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Antenna-plasma and antenna-spacecraft resistance on the Wind spacecraft

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Abstract. Measurements have been made of the resistance of three different electric field sensing antennas on the Wind spacecraft in the solar wind. The measurements have been separated into base resistance and plasma resistance by assuming that the plasma resistance is inversely proportional to the antenna length. Simple formulas for the resistances, as functions of the plasma electron flux, are given and fitted to the data. The results imply that the division of the signal by the base resistance is important and needs to be taken into account in low-frequency measurements of electric fields when the antennas are shorter than a few tens of meters.

1. Introduction

The antennas used on spacecraft to measure electric fields are, at low frequencies and in rarified plasmas like the solar wind, mainly coupled to the plasma by photoelectrons. They are also coupled to the spacecraft by exchange of photoelectrons. The net exchange current in each case varies with the relevant potential difference, and so the photoelectrons provide effective resistances, the plasma resistance R_{plasma} and the base resistance R_{base}, which divide the wave signal voltage V_{wave} to give an input voltage V_{in}:

$$V_{\text{in}} = V_{\text{wave}} \frac{R_{\text{base}}}{+R_{\text{plasma}}}. \quad (1)$$

Figure 1 shows the resulting equivalent circuit together with the measuring circuit described below. This effect is more important in the case of wire or cylindrical antennas as opposed to double probes, which are spheres mounted at the end of booms which are not part of the sensor. Various attempts have been made to reduce the division of the signal. Helios [*Gurnett and Anderson*, 1976] carried "ion guards" around the bases of its antennas. Several experiments [*Heppner et al.*, 1978] have used insulating coatings on the inner part of the antenna. The Waves experiment on the Wind spacecraft [*Bougeret et al.*, 1995] had no special treatment to reduce the attenuating effect of the base resistance but did include a measurement of these resistances. The usual measurement of antenna impedance [e.g., *Tsutui et al.*, 1997] measures the base resistance and the plasma resistance in parallel. Here we use the difference in length between two antennas to separate the measurements into base and plasma resistance.

Wind carried three dipole antennas, here designated EX, EY, and EZ. The Wind spacecraft is a cylinder, rotating at 20 rpm, and the EZ antenna was extended along the spin axis, while the other two were deployed in the spin plane and held out by centrifugal force. The EX and EY antennas, of monopole lengths 50 and 7.5 m respectively, were made of seven strands of AWG #36 Cu-Be wire for an effective diameter of 0.38 mm. Each of these monopoles had a small tip mass of area 2 cm^2 when viewed along the antenna axis and 4 cm^2 when viewed from the side. The EZ monopoles were of Cu-Be strips, locking together on two sides to make a cylinder of 2.8 cm diameter. They were extended to a length of 5.28 m during the measurements reported here. The antennas were not biased but were connected to spacecraft ground through very large resistances. The effect of these resistances is essentially negligible but has been removed from the analysis which follows.

The measurement consisted of applying a series of known voltages V_0 to one monopole of the dipole antenna through a known resistor R_m and measuring the change in potential of the antenna V_A. This measuring circuit is shown in Figure 1 together with the plasma resistances to be measured. The antenna resistance R_A is then

$$\frac{R_A}{R_m} = \frac{V_A}{V_0 - V_A}. \quad (2)$$

The results of applications of a sequence of drive voltages V_0 are shown in Figure 2. The resistance is determined by making a least squares fit of (2) to data of this kind.

This measured resistance, as discussed above, is the resistance to the plasma and the resistance to the spacecraft in parallel. We separate them by assuming that since the coupling to the plasma is due to the exchange of photoelectrons and to ambient electron pickup, the plasma resistance is inversely proportional to the length of the antenna and the base resistance is the same for both antennas.

