REVIEW OF CRITICAL PARAMETERS FOR MODELING

ELECTRIC ANTENNAS IN SPACE PLASMAS

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ABSTRACT

In spite of the usual precautions, such as long booms, bootstrapping and electrostatic shields, several experiments have revealed that the behavior of electric antennas in space plasmas is much more complex than conventional theories suggest. New theoretical approaches have been developed for modeling real systems, taking into account the actual size and shape of the sensors as well as the spacecraft structure, on a scale related to the characteristic lengths of the plasma. By these means various secondary effects can be estimated, such as disturbances due to large conductive structures, to the non-uniform charge distribution and to ion sheaths.

INTRODUCTION

The electric-field antennas that are used for passive as well as active experiments on spacecraft (S/C) are mostly of the dipole type. This applies both to the Hertz-like double-sphere dipoles with built-in pre-amplifiers, such as those used during the past several decades on magnetospheric missions, from GEOS to CLUSTER [1], and to the double-wire dipoles, more specially designed for the interplanetary medium, as used from ISEE to ULYSSES [2]. Monopoles are rarely used for passive experiments, mainly because they are too sensitive to quasi-static disturbances originating in the S/C body, which nominally are canceled with a differential, symmetrical dipole. In the electromagnetic (EM) domain, the theoretical behavior of antennas shorter than a wavelength has been well known since the early days of radio. Nevertheless, despite countless theoretical studies of their characteristics in a plasma, including or not the thermal motions of particles, unexpected and unreliable data can still be acquired on occasions. Unfortunately, for various reasons very few space missions, if any, are dedicated to metrology itself, so instruments are being improved in performance only slowly, at the mercy of technical heritage and the cure of identified problems. Here we review succinctly the main sources of disturbance that have made the application of usual principles unreliable, and we emphasize particularly the help offered by the use of advanced methods for modeling real systems.

USUAL BASELINE

The first condition that must be satisfied for applying the results of the baseline theory concerns the effective length of the antenna. Briefly, most experimenters assume that the effective length of a short dipole is its tip-to-tip length in the case of the double sphere, and half this length for the double wire. Now, in free space, such an approximation is valid only when the electric field can be assumed uniform on the scale of the entire device, i.e., for wavelengths so large that the field can be considered as quasi-static on that scale. In a plasma, this approximation is again applicable so long as the plasma can be considered as a pure dielectric, and when the antenna is much longer than the size of the S/C body. One example of a distribution of equipotential surfaces, as obtained by solving the Laplace equation with boundary conditions at the conductor surfaces, is plotted in Fig. 1. For a ratio of about 4 between the dipole length (l) and the S/C diameter ($D_{S/C}$), the effective length (l') is reduced by roughly 8%. Even though secondary effects due to wakes and ion sheaths are ignored as well, we shall see some examples below where these approximations may fail completely, especially near the plasma resonances.

The second condition concerns the impedance matching of the electronics to the antenna, including the cabling. Since the antenna impedance can be highly variable, unlike the free-space case, no impedance matching can be achieved over the frequency range of interest, where resonances may occur. Consequently, for receiving antennas, the general rule is to use a high input-impedance

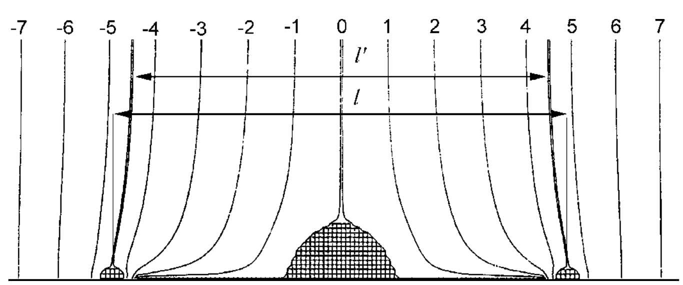

Fig. 1. Free-space distribution of equipotential surfaces, in a uniform external electric field, around a simplified model of a double-sphere dipole with a tip-to-tip length of about 8 S/C radii (arbitrary units).

coupling. Then, for DC and extra-low frequencies, the transfer function is essentially controlled by the balance between the leakage current due to the input circuit and the conduction current from the plasma [3], while for higher frequencies one must consider the input capacitance of the pre-amplifier, and possibly that of the feeder cable, as loads for the complex impedance of the antenna.

