Planet. Space Sci. 1973, Vol. 21, pp. 993 to 1000. Pergamon Press. Printed in Northern Ireland

ELECTRON DEPLETION IN THE WAKE OF IONOSPHERIC SPACECRAFT—A COMPARISON BETWEEN RESULTS FROM LANGMUIR PROBES AND ANTENNAS

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(*Received* 24 *August* 1972)

Abstract—*In situ* observations of the electron depletion in the wakes of satellites and rockets in the ionosphere using Langmuir type probes and antennas are analyzed and compared. The quantitative degree of agreement between the results is demonstrated and discussed. One consequence is an improved interpretation of results previously presented for the OGO II Satellite wake.

The distribution of electron and ion densities in the vicinity of a satellite in the ionosphere has been extensively studied by theoretical and numerical methods. Because the problem is a difficult nonlinear one, each analysis in the literature has involved various simplifying assumptions in the basic physics. One avenue to a better understanding of the significance of the assumptions made in the models would be coupling *in situ* measurements with the predictions of the theoretical models.

Compared with the amount of theoretical studies available in the literature, the amount of *in situ* observations is meagre. In particular there are few experimental results regarding the wake behind the satellite which is the most prominent feature of the interaction between the satellite and its ambient plasma. It is the purpose of this brief report to summarize and compare the results of electron depletion measurements in the wake as obtained by different *in situ* diagnostics. The degree of agreement (or disagreement) between the *in situ* results will allow us to assess the possibility of a theory–experiment comparison stated above.

The *in situ* measurements may be divided into two classes according to the type of measurement procedure. One class deduces the electron number density from measurements of the a.c. impedance of a thin cylindrical antenna extending from the vehicle. The antenna length, L, in each case is several times the characteristic dimension R_0 of the spacecraft which determines the 'extent' of the wake. For a cylindrical rocket body R_0 would be the radius of the body. Measurements of this type have been reported by Stone, Fainberg and Alexander (1969) for the wakes of two Nike–Apache rockets and Oya (1970) for a K-9M-21 rocket wake and by Weil and Yorks (1970) for the wake of the OGO II Satellite. In each case the impedance measured was converted, via theory applicable to antennas in magnetoplasma, to an 'effective' number density $\bar{n}_e$. $\bar{n}_e$ is in some sense an average number density for the region surrounding the antenna. Both Oya and Weil and Yorks considered this average to be given by

$$\bar{n} = L^{-1}\int_{L_1}^{L_2} n(l)\,\mathrm{d}l \tag{1}$$

where $n(l)$ is the electron density which would exist in the wake in the absence of the antenna; the antenna of length L extends in the direction of coordinate l from L_1 to L_2. Stone *et al.* (1969) considered $\bar{n}$ to be simply the n value at the base of their antenna where

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it emerged from a guard sleeve which was maintained at the spacecraft body potential. In our subsequent discussion we will set $l = 0$ on the vehicle wall.

The second class or type of measurement is based on Langmuir type probes. Henderson and Samir (1967) applied the Druyvesteyn method with a planar probe to find the electron angular distribution at a distance of $4R_0$ from the Ariel I Satellite's surface. Findlay and Brace (1969) applied the conventional Langmuir method for a cylindrical probe on the Explorer 31 Satellite. From the data of Brace and Findlay, Samir (1972) has deduced that ratio $n(R_0)/n_0$ of electron density at a distance $l = R_0$ from the surface of the satellite to the unperturbed electron density n_0. The type of data involved is illustrated in Miller (1972). The cylindrical probe measurements yield the electron density at $l \simeq R_0$ from the surface of the Explorer 31 Satellite. Since the Langmuir probes were much smaller than the characteristic body dimensions the results obtained are appropriately considered as values of n at the location of the probe.

We are interested in the wake structure which can be described by the ratio $\bar{n}/n_0$ or n/n_0 as a function of position in the wake where n_0 is the unperturbed number density. In each experiment this ratio is available because of the vehicle spin which rotated the measurement device probe continuously through the wake to the region ahead of the satellite and back into the wake.