This latter requires that the measurement be made when the antennas make equal angles to the Sun. During the period of November 27, 1999, to May 5, 2000, the measurements were made at the instant that both the EX and EY antennas were at 45° from the anti-Sun direction so that the bases of the antennas were both in the shadow of the spacecraft. From May 5, 2000, onward both antennas were at 45° from the sunward direction, so that the

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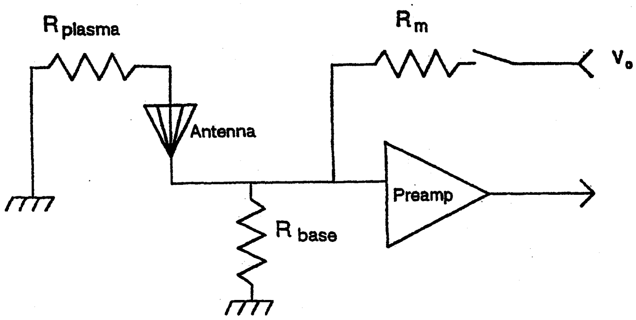

Figure 1. Equivalent circuit (R_{base} and R_{plasma} are effective resistances due to photoelectron exchange) and measuring circuit used for the measurements of this work.

surface around the antenna bases was illuminated. Figure 3 shows the relations of the antennas to the spacecraft and to the shadow of the spacecraft at the times of measurement. X_{shade} and Y_{shade} denote the positions of the measured (monopole) antennas for the period before May 5, 2000, and X_{sun} and Y_{sun}, the positions after May 5.

When the separate resistances of EX and EY antennas, R_{A_x} and R_{A_y}, respectively, have been determined in (2) by least squares fit, then the assumption of identical base resistances and plasma resistance inversely proportional to length leads to a determination of the separate resistances R_X, R_Y, and R_{base} through a solution of

$$\frac{1}{R_{A_x}} = \frac{1}{R_X} + \frac{1}{R_{base}}$$
$$\frac{1}{R_{A_y}} = \frac{1}{R_Y} + \frac{1}{R_{base}} = \frac{\alpha}{R_X} + \frac{1}{R_{base}}, \qquad (3)$$

where $\alpha = 7.5/50$ is the ratio of the lengths of the antennas. A small part of the base resistance is the preamp circuit resistance, and this is then removed from R_{base}. Since the results as used here are essentially an expansion around zero applied voltage, the resistances which we find are for antennas which have not been voltage biased with respect to the spacecraft [*Scudder et al.*, 2000]. However, Figure 2 shows that the results would not be changed much for modest bias voltages.

In addition to the measurement made at an angle between the EX antenna and the Sun fixed by command, another (EX and EY

