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IONOSPHERIC RESULTS WITH SOUNDING ROCKETS AND THE EXPLORER VIII SATELLITE (1960 ξ)

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SUMMARY

A review is made of ionospheric data reported since the IGY from rocket and satellite-borne ionospheric experiments. These include rocket results on electron density (RF impedance probe), D-region conductivity (Gerdien condenser), and electron temperature (Langmuir probe). Also included are data in the 1000 kilometer region on ion concentration (ion current monitor) and electron temperature from the Explorer VIII Satellite (1960 ξ). The review includes suggestions for second generation experiments and combinations thereof particularly suited for small sounding rockets.

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IONOSPHERIC RESULTS WITH SOUNDING ROCKETS AND THE EXPLORER VIII SATELLITE (1960 ξ_1)*

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INTRODUCTION

Since their advent as tools for conducting research in the earth's environment, the importance of rockets in many scientific disciplines has become increasingly apparent. With reference to ionospheric studies, the CW propagation experiments of Jackson and Seddon (Reference 1) have yielded electron density profiles with much better altitude resolution than was previously obtainable from ground-based ionosondes. The resulting improvement in the interpretation of ionosonde data (Reference 2) is particularly important in view of the world-wide use of such data for monitoring ionospheric conditions. Through the combining of electron density data with absorption data on the E_o and E_x modes, electron collision frequencies in the D-region were also derived from the above CW propagation experiments. Kane's analysis (References 3, 4) of the data from one of these experiments has led to the best collision frequency model of the D-region. Important, too, has been the work of Johnson, Meadows, and Townsend (Reference 5) whose measurements of both neutral and ionic composition with rocket-borne spectrometers have contributed to a better understanding of dissociative processes in particular and the chemistry of the ionosphere in general.

The impetus of the International Geophysical Year (IGY) has brought about many new experiments, some of which measure the same parameters as those just mentioned, and some of which directly measure other quantities important to a complete description of ionospheric processes. Predominant among the latter are RF impedance probes for measuring electron density, ion current monitors for total ion concentration, Langmuir probes for electron temperature, and Gerdien condensers for D-region conductivity. It is possible to combine these new devices on small sounding rockets with either the

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pre-IGY ionospheric experiments or those developed in other disciplines, to obtain a more thorough explanation of the many remaining ionospheric problems.

For example, combining the RF impedance probe with a CW propagation experiment can provide useful information concerning ionospheric irregularities (Reference 6). Combining an electron temperature probe with a measurement of the kinetic gas temperature can resolve the question of thermodynamic equilibrium. In this respect a valid direct measurement of electron temperature would enhance the value of ground-based radar back-scattering techniques, which hold the promise of continuous monitoring of this same parameter. Combining solar flux measurements in pertinent parts of the spectrum with a measurement of total ion density and with one of the percentage content of the individual ion species should place confidence in the continuity equations. Specifically regarding the problems of the D-region, measurements of charged particle concentrations by techniques particularly adaptable to very small rockets, combined with equally miniaturized techniques for measuring differential absorption, should lead to improved collision-frequency models — including their diurnal and latitude effects. There is also the need to combine a measurement of the increase in ionization in the D-region during solar flares with a measurement of hard and soft radiation fluxes. Equally important is a simultaneous measurement of ionospheric and meteorological parameters.

The present discussion will review ionospheric data from rocket-borne experiments designed to measure electron density, collision frequency, D-region ionization, and electron temperature. Also presented are data from the Explorer VIII Satellite (1960 ξ), which contained experiments that directly sampled the immediate environment of the spacecraft. It will be shown how planned refinements based on both the rocket and satellite results can lead to some important ionospheric studies.

ROCKET MEASUREMENTS OF ELECTRON DENSITY

The theory of the Seddon CW propagation experiment has been treated elsewhere (Reference 1). This remains the most unambiguous method for obtaining the absolute value of electron density as a function of altitude, provided that two requirements are satisfied: (1) the rocket's transverse-to-radial velocity ratio is small, and (2) the ionosphere is unchanging with time (Reference 7). The experiment is most useful, then, on an ascending near-vertical trajectory into an undisturbed ionosphere; however, some important results have been obtained for such ionospheric abnormalities as sporadic E (Reference 8) and auroral ionization (Reference 9). A recent theoretical analysis shows that if full use is made of all the recorded quantities, corrections can be made for the time variations of the ionosphere.

Of the alternative methods of measuring electron density from rockets, the most promising is the RF impedance probe. The probe developed by Jackson and Kane (Reference 10) consists of a shortened dipole antenna; the electron density is computed from a comparison of the probe's in-flight capacitance with its free-space value. As with any technique which makes measurements sensitive only to the vehicle's immediate environment, the accuracy of this method depends on an evaluation of the local disturbance due to the presence of the vehicle. This particular type of disturbance does not significantly affect propagation experiments.

The most accurate measurements of electron density in the United States by the probe method have been obtained by Jackson and Kane (Reference 11), whose results are shown here in Figure 1. It is apparent that the electron densities obtained from the simultaneous CW propagation experiment agree quite well with the ionosonde data. The RF probe data, however, yield electron densities about 50 percent lower.

A recent appraisal (Reference 6) of the correction required for the RF probe data supports a preliminary conclusion that the difference can be explained on the basis of an ion sheath forming about the probe. Two refinements proposed for future flights should reduce this calibration factor even further: (1) a variable bias applied to the probe, thus collapsing the ion sheath (Reference 11); and (2) Whale's suggestion of a "guard ring" that would essentially remove the largest sheath uncertainty (where the probe adjoins the rocket body).

Both the CW propagation and the RF probe experiment are enhanced in value if included on the same vehicle. This is illustrated by Figure 2, in which the electron densities for the same rocket flight are replotted as a function of time from launch. On the ascent portion, the CW propagation experiment provided information on altitude dependency of the correction factor for the RF probe results. At the zenith, the RF probe continued to obtain results where the CW propagation data had large excursions due to the rocket's transverse velocity, by then an appreciable factor. Also, significantly, a comparison of the difference between the two curves on the descent with the difference on the ascent permits the inference (Reference 6) that an ionospheric irregularity existed between the descent and the launch positions. An appropriately timed rocket flight wherein experiments responsive to gross effects are conducted simultaneously with localized measurements would probably narrow down the altitude regions and the time-constants of sudden ionospheric disturbances.

It should be emphasized that in obtaining the RF probe results presented in Figures 1 and 2, care was taken to minimize other errors which the rocket carrier can introduce. Errors due to outgassing were minimized by sealing the propellant tanks after rocket burnout. In rocket flights conducted recently, appreciable errors attributed to outgassing were reported by Pfister and Ulwick (Reference 12).

