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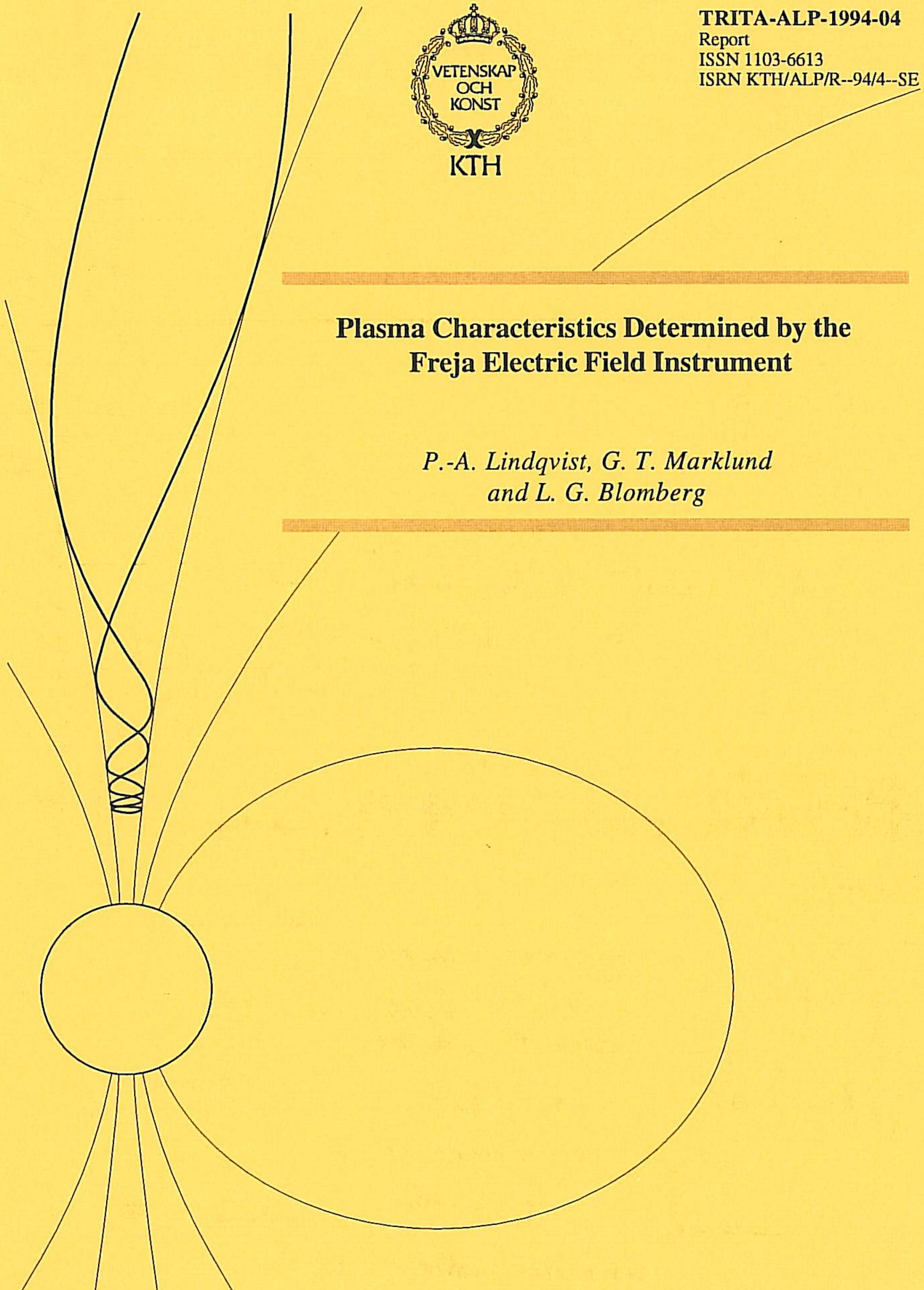

Plasma Characteristics Determined by the Freja Electric Field Instrument

P.-A. Lindqvist, G. T. Marklund
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Division of Plasma Physics
Alfvén Laboratory
Royal Institute of Technology
S–100 44 Stockholm, Sweden

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Division of Plasma Physics
Alfvén Laboratory
Royal Institute of Technology
S-100 44 Stockholm
Sweden

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Abstract.

A new approach to the study of ionospheric plasma characteristics is presented using data from the Freja double probe electric field instrument. Plasma characteristics are derived from continuous measurements of the satellite potential and from intermittent Langmuir sweeps. These provide information on both relative variations in the plasma density and absolute density and temperature, useful for comparisons with other plasma measurements on Freja, and essential for the interpretation of the electric field measurements. The on-board memory makes it possible to obtain full-orbit coverage of this type of information, which is a new feature of the Freja measurements. The memory is also used for high time resolution Langmuir sweeps which allow for the first time detailed studies of the time behavior of the probe response and computation of the probe-plasma capacitance. Comparisons are also made with similar measurements on earlier missions.

1 Introduction

The Swedish-German satellite Freja was launched on 6 October 1992, into an orbit with inclination 63 degrees and altitude between 600 and 1770 km [*The Freja Team*, 1993]. The present paper describes measurements by the double probe electric field experiment [*Marklund et al.*, 1994*a*, 1994*c*], and focusses on the measurements that provide information about the plasma environment along the Freja trajectory. These are the continuous measurements of the satellite potential and the intermittent current sweeps. The electric field instrument is designed to measure the electric field in the spin plane, using spherical probes with diameters of 6 cm at the end of 10 m long booms. The satellite potential is monitored continuously as the potential difference between the satellite body and selected probes. This is possible since the probes are kept at or near the plasma potential by means of a bias current. Current sweeps, performed intermittently on selected probes, are used to find the optimum operational value of the bias current, and also to determine the absolute values of the plasma density and temperature.