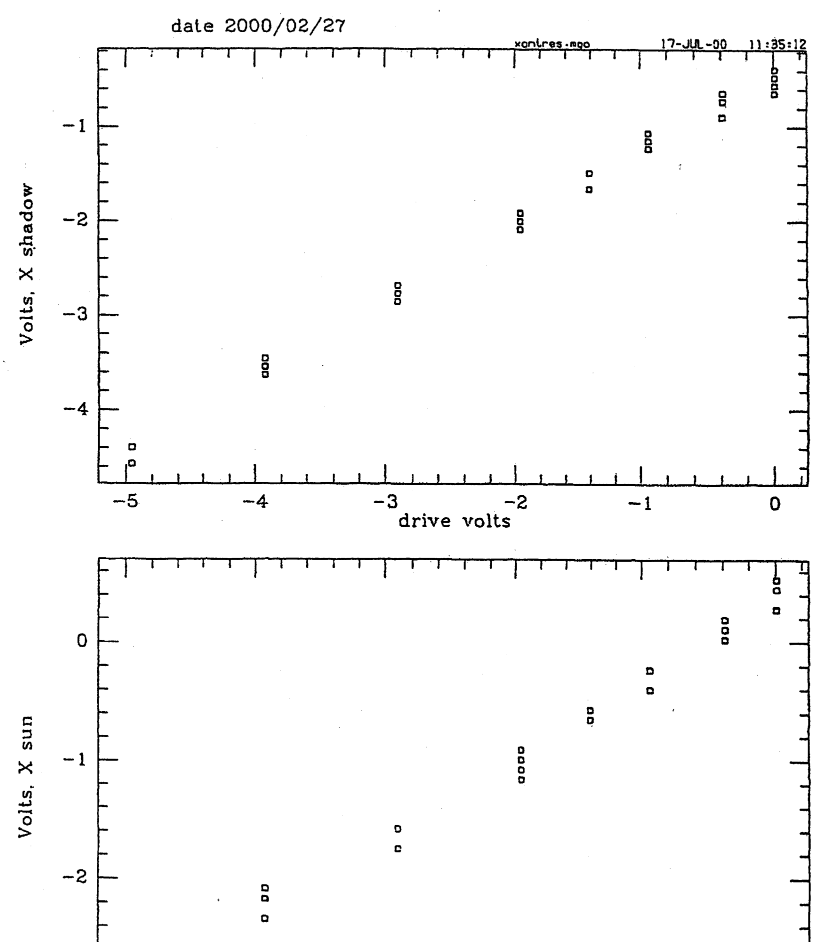

Figure 2. Results of a resistance measurement on EX. The top panel shows measurements of antenna voltage when the antenna is in the shadow of the spacecraft. The bottom panel shows measurements of antenna voltage when a drive voltage V_0 is applied at a commandable angle to the Sun.

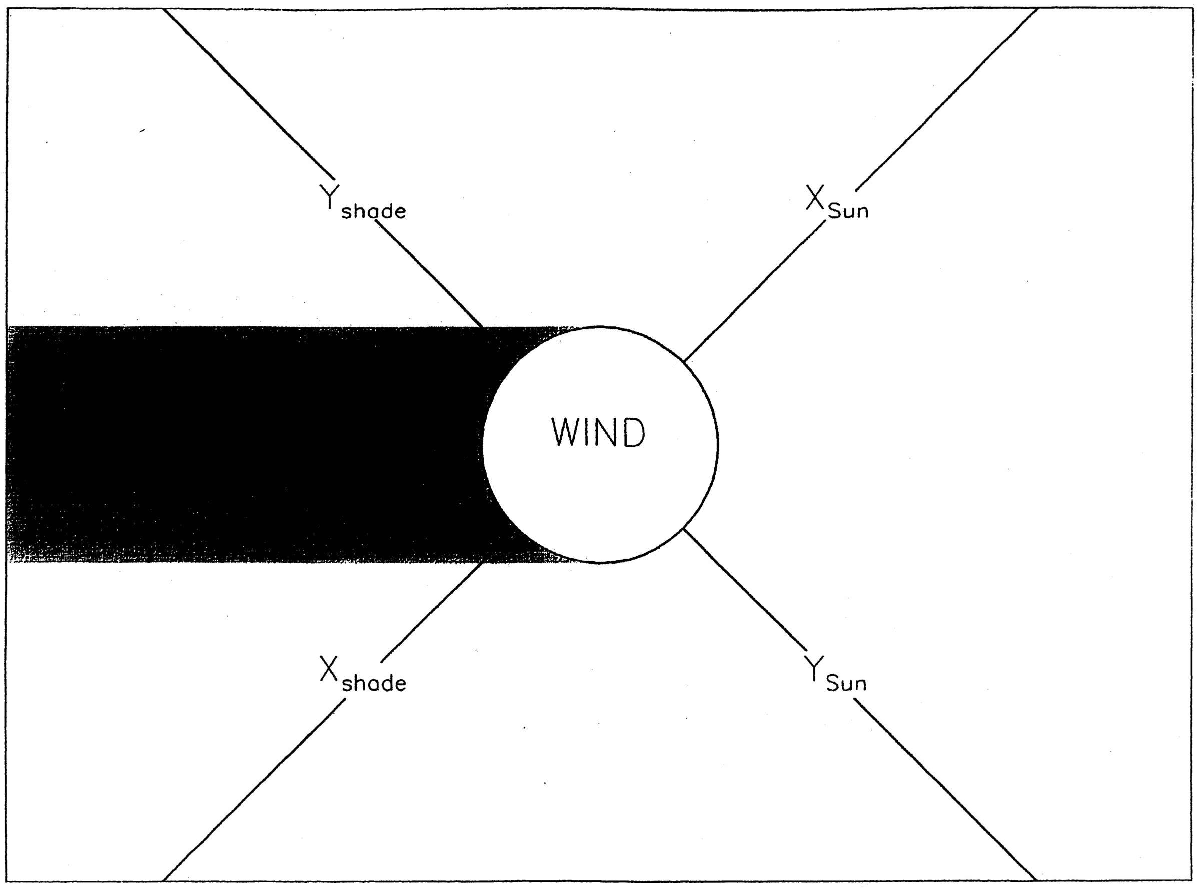

Figure 3. Relation of the measured monopole antennas at the time of measurement. X_{shade} and Y_{shade} denote the positions of the measured antennas for the results shown in Figure 4, and X_{sun} and Y_{sun} show their positions for Figure 5.

