NONLINEAR PLASMA SHEATH PHENOMENA AFFECTING THE ANTENNA IMPEDANCE FOR HIGH POWER SATELLITES

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The paper reports of research work supported by the German Federal Ministry of Research and Technology (BMFT). The investigations of this paper are concerned with plasma-induced signal degradations to be expected for a new generation of communication satellites such as the German TV-SAT (launching date now scheduled for 1986) or the L-SAT project of the European Space Agency (ESA). Such kind of satellites are planned to carry high power transmitter (TX) capabilities of several hundred Watt in order to enable direct reception of broadcasting and TV. So far typical satellite TX output powers radiated are on the order of 1o or 2o W. High power capabilities became possible by substantial progress achieved in the technology of satellite-borne TWTs. The downlink signal frequency of TV-SAT, for example, is approximately 12 GHz serving up to 5 RF channels of about 17o W net output power each, directly to be received by ground-based parabolic antennas with a diameter as small as 1 m or so.

Generally on-board satellite antenna systems use single or dual reflector antennas of symmetrical or offset-configuration. The paper discusses various technical implications of such antenna systems used for high power satellites, especially as far as operation in geosynchronous orbit is concerned. Nonlinear plasma phenomena are expected to build up a plasma sheath in the near-field of the TX antenna feed (and reflector) system involving electrons of the earth's ionized atmosphere (magnetosphere and ionosphere) and, above all, electrons due to photoionization and secondary electron emission from the sunlit regions of the satellite structure (1). Two aspects of antenna-to-medium coupling are discussed in detail: plasma discharge effects and mismatching of the TX antenna input impedance. It is shown that plasma-induced signal degradations may be important even for high signal frequencies, if the satellite TX output power exceeds a certain value of threshold.

Plasma discharge effects arise from high differential voltages locally maintained across sunlit and shadowed areas of the composite structure of the satellite surface with respect to the ambient space plasma (2). By means of computersimulations the paper illustrates how small perturbations of the incident charged particle flux cause abrupt changes of the surface floating potential on the order of several thousand Volt. Current-voltage characteristics of typical surface materials in space technology show stable and unstable states of balance for the floating potential. The local distribution of surface potential may strongly be influenced by the RF fields associated with the TX antenna system. Such transient plasma effects are enforced, if a high power RF transmitter of pulsed type is used (e.g. radar antenna system of a remote sensing satellite). Plasma discharge effects may give rise to uncontrolled cascades of arc discharges disturbing electronic circuitry aboard as already verified experimentally for several satellites such as Scatha, Hermes (Canadian Communication Technology Satellite; TX power$\sim$2oo W), and ESA's Meteosat 1 (3), (4). One preventive measure is, for example, to protect the front and rear side of a satellite antenna reflector by a sunshield foil with specified charge-resistant and thermal-optical properties.

A novel kind of plasma disturbance is due to mismatching of the TX antenna impedance (5)-(7). Including sheath effects the plasma interactions across the antenna system are shown to cause nonlinear terms of Coulomb- and Lorentz-force and convective acceleration in the electrons' equation of motion, coupled to the equation of continuity of charge and governed by the EM radiation field according to Maxwell's equations (1). Nonlinear terms, for instance, turn out to be proportional to the gradient of the squared modulus of the electric field strength transmitted, i.e. the antenna-to-plasma coupling is strongest in the near-field of the TX antenna feed. Moreover there is a distinct influence due to the spatial decay of fields specifically emerging from the surface charge and current distribution along the contours of antenna feed and reflector(s) as caused by photoionization and secondary electron emission. An equivalent circuit model is developed to show the nonlinear features of the input impedance of the satellite antenna: (a) DC component of current density due to rectification building up current-voltage characteristics; (b) additional AC component of current density for the signal frequency applied due to higher order terms (starting with third power of field strength radiated), i.e. the input impedance gets mismatched; (c) excitation of intermodulation products (e.g. generation of multiple frequency terms starting with second power due to ponderomotive forces acting on plasma environment). Mismatching means increase of antenna VSWR due to interaction with the antenna-plasma interface causing decreased SNR on ground and additional thermal load (and instabilities) by the TX power reflected aboard. Intermodulation causes cross-talk between the RF channels allocated, for FDMA satellite communications also combination frequencies deteriorate channel separation.

