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ELECTRIC DIPOLE ANTENNAE USED AS MICROMETEOROID DETECTORS

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Abstract - The possibilities to use electric antennae made of two small spheres to study the velocity distribution of charged dust grains in space are shortly examined in this paper. The electric potential difference $\Delta\Phi$ between the two spheres is determined by solving the Poisson's equation in a dusty plasma and several examples of "waveforms" ($\Delta\Phi$ as a function of time t) are shown as illustration. Typical are for dust grains of radius of 100 microns, signals of the order of 500 microvolts are produced. The limitations due (i) to the anntenna (the discharge time must be smaller than the characteristic time of the signal) and (ii) to the plasma (noise due to a large number of plasma particles) are also examined. A table summarizes the results in different conditions. We come to the conclusion 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.

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 used 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 electrons. Depending on the ambient plasma density and temperature the equilibrium surface potential (Φ_o) of micrometeroid (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 Fechting 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 $a \ll L_D$ velocity V, carrying an electrostatic charge Q. In most casses of practical interest, the velocity satisfies $V_i \ll V \ll V_e$,

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

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

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

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

Now, let us consider a dipole electric antenna made of two small spheres of radius $R \ll L_D$ located a $z_1 = - L/2$ and $z_2 = + L/2$ along the 0_z axis (parallel to the dipole electric antenna whose tip to tip length is $L \gg R$ - figure 1). The electric potential difference on the antenna, produced by the charge Q located at x, y, z is given by

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

where
$$r_1 = x^2 + y^2 + (z-z_1)^2$$
$$r_2 = x^2 + y^2 + (z-z_1-L)^2 \tag{3}$$

Let the charged dust grain velocity components be

$$v_z = v \cos\theta$$
$$v_y = v \sin\theta \sin\varphi \tag{4}$$
$$v_x = v \sin\theta \sin\varphi$$

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

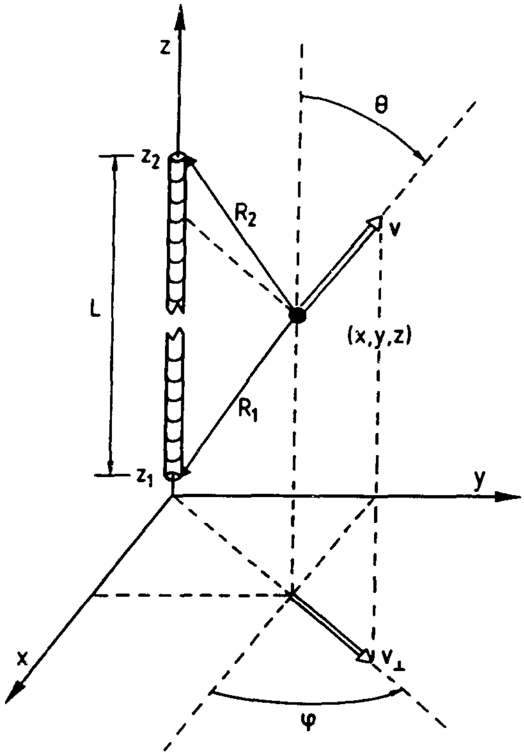


Fig. 1. Antenna geometries and dust location

$$\begin{aligned} x(t) &= x_o + v_x t \\ y(t) &= y_o + v_y t \\ z(t) &= z_o + v_z t \end{aligned} \qquad (5)$$

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 $L_D/$ = 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 was 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, φ = 90°, the distance of closed approach is then equal to x_o when the dust grain crosses by 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 had 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. The 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 withh antennae of different lengths L, (figure 3a) and in fig. 3b for different Debye lengths L_D. The figure 3a shows that the bigger the antenna length L is, the better 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".