The results presented below are mainly from the Freja satellite, but comparisons are also made with plasma diagnostic measurements on two earlier missions, namely Viking, in a nearly polar orbit between 800 and 13500 km altitude [*Block et al.*, 1987], and the International Sun Earth Explorer (ISEE-1), in a 20 degree inclination orbit with perigee at 1.2 Earth radii (R_E) and apogee at 23 R_E, [*Pedersen et al.* 1984]. The electric field instruments on the three satellites were similar in the sense that thay all had the capability to monitor the satellite potential, to send a bias current to the probes for optimization of the electric field measurements, and to perform current sweeps to determine the plasma characteristics. Comparisons between these measurements are of interrest since they provide valuable insight into the behavior of probes in different plasma environments.

2 Theoretical considerations

The potential of a probe in a plasma is determined by a balance of the currents flowing to the probe. The main currents contributing to this balance are the photoelectron current (I_{ph}), the ambient plasma thermal electron current (I_e), and the ambient plasma thermal ion current (I_i). In addition, for the instruments decribed in this paper, the bias current to the probe (I_b) must be taken into account. Thus the current balance becomes

$$I_e + I_{ph} + I_b + I_i = 0, \tag{1}$$

where all currents are taken positive towards the probe. In the simplest model of the currents for a spherical probe, the above relation may be written [*Fahleson et al.*, 1974]

$$-4\pi r_p^2 n_e e\sqrt{\frac{kT_e}{2\pi m_e}}\left(1+\frac{eV_p}{kT_e}\right) + \pi r_p^2 i_{ph} e^{-\frac{eV_p}{kT_{ph}}} + I_b + 0 = 0 \tag{2}$$

for a positive probe, and

$$-4\pi r_p^2 n_e e\sqrt{\frac{kT_e}{2\pi m_e}} e^{\frac{eV_p}{kT_e}} + \pi r_p^2 i_{ph} + I_b$$

$$+4\pi r_p^2 n_e e\sqrt{\frac{kT_i}{2\pi m_i}+\frac{v^2}{16}}\left(1-\frac{eV_p}{8m_i(\frac{kTi}{2\pi m_i}+\frac{v^2}{16})}\right)=0 \tag{3}$$

for a negative probe, where r_p and V_p are the probe radius and potential, e, m_e, n_e and T_e are the electron charge, mass, density and temperature, i_{ph} and kT_{ph} are the photoemissivity and the energy of the emitted photoelectrons, and v is the relative velocity of the probe to the plasma. Equations (2) – (3) are strictly valid only in an unmagnetized plasma, but even at Freja, where the gyroradius of a 1 eV electron is only 13 cm, they appear to hold reasonably well. If the satellite is approximated by a spherical body, large compared to the probes, (2) and (3) are valid also for the satellite potential V_s, with $I_b \approx 0$.

In this paper, when reference is made to a measurement of the satellite potential, the actual measurement is of

$$V_{ps} = V_p - V_s. \tag{4}$$

In a plasma of high enough density, or, equivalently, if I_b is small enough, the probe and the satellite will float at the same potential relative to the plasma ($V_{ps} = 0$), if they have the same shape and surface properties. For differing surface properties, or if the satellite is only poorly approximated by a sphere, $V_{ps}(I_b = 0)$ may be non-zero. If, for example, the satellite is better approximated with a cylindrical disk, the value of V_{ps} for $I_b = 0$ may be either negative (if the disk is facing the sun) or positive (if the disk has its edge towards the sun). If a bias current I_b is now applied, V_{ps} will change from its floating value. For $I_b < 0$, V_{ps} will be more negative, and for $I_b > 0$, V_{ps} more positive. Since the relative importance of I_b in the current balance decreases in a dense plasma, increasing the plasma density will have the same effect on V_{ps} as decreasing I_b. This also means that, for a fixed bias current, V_{ps} may change sign in an extremely dense plasma.

3 Measurement principle

The current sweeps on Freja are performed by varying the bias current to one probe from +950 nA to −534 nA in 53 steps, while measuring the potential difference between the swept probe and the opposing probe, which is at floating potential. Normally the two probes in one pair are swept alternately, once every 30 seconds, and the duration of each current step is 5.2 ms. Figure 1 shows a selection of four current sweeps, taken in different plasma environments. For each sweep, the probe voltage due to the ambient electric field (including $\mathbf{v}_{\text{satellite}} \times \mathbf{B}$) has been removed by subtracting the probe potential difference exactly one spin period later. From the sweeps, it is easy to determine the photoemission current from the location of the "knee" in the curve, and the optimum bias current from the steepest slope in the curve (largest dI/dV). With more careful analysis, it is also possible to determine plasma parameters such as n_e and T_e, as discussed further below. Similar current sweeps were performed on Viking and ISEE-1.

