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# 3D characterization of the deep sub-surface by a bistatic HF GPR operating from the surface

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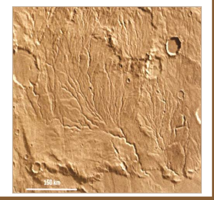
■ Despite several past and present missions to Mars, very little information is available on its subsurface outside of its polar caps and its very superficial layer. One of the scientific objectives of the European ExoMars mission (ESA) is to characterize the water/geochemical environment as a function 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. The LATMOS is currently developing a ground penetrating radar (GPR) called EISS "Electromagnetic Investigation of the Sub Surface", developed in the frame of the ESA's ExoMars mission, initially planned (with 2 stations on Mars).

■ The GPR main objective is to perform sounding of the sub-surface down to kilometric depth. Because the current conditions of pressure (~6.1mbar) and temperature (Tmoy = -63°C) on March 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

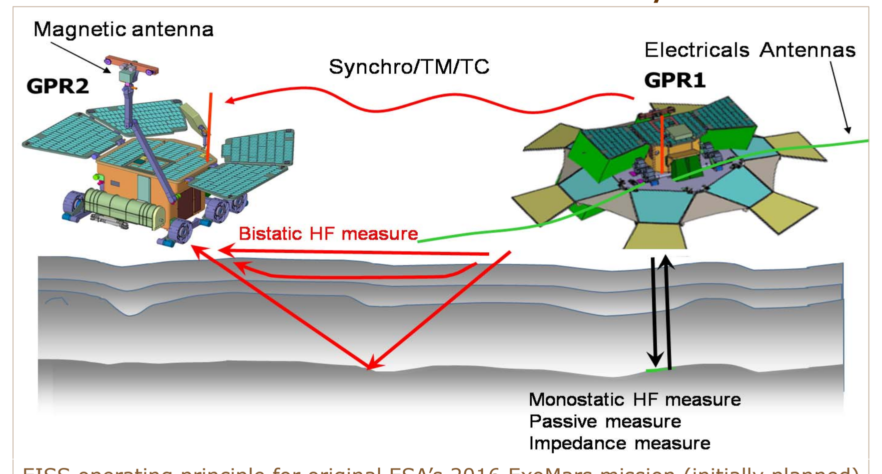
■ EISS "Electromagnetic Investigation of the Sub Surface" is an impulse GPR operating, at HF frequencies (~2-4MHz) in order to perform deep soundings of the subsurface down to kilometric depth, with a wide bandwidth (100kHz-5MHz) for relatively good spatial resolution. The work at HF frequencies, EISS uses a half-wave resistively loaded dipole electrical antenna i.e. two monopoles 35 meters long each to transmit (and also receive in mono-static mode) the signal.

■ EISS can operate in four modes: impedance measurement, mono and bi-static survey, passive mode. The EISS radar is based on the bistatic sounding. The original idea of the EISS experiment is to take benefit of the unique opportunity offered by the simultaneous presence on the surface of Mars of a fixed station and a mobile rover, initially planned for the ESA's ExoMars mission. EISS will allow to perform bi-static soundings of the subsurface: the long loaded dipole antennas will transmit the electromagnetic waves from the fixed station and a much smaller magnetic antenna located on the rover will be used as the receiver. The displacement of the rover over distances of 1 to 2 kilometers allows to perform successive soundings that can be subsequently analyzed to get a 3D description of the subsurface structure along the paths of the rover even if only magnetic measurements is performed at the receiver based on the study of radargramme (cf section '3D imaging').

