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RAM-WAKE MEASUREMENTS OBTAINED FROM THE IONOSPHERIC SOUNDING ROCKET *MAIMIK*

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Abstract—Results of plasma measurements from the ionospheric sounding rocket *MAIMIK* are reported. Data obtained by high-resolution plasma probes show distinct "classical" wake signatures during the entire flight. That is, the electron temperature was enhanced "behind" the rocket in a region where both the electron and ion density were well below the ambient values. In addition, electron temperature enhancements were also detected in the ram ("forward") direction on the downleg. The measurements are presented and discussed in relation to the prevailing ionospheric conditions.

1. INTRODUCTION

For a considerable time it has been recognized that a region of depleted plasma density will exist behind a vehicle travelling through space. The existence of this region, called the wake, has already been established experimentally from measurements obtained during such comparatively early space flights as those of *Gemini-Agena* 10 and 11 (Medved, 1969) and *Explorer* 31 (Samir and Wrenn, 1969). Since then several measurements have also indicated that the electron temperature in the wake region is higher than in the surrounding plasma (see e.g. Samir and Wrenn, 1972, Troy *et al.*, 1975).

Since the arrival of the *Space Shuttle*, which due to its large size produces a much more pronounced wake, even more detailed measurements have been carried out. Distributions of ions and electrons along with electron temperatures have been obtained by measurements from the open cargo bay and the Remote Manipulator System during the *Spacelab*-1 mission in 1982. These results have been reported by e.g. Siskind *et al.* (1984), Murphy *et al.* (1986) and Ingsoy *et al.* (1986). Later on, during the *Spacelab*-2 mission in 1985, similar measurements were carried out both from the cargo bay and from the free flying Plasma Diagnostic Package. The results obtained from these experiments have been reported by e.g. Raitt *et al.* (1987), Murphy *et al.* (1989) and Tribble *et al.* (1989).

Such measurements have led to the formulation of models describing the plasma both analytically (e.g. Samir and Wilmore, 1965, Gurevich *et al.*, 1969; Whipple *et al.*, 1974) and numerically (e.g. Parker, 1977, Samir and Fontheim, 1981; Katz *et al.*, 1984). All of these authors used the notion of expansion of plasma into vacuum to model the particle distributions in the wake region. The ion depletion behind the vehicle is thereby due to the fact that the spacecraft usually travel with velocities higher than the thermal speed of the ions. Thus, these are not able to fill in behind the vehicle before some finite time after its passage.

The electrons on the other hand have much higher thermal speeds, but due to the charge imbalance created by the lack of ions the electrons will not be able to instantaneously fill in behind the vehicle either.

Thereby an electron density depletion is created in the wake region as well. In order to explain the enhanced electron temperatures detected in the wake several mechanisms have been proposed. Samir and Wrenn (1972), Troy *et al.* (1975) and Stone (1981) have suggested that selective effects due to potential wells near the vehicle, plasma instabilities and/or turbulence in the wake region are causing these temperature enhancements, while others have proposed adiabatic compression (Murphy *et al.*, 1986) or interaction between counterstreaming electrons (Singh *et al.*, 1987) as the mechanisms causing the temperature increase. This issue still remains open though.

The considerations mentioned above are all quite general, and accordingly wake phenomena should also have been observed in connection with rocket flights. However, only a few such observations have been reported. Berthelier and Sturges (1967), Klueyva (1973), Bering (1983) and Gupta (1988) have all reported phenomena which could be attributed to wake effects without actually measuring the particle distributions around the rocket. In addition, Svenes *et al.* (1990) reported interactions between auroral beams and the wake region of the rocket. However, the time resolution of these measurements was rather low. Thus, the present study is to the authors' knowledge the first in which the particle distributions around an ionospheric sounding rocket have been measured with sufficient resolution to definitely establish the existence of a wake region.

2. DESCRIPTION OF THE INSTRUMENTS

The *MAIMIK*-rocket, which carried a payload of the "mother daughter" type, was launched from the Andøya rocket range in the northern part of Norway on 10 November 1985 at 18:56 U.T. It was equipped with an accelerator emitting 8 keV electrons at currents up to 800 mA, and several plasma instruments designed to monitor the effects of the beam with a very high time resolution. A detailed description of the experiment is given in Maehlum *et al.* (1987), and in Fig. 1 a sketch of the experiment configuration is displayed.

Here, we will concentrate upon the measurements carried out from the passive "mother"-payload later than about 150 s time of flight. The results obtained prior to this have been described in previous articles (see Svenes and Trøim, 1987, Maehlum *et al.*, 1988, Svenes *et al.*, 1988, Maehlum *et al.*, 1989). Due to the relative speed between the two payloads the "mother" was no longer influenced by the disturbances created by the accelerator on the "daughter" after this point. Thus, the results presented here represent measurements from a region of the ionosphere which has not been artificially disturbed.