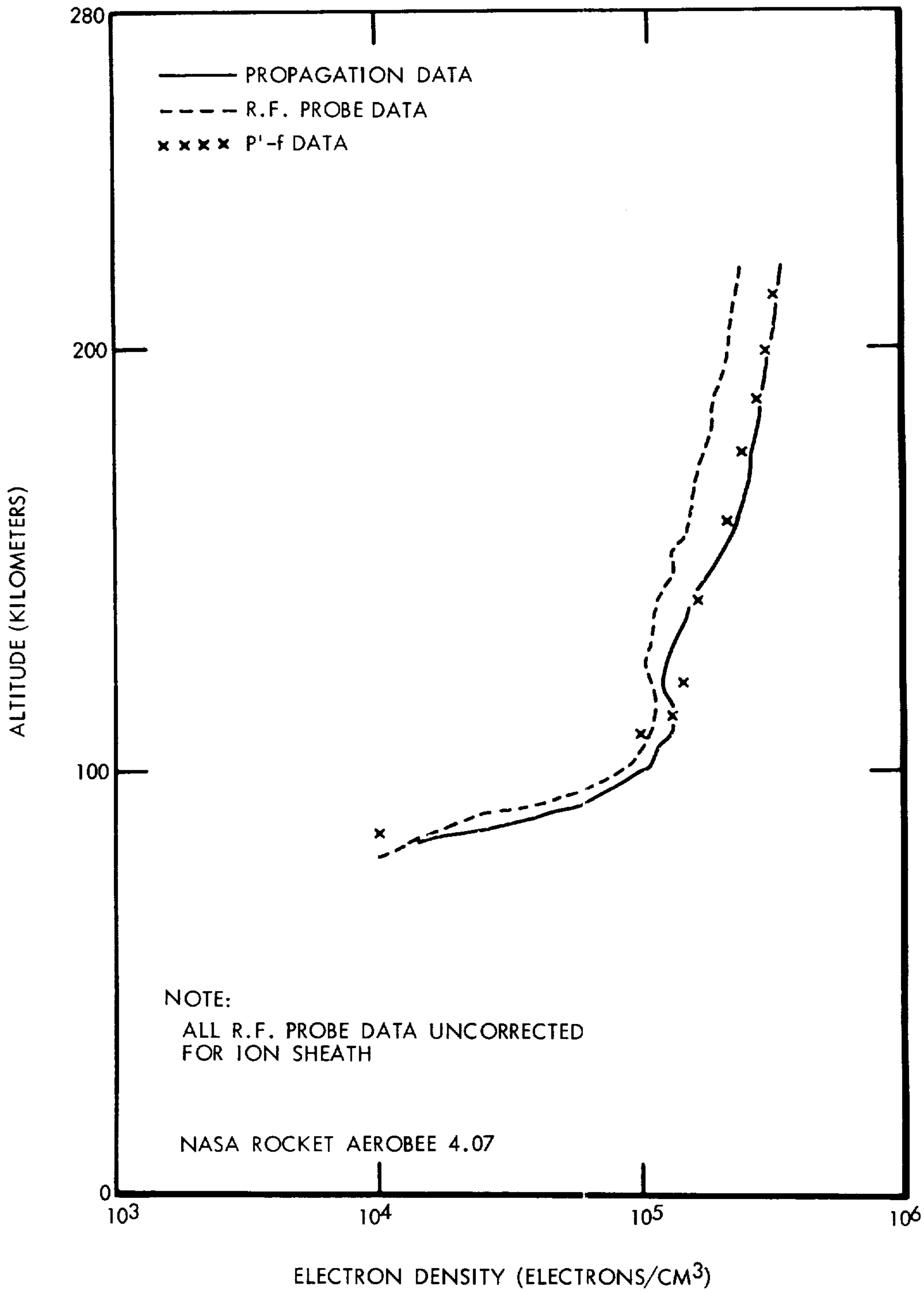

Figure 1 - Electron density versus altitude for Aerobee 4.07

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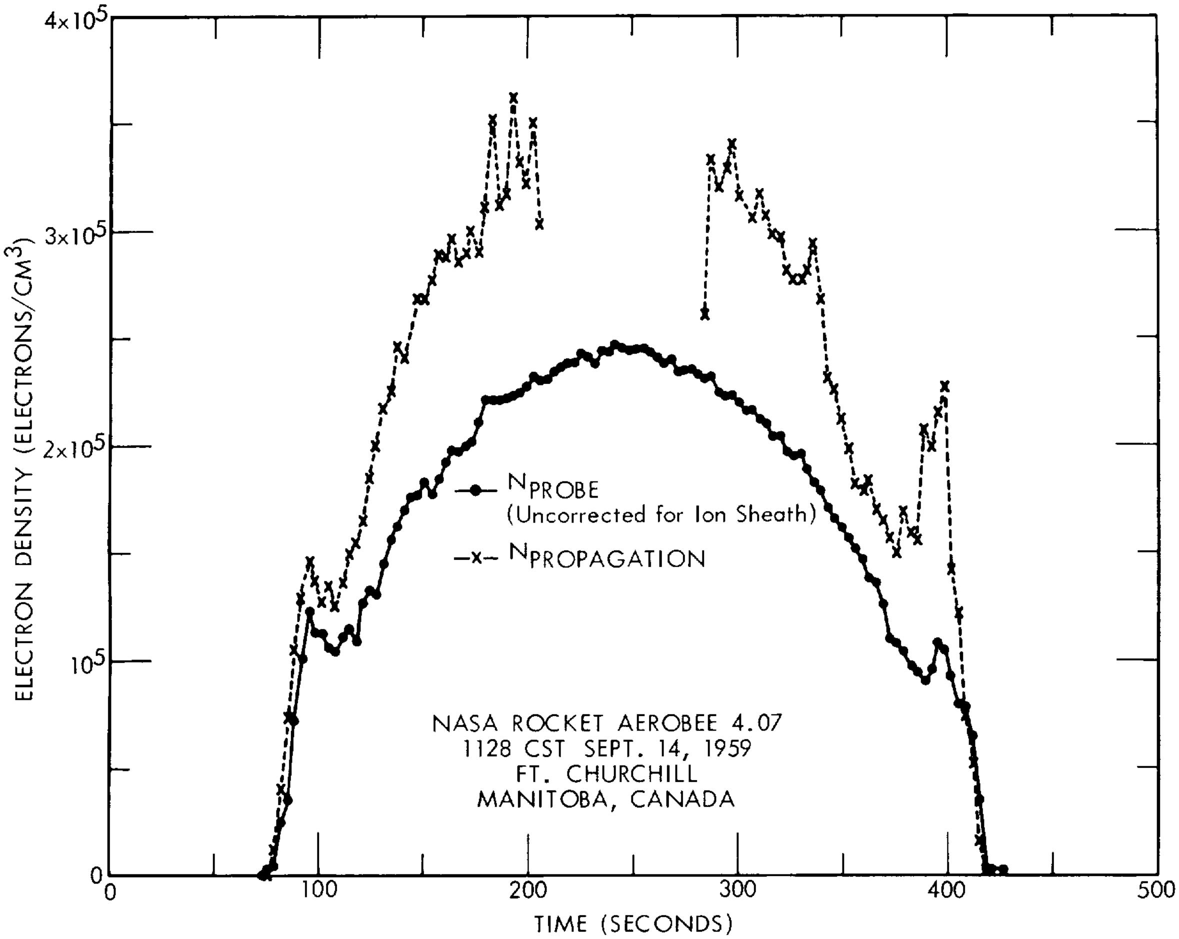

Figure 2 - Electron density versus launch time

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ROCKET MEASUREMENTS IN THE D-REGION

Most studies of the D-region of the ionosphere have been made by either ground-based or rocket-borne propagation experiments. However, the large effects of collision and absorption processes that are characteristic of this altitude region complicate experiments based on radio propagation alone. A knowledge of the ratios of positive and negative ions to electrons is needed for a better understanding of electron production, diffusion and recombination processes. Similarly, more data are needed on the altitude dependency of electron density and collision frequency in order to improve the interpretation of ground-based observations of radio absorption. Recently reported results give cause for confidence that a rocket payload can be developed which, by simultaneous measurement of conductivity, of ion and electron densities, and of collision frequencies, would improve D-region models greatly.