**Antennas :**

■ 2 resistively loaded HF monopoles electrical antennas » $E_x$

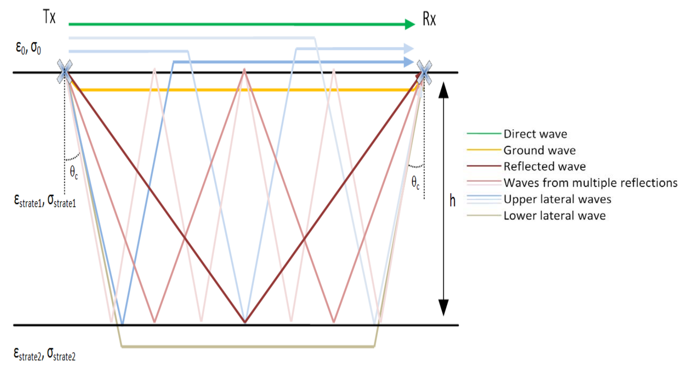
■ 1 swivelingmagnetic antenna located on the rover » $H_x$ - $H_y$ - $H_z$

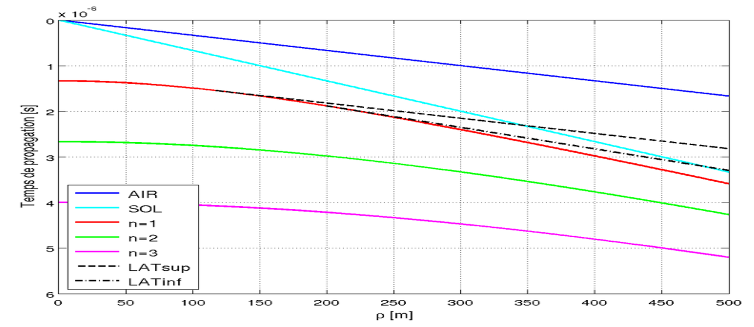


EISS operating principle for original ESA's 2016 ExoMars mission (initially planned) and glimpse of different kinds of received waves

## Identification of received echoes (bistatic mode)

Following figures shows the different kinds of waves the receiver can potentially receive:



Analytical radargram of the horizontal stratification

The propagation delay for the main waves is given by :

- Direct wave travelling in the air : $\tau_d$
- Ground wave travelling in the layer : $\tau_g$
- Waves reflected n times : $\tau_{rn}$

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

■ Radargrams showing the envelope of the received signal for one component as a function of the distance between the transmitter and the receiver. The first radargram is for a horizontal stratification with a thick layer of 500m and a relative permittivity of $\varepsilon_{r1}$=3. The second radargram is for the inclined stratification as shown for the illustration figure. At the bottom of this layer, a perfectly reflecting horizontal layer is place.

