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Reply to the Matters Arising

Explaining Bright Radar Reflections Below the Martian South Polar Layered Deposits Without Liquid Water, by D. E. Lalich, A. G. Hayes and V. Poggiali

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In their Matter Arising Lalich et al.[1] simulate MARSIS echoes at the base of the South Polar Layered Deposits (SPLD) assuming three different layering scenarios (Fig. 1 in ref.1): (a) dusty water ice overlaying bedrock; (b) one CO_2 ice layer between dusty water ice and bedrock; and, (c) two basal CO_2 ice layers interbedded with one layer of dusty water ice. A surficial layer of CO_2 ice ranging from 0 m (no layer) to 2 m in thickness is also considered. The first layer in each simulation is a semi-infinite half space assigned the permittivity of free space, and the bedrock is a semi-infinite half space with pure basaltic rock permittivity. These authors argue that constructive interference generated by some layered configurations produce waveforms (Fig. 2 in ref.1) with local maxima corresponding to the bright basal reflections observed by MARSIS at Ultimi Scopuli [2,3]. They conclude that this explanation is more plausible than liquid brines being the source of the bright reflections, as posited instead by Orosei et al.[2] and Lauro et al.[3].

In an earlier paper, however, Orosei et al.[4] explored the same model and mathematics covering the entire range of possible parameters for two and three basal CO_2 ice layers. Through the quantitative analysis of 3.45×10^8 simulation results, these authors demonstrated that local maxima at one of the MARSIS operating frequencies are not matched by local maxima at the other operating frequencies: that is, a layer stack producing constructive interference at one frequency, does not produce the same effect at the other frequencies, which is inconsistent with MARSIS real data. Thus, constructive interference by basal layers is not a viable mechanism to explain the bright basal reflections at Ultimi Scopuli.

Because most of the points in Lalich et al.[1] are superseded by Orosei et al.'s[4] work, we refer interested readers to that earlier paper for a full discussion of the models and results. Here, we focus on three critical aspects: electromagnetic model; dielectric values used in the simulations; and materials and geology.

Electromagnetic model

Table 1 in Lalich et al.[1] reports the values of the first maximum (Fig. 3 in Lalich et al.[1]) for each MARSIS frequency (3, 4, and 5 MHz) computed for scenarios (a), (b) and (c). We focus on (c), because it is the one presented as generating normalised basal echo power (NBEP) values comparable to those measured by MARSIS (Fig. 2 in Lalich et al.[1]). We note furthermore that scenario (b) was already explored and discarded by Orosei et al.[2] and is therefore not discussed here, except to note that Lalich et al.[1] suggest that their assumption of a much lower basal temperature (175 K) than that considered by Orosei et al.[2] (205 K), explains the difference between their scenario (b) results and those published in that previous work. A difference in basal temperature is however irrelevant, as we show in Fig. 1, where the variation of attenuation of the radar signal propagating with frequency in dusty water ice is plotted for different values of temperature: it is clear that temperature has a negligible effect on attenuation (~ 0.01 dB/km), when compared to the effects of frequency and dust (shergottite grains) content.

In the bottom panel of Fig. 3 of Lalich et al.[1] the first maximum obtained for each frequency (3, 4 and 5 MHz) is associated to a different layer thickness (15 m, 11 m, and 9 m, respectively). This is hardly unexpected, considering that constructive interference occurs when the CO_2 layer thickness is ~ $\lambda/4$ (with λ the probing wavelength). Thus, for a given thickness, two frequencies might return a similar NBEP value, but the third one will be always much lower or much higher than the other two. This is a clear point of difference between simulated results and real MARSIS observations in Ultimi Scopuli (see Supplementary Fig. 1 in Lauro et al.,[3]).

We replicated Lalich et al.[1] configuration (c) models, except for the fact that we did not include a surficial layer of CO_2 ice, because this is absent at Ultimi Scopuli (see Geological Context).

