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MAGNETOPLASMA SHEATH WAVES ON A CONDUCTING TETHER IN THE IONOSPHERE, WITH APPLICATIONS TO EMI PROPAGATION ON LARGE SPACE STRUCTURES

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ABSTRACT

Electromagnetic waves called "sheath waves" can propagate with low attenuation in the ion sheath, a region of low electron density that separates any conducting surface from an ionized-gas plasma in which it is immersed. Cold-plasma theory predicts propagation in a passband from zero frequency up to $1/\sqrt{2}$ times the electron plasma frequency for isotropic plasmas and up to $1/\sqrt{2}$ times the upper hybrid frequency for anisotropic plasmas permeated by a magnetic field in the direction of propagation. A recent space experiment has confirmed sheath-wave propagation on a kilometer-long insulated wire in the ionosphere, oriented parallel to the earth's magnetic field. This space-tether experiment, OEDIPUS-A, showed a sheath-wave passband up to about 2 MHz and a phase velocity somewhat slower than the velocity of light in a vacuum, and also demonstrated both ease of wave excitation and low attenuation. The evidence suggests that, on any large structure in low earth orbit, transient or continuous-wave electromagnetic interference, once generated, could propagate over the structure via sheath waves, producing unwanted signal levels much higher than in the absence of the ambient plasma medium. Consequently there is a need for a review of both EMI/EMC standards and ground test procedures as they apply to large structures in low earth orbit.

INTRODUCTION

An ionized gas plasma in contact with a solid surface is not homogeneous near the surface. Rather, it is inhomogeneous, forming a thin layer which contains ions from the plasma but very few electrons, so it is known as the "ion sheath". At the frequencies of interest, the ions are massive enough to be almost immobile, so it is the electrons that govern sheath behavior. Because the sheath is electron-depleted, to a first approximation it may be regarded as a vacuum gap. If the solid surface in question is a metal, then the picture that emerges is that of a vacuum gap separating a good conductor from a plasma which is also a conductor, albeit a very complex one. It is plausible that a vacuum gap between these two conductors can act as a guiding channel for an electromagnetic wave, and indeed this is known to be the case, the waves being called "sheath waves".

Early theoretical studies of sheath waves on a cylindrical conductor were done by *Seshadri* [1965], and by *Miller* [1968] who analyzed the case with a static magnetic field parallel to the conductor axis. Experimental studies were included in the papers by *Ishizone et al.* [1969, 1970a, 1970b], *Lassudrie-Duchesne et al.* [1973], *Meyer et al.* [1974], *Marec* [1970, 1974] and *Marec and Mourier* [1970, 1972]. Recently, *Laurin et al.* [1989] analyzed sheath-wave propagation over a planar surface, propagating in a direction parallel to the ambient static magnetic field, and they compared their analysis with laboratory experimental results for a thin wire in a magnetized plasma. Their conclusion was that sheath waves propagate in a frequency range from zero to $1/\sqrt{2}$ times the upper hybrid frequency, at least for the special case of wave propagation parallel to the magnetic field. Moreover they concluded that the waves propagate with a phase velocity that is slower than the velocity of light in a vacuum and approaches a nearly constant value at low frequencies (i.e. it is nearly dispersionless). Propagation in isotropic (unmagnetized) plasma is similar, with the plasma frequency f_p replacing the upper-hybrid frequency f_u, where $f_u^2 = f_p^2 + f_c^2$ and f_c is the electron cyclotron frequency.

THE "OEDIPUS-A" ROCKET EXPERIMENT

This project involved an ionospheric rocket which was launched in January 1989 from Andoya, Norway. It was separated into two parts early in its flight, the two parts remaining connected by a thin, insulated wire (or "tether") that unreeled from a spool in the rocket nose section, reaching a maximum wire length of 985 m near apogee. During the flight, the tether orientation stayed within 5° of being parallel with the earth's magnetic field. A stepped-frequency transmitter with an output level of 50 Vrms and covering the range 50 kHz - 5 MHz was located in the nose section and a synchronized receiver was located in the tail section. There were several experiments on board, the one of primary interest in this paper having the configuration shown in Figure 1, the purpose being to measure the transmission of signals end-to-end along the tether. The particulars of the tether are shown in Figure 2, in which it can be seen that the tether unreeled steadily, reaching maximum extension midway during the flight.