In this paper only data from the three plasma probes and the electric field probes are utilized. To minimize the interference on the measurements from the plasma sheath surrounding the "mother"-vehicle, the three plasma probes were all mounted on 80 cm long booms at the "top" end of the payload. The probes were deployed after 60 s at 82 km, and they appeared to function properly during the whole flight. The electric field booms were gradually deployed between 70 and 110 s time of flight, and they too performed flawlessly during the whole flight. A short description of these instruments is given below.

However, first a note on the spin rate of the rocket. The "mother"-payload was despun after 68 s time of flight, and the spin rate was then constant during the whole period under consideration here. This spin rate amounted to 0.30 r.p.s., corresponding to 9 ms per degree of turning. This should be kept in mind when comparing the different time resolutions of the various instruments.

The electron temperature probe, later referred to as the ETP, basically measured the electron part of the current towards the payload. It consisted of a spherical grid 5 cm in diameter surrounding a collector with a bias of +10 V with respect to the rocket ground. The amplifier was logarithmic, enabling current measurements from 10^{-10} to 10^{-5} A, using an 8-bit resolution limited by the telemetry. In an effort to obtain a uniform surface contact potential the whole probe was also coated with a highly conductive paint.

During operation the outer grid of the probe was continuously changed or "swept" in potential. Each "sweep" was aimed at obtaining an integrated electron spectrum. This was done by stepping the potential of the grid relative to the payload from -1.9 to $+4.9$ V and back. A "sweep" was carried out in 13.1 ms and consisted of 128 potential steps (both "up" and "down"). Hence, the time resolution of the measurements was 13.1 ms while the corresponding angular resolution was less than 2°.

From this kind of measurement it is possible to obtain the Boltzmann distribution of the electron population. Hence, both the electron density and temperature could be obtained with a time resolution of 13.1 ms. In addition, it was also possible to estimate the potential of the payload relative to the ambient plasma with the same resolution. The details of this procedure are described by Svenes and Trøim (1987).

The ion part of the current was measured by the ion probe, later referred to as the IP. This is a dc-probe consisting of a solid spherical collector, 4 cm in diameter, with a bias of -2 V with respect to the

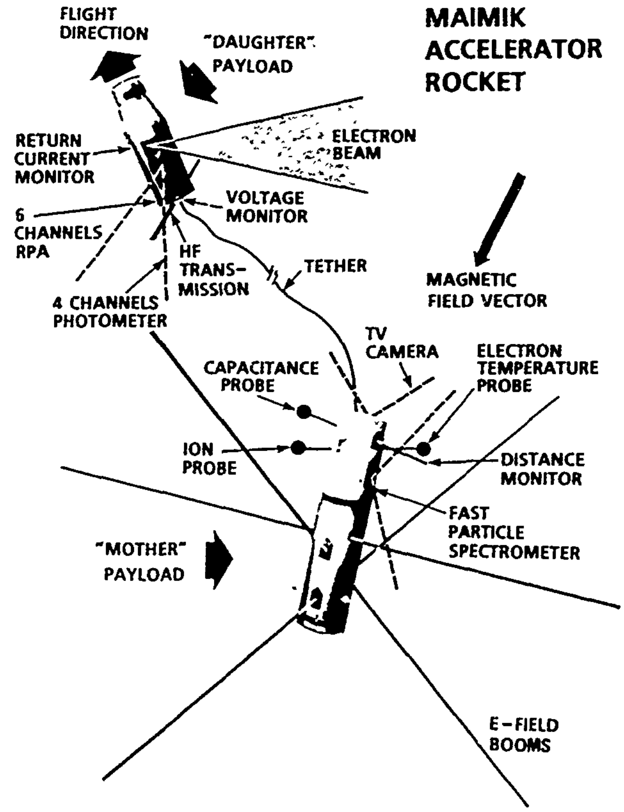

FIG. 1. AN ARTIST'S CONCEPTION OF THE *MAIMIK* GEOMETRY

rocket ground. For reference purposes the probe was also "swept" in potential a few times during the flight. In addition there was also an ac part of the probe, but these data will not be utilized in the present context.

A logarithmic amplifier made current measurements possible in the range from 10^{-11} to 10^{-4} A, again using an 8-bit resolution. The probe enabled sampling with a time resolution of 1.6 ms for these measurements. Hence, the corresponding angular resolution was much less than 1°.

The capacitance probe, later referred to as the CAP, basically measured the capacitance of a sphere vs the surrounding plasma. The probe was separated from the plasma by a sheath whose thickness is assumed to be 5–8 Debye-lengths. It can be shown that the capacitance of the probe is a measure of the square root of the ratio of the electron density to the electron temperature, see e.g. Balmain (1966) or Jacobsen (1972).

