Modeling and optimization of loaded electrical antennas dedicated to deep Martian subsurface sounding by a bistatic HF GPR operating from the surface

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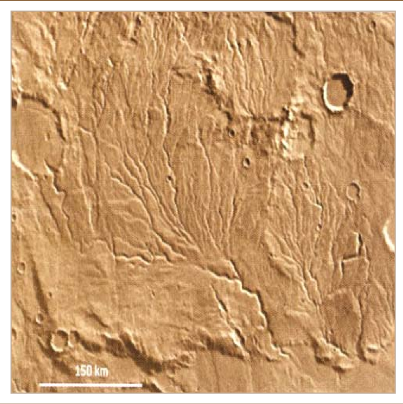
■ Despite several past and present missions to Mars, very little information is available on its subsurface outside of its polar caps and its very superficial layer. One of the scientific objectives of the ESA's ExoMars mission is to characterize the water/geochemical environment as a function of depth and investigate the planet subsurface to better understand the evolution and habitability of the planet. The electromagnetic survey of subsurface will provide a nondestructive way to probe the subsurface and look for potential deep liquid water reservoirs.

■ In the frame of this spatial mission, the LATMOS is currently developing a ground penetrating radar (GPR) called EISS "Electromagnetic Investigation of the Sub Surface", which is a enhanced version of Netlander's GPR (mission cancelled in 2004). The GPR main objective is to perform sounding of the Martian sub-surface down to kilometric depth from the surface. Because the current conditions of pressure (~6.1mbar) and temperature (Tmoy = -63°C) on Mars prohibit the presence of liquid water on its surface. However, the presence of paleo-hydrological structures suggests that water flowed on Mars as following photography of old river valleys. (Viking, Mars Orbiter, ...).

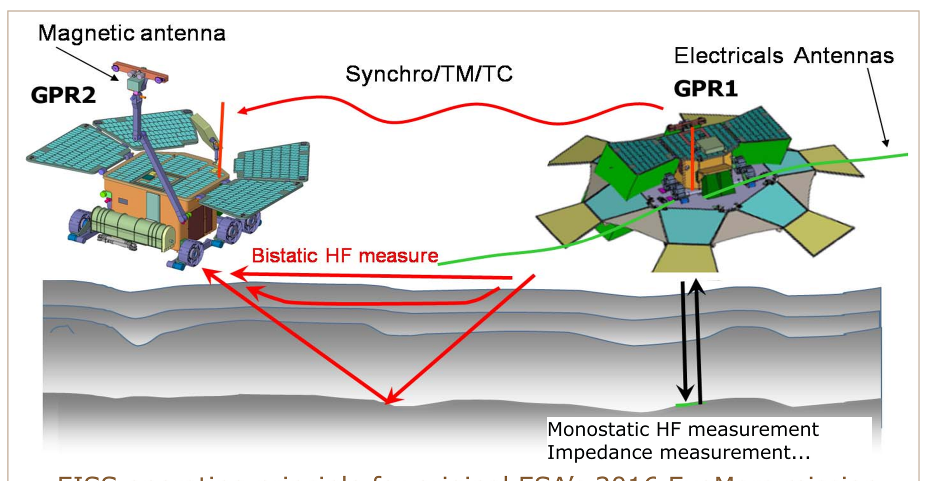


EISS: Impulse HF Ground Penetrating Radar

■ EISS "Electromagnetic Investigation of the Sub Surface" is an impulse radar operating at HF frequencies (~ 2-4MHz). EISS can operate in four modes, including: surface impedance, subsurface monostatic and bistatic, and passive (i.e., atmospheric monitoring) mode. EISS makes use of an electrical dipole antenna made of two 35 m resistively loaded monopoles, to transmit (and also receive in mono-static mode) the signal. The resistive profile of each monopole is carefully optimized to transmit the pulse without noticeable distortion and avoid ringing. The two monopoles are deployed on the surface in nearly opposite directions, at an angle which, when EISS is used in bistatic mode, ensures good volume coverage around the Lander. The bistatic mode made possible by the placement of a small magnetic sensor on the Rover which can be rotated to measure all 3 components of the wave.

