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Note

Dielectric measurements and radar attenuation estimation of ice/basalt sand mixtures as martian Polar Caps analogues

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ABSTRACT

The nature of the materials underlying the superficial deposits of Mars can be inferred, applying an inversion algorithm, from the data acquired by the orbiting HF radars MARSIS and SHARAD. This approach requires the knowledge of the electromagnetic properties of the shallow deposits and an accurate evaluation of the signal attenuation. The present work is focused on the determination of the dielectric parameters of several geo-materials. We performed the measurements of the complex permittivity, in a wide range of temperature (150–250 K) and frequency (20 Hz–1 MHz), on pure water ice, dry basalt sand and ice/basalt mixtures with different sand volume fractions. The data are presented in terms of attenuation as a function of basalt volume fraction, frequency and temperature, and discussed in terms of extrapolation to MARSIS and SHARAD frequency bands. The results show that, besides the expected dependence of the attenuation from temperature, the presence of the solid inclusions in the ice strongly affects the behaviour of the attenuation versus frequency.

1. Introduction

Since 2005 the HF radars MARSIS (Mars Subsurface and Ionosphere Sounder) and SHARAD (Shallow Radar) (Picardi et al., 2004; Seu et al., 2004) have intensively sounded the martian subsurface, producing thousands of electromagnetic images of the shallow Mars interior. A large amount of these images were collected on the martian Polar Caps because the icy materials are particularly transparent to radio waves, resulting in a maximum signal penetration of about 3.7 km in the South Pole (Plaut et al., 2007). In principle, the radar data can also be used to infer the nature of the materials underlying the superficial deposits, applying some robust inversion algorithm and imposing some constraints to the electromagnetic behaviour of such deposits (Zhang et al., 2008; Grima et al., 2009; Mouginot et al., 2010, 2012; Carter et al., 2009; Lauro et al., 2010, 2012; Grima et al., 2012). In particular, if the goal of the analysis is the conversion of the electromagnetic image into a geological stratigraphy (i.e. the transformation of two-way travel time in depth), the key parameter is the wave velocity which, for low-loss and non-magnetic materials, is mainly dependent on the real part of the complex dielectric permittivity. Note that in the MHz range, the real part of the permittivity of geo-materials (including ice) can usually be assumed frequency independent. On the other hand, if the aim of the prospection is the estimation of the permittivity of the buried materials, the inversion procedure requires the knowledge of the attenuation, which is dominated by the imaginary part of permittivity.

The martian Polar Caps are the only areas where the inversion techniques can be considered more reliable, being the H_2O ice the main component of the caps (Plaut et al., 2007; Phillips et al., 2008), even though a variable percentage of CO_2 ice and silicates is also present in the shallow deposits (Mitrofanov et al., 2002; Bibring et al., 2004). It is generally accepted that the North Polar Layer Deposits (NPLD) are made of almost pure water ice (maximum 5% of dust admixtures as estimated by Grima et al., 2009), and the South Polar Layers Deposits (SPLD) are predominantly composed by "dirty ice" (up to 15% of dust admixtures, as evaluated by Zuber et al., 2007; Li et al., 2010). In these terrains, which do not have any terrestrial analogue as the dust content in the Earth polar caps is much lower than 1% (Petit et al., 1999), the inversion procedure is challenging due to the lack of information on the behaviour of the attenuation versus frequency and temperature. In fact, the inversion procedure applied so far to radar data acquired on the martian Polar deposits has been addressed assuming rather different attenuation models. For example, Zhang et al. (2008) considered a frequency independent attenuation as usually assumed in terrestrial polar ice sheets (Gudmandsen, 1971; MacGregor et al., 2007), whereas Picardi et al. (2008) used a linear increase of attenuation in dB with frequency.

The dielectric properties of pure water ice and dry rocks behave differently in terms of temperature and frequency, and have been

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extensively studied (see for example Petrenko and Whitworth, 1999; Guéguen and Victor, 1994; Fujita et al., 2000 and references therein). However, the ice/rocks mixtures have a much more complex dielectric behaviour, depending on the two phases relative content. At the ice freezing point and above the Debye relaxation frequency ν_{rel} ($\nu_{rel} \cong 10$ kHz at $T \cong 273$ K), the real part of pure water ice permittivity is $\varepsilon' = 3.15$ and the imaginary part ε'' decays as ν_{rel}/ν. The ice relaxation frequency is strongly affected by the temperature as ν_{rel} moves towards lower frequencies when the temperature decreases. The cooling process does not modify the value of the real part of permittivity above ν_{rel} but significantly reduces the imaginary part. As a consequence, because the attenuation of pure water ice is proportional to $\nu\varepsilon''/\sqrt{\varepsilon'}$ (see below), any temperature variation will affect this quantity (Fujita et al., 2000; MacGregor et al., 2007). On the other hand, at a fixed temperature, the attenuation of pure water ice can be considered frequency independent in the kHz–MHz range (Gudmandsen, 1971; Fujita et al., 2000), i.e. in the operating frequency band of MARSIS and SHARAD. In contrast, both real and imaginary parts of permittivity of dry rocks and soils are usually frequency independent (in the MHz range), and virtually insensitive to low temperatures (Guéguen and Victor, 1994; Rust et al., 1999). Very little is known about the dielectric behaviour of an ice/grain (rock or soil) mixture as a function of frequency and temperature. The few data available from laboratory experiments are very heterogeneous in terms of mixture composition, frequency and temperature ranges (see for example Herique et al. (2002), Stillman et al. (2010) and Heggy et al. (2012)). Moreover, some attempts have also been made to predict the dielectric behaviour of an ice/soil mixture (at fixed frequency) applying a mixing formula (Chyba et al., 1998; Nunes and Phillips, 2006), however the lack of extensive laboratory measurements prevented any validation on the reliability of such predictions.

