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 affects all communications of spacecrafts with ground and satellites.

The flight of the Atmospheric Re-entry Demonstrator (ARD) of the European Space Agency (ESA) has allowed the experimental characterization of the communication channel between the capsule and one of the NASA Tracking and Data Relay Satellite (TDRS), flying at geosynchronous orbit.

This paper deals with the study of antenna radiation trough plasma during re-entry of the ARD vehicle. Despite some approximations, the obtained results are remarkably close to measured link losses, and provide an explanation of why these losses are much less severe than the initially expected "blackout".

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 [1]. This plasma affects all radio links between the vehicle and ground, since the electron plasma frequency [2] reaches beyond several GHz, thereby constituting a screen to radio links to Earth. 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 (ARD) has allowed the experimental characterization of the communication channel between the capsule and one of the NASA Tracking and Data Relay Satellite (TDRS); other experimental campaigns on this "blackout" phase might be flown on the EXPERT [3] mission of ESA.

According to experimental measures, only limited signal attenuation was experienced over the Telemetry Tracking and Control channel at S-band. Pre-flight studies based on simplified models, had instead led to the expectation that the attenuation induced by the plasma effects would exceed 100 dB.

This paper describes a significantly more refined model of the radio-wave propagation in the presence of the plasma blocking, which predicts attenuations comparable to the measured ones. Such a model can be used for a realistic estimate of the link budget both at re-entry into the Earth's atmosphere, or when entering other planet's atmosphere, like in the case of the Mars Exploration Rover (MER) [1].

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 (e.g. as in [4]).

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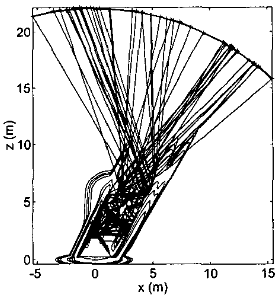

Figure 1: Example of ray tracing at height of 61.5 km. Contour lines show plasma frequency. Only a few rays are shown for ease of visualization.

Altitude	85.0 km	61.5 km	46.0 km
Link direction	37.54°	28.10°	22.44°
Computed gain	-11.0 dB	-11.6 dB	-0.8 dB
Computed attenuation	14.0 dB	14.6 dB	3.8 dB
Measured attenuation	12 dB	21 dB	4 dB

Table 1: Comparison between measured and computed plasma attenuation.

The Ray-Aperture Radiation Approach

The complex global problem is modelled by separating the region where plasma is present, and it has varying parameters, from the region where no plasma is present. Geometrical optics (GO) is used to follow field propagation from the antenna in the inhomogeneous region, and until wavefronts have emerged from plasma. Knowledge of the field just outside the plasma region is used, via the equivalence theorem [5] to find equivalent sources whose radiation produces 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 order to understand the relevant wave phenomena that take place here, and assess the 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 represent within an acceptable approximation the available plasma parameter distributions.

The TDRS System link frequency is $f = 2.267$ GHz, close to the electron plasma frequency (f_p) values found for this plasma; in this frequency regime the plasma model is the electron plasma oscillation model [2, 6]. The typical values of the collision frequency present here ($\nu \ll f_p$), 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 [7, 8]. 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 as well as phase shifts at reflections on the spacecraft metal body, or when the ray hits a cut-off layer (where $f = f_p$).

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 was 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 [9] has been employed for the fast phase variation, and the employed approach to AI radiation is very similar to that in [10]. Absorption due to collisions has been investigated but revealed a weak effect on plasma attenuation, so it is not considered further in this model.

Results and discussion

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).

Measured data and plasma calculations were available for ARD heights of 85, 61.5 and 46 km. Figure 1 shows the case of 61.5 km, where 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 Figure 2; where the TDRSS link direction in the 61.5 km case, is marked with a bold vertical line. The radiation pattern has been "low pass" filtered through a sliding window averaging, since the fast variation of the pattern ("fading") is very dependent of the specific geometry of the plasma, that need to be interpreted in an average manner.

In Figure 3 the effect of the considered number of rays on the radiation pattern is assessed (only the filtered fields are shown for ease of representation), showing a

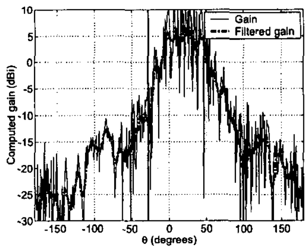

Figure 2: Example of radiation pattern at height of 61.5 km. The TDRSS link direction is marked with a bold vertical segment.

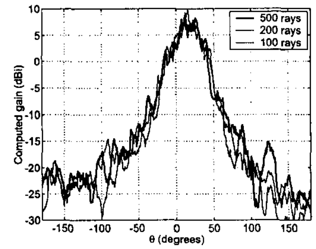

Figure 3: Radiation pattern as a function of the number of shot rays, at height of 61.5 km.

convergence with respect to this accuracy parameter.
The overall results are summarized in Table 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 3 dB: the agreement shown in Table 1 can be considered very good.
An important result obtained by these simulations is the explanation of the comparatively low values of link attenuation. 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 15-30 dB, and this can be attributed to diffraction from the plasma rim (accounted for here in the Kirchhoff-Fraunhofer approximation).

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