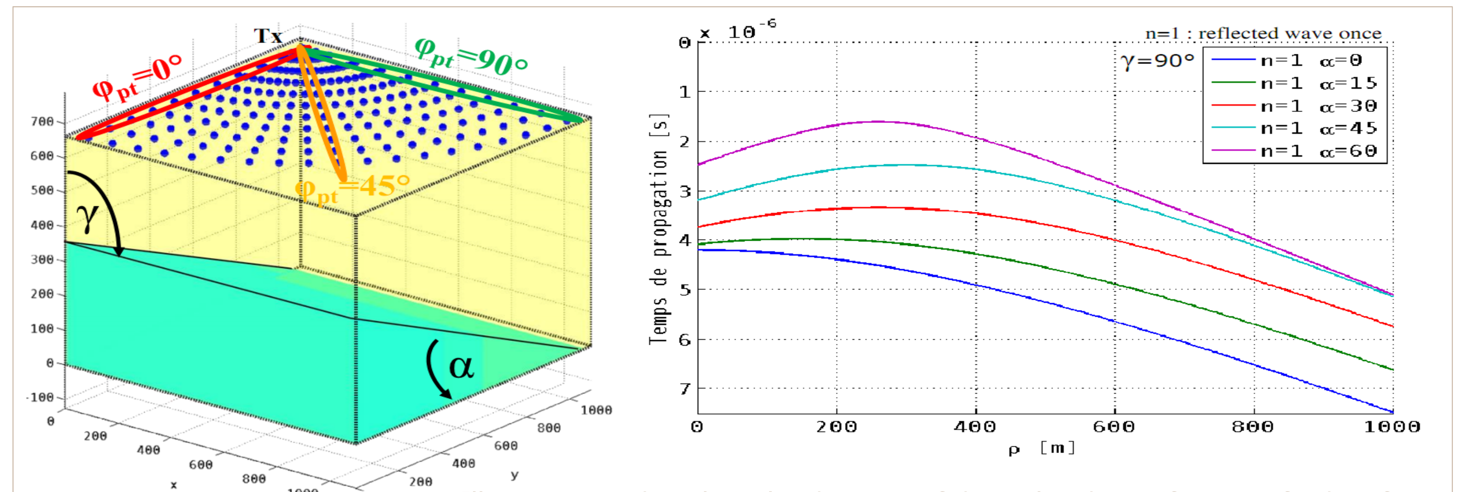


Illustration and analytical radargram of the inclined stratification of subsurface

## 3D imaging of the deep subsurface with study of radargram

■ Synthetic data obtained by FDTD simulations are used to test and validate the interpretation data methods presented in the following. FDTD simulation has been chosen because it allows to take into account the complexity of the various environments : homogeneous subsurfaces with horizontal stratification, non homogeneous layer (inhomogeneous permittivity generated by a fractal model (see the cross section of the medium)), and inclined interface inside the subsurface. For each situation, our aim is to characterize the subsurface structure and get estimate values for the detected structure parameters (depth, permittivity, orientaion,..).

■ In radargram representations, the same wave is received for each position of the moving receiver , in such a way that each wave appears as a curve in the space of propagation time - distance between the transmitter and receiver (see Analytical radargrams on left). The proposed method is based on the comparison of this series of delays with the theoretical delays that would be observed for different subsurface configurations. The direct model used is an analytical one based on ray tracing.

■ The first step of the processing is the manual selection in a series of soundings that form a radargram of the area that could correspond to the same single wave. Then the set of selected delays are compared to analytical delays in order to find the combination of physical parameters that allows the best fit. The adjustment is made with a least squares method weighted by the received level for each point of the area selected in the radargram.

■ In the 3D case, the analytical expression of the propagation delay for the reflected wave once is:

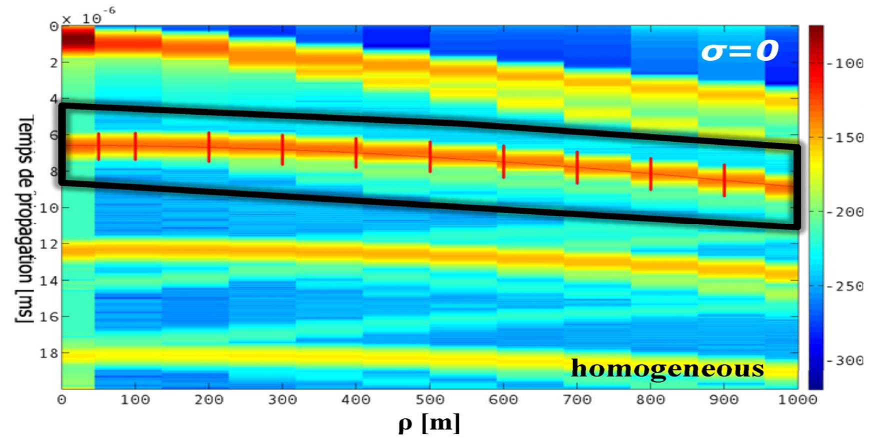
$$tps_{n=1}(\rho) = \sqrt{(-2d_1 \sin\alpha\cos\alpha\sin\gamma - \rho\sin\varphi_{pt})^2 + (-2d_1\sin\alpha\cos\alpha\cos\gamma - \rho\cos\varphi_{pt})^2 + (-2d_1\cos^2\alpha)^2}\,\frac{\sqrt{\varepsilon_{r-sol1}}}{c}$$