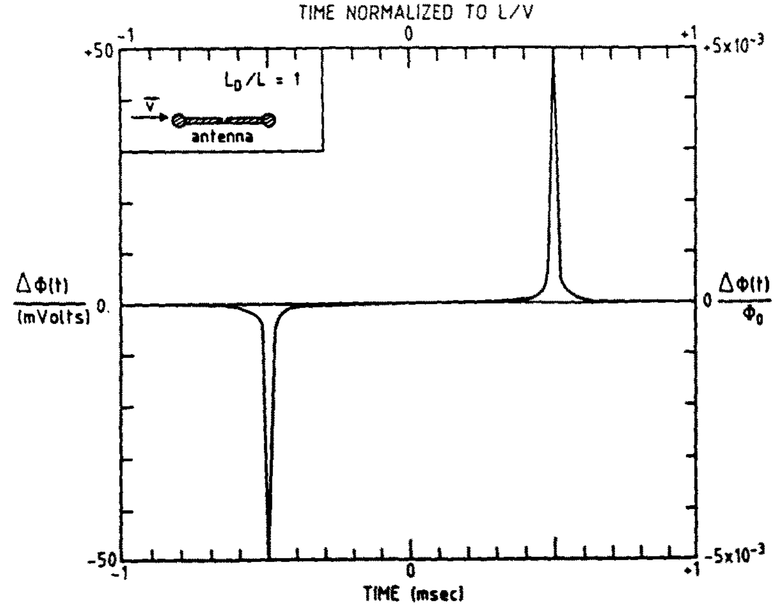
In order to show all the realistic cases, the figure 4 shows a series of responses for $x_o = 2$ m, $z_o = 0$, $L_D/L = 1$ but for different values of the polar angles θ. The "wave-form" comes from an antisymmetric form ($\theta = 90°$), passing by an asymmetric ($0° < \theta < 90°$) one to reach a symmetric one (one peak $\theta = 0°$). Finally, the 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, $\Phi_o a$.



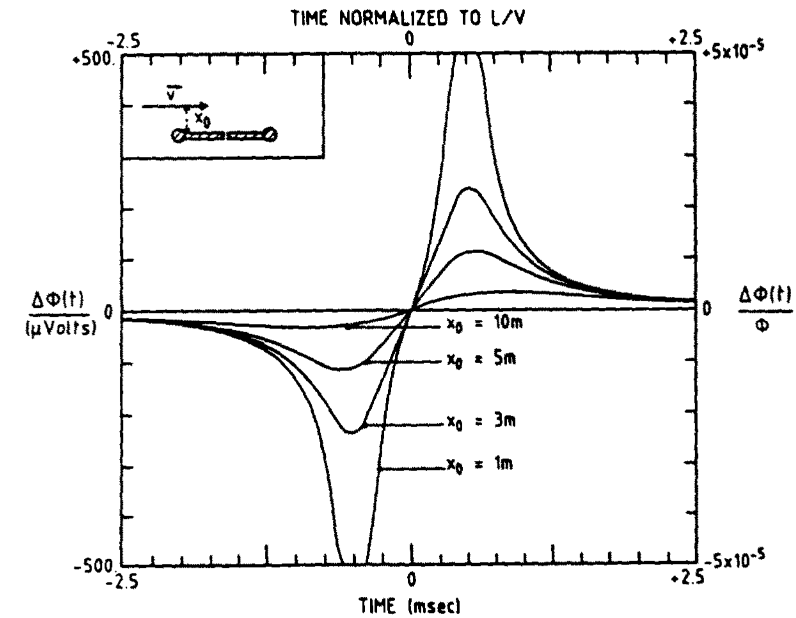


Fig. 2. Electric potential difference $\Delta\Phi$ as a function of time t, produced in a dipole antenna of length L = 10 m by a dust of radius a = 100 microns charged to Φ_o = 10 Volts in a plasma characterized by Debye length L_D = 10 m. The dust comes along the antenna axis (θ = 0, Z = 0) with a velocity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

