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A Subsonic Probe for the Measurement of D-region Charged Particle Densities

by

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ABSTRACT

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The philosophy, theory, and preliminary results of a program to measure charged particle number densities in the D-region of the ionosphere are presented. The instrument used is a subsonic, parachute-borne, bipolar probe with a planar collector. The probe geometry and electronics, the relevant theory, and the experimental results from recent Arcas rocket shots are reported. Results indicate positive ion densities of the order of 10^3 cm^{-3} from 60 to 70 kilometers. An error analysis of these results shows that the principal error results from an uncertainty in probe potential stemming from solar ultra-violet irradiation of the sides of the probe during daytime shots.

This probe system is significant in that the results are independent of angle of attack, and in that the commonly used free-molecular "ram" theory is replaced a continuum theory more appropriate to the region 40 to 80 kilometers. Author

I. INTRODUCTION

A. General Statement of the Problem

Because of its complexity and inaccessibility to ordinary exploratory techniques, the D-region of the ionosphere remains relatively unexplored. A complete description of this region requires a detailed study of its ionic composition. A logical first step in this direction is the development of a technique for measuring charged particle densities in the region 40 to 80 kilometers. Such measurements may be made using a subsonic, bipolar probe. It is the purpose of this paper to describe and evaluate a reliable method for determining positive ion densities in the region 40 to 80 kilometers using such a probe.

B. Origin and Importance of the Method

The ionospheric D-region is characterized by its complex chemistry and ionic composition. Charged particle densities are small, the positive ion density being roughly 10^3 ions/cm^3 over the range 55 to 80 kilometers. A distinctive feature is the presence of large numbers of negative ions, the density of which increases with decreasing altitude. Theoretical estimates by Nicolet and Aikin (1960) lead to a daytime negative ion to electron ratio ranging from essentially 0 at 80 kilometers, to about 10 at 50 kilometers. The ionizing radiations in this region are primarily cosmic rays and Lyman-alpha radiation, although under disturbed conditions X-rays can be an important source of ionization.

It is generally accepted that the principal positive ions present in the D-region are O_2^+ and N_2^+ with the possibility that NO^+ dominates at certain altitudes (Nicolet and Aikin, 1960). Although it is generally agreed that negative ions are present in significant numbers below 70 kilometers, there remains considerable uncertainty as to which type or types of negative ions are dominant. These negative ions are probably formed by electron attachment at night. During the day photo-detachment of these electrons tends to increase the overall D-region electron content.

There is evidence pointing to the presence of significant numbers of heavy ions in the D-region. Whether they be dust, vapor or other impurities is not clear, although they are probably formed by electron attachment, due to high electron thermal velocities, and are hence negative ions. (See Pederson (1964) for a summary of heavy ion properties and measurements.) These heavy ions are characterized by their extremely small mobilities and hence may not be expected to behave as small ions in the presence of an electric field.

The above description points to the need for reliable information concerning D-region ion types and concentrations, in order that a more complete understanding of this region may be effected.

The difficulties associated with D-region measurements arise from its unique composition and altitude. Despite its low altitude the D-region is still too high for practical stationary balloon measurements. Historically, the most important ionospheric tool has been the radio sounding technique. This method consists of sending a radio wave into the ionosphere and deducing ionospheric properties from the characteristics of the reflected wave. Under exceptional solar conditions such methods can yield data as low as 45 kilometers, but under normal daytime conditions their usefulness below 70 kilometers is limited. A disadvantage to radio techniques is their inability to measure other than electronic properties (density and collision frequency). This inability prevents their use in the study of the nighttime D-region, when electron densities are extremely low. A survey of ionospheric radio techniques may be found in Budden (1961).

A more recent technique involves the use of bipolar probes to measure such parameters as charged particle densities and temperatures. Probes of this type have had success in recent years in orbiting satellite measurements and in upper ionospheric work using both rocket-borne and free-falling probes. Their disadvantages include high cost and low reliability. The method consists, essentially, in measuring the current to a conducting surface which is charged to a known potential with respect to the ambient medium via a second electrode (hence the name "bipolar"). Using a known relationship between the measured potential, measured current, and the parameters of the ambient medium, one may deduce the values of these parameters.

This method must be used with caution below 90 kilometers, for the usual free-molecular probe theory will no longer hold and a continuum theory must be employed.

Probes attached to rockets, with a small collector and the rocket body serving as the second, return electrode have two main disadvantages in D-region work. First, gas contamination from the rocket may introduce an indeterminate error. Second, rocket velocities are generally supersonic and probes travelling at supersonic velocities may drastically alter the composition of the medium in the vicinity of the probe (Hoult, 1964), thus rendering measurements with supersonic probes highly inaccurate.

The bipolar probe system described in this paper is free from the above objections. It is parachute-borne (and hence subsonic), and its operation is described by an appropriate continuum probe theory. The use of a reliable and inexpensive meteorological launch vehicle tends to alleviate the high cost and low reliability associated with probe work.

C. Previous D-region Probe Work

There have been but a limited number of D-region ion density measurements using bipolar electrostatic probes. Several workers, however, have reported measurements using Gerdien condenser type probes. The Gerdien condenser consists, essentially, of two concentric cylinders between which a known electric field is applied. Knowing the current collected by the center electrode enables one, in principle, to compute the ambient ion density.

Bourdeau, Whipple, and Clark (1959) have described an experiment using Gerdien condensers mounted on the nosetip of a Viking rocket. The authors have questioned the interpretation of their results, since the high Mach number involved (about $M = 4$) probably disturbs the air flow through the condenser. The resultant shock wave may cause considerable alteration of the composition of the medium as pointed out earlier. Whipple (1964) has presented results obtained from similar experiments using Aerobee rockets. Ion densities obtained at Fort Churchill, Canada on November 27, 1960, show ion densities of about 50 cm^{-3} at 50 kilometers. These unexpectedly low values may be the result of dust particles acting as recombination surfaces, or, as Whipple points out, may be due to misinterpretation of Gerdien condenser behavior. A similar Aerobee shot at Wallops Island, Virginia shows larger densities, about 5×10^3 cm^{-3} at 60 kilometers.

A probe with electrical characteristics similar to those of the Gerdien condenser has been described by Sagalyn and Smiddy (1963). This spherical probe consists of a charged central collector and a wire mesh outer grid. The grid tends to confine the spherical electric field, preventing stray fields from affecting the ion collection process. This probe is again supersonic and subject to the uncertainties associated with supersonic probes. Wind tunnel experiments are underway to study the shock structure about this probe.

A bipolar electrostatic probe has been described by Smith (1963). His collecting electrode consists of the rocket nosetip, the remainder of the rocket body acting as the return electrode. Difficulties in interpreting the flow to this supersonic probe are a present limitation to understanding its operation, although its simplicity and resultant low cost are advantages.

Pederson (1964) employs a parachute-borne Gerdien condenser for the measurement of positive and negative ion densities in the D-region. The advantage of this probe over those described earlier is its subsonic operation and the resultant lack of shock effects. Disadvantages are the angle of attack dependence of Gerdien condenser theory, and the uncertainty in determining the air flow through the condenser. Pederson's probe is in the wake of the detached rocket nosecone, which complicates the aerodynamics of his probe. His results indicate anomalous negative to positive ion ratios which may be interpretable in terms of high dust concentrations in the D-region.

D. Specific Statement of the Problem

A survey of D-region properties indicates that reliable information is lacking concerning ionic concentrations. A fuller understanding of this region requires that such information be made available.

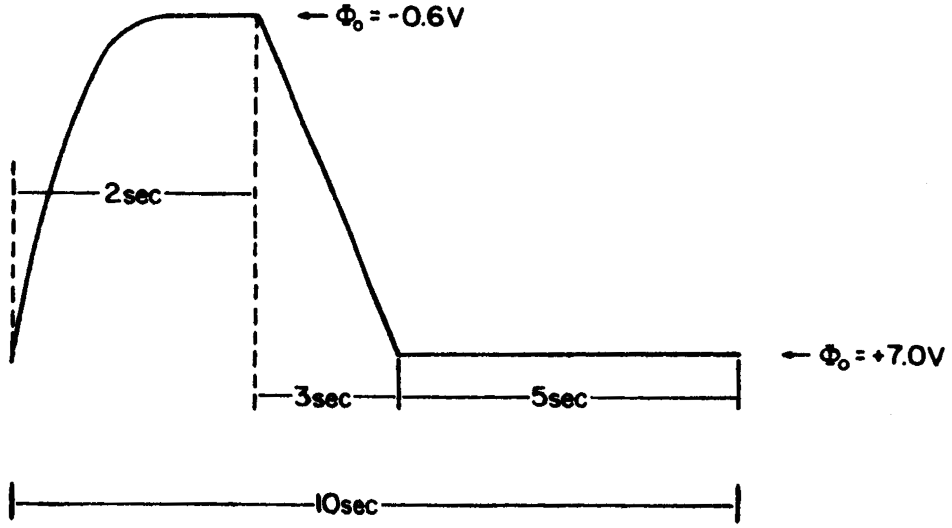
With this in mind, a bipolar probe system capable of measuring ion densities in the region 40 to 80 kilometers is described and evaluated. The philosophy of its design and construction is discussed. A continuum probe theory is used and the commonly used free-molecular ram theory is discarded. Experimental results from an Arcas rocket shot are presented and errors resulting from compressibility effects, angle of attack, and photo-emission are discussed and estimated. The possibility of measuring electron and negative ion densities with the present probe system is investigated, and future work is discussed.

