3D characterization of the surface by a bistatic HF GPR operating from the surface

Optimization of electrical antennas

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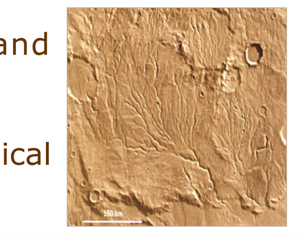
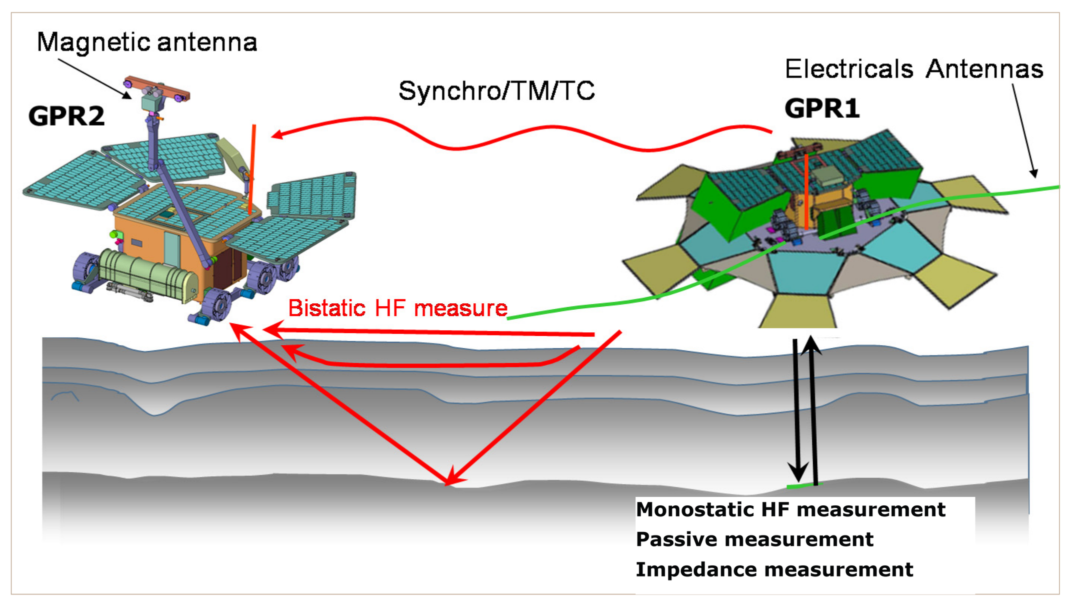
■ Despite several past and present missions to Mars, very little information is available on its subsurface outside of its polar caps and its very superficial layer. One of the scientific objectives of the ESA's ExoMars mission is to characterize the water/geochemical environment as a function of depth 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

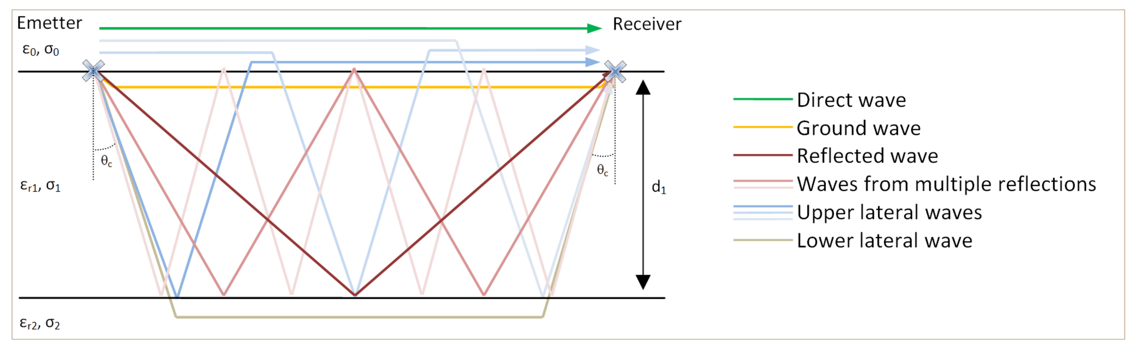
■ EISS "Electromagnetic Investigation of the Sub Surface" is an impulse radar operating at HF frequencies (~ 2-4MHz). EISS can operate in four modes, including: surface impedance, subsurface monostatic and bistatic, and passive (i.e., atmospheric monitoring) mode. EISS makes use of an electrical dipole 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
■ 2 synchronization VHF antennas for bi-static mode.