■ EISS is designed to take advantage of the potential for bistatic radar investigations of the Martian subsurface between the fixed station (Lander) and the mobile rover. Using this approach, EISS can be used to characterize the 3-D structure and stratigraphy of the subsurface at depths ranging from 100 m to a few kilometers out to a 1-km radius around the Lander.

Antennas: ■ 2 resistively loaded HF monopoles electrical antennas » E_x ■ 1 small magnetic sensor located on the rover » H_x - H_y - H_z



EISS operating principle for original ESA's 2016 ExoMars mission and glimpse of different kinds of received waves

Coupling between the subsurface and the HF monopoles

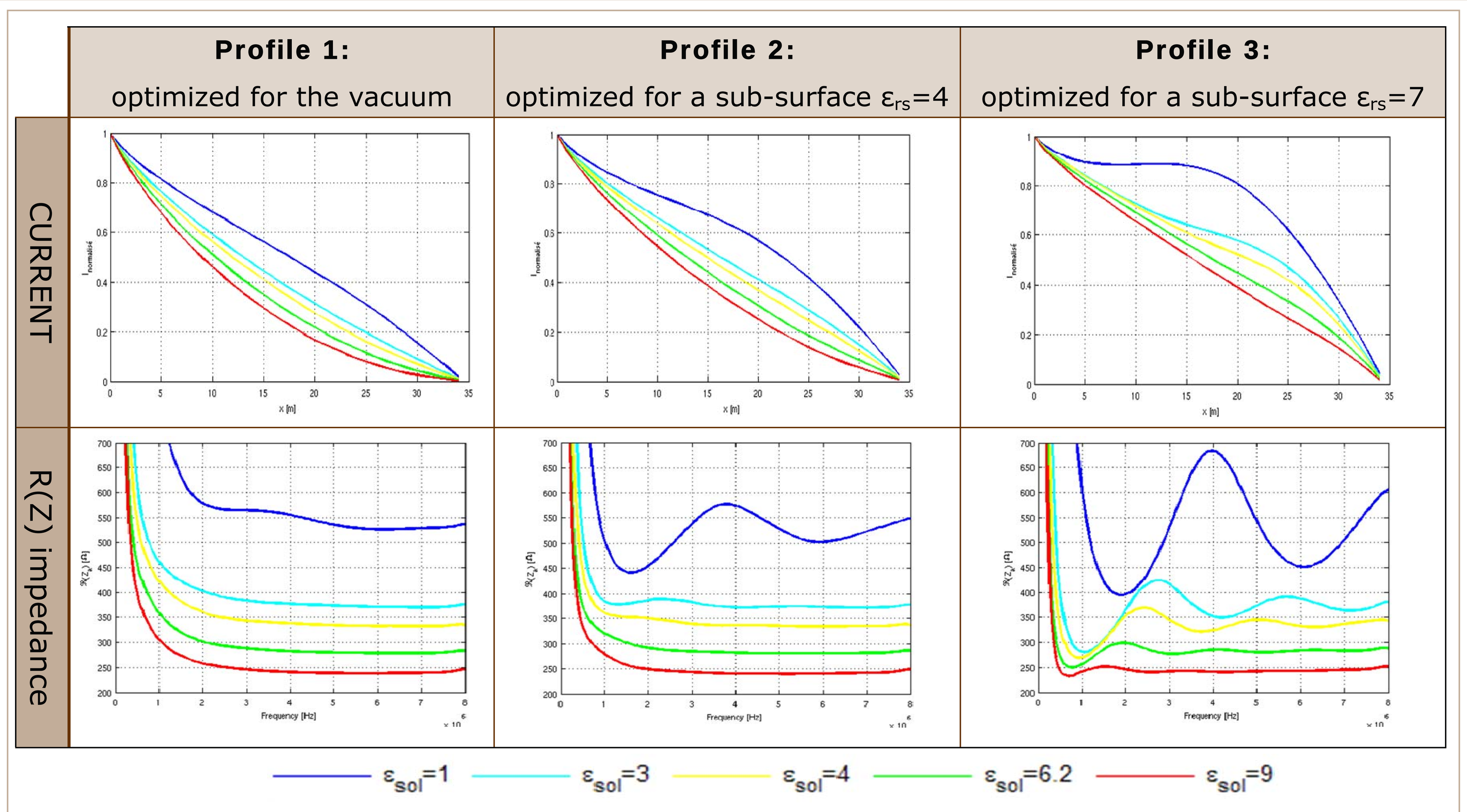
■ To keep the mass and volume of the antenna within reasonable limits, loaded dipole, composed of two identical monopoles is used. The resistive profile of the antenna follows a Wu-King profile which is optimized to transmit the pulse without noticeable distortion and avoid ringing phenomenon. The downside of the design is the low efficiency of such an antenna (only a few percents) because of the power that is dissipated into the resistors. The resistive profile of each monopole must be chosen in order:

- to ensure that the current intensity at the end of the monopole is null over the whole bandwidth: it guarantees a progressive wave traveling without distortion along the antenna with no reflection at the end.
- to obtain an antenna impedance as flat as possible over the whole frequency bandwidth: each monopole impedance needs to be matched to the electronics impedance to optimize the signal transmission and optimize thus instrument efficiency.

■ The following results will focus on the performances of the antenna (decrease of the current along the antenna and measured impedance) obtained when the antenna is deployed on the surface thus the interface between the two media: vaccum and homogeneous sub-surfaces with different relative permittivity values. The antenna behaves as if it were surrounded by a medium having the following electrical properties equal to the arithmetic average.

■ The exact characteristics of the Martian subsurface at the landing site are not a priori known values but a relative permittivity value ε_{rs} around 4 seems a realistic one. To obtain the best performances, the resistive profile should be optimized according to the geolectrical properties of the sub-surface ε_{rs}(relative permittivity) et σ_s (conductivity). Three different resistive profiles have be considered:

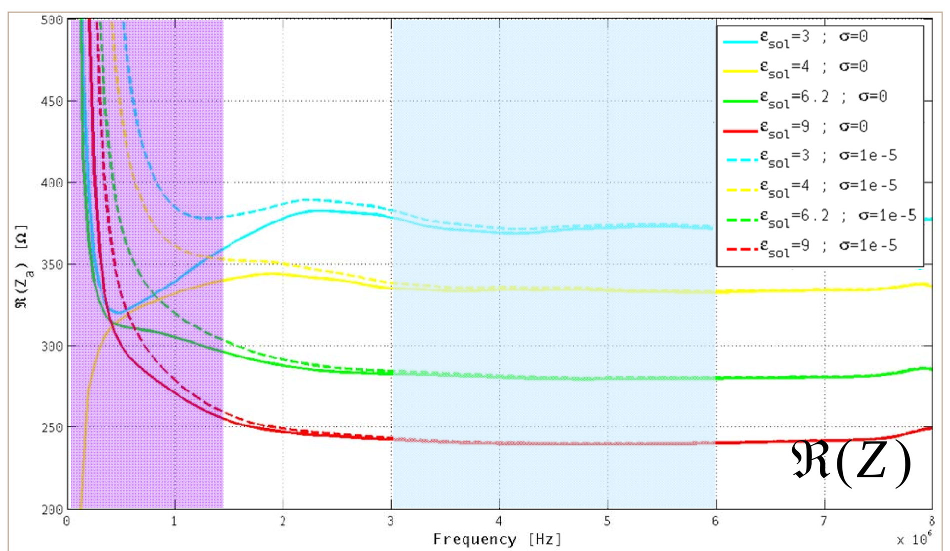
- profile 1: optimized for the vacuum
- profile 2: optimized for a sub-surface with a relative permittivity of ε_{rs}=4
- profile 3: optimized for a sub-surface with a relative permittivity of ε_{rs}=7