The capacitance of the sphere, which is 4.2 cm in diameter, forms part of an LC-oscillator operating near 1 MHz. The oscillator frequency was measured with a very high resolution in time and frequency. Variations in the capacitance (or frequency) are partly due to changes in the electron density or the electron temperature, and partly due to changes in the potential of the payload. For a description of the details of the theory concerning this kind of fixed frequency impedance probe, see e.g. Balmain (1966) or Jacobsen (1972). The probe had a temporal resolution of 0.4 ms again corresponding to an angular resolution well below 1°. The data are displayed as the square of the deviation from the capacitance of free space.

For the *E*-field measurements the double floating probe technique was utilized. This technique depends on deploying symmetrical sensors some distance away from the vehicle, and measuring the potential difference between the probes and the vehicle. By subtracting for the vehicle potential and the $v \times B$-effect, the vector electric field is arrived at. More detailed discussions of this technique may be found in Maynard (1972) and references therein.

During the flight of *MAIMIK* two stainless steel booms were mounted at ±45° to the main rocket axis. These rigid booms had a nominal double probe separation distance of 5.7 m. The third boom, mounted orthogonally to the rocket in the spin plane, had a probe separation length of 8.8 m and was fabricated from beryllium–copper. The inner portion of each boom was covered by an insulating layer of kapton except at the tips. Thus, only the outer 0.6 m of the booms was conducting.

The potential of each sensor was referenced to the rocket body through a preamplifier input of 10^{12} Ω. During the flight time the sensitivity of the vector instrument ranged from 2 mV m^{-1} to more than 1 V m^{-1} The maximum sampling frequency was 2.4 kHz, corresponding to an angular resolution of about 0.5°.

3. WAKE MEASUREMENTS

In this section a description is given of the complete set of measurements, obtained by the ETP, above an altitude of approx. 250 km on the upleg and 120 km on the downleg. These measurements enabled us, as previously explained, to estimate the electron density and temperature along the trajectory. Thus, the behaviour of the electron population surrounding the rocket at any time could be continuously monitored.

The measurements are displayed in Fig. 2, which is divided into four parts. In the upper half the electron temperature measurements are shown with the upleg results on the left and the downleg to the right. The lower part contains the electron density measurements, again with upleg results to the left and downleg to the right Note also that the altitude is plotted along the vertical axis.

It should be mentioned here that *MAIMIK* carried an active experiment which influenced significantly the measurements below about 250 km on the upleg. However, these measurements have been presented previously by Svenes *et al.* (1988), and will not be discussed further here.

Thus, looking at data from above 250 km on the upleg and the entire downleg, it is seen that the electron temperature was about twice as high near apogee as below 200 km. This is in accordance with previous experience which shows that *F*-layer electron temperatures are generally higher than in the *E*-layer (see e.g. Munninghoff, 1979).

As for the density measurements, it is seen that the electron density in general was somewhat higher on the downleg than on the upleg. This was especially apparent in the measurements carried out in the *E*-layer. This matter will be elaborated later on in the text.

The regular oscillations appearing in the data set throughout the flight were due to the spin of the rocket. This is shown in more detail in Fig. 3. These measurements were obtained during a single spin period at an altitude of about 340 km on the upleg. The spin period has been established from measurements by the on board magnetometer and gyro. During the part of the flight under consideration here, the spin period did not depart significantly from 3.3 s.

In the figure the electron temperature is displayed in the upper part, while the electron density is plotted in the lower part. Both parameters are plotted as functions of the relative azimuth between the velocity vector of the rocket and the direction vector of the ETP. Thus, the centre of the wake is at 180° and the ram direction is at 0° (or 360°).

It is seen that the density in the mid-wake position decreased to about half the ambient value, from just below $1 \cdot 10^{10}$ m^{-3} to about $4 \cdot 10^{9}$ m^{-3}. At the same time the electron temperature increased by almost a factor of three, from somewhat below 1000 to about 2700 K. These factors represent maximum values from the flight, and differences could amount to as little as 20% both in temperature and density at other times. This is much smaller than the ratios measured on board satellites (Samir and Fontheim, 1981) or the *Space Shuttle* (Ingsoy *et al.*, 1986 and Murphy *et al.*, 1986). However, that is entirely as expected since the diameter of *MAIMIK* was only 40 cm which is much smaller than the dimension of the *Space Shuttle* and even that of satellites.

The extent of the disturbed region was fairly constant during the entire flight. Typically it covered an angle of about 180°, as seen in both Figs 3 and 4. In Fig. 4 the electron density distribution around the rocket is shown in the upper part and the ion distribution in the lower part. Even though the ion depletion was much less than for electrons, only about 20%, the ion wake had the same angular extension.

This means that the region of disturbance created by the rocket was far broader than the geometrical wake region. That is, the wake region extended past the region which was in the "shadow" of the rocket body relative to the velocity vector. It may be speculated upon whether this could be connected to the plasma flow about the rocket body, but so far this question in reality remains open.

4. RAM MEASUREMENTS

This section contains a more detailed description of plasma measurements obtained during the latter half of the *MAIMIK* flight. It comprises results from the electron temperature probe (ETP), the capacitance probe (CAP) and the electric field probes (*E*-field).

