Planetary and Space Science 111 (2015) 55–61

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

CONSERT line-of-sight link budget simulator

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ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form
24 February 2015
Accepted 12 March 2015
Available online 20 March 2015

Keywords:
CONSERT
67P/Churyumov–Gerasimenko
Rosetta
Philae
Polarization loss
Link budget calculation

ABSTRACT

In bistatic radar systems utilizing elliptical polarization on both the sending and receiving side, great care must be taken to correctly calculate the received power, as a mismatch in polarization may incur significant additional losses. In this paper, we present a method to simulate the link budget of the CONSERT instrument aboard the Rosetta mission, including polarization effects. The correctness of the simulation method is demonstrated by comparing with a state-of-the-art Method of Moments solver.

The CONSERT instrument's components aboard the Philae lander and the Rosetta orbiter need to be synchronized before the actual sounding. This synchronization can only be performed in line-of-sight conditions. In order to maximize sounding time for the propagation through 67P's core, the synchronization should happen as close to the approximate point of occultation as possible. A statistical analysis is presented to determine the probability of sufficient received power for the synchronization regarding uncertainties in the orbiter's pointing accuracy.

1. Introduction

The main scientific objective of the Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT) (Kofman et al., 2007) is to measure the dielectric properties of comet 67P/Churyumov–Gerasimenko's nucleus by performing a sounding of the comet's core between the lander Philae, launched onto the comet's surface, and the orbiter Rosetta. The lander will receive and process the radio signal emitted by the CONSERT instrument aboard the orbiter and retransmit a signal to the orbiter. With the obtained data, a three-dimensional model of the material distribution with regard to the complex dielectric permittivity of the comet's nucleus is to be reconstructed (Plettemeier et al., 2007).

CONSERT measures the absolute time delay between the transmission and the reception of the measurement signal. In order to collect meaningful data, the drift between the CONSERT clocks aboard Rosetta and Philae needs to be minimized. Therefore, before an actual sounding, the CONSERT clock aboard Rosetta is synchronized to Philae's CONSERT clock. The procedure is described in detail in Barbin et al. (1999). The synchronization should be performed as close as possible to the point of occultation in order to maximize the time for the main operation mode, the sounding of 67P's core. This latest synchronization point can be found from the direct propagation path between lander and orbiter, using the free space antenna pattern of the orbiter and the pattern of the lander above an infinite dielectric half-space, with the material properties assumed to be those of 67P.

The main effects impacting the received signal power in this configuration are the distance between orbiter and lander, the permittivity-dependent coupling of the Philae lander and its underground and the position and attitude dependent polarization losses of the elliptically polarized lander and orbiter antenna systems.

2. Link budget calculation

A link budget is usually defined as the ratio of the transmitted vs. the received power (Friis, 1946). In our case, we are interested in the absolute received power P_r, using the following model (in log scale):

$$P_r \text{ [dB W]} = P_{rad} + G_r - L_i^{\{r,t\}} - L_p, \tag{1}$$

with P_{rad} being the transmitters' radiated power at the location of the receiver, G_r the receiver's antenna gain, and the loss terms

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http://dx.doi.org/10.1016/j.pss.2015.03.011
0032-0633/

insertion loss(es) for receiver and transmitter $L_i^{\{r,t\}}$ and polarization loss L_p.

As the base of the following considerations, the far field radiation patterns of both sender and receiver have to be known. These usually calculated with commercial tools. They are represented by the spherical complex electric field vector $\vec{E}^{far}$ in a reference distance of 1 m, therefore the unit is 1 m V m^{-1} = V. The patterns are calculated with an angular step increment of $\Delta\vartheta = \Delta\varphi = 1°$, therefore, interim values have to be interpolated. Return losses due to impedance mismatch of the antenna system can be included in the radiation pattern, depending on the simulation setup.

The calculation of the radiated power is laid out in the following subsection, followed by the calculation of the gain at the receiver and finally the calculation of the polarization loss.

2.1. Radiated power

Using the fields E_ϑ^{far} and E_φ^{far} provided by the far field radiation patterns, the distance r between transmitter and receiver and their relative orientation towards each other, we can obtain the complex fields E_ϑ and E_φ at the location of the receiver:

$$E_\chi(\vartheta, \varphi, r) = \frac{e^{-jkr}}{r} \cdot E_\chi^{far}(\vartheta, \varphi), \quad \chi \in \{\vartheta, \varphi\}. \tag{2}$$