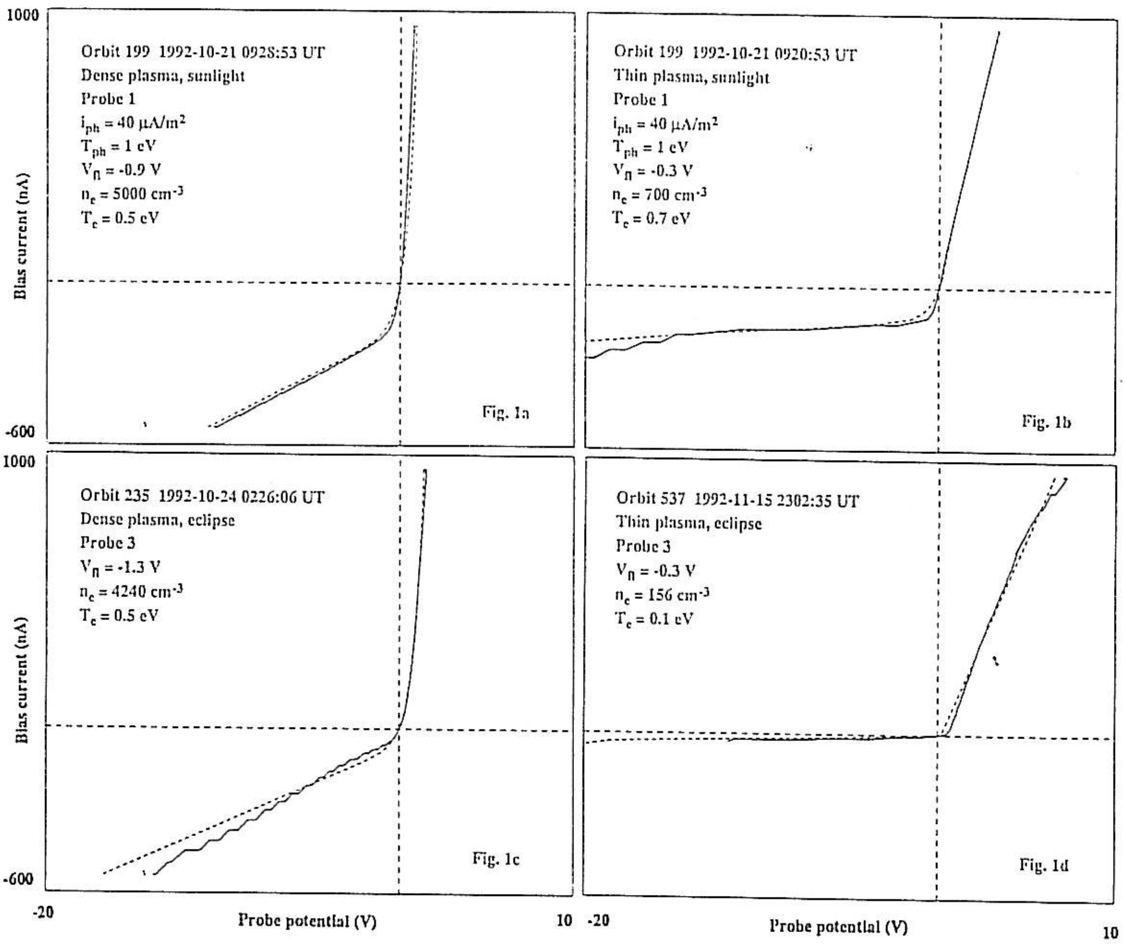


Fig. 1. Current sweeps on Freja in different plasma environments. The dashed lines show theoretical curves, using the values for n_e and T_e given for each case. Also indicated are values of i_{ph}, T_{ph}, and the probe floating potential V_{fl}.

For optimum operation of an electric field probe in a plasma, the probe should be kept near the plasma potential, where the probe-plasma impedance is small. This is done by sending a bias current I_b to the probe. In a low density plasma, and in sunlight, the photoelectron flux emitted from the probe exceeds the thermal electron flux collected by the probe, and therefore I_b should be negative to compensate for this excess. In a high density plasma, and in eclipse, I_b should be positive to compensate for the excess thermal electron flux collected by the probe. Freja traverses a region of relatively high plasma density, and is operated in both sunlight and in eclipse. It was found that a small positive bias current I_b of +22 nA serves very well for all plasma conditions encountered by Freja, as illustrated in Figure 1. It is seen in this Figure that the differential probe-plasma impedance is low (of the order of 5 MΩ), which means that the electric field measurement is not severely influenced by differences in plasma conditions at the two probes. The inaccuracy due to such differences is estimated to be less than a fraction of a mV/m. (A much larger source of uncertainty in the electric field measurement is the uncertainty in the spacecraft attitude, due to the relatively large $\mathbf{v} \times \mathbf{B}$ induced electric field.) On Viking and ISEE-1, which travelled through more tenuous plasma regions, and were operated only in sunlight, the selected bias currents were −150 nA, and between −40 and −180 nA, respectively. The electric field instrument on Freja (and ISEE-1) has the on-board capability of automatically determining a suitable bias current from the current sweeps. This feature has not been used very often, since experience shows that it is better to keep I_b at a fixed value, and minimize those changes in the satellite potential that are due to changes in I_b. The photoemission on Viking and ISEE-1 increased with time (which required the increase in I_b on ISEE-1), an effect which has not yet been detected on Freja, probably due to the lower altitude of the Freja perigee. The probes appear to be "reset" to their initial condition when they pass through the dense plasma near perigee. This was seen also on ISEE-1, when the satellite occasionally reached exceptionally low altitudes, which led to decreased photoemission for a period thereafter.