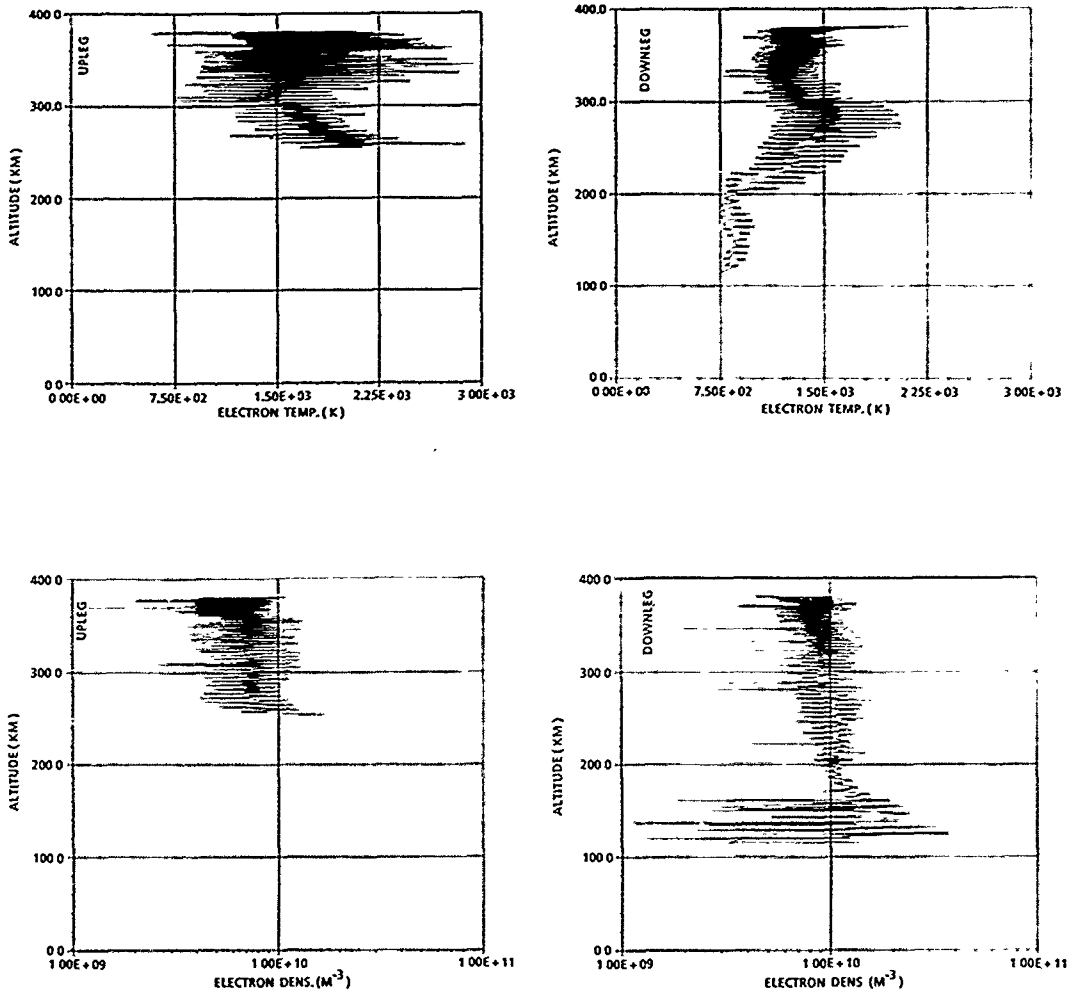

FIG. 2 ELECTRON TEMPERATURE AND DENSITY MEASUREMENTS FROM THE *MAIMIK* FLIGHT.
The upper part contains temperature measurements while the lower part contains density measurements. The left-hand side of the figure contains the results from the upleg while the downleg results are displayed to the right.

4.1. E-*field*

The E-field data are displayed in Fig. 5. For purposes of analysis these are presented in the form of 5 s sliding averages, covering the period of some 80-520 s time of flight. This is equivalent to an altitude interval of about 127 km on the upleg to 204 km on the downleg. The measurements have been transferred to a geomagnetic frame of reference. That is, the x-component corresponds to the North-South (N/S) direction, the y-component to the East-West (E/W) direction and the z-component to the down-up (D/U) direction.

It is clearly seen that the most conspicuous feature in the latter half of this data set was the increase in the North-South component of the electric field, occurring somewhat after the apogee passage. This component then increased from zero at 340 s to about 25 mV m^{-1} at 380 s. The corresponding altitude decrease was from about 379 to 365 km. In this period the rocket also increased its range by roughly 22 km.