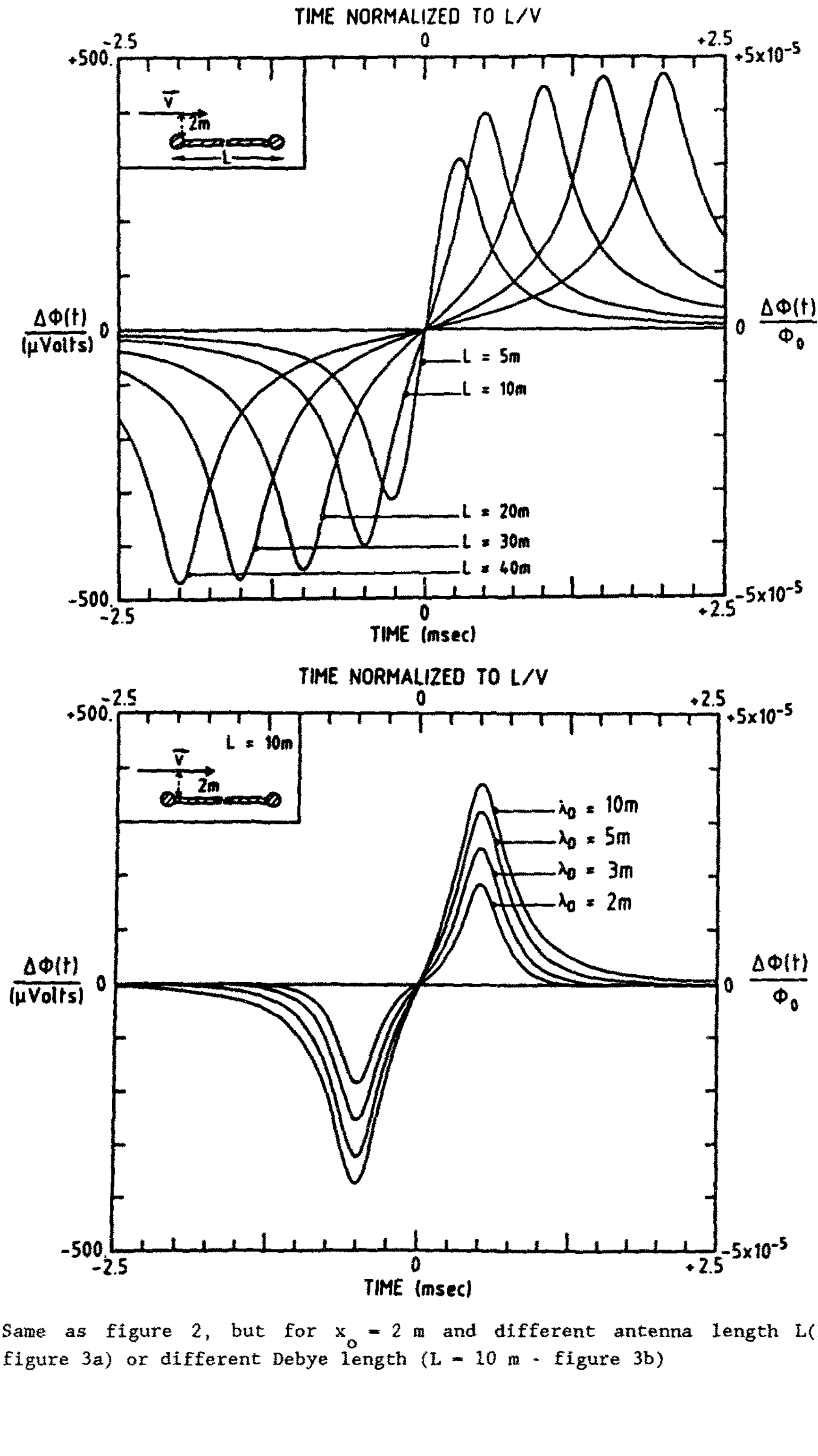


Fig. 3. Same as figure 2, but for x_o = 2 m and different antenna length L(L_D = 10 - figure 3a) or different Debye length (L = 10 m - figure 3b)