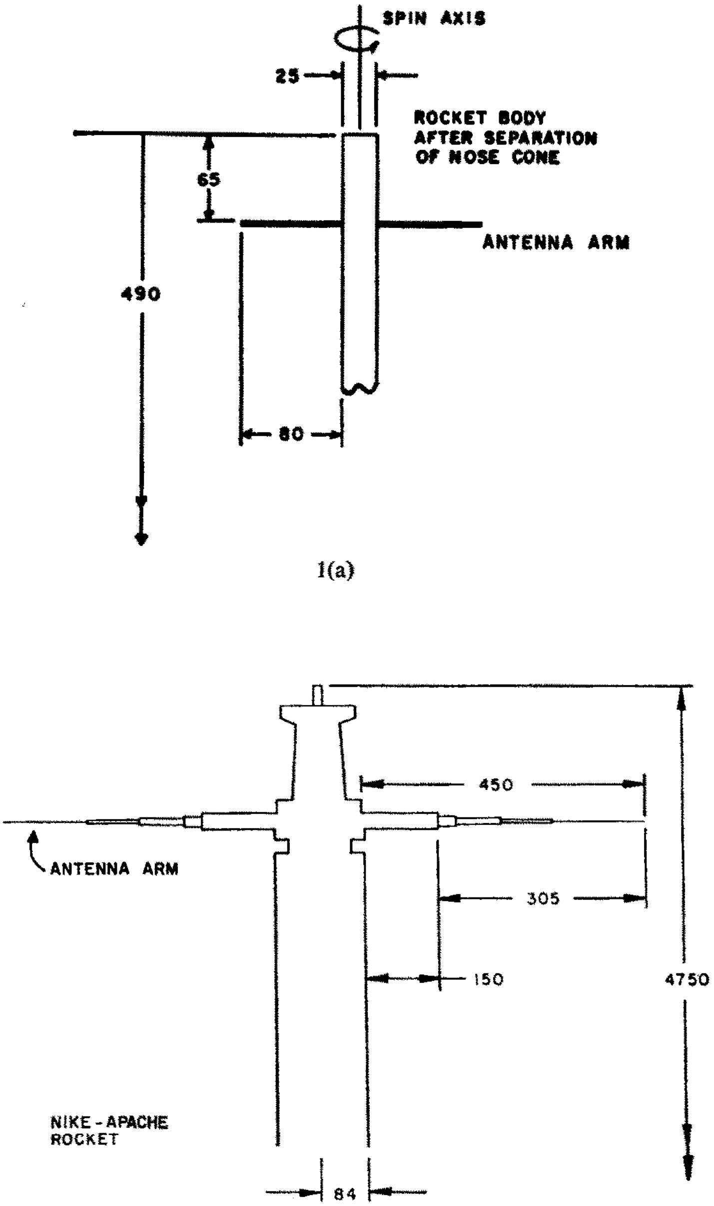
A slight difficulty occurs however in determining the unperturbed density n_0 since all the satellite data and the higher velocity values of the rocket data indicate that often the n values ahead of the vehicle are slightly less than those on the side. More information on this effect is given in Samir and Willmore (1965). This might be due to a buildup of electrons on the vehicle sides or to a depletion of electrons ahead of the vehicle. We will follow the commonly accepted procedure of using values measured with the probe directly ahead of the satellite for n_0.

For the impedance based measurements it is fortunate that density ratios and not absolute values are desired since the only antenna theory extant is based on the antenna being immersed in a medium which does not vary along the length of the antenna; in fact the antenna theories applied in the references assume the medium is uniform radially as well. The effect of such approximations on the deduced values of $\bar{n}$ is unknown as are other effects such as the neglected perturbing effect of the antenna itself on the wake; but in any case the approximations are less likely to invalidate ratios of measured values than absolute values. Details of the methods by which the density (or current) ratios are deduced from probe observations are discussed in the papers referenced above. These papers contain references to theoretical work as well.

In Fig. 1 we present sketches of each space vehicle used indicating the location of the probes and the direction of the spin axes.

In Fig. 2 we plot the principal available data for $\bar{n}/n_0$ and n/n_0 as a function of Mach number $M_0 = v_0/v_i$ where v_i is the ion thermal speed $\sqrt{2kT_i/m_i}$ and v_0 the vehicle's translational speed. The data is for the probe lying directly on the wake axis, i.e. the axis of greatest electron depletion. The values for M_0 were obtained as follows: For Stone *et al.* they are the values given in their paper based on mean ion mass of $m_i = 28$ and $T_i = 230$°K appropriate to 100 km altitude; their rockets reached to 135 km altitude and their data corresponds to various times during descent. Oya's data is for a rocket descent from 320 km and, while he gave values of M_0 for each point, he did not describe his ionosphere model for m_i and T_i.