II. EXPERIMENTAL TECHNIQUES

A. Description of Experiment

The launch vehicle employed in this program is the Arcas meteorological rocket. This rocket is routinely used for wind and temperature measurements and has been proven capable of high reliability. Its payload capabilities and low cost make it an excellent choice as the carrier for this program. The Arcas is designed to carry a parachute-borne payload for ejection near apogee, which is about 75 kilometers. A booster for the Arcas is available when wind conditions and/or altitude requirements justify its use. The rocket launchings are done in conjunction with the United States Army Electronics Research Development Activity at White Sands Missile Range, New Mexico.

The probe is activated and calibrated on the ground just prior to launch, although a certain amount of in-flight calibration is possible. The probe collecting surface potential varies from about -7.0 volts to +0.5 volts according to the pattern illustrated in Figure 1, and with a period of about 10 seconds. Current data from the probe is telemetered to the ground, and the probe's space-time coordinates are obtained via a continuous radar track throughout its trajectory. These current and radar data provide the information necessary to compute ion density as a function of altitude.



PROBE POTENTIAL SWEEP PATTERN USED IN PRELIMINARY SHOTS. TIMES SHOWN ARE APPROXIMATE.

FIGURE 1

B. Probe Geometry

The probe geometry chosen should meet several criteria:

(1) Low-cost and simple construction

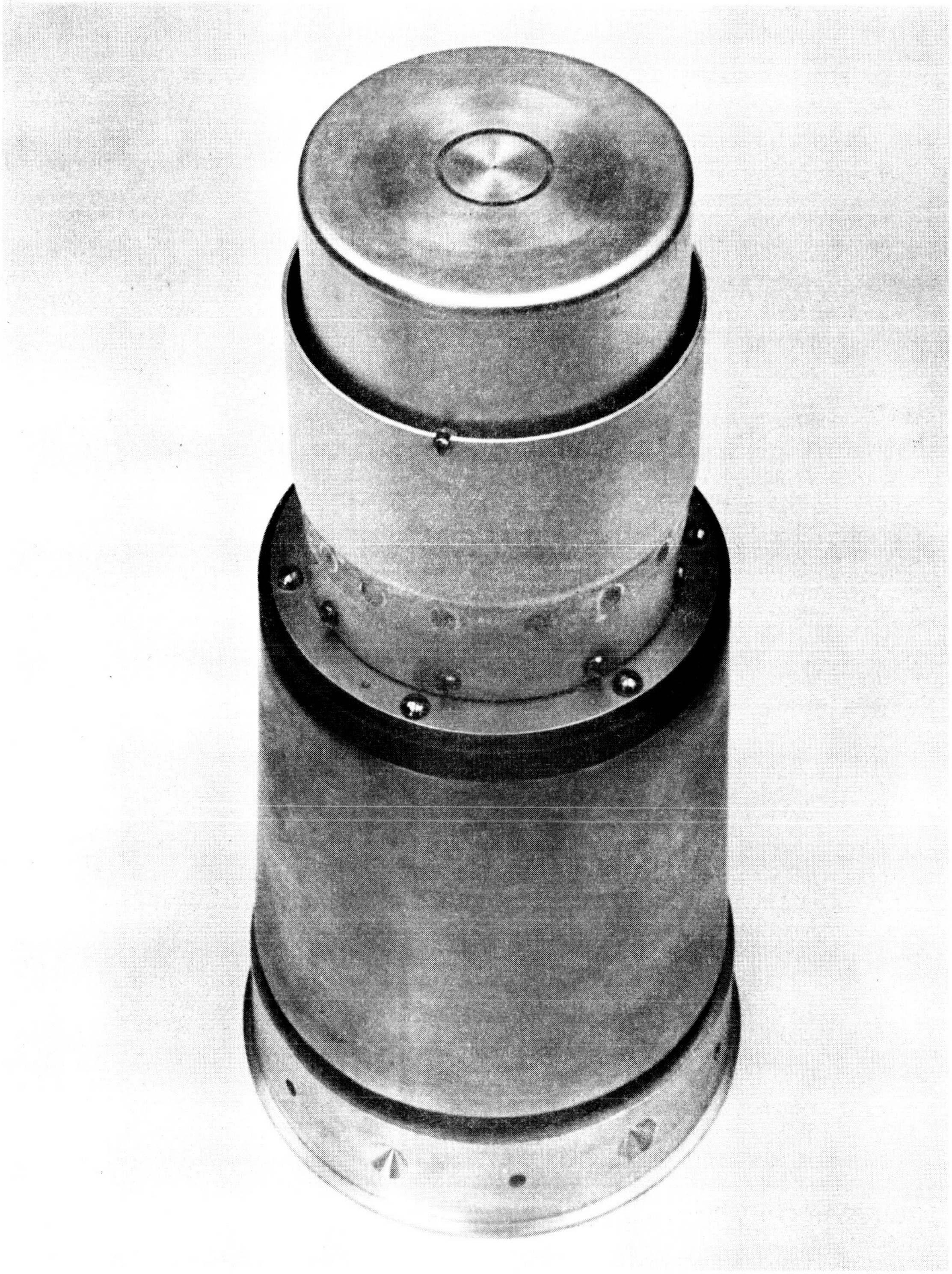
(2) Size and weight compatible with rocket payload requirements, yet sufficient space for electronics

(3) Amenable to straight-forward theoretical description

(4) Insensitive to angle of attack

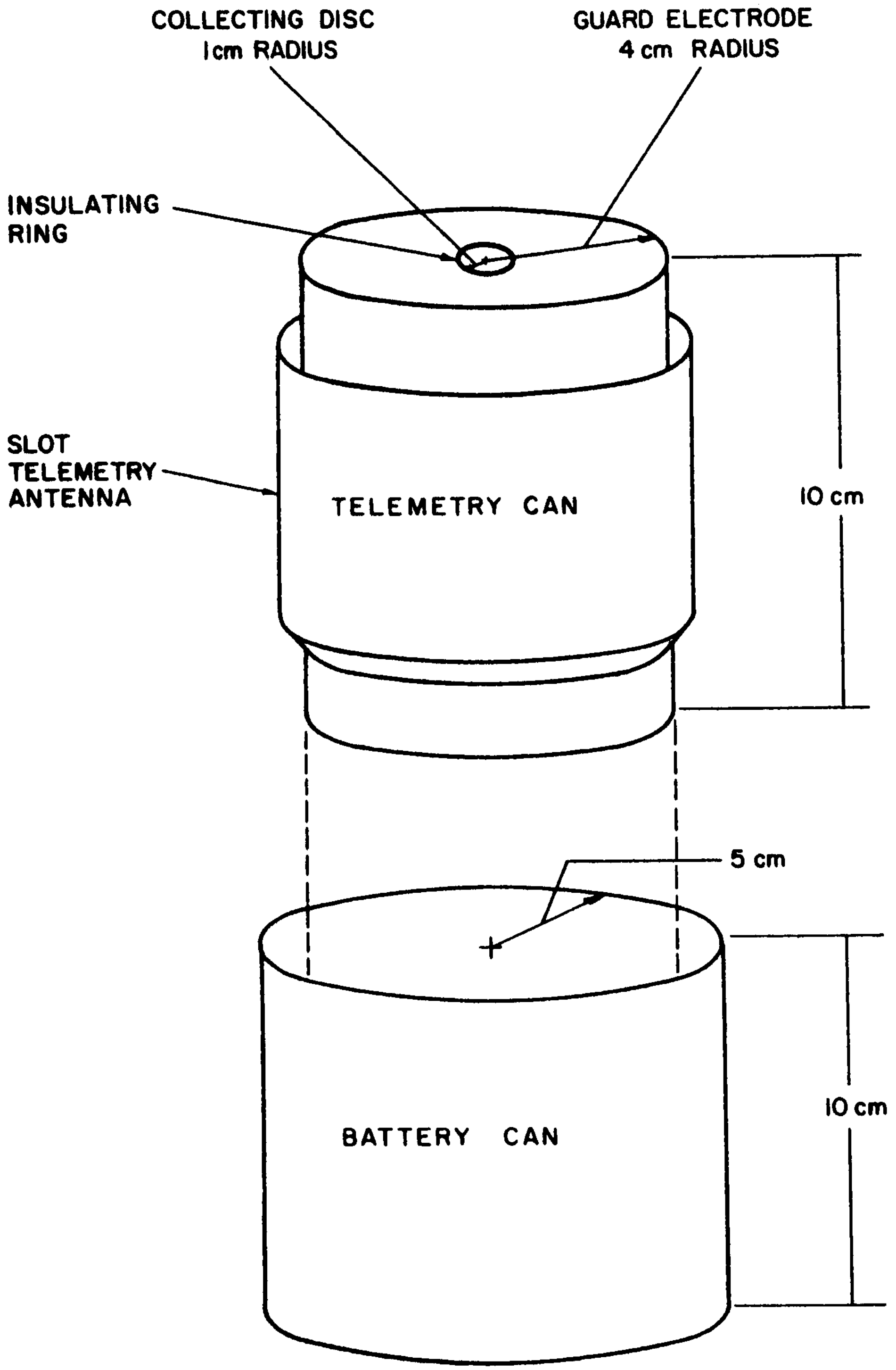
(5) Unaffected by photo-electric effects.

