MODELLING OF ANTENNA RADIATION PATTERN OF A RE-ENTRY VEHICLE IN PRESENCE OF PLASMA

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Abstract

Upon re-entry in the Earth's atmosphere, space vehicles become shrouded in a plasma that obviously affects all communications between vehicle and ground, abut also with geosynchronous satellites. This paper deals with the study of antenna radiation trough plasma during re-entry of the European Atmospheric Re-entry Demonstrator (ARD). The task is accomplished via a combined technique involving 1) ray-tracing from the antenna through the plasma region around the ARD vehicle up to a surface in free space, and 2) application of the equivalence theorem and radiation in far field of the equivalent sources on that surface. The gain of the antenna+plasma +ARD is calculated, that allows to determine the link budget as in free space. The study is confined to a 2D model situation, the plasma profile is approximated by a convenient analytical (parametrical) expression, and losses due to plasma collisions are neglected in this first study. The results are significatively similar to measured link losses, and show that multipath inside the plasma region, and diffraction from plasma "rim" allow to afford link losses well below initial expectations.

INTRODUCTION

All space vehicle re-entering Earth's atmosphere at high velocity produce a bow shock wave which compresses and heats up the gases producing a flow of plasma around the vehicle body. This plasma obviously affects all radio links between the vehicle and ground. However the presence of relay satellites in geostationary orbit offers a chance to avoid the total blackout experienced in early space-flights that were required to communicate directly with ground based stations. The flight of the European Atmospheric Re-entry Demonstrator has allowed the experimental characterization of the communication channel between the capsule and one of the NASA Tracking and Data Relay Satellite (TDRS). Contrary to the initial expectation only limited signal attenuation was experienced over the Telemetry Tracking and Control channel at S-band. The particular unfavorable position of the antenna had instead led to the expectation, supported by predictions based on simplified models, that the attenuation induced by the plasma effects would exceed 100dB. The paper describes a significantly more refined model, which predicts attenuations comparable to the measured ones and that will allow a more realistic estimate of the link budget during the re-entry phase for future missions. The model uses as input, beside the vehicle geometry and antenna characteristics and location, the maps of the plasma parameters distribution around the body produced by non-equilibrium hypersonic gas-dynamic simulations. The propagation of the field radiated by the antenna through the plasma is

modelled using a combined technique involving 1) ray "shooting-and-bouncing" from the TDRS (patch) antenna through the non-uniform plasma region around the ARD Re-entry Vehicle (REV) up to a surface in free space, and 2) application of the equivalence theorem and radiation in far field of the equivalent (Huygens) sources on that surface. The gain of the antenna+plasma +REV system is then calculated, that allows to determine the link budget.

SOLUTION STRATEGY

In the following, we will attack the complex global problem by separating the regions where plasma is present, and it has varying parameters, from the regions where no plasma is present. We will employ geometrical optics (GO) to follow field propagation from the antenna in the inhomogeneous region, and until wavefront have emerged from plasma. Knowledge of the field just outside the plasma region will be used, via the equivalence theorem [3] to find equivalent sources whose radiation will produce the far field pattern; the latter step is customarily called "aperture integration" (AI) in the context of reflector antennas. In analogy to that, we will call GO-AI this approximation.

In this work, the effect of tunnelling through the plasma layer where the operation frequency is below cutoff will not be considered; the depth of the evanescent layers in the link direction are large, and no significant tunnelling is expected.

In order to understand the relevant wave phenomena that take place here, and conduct a feasibility study of ability of the proposed model to predict the link attenuation, in the following we will confine our attention to the 2D case derived from cutting the structure (REV and plasma) in the windward plane. As the results will show, this simplified model yields relevant information. It is also to be mentioned that in complex case like prediction of terrestrial mobile (or LMS) communication path loss, a "2.5D" approach is often used, in which several 2D ray tracing are performed over cuts of the actual 3D geometry.

For the same reason, the plasma parameters have been simulated by analytic closed-form parametric forms, whose parameters have been chosen so as to reasonably represent the available plasma parameter distributions.

The TDRSS link frequency is f =2.267 GHz, close to the electron plasma frequency (f_p) values found for this plasmas; in this frequency regime the plasma model is the electron plasma oscillation model [1, 2]; the typical values of the collision frequency $\nu \ll f$ present here imply a weakly collisional electron plasma model that yields an isotropic electric permettivity that varies according to local plasma density.

Propagation from the antenna and into the plasma-occupied region will follow GO; for numerical solution of the ray equation in a non-homogeneous medium, the eikonal equation is best formulated in terms of canonical (characteristic) equations [4, 5]. Caustics are present, but since one is interested in the field away from caustics, the power density rule still applies. However, the higher order asymptotics $\pi/2$ phase shift along rays passing through a caustic needs to be retained. Another critical point in this problem is the cut-off layer, i.e. a layer where $f = f_p$, and rays are reflected back. Finally, when rays reach back onto the REV surface because of deflections in the plasma, metallic reflection has to be enforced at points when rays encounter the REV surface.