Introducing a small-signal approximation a perturbation theory is presented to determine the input impedance of a dipole antenna modelling radiation into a nonlinear, compressible, and homogeneous electron plasma (magnetostatic fields being negligible) (1). Using the hydrodynamic approach a series expansion up to the third power is taken to solve for the magnetic field and the electron density involved. Starting from linearized wave equations the fundamental solution (index 1) results from a set of coupled integral equations derived for the equivalent surface current density (associated with $\vec{n} \times \vec{H}_1$) and the plasma density N_1 to be integrated along the cylindrical antenna surface A

$$\frac{1}{2}\vec{n}(r)\times\vec{H}_1(r) = \int \vec{n}(r)\times\Big\{\Big[\vec{n}(r')\times\vec{H}_1(r') - \frac{ea^2}{j\omega}\vec{n}(r')N_1(r')\Big]\times \times\vec{\nabla}'G_e(R) + j\omega\varepsilon_0\varepsilon_r\vec{n}(r')\times\vec{E}_1(r')\,G_e(R)\Big\}\rho' d\varphi' dz'; \quad (1)$$

$$\frac{1}{2} N_1(r) = \int\Big\{\Big[\frac{1}{j3\omega e \lambda_D^2} \vec{n}(r')\times\vec{H}_1(r') + \vec{n}(r') N_1(r')\Big]\cdot\vec{\nabla}' G_a(R) + \frac{j\omega_2}{a^2} N_o \vec{n}(r')\cdot\vec{v}_1(r') G_a(R)\Big\} \rho' d\varphi' dz', \quad (2)$$

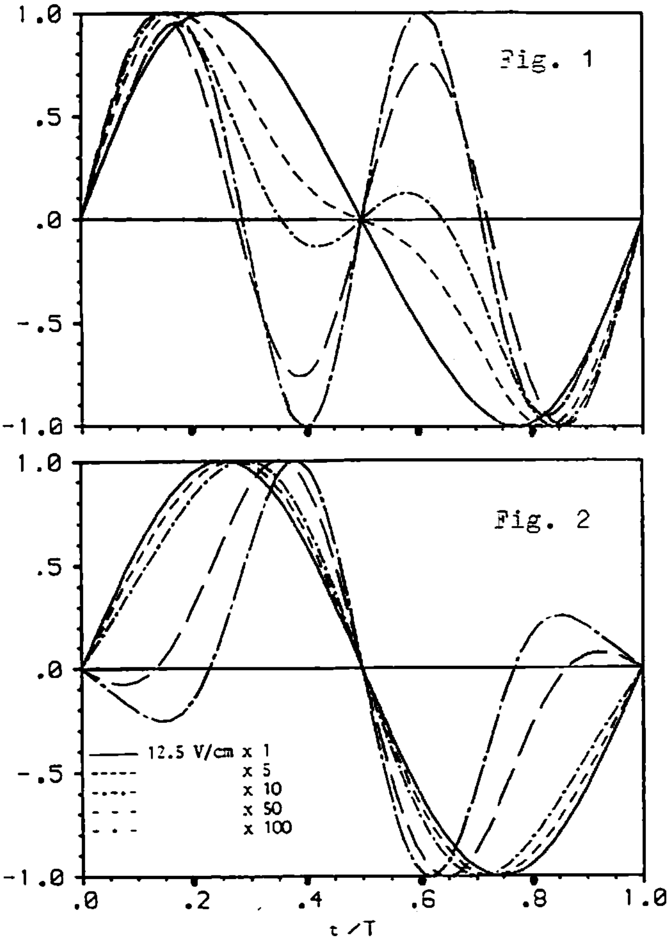
where the following notations hold: n – normal vector of surface A; dielectric constant $\varepsilon_r = 1 - \omega_0^2/\omega^2$ with plasma frequency ω_0; N_o – state of equilibrium for plasma density; a – sound velocity of plasma; λ_D – Debye length; time dependence $\sim e^{j\omega t}$. The Green's functions G_e and G_a, respectively, allow for electromagnetic and acoustic wave modes. The normal component of the plasma velocity $\vec{v}_1$ is related to N_1 via an absorption coefficient α describing any interaction of electrons with the antenna surface. Limiting cases are considered for total electron reflection or absorption, respectively. The integral equations are coupled by the relevant conditions of continuity (and by higher order terms). A multi-layer configuration is taken to account for plasma inhomogeneities due to sheath phenomena. A solution of the integral equations is given for the surface current density along the dipole by inverting a generalized impedance matrix. Nonlinear, higher order terms for the field quantities involved are included as additional source contributions to the integral equations: following the perturbation concept the azimuthal component $H_\varphi(z)$ of the magnetic field along the dipole axis, e.g., is given by integral representations in terms of the fundamental solutions $H_{\varphi 1}$ and N_1, where the nonlinear contributions are denoted by indices 2 and 3