Figure 3 is a gray-scale representation of received signal strength as a function of both frequency and elapsed time during the flight. The dominant feature is a strong passband from zero frequency up to a sharp cutoff frequency between about 1.7 and 2.3 MHz. Above the cutoff frequency is a strong stopband extending upward to a frequency between 3 and 4 MHz where there is a return to fairly strong signal levels. As an aid to interpretation, Figure 3 includes a graph of plasma frequency f_p (taken from delayed-pulse measurement data supplied by one of the authors, H.G.J.) along with a graph of cyclotron frequency f_c . Also included are graphs of upper-hybrid frequency f_u and sheath-wave cutoff frequency $f_s = 1/\sqrt{2}\, f_u$, as well as harmonics of the cyclotron frequency.

The theoretical sheath-wave cutoff frequency f_c is about 30% higher than the measured cutoff frequency. This may be due to the expected high attenuation of sheath waves just below the cutoff frequency. Above the cutoff frequency is the stopband which extends upward to the upper-hybrid frequency f_c , as predicted by cold-plasma theory.

Within the low-frequency passband and for the earlier part of the flight, some very faint curved lines can be seen. These are enhanced by adjusting the gray-scale and are shown much more clearly in Figure 4. It is postulated that they are resonances occurring whenever the tether length is a multiple of a sheath-wave half-wavelength. Based on this postulate, contours for different sheath-wave phase velocities (refractive indices or wavenumbers) were drawn until a reasonable fit was obtained as shown, which is for a constant refractive index of 1.7 : this indicates that a relatively non-dispersive slow wave exists on the tether, in agreement with the sheath-wave postulate. The resonances are clearly visible at all frequencies up to the cyclotron frequency f_c , above which only faint indications of resonances can be seen and only up to an elapsed time of about 260 seconds. It will require further study to determine whether or not the rapidly rising attenuation (with increasing frequency) as predicted by *Laurin et al.* [1989] is sufficient to explain the disappearance of the resonances at or just above f_c for the greater part of the flight duration.

As an aside, it is interesting to note that dipole-to-dipole transmission experiments (with one dipole on the nose section and one on the tail section) produced gray-scale plots similar to Figures 3 and 4. In particular, the tether-length resonances were clearly visible even though the tether was not connected either to the transmitter or the receiver. This indicates that there was strong excitation of sheath waves in a situation where it was not intended.

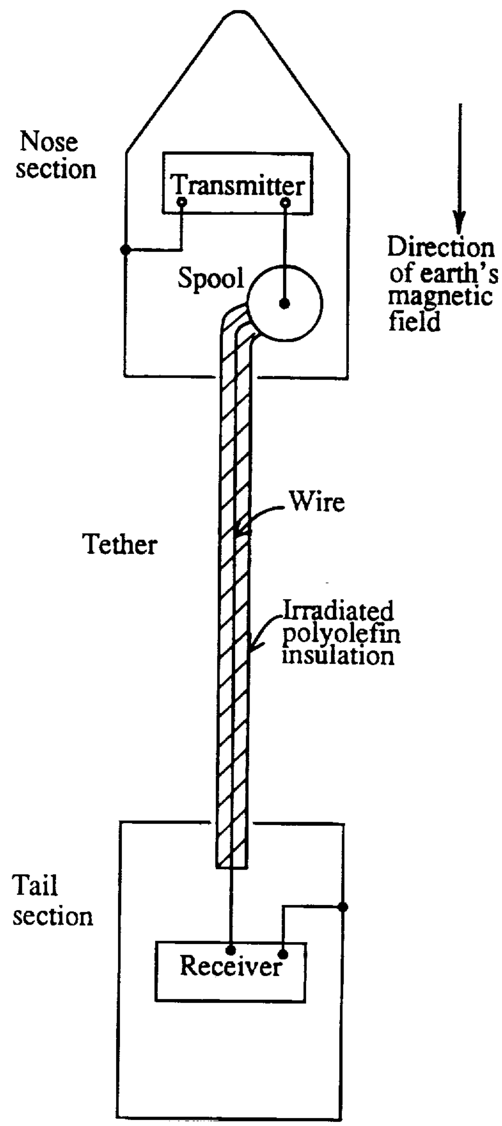

Figure 1. Diagram of the "OEDIPUS A" rocket experiment configuration used for the study of sheath waves.