The geometry chosen is shown in Figures 2 and 3. It is in the form of a blunt cylinder with a planar collecting surface. The lower and somewhat larger can contains the batteries for the telemetry system and serves as the return electrode for the bipolar probe. The upper can contains the probe electronics and experimental batteries, and acts as the primary electrode. The sleeve on the side of the upper can is a slot telemetry antenna, which was developed to provide an adequate radiation pattern consistent with clean geometry. A hole is cut in the upper planar surface. The actual collecting disc is centered within this hole and insulated from the remainder of the can by a narrow insulating ring in such a manner as to maintain the disc flush with the surrounding surface. The remainder of the upper can is at the same potential as the collecting electrode and hence acts as a guard surface in the sense that it maintains the planar electrical characteristics of the collecting electrode. The upper can and collector are at a known potential with respect to the lower can, enabling current versus voltage data to be obtained. The parachute



ASSEMBLED PROBE ASSEMBLY
LESS PARACHUTE

FIGURE 2



DETAILS OF PROBE ASSEMBLY
FIGURE 3

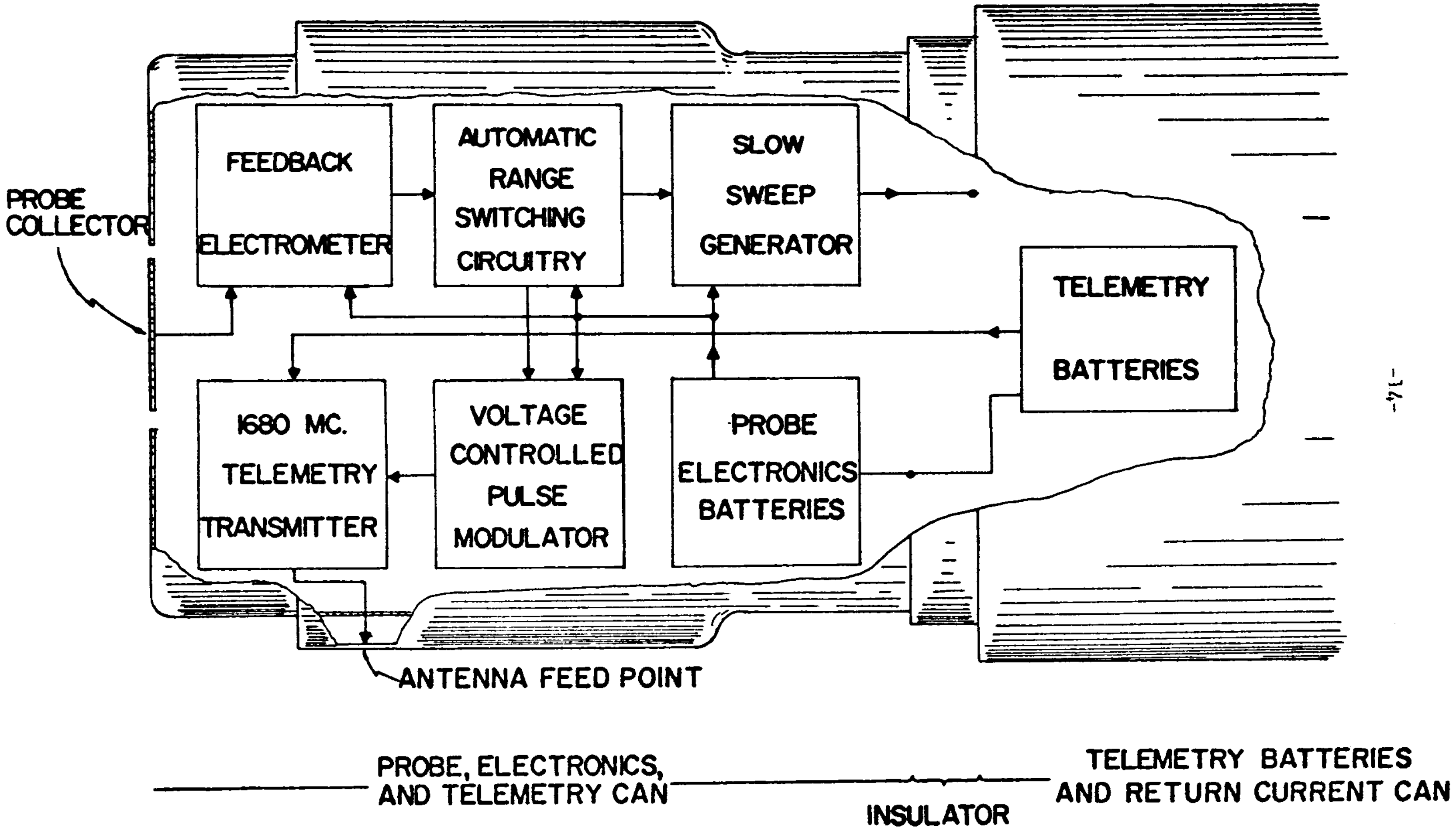
attaches to a plate at the bottom of the lower can such that the entire assembly hangs inverted with collector down. This orientation permits straight-forward description of the medium flow pattern about the probe, and shields the collector from solar radiation and the resultant contaminating photo-currents.

It has been shown by Hoult (1965), that the geometry described above is insensitive to angle of attack. The "Gerdien condenser" and other angle of attack sensitive devices suffer from errors resulting from the swinging of the probe-parachute assembly upon descent, and from the fact that the probe velocity and wind velocity vectors are not in general in the same direction, even under no-swing conditions.

Both the upper can with its collector, and the lower can, are constructed of aluminum, and the entire assembly (less parachute) weighs approximately 2 kilograms.

C. Probe Electronics and Telemetry

A block diagram of the probe electronics system is shown in Figure 4. This system was principally designed by Hale (1965). A sensitive feedback electrometer is used to improve frequency response and to hold the collecting disc at a fixed potential. An automatic range-switching circuit is employed in order to measure a wide dynamic range of positive and negative currents, the usable range being about $\pm 10^{-13}$ to $\pm 5 \times 10^{-11}$ amperes. The use of the automatic range-switching circuit provides an inflight calibration, the switch points always occurring at known current values. Also, the circuit permits the use of the low-cost



PROBE ELECTRONICS AND TELEMETRY

FIGURE 4

"radiosonde" 1680 mc/s telemetry transmitter used on weather balloons, since there is no need for a multichannel IRIG system. A transistorized, voltage controlled, blocking oscillator pulse modulator for the transmitter, slow voltage sweep generator, and voltage regulation (about one part in 10^4) circuitry complete the electronics package. The telemetry antenna is in effect a $.925\ \lambda \times .25\ \lambda \times 1/8''$ slot wrapped around the electronics can in the form of a sleeve, and provides an adequate, relatively null-free, radiation pattern.