The Weil and Yorks data represent a range of measured $\bar{n}/n_0$ values corresponding to

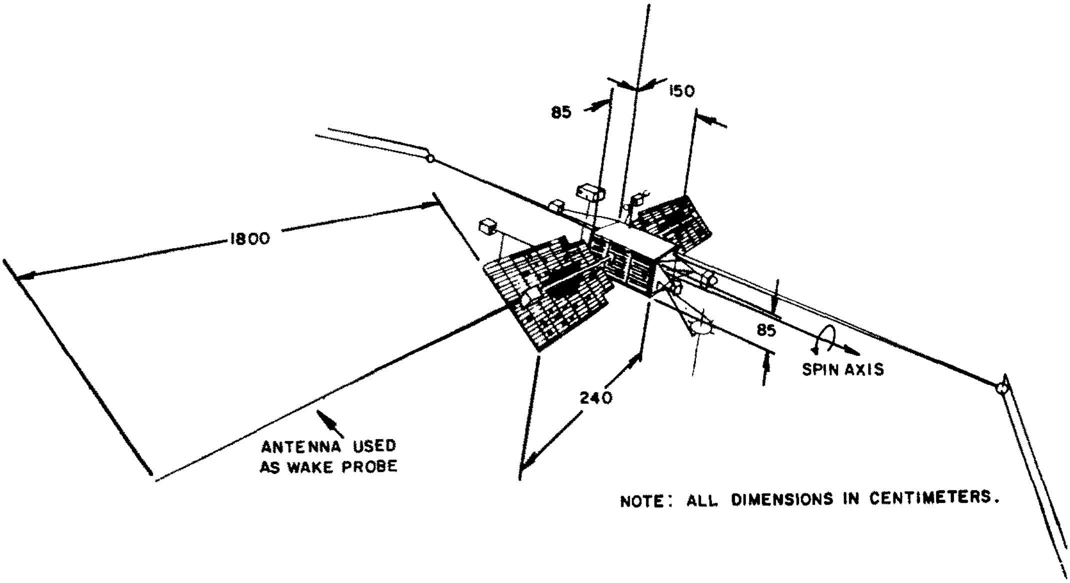


1(a)

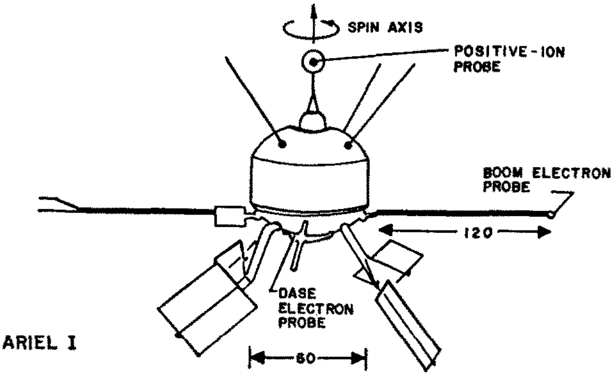
1(b)

FIG. 1. SPACECRAFT AND PROBE CONFIGURATIONS. APPROXIMATE DIMENSIONS ARE SHOWN IN CENTIMETRES.

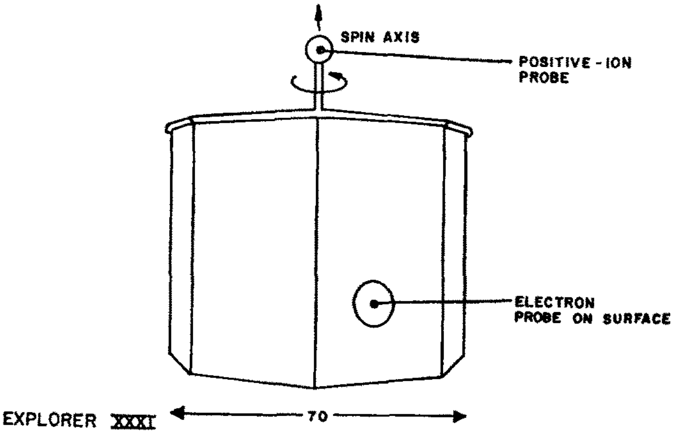
(a) K-9M-21 rocket with dipole antenna
(b) Nike–Apache rocket and dual monopole antennas
(c) OGO II satellite with monopole antenna
(d) Ariel I satellite
(e) Explorer 31 satellite.