From then on and until the end of the data set the rocket measured a steady electric field of about 25 mV m^{-1} directed almost exactly northwards. During this period the altitude decreased to about 200 km and the range was increased by nearly 80 km. Such stable large

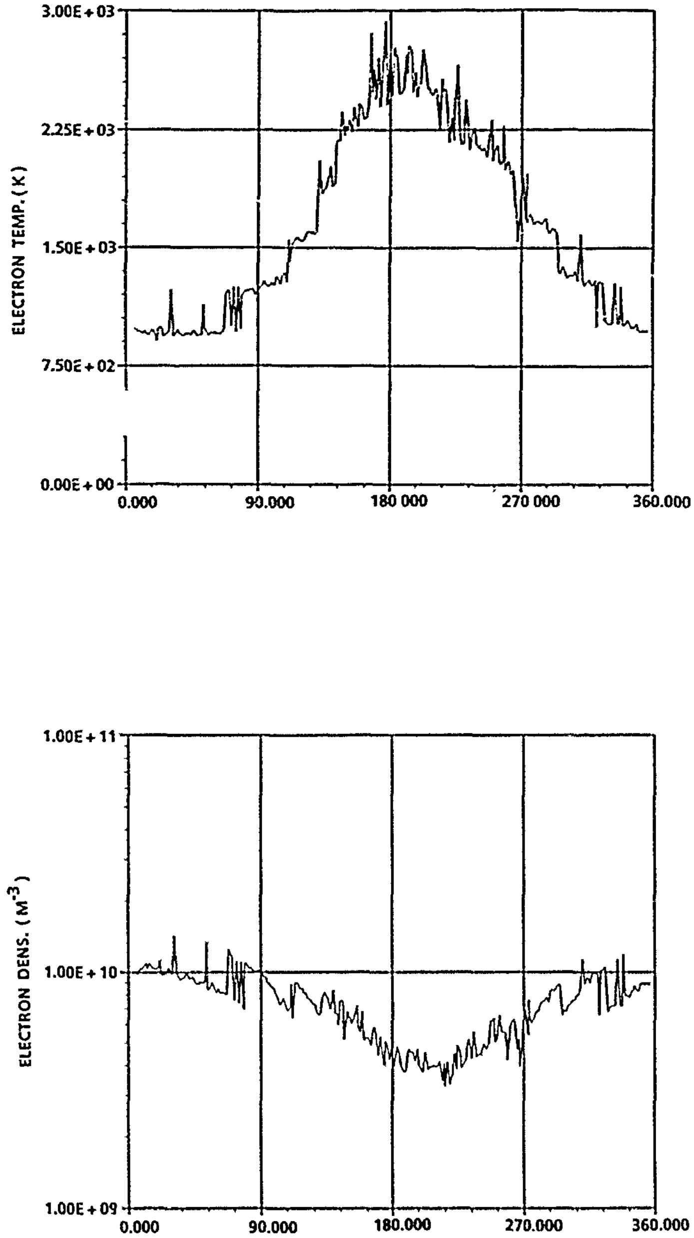

FIG. 3. THE ELECTRON TEMPERATURE AND DENSITY, AT AN ALTITUDE OF ABOUT 340 km, AS A FUNCTION OF THE SPIN ANGLE.

The upper part shows the electron temperature as a function of the angle between the direction of the velocity vector and the direction vector of the probe. The lower part shows the corresponding electron density measurements.

scale fields are usually associated with the auroral oval and thus it suggests that the rocket entered an aurora in the descending part of the trajectory, although due to poor visibility no auroral features could actually be seen from the ground.

4.2. *ETP*

As mentioned previously the ETP measurements showed significantly enhanced electron temperatures in the wake region of the rocket during the whole flight. In the latter half of the flight there was also a

