issn 0065-3713

INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE

3 - Avenue Circulaire
B - 1180 BRUXELLES

AERONOMICA ACTA

A - N° 351 - 1989

Electric dipole antennae used as micrometeoroid detectors

by

J.M. LESCEUX, J. LEMAIRE and N. MEYER-VERNET

BELGISCH INSTITUUT VOOR RUIMTE-AERONOMIE

3 - Ringlaan
B - 1180 BRUSSEL

FOREWORD

The article "Electric Dipole Antennae used as Micrometeoroid Detectors" will be published in "Planetary and Space Science".

AVANT-PROPOS

Le travail intitulé "Electric Dipole Antennae used as Micrometeoroid Detectors" sera publié dans la revue "Planetary and Space Science".

VOORWOORD

De tekst getiteld "Electric Dipole Antennae used as Micrometeoroid Detectors" zal gepubliceerd worden in "Planetary and Space Science".

VORWORT

Der Text "Electric Dipole Antennae used as Micrometeoroid Detectors" wird in dem "Planetary and Space Science" publiziert werden.

ELECTRIC DIPOLE ANTENNAE USED AS MICROMETEOROID DETECTORS

by

J.M. LESCEUX[1], J. LEMAIRE[1] and N. MEYER-VERNET[2]

[1]Institut d'Aéronomie Spatiale de Belgique
Avenue Circulaire 3, B-1180 BRUSSELS, Belgium
[2]Observatoire de Paris, Département de Recherche Spatiale, Meudon, France

Abstract

The possibilities to use electric antennae made of two small spheres to detect charged dust grains in space are shortly examined in this paper. The electric potential difference $\Delta\Phi$ between the two spheres is determined from Poisson's equation in a plasma and several examples of "waveforms" ($\Delta\Phi$ as a function of time t) are shown as illustration. For dust grains of radius of 100 microns, signals of the order of 500 microvolts are produced. The limitations due to the anntenna shot noise and and to the plasma thermal noise are also examined. A table summarizes the results in different conditions. We conclude that with a system of antennae it is possible to detect (especially near comets and planetary ionospheres) dusts in view to determine their velocity characteristics.

Résumé

Ce travail étudie brièvement les possibilités d'utiliser des antennes électriques constituées de deux petites sphères en vue de détecter des grains de poussières chargées. La différence de potentiel électrique $\Delta\phi$ entre les deux sphères est déterminée à partir de l'équation de Poisson dans un plasma et plusieurs exemples de "signaux" ($\Delta\phi$ en fonction du temps t) sont montrés à titre d'illustration. Ainsi pour des grains de rayon 100 microns, des signaux de 500 microvolts sont produits. Ce travail présente également les limitations dues à l'antenne (le temps de décharge doit être plus petit que le temps caractéristique du signal) et au bruit de fond thermique du plasma. Un tableau résume les résultats dans différentes conditions. La conclusion est qu'il est possible avec un système d'antennes de détecter (plus particulièrement près des comètes et de l'ionosphère des planètes) les poussières en vue de déterminer les caractéristiques de leur vitesse.

Samenvatting

De mogelijkheid, elektrische antennen, bestaande uit twee kleine kogels, te gebruiken, om de snelheidsdistributie van elektrisch geladen stofkorreltjes in de ruimte te bestuderen, is hier beknopt onderzocht. Het elektrisch potentieelverschil $\Delta\phi$ tussen de twee kogels is bepaald door het oplossen van Poisson's vergelijking in een, met stof gevuld plasma, en verschillende voorbeelden van "waveforms" (golven - vormen) ($\Delta\phi$ als funktie van tijd t) zijn als illustratie ervan, getoond. Typisch zijn, voor stofkorreltjes met een straal van 100 mikrons, signalen van omstreeks 500 microvolts. De beperking, aan de antenne te wijten (de ontladingstijd moet kleiner zijn dan de specifieke tijdperiode van het signaal) en (II) aan het plasma (geluid aan een groot aantal plasma-deeltjes te wijten) worden onderzocht. Een tabel vat de resultaten in verschillende toestanden samen. We komen tot de conclusie dat het, met een antennesysteem, mogelijk is, de stofkorreltjes op te sporen (in het bijzonder, dichtbij kometen en planetarische ionosferen), om hun snelheidskarakteristieken te bepalen.

Zusammenfassung

Die Möglichkeiten, elektrische Antennen, aus zwei kleinen Kugeln gemacht, zu benutzen, um die Geschwindigkeitsverteilung von elektrisch beladen Staubkörnchen im Weltraum zu studieren, ist hier kürzlich untersucht. Die elektrische potentielle Differenz $\Delta\phi$ zwischen den zwei Kugeln ist bestimmt durch die Lösung der Poisson Gleichungen in einem mit Stoff beladen Plasma und verschiedene Beispiele von "Wave-forms" (Welle-Form) ($\Delta\phi$ als Funktion von Zeit Z) sind als Illustration gegeben. Typisch sind, für Staubkörnchen mit einem Radius von 100 Mikrons, Signale in der Größenordnung von 500 Mikrovolt. Die Einschränkung die auf der Antenne beruht (die Entladezeit muß kleiner sein als die spezifische Zeitperiode von Signal) und (II) auf dem Plasma (Geräusch, das auf der großen Zahl Plasmateilchen beruht) sind ebenfalls untersucht. Eine Tafel faßt alle Ergebnisse in verschiedenen Zustanden zusammen. Zum Schluss können wir sagen, daß ein System mit Antennen es möglich macht die Staubkörnchen (speziell in der Nähe von Kometen und planetarischen Ionosphären) auf zu spüren, um ihre Geschwindigkeitskarakteristiken zu bestimmen.