150
85
1800
85
SPIN AXIS
240
ANTENNA USED AS WAKE PROBE
NOTE: ALL DIMENSIONS IN CENTIMETERS.

1(c)


SPIN AXIS
POSITIVE-ION PROBE
BOOM ELECTRON PROBE
120
DASE ELECTRON PROBE
60
ARIEL I

1(d)


SPIN AXIS
POSITIVE-ION PROBE
ELECTRON PROBE ON SURFACE
EXPLORER XXXI
70

1(e)

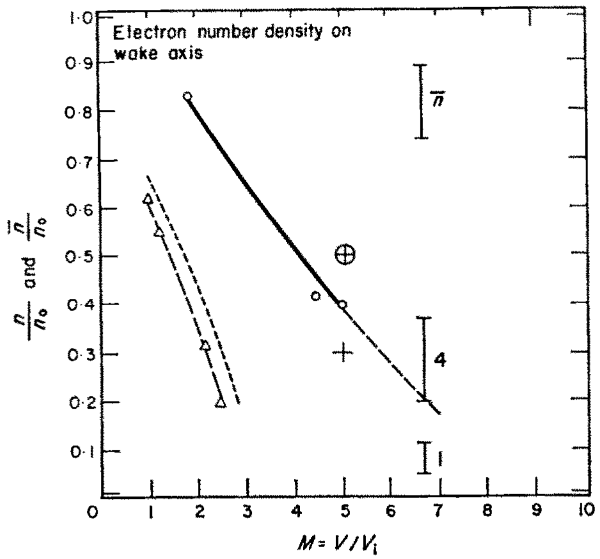


FIG. 2. ELECTRON DENSITY ON WAKE AXIS-COMPARISON BETWEEN SEVERAL *in situ* OBSERVATIONS. Pointwise (i.e. probe) data $n(l)/n_0$ are indicated by symbols as listed in this array

l/R_0 satellite	1	4
Explorer	+	
Ariel		⊕
OGO	I 1	I 4

Averaged data $\bar{n}/n_0$ are indicated by the symbols
⊙ K-9M-21 (Oya)
△ Nike–Apache (Stone *et al.*)
I $\bar{n}$ OGO (Weil and Yorks).

measurements on several different satellite perigee passes. The M_0 values for these passes were not given in their paper but the five sections of data given there all corresponded to altitudes of 430–520 km and low latitudes (except for one at 58°N) and magnetically very quiet times. Since specific data on m_i and T_i were not available 'typical' values are chosen here; $m_i = 20$ and $T = 1600°\mathrm{K}$, which with the measured v_0 values result in $M_0 \simeq 6{\cdot}6$.

The Henderson and Samir and the Findlay and Brace M_0 values were determined by actual measurements on the satellites themselves of v_0, T_i and m_i.

We first discuss the n/n_0 data derived from the impedance measurements. We note that the two rocket experiments show $\bar{n}/n_0$ decreasing with increasing M_0 although for a given M_0 the n/n_0 values differ greatly, the values found by Stone *et al.* being much smaller than those of Oya (e.g. for $M_0 \approx 3$). If we scale the Stone *et al.* results to what they might have been if their antenna had been longer so as to give the same ratio of L/R_0 as Oya used ($L/R_0 = 6{\cdot}4$) their $\bar{n}/n_0$ values will be increased. This increase is however only minor, as we now show.

For a rough estimate of what the effect of a longer antenna would be we can use the approximate expression

$$\frac{n}{n_0} = 1 - \mathrm{e}^{-\beta l} \qquad (2)$$

in Equation (1). In this case (1) becomes

$$\frac{\bar{n}}{n_0} = 1 - \frac{1}{\beta L}\,(\mathrm{e}^{-\beta L_1} - \mathrm{e}^{-\beta L_2}). \tag{3}$$

Using a value of $\bar{n}/n_0$ and the appropriate L_1 and L_2 for the rocket and antenna of Stone *et al.* one can compute β from (3). Then reinserting β into (3) but this time with an increased L_2 so as to make $L/R_0 = 6{\cdot}4$, yields an hypothetical $\bar{n}/n$ value for a longer antenna to compare with Oya. For example the point at $M_0 = 1$ increases from $\bar{n}/n_0 = 0{\cdot}62$ to $0{\cdot}68$ by this correction. The 'adjusted' results are shown by a dashed curve in Fig. 2.