Identification of received echoes (bi-static mode)

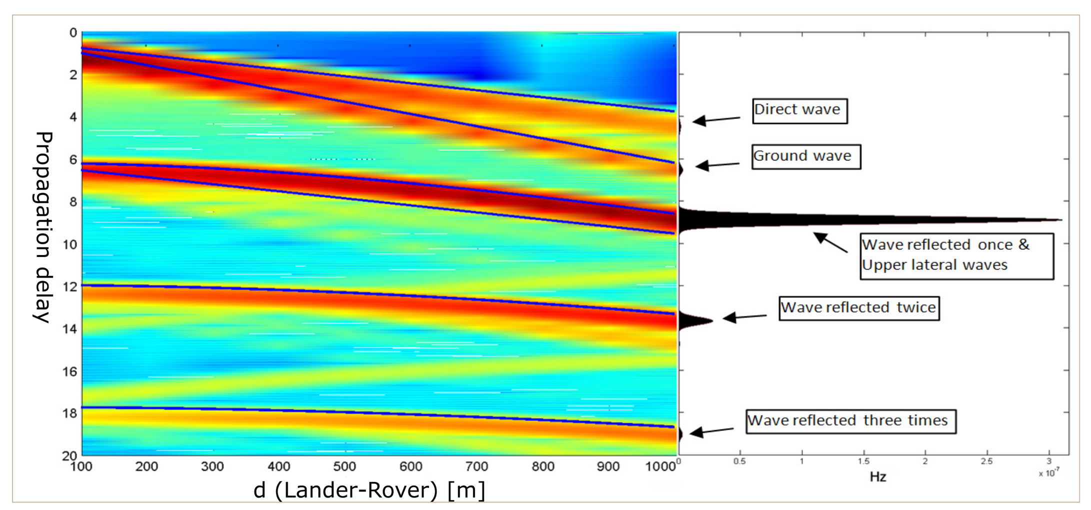
The figure below shows the different kinds of waves the receiver can potentially receive:



The propagation delay for the main waves is given by:
- Direct wave travelling in the air: τ_d
- Ground wave travelling in the layer: τ_g
- Waves reflected n times: τ_{rn}

$$\tau_d = \frac{d}{c} \qquad \tau_g = \frac{d\sqrt{\varepsilon_r}}{c} \qquad \tau_{rn} = \frac{\sqrt{d^2+(2nh)^2}\sqrt{\varepsilon_r}}{c}$$

■ Radargram showing the envelope of the received signal for the H_z component as a function of the distance between the transmitter and the receiver. The homogeneous layer is 500m thick and has a relative permittivity of $\varepsilon_{r1}=3$. At the bottom of this layer, a perfectly reflecting horizontal layer is placed. The direction between the transmitter and receiver makes an angle of 45° with respect to the direction of the transmitting electrical antenna.



Coupling between the sub-surface and the HF monopoles

Paper under submission for GJR

■ 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:

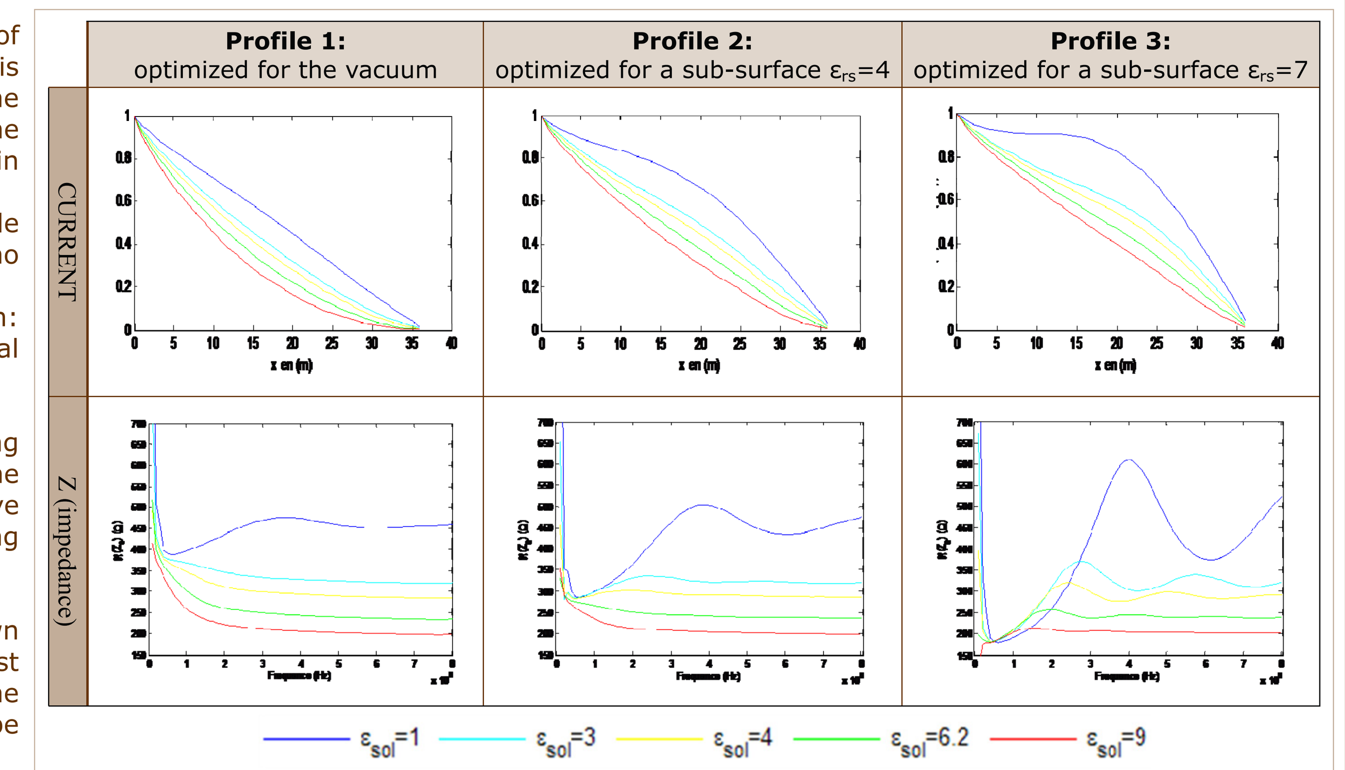
□ to ensure that the current intensity at the end of the monopole is null over the whole bandwidth: it guarantees a progressive wave traveling without distortion along the antenna with no reflection at the end.

□ 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.

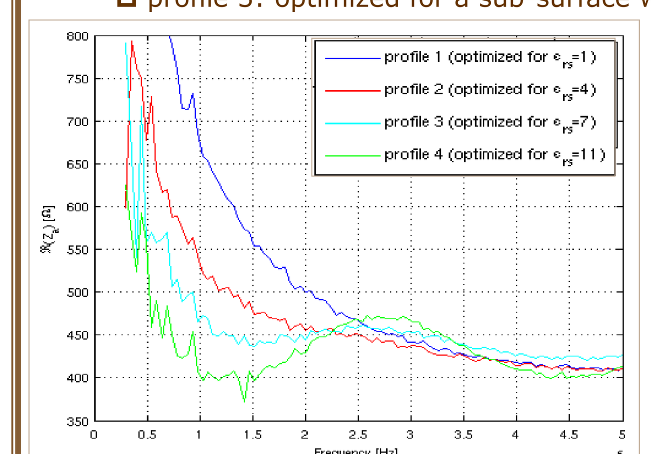
■ The following results will focus on the performances of the antenna (decrease of the current along the antenna and measured impedance) obtained when the antenna is deployed on the surface thus the interface between the two media: vaccum and homogeneous sub-surfaces with different relative permittivity 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:

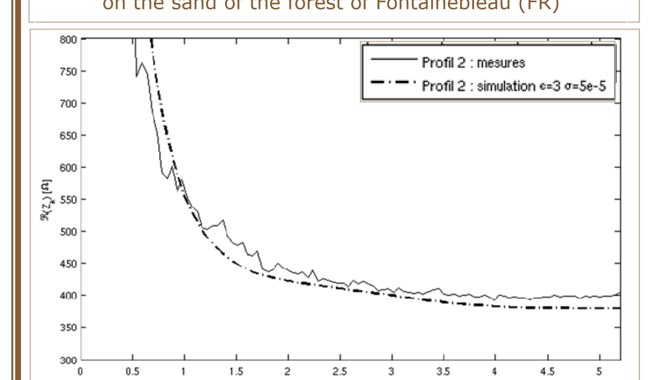
□ profile 1: optimized for the vacuum
□ profile 2: optimized for a sub-surface with a relative permittivity of $\varepsilon_{rs}=4$
□ profile 3: optimized for a sub-surface with a relative permittivity of $\varepsilon_{rs}=7$



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}, $\sigma=0$, μ_0 for the 3 studied profiles (FDTD simulations)



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



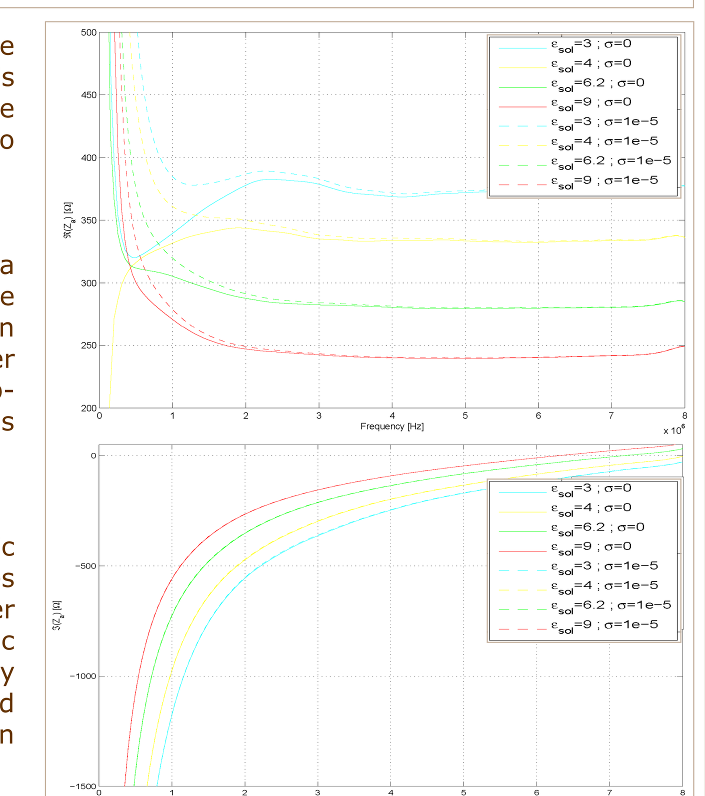
Retrieval of the top layer permittivity and conductivity value

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.

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:
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 conductivity value:
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).

