A PHASE SIGNATURE FOR DETECTING WET STRUCTURES IN THE SHALLOW SUBSURFACE OF MARS USING POLARIMETRIC P-BAND SAR.

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Introduction: Over the last two decades, remote sensing using polarimetric synthetic aperture radar (SAR) has been widely used to study the earth’s surface. One of the main interesting applications is the mapping of the near-surface soil moisture from space-borne SAR data (ERS 1/2, JERS1, ENVISAT, and RADARSAT). Several experiments demonstrated that low-frequency radar has penetration capabilities that can be used to map subsurface heterogeneities such as geological interfaces or wet layers. As regards soil moisture, it is well known that the presence of water significantly influences the radar response of a terrain. Nevertheless, very few authors used the phase information from SAR data to detect moisture. In previous studies, we showed that a copolarized phase difference between horizontal (HH) and vertical (VV) channels observed on SAR images is correlated to buried wet layers. It can be used to detect wet subsurface layers down to a larger depth than when only considering HH and HV amplitude signals [1].

As Mars is concerned, recent measurements by the Gamma Ray Spectrometer (GRS) on board the Mars Odyssey spacecraft allowed the mapping of ground-ice (in the form of water or hydrated minerals) in the upper few meters of the southern hemisphere of Mars at mid and high latitudes [2]-[5]. Since the geographic range of ground-ice stability strongly depends on the abundance of atmospheric water, several studies discuss the possible location and occurrence of liquid water on Mars [6]-[7]. Using a general circulation model to calculate ground temperature, Haberle et al. [7] determine the current locations on Mars where pure liquid water or brine solutions could exist, that is where the ambient \(CO_2\) pressure is greater than the water vapor pressure at the local temperature. One could then reasonably assume the presence of liquid water in the few upper meters of the Martian surface, at least temporarily. Since radar is sensitive to dielectric contrasts, the liquid water in the shallow subsurface could lead to easily detectable interfaces because of a high permittivity due to the moisture. Moreover, Mars has been shown to have a wide range of scattering properties in the wavelength range from C-band (3 cm) to L-band (18 cm) including volume scattering from buried terrains, and specific dielectric and magnetic properties due to iron-rich materials [8]. We propose the use of P-band (70 cm) polarimetric SAR system to investigate the presence of wet structures in the first few meters of the Martian soil.

Geoelectrical model of the near subsurface: Numerous studies of ground-ice stability predicted the occurrence of a layered subsurface, in which a dry (ice-free soil) upper layer covers a wet lower layer (ice-cemented soil) [2],[5]. For that reason, we considered a two-layers scattering problem in order to assess the capabilities of a P-band SAR system to penetrate soil for retrieving information about subsurface, in particular detecting moisture using the radar copolarized phase signal. Since the alpha X-ray spectrometer on the Spirit rover showed that the composition of Gusev soil is similar to the Viking 1/2, and Pathfinder landing sites [9]-[11], we assumed a upper dry layer composed of a mixture of iron oxides, basalts, salts, and meteoritic materials, covering a wet lower layer mainly basaltic in composition, with a variable water content (Fig. 1). Each layer is characterized by its roughness and electromagnetic parameters. Permittivity measurements were performed on several minerals that appear to be good analogs to those observed on the surface of Mars. The permittivity of the mixture for the upper dry layer is derived from the dielectric constant of each mineralogical component using the second formula of Lichteneker [12]. According to our laboratory measurements around 400 MHz, we found a complex permittivity of \(\varepsilon_1 = 5.87 - i0.141\) for an upper layer mainly composed of basaltic materials mixed with small amounts of iron oxides (goethite, hematite) and meteoritic materials. The permittivity of the underlying basaltic layer is set at \(\varepsilon_2 = 4.19 - i0.178\) when dry and will increase with respect to the moisture content.

![Fig. 1. Geometry of the two-layers scattering problem.](image)

The two-layers scattering IEM model: In order to determine the copolarized phase difference \(\Phi_{HH-VV}\), we had to compute the backscattering coefficients for each layer. Since smooth to medium rough surfaces are considered here, the Integral Equation Model (IEM) proposed by Fung [13] can be used. We initially only considered the single- and multiple-scattering terms and neglected volume scattering. The total backscattered power \(\sigma_{pp}^0(\theta)\) can be written as:

\[
\sigma_{pp}^0(\theta) = \sigma_{S1pp}^0(\theta) + \sigma_{S2pp}^0(\theta)
\]

where \(pp\) is the polarization state (HH or VV), and \(\sigma_{S1pp}^0(\theta)\) is the surface backscattering coefficient from the upper layer.
written as the sum of single and multiple terms:

\[
\sigma^o_{S1pp} (\theta) = \frac{k}{4} e^{-2k^2 \cos^2 (\theta) \sigma^2} \sum_{n=1}^{\infty} \left| I_{pp} \right|^2 \frac{W(2k \sin (\theta))}{n!} + \frac{k^2}{4\pi} e^{-3k^2 \cos^2 (\theta) \sigma^2} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{(2k \cos^2 (\theta) \sigma^2)^{n+m}}{n!m!} \\
\cdot \int \int R e [I_{pp} F_{pp} (u, v)] W^{(n)} (u-k_x, v) W^{(m)} (u+k_x, v) dudv + \frac{k^2}{16\pi} e^{-2k^2 \cos^2 (\theta) \sigma^2} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{(2k \cos^2 (\theta) \sigma^2)^{n+m}}{n!m!} \\
\cdot \int \int [I_{pp} (u, v)]^2 + F_{pp} (u, v) F_{pp}^* (-u, -v) W^{(n)} (u-k_x, v) W^{(m)} (u+k_x, v) \\
.dudv
\]  

where \( \theta \) is the radar incident angle, \( k \) is the radar wave-number, \( W^n \) is the Fourier transform of the \( n \)th power of the Gaussian surface correlation function and \( u, v \) are the spectral variables from the Green’s function. \( I_{pp} \) are the Kirchhoff field coefficients while \( F_{pp} \) represents the complementary field coefficients. The non-coherent scattering of the lower layer \( \sigma^o_{S2pp} (\theta) \) is derived from (2) taking into account the wave attenuation due to the propagation through the upper layer. Since (1) could be represented as the sum of two vectors, the phase difference between HH and VV signals can be written as [1]:

\[
\Phi_{HH-VV} = \arctan \left( \frac{\sigma^o_{S2HH} \sin (\varphi_p)}{\sigma^o_{S1HH} + \sigma^o_{S2HH} \cos (\varphi_p)} \right) - \arctan \left( \frac{\sigma^o_{S2VV} \sin (\varphi_p)}{\sigma^o_{S1VV} + \sigma^o_{S2VV} \cos (\varphi_p)} \right) 
\]  

**Results:** We performed simulations of \( \Phi_{HH-VV} \) for several moisture contents of the lower layer at three incidence angles: \( \theta = 20^\circ, 30^\circ, \) and \( 40^\circ \) for a central radar frequency of 430 MHz. The roughness parameters (rms-height \( \sigma \) and correlation length \( L \)) are \( \sigma_1 = 1.5 \) cm and \( L_1 = 10 \) cm, and \( \sigma_2 = 3.5 \) cm and \( L_2 = 10 \) cm for the upper and lower layer respectively. As shown in Fig. 2, \( \Phi_{HH-VV} \) is very sensitive to the incidence angle. Wet subsurface structures should be more easily detectable at larger incidence. Fig. 2 also shows that for a moisture content of the lower layer leading to a permittivity close to the upper layer, \( \Phi_{HH-VV} \) decreases to zero, indicating that the phase signal is mainly related to the dielectric contrast at the upper-lower layer interface. Indeed, when \( \epsilon_2 = \epsilon_1 \), the scattering problem reduces to a single layer problem and only the surface signal contributes to the backscattering. Monitoring changes in \( \Phi_{HH-VV} \) value could then be an interesting method to map seasonal changes of the subsurface moisture on Mars.

Fig. 3 displays the backscattering coefficient for HH polarization for the subsurface layer \( \sigma^o_{S2HH} \) at \( \theta = 40^\circ \). It may be seen that \( \sigma^o_{S2HH} \) strongly decreases when \( \epsilon_2 \) is close to \( \epsilon_1 \) that is when only the surface signal contributes to the backscattering, confirming that the phase signal is related to the buried wet structure. Furthermore, when the moisture content of the lower layer increases, single and multiple scattering occur at the buried wet interface which significantly contribute to the backscattered signal, increasing the backscattering coefficient to an easy detectable level (-25 dB) for P-band SAR even for a 3m deep wet layer.

**Future work:** We initially considered single and multiple scattering and limited our study to a pure water case. Further studies will consider volume scattering that could occur inside the dry upper layer because of the presence of rock clasts comparable to the radar wavelength in size. We will also investigate the effects of brine solutions on \( \Phi_{HH-VV} \) because of the occurrence of small amounts of salts in the Martian crust that could significantly affect the conductivity in the few upper meters of the Martian subsurface. Finally, we shall also test the capabilities of airborne P-band polarimetric SAR on terrestrial sites that could be good analogs to Mars.

**References:**