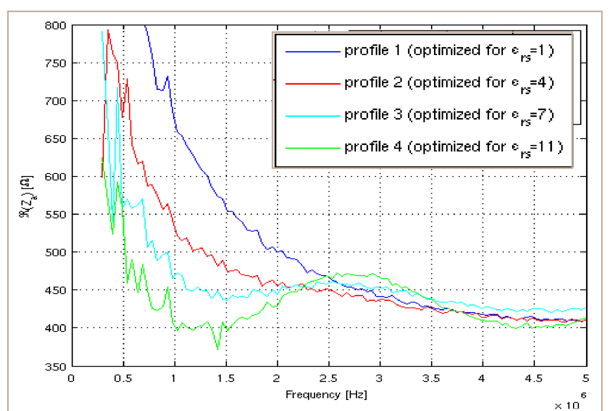
Normalized current along the antenna I(x)/I(0) and antenna impedance over the whole frequency bandwidth, when deployed on a non conductive layer having a relative permittivity ε_{rs}, σ=0, μ_0 for the 3 studied profiles (FDTD simulations)

Decrease of the current along the antenna:

If the antenna is deployed on a layer having a higher permittivity than the one expected, then the decrease will be much faster (leading to a not optimal use of the antenna length). If the antenna is deployed on a surface having a lower permittivity than the one expected, then the decrease will be too slow; potentially leading to reflection of the signal at the antenna's extremity and eventually to distortion of the pulse. The choice was be restricted to profile 2 and 3.



The variation of real part of impedance depending on permittivity and conductivity of the top layer. The variation of conductivity only influences the values of impedance measured at very low frequencies (<2MHz) unlike the permittivity.



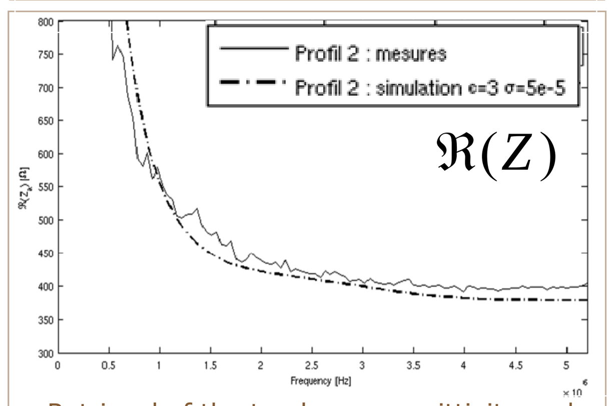
Measurements of the antenna impedance on the sand of the forest of Fontainebleau (FR)

Antenna impedance over the whole frequency bandwidth:

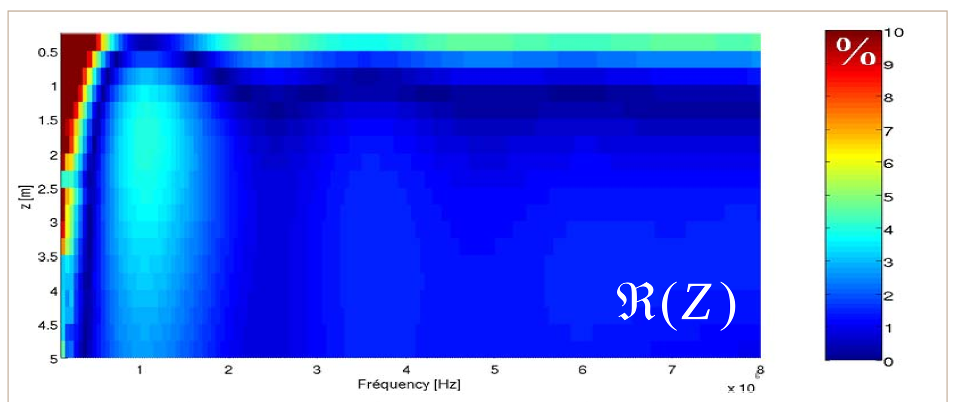
Simulations run for different permittivity values on the sub-surface characteristics show that there is a coupling between the antenna and the sub-surface top layer and that it has have an impact on the antenna effective impedance. The sub-surface impedance is a decreasing function of its own permittivity er. Simulations show that the real parts of the measured impedance is not constant over the whole frequency range and that the obtained variations with frequency depend on the pair sub-surface permittivity value – resistive profile. The best matching can be obtained for an impedance as flat as possible over the whole band width: profile 2.