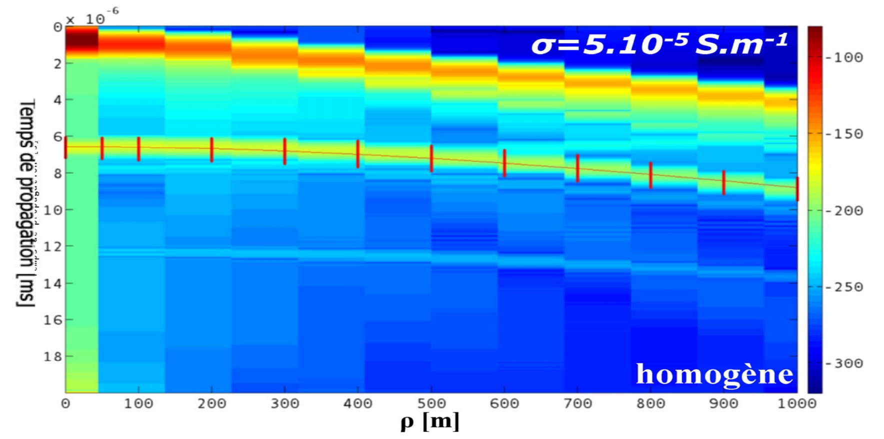
with
- $\varphi_{pt}$ the horizontal angle defining the position of the receiver on the surface,
- $\alpha$ the angle of the inclined layer in the yOz plane relative to the horizontal,
- $\gamma$ the angle of the inclined layer in the x0z plane relative to the vertical.

### HORIZONTAL STRATIFICATION

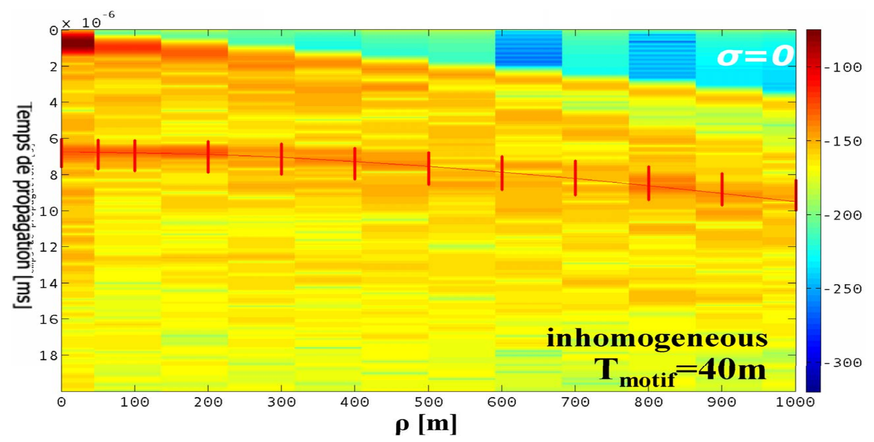
**(horizontal interface inside the subsurface)**

**Homogeneous subsurface**

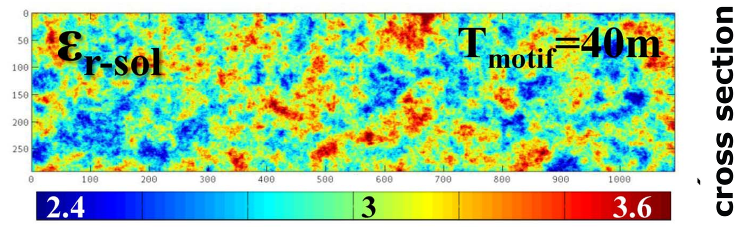



**Non homogeneous subsurface**




**Inhomogeneous permittivity (fractal model)**




**Parameters to find**: $d_1$=500m and $\varepsilon_{r-sol1}$ =3 (or <$\varepsilon_{r-sol1}$>=3 for inhomogeneous subsurface)