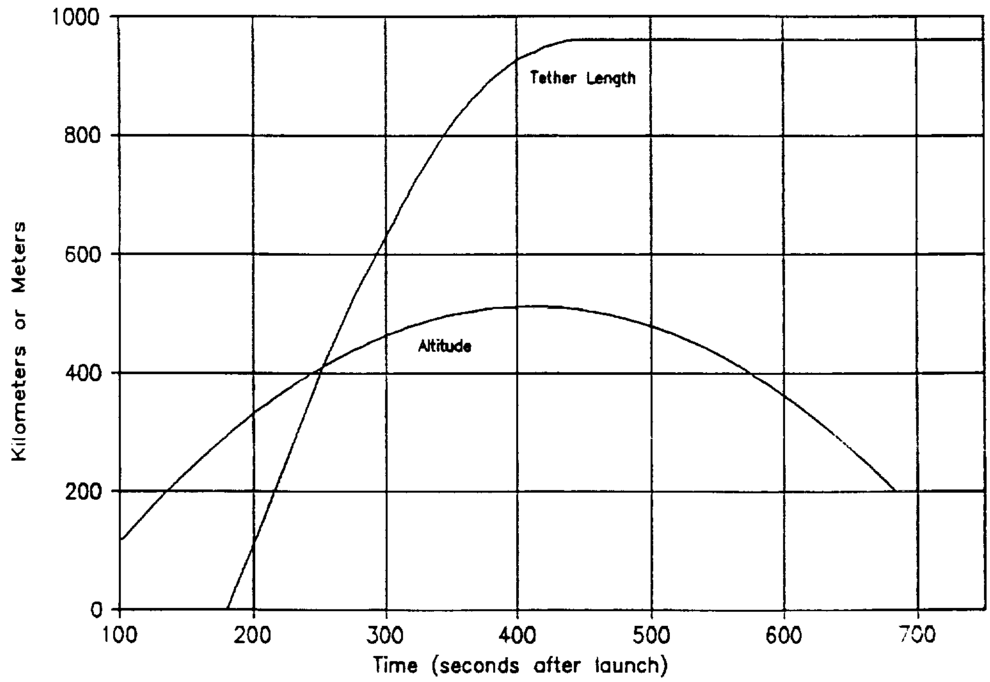

Figure 2. Tether length and altitude as functions of elapsed time. Tether wire length: 1300 meters; tether wire: No. 24 AWG, 19 strands of No. 36 copper, diameter 0.020"; tether wire coating: irradiated polyolefin, diameter 0.057", $\varepsilon_r = 2.32$; wire resistance: < 100 ohms over 1300 meters; spool-to-chassis resistance: > 3×10^{14} ohms; contact: slip ring; braking: constant-torque of 6.5 oz-in.