Retrieval of the top layer permittivity value (blue area in right plots):

Simulations have been performed for each selected antenna resistive profile for a variety of realistic permittivity and conductivity values and will be compared to the measured. This method makes possible the retrieval of the top layer permittivity value and in a less accurate way of the top layer conductivity value. This method was tested and validated during fields tests in Egypt and in Antarctic (LEGALL 2007) and on the sand of the forest of Fontainebleau (France). The subsurface survey requires knowledge of the permittivity of the studied sub-surface layers to convert the measured propagation delay into distance. Access to electrical characteristics of ground without samples return and in situ analysis is unusual in space missions and aroused great interest.



Retrieval of the top layer permittivity and conductivity value



The inverted parameters of permittivity and conductivity correspond to the electrical properties of the first meters deep of subsurface.

Retrieval of the top layer conductivity value (purple area in right plot):

The estimation of the top layer conductivity from impedance measurements remains difficult, but possible with the study of the values measured at very low frequencies (<2MHz).

Impact of the angle between the two monopoles of the HF antenna (bistatic mode)

■ As it was the case for Humbold payload of th e ExoMars mission, the exact value of the angle between the two monopoles might not be 180° but would rather be chosen to minimize the contact between the antennas and the lander and solar panels structure, keeping the radiation pattern as omni directional as possible. This is essential given the fact that, in bi-static configuration, the rover egress direction might only be chosen once on Mars. Electromagnetic simulations have been performed to optimize the value of this angle based on its impact on the radiation pattern of the two monopoles and the best position is θ_{ant}=225°.

■ Each map shows the amplitude of the three magnetic field components of the reflected wave for a distance Lander-Rover ranging from 100 to 500m.

■ With aligned monopoles θ_{ant}=180°, the map clearly brings to light the fact that in some directions (aligned with and perpendicular to the antenna direction) one or two of the components are null, while the other angle value (θ_{ant}=225°) does not create such features. Configurations with non aligned monopoles do offer the best coverage of the whole area.

Modeling approach based on the point current sources :