only) was made at the negative peak in the antenna potential, presumed to be when each antenna was in the shadow of the spacecraft. This gives a measure of the antenna resistance when there is little or no photoemission. The qualifier "little" photoemission refers to the fact that the antenna values never are as negative in shadow as they ought to be. *Kellogg* [1980] discussed this for Helios, attributing the difference is perhaps due to scattered sunlight hitting the supposedly shadowed antenna. However, the same is true for experiments on Wind and Ulysses.

The resistance of the EZ antenna was also measured, but as there is no antenna with the same diameter but different length, the plasma and base resistances cannot be separated by this method. Nevertheless, the formulas derived from the EX and EY antenna measurements can be checked against the measurements for this very different antenna.

A simple theory for the plasma resistance will help in analyzing the results. Suppose that the escaping photoelectron current I_ϕ is given by

$$I_\phi = j_\phi A_\phi \exp\left(\frac{-eV}{k_B T_\phi}\right) \tag{4}$$

[*Hinteregger et al.*, 1959], where T_ϕ is an effective temperature for photoelectrons, V is the potential difference between antenna and plasma, A_ϕ is the effective area for photoemission, and j_ϕ is the photoemission current density, and that the current from the plasma is given by

$$I_p = j_p A_p = e\, n_e \sqrt{\frac{k_B T_e}{2\pi m}}\, A_p, \tag{5}$$

where T_e is the plasma electron temperature, n_e is the electron density, and m is the electron mass. Here j_p is the current density due to plasma electrons, and A_p is the effective area for electron pickup, usually the physical area. Note that we neglect any effect of the antenna potential on the plasma current since the antenna potentials are generally small compared with the solar wind electron temperatures of the order of 10 eV.

We have not found measurements of the photoelectron spectrum from Cu-Be in sunlight but only a measurement at wavelengths >150 nm [*Schwetzoff et al.*, 1952], which therefore does not evaluate the important emission due to Lyman alpha at 121.6 nm. Hence we use the photoelectron effective temperature as a free parameter to fit our measurements. The result of a fit was $k_B\, T_p$ = 1.3 eV. This is in reasonable agreement with the value of 1.7 eV obtained in the extensive analysis of *Scudder et al.* [2000], although their value is for the average surface of the Polar spacecraft. Polar, like Wind, was covered with indium tin oxide, a transparent semiconductor, and there is no reason why the photoelectron temperature should be the same as for Cu-Be [see *Feuerbacher and Fitton*, 1972]. The net current to the plasma must be zero,