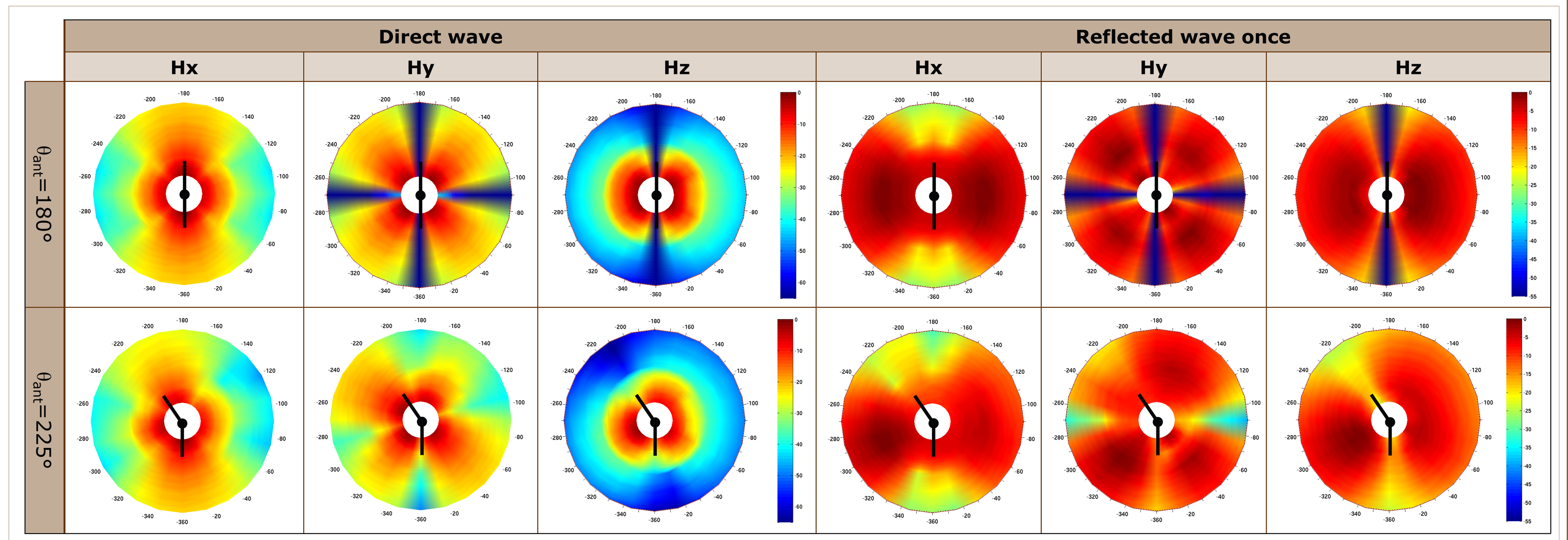


The variation of impedance Z depending on permittivity and conductivity of the top layer. The variation of conductivity only influences the values of impedance measured at very low frequencies (<2MHz) unlike the variation of permittivity.

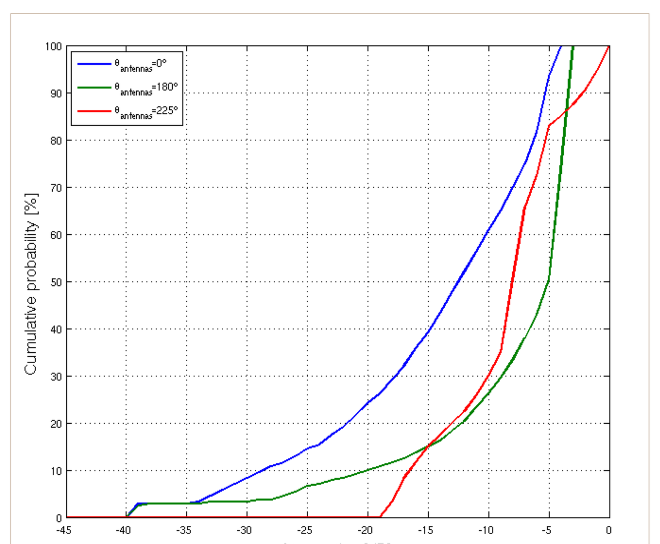
Impact of the angle between the two monopoles of the HF antenna (bistatic mode)

Paper under submission for IEEE

■ 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 $\theta_{ant}=225°$.



Amplitude map of the three magnetic field components of the direct wave and 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 probability to encounter an attenuation compared to the best situation larger than the abscissa value, for reflected wave once.

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

■ With aligned monopoles $\theta_{ant}=180°$, 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 ($\theta_{ant}=225°$) does not create such features. Configurations with non aligned monopoles do offer the best coverage of the whole area.