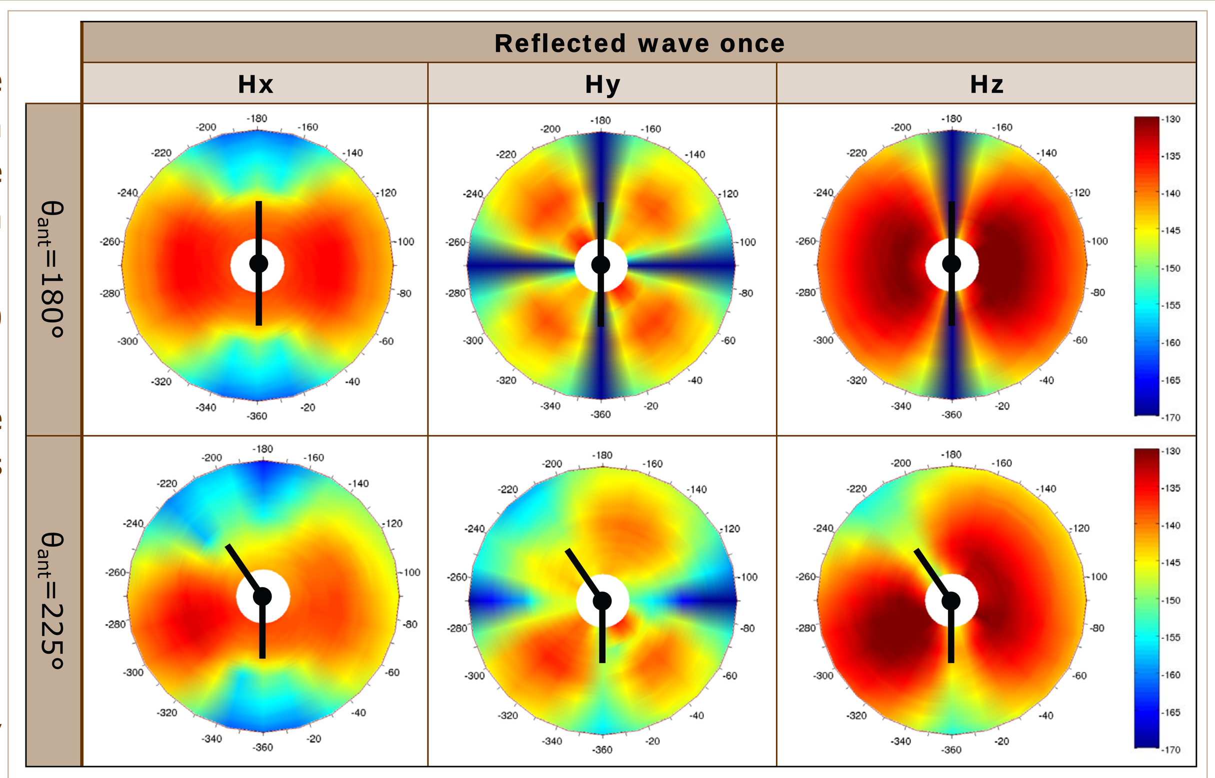
■ FDTD code with orthogonal mesh = unaligned antennas impossible (under study at XLIM)

■ Using point current sources and a space step adapted to the angle between the two monopoles

■ Each current source is associated to a time function describing the shape of the excitation. Its amplitude is calculated analytically considering the decrease of the current along the antenna according to the near sub-surface and the resistive profile.

► Each monopole is considered as the sum of elementary dipoles with varying intensity of currents (Huygens' Principle).

This modeling approach has been validated by simulation of an aligned dipole and orthogonal monopoles : error of 0-2% on the magnetic fields.



Amplitude map of the three magnetic field components of the reflected wave, for a distance Lander-Rover ranging from 100 to 500m. The configuration with two monopoles perfectly aligned =180° is also shown for a reference.

■ The HF antennas resistive profile must be chosen to optimize the transmission of a non distorted signal into the sub-surface. Given the range of expected permittivity values on the landing site, we are able to select a profile than will ensure good performances of the instrument. Taking advantage of the coupling between the subsurface and the HF monopoles deployed on it, EISS is able to provide an estimate of the permittivity and the conductivity of the subsurface which will help characterizing the top layer and at the same time will allows to translate the measured propagation delays in distance. The measurement of the three components of the magnetic field at the receiver location provides information on the reflecting structures 3D location, enable to discard the echoes due to subsurface clutter and eventually allows to provide a mapping of the deep subsurface stratigraphy along the rover path (in study). Experimental validation is planned to validate on experimental data acquired on well documented areas the theoretical results.

■ Nevertheless EISS can also take advantage of the existence of a single stationary platform and perform monostatic soundings of the terrestrial subsurface, estimate the near subsurface properties. After the last redesign of the original ESA's 2016 ExoMars mission, the whole lander payload was removed; EISS (in its monostatic version) will be also proposed for the ESA EDL (Entry, Descent and Landing) demonstrator (2016).