D. Data Acquisition and Reduction

The data acquisition system is currently undergoing considerable improvement. The telemetry ground station is a modified TMQ-5 meteorological system. This system, designed for the radiosonde units launched on weather balloons, has been considerably upgraded by the United States Army Electronics Research and Development Activity at White Sands Missile Range. The recent addition of a parametric amplifier insures quite noise-free reception on future launch operations. The probe telemetry pulse-modulated signal is received by this system and recorded simultaneously with range time upon a dual-channel tape recorder. The taped telemetry data is capable of a frequency response of about 50 cycles per second. This in principle enables fine structure in the current data (and therefore in the medium) to be carefully studied as a function of time and altitude. The probe radar track is performed by radar equipment at White Sands and gives digital position, velocity, and acceleration data every one-tenth of a second throughout the flight.

The taped telemetry data is played back through a noise filter of adjustable characteristics and into a Sanborn dual-channel recorder. This gives a detailed plot of current versus time. The initial probe calibration also appears on this chart enabling straightforward calibration. A check on this calibration is afforded by studying the automatic range-switching points which occurred during flight, since these points always occur at known current values. A portion of a current-time chart is shown in Figure 5. The conversion of current-time data to current-altitude data is accomplished via the radar space-time data. This completes the initial data reduction, the next step being the conversion, by means of the appropriate probe theory, to ion density versus altitude data.

PORTION OF CURRENT VS. TIME CHART

FIGURE 5

III. THEORETICAL CONSIDERATIONS

A. D-region Probe Theory

As stated previously, the probe theory appropriate to altitudes below 80 kilometers should refer to a subsonic probe, and should be a continuum theory. Such a theory has been carried out by Hoult (1965) for a blunt probe operating at high potential, moving in an incompressible, collision-dominated medium. The results of his analysis will be summarized here.

Previous continuum probe theories, for example, Lam (1964), are not applicable to D-region work in that they ignore negative ions and refer to a medium having much higher charge densities than are present in the D-region.

Considerable simplification results from the two following conditions, which are true for the probe described below 80 kilometers:

(1) The ionization density is so low that the potential due to the probe is described by Laplace's equation ($\nabla^2 \phi = 0$).

(2) The probe velocity, although not supersonic, is large enough that convection of charged particles dominates electrical mobility and diffusion effects until well inside the viscous boundary layer.

The first condition states, in essence, that even very near the probe where medium neutrality is not maintained, the net charge density is so small as to permit Poisson's equation to reduce to Laplace's equation. This condition serves to completely uncouple the potential problem from the hydrodynamic flow and charge transport problems. The second condition enables the charge transport problem to be reduced to one governed by the electric field at the probe surface.

It is shown that the principal component of current to the planar probe considered, at high negative potential, is given by

$$I^{+} = An^{+}eK^{+}E_{w} \qquad (1)$$

and is a positive ion current. Here E_{w} is the electric field at the collector surface, A is the collector area, e is the electronic charge, and n^{+}, K^{+}, and I^{+} are respectively ambient positive ion number density, mobility, and current.

A similar result is derived for a highly positive probe under daytime conditions

$$I^{e} = An^{e}eK^{e}E_{w} \qquad (2)$$

and is an electron current. Here superscript e denotes electron. The terms "highly positive" and "highly negative" refer to the condition

$$\frac{e\phi_1}{kT} >> 1$$

where ϕ_1 is the collector potential, k is Boltzmann's constant, and T is the neutral gas temperature.

A small negative ion current will reach the probe in both high positive and high negative potential cases, but it is too small to distinguish from the principal components of probe current by simple techniques, under daytime conditions. It should be pointed out that the situation under nighttime conditions may be quite different. At night, D-region electron densities are extremely small, and possibly small enough to allow negative ions to dominate the current to a positive probe.

A simple way of looking at the results of this theory is as follows: The viscous flow maintains a stagnant sample of the medium near the surface of the probe. Convection into this region maintains an ionization density not greatly different from the density of the ambient medium, at which point electrical mobility becomes the dominant process.

Note that the use of a free-molecular flow theory (current = area x velocity x number density x charge) can be in error by a factor of 10 for a negative probe and by a factor of 100 for a positive probe.

Since the electric field at the surface of the probe collector shown is given by

$$E_W = \frac{2\phi_1}{\pi a}$$

where a is the total probe guard ring radius, equations (1) and (2) may be put into a form more convenient for the calculation of number densities as follows:

$$n^+ = \frac{\pi a I^+}{2eA\phi_1 K^+} \qquad (3)$$

$$n^e = \frac{\pi a I^e}{2eA\phi_1 K^e} \; . \qquad (4)$$

A most important result of the above theory is that equations (3) and (4) are independent of angle of attack. This means that pendulum-like swinging of the probe-parachute assembly has no effect upon the current collected and thus causes no error in number density measurements.

B. Ionic Mobilities

Equations (3) and (4) indicate that the important quantities to be evaluated are positive ion and electron mobilities, K^+ and K^e. This paper will concern itself with the determination of K^+, since the data to be presented is positive ion data.

The parameter generally associated with the concept of mobility is the ratio of electric field to ambient pressure (E/P), and is a measure of the mean energy of impact of the drifting ions. It is well known that ionic drift velocities in air are essentially linear in E/P at a given temperature for $E/P \lesssim 200$ volts/ (cm-mmHg) (Varney, 1953). This fact leads to the definition of mobility

$$K = \frac{v_D}{E}$$

where v_D is the ionic drift velocity, and the quantity KP (mobility times pressure) is a constant for a given temperature. Since K is inversely proportional to pressure (and therefore number density, n), it is customary for reference purposes to define a reduced mobility, K_0, referred to the number density $n_0 = 2.69 \times 10^{25}\ m^{-3}$ and temperature $T_0 = 290^0K$. With this definition we have

$$K = \frac{n_0}{n} K_0 \qquad (5)$$

It will be assumed that the dominant positive ions present in the D-region are N_2^+, O_2^+, and NO^+. The mobility of NO^+ in air may be calculated for temperatures less than about 300^0K to good accuracy, probably within 10 % . The calculation, due to Dalgarno (1961), gives the reduced mobility of NO^+ in air as

$$K_0^+ \ (NO) = 1.9 \times 10^{-4} \ \frac{m^2}{\text{sec-volt}}$$

The situation in the case of ions moving in their parent gas is by no means so simple. Charge transfer effects between ion and parent molecule prevent the derivation of a general formula describing the mobility of such an ion. However, a limited amount of experimental data is available for the ions O_2^+ and N_2^+ in their parent gases. Dalgarno (1961) has reviewed the available data for O_2^+ in O_2 and has arrived at the value

$$K_0^+ \ (O_2) = 1.9 \times 10^{-4} \ \frac{m^2}{\text{sec-volt}}$$

This value is probably good to within 20 %.

There are no measurements of K_0 for N_2^+ for values of E/P less than about 100 volts cm^{-1} $mmHg^{-1}$. The behavior of nitrogen ions at low E/P values has been explained by Varney (1953) as due to the presence the ion N_4^+ . At high E/P values, N_4^+ is dissociated into N_2^+, but at lower values of E/P, N_4^+ seems to be the dominant ion. The dominance of N_4^+ at low E/P has been confirmed by Saporoschenko (1958), who employed a mass spectrometer in his investigation of the ions of nitrogen. His work also revealed the presence of N_3^+ at intermediate values of E/P. The measurements of Varney (1953) indicate that the mobility of N_4^+ is nearly twice that of N_2^+. The question arises as to whether or not such exotic ions as N_3^+ and N_4^+ are present in significant numbers in the ionosphere, or whether they are peculiar to laboratory conditions. The low stability of these ions would indicate that their number is small compared to the number of N_2^+ ions. Nevertheless, in the absence of definitive ionic composition measurements in the D-region, it is difficult to rule out any possibility. Assuming that N_2^+ is the dominant nitrogen ion, the estimate of Dalgarno (1961) for the mobility of N_2^+ in air may be used. Based upon the measured mobility of O_2^+ in O_2, Dalgarno has arrived at the value

$$K_0^+ \, (N_2) = 1.5 \times 10^{-4} \, \frac{m^2}{\text{sec-volt}}$$

for N_2^+ in N_2. If the mobilities of N_2^+, O_2^+, and NO^+ are averaged, taking into account their expected relative abundances, a value of

$$K_0^+ = 1.7 \times 10^{-4} \, \frac{m^2}{\text{sec-volt}}$$

is arrived at as a representative value for the reduced mobility of positive ions in the D-region. This value has been used in the calculation of positive ion densities from equation (3).