Except at DC and very low frequencies, the impedance of an antenna in a plasma is generally expressed as a multiple of its value in free space, which is a pure capacitance in the quasi-static domain that we are considering. Since the space-plasma parameters are extremely variable, it has been known for a long time that the antenna impedance can differ considerably from its free-space value; indeed, it may behave like that of a high-quality tuned circuit [4]. Nevertheless, it is customary to ignore these special resonant conditions and to model the transfer function with a simple capacitance voltage-divider, as in free space. With such drastic approximations, electric antennas in space plasmas cannot be considered as true measuring instruments [5]. Anomalies are often observed when both the electric and the magnetic components of the field are needed, as for wave-vector determination, though in some cases the transfer function can be estimated from a condition for the data to be self-consistent [6]. Fortunately, it is possible to improve this situation somewhat by using advanced modeling methods such as those discussed below.

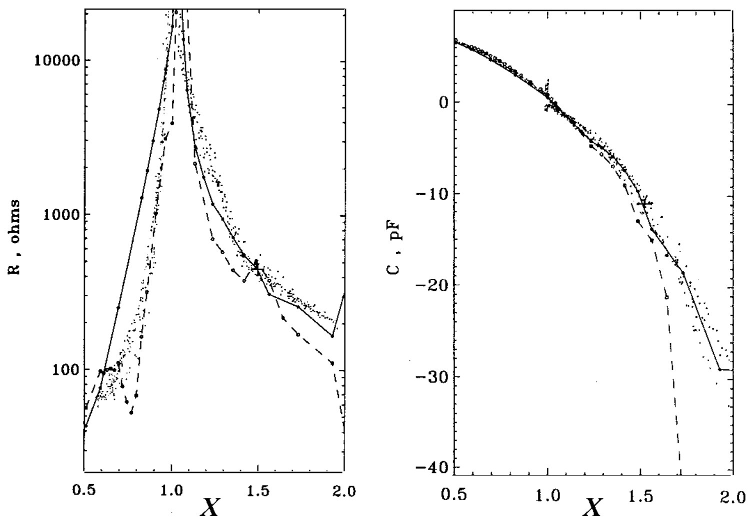

Fig. 2. Resistance and shunt capacitance of a double-wire dipole obtained by theoretical modeling using the SCD method (solid and dashed lines), compared with data from the EIDI-1 rocket experiment (dots), after [8].

THE SURFACE-CHARGE-DISTRIBUTION METHOD

In the context of the quasi-static approximation in a thermal plasma, any conducting surface is an equipotential, i.e., in the plasma at the surface, the parallel component of the electric field is zero. The potential distribution in the rest of the plasma is then determined by Poisson's equation, together with boundary conditions defined by the voltages on the surfaces concerned. From the relations between the voltages and the currents applied to all these surfaces, including the return current through the S/C body, the unique solution is found that yields both the unknown surface-charge distribution and the current-voltage characteristics of every conductor [7]. This is the Surface-Charge-Distribution (SCD) method; it can be applied to conductors of any shape and any size, and even to dielectrics. Its main feature is that no charge or current distribution needs to be assumed a priori; specifically, there is no need for the approximation of uniform charge distribution, which leads to the conventional triangular current profile for wire antennas. Initially, the SCD method was developed for modeling antennas in uniform and isotropic thermal plasmas. This approach takes into account the first moments of the boundary equations at the body surfaces, i.e., those concerning the electric field only, assuming as a first approximation that the particle velocity distribution is not perturbed, as it is reasonable to assume for surfaces of thin wire mesh in contact with the plasma [7]. The ion sheath can be introduced, if appropriate, as a dielectric electron-free layer around each conducting surface, and using additional boundary conditions.

APPLICATIONS OF THE SCD METHOD

One of the first applications of the SCD method, involving a numerical code based on the technique of finite elements [8], was stimulated by the unexpectedly high resistance values of a double-wire dipole in the vicinity of the plasma frequency (f_p), as measured by the rocket experiment EIDI-1. This was one of the rare space experiments dedicated primarily to antenna methodology [9]. Each half-dipole was 2 m long, i.e., about 400-500 Debye lengths (8_D) in the F2 layer of the ionosphere. The results are shown in Fig. 2, versus the usual normalized frequency parameter, $X = (f_p / f)^2$. The measurement was made at a fixed frequency, so the wide range of variation of X resulted from the variation of f_p along the rocket trajectory. The modeling involved two possible values for the thickness of the ion sheath (solid and dashed lines), around the antenna and also around the rocket body, both of which fit the data satisfactorily (for details, see [8]). The physical interpretation of the unexpectedly high value of the antenna resistance below f_p, i.e., $X > 1$, is that for such long antennas, the current distribution ceases to be triangular in the vicinity of f_p, due both to charge accumulation at the feed points, close to the rocket body, and to standing surface waves along the wires.