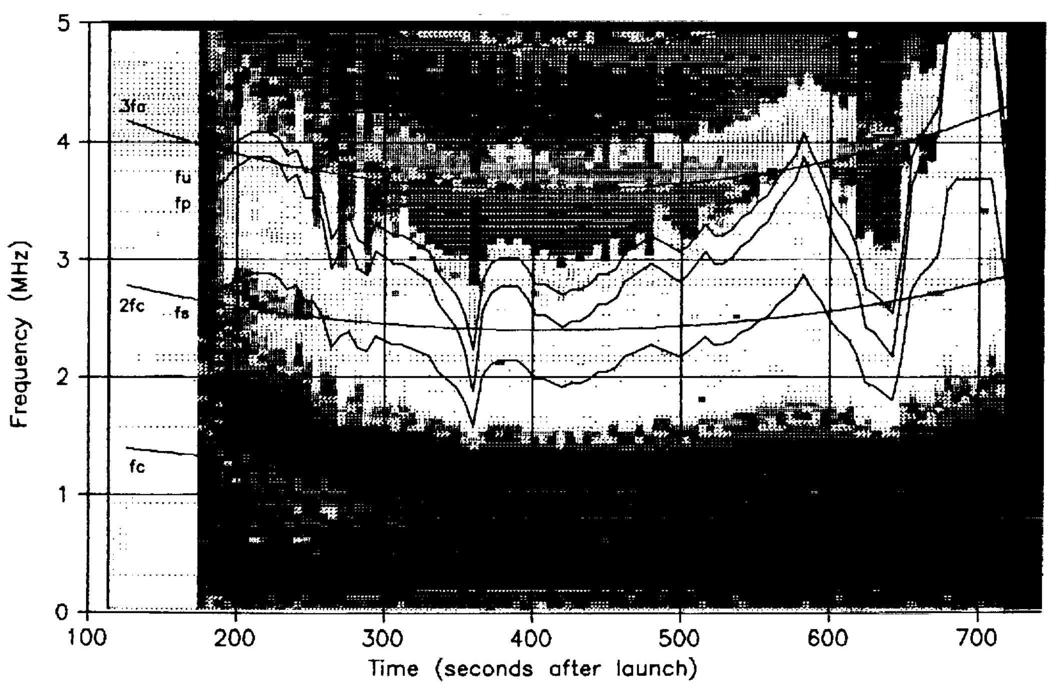

Figure 3. Received signal strength (darker gray scale means higher signal level) showing the cyclotron frequency f_c and its harmonics, the plasma frequency f_p, the upper-hybrid frequency f_u, and the nominal sheath-wave cutoff frequency $f_s = f_u / \sqrt{2}$.

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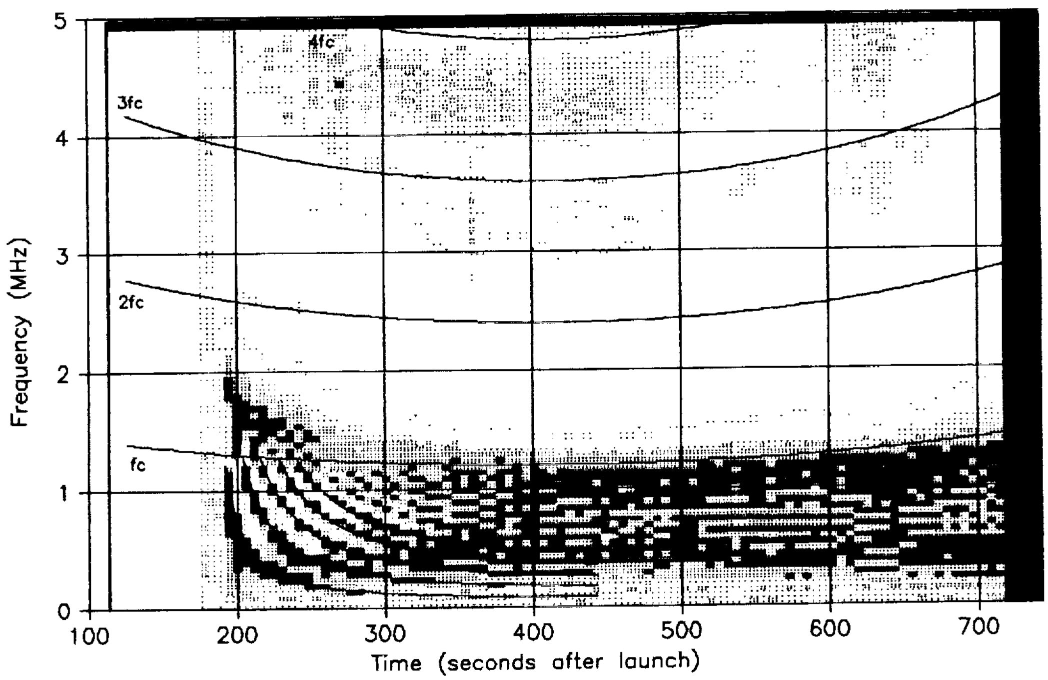

Figure 4. Received signal strength with gray-scale adjusted to show tether-length resonances. Lines show where tether is a multiple of a half wavelength long, assuming a wavenumber of 1.7.

Figure 5 shows received amplitude plotted against frequency at four different times during the flight. The features already discussed are evident, but most prominent is the high level of the low-frequency passband and the depth of the stopband, the difference in levels being of the order of 70 dB.

A particularly interesting feature visible in Figs. 3, 4 and 5 is the association of gray-scale boundaries with the harmonics of the cyclotron frequency. This suggests that cyclotron-harmonic waves which propagate *across* the magnetic field play a part in sheath-wave attenuation, say by carrying energy away from the tether (a suggestion made by one of the authors, H.G.J.). There are two implications, the first that this is a "leaky wave" phenomenon (and that the tether has become a leaky-wave antenna), and the second that kinetic theory will be required to explain fully the phenomenon of sheath waves.