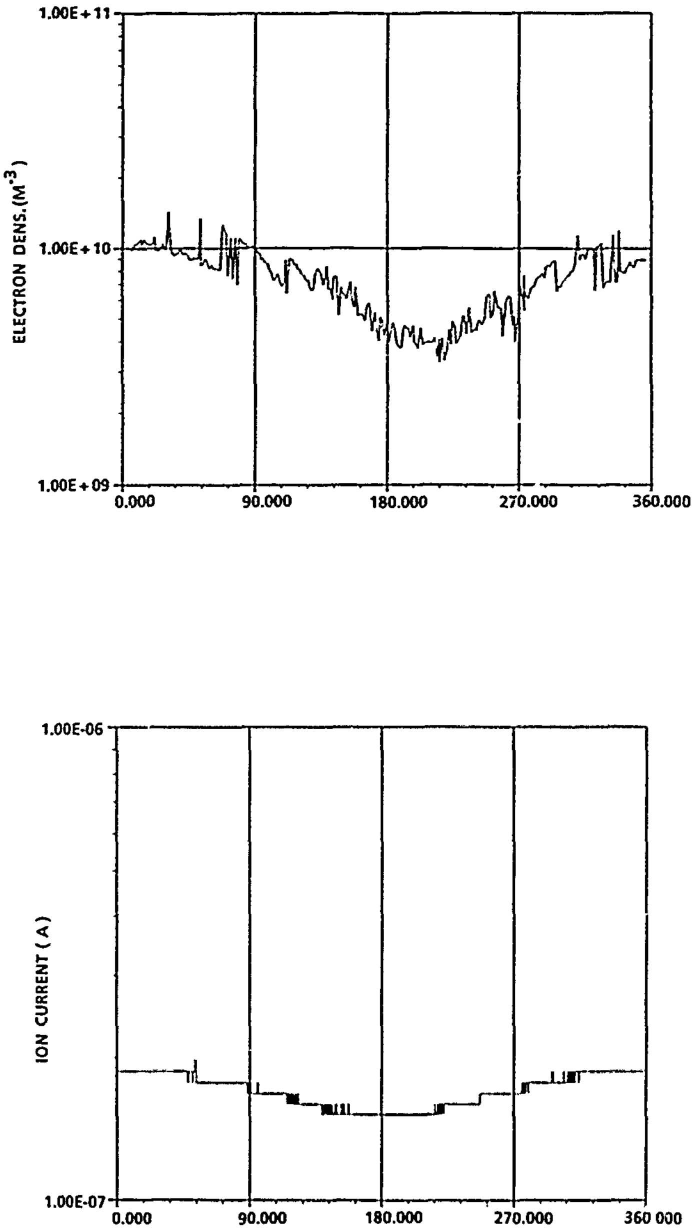

FIG. 4. MEASUREMENTS FROM THE ETP AND THE IP, AT AN ALTITUDE OF ABOUT 340 km, AS A FUNCTION OF THE SPIN ANGLE.
In the upper part the electron density is displayed while the corresponding ion current is shown in the lower part.

period during which an additional electron temperature enhancement was observed in the ram direction. That period lasted from about 380 to 520 s. This was preceded by a transitional period, which lasted for about 30 s, during which no clear trend in the measurements was seen at all.

In Fig. 6 this development is illustrated by electron measurements carried out at three different points along the path. Here, the temperature data are plotted as a function of the difference in azimuth angle

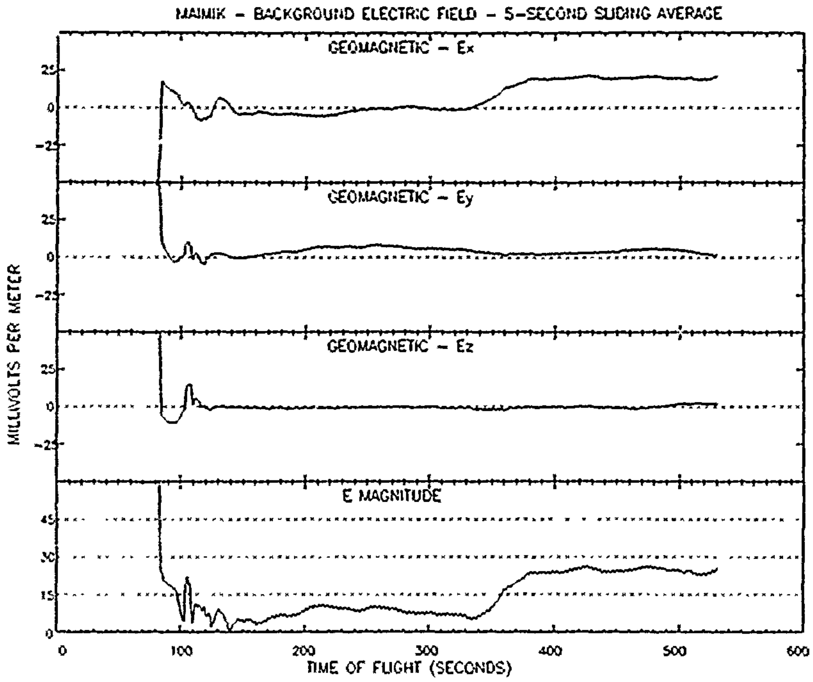

FIG. 5. BACKGROUND ELECTRIC FIELD MEASUREMENTS FROM *MAIMIK*.
The measurements are displayed as 5-s sliding averages, and they represent the geomagnetic x-component (top), the geomagnetic y-component (second from top), the geomagnetic z-component (third from top) and the total magnitude of the field (bottom).

between the velocity vector and the probe vector. Thus, 0° is the ram direction of the rocket and 180° is the mid-wake position. Positive angular increments are in the opposite direction to the spin.

The upper part of the figure shows measurements obtained close to apogee. It is clearly seen that the electron temperature reached a maximum in the mid-wake region. In the middle part of the figure measurements from an altitude of about 370 km are presented. This is inside the transitional period, from roughly 350 to 380 s, as mentioned above. It is seen that the temperature measurements then were fairly unstructured during the whole spin period. This indicates that a region of severe plasma disturbance was transversed during the descent.

The lower part of the figure shows measurements obtained at an altitude of about 280 km. Here, the mid-wake electron temperature enhancement is flanked at both sides by an additional secondary enhancement. The partition of this enhancement in the figure is of course only a result of the method of plotting. As is readily seen, this broad region typically covered almost the whole of the ram direction. This feature was observed regularly during the period 380–520 s.