1. INTRODUCTION

Electric-field antennae are generally used on board of spacecraft to detect plasma waves and radio waves propagating in space plasmas.

A comprehensive review of different types of antenna responses as a function of wave frequency ω, has recently been published by Meyer-Vernet and Perche (1989).

Generally, the input electric waves are Fourier analyzed and the power spectrum is transmitted to ground for different wave frequencies (ω_i) in finite bandwith $(\Delta\omega_i)$. The problem is then to recover the whole wave spectrum of interest.

The aim of this short paper is to point out the possibility to use these electric dipole antennae to investigate dust grains which become charged as a result of photoelectron emission by solar UV radiation, as well as by bombardment by ambient plasma particles. Depending on the ambient plasma density and temperature the equilibrium surface potential (Φ_o) of micrometeroids (See Wipple, 1981) ranges from a few Volts to + 10 Volts with respect to the plasma in interplanetary space, and reaches negative values of order the ambient electron temperature in higher density plasmas such as planetary ionospheres or comets.

When a charged dust grain is passing next to an electric dipole antenna, it produces an electric impulse whose characteristics are described in this paper. These electric signals could be used to determine the velocity of the micrometeoroid and its orientation with respect to the antenna.

The conventional dust detectors aboard space probes (see for instance Fechtig 1978) are based upon grain impacts on a physical target. Even the recent use of electric antennae as dust detectors (see for instance Meyer-Vernet et al. 1986, Gurnett et al. 1987) was based upon grain impacts on the spacecraft or antenna structure itself, and their subsequent ionization. In each case, the cross-section for grain detection was limited to a rather small physical surface. What we propose here would be useful in media with a small dust concentration, by having the advantage of a very large cross-section for grain detection, of order the square of the ambient plasma Debye length.

2. THEORY

We consider a plasma with electron density n and electron and ion temperature T_e and T_i respectively. Let $L_D = (\epsilon_o KT_e/ne^2)$ be the (electron) Debye length, and ω_p the (angular) plasma frequency. Let a grain with radius $a << L_D$ velocity V, carrying an electrostatic charge Q. In most casses of practical interest, the velocity satisfies $V_i << V << V_e$,

where
$$V_{e,i} = \left(\frac{2k\, T_{e,i}}{m_{e,i}} \right)^{1/2}$$

are the electron (ion) thermal velocities. Then, the relevant plasma shielding scale is L_D since the ions do not contribute to the shielding, and the potential distribution around the grain is the well-known Debye potential

$$\Phi(r) = \Phi_o \frac{a}{r} \exp - \left[(r - a)/L_D\right] \quad (1)$$

with $\Phi_o = Q/4\pi\epsilon_o a$. We have assumed that the linearization is valid, i.e. $e\Phi/KT_e << 1$, and that the grain concentration is sufficiently small so that the intergrain distance $d >> L_D$.

Now, let us consider a dipole electric antenna made of two small spheres of radius $R << L_D$ located a $z_1 = - L/2$ and $z_2 = + L/2$ along the O_z axis (parallel to the dipole electric antenna whose tip to tip length is $L >> R$ - figure 1). The electric potential difference on the antenna, produced by the charge Q located at x, y, z is given by

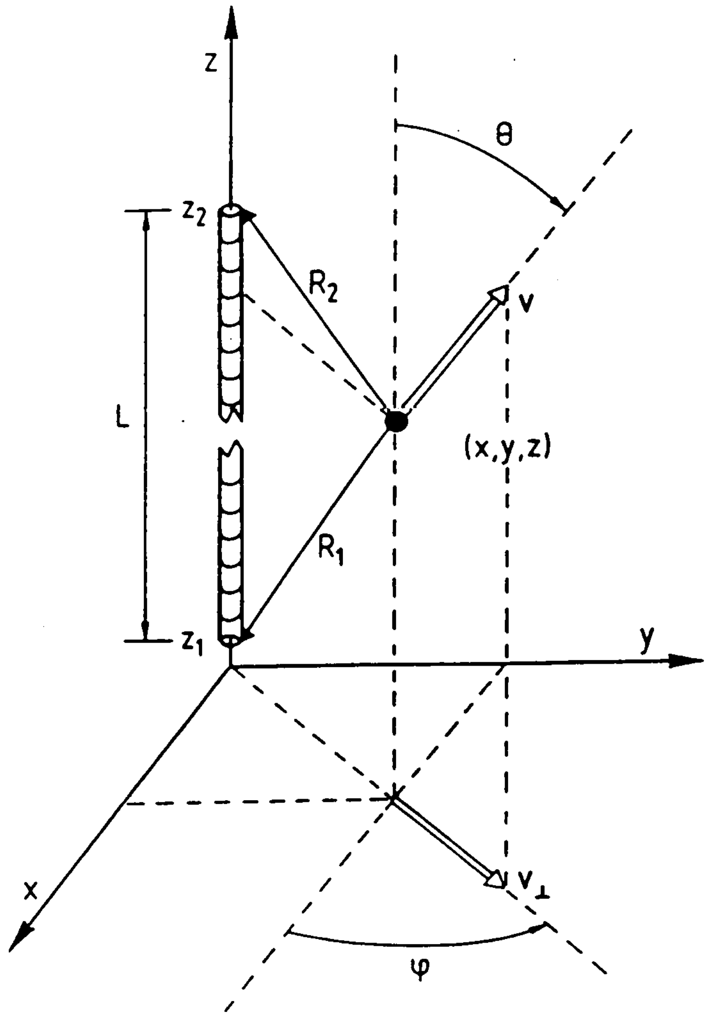


Fig. 1. Antenna geometries and dust location.