Highly simplified theory may still be helpful, however, especially in view of the scarcity of theoretical developments adequate for the computation of fields due to given sources in finite-temperature anisotropic plasmas. Consider isotropic, cold plasma : existing thin-wire computer programs for lossy media can be adapted readily to cover this case, for example the program developed by *Richmond* [1974] and improved by *Tilston and Balmain* [1990]. This program can model isotropic cold plasma and a vacuum-gap sheath surrounding any interconnected network of thin wires. Its utility in application to anisotropic plasma will always be limited but, for the case of a wire parallel to the magnetic field, the strong radial electric field is always perpendicular to the magnetic field. This means that the perpendicular permittivity will predominate, with its zero at the upper-hybrid frequency rather than at the plasma frequency as would be the case with no magnetic field. This suggests that isotropic cold-plasma theory could be useful as a rough first approximation provided that the numerical value of the upper-hybrid frequency is substituted for the plasma frequency. The result of doing this is shown in Figure 6 in which the sheath-wave refractive indices deduced from measured resonances (ranging from 1.20 to 1.75) are bracketed by theoretical values computed by selecting two isotropic plasma frequencies spanning the range of upper hybrid frequencies in the experiment.

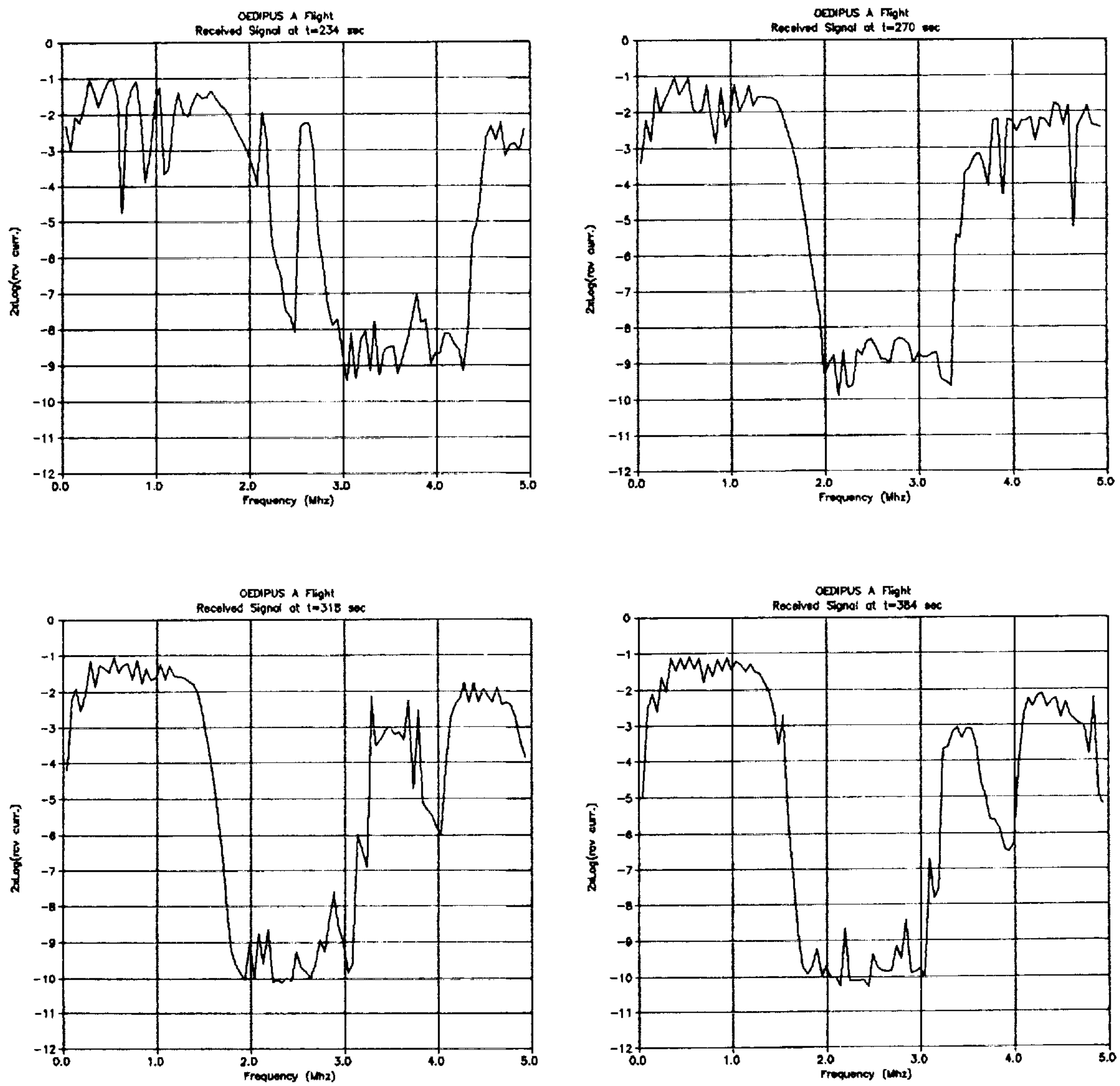

Figure 5. Frequency sweeps of received signal level at elapsed times 234 sec., 270 sec., 318 sec., and 384 sec.

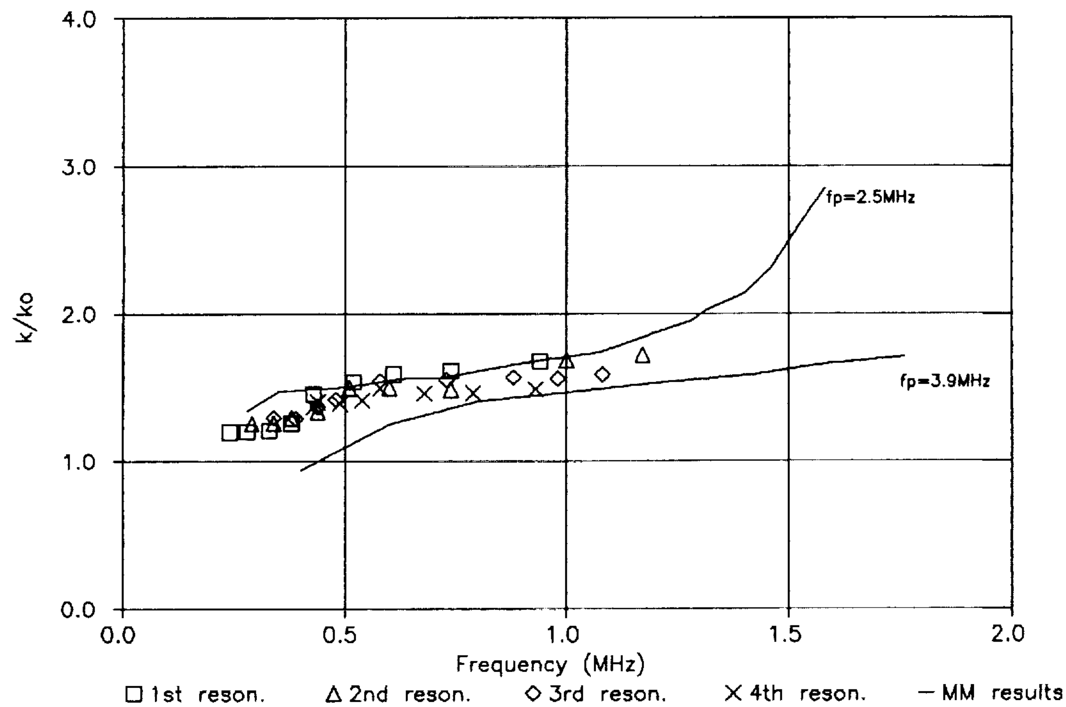

Figure 6. Wavenumbers derived from various resonances, together with moment-method calculations of wavenumbers in isotropic plasma, using two different values of plasma frequency intended to span the actual experimental values of upper hybrid frequency. The assumed sheath radius is 2.5 cm.