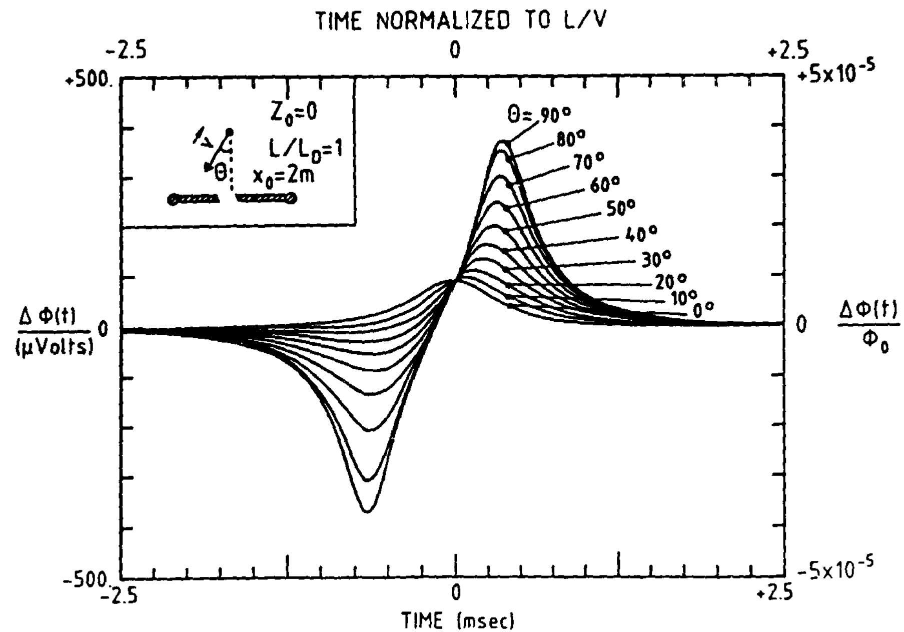


Fig. 4. Same as figure 2, but for $z_o = 0$, $x_o = 2$ m and different angle θ ranging from 0° to 90°.

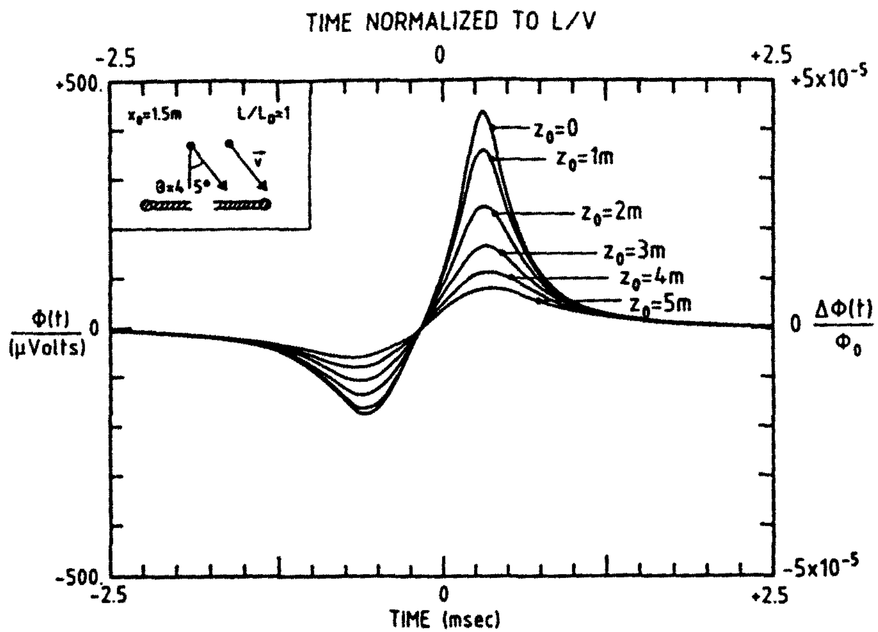


Fig. 5. Same as figure 2, but for x_o = 1.5 m, θ = 45° and different values of Z_o.