Previously reported results (Reference 13) on the ionic conductivity in the D-region are reproduced in Figure 3. This conductivity is proportional to the product of ionic density and mobility. The experimental rocket results were obtained by use of a Gerdien condenser adapted from those used on aircraft and balloons by workers in atmospheric electricity. The two solid lines are analytic predictions based on the assumption of cosmic rays as the sole ionization source. Below 30 kilometers the analytic curve is computed from the tropospheric value for an ionic molecular weight of 110 AMU; above 30 kilometers it is based on a value of 32 AMU.

Several important conclusions were drawn from these data. First, the agreement of the rocket results with an altitude extrapolation of the balloon results and with the theoretical curve at altitudes up to 50 kilometers lends validity to the experimental method. Second, the experimental data are in support of cosmic rays as the principal source of D-region ionization under normal ionospheric conditions. Future flights during solar flares should shed light on the relative importance of hard and soft ionization sources during disturbed conditions. Finally, the decrease of conductivity in the altitude region corresponding to the temperature inversion region (60-80 kilometers) has been attributed by Whipple (Reference 14) to the presence of particulate matter. His computations of the amount and size of meteoric dust needed to account for this decrease agree with Ludlam's estimate (Reference 15) based on observations of noctilucent clouds.

The decrease in conductivity from that theoretically expected in the 60-80 kilometer region was recently confirmed and similarly interpreted by Smith (Reference 16) in a

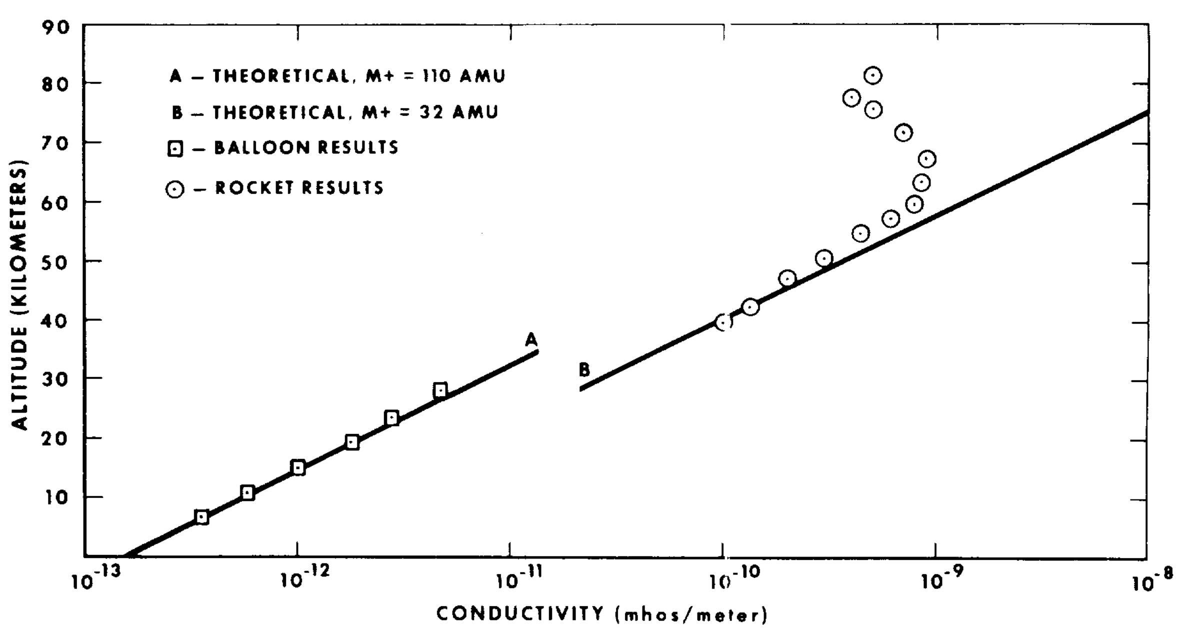


Figure 3 - Ionic conductivity as a function of altitude

recent Nike-Cajun rocket flight wherein the positive ion current flow to an isolated portion of the rocket skin was monitored. Smith's results (Figure 4) agree in the absolute values of measured conductivity at altitudes up to 60 kilometers. As his results show, there is the same general trend, though less pronounced, toward decreased ionization starting at 60 kilometers. These conductivity data are indices of the shape of the electron density profile in the D-region. Kane's electron density model (Reference 4) does show a slight decrease near the 60 kilometer region, although the valley is not as steep as would be expected from the conductivity data. It should be emphasized that the three sets of data were taken at separate latitudes and at different times. Despite the known variability of the D-region, however, the similarity of the trend at the temperature inversion level suggests a meteorological dependency, the likeliest explanation being Whipple's hypothesis of diffusion to particulate matter.

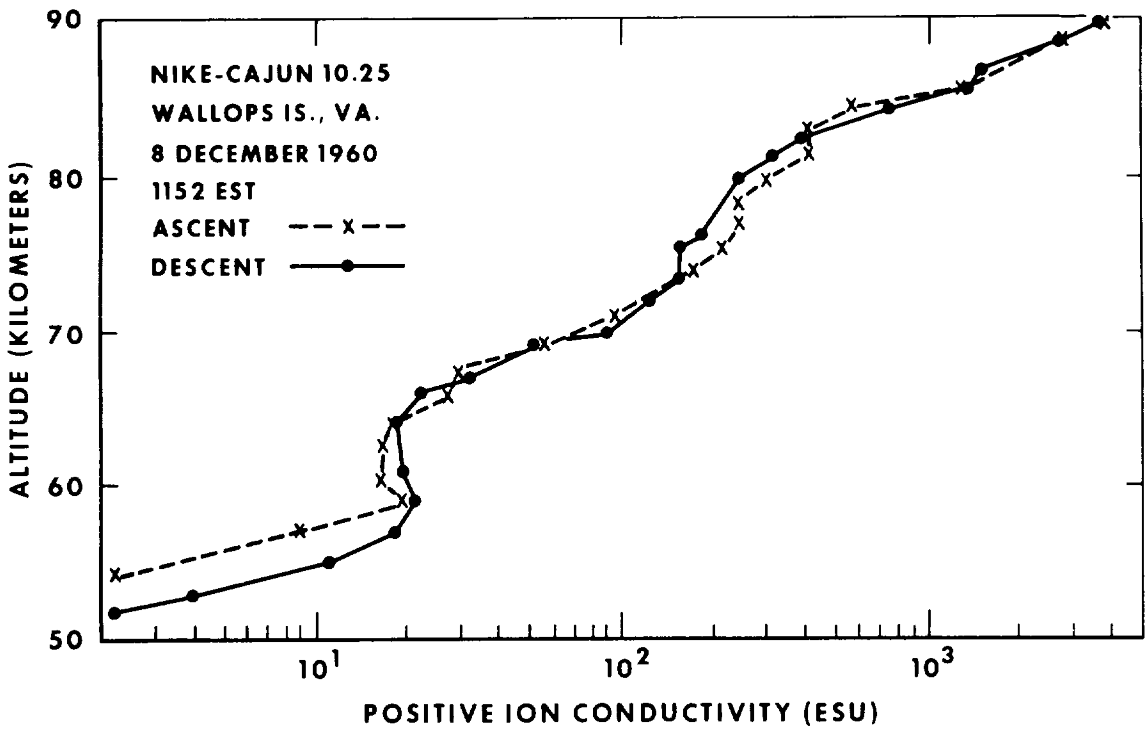


Figure 4 - Recent rocket measurement of ionic conductivity

Ion densities can be computed from the conductivity by assuming an ionic mobility or by a modification to the Gerdien condenser experiment. Despite the non-simultaneity of the data, computations based on conductivity (References 14, 16) generally suggest a preponderance of ions over electrons in the D-region. They indicate a ratio of 30 at 55 kilometers down to 1 at 80 kilometers, in accordance with Mitra's prediction.