The use of gridded end-plates to represent the rocket nose and tail in this cold-plasma numerical calculation enables a calculation of typical transmitted signal level along with a free-space comparison as shown in Figure 7. The low-frequency passband and the transition to a deep stopband around 70 dB lower are clearly evident, along with tether-length resonances. The calculated cutoff frequency f_s at 2.6 MHz is clearly too high (compared with the measured value of 1.8 MHz at an elapsed time of 590 sec.). Nevertheless, the calculations up to 1 MHz or somewhat higher still are the best available theoretical results that include approximate representations of the rocket nose and tail sections. In particular, the comparative plasma-with-sheath and free-space calculations deserve attention. With the sheath, the signal level in the plasma is 30 dB to 60 dB higher than in free space, at frequencies below 1 MHz. It is this strong coupling that has implications for EMI/EMC on large structures such as the Space Station. Without the sheath, Figure 7 shows essentially no coupling, as expected.

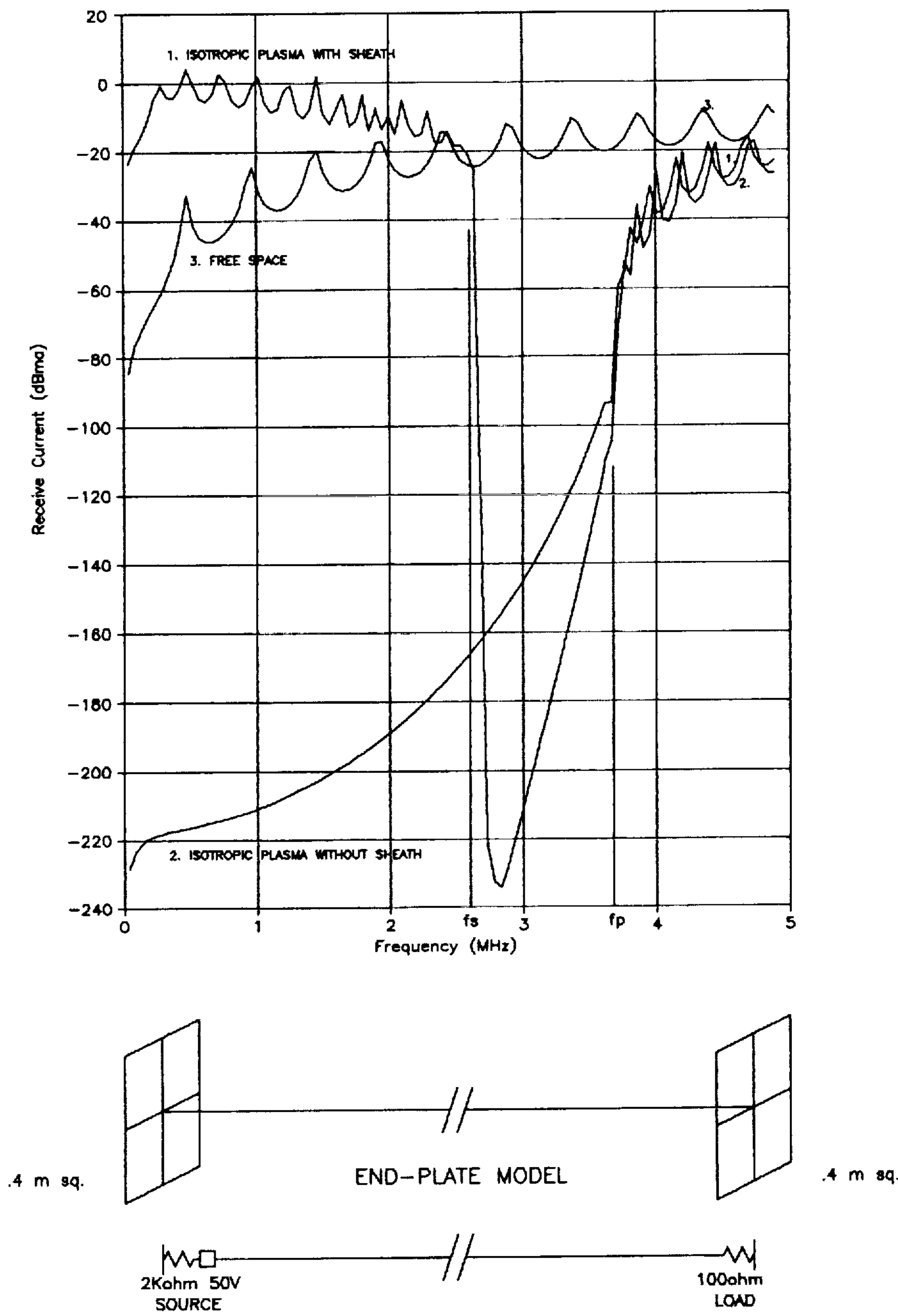

Figure 7. Moment-method calculation of coupling from one end of the tether to the other, for both free space and plasma environments, the latter for two conditions, with no sheath and with a 2.5 cm diameter sheath. The tether length is 300 m.