It will be noted that equation (5) expresses no temperature dependence for mobility. There is, in fact, a small mobility temperature dependence, although for the ions considered the functional form of this dependence is not clear. Dalgarno (1961) has indicated that the temperature dependence of K^+ (NO) is roughly $T^{\frac{1}{2}}$ for $T > 300^\circ K$, with a more complicated but weaker dependence for lower temperatures. The temperature dependences of K^+ (O_2) and K^+ (N_2) are virtually unknown, although the work of Kovar, Beaty, and Varney (1957) indicates a small increase in mobility with decreasing temperature in the case of N_2^+. In view of the above it was thought unwise to include any sort of temperature dependence in equation (5).

C. Heavy Ions

There is evidence, as pointed out in the introduction, indicating that appreciable numbers of "heavy" ions may be present in the D-region. Because of their extremely small mobilities it would be expected that all such particles would be collected to a planar probe by some sort of "ram" process. Assuming no secondary emission from the probe surface, and that these heavy ions are predominately negative, we would conclude that the heavy ion current to the probe would be angle of attack dependent, as characteristic of any ram collection process. If these heavy ions exist in numbers comparable to those of simple ions, we could expect to observe this angle of attack dependence in the current-time characteristic telemetered from the probe, as an oscillatory phenomenon having a period comparable to that due to the swinging motion of the probe.

D. Photo-electric Effects

In the case of a bipolar probe in a charged particle environment containing electrons and ions, it is well known that, if the probe surfaces have comparable area, the more positive electrode will aquire a slightly positive potential with respect to the medium, while the more negative electrode will rise to a high negative potential. This is because the electrons which carry current to the positive electrode have a much greater mobility than the ions which carry current to the negative electrode. In effect, a low impedence connection is provided between the positive electrode and the medium.

In the presence of solar radiation capable of producing photo-electric currents, this situation may be drastically altered. The greater photo-current will flow to the less negative electrode, and this current will be carried by the high mobility photo-electrons. If this photo-current is sufficiently large, it may dominate the environmental effect described above. The equilibrium situation may be with the more negative electrode near space potential, or even positive with respect to it, and the more positive electrode at a large positive potential, giving a large electron current to balance the photo-current to the more negative electrode.

The probe used in this experiment is oriented such that sunlight cannot fall upon the collecting disc with a moderately high (about 60° zenith angle) sun and normal swinging motion of the probe. However, sunlight does fall upon the cylindrical sides of the probe, and it must be remembered that the entire lower can is swept with a potential with respect to the entire upper can, even though the current to these side surfaces is not directly measured. In order to estimate the importance of the effect described in the previous paragraph, the equilibrium potential of the probe was estimated as follows.

The equilibrium current balance to the probe is

$$I_1^e - I_1^{ph} - I_1^+ + I_1^- = -I_2^e + I_2^{ph} + I_2^+ - I_2^-. \qquad (6)$$

Here, and in the discussion which follows, subscript 1 refers to the upper can containing the collecting electrode, and subscript 2 refers to the lower electrode. Superscripts e, ph, +, and - refer respectively to electrons, photo-electrons, positive ions, and negative ions. Also

I = current

ϕ = potential

A = electrode area

J = current density.

Consider $\phi_1 < 0$, $\phi_2 > 0$, where $\phi_2 - \phi_1 = \phi_0$ and ϕ_0 is the potential difference maintained by the probe electronics (about +7.0 volts). Under these conditions we can approximate (6) by

$$I_1^+ + I_1^{ph} = I_2^e - I_2^{ph}$$

or

$$A_1 J_1^+ + A_1^{ph} J_1^{ph} = A_2 J_2^e - A_2^{ph} J_2^{ph}$$

where A_1^{ph}, A_2^{ph} represent effective sunlit areas for electrodes 1 and 2. Now $A_1 \approx A_2$ and $A_1^{ph} \approx A_2^{ph}$. Also, under representative sunlight conditions, $A_2^{ph} \approx \frac{1}{4} A_2$. Hence

$$4J_1^+ + J_1^{ph} = 4J_2^e - J_2^{ph}. \qquad (7)$$

From equations (1) and (2) we can approximate

$$J_1^+ = n^+ eK^+ E_1 \text{ and } J_2^e = n^e eK^e E_2$$

where E_1 and E_2 are the electric fields at the cylindrical surfaces, which can be represented as

$$E_1 \approx \frac{\phi_1}{L} \text{ and } E_2 \approx \frac{\phi_2}{L}$$

where L = cylinder length. Since electrode 2 is positive,

$$J_2^{ph} = J_0^{ph} \exp\left(-\frac{e\phi_2}{E_{ph}}\right) \text{ and } J_1^{ph} = J_0^{ph}.$$

Here E_{ph} is a representative photo-electron energy, and J_0^{ph} is the zero-field photo-current.

Under the above conditions, equation (7) becomes

$$\frac{4e}{L}\left[n^e K^e \ (\phi_0 + \phi_1)\right] = J_0^{ph}\left[1 + \exp\left(-\frac{e}{E_{ph}}\ (\phi_0 + \phi_1)\right)\right] \qquad (8)$$

which determines ϕ_1, the collector potential, in terms of the photocurrent density, ambient electron density, and ϕ_0. Equation (8) may be used to estimate the extent of collector potential control due to photo-emission provided estimates of J_0^{ph} and the energy function $\exp\left[-\frac{e}{E_{ph}}\ (\phi_0 + \phi_1)\right]$ are available.

Table 1

Collector Potential (ϕ_1) Computed for Two Values of Potential Difference Between Electrodes (ϕ_0)

	$\phi_0 = +7.0$ V	$\phi_0 = +0.6$ V
Alt. (km)	ϕ_1 (volts)	ϕ_1 (volts)
80	-6.8	-0.1
70	-6.3	+0.4
60	-2.0	+1.1
50	+1.3	+1.8

Although most solar ultra-violet radiation is absorbed above 50 kilometers, radiation in the 2000-3000 Å range penetrates to the ozone layer. This radiation has been found by Bourdeau and Whipple (1965) to produce photo-electric currents of the order of 6×10^{-10} amp/cm^2 at 70 kilometers and 3×10^{-10} amp/cm^2 at 50 kilometers. These currents were not found to be a strong function of the material used, being similar for tungsten and aluminum. Using these photo-electric intensities along with photo-electron energy information obtained by Bourdeau (1965), equation (8) may be evaluated so as to give the equilibrium collector potential for the probe. The electron mobility (K^e) has been determined from electron drift velocity measurements reported by von Engle (1955). Electron densities are those predicted by Nicolet and Aiken (1960).

The results of the calculation are shown in Table 1 above. For comparison the case ϕ_0 = +0.6 volts is also shown. It is seen that under normal operating conditions (ϕ_0 = +7.0 volts), strong photo-control begins at about 65 kilometers, and by the time the probe reaches 50 kilometers the collector potential is positive with respect to the medium. Lowering the value of ϕ_0 worsens the situation as the case ϕ_0 = +0.6 volts indicates. It should be remarked that the calculation performed using equation (8) is conservative in the sense that any refinement which takes into account the effect of the parachute shadow, or a more accurate computation of the electric field on the cylindrical surface (edge effects), would tend to decrease the ratio of photo-current to medium electron current and hence decrease the altitude at which photo-electric control of potential becomes important. Nevertheless, photo-electric control of probe potential is not by any means a negligible effect and must be borne in mind when estimating the accuracy of the ion density data to be presented.