It is evident that the Weil and Yorks $\bar{n}/n_0$ values for OGO II are completely different from the rocket results. By proper interpretation we will show that they are in fact consistent with Oya's results and the other satellite results. First however we turn to the pointwise satellite results. Two points for $M = 5$ are shown, the one for $l/R_0 = 1$ is from Explorer XXXI and the point for $l/R_0 = 4$ from the Ariel I data (where l is measured from the satellite surface). These are typical of values observed on several orbits. In this case it does appear that Oya's data (averaged as it is over the range $1 \leq l/R_0 \leq 6{\cdot}4$) does lie between the point values for $l/R_0 = 4$.

Let us now turn to the OGO II data which seems so out of line, $\bar{n}/n_0$ being much too high. We suggest that these high values for $\bar{n}/n_0$ are reasonable for the OGO II geometrical shape taking into account the location of the antenna at the end of a solar paddle. Except when the velocity vector of the satellite lies in the plane of the solar paddle the antenna will not be lying in the thin flat wake of the unshadowed part of the paddle but sampling instead the wake of the central box. Even in the case when the velocity vector of the satellite, the antenna and the solar paddle are in the same plane, because the paddle is quite thin, the wake of the paddle will be very short compared to the antenna length so the antenna will still be sampling mostly the wake of the central box. The antenna is therefore not in the most electron depleted part of the wake; that is, it is not sampling the very near wake as Oya's antenna does. Hence it should be expected to yield larger values of $\bar{n}/n_0$ than it would if it were sampling the near wake. We show that this indeed appears to be the case. As we did previously with the Stone *et al.* results we use (3) to determine a value of β from the measured $\bar{n}/n_0$. In (3) we use L_1 to be the distance from the box to the antenna base at the outer edge of the solar paddle and $L_2 = L_1 + L$. Then, with this value of β, we enter (2) to determine $n(l)$ at $l = R_0$ and $l = 4R_0$ with R_0 the half width of the central box. This yields the two OGO II ranges for n/n_0 at $M_0 = 6{\cdot}7$, labeled 1 and 4 indicated on Fig. 2. An extrapolation of Oya's results to $M_0 = 6{\cdot}7$ would fall into the same region as indicated on Fig. 2 by the dashed line.

In summary, it appears that the results of the measurements are generally consistent with the exception that the Stone *et al.* curve apparently needs a large horizontal translation, the reason for which is not evident. There are factors such as the vehicle potential which might possibly account for this but we have no information on their values. We also do not know if perhaps the actual T_i and m_i were not what they were assumed to be because of perturbed ionospheric conditions; this could affect M_0 and shift the curve horizontally.

We must emphasize that the Weil and Yorks results for OGO II have been shown to fit with the other data on the interpretation that the wake measured is primarily that of the central box. This is not, however, the way these authors interpreted their data in their paper. They assumed the wake was that of an effective ellipsoidal body which enclosed the