4 Relative plasma density variations

Figure 2 shows a Freja crossing of the northern auroral oval. The satellite potential is seen to vary along the orbit, as the satellite traverses different regions of plasma, and also moves from shadow to sunlight. Outside the auroral oval, before 0740 UT and after 0755 UT, V_{ps} is generally quite small and steady, indicating rather high and constant plasma density. Inside the oval, the density is lower and much more irregular, and V_{ps} also becomes irregular and increases. At 0748 UT, the satellite moves from shadow to sunlight, causing a decrease in V_{ps}. In sunlight, the emission of photoelectrons from the satellite helps to compensate for the bias current from the satellite to the probes, which must otherwise be balanced by the collection of ions from the ambient plasma, requiring a more negative satellite. On Freja, the satellite potential is also influenced by the operation of other experiments, in particular the wave experiment (F4) and the cold plasma analyzer (F3C) which normally operate their probes at a positive (negative) potential to collect the thermal electron (ion) current. In Figure 2, third panel from top, the glitches at 130 second intervals are sweeps done by the F4 instrument (seen more clearly in eclipse). The satellite potential ($-V_{ps}$) on Freja varies generally between 0 and −10 Volts, except in extreme cases such as the very low density in the black auroral vortex discussed by *Marklund et al.* [1994*b*], where it reached close to −15 Volts.

On Viking, the plasma densities encountered were generally lower than on Freja, and the satellite potential was correspondingly higher (up to +20 Volts. It was shown [*Marklund et al.*, 1990] that the satellite potential was a very good indicator of the location of the polar cusp (high, smooth density, small V_{ps}), and of auroral flux tubes (low, irregular density, large V_{ps}). Figure 3 shows a crossing of the northern hemisphere which includes both these features around 2020 UT and 2125 UT, respectively. Also illustrated is the fact that the extremely high density in the cusp can cause V_{ps} to change sign and become positive, even though the bias current used is negative. This may be understood on Viking by approximating the

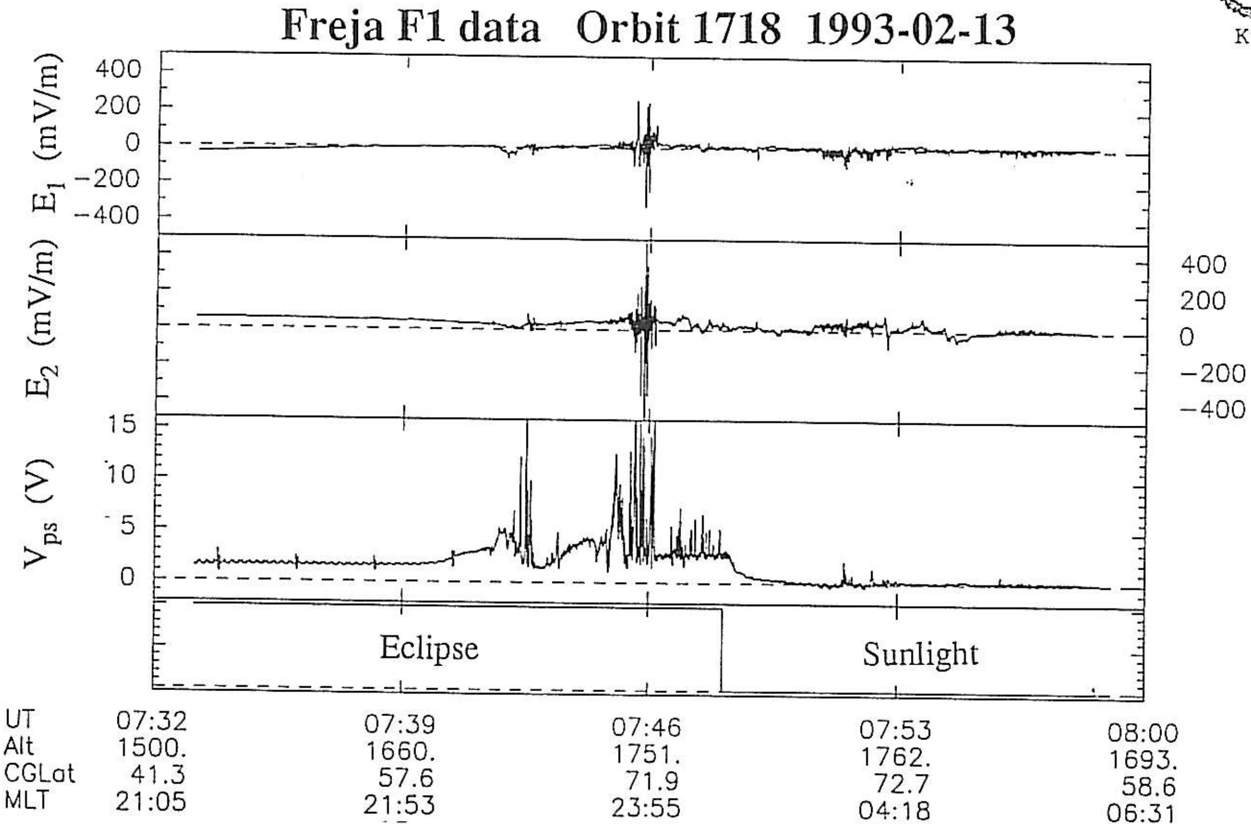


Fig. 2. Example of a Freja orbit showing the variation of V_{ps} as Freja traverses different plasma environments. The panels contain, from the top, two components of the electric field in the satellite spin plane (E_1 and E_2), the negative of the satellite potential (V_{ps}), and an indication of whether Freja is in sunlight or eclipse.

satellite with a disk instead of a sphere, and the fact that the angle between the spin axis and the sun direction is around 45°. Note the good correlation between V_{ps} and the electron density, measured by the on-board particle experiment.

ISEE-1 made measurements at distances even farther away from the Earth, and entered the very tenuous and hot plasma in the tail lobes. In extreme cases the satellite potential reached more than +60 Volts. In such a plasma, $I_{ph} >> I_i$ in Equation (1), both the satellite and the probe will float at positive potentials, and V_{ps} will be roughly proportional to the logarithm of the ambient electron flux, $n_e\sqrt{T_e}$, as demonstrated by *Lindqvist* [1983].