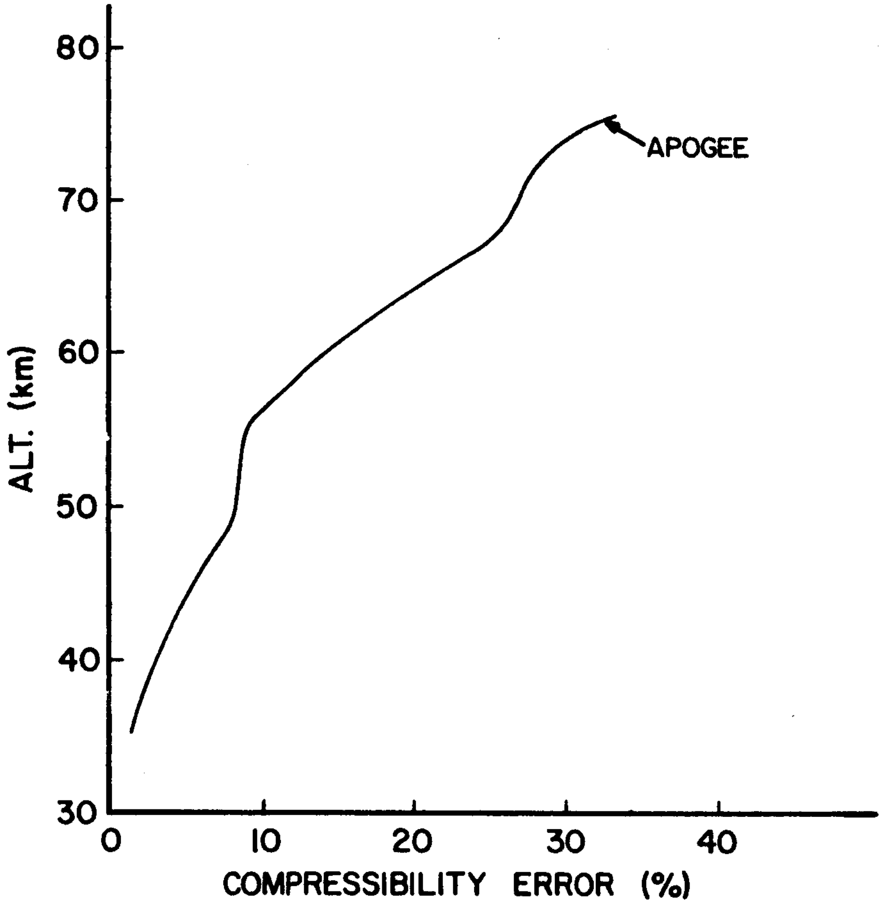
The uncertainty in probe collector potential described above will hopefully be eliminated in future work by covering the probe sides with some sort of material opaque to ultra-violet radiation. The presence of some photo-electric effect has been observed in the day shot of December 11, 1964. This effect will be described later in connection with the data from this shot.

E. Compressibility Effects

As pointed out before, the D-region probe theory described in section III-A neglects the effects of medium compressibility. That is, equations (3) and (4) effectively measure charged particle densities in the flow field of the probe. Since the Mach number for this probe, though less than one, is not small, there exist compressibility effects which tend to increase the number density in the vicinity of the probe (Hoult, 1964). To a first approximation we may estimate compressibility errors with the well-known relation

$$\frac{n_0}{n} = \frac{\rho_0}{\rho} = \left[1 + \left(\frac{\gamma - 1}{2}\right) M^2\right]^{\frac{1}{\gamma - 1}}$$

which results from a consideration of the density change in the medium caused by adiabatically bringing it to rest (Liepmann and Roshko, 1957). Here $\gamma = 1.4$, M = Mach number, ρ = mass density, and the subscript zero denotes conditions far from the probe. Since drag forces decrease the velocity of the probe-parachute assembly as it descends, compressibility errors are larger at higher altitudes. For a typical apogee (about 75 kilometers) the Mach number ranges from about 0.8 at 70 kilometers to about 0.2 at 40 kilometers. Figure 6 gives the approximate percentage compressibility error in number density as a function of altitude for a typical shot.



APPROXIMATE PERCENT ERROR IN NUMBER DENSITY DUE TO COMPRESSIBILITY EFFECTS AS A FUNCTION OF ALTITUDE FOR A TYPICAL SHOT (APOGEE ABOUT 75 km.)

FIGURE 6

IV. EXPERIMENTAL RESULTS

A. Developmental Launches

Four developmental launches have been made at White Sands Missile Range of the probe system described, the first of which in September, 1964. Probe operation was apparently normal, as indicated by subsequent recovery of the payload in working order. No data was received during the interesting portion of the flight due to interference from a weather balloon operating on the same frequency. On December 16, 1964 a launch was made using a Sirocco rocket. The resulting data was very noisy, perhaps because the payload functioned in a more severe environment, the Sirocco being a much higher acceleration vehicle than the Arcas.

The first successful shot took place at 11:05 AM MST on December 11, 1964. Apogee was 75.2 kilometers, and the probe appeared to function normally to below 40 kilometers. A radar track of the entire descent was obtained and clean telemetry data received during most of the flight.

On March 22, 1965 at 3:00 AM MST, another Arcas shot was launched. Apogee was about 80 kilometers, and the probe appeared to function normally down to about 40 kilometers. Unfortunately, no digital radar track of the descent was obtained due to an equipment failure. This failure has prevented an accurate current-altitude correlation for this shot.

B. Angle of Attack Effect

Figure 7 is a plot of the raw current data versus altitude for the December 11, 1964 daytime shot. Below about 65 kilometers, it will be noted that a regular, periodic phenomenon is present in the current data. It was not obvious that these oscillations were due to the periodic swinging of the probe-parachute assembly, since the probe theory predicts no dependence of probe current upon angle of attack. It was therefore thought necessary to confirm that these oscillations were not real periodic variations in the medium itself.

To further investigate the oscillations, the natural pendulum period of the probe-parachute assembly was computed and compared with the period observed in the data. The period of a damped pendulum is given by

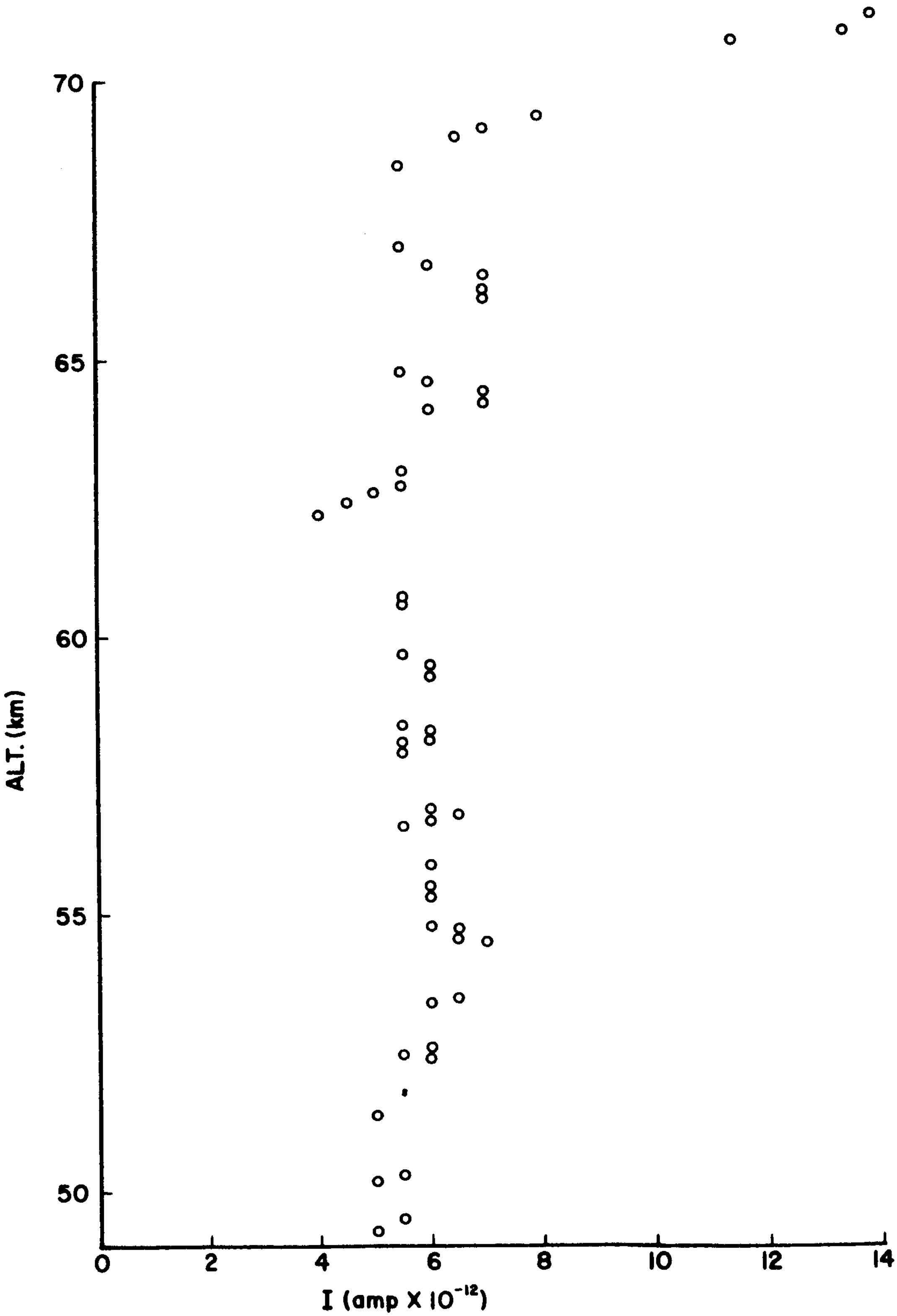
$$\tau = 2\,\pi\left(\frac{g}{\ell} - \kappa^2\right)^{-\frac{1}{2}}$$