$$\Delta\Phi(X,Y,Z) = \Phi(r_1) - \Phi(r_2) = \Phi_o a \left(\frac{\exp(-r_1/L_D)}{r_1} - \frac{\exp(-r_2/L_D)}{r_2} \right) \quad (2)$$

where

$$r_1 = x^2 + y^2 + (z-z_1)^{1/2}$$
$$r_2 = x^2 + y^2 + (z-z_1-L)^{1/2} \quad (3)$$

Let the charged dust grain velocity components be

$$v_z = v \cos \theta$$
$$v_y = v \sin \theta \sin \varphi \quad (4)$$
$$v_x = v \sin \theta \sin \varphi$$

If **v** is independent of time, v, θ, are constant and the dust particle moves along a straight trajectory whose parametric equations in the Oxyz frame of reference are

$$x(t) = x_o + v_x t$$
$$y(t) = y_o + v_y t \quad (5)$$
$$z(t) = z_o + v_z t$$

where x_o, y_o, z_o define the position at time t = o. Replacing x, y, z in (2) by (5) one obtains the potential difference $\Delta\Phi(t)$ as a function of time t.

3. CASE STUDIES

In this section we calculate the tip to tip electric potential difference to be observed with an antenna of 10 m length, in a fully ionized H^+ plasma whose Debye length is L_D = 10 m. In this case $L_D/L = 1$.

Let us assume that the velocity of the dust grain relative to the antenna has a typical value of v = 10 km/s, its surface potential is for instance Φ_o = + 10 Volts. The radius "a" of the dust grain is taken to be 100 microns. Since the electric potential difference $\Delta\Phi$ given by (2) is proportional to "a" and to "Φ_o"; it is easy to obtain the signal for other values of "a" or "Φ_o", by multiplying the values of $\Delta\Phi$ by $a/100\mu$

and $\Phi_o/10$ V. Furthermore, in all case studies considered below we will assume, without loss of generality, that $y_o = 0$, $\varphi = 90°$, the distance of closed approach is then equal to x_o when the dust grain crosses the y = 0 plane at t = 0, its velocity vector being parallel to the (x,z) plane.

Figures 2 show a series of curves corresponding to the electric field impulse produced in a dipole antenna for $\theta = 0°$, for $z_o = 0$ and for different values of x_o ranging from $L_D/10$ to L_D (i.e. 1 m to 10 m) in fig. 2b and $x_o = 0$ in fig. 2a.

The right hand side gives the potential difference normalized to the surface potential Φ_o, while the left hand side scale gives $\Phi(r)$ in Volts for $\Phi_o = + 10$ V and a = 100 microns. The pulse would be reversed if Φ_o was negative. The maximum or minimum potential difference is reached, in first approximation, when the dust grain reaches the closest distance to the tip of the antenna while it is moving parallel to the antenna in the + oz direction. The abcissa in figs. 2 is the time, normalized to L/v : i.e. the minimum time necessary to reach a distance equal to the length of the antenna. Figure 2a gives the "ideal" signal (closest distance = 0 and v parallel to the antenna axis), which is very sharp. When the distance is increasing (figure 2b), the signal decreases in intensity and becomes much wider but it is still clear enough to be detected.

Fig. 3 shows a series of signals obtained for the same grain with the same velocity but measured with antennae of different lengths L, (figure 3a) and in fig. 3b for different Debye lengths L_D. Figure 3a shows that the bigger the antenna length L is, the clearer the signal is (the minimum and the maximum are greater and better separated). The influence of the plasma via the variation of L_D (figure 3b) on the signal, shows that it could be possible to determine L_D from the "wave-form".

In order to show most realistic cases, Figure 4 shows a series of responses for $x_o = 2$ m, $z_o = 0$, $L_D/L = 1$ but for different values of the