With reference to future work, a D-region payload has been suggested which would add conductivity apparatus to the simultaneous measurement of electron density (RF probe) and differential absorption. Kane's latest approach — transmitting from the ground to the receiver — should be an improved method for the differential absorption measurement, from the standpoint both of miniaturization and of circumventing antenna breakdown complications in the critical pressure region. Such a rocket flight would be even more valuable if simultaneous observations could be obtained from an extremely high-powered low-frequency ionosonde.

MEASUREMENTS OF ELECTRON TEMPERATURE

One of the most difficult parameters to measure directly from a rocket or satellite is the ionospheric electron temperature. Since the IGY there has been an accelerated effort in the United States toward rocket application of Langmuir probes for this measurement. In this author's opinion, further evaluation and refinement of the general experimental method are needed before complete confidence can be placed in the past or the future results, particularly those obtained from rockets. However, the exploratory experiments have shown that many of the complications previously believed to be limitations can either be neglected or circumvented. Thus the Langmuir probe does show promise of soon becoming a valuable electron temperature gauge, and has already become a powerful tool for measuring total thermal ionization.

The Langmuir probe experiment depends upon measuring, by first a retarding and then an accelerating process, currents due to electrons with only thermal energies; thus the list of rocket disturbances that obstruct studies of the properties of electrons in their ambient condition is a long one. Including those disturbances which now can be neglected under appropriate experimental conditions, the list is as follows:

1. the effects of RF fields used for telemetry transmissions;
2. outgassing contamination from the rocket carrier;
3. magnetic field effects;
4. the overall retarding effect due to the negative potential which the main body assumes relative to the plasma;
5. aerodynamic phenomena;
6. the presence of negative ions;
7. the ratio of the mean free path to the thickness of the rocket's ion sheath;
8. the presence of positive ions;
9. photoelectron emission (due to solar radiation) from both the probe and the rocket surfaces.

Two types of probes have been flown on rockets by the United States: Serbu (Reference 17) and Smith (Reference 16) have conducted separate rocket flights of an asymmetric probe in which a small planar conductor is one electrode and the main rocket body is the other; the other type is a symmetric bipolar probe ejected from the rocket carrier (Reference 18). The techniques are similar in that the temperature measurement is derived from the electron current to an electrode as its potential is varied.

From comparisons of data taken during RF silence with those taken during RF transmissions on the same rocket flight of an asymmetric probe, it can be seen that — for the telemetry frequency and power used (Reference 16) — the RF field effect can be neglected. The agreement between ascent and descent data from an asymmetric probe (Reference 17) indicates that with proper handling the errors due to outgassing are small. The ejectable bipolar probe should be free of this effect. As will be shown in the next section, the magnetic field effect can be neglected if care is taken to obtain a volt-ampere curve for a minimum change in rocket orientation.

There is still the question of whether the overall retarding influence of a negative rocket could be such that the measured temperatures are those of non-Maxwellian electrons in the higher energy part of the spectrum. All recent rocket flights in the United States, including those of RF ion spectrometers, have consistently shown rocket potentials between −1 and −2 volts relative to the plasma. The existence of the retarding effect favors the use of an asymmetric probe, since at least the area immediately surrounding the electrode is brought to the plasma potential. Neither of the two electrodes of a bipolar probe are permitted to approach plasma potential. Yet the bipolar and asymmetric probe data should agree if the energy distribution is Maxwellian.

There are three effects which could be influential at altitudes below 115 kilometers. First, if the mean free path is small compared to the rocket diameter, there can be problems associated with viscous flow. Such an effect, if it exists, favors the use of the bipolar probe. Secondly, the general Langmuir theory assumes the absence of negative ions, which might be present in significant numbers in this altitude region. Finally, the mean free path must be larger than the thickness of the rocket's ion sheath. All three of these effects, which admittedly might be small, demand a more complete analysis than has been made to date.

Photoemission can be serious unless care is taken in evaluating its contribution to the volt-ampere curve. This is avoided in the asymmetric probe by taking data only when the probe is shaded by the main rocket body. The bipolar probe, however, always has some portion of its electrodes in sunlight. There is also the question of evaluating the contribution of positive ion current to the volt-ampere curve. In rocket flights to date this has been accounted for by assuming a behavior characteristic of the positive ion current as a function of probe potential. If, for example, the positive ion current is treated as a constant function, high electron temperatures are computed (Reference 19).

On the Explorer VIII satellite, both photoemission and positive ion effects were actually removed by appropriate biasing. The use of this second-generation device on small rockets would permit greater confidence to be placed in both past and future results.

Experimentally obtained electron temperatures are compared in Figure 5 with Jastrow's kinetic gas temperature model. The rocket data are presented as a spread of results at specific altitude increments. They include two flights of an asymmetric probe, one by Serbu and one by Smith, and one flight of a bipolar probe. Also plotted are recent data at 1000 kilometers obtained from the second-generation electron temperature probe flown on the Explorer VIII satellite (Reference 20). It should be emphasized that the large spread in the rocket data could be due to the fact that they were obtained under ionospheric conditions, at different times, and at different latitudes.

Kallman (Reference 21) has recently presented a model of neutral scale height and temperature, based on rocket and satellite results, which indicates a diurnal variation.

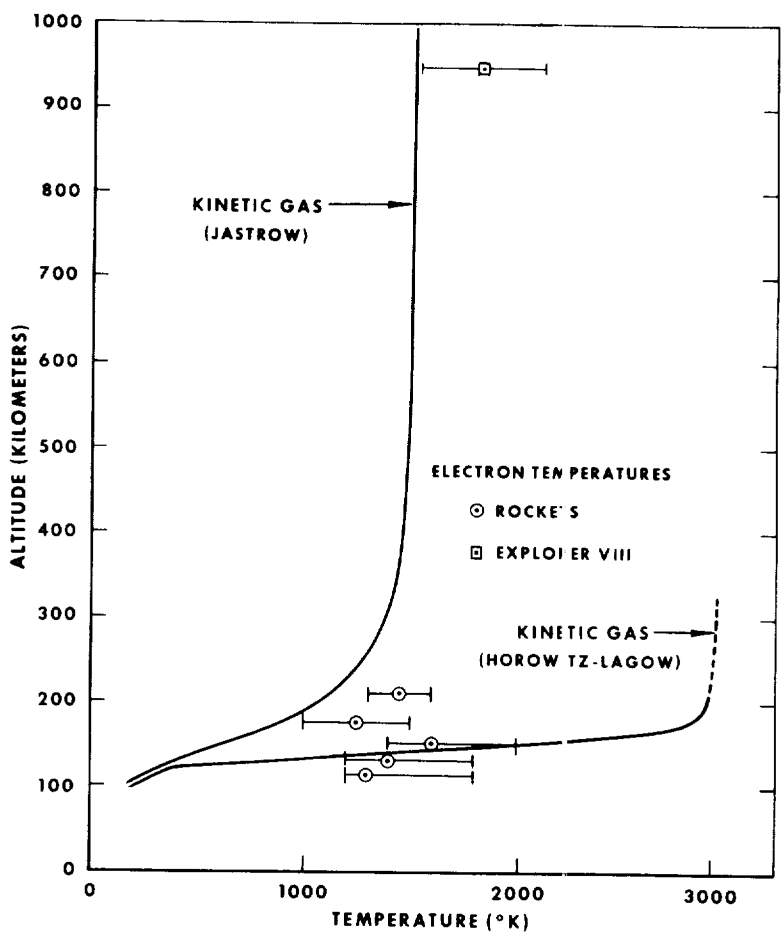


Figure 5 - Comparison of electron with kinetic gas temperature

Her daytime value of temperature in the isothermal region (1800°K) is in exact agreement with the Explorer VIII electron temperature data, also taken in daytime conditions. With regard to the region below 250 kilometers, according to Kallman there is a kinetic gas temperature inversion in the F1 region with a maximum at 180 kilometers and a minimum at about 210 kilometers. A similar pattern appears to occur in the rocket electron temperature data although shifted to lower altitudes. It should be re-emphasized, however, that the rocket results are not yet significant enough, statistically, to permit a firm conclusion.