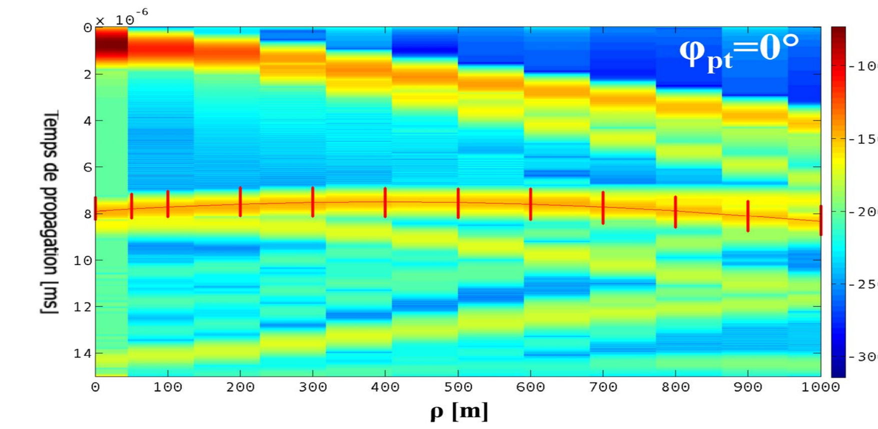
| | homogeneous | Inhomogeneous | | |
|---|---|---|---|---|
| | | T=62m | T=54m | T=40m |
| $d_1$ | 514,81m | 499,72m | 506,57m | 504,69m |
| $\varepsilon_{r-sol1}$ | 2,8 | 3,21 | 3,17 | 3,24 |

**The error on the inverted parameters is very low : 0.25% on $d_1$, 6% on $\varepsilon_{r-sol1}$ on average.**

### INCLINED STRATIFICATION

**(inclined interface inside the subsurface)**

**Homogeneous subsurface**




**Parameters to find**: $d_1$=650m and $\varepsilon_{r-sol1}$ =3, $\alpha$=-20°, $\gamma$=90°

| | $\varphi_{pt}=0°+\varphi_{pt}=90°$ ($\Delta\rho=100m$) | $\varphi_{pt}=45°+\varphi_{pt}=90°$ ($\Delta\rho=100m$) | $\varphi_{pt}=15°+\varphi_{pt}=75°$ ($\Delta\rho=100m$) | $\varphi_{pt}=15°+\varphi_{pt}=75°$ ($\Delta\rho=200m$) |
|---|---|---|---|---|
| $d_{1_{reel}}$ | 650m | 650m | 650m | 650m |
| $d_1$ | 646,34m | 652,13m | 664,35m | 661m |
| $\varepsilon_{r_{sol-reel}}$ | 3 | 3 | 3 | 3 |
| $\varepsilon_{r_{sol1}}$ | 3,09 | 3,02 | 2,92 | 2,94 |
| $\alpha_{reel}$ | -20° | -20° | -20° | -20° |
| $\alpha$ | -19,33° | -18,99° | -18,62° | -19,2° |
| $\gamma_{reel}$ | 90° | 90° | 90° | 90° |
| $\gamma$ | 91,81° | 90,80° | 88,47° | 89,5° |

