the vehicle potential at steady-state by combining Eqs. (4) and (5) yields

$$\phi_v = \frac{kT_e}{2e} \left( \frac{1.4 \times 10^{-7} m_e I V^{5/2}}{e^2 A_v^2 n kT_e} - 1 \right) \quad (6)$$

where  $m_e$  is the electron mass,  $I$  the current in amperes,  $V$  the beam voltage in kV,  $e$  the electronic charge and  $A_v$  the vehicle area in  $\text{cm}^2$ . Substituting representative values into Eq. (6), a theoretical vehicle potential, which is a function of vehicle orientation was obtained.

The vehicle skin potential is a function of the total area of the vehicle as well as the orientation of the vehicle with respect to the geomagnetic field. Because the electrons are essentially restricted from moving across geomagnetic field lines, an effective area was used in the calculation of vehicle skin potential. This area has been taken to be the vehicle cross-sectional area normal to the geomagnetic field, plus the added cross-section provided by the Larmor radius of a mean secondary electron. At high vehicle potentials, some distortion of the field lines may result, giving a larger effective vehicle skin area (Linson, 1969). The return current to the RPA is also affected by its orientation with respect to the geomagnetic field, and it would see a maximum electron flux if the aperture of the RPA was field aligned. The predicted vehicle skin potential was, thus, tailored to the specific geometry associated with the vehicle orientation.

The vehicle was canted with respect to the geomagnetic field during the entire period of electron beam operation, processing between 9 and 33°. The effective area presented to the backscattered electrons varied from  $3.5 \times 10^3 \text{ cm}^2$  to  $1.0 \times 10^4 \text{ cm}^2$ , normal to the geomagnetic field, compared to a total vehicle skin area of approximately  $5.4 \times 10^4 \text{ cm}^2$ . The theoretical estimate of vehicle skin potential was obtained by combining the altitude dependence of the vehicle cant angle, atmosphere number density, and velocity across the geomagnetic field lines. The number density of electrons in the vicinity of the vehicle is a function of all three parameters. However, calculations become somewhat simplified when the vehicle is moving along the geomagnetic field, and a steady-state electron concentration could be established. The vehicle potential determined theoretically by the steady-state model is shown in Fig. 8 along with the experimentally determined values. The theoretical curve was produced from Eq. (6) using the PRECEDE nominal accelerator operating parameters, 2.5 kV and 0.8 amperes, and a representative Jacchia (1971) model atmosphere. The theoretical approximation indicates the vehicle potential is inversely proportional to atmospheric number density and provides an estimated vehicle potential of 2.8 volts at 104 km and 28 volts at 120 km in good agreement with the experimental results.

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