$$I = I_\phi + I_p = 0,$$

and the resistance, the inverse of dI/dV, is therefore

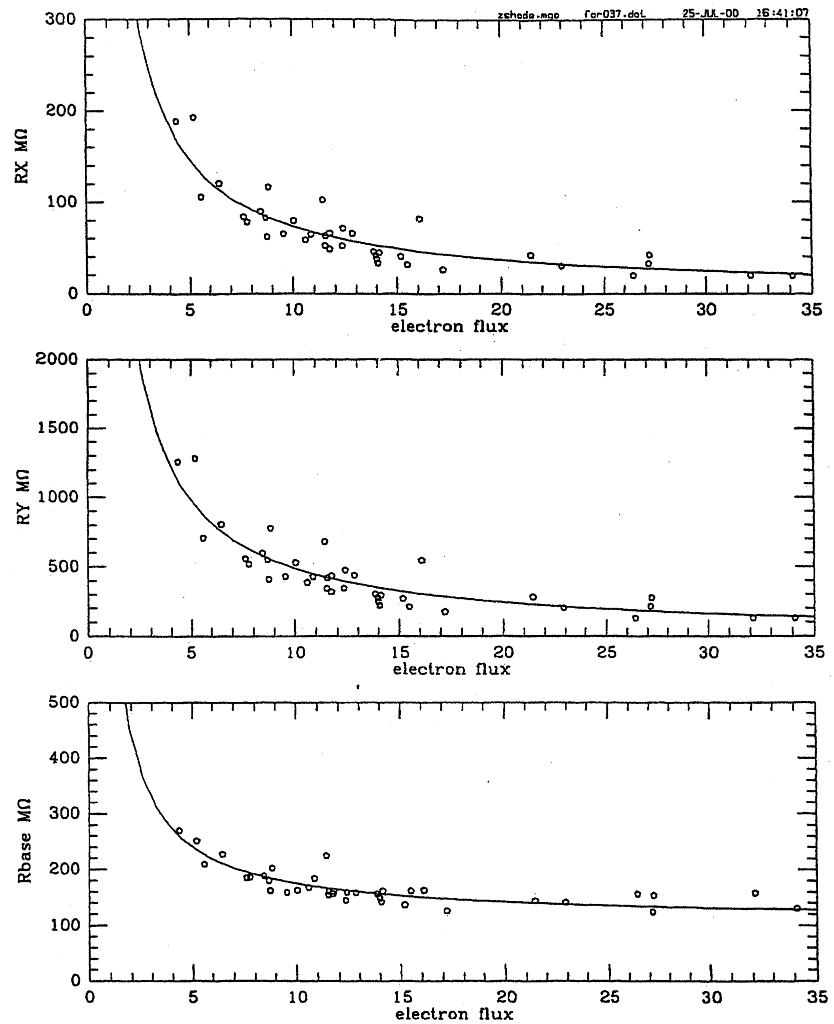

Figure 4. Measured resistance for EX (top panel) and EY (middle panel) and base resistance (bottom panel) as function of electron flux for the case when the antenna bases are both in the shadow of the spacecraft. Electron flux is in units of density (in cm^{-3}) times $\sqrt{k_B T_e}$ (in eV). The curves are explained in the text.

$$R = \frac{k_B T_\phi}{e j_p A_p}. \qquad (6)$$

It will be seen that the resistance is independent of the photoemission coefficient and depends only on the plasma current and the photoelectron temperature. This also implies that the resistance is insensitive to variations in the solar ultraviolet flux. The floating potential, however, which in this simple theory is given by

$$V = \frac{k_B T_\phi}{e} \ln\left(\frac{A_\phi j_\phi}{A_p j_p}\right), \qquad (7)$$

does depend on the photoemission coefficient. If a more accurate formula using a two-temperature photoelectron spectrum [*Pedersen*, 1995; *Scudder et al.*, 2000] were to be used, the floating potential would bring a variable photoelectron temperature into play, and so the resistance would depend on the photoemission coefficient. However, the one-temperature expression proves to be sufficiently accurate for our purposes.

2. Results

2.1. General Results

As seen in (6), the resistance is expected to depend on the flux of plasma electrons, as given in (5). The flux has been taken from the measurements of the 3DP experiment on Wind [*Lin et al.*, 1995]. The voltages used in the measurement of the antenna resistance are only sampled every 3 min at low bit rate and 90 s at high bit rate (low bit rate applies to most of the measurements used here). As a number of different drive voltages were used, an entire measurement sequence took an hour and was carried out between 0200 and 0300 UT on every second day. The density and temperature of the solar wind electrons may change during an hour, so measurement sequences in which the variance of the density was larger than a certain limit were excluded from the analysis.

2.2. Bases in Shadow and Antennas in Sunlight

In Figure 4 the results obtained by the procedure described above are shown for the period February 2 to May 5, 2000, with the exclusion of a short period when Wind was within the Earth's