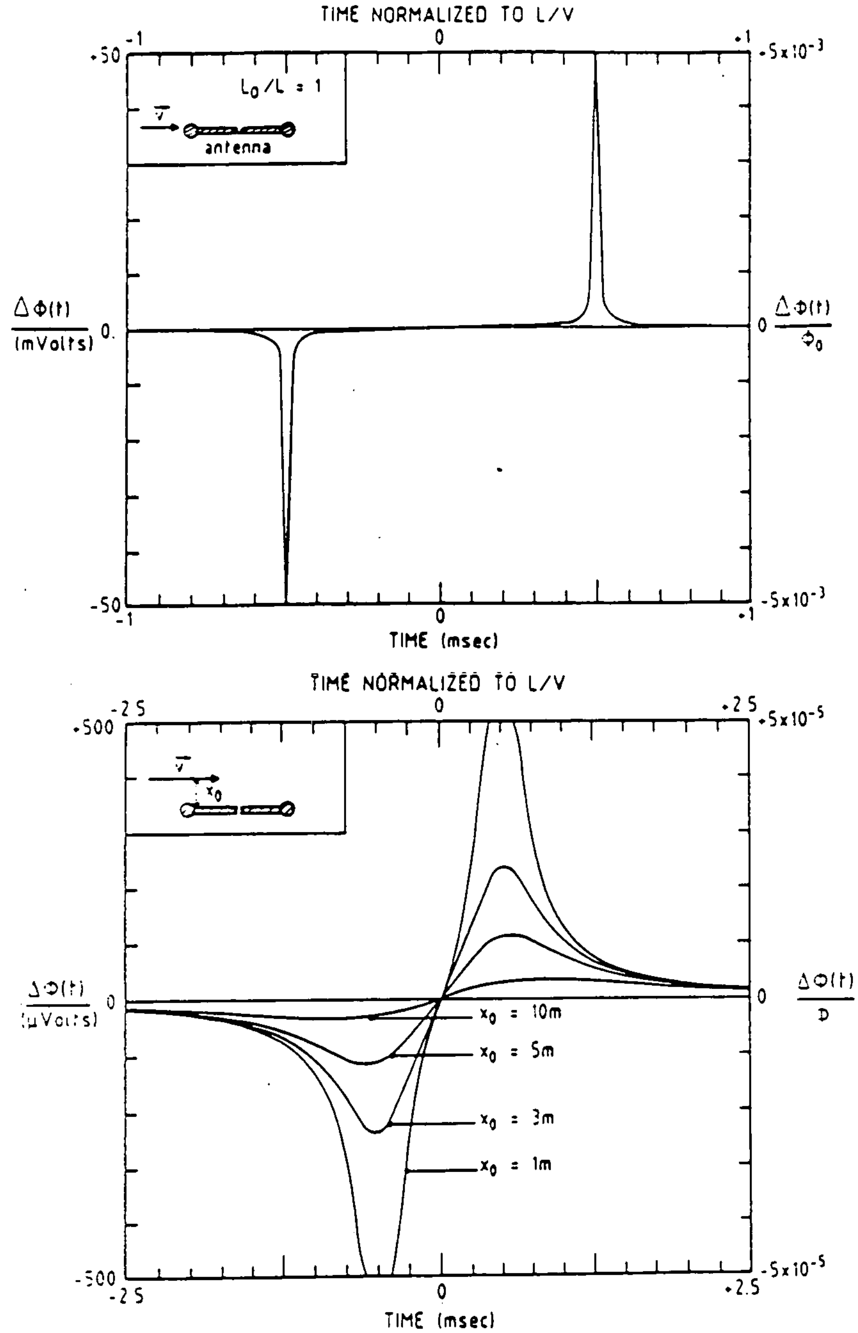


Fig. 2. Electric potential difference $\Delta\phi$ as a function of time t, produced in a dipole antenna of length L = 10 m by a dust of radius a = 100 microns charged to Φ_o = 10 Volts in a plasma characterized by Debye length L_D = 10 m. The dust comes along the antenna axis (θ = 0, Z = 0) with a velocity V = 10 km/s. Figure 2a shows $\Delta\Phi$ for x_0 = 0 and figure 2b for $x_o = L_D/10$ to L_D.