where ℓ is the effective pendulum length, g is the acceleration of gratity, and κ depends upon the drag force. The drag coefficient for this parachute is about one or less, and a simple calculation shows that in this case

$$\kappa^2 << \frac{g}{\ell}$$

for altitudes greater than about 45 kilometers. Hence for our purposes

$$\tau = 2\,\pi\sqrt{\frac{\ell}{g}}$$



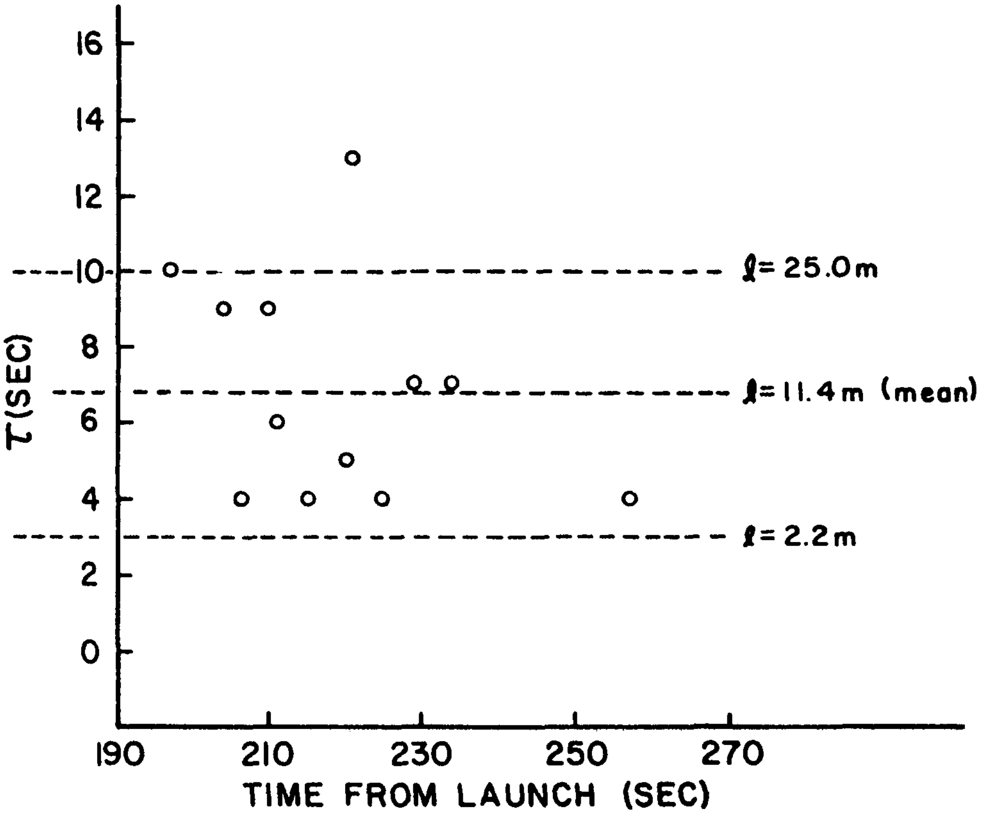
CURRENT VS ALTITUDE, DAY SHOT.
NOTE OSCILLATIONS (ABOUT 10 %)

FIGURE 7

Figure 8 shows the period observed in the data versus time from launch. The horizontal lines indicate the pendulum length, ℓ, corresponding to such a period. (The spread in the periods results from measurements being taken over only a portion of a period, since the collector remains at a constant negative potential over only about half the total ten-second sweep time.) It is seen that a line drawn through the mean of these points corresponds to a period of about 6.8 seconds and therefore a length of $\ell = 11.4$ meters. This agreement with the actual probe-parachute length of about 10 meters is considered excellent, and confirms the hypothesis that the data oscillations are due to swinging of the probe in a pendulum-like manner.

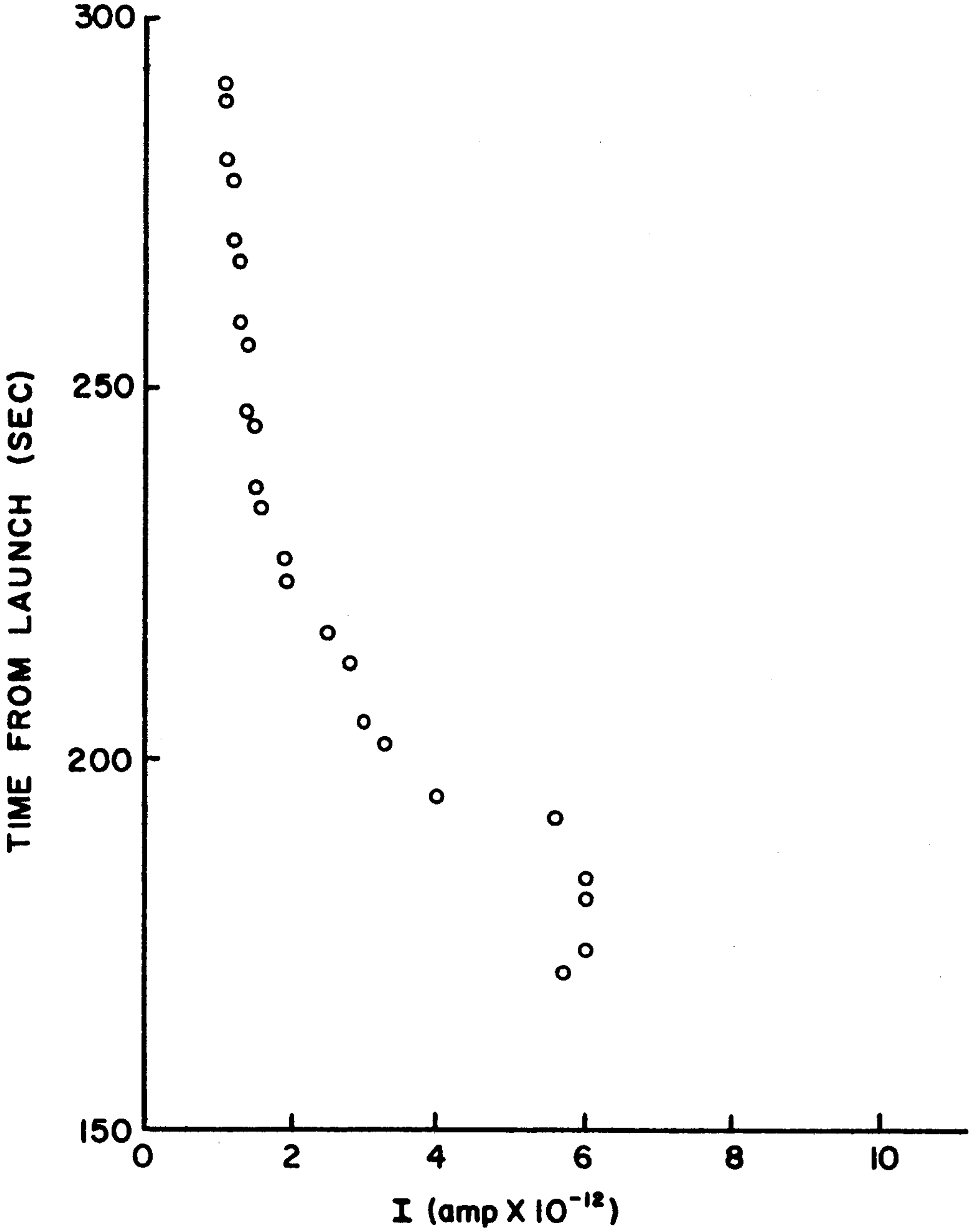
The question arises: Since the probe theory predicts no dependence of current upon angle of attack, how is the apparent dependence described above explained? Two possibilities present themselves. First, heavy ions would be expected to obey some angle of attack dependent ram theory, and large numbers of them could cause the probe to display a significant angle of attack effect. Second, photo-electric control of potential, described earlier, could cause the 10% oscillations in current, even though the control was so weak as to only cause a 0.5 volt difference in probe potential as compared with no-sunlight conditions.

It was felt that the logical way to resolve this angle of attack probelm was to fire a night shot. At night, photo-electric



PERIOD (τ) OBSERVED IN DAYTIME DATA (11 DEC 1964) VS. TIME FROM LAUNCH. HORIZONTAL LINES INDICATE SIMPLE PENDULUM LENGTH CORRESPONDING TO GIVEN PERIOD.

FIGURE 8



CURRENT VS TIME FOR NIGHT SHOT. NO OSCILLATIONS DISCERNABLE. CHART MAY BE READ TO WITHIN ABOUT 2%.