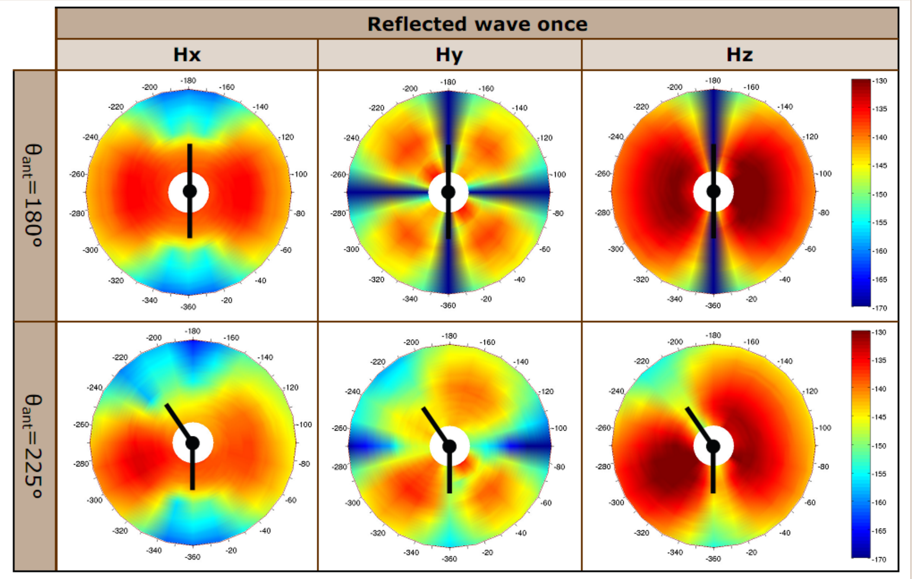
**The error on the inverted parameters is extremely low : 0.7% on $d_1$, 0.33% on $\varepsilon_{r-sol1}$, 5% on $\alpha$ angle and 0.4% on $\gamma$ angle on average.**

## Optimization of radar coverage : Impact of the angle between the two monopoles of the HF antenna

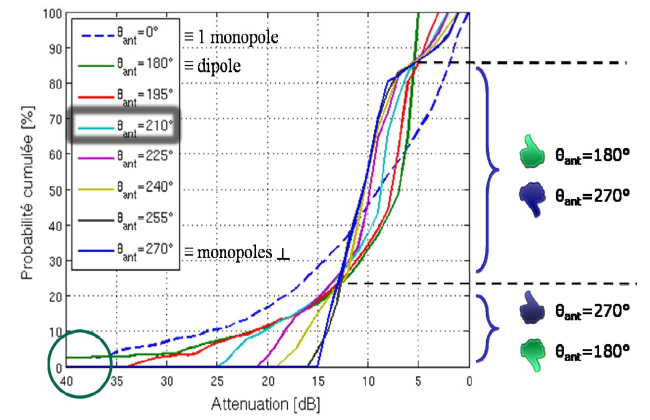
■ As it was the case for Humbold payload of th e ExoMars mission, the exact value of the angle between the two monopoles might not be 180° but would rather be chosen to minimize the contact between the antennas and the lander and solar panels structure, keeping the radiation pattern as omni directional 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°.

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

■ 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.



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 probability to encounter an attenuation compared to the best situation larger than the abscissa value, for reflected wave once.

**Modeling approch based on the fictive 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 subsurface and the resistive profile : Each monopole is considered as the sum of elementary dipoles with varying intensity of currents (Huygens).

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

► 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 $\theta_{ant}$=225° configuration, the probability to encounter an attenuation larger to 21dB (compared to the best situation at 500m) is null while it's around 10% for the configurations whose the angle is less ($\theta_{ant}$=180-195-210°) and 16% for one monopole configuration. The best configuration offering a relatively omnidirectional coverage without little (no more) attenuation is obtained by $\theta_{ant}$=210° configuration.

In conclusion, the proposed method allows the retrieval of the permittivity value, the depth and inclination of the first interface. However, it is necessary to do surveys for receiver locations distributed over the area to characterize. Indeed a single radial trajectory would not allow to resolve all ambiguities. The measurements of the three components of the magnetic field at the rover location will provide information on the reflecting structures 3D location, discard the echoes due to subsurface clutter (and enable a mapping of the deep subsurface stratigraphy along the rover paths). Experimental validation is planned to validate on experimental data acquired on well documented areas the theoretical results.