Then, the power density S at the receiver can be determined:

$$S = S_\vartheta + S_\varphi = \frac{|E_\vartheta(\vartheta, \varphi, r)|^2 + |E_\varphi(\vartheta, \varphi, r)|^2}{2Z_0}, \tag{3}$$

where Z_0 is the characteristic impedance of free space. The transmitters' antenna gain is included in the far field patterns, therefore, P_{rad} is calculated as follows:

$$P_{rad} = \frac{\lambda^2}{4\pi} \cdot S. \tag{4}$$

2.2. Receiver antenna gain

On the receiver's side, given the far field radiation pattern in the direction towards the transmitter $\hat{E}_\vartheta$ and $\hat{E}_\varphi$ and the fed power P_f, the receiver's total gain G_r can be determined as follows:

$$G_r = G_\vartheta + G_\varphi = \frac{2\pi}{Z_0} \frac{|\hat{E}_\vartheta(\vartheta, \varphi)|^2 + |\hat{E}_\varphi(\vartheta, \varphi)|^2}{P_f}. \tag{5}$$

2.3. Polarization loss

The polarization loss has to be considered if the transmitting and receiving antenna systems are not perfectly matched in polarization. For a complex antenna system radiating elliptically polarized waves, the calculation is quite complex, as this is the most general case. In order to carry out the calculations, all parameters of the polarization ellipse shown in Fig. 1 have to be known.

At first, the major and minor axes E_{max} and E_{min} of the polarization ellipse are calculated as follows (Balanis, 1989):

$$E_{max,min} = \frac{1}{\sqrt{2}} \left(|E_\vartheta|^2 + |E_\varphi|^2 \pm \sqrt{|E_\vartheta|^4 + |E_\varphi|^4 + 2|E_\vartheta|^2 |E_\varphi|^2 \cos(2\delta)} \right)^{1/2}, \tag{6}$$

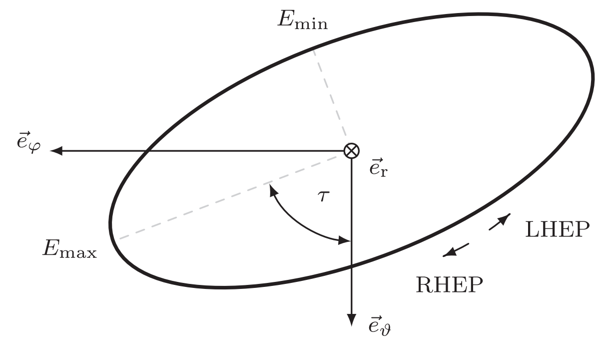

Fig. 1. Polarization ellipse.

with $\delta = \alpha - \beta$, $\alpha = \text{angle}(E_\vartheta)$, and $\beta = \text{angle}(E_\varphi)$. A plus sign before the square root yields the major axis E_{max}, a minus sign yields the minor axis E_{min}.

With the axes determined, the axial ratio ν is computed as follows:

$$\nu = \frac{E_{max}}{E_{min}}. \tag{7}$$

With this definition, $1 \le \nu \le \infty$, with $\nu = 1$ denoting perfect circular polarization and linear polarization as $\nu \to \infty$. All values in between denote elliptic polarization. In practice, $\nu \le 2$ is considered good circular polarization.

The sign of the axial ratio yields the direction of rotation of the polarization ellipse. If $0 < \delta < \pi$, the rotation is defined as right-handed, therefore, right hand elliptic (RHE) polarization exists, and the axial ratio is *negative*. If $\pi < \delta < 2\pi$, left hand elliptic (LHE) polarization exists and the axial ratio is *positive*.

The final parameter of the polarization ellipse (see Fig. 1) is the tilt angle, τ, defined as

$$\tau = \frac{\pi}{2} - \frac{1}{2} \arctan\left[\frac{2|E_\vartheta||E_\varphi|}{|E_\vartheta|^2 - |E_\varphi|^2} \cos(\delta) \right]. \tag{8}$$

It is the angle between the major axis and the spherical unit vector $\vec{e}_\vartheta$.

Now, the circular polarization ratios of the incident field ρ_t and of the receiving antenna ρ_r have to be calculated:

$$\rho_f = \frac{\nu_f + 1}{\nu_f - 1}, \quad f \in \{r, t\}. \tag{9}$$

With Eqs. (7)–(9), the polarization loss can now be determined as (Schrank, 1983)

$$L_p = \frac{1 + \rho_t^2 \rho_r^2 + 2\rho_t \rho_r \cdot \cos(2(\tau_t - \tau_r))}{\left(1 + \rho_t^2\right)\left(1 + \rho_r^2\right)}. \tag{10}$$

The model described above was implemented in a "Line-of-Sight Link Budget Simulator" (LBS) software tool, and applied to the CONSERT instrument setup aboard the ESA Rosetta mission.

3. CONSERT antenna system configuration

The CONSERT instrument consists of an antenna system and an electronics box both aboard the Rosetta orbiter and the Philae lander (Kofman et al., 2007; Nielsen et al., 2001). Their modeling and simulation were performed with a software tool employing the Method of Moments (MoM). The radiation patterns include ohmic losses and losses due to antenna mismatch. They were simulated for CONSERT's center frequency f_c = 90 MHz, which is also the carrier frequency in synchronization mode. Attitude