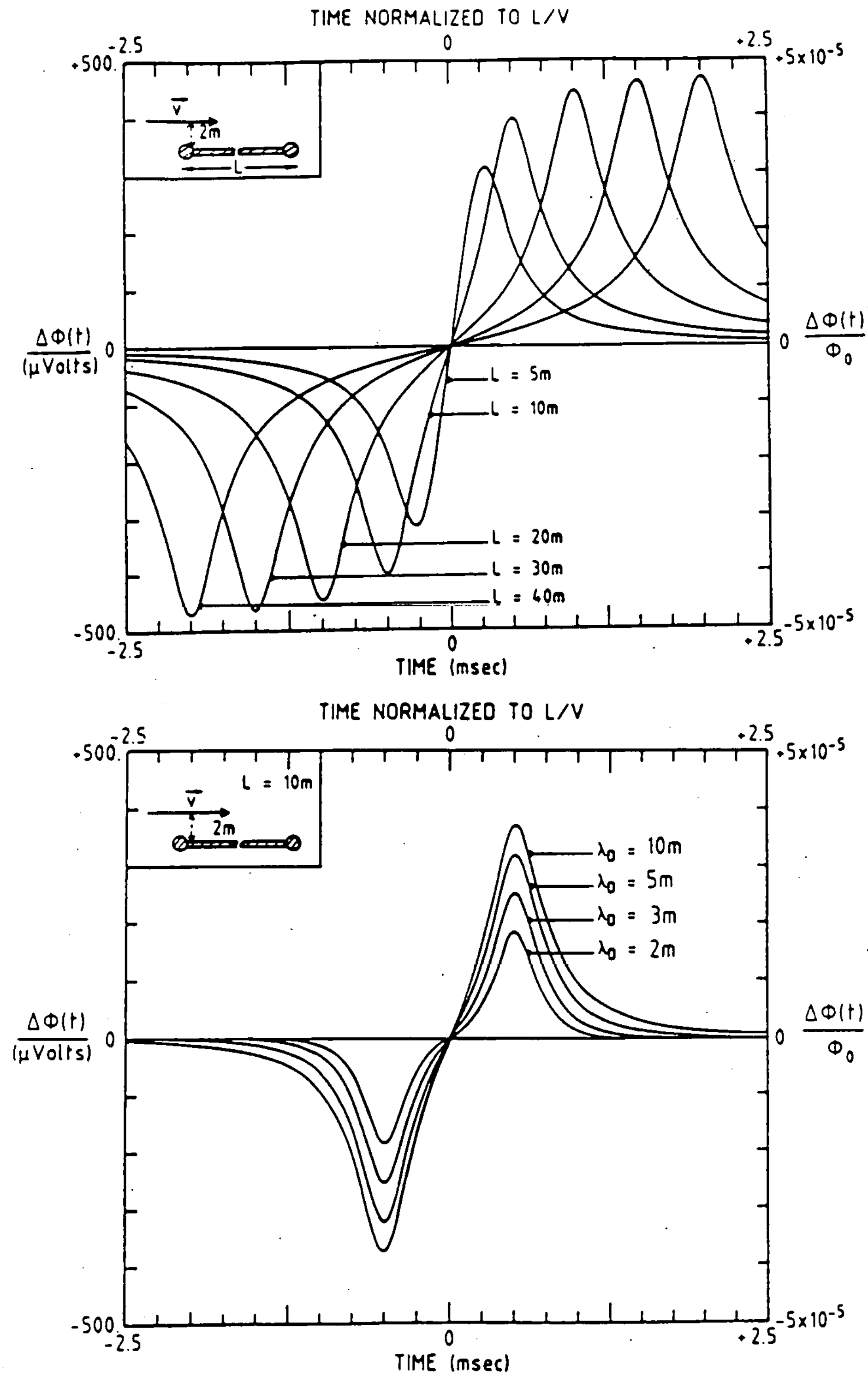
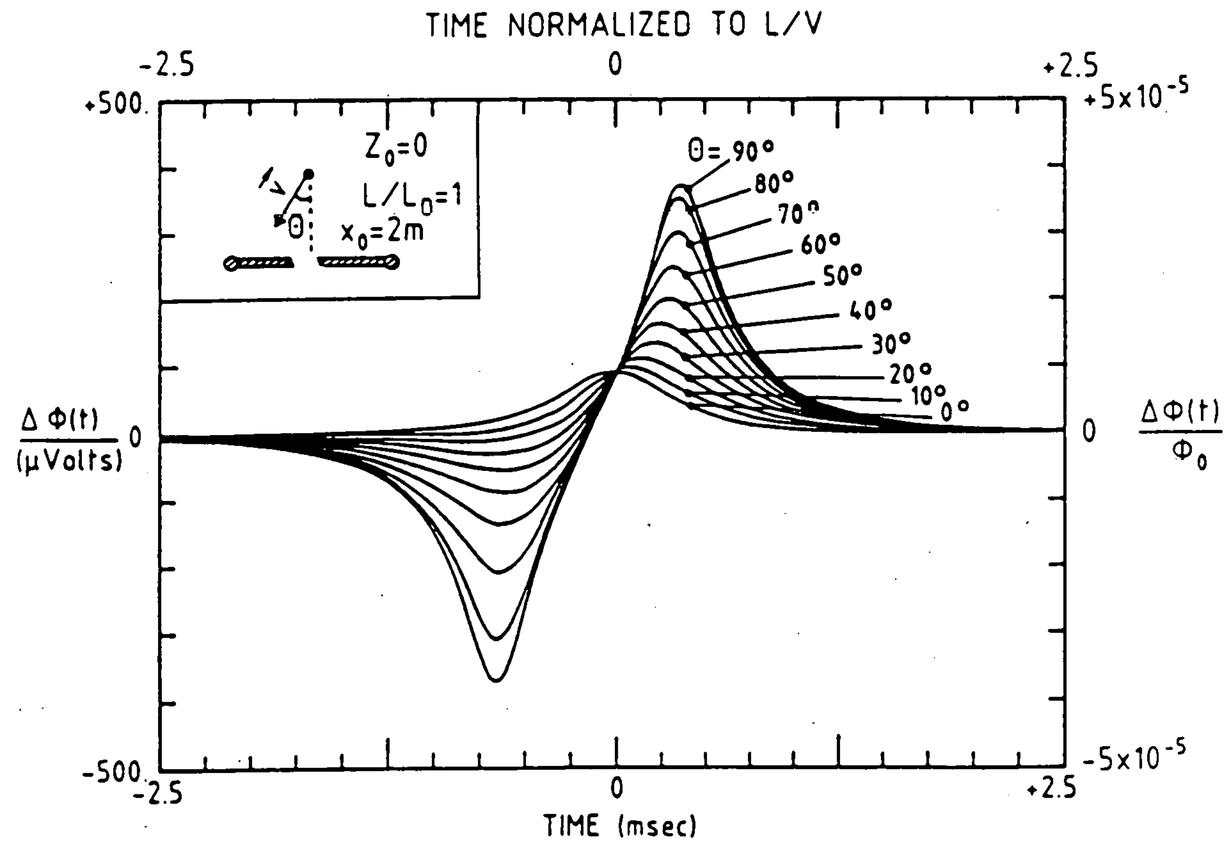


Fig. 3. Same as figure 2, but for $x_o = 2$ m and different antenna length $L(L_D = 10$ m - figure 3a) or different Debye length ($L = 10$ m - figure 3b).