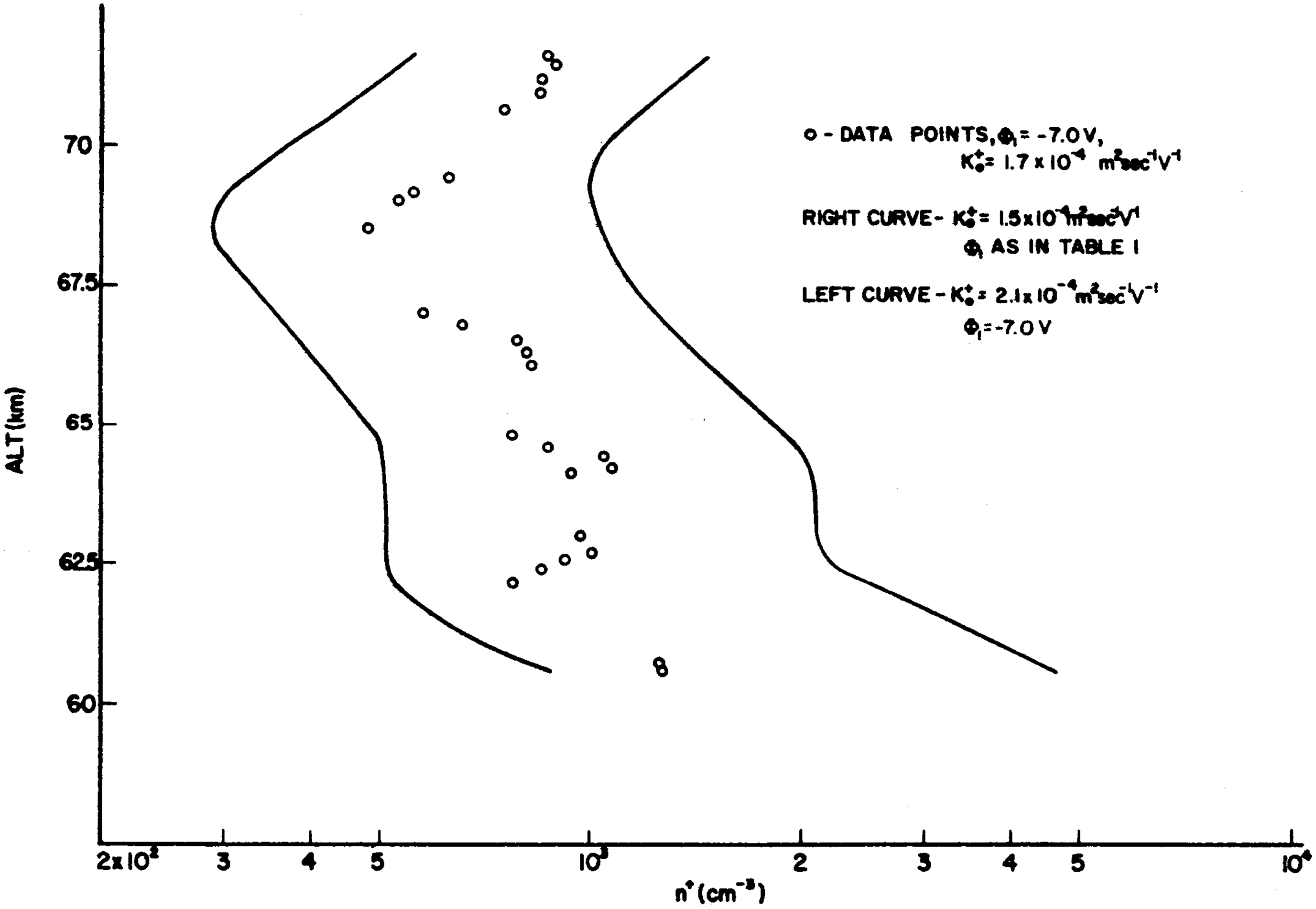
FIGURE 9

effects cannot exist, although one would still expect to encounter significant numbers of heavy ions, if they are of importance.

Such a night shot was fired on March 22, 1965, at 3:00 AM MST. A lack of accurate radar data prevented accurate altitude-time correlation; however, the current versus time data for this shot is shown in Figure 9. Note that the oscillations present in Figure 7 do not appear in Figure 9, even though it is possible to determine current to an accuracy of less than 2%. If the possibility that the probe did not swing is neglected, this night shot gives strong support to the photo-control hypothesis advanced earlier, and it may be concluded that the oscillations observed in the day shot are indeed due to a photo-effect.

C. Positive Ion Density Data

Figure 10 shows the positive ion densities obtained from the Arcas shot of December 11, 1964, at 11:05 AM MST. Radar data indicate that the parachute functioned normally, resulting in a subsonic probe velocity from 74 kilometers down. The probe collector potential assumed in computing n^+ was $\phi_1 = -7.0$ volts, which is equivalent to assuming that the more positive electrode was at space potential. The potentials computed from the current-balance equation (8) and illustrated in Table 1 indicate that this may be a bad assumption, due to photo-control of potential. The dominant positive ions are assumed to be O_2^+, N_2^+, and NO^+, and the corresponding reduced mobility employed is $K_0^+ = 1.7 \times 10^{-4}$ m²/sec-volt as discussed in section III-B. Taking into account experimental errors in the determination of mobility and possible combinations of the ions



DAYTIME ION DENSITY VS. ALTITUDE

FIGURE 10

O_2^+, N_2^+, and NO^+ leads to probable mobility limits of $(1.5 \times 10^{-4} < K_0^+ < 2.1 \times 10^{-4})$ m²/sec-volt. The two error curves in Figure 10 represent upper and lower limits on ion density taking into account errors resulting from photo-control of potential, mobility uncertainty, and compressibility effects.

It is seen that the positive ion density obtained between 60 and 70 kilometers is roughly 10^3 cm^{-3}. A comparison of these results with those obtained by the workers discussed in section I-C show ion densities larger by at least a factor of five than those obtained with the present system. It is felt that the discrepancies between various workers are more likely due to differences in technique rather than to differences in ionospheric conditions, although further work is required to confirm this supposition.

V. SUMMARY AND CONCLUSIONS

The absence of reliable data describing D-region ionization has resulted in the design of a bipolar probe system believed capable of accurately measuring positive ion densities in the region 40 to 80 kilometers. The choice of a planar geometry has resulted in a straight-forward theoretical description of the probe's operation, and the use of a parachute-borne, and hence subsonic, system has eliminated the uncertainties inherent to supersonic probes. An important result of the probe theory is its independence of angle of attack, and resultant insensitivity to the probe's swinging motion upon descent. The high cost and low reliability often associated with probe work have been alleviated through the use of the reliable and relatively inexpensive Arcas meteorological launch vehicle.

The presence of unexpectedly large photo-effects at D-region altitudes has resulted in considerable uncertainty in probe collector potential during daytime shots, and neccessitates either shielding the probe sides from solar ultra-violet radiation or conducting nighttime experiments.

An examination of the day shot of December 11, 1964, revealed a periodic fluctuation in current as a function of time. It was surmised that these oscillations were the result of a photo-effect, and the absence of such oscillations in a subsequent night shot confirmed this hypothesis.

Positive ion density obtained during daytime quiet solar conditions indicate a number density of roughly 10^3 cm^{-3} in the region 60 to 70 kilometers. This value is generally lower than those reported by other workers in this field. The principle error in the ion densities obtained arises from the uncertainty in probe potential resulting from photo-effects.

Future work with this system should resolve some of the difficulties mentioned. The possibility of making accurate measurements of nighttime positive (and possibly negative) ion densities has interesting possibilities. At night D-region electron densities are nearly zero, and the only ionization process operative is the ionization by cosmic rays. These facts greatly reduce the complexity of the important chemistry over that of the daytime. Investigations are being conducted into the possibility of measuring reaction rate coefficients for nighttime processes using the ion density data obtained from this probe system.

At present, the effects of compressibility upon the data have only been indicated by an error estimate. It is hoped that the explicit dependence of ion density upon Mach number may be worked out. Work in this direction is currently being carried through.

The uncertainties in ionic mobilities mentioned earlier can only be resolved by an investigation of the dominant ion species in this region. The development of a mass spectrometer capable of functioning at high D-region pressures is desirable. Identification of the dominant ions should be followed by accurate mobility measurements, either in the laboratory or by some direct ionospheric technique.

The correlation of measured ion density to specific ionospheric reactions will require accurate cosmic ray ionization measurements in the D-region. Present available data are estimates based upon balloon measurements below 40 kilometers.

Acknowledgments

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