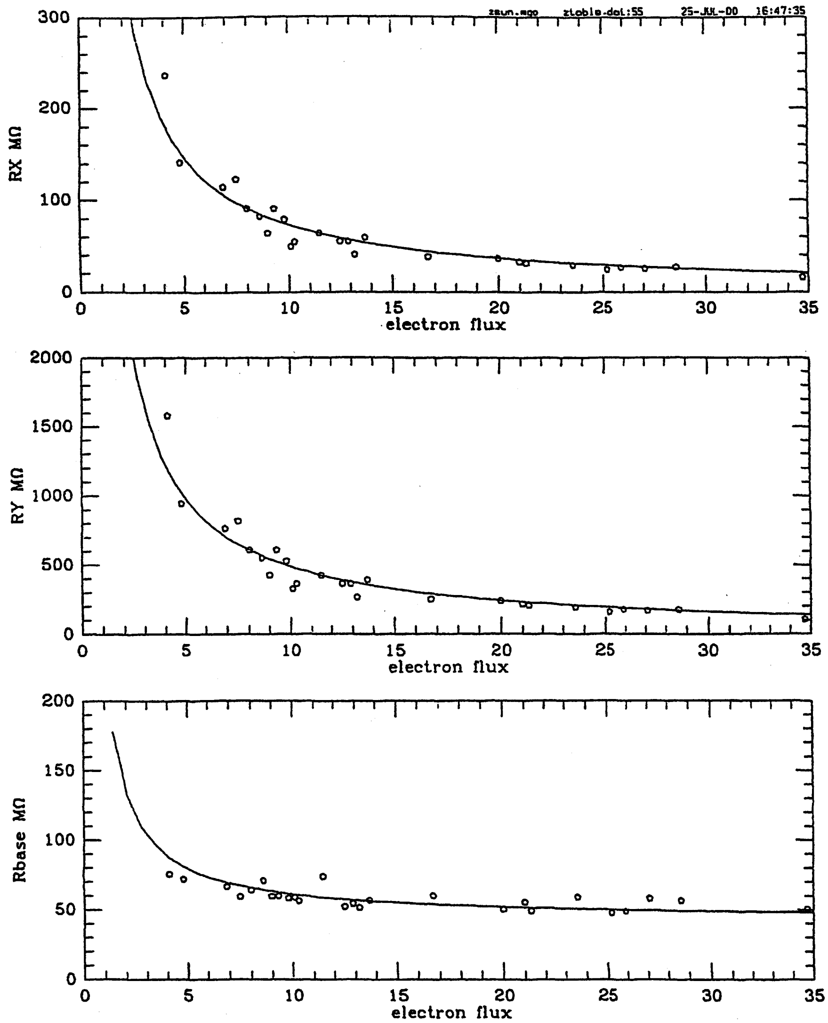

Figure 5. Same as Figure 4 but with antenna bases in sunlight.

bow shock and magnetosphere. The top panel shows the resistance of the long EX antenna to plasma, the middle panel shows the resistance of the EY antenna, and the bottom panel shows the base resistance. Also shown in each antenna panel are curves corresponding to (6) with a photoelectron temperature of 1.3 eV. The unit of electron flux is the product of density in cm^{-3} and square root of temperature in eV, for convenience. Proper flux in electrons /cm^2 s^- can be obtained by multiplying by 1.67 x 10^7.

The base resistance in the bottom panel is not such a strong function of electron flux. A curve of the form $R = A + B/\text{flux}$ has been fitted to the data, the values obtained for A and B are shown in Table 1, and the fitted curve is shown. (Again, the units of flux are density (cm^{-3}) times $\sqrt{kT}$ in eV). Since the antennas are sufficiently long to extend well beyond the expected photoelectron sheath, the effective area for photoelectron emission and capture of the antenna is proportional to its diameter. We therefore assume that the coefficients A and B for any antenna should be inversely proportional to the diameter, here 0.38 mm. This will be checked in section 2.5 with the EZ antenna measurements.

A full treatment of the time-dependent variation of antenna potential as the antennas are more and more shadowed has not been made, but these measurements allow estimation of the time constants to reach potential equilibrium. Typical values for the antenna resistance and base resistance in parallel are 100 Mohm for EX and 700 Mohm for EY. The antenna and input capacitances in parallel are 280 and 81.4 pF, respectively, leading to time constants of 28 and 57 ms, respectively.

The Wind spacecraft is a cylinder ~2.4 m high and 1.8 m in diameter, so that its umbra extends for ~190 m. It rotates at 20 rpm, so each antenna is completely in the umbra for only a short time: 2.0 ms for the EX antenna and 16 ms for EY. As can be seen, this gives insufficient time to reach equilibrium. Hence the interpretation of the measurements in the umbra is uncertain.