<u>Fig. 4.</u> Same as figure 2, but for $z_o = 0$, $x_o = 2$ m and different angle θ ranging from 0° to 90°.

polar angles θ. The "wave-form" comes from an antisymmetric form ($\theta = 90°$), passing by an asymmetric ($0° < \theta < 90°$) one to reach a symmetric one (one peak $\theta = 0°$). Finally, Figure 5 presents the curves obtained for different values of z_o ($\theta = 45°$, $x_o = 2$ m, $L_D/L = 1$). Such cases are simulating a "stream" of dusts.

4. DISCUSSION

From these graphical results it can be seen that a wide variety of anti-symmetric or asymmetric "wave-forms" can be obtained, depending on the values of L_D/L (normalized Debye length) x_o (the distance of closest approach), θ (the polar angle) and z_o (the location of closest approach along the antenna).

If these "wave-forms" could be stored in a fast Ring Memory and transmitted to Earth, or directly processed on board by a dedicated DPU, one could then determine the value of the parameters x_o, z_o, θ and $\Phi_o a$. A complete description of a method to compute such parameters from the "wave-form" will be given in a future paper. We are here only giving some indications of the relations between the features of the wave-form and the values of those parameters.

The most "general wave-form" is an asymmetric one, as shown in figure 6, obtained for $x_o = 2$ m, $z_o = 1.5$ m, $\theta = 30°$, $\Phi_o a = 0.1$ Volt cm, $L_D = 10$ m, $L = 10$ m. The key parameters deduced from the observed wave-form are the values of t_1 (time for $\Delta\Phi$ minimum), t_o (time for $\Delta\Phi = 0$), t_2 (time for $\Delta\Phi$ maximum), Φ_1 ($\Delta\Phi$ at minimum), Φ_2 ($\Delta\Phi$ at maximum). These quantities can be used to determine the parameters v, cos θ, $\Phi_o a$.

A more complex antenna system (f.i. a triple or quadrupole) could be used to determine completely the direction of the velocity vector in the 3 dimensional space.

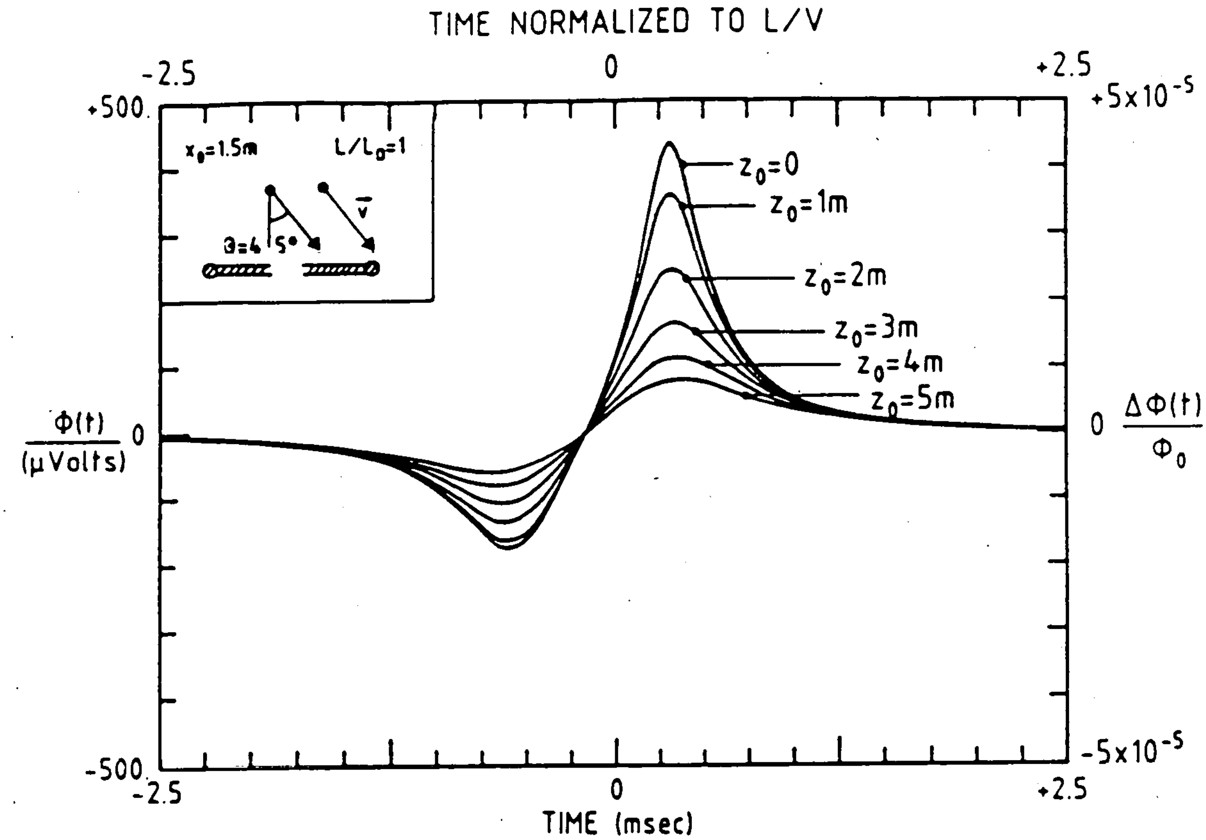


Fig. 5. Same as figure 2, but for x_o = 1.5 m, θ = 45° and different values of Z_o.