$$\frac{1}{2} H_{\varphi 2}(z) = \int\Big\{ \frac{ea^2}{N_o}\Big(\frac{1}{2} - \alpha^2\Big) \frac{N_1^2(z')}{j2\omega} \frac{\partial G_e(R)}{\partial z} \cos(\varphi-\varphi') + \frac{\alpha}{j2\omega}\Big[\Big(\frac{e^2 a}{m} \frac{E_{z1}(z')}{j\omega} + \frac{ea^3}{N_o} \frac{1}{j\omega} \frac{\partial N_1(z')}{\partial z'}\Big) N_1(z')\Big] \frac{\partial G_e(R)}{\partial \rho} + \alpha \frac{e^2 a}{m}\mu_0 \frac{H_{\varphi 1}(z') N_1(z')}{j2\omega} G_e(R) \cos(\varphi-\varphi')\Big\} \rho' d\varphi' dz'; \quad (3)$$

$$\frac{1}{2} H_{\varphi 3}(z) = \int\Big\{ -\alpha^2 \frac{ea^2}{N_o^2} \frac{N_1^3(z')}{j3\omega} \frac{\partial G_e(R)}{\partial z} \cos(\varphi-\varphi') + \frac{\alpha}{j3\omega}\Big[\Big(\frac{e^2 a}{m N_o} \frac{E_{z1}(z')}{j\omega} + \frac{ea^3}{N_o^2} \frac{1}{j\omega} \frac{\partial N_1(z')}{\partial z'}\Big) N_1^2(z')\Big] \frac{\partial G_e(R)}{\partial \rho} + \alpha \frac{e^2 a}{m N_o}\mu_0 \frac{H_{\varphi 1}(z') N_1^2(z')}{j3\omega} G_e(R) \cos(\varphi-\varphi')\Big\} \rho' d\varphi' dz'. \quad (4)$$

The quantities e, m represent the electron's charge and mass, respectively. The axial component $E_{z1}(z')$ of the electric field is thought to be non-zero only along the feed zone of the dipole antenna's surface. Similar relationships hold for the higher order electron density terms $N_{2,3}$.

A numerical solution is accomplished by segmenting the dipole length (here up to 55 equally spaced segments were taken) and using the method of collocation. A matrix equation is set up and solved by an iterative procedure to account for nonlinear source terms up to the third order. Computersimulations have been performed modelling two cases of application: experimental instrumentation aboard the space shuttle (ionospheric plasma conditions; signal frequency f=2o MHz) and operation of TV-SAT in the geosynchronous orbit (magnetosphere; 12 GHz). Mainly due to limited capacity in computer storage so far only a homogeneous plasma environment has been simulated for an electrically short dipole (e.g. length$\sim$o.o1λ). The real and imaginary part of the nonlinear input impedance were calculated and compared with the corresponding values valid for free space. As far as the space shuttle antenna experiment is concerned preliminary results show that the relative deviations in resistance and reactance typically are $\Delta R/R\sim 3\%$ and $\Delta X/X\sim 1\%$, respectively. For the TV-SAT the corresponding deviations turn out to be significantly reduced by more than one order of magnitude. A Fourier analysis of the nonlinear antenna feed current is in progress indicating, e.g., that the real part of the second harmonic component is more sensitive as to nonlinear plasma effects than the imaginary part. In figs. 1,2 this feed current is normalized with respect to its maximum value for the space shuttle experiment (N_o=1o^{12} m^{-3}; i.e. plasma frequency f_o= o.45 f; temperature T_o=1965 K assuming a velocity ratio of c/a=1o^{3}; length of dipole o.93 m≙o.o62λ with radius o.93 cm and length of feed segment o.65 cm). Both figs. show a significant increase of the nonlinear behaviour of the feed current with increasing magnitude of the feed voltage applied. The nonlinearity of the antenna input impedance is expected strongly to increase for longer dipoles embedded in inhomogeneous plasma. Investigations started to include aperture antennas.



Figs. 1(2) - Real (imaginary) part of nonlinear antenna feed current versus fundamental time period (T=1/2oμs).

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