2.3. Bases and Antennas in Sunlight

In Figure 5 the results obtained by the procedure described in section 2.2 are shown for the period May 5 to July 8, 2000, with the exclusion of periods when Wind was within the Earth's bow shock and magnetosphere. Again, the top and middle panels show the resistances of EX and EY, respectively, and the bottom panel shows the base resistance. In this case, since the exposure of the antennas to the Sun is almost exactly the same as when the bases are in shadow (when the bases are in shadow, ~0.4 m of the antenna is also shadowed), we should expect that the antenna

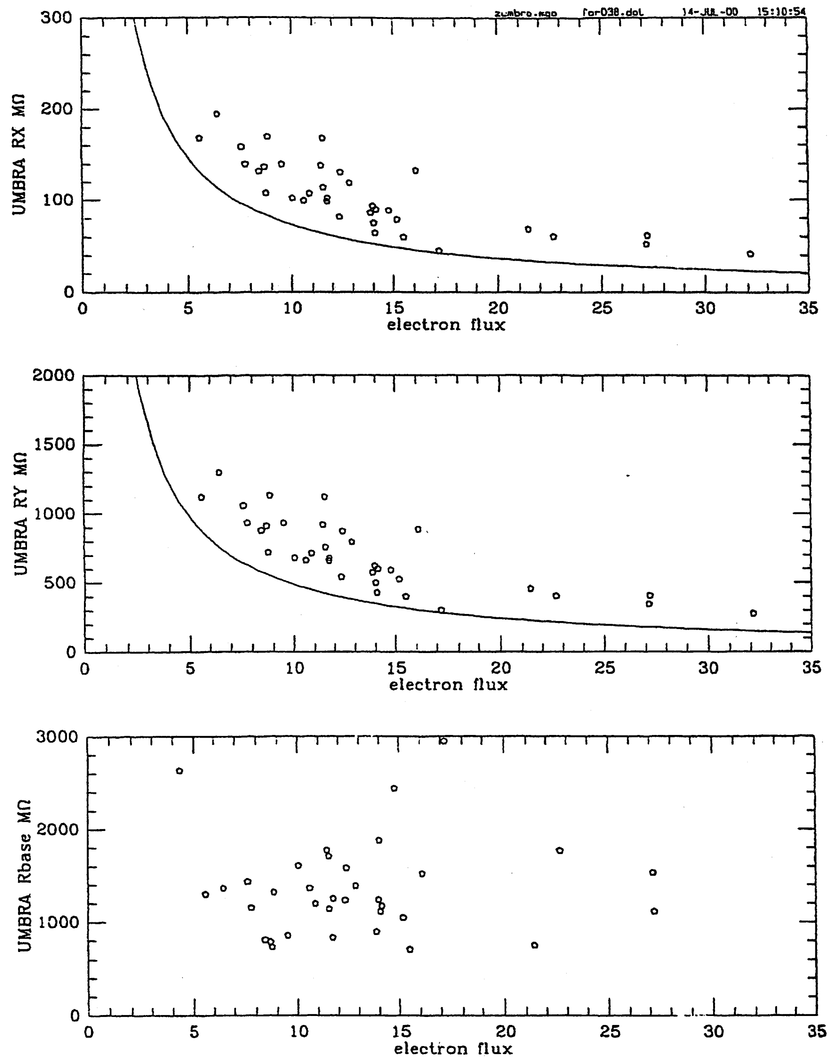

Figure 6. Same as Figure 4 but with the antenna in the umbra of the spacecraft.

resistances are the same, which provides a check on the analysis procedure. However, we should expect the base resistance to be different and smaller. The same curves as in Figure 4 are drawn to facilitate the comparison. It will be seen that the resistances of EX and EY are about the same, but the base resistance is considerably smaller in accordance with expectations.