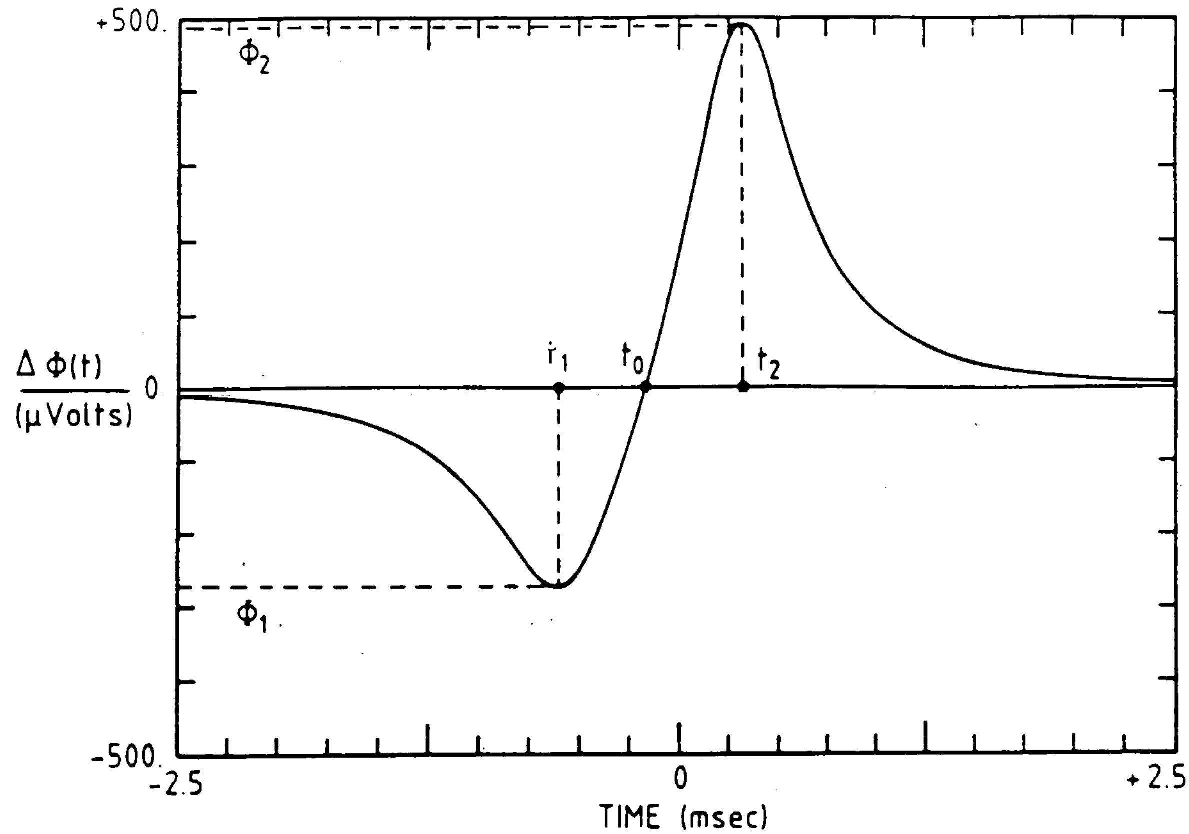


Fig. 6. Same as figure 2, but for a typical general case ($L/L_D = 1$, $x_0 =$ 2 m, $Z_o = 1.5$ m, $\theta = 30°$).

5. PRACTICAL LIMITATIONS

The practical use of antennae as grain detectors has some limitations. First, the coupling has to be sufficient, which is a known practical problem for low frequency measurements whenever the antenna resistance R_a due to the pick-up and emission of electrons (and ions) becomes important.

A more fundamental limitation stems from the random voltage induced by the plasma electrons passing near the antenna and/or picked-up or emitted by its surface. The power spectrum of this signal is known and currently used for electron diagnosis (see Meyer-Vernet and Perche 1989 and references therein).

First, let us consider the plasma electrons passing-by the antenna. The typical duration of each individual event is ω_p^{-1}, thus much smaller than the duration Δt of the signal to be measured, and the whole process is stationary.

The mean square voltage $<V_T^2>$ due to this "thermal noise" can therefore be deduced from

$$<V_T^2> = \frac{1}{2\pi} \int_o^{\infty} V_{T\omega}^2 \, d\omega \qquad (7)$$

where $V_{T\omega}^2$ is the thermal noise spectrum whose expression can be found in Meyer-Vernet and Perche (1989) with different antenna geometries. For a double sphere dipole $L \geq L_D$, we deduce the aproximate result

$$<V_T^2> \sim \frac{m_e V_e \omega_P}{\pi^{5/2} \epsilon_o} \qquad (8)$$

Now, let us consider the impacts or emission of electrons (or ions) on the antenna surface. Broadly speaking, each event produces a step-like voltage, with a decay time $\tau \sim R_a C$, and amplitude $\Delta V_I = \pm e/C$.

In the interplanetary medium or planetary and cometary outer environment, the main changing mechanisms are plasma electron pick-up and photoemission (with photoelectron temperature $T_{ph} < T_e$), so that

$$\tau \sim \left(\frac{dI}{d\Phi} \right)^{-1} C \sim \frac{KT_{ph}C}{e^2 N} \qquad (9)$$

where $C \sim 4\pi \epsilon_o R$ is the sphere capacitance and

$N \sim 4\pi R^2 n V_e/(2\sqrt{\pi})$ is the approximate number of plasma electrons collected by one sphere per second.