This behavior appears as a general feature in all applications of the SCD method, as being due to kinetic standing waves on

any surface with dimensions larger than about 15 8_D. These waves are the cause of a loss mechanism invoked for the first time by Seshadri [10], leading to abnormal antenna resistance.
Consequently, such antennas should have transfer functions very different from their free-space ones in this range of frequency. Here, assuming the receiver has an input capacitance of the order of 50 pF including the feed cable, electrostatic signals would be reduced by about 20 dB with respect to their free-space intensities, with a phase shift of nearly 90° around the parallel resonance of the antenna.
Another example, concerning now the effective length of a double-sphere dipole, is shown in Fig. 3. Here, we consider an ideal dipole without any structure in the gap between its two constituent monopoles, except for the grounded booms supporting the spheres. An external quasi-static electric field is assumed to be present, and to be uniform everywhere in the absence of the antenna. The tip-to-tip dipole length is 168_D, while the sphere and boom radii are both 8_D/32, so the ion sheaths may be ignored in this case. In free space the equipotential surfaces would be distributed around the antenna as in Fig. 1, but in the plasma at the frequency f_p they are strongly disturbed at large distances from the central gap, due to the charges that are induced on the boom surface so as to maintain it at the same voltage as the neutral equipotential surface crossing the dipole center. Consequently, assuming an ideally high input impedance for the built-in pre-amplifier, the sphere floats at a potential more than three times larger than its value in free space, with an additional phase shift of about - 0.6 radian, so the effective length changes accordingly.
In this example, the boom diameter is exaggeratedly larger than it is in most well-designed real double-sphere antennas, which, when they are installed in the S/C spin plane, have booms made of thin wire (10^{-2} - 10^{-3} 8_D). Nevertheless, the presence of the outer shields on such wire booms must be considered, as discussed now.

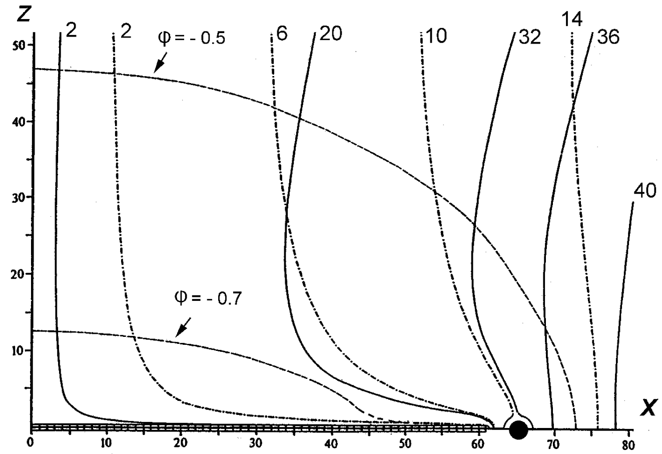

Fig. 3. Distribution of equipotential surfaces (in arbitrary units) around one half of a double-sphere dipole, including a grounded boom support, in the presence of an HF external electrostatic field, in free space (dashed lines) and in a thermal plasma at the plasma frequency (solid lines). The *Z* and *X* scale unit is 8_D / 8.

BOOTSTRAPPING TECHNIQUE

In order to decrease the stray capacitance of double-sphere antennas, or of double-probe antennas in general, the bootstrapping technique is often used. This consists of forcing the voltage of an electrostatic shield, located between the sensor and a grounded structure, to follow that of the sensor as closely as possible. Bootstrapping is used for HF antennas, and also for DC and very-low-frequency probes where its purpose is mainly to control the stray photoelectron current. Here again, the above principle implies that the plasma can be modeled as a dielectric, so that the Nyquist contour of the transfer function of the feedback loop does not enclose any singularity.
According to the above discussion about the antenna impedance, the stability condition is generally satisfied when the dimensions of the surfaces involved are not too large compared to the Debye length, at any rate in the case of an isotropic plasma. But this state of affairs may not always be encountered everywhere along the S/C trajectory. That is indeed the case for the two largest double-sphere antennas installed on the POLAR satellite [11], which exhibit in some special circumstances strong HF oscillations that have been attributed to the bootstrap instability [12]. A sketch of the sensor layout at the tip of one half of a dipole is shown in Fig. 4. The two bootstrapped stubs are formed of braid, of the same type as is used for the outer braid of the cable of the wire boom; they are disconnected from the S/C ground and connected instead to the pre-amplifier output.
The complex impedance of such an antenna (Fig. 5) has been computed by using the SCD method to model an ideal double-sphere dipole similar to the one drawn in Fig. 3, with just one new constraint added to the usual procedure, namely the transfer function of the bootstrap loop between the stubs and the sensor through the built-in pre-amplifier has been introduced. The equivalent circuit of this bootstrap loop (Fig. 5, inset) shows that the spherical sensor is closely coupled to the stub impedance through the stray capacitance C_1 which is the same as it is in free space, so long as 8_D is larger than the sphere radius (4 cm). Provide that the boom length is smaller than about 10 8_D, the stub impedance remains close to its free-space value, then the