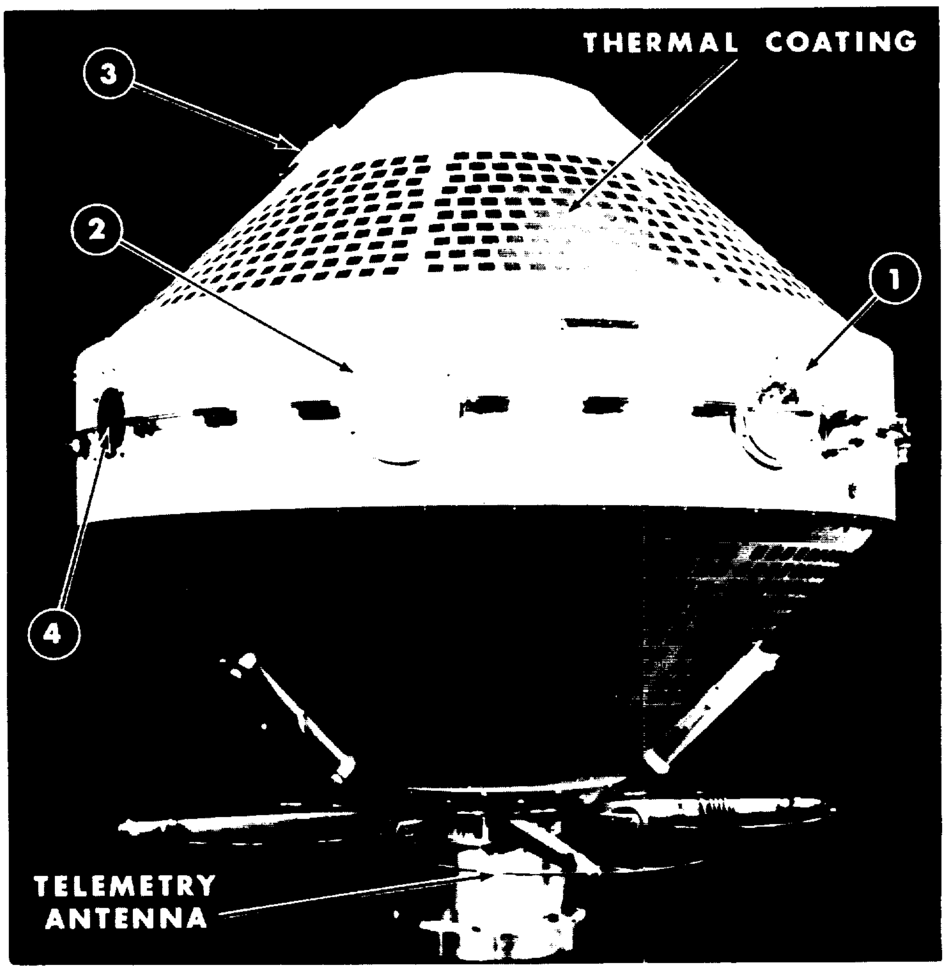
Again regarding the lower altitude regions, the rocket electron temperatures are higher in absolute magnitude than most kinetic gas models, although high values of kinetic gas temperatures have been observed experimentally. Even when those of Horowitz and LaGow (Reference 22) plotted in Figure 5, which assume a constant molecular weight of 29, are corrected for molecular weight distribution, temperatures somewhat higher than Jastrow's will result. Because of the exploratory nature of the rocket experiments and the scarcity of electron temperatures, it is not intended here to make a case for or against thermodynamic equilibrium. Several things must be done before this important question can be resolved.

First, according to current concepts the electron temperature should not exceed the neutral gas temperature, because of the effectiveness with which excess photo-electron energy is transferred to neutral particles. But it is not absolutely certain that all energy transfer mechanisms — one of which could make a case for higher electron temperatures— have been explored theoretically in sufficient detail. Second, there is a need for simultaneous kinetic gas and electron temperature measurements, preferably along with radar back-scattering data after the latter process has undergone further development. Finally, the factors which could introduce errors into the rocket use of Langmuir probes should be evaluated critically. The most significant of these factors are those listed as being effective below 115 kilometers. Important also are possible errors due to positive ion and photoemission currents. These can be eliminated in future flights by a device similar to that used on the Explorer VIII satellite.

THE IONOSPHERE DIRECT MEASUREMENTS SATELLITE

The Explorer VIII satellite was launched from Cape Canaveral on November 3, 1960, into an orbit with a 50 degree inclination to the equator. An active life of two months was planned for this satellite. Of its ten experiments, four are pertinent to this discussion. They were designed to measure the density and temperature of the thermal electrons and the density and mass of the thermal ions, by techniques which depended on sampling the spacecraft's immediate environment.

A photograph of the satellite, indicating the pertinent features, is presented in Figure 6. The aluminum shell, consisting of two truncated cones joined at the equator by a short cylinder, is 30 inches in diameter at the equator and 30 inches high. Both cones have non-conductive thermal coatings in patterns conducive to the maintenance of an equipotential surface. Retracted inside the satellite is a shortened-dipole, each half of which is ten feet long, which was extended after injection into orbit. It acted as an RF impedance probe for measuring electron density. The second experiment is the ion current monitor which measured positive ion concentration. Shown on the upper cone is the electron temperature probe mentioned earlier. Also not visible is the fourth experiment discussed here, a retarding potential experiment whose sensor is located on the equator



(1) ELECTRON CURRENT MONITOR (3) ELECTRON TEMPERATURE PROBE
(2) TOTAL CURRENT MONITOR (4) ASPECT SENSOR

Figure 6 - The ionosphere direct measurements satellite, Explorer VIII

diametrically opposite the ion current monitor. The total current monitor merely assisted in the data interpretation by measuring the net current to the satellite skin at its location. All data reported here will be for a daytime condition at an altitude of 1000 kilometers.

The electron temperature probe, shown schematically in Figure 7, consists of a grid flush with and insulated from the satellite skin. Behind the grid is a collector biased positively so that the electron current is measured free of positive ion and photoemission current effects. This is a significant advantage over the previously described rocket models. It is especially important for satellite use where, because of the low electron densities, both the positive ion and the photoemission effect can predominate at certain orientations.