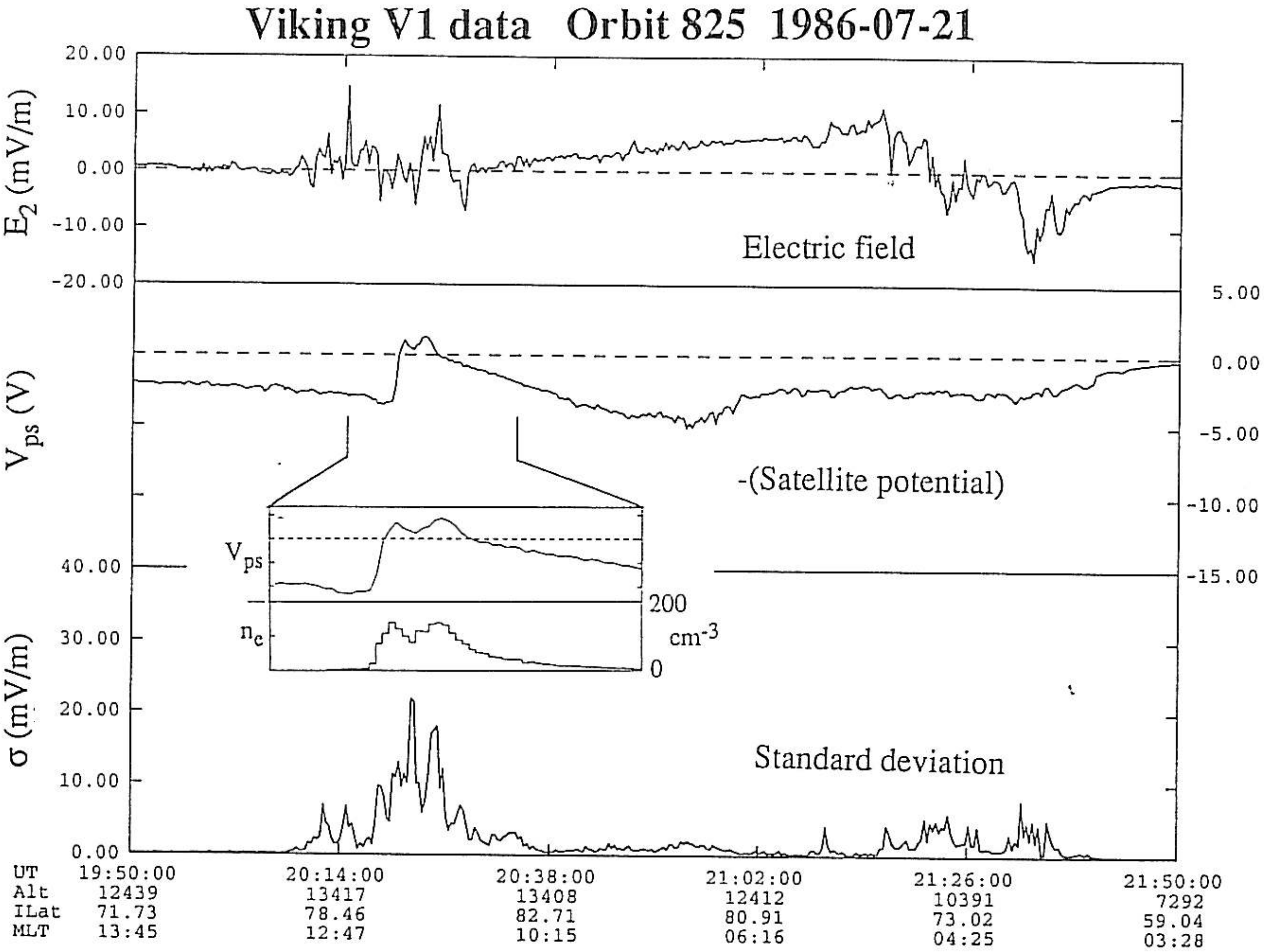


Fig. 3. Example of a Viking orbit showing the variation of V_{ps} as Viking traverses different plasma environments. E_2 is the electric field and σ is the standard deviation in E. The insert shows the electron density n_e determined from the particle experiment.

5 Absolute values of plasma density and temperature

By fitting theoretical relations to the measured sweeps, it is possible to determine the parameters n_e and T_e. Examples of such fits, using only the simple, unmagnetized, theory in Equations (2) – (3), are seen in Figure 1, where the solid lines are the measured current sweep, and the dashed lines are the theoretical curve using the parameters given in the Figure. The values used for i_{ph} and T_{ph} are chosen to model the photoemission in the top two panels as well as possible, and agree well with values reported by, e.g., *Grard* [1973]. A problem in determining the best fit is that it is sometimes difficult to differentiate between changes in n_e and changes in T_e. A preliminary analysis of the sweeps in Figure 1 gives the results for n_e and T_e listed in the Figure, where each fit has been done by iterating manually the value of T_e, and obtaining n_e by a least-squares fit. The uncertainties in these estimates are within a factor of 2 or so.

A unique feature of the Freja electric field instrument is that the burst memory can be used to collect data over entire orbits [*Marklund et al.*, 1994*a*]. Normally these overview data are collected with 8 samples/s, but there is also a "compressed" mode with 192 samples/s, which is enough to resolve the current sweep. An example of plasma density determined from the current sweeps on such an orbit is given in Figure 4, which also contains the satellite potential V_{ps} for comparison. By studying the individual sweeps, it was found that T_e was generally of the order of 0.5 eV (cf. Figure 1), and for computational reasons this value was assumed, and only n_e was determined automatically from each sweep.