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.

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 $\langle V_T^2 \rangle$ due to this "thermal noise" can therefore be deduced from

$$\langle V_T^2 \rangle = \frac{1}{2\pi} \int_o^\infty V_{T\omega}^2 \, d\omega \tag{7}$$

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

$$\langle V_{T\omega}{}^2 \rangle \sim \frac{n V_e \omega_P}{\pi^{5/2} \epsilon_o} \tag{8}$$

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 $\Delta V_I = e/C$.

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

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

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

$$\tau \sim 2\sqrt{\pi} \frac{T_{ph}}{T_e} \frac{L_D^2}{R V_e} \tag{10}$$

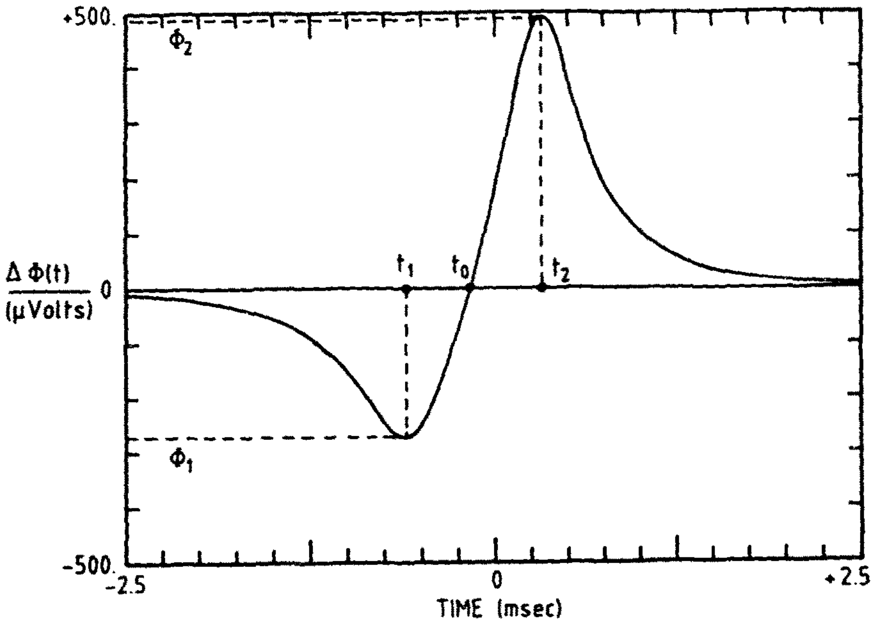


Fig. 6. Same as figure 2, but for a typical general case ($L/L_D = 1$, $x_0 = 2$ m, $Z_o = 1.5$ m, $\theta = 30°$).

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 $\Delta t \gg \tau$ (using (7))

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

i.e. using (9)

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

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

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

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

$$<V_I^2> \sim \frac{m\, V_e\, \omega_p^2\, \Delta t}{2\pi^{3/2}\, \epsilon_o} \qquad (12)$$

In most practical cases $\Delta t > \tau$ and the relevant expression to be used for $<V_I^2>$ is (11). For instance, in the interplanetary medium, we get $\sqrt{<V_I^2>} \sim 2.10^{-4}$ Volts, while the thermal noise yields (from (88)) $\sqrt{<V_T^2>} \sim 4.10^{-5}$ 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 mashed 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 from a dipole (mashed) antenna of length $L > L_D$, which includes the voltage amplitude $\Delta\Phi \sim Q/4\pi\epsilon_o L_D$). We then obtain using (8)

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

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_oF_2	300000	0.005	1000
Comet Halley at 10^5 km from nucleus	100	0.5	60

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 I shows typical values for a 100 μ dust grain at potential Φ_o ~ 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.

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