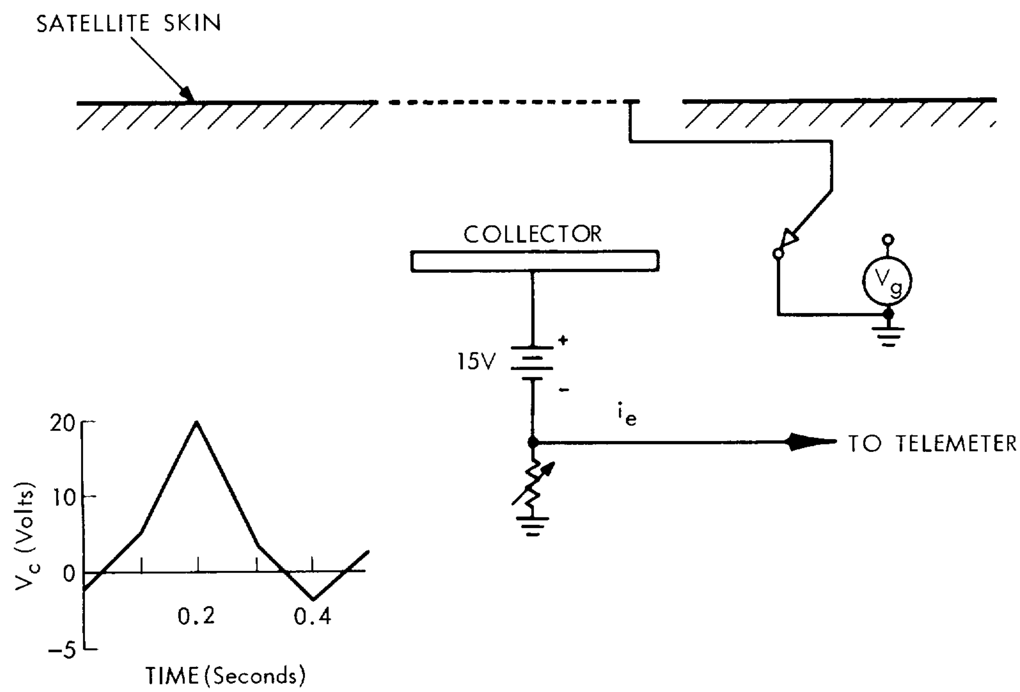


Figure 7 - Electron temperature probe employed in the Explorer VIII satellite

In alternate halves of the sensor's duty cycle a variable voltage (whose waveform is indicated in Figure 7) was applied to the grid, permitting a measurement of both the electron temperature and the satellite's potential relative to the medium at the sensor location. The satellite's spin rate was 21.4 rpm at this time; thus the volt-ampere curve was taken for a change in orientation of only 25 degrees. A typical result showing actual experimental data is presented in Figure 8. It differs from the classical Langmuir probe

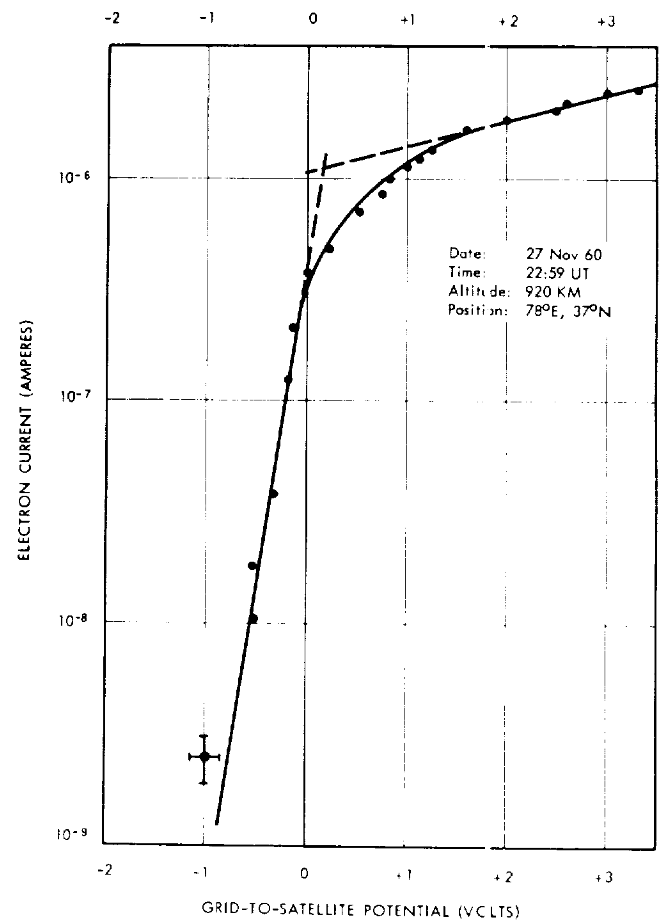


Figure 8 - Typical volt-ampere curve for the electron temperature probe employed in the Explorer VIII satellite

curve only in that the bothersome positive ion and photoemission currents are removed. Two distinct slopes where the grid is below and above the plasma potential are clearly apparent. When the grid potential is negative, the slope of the curve is a measure of the electron temperature. The potential of the grid relative to the plasma is generally taken as the negative value of either the point where the curve departs from this slope or the point of intersection of the two slopes. For the curve shown, an electron temperature of 1800° ± 300°K and a satellite potential between 0 and -0.15 volts are obtained. The ±300°K error is quoted in the temperature firstly because of the limited resolution necessitated by the telemetry bandwidth, and secondly to account for possible change in the grid's electrical transparency with applied voltage.

It is important now to re-evaluate the factors listed in the previous section as affecting the validity of the measurement. Care was taken to limit the radiated telemetry power to a value (100 mw) well below that which was shown by the rocket results to have no effect on the measurement. Outgassing contamination may be deemed negligible because of the long time in orbit. With regard to magnetic field effects, volt-ampere curves were taken for one complete satellite spin and consistency was observed in the computed temperature. At other locations on the satellite a measurable magnetic field dependency was observed; but the freedom of the total collector current from positive ion and photoemission currents would have permitted a correction for this dependency had the probe been located there. Returning to the list of factors influencing the measurement, the retarding effect of the body's negative potential greatly favors this particular satellite measurement, since the spacecraft was near the plasma potential. It should be re-emphasized that this affects the rocket measurements only if the energy distribution is not Maxwellian, in which case the rocket-borne bipolar probes should tend to indicate higher temperatures than the asymmetric probes. The three factors listed earlier for consideration only below 115 kilometers are not pertinent here. Finally, the biasing technique serves to remove the last two factors listed, the positive ion and photoemission currents.

The ion current monitor, shown schematically in Figure 9, consists of three parallel electrodes. The outermost grid is flush with and electrically connected to the satellite skin. The inner grid is negatively biased to suppress photoemission from the collector and to remove incoming electron current from the measured collector current. Figure 10 shows experimental data compared with a theoretically predicted curve (Reference 23) as