Rays are followed until they emerge from the plasma region, up to an arbitrary surface Σ that encloses the plasma and REV. On Σ, fields determine the equivalent surface electric and magnetic currents; their radiation - in free space - determines the field radiated by the antenna in the presence of the plasma region around the REV, and of the REV itself. According to the GO approximation, field is zero in the shadow regions, so that integration in the radiation integrals is limited to the lit portions of Σ. Because of the presence of

lit and shadow regions, the field radiated by the equivalent sources will therefore contain diffraction effects ("windowing", or Fraunhofer, diffraction).

The ARD antenna is a patch; since the phenomena are dominated by the intense multipath propagation in the plasma region, the antenna pattern has been simplified to omnidirectional.

The GO-AI radiated far field is found in a trivial manner from the results of free-space radiation once the (GO) field on Σ is known. While any surface that encloses the plasma and REV can be used, a marked simplification in the determination of the radiation field is achieved if it is taken along the GO wavefront(s). Care must be taken in performing the integration, since these WF extend typically over tens of wavelengths: the integrand is strongly oscillatory, yet with slowly varying amplitude. Ludwig's integration algorithm [6] has been employed for the fast phase variation.

In order to characterize the antenna+REV+plasma environment, an *equivalent gain* function has been introduced. It is defined as the gain of the *entire* structure, i.e. (according to the IEEE standard)

$$g(\theta) = \epsilon U(\theta)/U_{\text{average}} \tag{1}$$

where $\epsilon = P_{\text{rad}}/P_{\text{source}}$ is the Ohmic efficiency due to losses in the plasma, and in this 2D case the radiation intensity is $U(\theta) = r|\underline{E}(r,\theta)|^2$, and

$$U_{\text{average}} = P_{\text{rad}}/2\pi, \quad P_{\text{rad}} = \frac{1}{\eta_0}\int_{WF} d\ell |\underline{E}(\ell)|^2 \tag{2}$$

where η_0 is the free-space impedance, and the integral is carried out along the chosen contour, i.e. the WF. The link budget from the REV to the TDRSS (or other) satellite can be computed from the input power to the antenna on the REV, the above gain, and the free-space link attenuation.

RESULTS AND DISCUSSION

Measured data and plasma calculations were available for ARD heights of 85, 61.5 and 46km. Figs. 1 and 2 show the case of 61.5 km, were plasma blocking is most severe, with an example of ray tracing; the plasma frequency (plasma density) contour lines are also shown. In plasma blocking conditions, it is apparent that complex multi-path phenomena occur in the plasma cloud surrounding the vehicle, and this carries over to the field that gives rise to equivalent radiation sources. The related radiation pattern is reported in Fig. 2; the TDRSS link is at $\theta = -28°$.

The overall results are summarized in Tab.1, that shows the attenuations introduced by the plasma blocking with respect to free-space link, where the antenna gain in this case would be about 3dB. As mentioned above, in this study (collisional) plasma losses (ϵ in (1)) has been neglected.

Table 1: *Comparison between measured and computed plasma attenuations.*

height	measured atten.	computed atten.
85 km	12 dB	15 dB
61.5 km	21 dB	23 dB
46 km	4 dB	0 dB

The agreement shown in the Table above can be considered very good. An important result obtained by the simulations is that even when placed in very unfavorable positions

the antenna is likely to provide good coverage over a very wide angular sector with attenuation of the order of 15-30dB; this result can be attributed to diffraction from the plasma rim (accounted for here in the Kirchhoff-Fraunhofer approximation). This value of plasma blocking attenuation is indeed confirmed by the data measured for the Atmospheric Re-entry Demonstrator but it is also likely to happen for bodies of other shapes and dimensions.

Figure 1: Example of ray tracing, height: 61.5km; contour lines show plasma frequency (GHz).

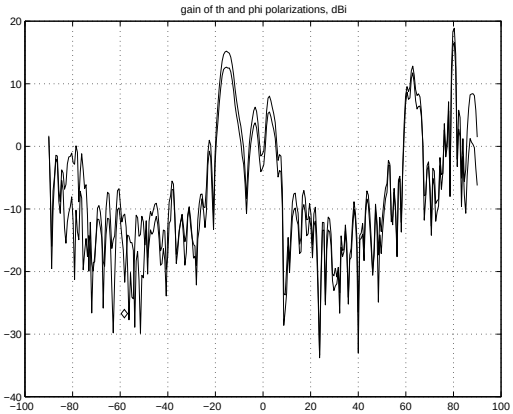

Figure 2: Radiation pattern for Fig.1. The REV axis is at $\theta = 0$.

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