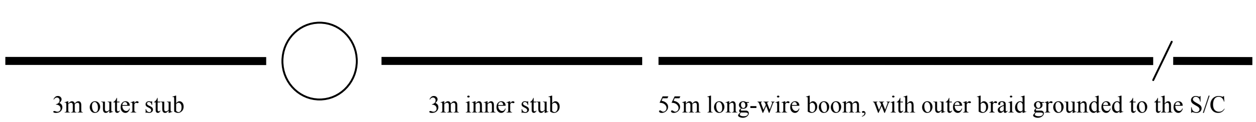

Fig. 4. Sketch of the sensor layout for a long-boom double-sphere dipole on the POLAR spacecraft.

bootstrapping is still efficient and the dipole impedance is nearly equal to the free-space capacitance ($Y < 0$) of the two spheres in series, while its resistance tends to zero like $1/8_D$. As usual, in the vicinity of f_p, the series resonance ($Y = 0$) appears when the Debye length decreases (here for $8_D \approx 2$ m), then both the inductance ($Y > 0$) and the resistance increase monotonically up to the parallel resonance ($8_D \approx 0.8$ m).The new feature, however, is the occurrence of negative values of resistance below about $8_D \approx 0.5$ m. This is clearly the signature of an instability resulting from the feedback coupling, when the stub impedance approaches its series resonance. Consequently, strong HF oscillations are generated by this system as soon as the above conditions are satisfied.

A detailed analysis of this phenomenon, using a different approach based on Nyquist's criterion and with a more sophisticated code, leads to similar conclusions, in agreement with the observations [12].

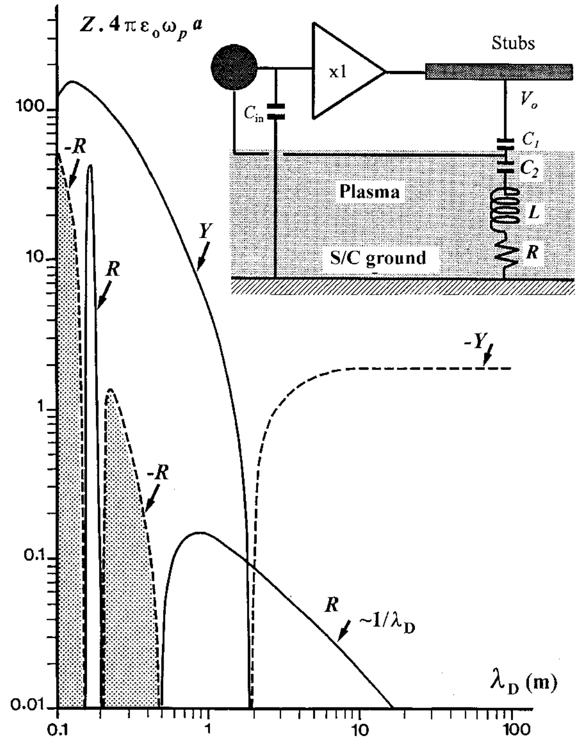

Fig. 5. Equivalent circuit of the bootstrapping system for the POLAR sensors (inset), and normalized impedance of the double-sphere dipole at f_p versus the Debye length.

CONCLUSION

The above examples prove the need to use the greatest care in interpreting measurements made with electric antennas, rather than take them at their face value. We have discussed here a limited choice of critical parameters, concerning essentially the sizes and shapes of hardware, together with the usual techniques, both of which must be considered in the design of plasma wave experiments. These factors can influence the data interpretation dramatically if they are not well suited to the desired mission. Many other factors that were ignored here might also have been considered, such as the behavior of antennas in non-maxwellian, anisotropic or dusty plasmas. For instance, in the presence of a significant steady magnetic field, it is well known that the orientation of a dipole may have a strong influence on its transfer function at the frequencies of the oblique plasma resonances, similar to what happens around f_p in an isotropic plasma. That is why theoretical as well as technical investigations of the methodology of electric antennas in space plasmas are far from being concluded, and should be valued because of the scientific returns that they can produce in the fields where these antennas are used.

***Acknowledgment*.** I am grateful to Dr L.R.O. Storey for his discerning comments about the manuscript.

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