The coupling factor is potentially important because EMI/EMC standards and test methods are based on the assumption of a free-space environment. Therefore a source of interference at one point on the Space Station will couple to a susceptible instrument at a distant point much more strongly than might be anticipated, implying that tighter standards would be needed either for emission or immunity, for interference with significant spectral content below about 1.5 MHz. The above computations using a computer program valid for isotropic dielectric media suggest that such programs could be useful in getting a first estimate of interference levels.

Another relevant aspect of EMI/EMC is ground test procedure for emission or susceptibility. Putting a large part of the Space Station in a plasma chamber is clearly out of the question when it comes to deciding whether a given unit emits excessive unwanted radiation. Because at low frequencies the plasma can be regarded as a conductor and because it is separated from any surface by the sheath region which is a few centimeters thick, it is postulated that a first-order laboratory equivalent model would consist of a wire mesh completely surrounding the part of the Space Station under test and separated from it by a few centimeters. To represent the cutoff frequency and the stopband, it is postulated that the wire mesh could be segmented and the segments separated by appropriately synthesized lumped-element networks, as shown in Figure 8. If the equivalence of this wire-mesh configuration could be established, then relevant emission and susceptibility test methods and standards could be derived.

CONCLUSIONS

The OEDIPUS-A ionospheric rocket flight involving radio transmission along a conducting tether parallel to the earth's magnetic field has established the existence in the ionosphere of sheath waves on the wire and revealed some of their properties, including passbands, stopbands and phase velocities. The existence of tether-length-dependent resonances shows that the sheath waves can propagate with little attenuation, especially at frequencies below the electron cyclotron frequency. Existing cold-plasma theory explains in part the properties of the sheath waves but kinetic theory analysis ultimately will be needed for indepth understanding.

The ease of coupling between widely separated parts of a long structure in the ionospheric plasma has implications for EMI/EMC standards applicable to systems on the Space Station. Some EMI/EMC calculations probably can be done with sufficient accuracy using existing computer programs valid for isotropic, lossy dielectrics. Ground test for EMI/EMC compliance may be possible using a modified wire mesh envelope to represent the sheath-plasma boundary.

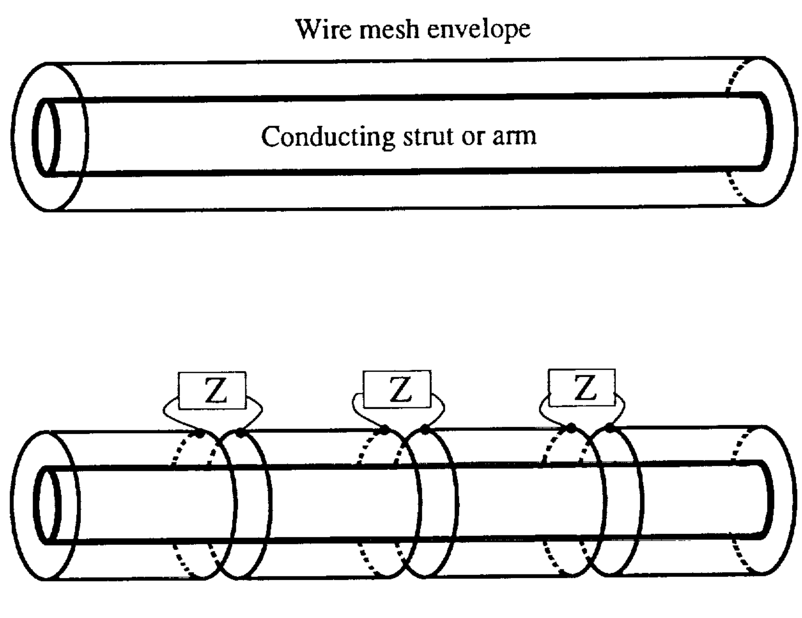

Figure 8. Proposed ground-test configuration with a wire mesh representing the sheath edge and the plasma beyond it. The lower part of the figure shows how synthesized impedance loading of the mesh might be employed to improve simulation in the vicinity of the primary stopband.

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