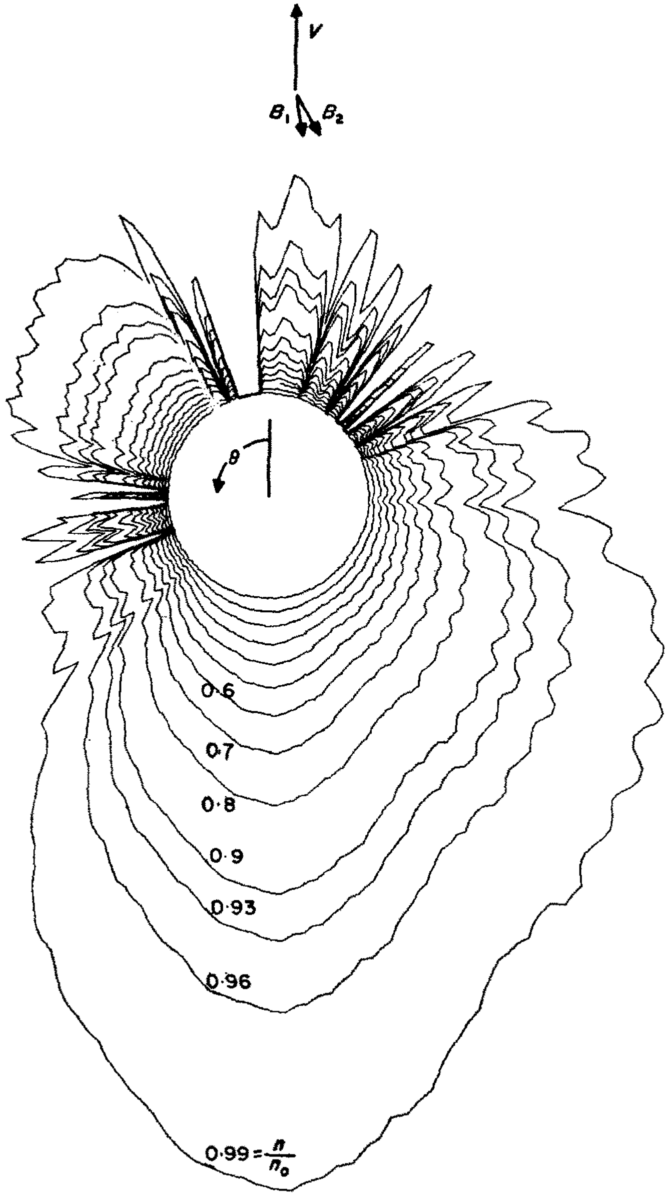


FIG. 3. CURVES OF CONSTANT RELATIVE DENSITY, n/n_0, ALONG THE ANTENNA IN THE WAKE OF OGO II PLOTTED ON A POLAR CHART WHERE RADIAL DISTANCE IS DISTANCE FROM THE 'CENTER' OF THE SATELLITE AND θ IS THE ANGLE BETWEEN THE SATELLITE VELOCITY DIRECTION AND THE ANTENNA DIRECTION.

These curves are computed according to the interpretation suggested in this paper and are for the same data as the corresponding curves in Fig. 8(a) of Weil–Yorks (1970). They are based on the data for one rotation of the antenna (3·67 min) during a perigee pass on 1/29/66. The arrows labeled B_1 and B_2 show the directions of the geomagnetic field at the beginning and the end of the satellite rotation from $\theta = 0$ to $\theta = 360°$.

solar paddles and computed values of β from the $\bar{n}$ which they deduced from the impedance measurements and using (3) with $L_1 = 0$.* Based on these β values and (1) they computed $n(l)$ values and presented polar plots of $n(l)/n_0 =$ const. as a function of the angle between the satellite velocity and the antenna direction. The curves showed asymmetries which were not correlated with geomagnetic field direction and small regions outside the downstream wake region where $n_e/n_0 \neq 1$. Similar curves can be generated for the β values computed from (3) with $L_1 \neq 0$ which, as we have suggested, probably provides a more appropriate interpretation of the data. In Fig. 3 we present one typical such set of constant n/n_0 curves for the data which entered Fig. 8(a) of the Weil–Yorks paper. The curves in Fig. (3) are qualitatively similar to those found with the earlier computation of β but indicate a considerably more extended perturbation region as measured in units of R_0 (the 'new' β values are smaller than the 'old' ones). For these computations R_0 was taken as half the width of the central box (0·43 m) while in the figures of the Weil–Yorks paper R_0 was taken as 3 m, roughly the distance from the 'center' of the box to the end of the solar paddle.

Since, subject to the qualifications discussed above, all the methods used seem adequate to the job of probing the near wakes it appears advisable to proceed further developing them as quantitative tools, using them, preferably together with more complete supplementary measurements, to enhance our knowledge of wake structure. It is quite likely that as more refined measurement procedures are applied they will more clearly show up body shape effects which are apparently of secondary importance in the near wake since we were able to get consistent n/n_0 results for a variety of body shapes using only distance downstream from the body and Mach number as parameters. In any case further development of *in situ* measurements is important because of the known difficulties and expense of analyzing vehicle and wake models by theoretical and numerical means or in plasma tunnels.

Acknowledgements—We wish to acknowledge the interest of Mr. G. R. Carignan, Director of the Space Physics Research Laboratory, The University of Michigan as well as the cooperation of Mr. R. G. Yorks. This work was supported by NASA Grant NGR 23-005-320.

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* This is Equation (4) in Weil–Yorks (1970) where, however due to oversight, the additive term 1, on the right is missing. It was not however missing in their computer program so that their plots of constant n/n_0 curves in their Figs. 6(b) to 8(b) are consistent with the correct form of their Equation (4).