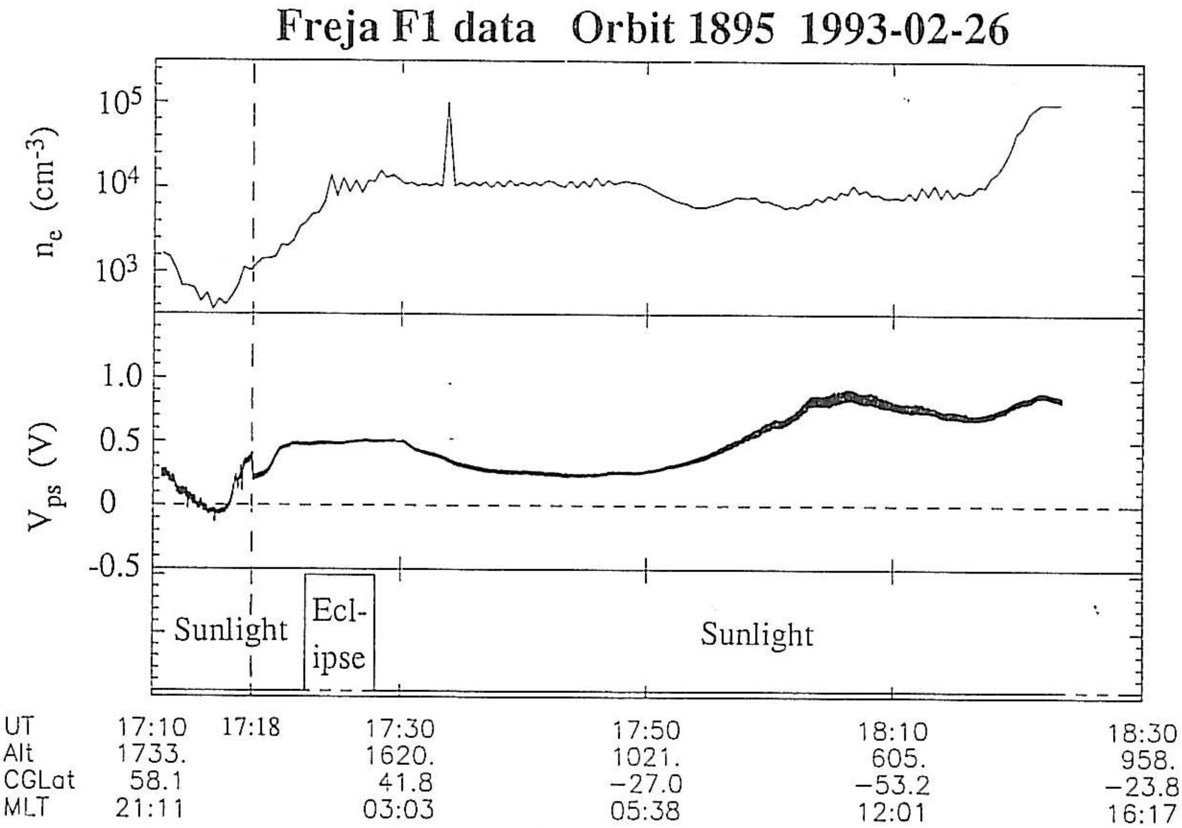
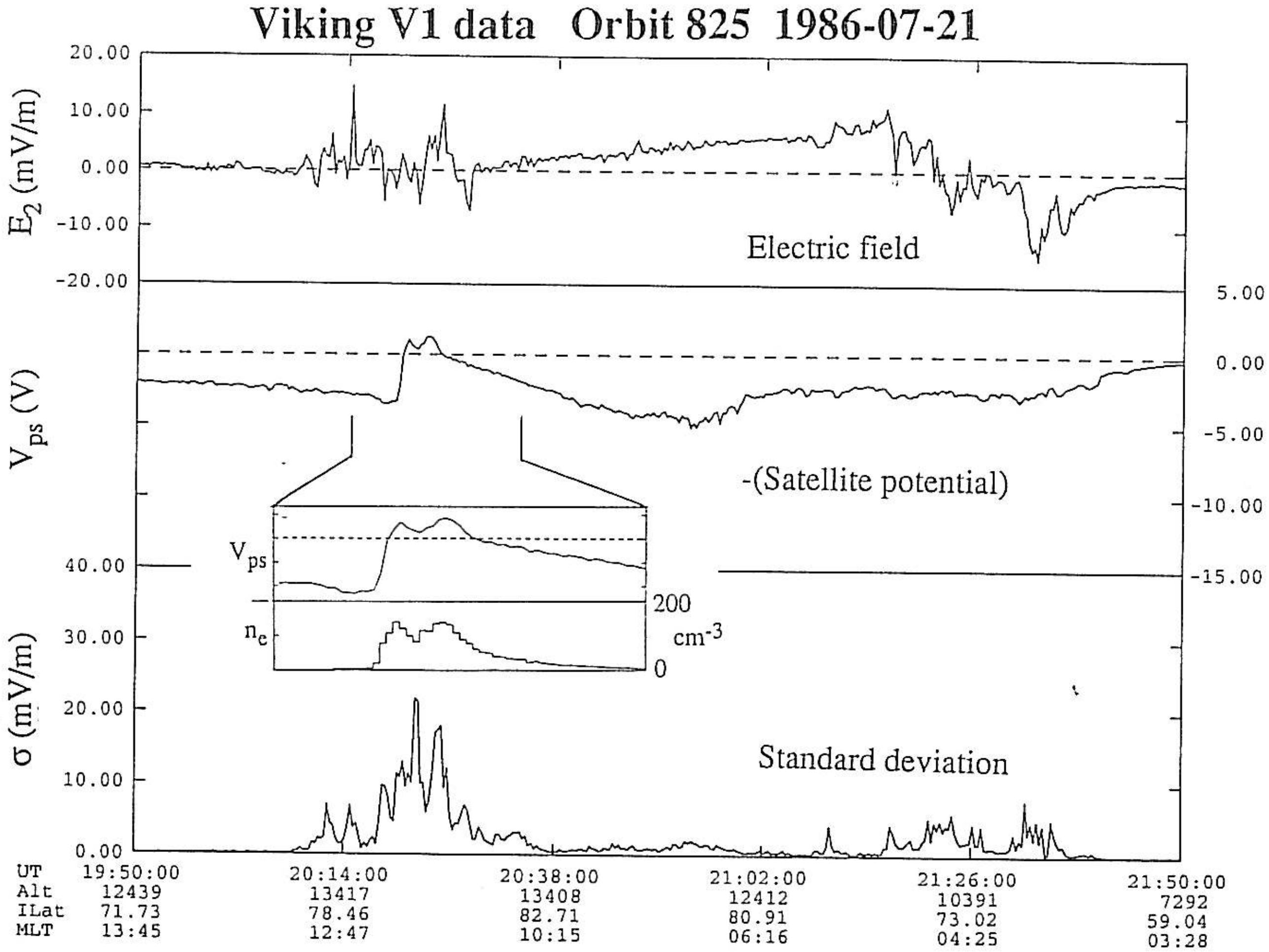