The present work contributes to filling the knowledge gap that exists regarding the dielectric properties of martian ice/basalt mixtures. To this goal, we measured the real part of permittivity and loss of pure water ice, dry basalt sand (60% porosity), ice/basalt mixture with 11.3% sand volume fraction (simulating the upper layer of the SPLD), and ice/basalt mixture with 43% sand volume fraction (which is appropriate to simulate the Basal Unit of the NPLD) (Tanaka et al., 2008; Lauro et al., 2012). The results are presented in terms of attenuation as a function of basalt volume fraction, frequency (20 Hz–1 MHz) and temperature (150–250 K), and discussed in terms of extrapolation to MARSIS and SHARAD frequency bands.

2. Methods

The dielectric properties of the samples were measured using an Agilent precision LCR meter HP4284A, operating in the frequency range 20 Hz–1 MHz; the instrument was coupled to a cylindrical capacitive cell, equipped with guard electrodes (Cereti et al., 2007), filled with the test material. The inner and outer electrodes have diameters of 2 cm and 3 cm respectively and the investigated sample volume is approximately 15 cm^3.

The equivalent circuit of the capacitive cell can be represented by a capacitor, which accounts for the polarizability of the material, in parallel to a resistor, which represents the electric losses. The measured quantities are the capacitance $C(\nu)$ and the loss tangent $\tan\delta(\nu)$. The real part of the dielectric permittivity is related to the capacitance through:

$$\varepsilon'(\nu) = \frac{C(\nu)}{C_0} \tag{1}$$

where $C_0 = 5.62$ pF is the capacitance of the empty cell. This quantity was measured with the LCR meter and found to be in full agreement with the theoretical value calculated on the basis of the cell geometry. In what follows the uncertainty in the permittivity $\varepsilon'(\nu)$ is calculated neglecting the uncertainty in C_0, being this value much smaller than that associated to $C(\nu)$.

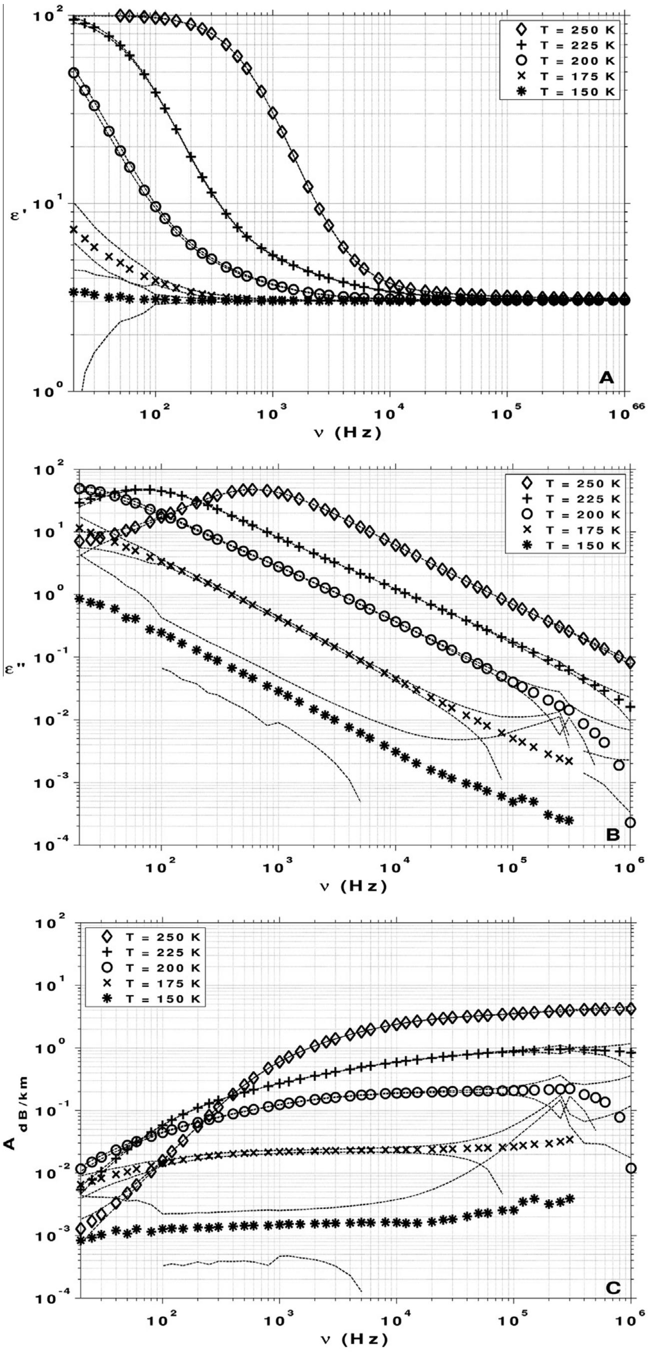

Fig. 1. Electromagnetic properties measured on pure water ice at different temperatures. The dashed lines represent the data uncertainty region indicating the envelope of the error bars. Panels A and B show the real and imaginary part of permittivity; panel C shows the attenuation calculated according to Eq. (2). The classical Debye behaviour is well visible on both $\varepsilon'(\nu)$ and $\varepsilon''(\nu)$ affected, at low frequency, by a Maxwell–Wagner effect.

The capacitive cell is inserted in a cryostat operating with liquid nitrogen, which is capable to cool the sample down to about 100 K. However, to cover the temperature profile expected for the martian Polar Caps from surface down to a depth where liquid water may exist (Larsen and Dahl-Jensen, 2000; Clifford et al., 2010), the range of temperature was limited to 150–250 K. The