2.4. Antennas in Shadow

A measurement was also made of the antenna resistance at the point where the antenna was most negative, presumed to be when the antenna was in the umbra of the spacecraft. The results of these measurements are shown in Figure 6. Also shown are the same curves derived from (6) as in Figures 4 and 5, but here they are not valid, as there is little or no photoemission, and they are shown only to guide the eye. It will be seen that both the base and plasma resistances are larger than those of the previous cases. It is quite reasonable that the antenna to plasma resistance becomes large, but one might at first think that the base resistance would be unchanged. This is not so, however, and the reason is that the antenna becomes a few volts or so negative with respect to the spacecraft, and so most photoelectrons from the spacecraft cannot reach the antenna.

2.5. EZ Antenna

As mentioned in section 1, there is no simple way of separating the base and plasma resistances for the EZ antenna, and further, the measurements are not as accurate, as the value chosen for R_m was too large, and so the change, V_A, is very often smaller than the digitization step or smaller than variations of floating potential during the measurements. For the period July 14 to December 5, 2000, an additional drive voltage step at the maximum possible drive voltage was added to try to overcome this, with partial success. The best measurements are concentrated toward low electron fluxes when the resistance is larger. Selected results from this period, selected by RMS residuals of the fit, are plotted as points in Figure 7. The formulas of (6) can be used with the dimensions of the EZ antenna to calculate a resistance, and the values of Table 1 can be

Table 1. Base Resistance Parameters

Condition	A, Mohm	B, Mohm – unit flow
EX, EY bases in shade	110	654.
EX, EY bases in Sun	42.7	184.

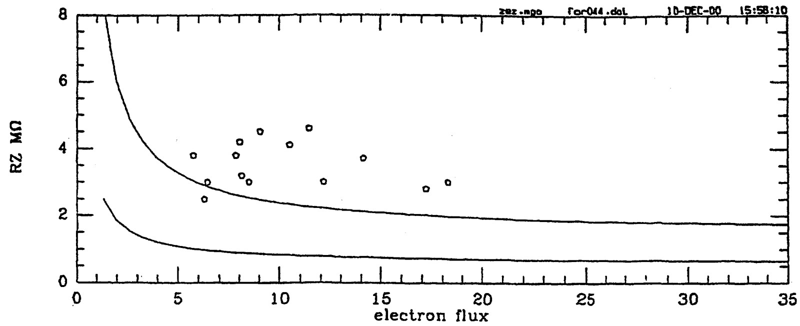

Figure 7. Parallel plasma and base resistances for an EZ monopole.

multiplied by the ratio of the antenna diameters, a factor of 1/74, to obtain a theoretical base resistance. The two curves in Figure 7 are the results of calculating the parallel base and plasma resistances for the two cases of Sun and shade in Table 1, the top curve being for shade. It will be seen that in spite of the very large difference in the antenna diameters, the shade formula is good to within about a factor of 2. It is to be expected that it is the shade formula which fits because the top and bottom of the spacecraft are only illuminated by glancing photons which cannot cause much photoemission. Further, examination of the contribution of the calculated base and plasma resistances shows that the base antenna resistance is generally smaller and therefore more important than the antenna resistance in this case, and so probably it is the calculated base resistance which is too low by a factor of ~2. If it were the antenna resistance which was in error, the correction would have to be larger and less believable.

3. Summary and Conclusions

Separating the resistance seen from the input to an electric fields experiment into base resistance and plasma resistance shows that the base resistance, due to exchange of photoelectrons with the satellite surface, is sufficiently small to seriously affect low-frequency electric field measurements in the solar wind. The effect is most serious, of course, when the electron density and temperature are low and when the antennas are shorter than 10-20 m. Accurate interpretation of the data from such electric field measurements must take this into account. To this end, formulas have been developed which can be used to extrapolate the results from Wind to other antennas. The antenna-to-plasma resistance is given as (6). The base resistance is given as $A + B$/flux, with flux in density (in cm^{-3}) times $\sqrt{Te}$ (in eV) and parameters A and B given in Table 1 for antenna diameter 0.38 mm. Otherwise, A and B should be inversely proportional to antenna diameter. These formulas were developed by fitting data to measurements of the 0.38 mm diameter antennas, but tests with the 28 mm diameter EZ antenna indicate that they are correct to within a factor of 2, even for this large-diameter antenna. There is indication that the calculated base resistance, assuming that A and B are inversely proportional to antenna diameter, is too small for this large-diameter case.

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