Fig. 4. Comparison of plasma density (n_e), determined from current sweeps, and V_{ps}, for almost a full Freja orbit.

There is some correspondence between the two curves, but also significant differences. At 1718 UT there is a clear jump in V_{ps} when the Freja wave experiment (F4) is switched off (F3C was not operated during this orbit). In this case, the satellite potential does not change as it moves into and out of eclipse. This is because of the relatively high plasma density, causing the photoelectron current I_{ph} to be small compared to the thermal ion current I_i for the negative satellite (typical values are $I_{ph,\text{satellite}} \approx 100\mu\text{A}$ and $I_{i,\text{satellite}} \approx 500\mu\text{A}$). More thorough studies are necessary to explain all the details of the V_{ps} variations, and are outside the scope of the present paper.



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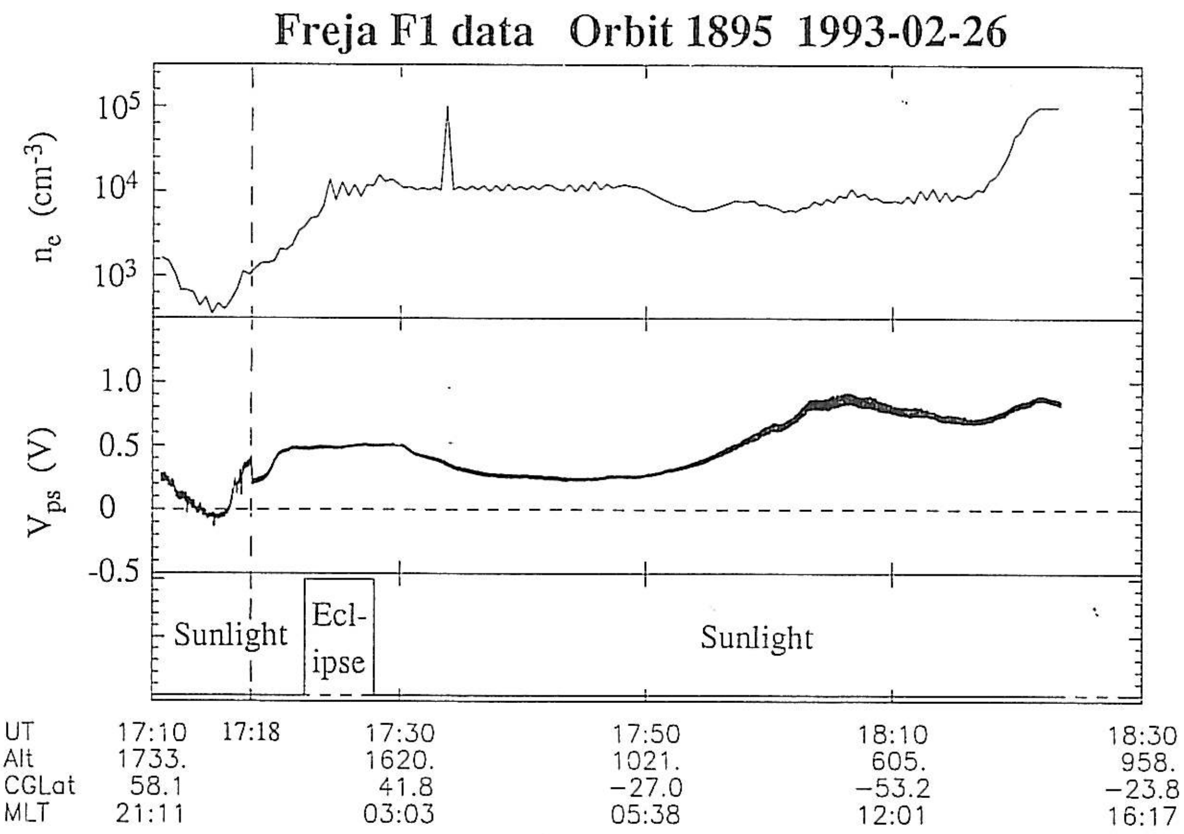