It should be mentioned that no significant change in the extremal values of density or temperature, encountered during a spin period, seemed to accompany these ram enhancements. Also, note that the narrow regions around the lowest temperature measurements carried out during a spin period usually covered only about 10°–20°. If this is taken to represent the electron temperature of the ambient ionosphere, it means that most of the plasma surrounding the rocket was significantly modified during this part of the flight.

4.3. *CAP*

The above-mentioned ram effect was also detected by the CAP. Figure 7 shows the response of the CAP at an altitude of 333 km. The parameter employed as the ordinate is here the square of the deviation from the free space capacitance. This unit is proportional to the electron density and inversely proportional to the electron temperature. In addition the potential of the rocket body may influence this unit, but in the case of *MAIMIK* the charging of the payload remained constant during a spin period.

From the figure it is seen that the CAP response decreased most significantly in the wake direction. This was probably due to a combination of low electron density and high temperature. In the ram direc-

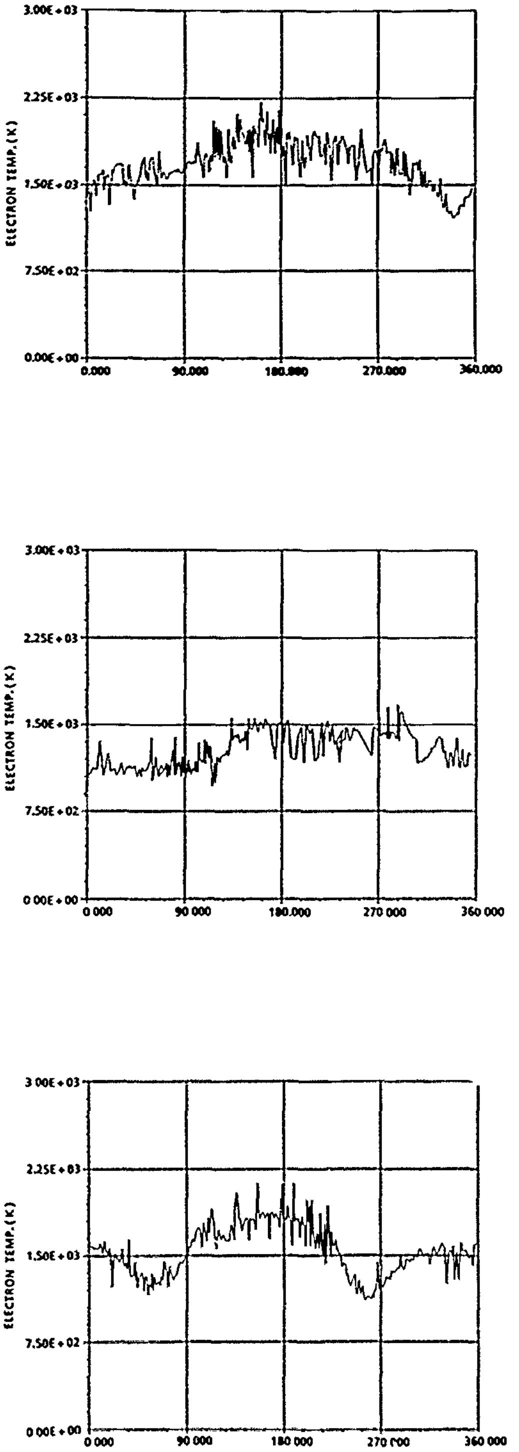

FIG. 6. ELECTRON TEMPERATURE MEASUREMENTS AS A FUNCTION OF SPIN ANGLE.

The electron temperature plotted as a function of the angle between the velocity vector and the direction vector of the probe at an altitude of about 380 km (top), 370 km (middle) and 280 km (bottom).

tion there was a secondary smaller decrease which was due only to the increased electron temperature here. Such an interpretation is entirely in accordance with the measurements of the ETP in the same region (see lower part of Fig. 6).

This double peak nature of the CAP response during a spin period persevered for the whole of the period between about 300 and 500 s time of flight. Thus, the CAP also made different measurements on the downleg than on the upleg during about the same period as the ETP and the *E*-field probes. The slight discrepancy in time involved here was probably due to some differences in the sensitivity of the various probes.

5. DISCUSSION AND CONCLUSION

As stated previously all the plasma probes on *MAIMIK* had a very high sampling rate. Since the spin rate was rather low, this in turn meant that all density and temperature measurements had an angular resolution of about 1°. Due to this it was possible to obtain a very good picture of the plasma distribution around the rocket.

From these distributions it can be concluded that the classical signatures of a wake region were obtained throughout the entire flight. That is, both electron and ion density depletions were observed in a direction anti-parallel to the velocity vector. In addition, the electron temperature was significantly enhanced in the same region. This is in accordance with previous experience both from satellite and laboratory measurements (see e.g. Samir *et al.*, 1986).