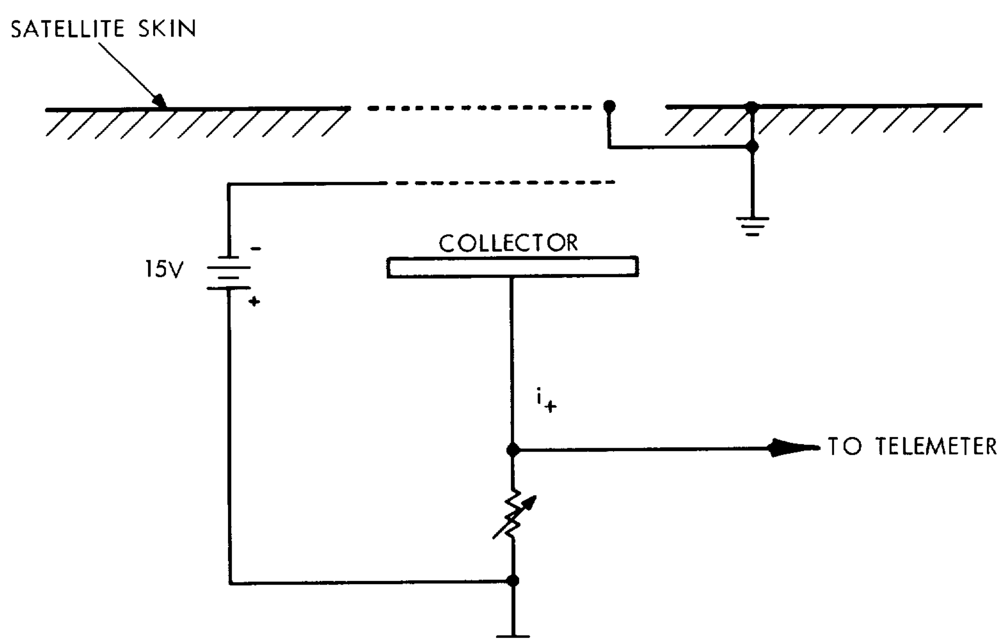
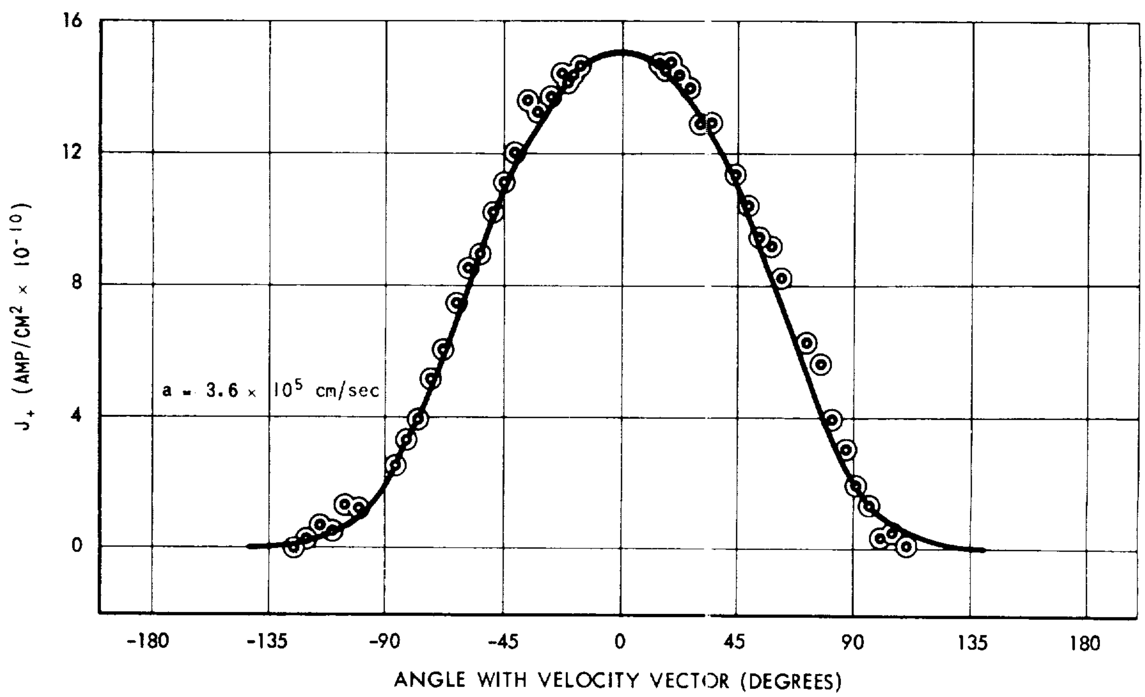


Figure 9 - Ion current monitor employed in the Explorer VIII satellite



$$J_+ = \alpha_+ eN_+V\cos\theta\left[\frac{1}{2} + \frac{1}{2}\operatorname{erf}\left(\frac{V\cos\theta}{a}\right) + \frac{a\exp-\left(\frac{V\cos\theta}{a}\right)^2}{2\sqrt{\pi}\,V\cos\theta}\right]$$

Figure 10 - Variation of positive ion current density with angle relative to velocity vector of satellite

a function of the angle θ that the sensor makes with the velocity vector; the agreement is good. At angles less than 45 degrees, the positive ion concentration N_+ can be computed simply from

$$i_+ = \alpha_+ AN_+ eV\cos\theta , \tag{1}$$

where i_+ is the measured current, α_+ the combined electrical transparency of the two grids, A the collector area, V the satellite velocity, and e the electronic charge. All the coefficients are known. The transparency coefficient was calibrated in flight by comparing the currents plotted in Figure 10 with the net current to a plate insulated from and flush with the satellite skin.

The more complete theoretical equation shown at the bottom of Figure 10 takes into account all values of satellite-to-ion velocity ratios or, alternatively, all angles of the sensor relative to the velocity vector. To get good agreement at the satellite's sides requires one of three assumptions: an extremely high ion temperature in a medium containing only O^+; a reasonable ion temperature in a medium containing some H^+; or leakage of the electric field between the medium and the spacecraft into the latter's ion sheath.

The measured ion concentration as computed from Figure 10 is $1.3 \times 10^4/cm^3$, a value consistent with the electron concentrations obtained from the RF impedance probe. Ionosonde data taken at the same time and geographical position yield an electron density of $7 \times 10^5/cm^3$ at an altitude of about 300 kilometers. The positive ion concentration measured from the satellite agrees with this value, on the assumption of an ionospheric model with a neutral gas scale height of 60 kilometers, diffusive equilibrium, and a predominant O^+ constituent.

The sensor of the retarding potential experiment (Figure 11) is mechanically identical to the ion current monitor and differs from it electrically only in that the collector potential was varied in accordance with the waveform shown on the figure. The shape of the volt-ampere curve obtained at this altitude is close to that predicted by Whipple and presented at the COSPAR symposium of 1960 (Reference 19); it is according to curve C of Figure 11. Curve D is a plot of experimental data from Sputnik III (1958 δ) obtained

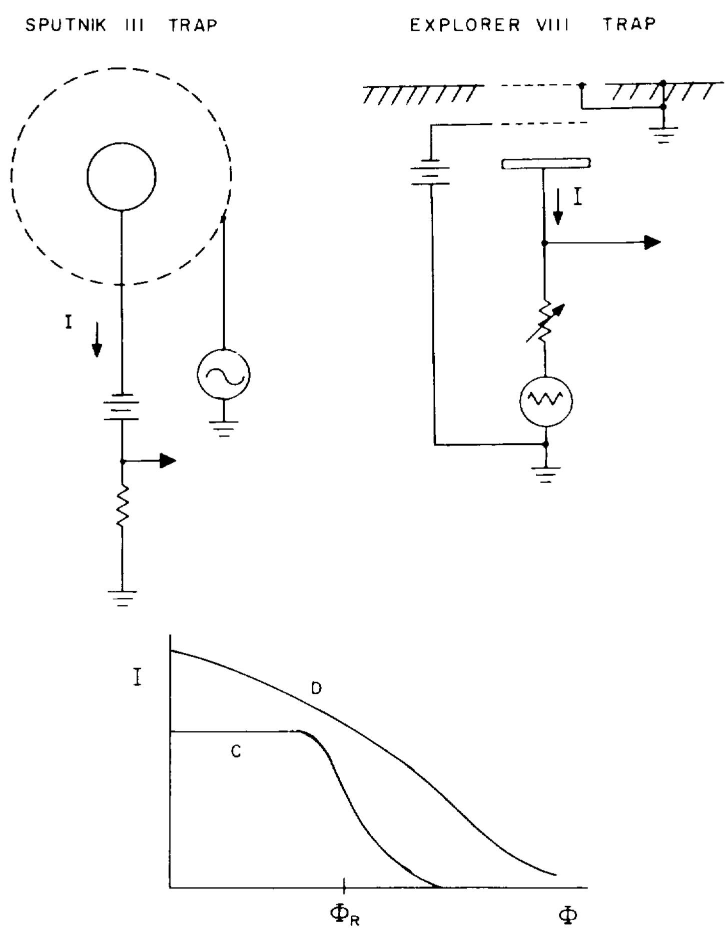


Figure 11 - Comparison of spherical with planar retarding potential experiment

through the use of the spherical trap shown to the left of the figure. The difference in resolution is attributed to the advantages of planar over spherical geometry.