This yields

$$\tau \sim 2\sqrt{\pi} \frac{T_{ph}}{T_e} \frac{L_D^2}{RV_e} \qquad (10)$$

thus about 5.10^{-4} seconds in the interplanetary medium if R = 0.1 m.

Now, the Fourier transform of the voltage produced by one event is approximately

$$\Delta V_I(\omega) = \frac{+e/C}{1/\tau - i\omega}$$

Thus the power spectrum produced by 4N events per second (impacts and emission on two spheres)

$$V_{I\omega}^2 = 8N \frac{(e/C)^2}{\omega^2 + 1/\tau^2}$$

and the mean square voltage over a time $\Delta t >> \tau$ (using (7))

$$\langle V_I^2 \rangle \sim 2 N \tau (e/C)^2$$

i.e. using (9)

$$\langle V_I^2 \rangle \sim \frac{2KTph}{4\pi\epsilon_o a}$$

$$\sim \frac{Tph\ m_e\ V_e\ \omega_p\ L_D}{T_e\ 2^{3/2}\ \pi\ \epsilon_o\ a} \qquad (11)$$

If on the other hand, $\Delta t < \tau$, then the mean square voltage over the time Δt cannot be obtained by the Parseval relation, and we have instead

$$\langle V_I^2 \rangle \sim (e/C)^2\ 4\ N\ \Delta t \qquad \text{i.e.}$$

$$\langle V_I^2 \rangle \sim \frac{m_e\ V_e\ \omega_p^{\ 2}\ \Delta t}{2\pi^{3/2}\ \epsilon_o} \qquad (12)$$

In most practical cases $\Delta t > \tau$ and the relevant expression to be used for $\langle V_I^2 \rangle$ is (11). For instance, in the interplanetary medium, we get $\sqrt{\langle V_I^2 \rangle} \sim 2.10^{-4}$ Volts, while the thermal noise yields (from (8)) $\sqrt{\langle V_T^2 \rangle} \sim 4.10^{-5}$ Volts. In other media, the noise due to electron impacts or emission is still the mean limitation. We conclude, therefore, that this method of grain detection should preferably use antennae with a small collecting surface, for instance, grid or meshed antennae, for which the grain detection is limited by the thermal noise, and the threshold of detectability is given by (8).

Let us consider the typical case of a grain passing at about one L_D from a dipole (meshed) antenna of length $L > L_D$, which induces the voltage amplitude $\Delta\Phi \sim Q/4\pi\epsilon_o\ L_D$. We then obtain using (8)

$$\frac{\text{Signal}}{\text{Noise}} = \frac{S}{N} = \frac{\Delta\Phi}{\sqrt{\langle V_T^2 \rangle}} \sim \frac{\epsilon_o\ a\ \Phi_o\ 3.5}{e\ (nL_D^{\ 3})^{1/2}}$$

in practical units

$$\frac{S}{N} \sim 0.2\ a_{(\mu)}\ \Phi_{o(V)}\ [n_{cm^{-3}}]^{-1/2}\ [L_{D(m)}]^{-3/2}$$

TABLE 1. Values of density n, Debye length L_D and the signal S divided by the Noise N for different media.

MEDIUM	$n(cm^{-3})$	$L_D(m)$	S/N
Solar wind at 1 AU	5	10	3
Saturn ring plane at 2.9 Rs (Voyager 2)	300	1	12
Uranus ring plane at 4.6 Ru (Voyager 2)	1(?)	10	7
Earth ionosphere near F_0F_2	300000	0.005	1000
Comet Halley at 10^5 km from nucleus	100	0.5	60

Table I shows typical values for a 100 μ dust grain at potential $|\Phi_o| \sim 10$ V in different media.

Similar calculations could be done for wire dipole antennae; in this case, the noise due to electron impacts or emission is expected to be less important in relative value than for a double sphere antenna (Meyer-Vernet and Perche, 1989).

It is important to note that the amplitude of the signal induced by a passing grain, $\Delta\Phi$, is much smaller than the signal induced when a grain impacts the antenna and is then vaporized and ionized (see for instance Meyer-Vernet et al, 1986, Gurnett et al. 1987). The detection of grains passing by the antenna therefore requires a low-grain-number density, so that very few grains impact the antenna or the conventional dust detectors.

6. CONCLUSION

We described above the principle of a method able to determine the velocity and direction of dust grains from the output signals of a system of dipole electric antennae.

This determination is based on the analysis of the wave-forms induced in the antenna by the passage of the charged dust grains in the vinicity of the antenna.

It would be interesting to reexamine the VEGA, GIOTTO and VOYAGER electric wave form data in the light of these theoretical results.

REFERENCES

[1] Fechtig, H., Grün, E. and Kissel, J., in Cosmic Dust, (J.A.M. McDonnell, Wiley) 1978.

[2] Gurnett, D.A. et al., Micron-sized particle impacts detected near Uranus by the Voyager 2 plasma wave instrument, J. Geophys. Res., 92, 14959, 1987.

[3] Meyer-Vernet, N., Aubier, M.G. and Pedersen, B.M., Voyager-2 at Uranus: Grain impacts in the ring plane, Geophys. Res. Lett., 13, 617, 1986.

[4] Meyer-Vernet, N. and Perche, C., Toolkit for antennae and thermal noise near the plasma frequency, J. Geophys. Res., 94, 2405, 1989.

[5] Whipple, E.C., Potentials of surfaces in space, Rep. Progr. Phys., 44, 1197, 1981.