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The instrument also has a burst mode, where the sampling rate is 6144 s^{-1}. This enables extremely detailed study of the behavior of the probe voltage during a current sweep. Part of such a sweep is shown in Figure 5, where both the current to the probe (I_b) and the probe voltage (V_{34}, measured relative to the opposite probe) are plotted as a function of time. The time constant for the probe to assume equilibrium after a change in the current is clearly seen, and is approximately 1.2 ms. Using this value and the differential probe-plasma impedance, estimated from the slope dV/dI of the current sweep to be 60 MΩ, the capacitance is found to be 20 pF. Subtracting the input capacitance of the electronics leaves 14 pF between the probe and the plasma, compared to the vacuum capacitance 3 pF between a sphere of radius 3 cm and infinity. A capacitance of 14 pF is obtained between an inner sphere of radius 3 cm and and outer sphere of radius 4 cm. In this case, the thickness of the sheath surrounding the probe is probably determined mainly by the photoelectron cloud around the probe, rather than by the Debye length, which in this case ($n_e = 55$ cm^{-3}, $T_e = 1$ eV) is $\lambda_D = 1$ m.

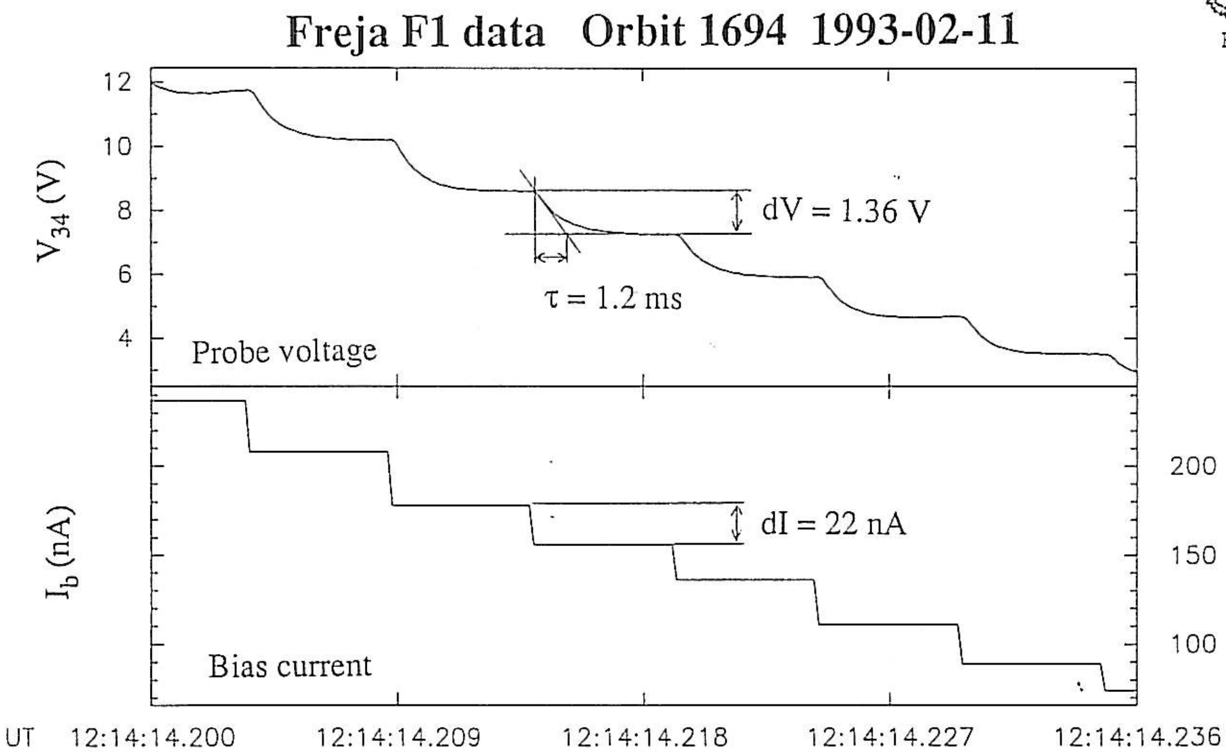

Fig. 5. Detail of a current sweep, showing the time constant for the probe to assume equilibrium after each current step. I_b is the current sent to one probe, and V_{34} is the voltage between this probe and the opposing, floating probe. The impedance is obtained as $R = dV/dI$, and the capacitance as $C = \tau/R$.

6 Summary

A new approach to the study of plasma characteristics in the upper ionosphere has been presented using high-resolution and overview data from the Freja double probe electric field experiment. Full orbit coverage of continuous relative plasma density variations (from satellite potential measurements) and of absolute density and temperature (from Langmuir sweeps) is a novel and unique feature of the Freja mission. Whereas a generally good consistency has been found between the results of these two measurements at higher altitudes in tenuous, sunlit plasmas (from Viking and ISEE), significant differences are occasionally seen within the denser plasma regions explored by Freja. These differences, even though not yet fully understood, are likely to provide additional and valuable insight into the complicated behavior of probes exposed to different plasma environments. The electron temperature in the Freja environment is generally of the order of 1 eV, and the density typically varies between 10^3 and 10^5 cm^{-3}. For the first time, detailed studies of the probe voltage response to Langmuir sweeps have been performed in space using high-resolution data, which allow the computation of the probe-plasma capacitance.

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Division of Plasma Physics, Alfvén Laboratory, Royal Institute of Technology,
S-100 44 Stockholm, Sweden

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Keywords: Freja, Electric fields, Plasma density, Plasma temperature, Langmuir sweeps, Measurement techniques, Satellite potential