However, what are perhaps more surprising are the results obtained during the downleg. Assuming that the lowest electron temperature encountered during a spin period is representative of the ambient plasma, Fig. 6 shows that electron temperature enhancements were then also observed in the ram region. These temperature enhancements were actually seen, during quite an extensive period of time, in data both from the ETP and the CAP. No corresponding density enhancements were observed in either the electron or ion population.

Previously, enhanced electron temperatures in the ram direction have been reported by Siskind *et al.* (1984). Furthermore, during these measurements no electron temperature enhancements were observed in the wake direction. These results were obtained during the *STS*-3 mission in March 1982. The instrument employed was an ac-sweeping Langmuir-probe which was part of the Vehicle Charging And Potential (VCAP) experiment. All reported measurements were carried out while the entire experiment was placed on a pallet in the payload bay of the *Shuttle*.

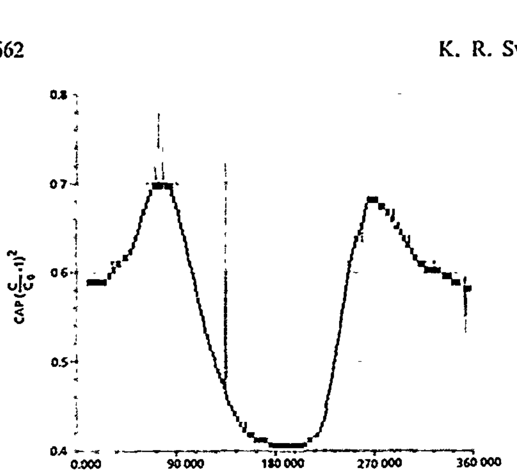

FIG. 7. RESULTS FROM THE CAP AT AN ALTITUDE OF ABOUT 333 km.

The ordinate is the square of the deviation from the free space capacitance, and it is plotted as a function of the angle between the velocity vector and the direction vector of the probe.

However, Murphy *et al.* (1986) also made observations from the same *Shuttle* flight using a different experiment. Although an ac-sweeping probe was employed in this case too, it was located in a different place of the pallet as a part of the Plasma Diagnostic Package (PDP). Furthermore, these measurements were carried out while the entire experiment was attached to the Remote Manipulating System (RMS) above the payload bay. The results from this experiment showed that the electron temperature enhancements occurred in the wake region though. In addition, there were no observations of electron temperature enhancements in the ram direction.

Even though these measurements were obtained in different locations they are still in opposition to each other and therefore the results remain controversial, whereas in the case of *MAIMIK* significant electron temperature enhancements were observed in the wake region during the whole flight. On the downleg there were in addition temperature enhancements observed in the ram direction. Thus, in this case both kinds of observations were obtained with the same probes for an extensive period of time.

This period covered, as previously mentioned, most of the descent through the *F*-layer. The experiment geometry was then of course different from the upleg part of the flight. On the upleg the direction vectors of the plasma probes were at large angles from the magnetic field, whereas on the downleg the probes became aligned much closer to the field lines. In addition, the angle between the rocket main axis and the velocity vector was increasing all through this period. However, since all three plasma probes were omni-directional this geometric difference in itself should not have been important.

On the other hand there were clear indications of the rocket crossing the southern border of the auroral oval on the downleg. As seen from Fig. 5 a steady northward pointing electric field of about 25 mV m^{-1} was encountered after about 350 s time of flight. This is an electric field which from previous experience is quite typical of the auroral regions (see e.g. Maynard, 1972).

In addition, measurements from *EISCAT* confirmed that significant particle precipitation also occurred during this period (T. Hansen, private communication). Also, as seen from Fig. 2, the electron density measured by the ETP on the downleg was significantly higher than on the upleg. This was particularly apparent in the *E*-layer. Unfortunately, the cloudy weather conditions which prevailed during the flight prevented the use of pictures from the all-sky camera as conclusive proof of the rocket crossing an auroral arc. However, it seems that the indications mentioned above are strong enough in themselves to imply that the rocket actually entered the auroral zone on the downleg. The detection of the enhanced electron temperatures in the ram direction of the rocket thus seemed to be connected to this event.

At present it is not yet clear how this might have affected the measurements. It is stressed again though that these measurements were obtained by two different probes. Thus, there is reason to believe that the results reflected a real physical change of the electron population surrounding the rocket during this period. An explanation of these measurements may therefore yield some interesting information on ionospheric physics.

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Results of plasma measurements from the ionospheric sounding rocket MAIMIK are reported. Data obtained by high-resolution plasma probes show distinct "classical" wake signatures during the entire flight. That is, the electron temperature was enhanced "behind" the rocket in a region where both the electron and ion density were well below the ambient values. In addition, electron temperature enhancements were also detected in the ram ("forward") direction on the downleg. The measurements are presented and discussed in relation to the prevailing ionospheric conditions. Keywords: Reprints, Plasma Sheaths, Plasma Wakes.

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