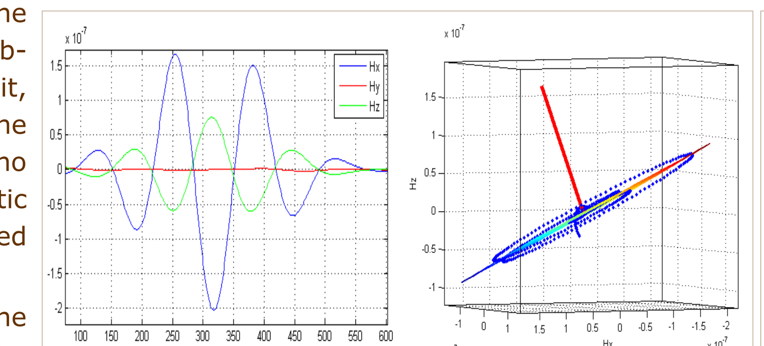
■ The following figure summarizes the situation. It shows, for each of the studied configurations, the probability to encounter an attenuation compared to the best situation larger than the abscissa value. For example: with one monopole only, for more than 50% of the rover azimuth angles, the attenuation (compared to the best situation) is larger than 12.5 dB, while it approximately goes down to 5-8 dB for the configurations with two monopoles.

3D location of the reflecting points (bi-static mode)

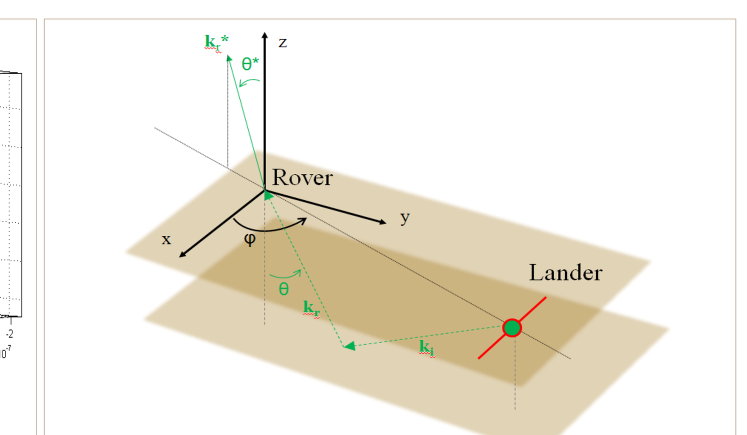
$$\vec{k_r^*} = \begin{pmatrix} \sin\theta.\cos\varphi \\ \sin\theta.\sin\varphi \\ \cos\theta \end{pmatrix} \qquad \left|\theta_{n\_théorik}\right| = \left|\sin^{-1}\left(\frac{d}{\sqrt{(d)^2+(2.n.h)^2}}\right)\right| < \theta_c = \sin^{-1}\left(\frac{1}{\sqrt{\varepsilon_{rs1}}}\right) \qquad \theta = \cos^{-1}\left(\frac{k_z}{|k|}\right) \qquad \theta^* = \sin^{-1}\left(\frac{\sin\theta}{\sqrt{\varepsilon_{rs1}}}\right) \qquad \varphi = \tan^{-1}\left(\frac{k_y}{k_x}\right)$$

■ This part is mainly dedicated to the bi-static mode that greatly improves the 3D representation of subsurface structure and on the associated instrumental requirements such as the perfect synchronization of the two parts of the instrument. A method to retrieve the direction of arrival for each detected echo will be presented that allows a more accurate sub-surface mapping. Only the three magnetic field components are required to implement it, which makes the EISS configuration particularly interesting. This method is based on the orthogonality between the propagation vector and the polarization plane for each echo detected at the receiver location. The method has been tested and validated for the bi-static configuration on simulated data for a simple configuration: two homogeneous layers separated by one horizontal interface.

■ The direction of arrival is characterized by two angles: the angle θ* measured in the vertical plane above the surface level and the angle φ. measured in the horizontal plane. The φ value retrieval does not require the permittivity value. But because of the refraction at the surface, the measured angle θ* is different from the angle value θ in the sub-surface. The permittivity of the top layer is essential to be able to retrieve the θ value.



Left, temporal representation of the three components of the magnetic field corresponding to a wave reflected by an interface located at 100 m below the surface level.
Right, Polarisation plane and direction of propagation



Geometry of the problem

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 sub-surface and the HF monopoles deployed on it, EISS is able to provide an estimate of the permittivity of the sub-surface 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.

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