For a single ionic constituent, since the satellite's velocity is large compared to the ionic thermal velocity, the ionic mass m can be computed from

$$\phi_R e = \frac{1}{2} m V^2 , \tag{2}$$

where ϕ_R is the potential measured at the point midway between zero and the maximum ion current. In doing this it is necessary to take into account the shift of the overall curve produced by the biasing effect of the satellite-to-plasma potential. The amount of this shift was measured by the electron temperature probe. The experimental data taken at 1000 kilometers indicate a mean ionic mass of about 16 AMU.

The total current monitor together with the devices described above made it possible to develop the model (Reference 20) of the plasma sheath surrounding the satellite. This model is shown in Figures 12 and 13; Figure 12 assumes no magnetic field. The lack of a positive ion current in the satellite wake (Figure 10) lends credence to the existence of

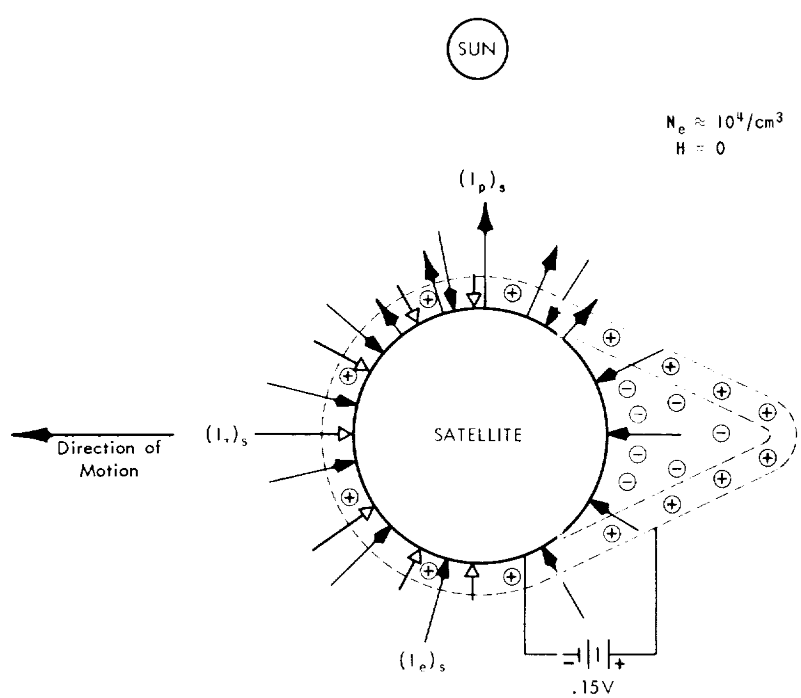


Figure 12 - Qualitative satellite sheath model postulated from experimental data

an electron sheath immediately adjoining the "back" surface of the satellite. If this sheath is assumed to have the form of a cone, its size may be estimated from the satellite-to-ion velocity ratio and the satellite diameter. In this case the cone has a half-angle of about 25 degrees and extends back a distance of about one satellite radius.

The slightly negative satellite potential (0 to −0.15 volts) measured by the electron temperature probe is evidence for the existence of a positive ion sheath enveloping both the satellite and the electron wake. The thickness of this sheath would be comparable to one Debye length, which is computed as 2.5 centimeters. The remainder of the model describes the current exchange between the satellite and the medium. A positive ion current flows from the medium at angles from −90 to +90 degrees relative to the velocity vector, peaking in the direction of the motion. The electron current from medium to satellite is modulated to a lesser extent in accordance with the velocity vector.

Finally, there is a photoemission current which is effective at angles of ±60 degrees relative to the sun, with a maximum density of 5×10^{-9} amp/cm^2. This value can be compared with the random electron current density to predict the altitude at which the satellite can be expected to go significantly positive. For most ionospheric models this will occur at about 4000 kilometers, just above the apogee of the Explorer VIII orbit.

The effect of the magnetic field is introduced in Figure 13. Here, as predicted by Beard and Johnson (Reference 24), the motion of a satellite with velocity V through the magnetic field produces an induced potential difference over the satellite surface given by

$$\phi = \phi_0 + \left(\vec{V} \times \vec{B}\right) \cdot \vec{d}, \qquad (3)$$

where ϕ_0 is the potential with no magnetic field and $\vec{d}$ the vector distance of any point on the surface from the satellite center. The maximum electron current would be expected where ϕ is most positive, near the point corresponding to the direction $\vec{V} \times \vec{B}$. This prediction is consistent with the observations. At the equator, it was observed that the electron current peaked when the total current

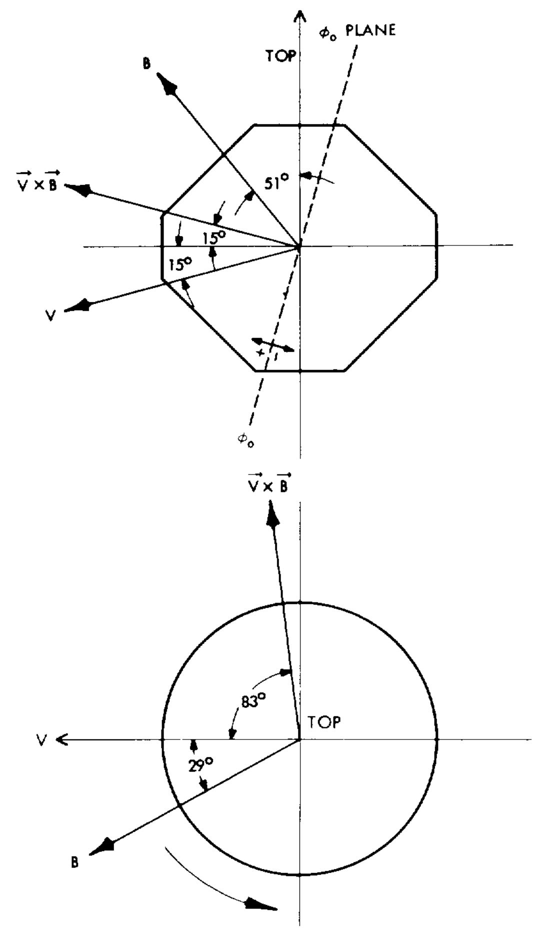


Figure 13 - Orientation of Explorer VIII satellite with respect to magnetic and velocity vectors

monitor pointed in the $\vec{V}\times\vec{B}$ direction as the satellite spun. The modulation of the current due to magnetic field was higher at the satellite's equator than in the upper cone, as would be expected since the change in distance from the ϕ_0 plane is greater. It is estimated that potential difference of 0.14 volts existed across the equator, and 0.04 volts at the top cone. As was expected, all points in the direction of $\vec{V}\times\vec{B}$ were more positive than ϕ_0 and all other points correspondingly more negative. The good agreement of the models expressed by Figures 12 and 13 with kinetic theory lends confidence to the ionospheric data presented herein.

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