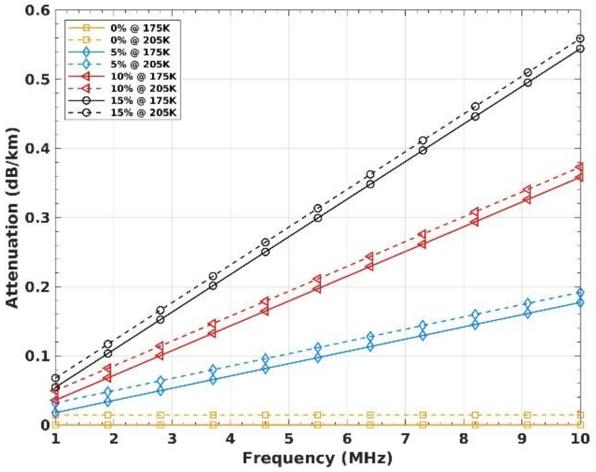

Fig. 1. Attenuation as a function of frequency in the SPLD. Attenuation computed at 175 K and 205 K, in water ice with different content of shergottite grains.

In Fig.2 we report the results of our simulations for scenario (c), showing the variation in NPEB at each MARSIS frequency in relation to layer thicknesses of up to 30 m, which corresponds to the range of thicknesses for which the normalized basal echo powers are highest (Fig. 3 in Lalich et al.[1]).

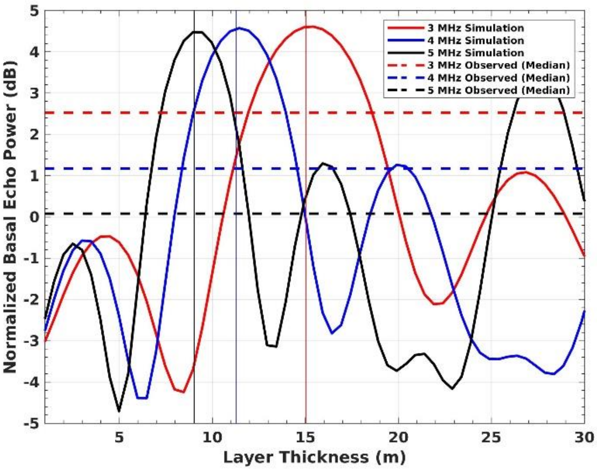

Fig. 2. Simulation results for scenario (c). The figure is analogous to Fig. 3 in Lalich et al.[1]. Vertical lines indicate the thickness of the layer corresponding to the maximum at each frequency. Dashed horizontal lines show MARSIS NBEP median values from Lalich et al.[1]. The figure depicts the relation between NBEP and layer thickness.

The values of the first maxima at the three frequencies reported in our Table 1 (red values) are comparable to those reported in Table 1 bottom row in Lalich et al.[1]. However, in our table we also show that, the NBEP at each frequency is obtained only for a specific layer thickness. There is no common thickness that concurrently maximizes the NBEP values at all three MARSIS frequencies.

Table 1. NBEP values at MARSIS frequencies for different layer thickness

MARSIS frequencies	Layers thickness 15.4 m	Layers thickness 11.4 m	Layers thickness 9 m
3 MHz	4.60 dB	1.74 dB	-3.69 dB
4 MHz	-1.19 dB	4.57 dB	2.50 dB
5 MHz	1.02 dB	1.74 dB	4.48 dB

In addition, the median values computed from MARSIS data (dashed lines in Fig.3 of Lalich et al.[1]) exhibit a decreasing trend with frequency, with an almost constant separation between NBEP values (1.3dB between 3 and 4 MHz, and 1.1dB between 4 and 5 MHz). Conversely, the simulated data reported for each layer's thickness in our Table 1 (columns) do not show a similar behaviour neither in terms of trend with frequency nor in terms of difference between NBEP values. In fact, for a same layer thickness, the difference between NBEP values computed at different frequencies is variable and can be very large (up to 6dB). These variations are typical of resonance phenomena but cannot explain the regular frequency trend exhibited by the three MARSIS median values. Conversely, such frequency trend could be explained by considering larger losses in the SPLD ice/dust mixtures with respect to those assumed in the simulations, that resulted in a linear dependence of signal attenuation with frequency (Fig.1).

Dielectric properties

In their Methods: Layer Permittivity section, Lalich et al.[1] attribute the CO_2 ice value of complex permittivity ($2.2 - i4.5\times10^{-4}$) to measurements performed by Pettinelli et al.[5]. We point out that no such value is reported in that paper. In fact, Pettinelli et al.[5] estimated the real part of permittivity (i.e., the apparent permittivity) of CO_2 ice at frequency > 500 MHz by the Time Domain Reflectometry (TDR) method from the signal velocity inside the sample. That paper reports the value of 2.1±0.04 as the real part of permittivity of CO_2 ice, and no value for the imaginary part. The only information about the loss was given in terms of DC conductivity for a powdered sample of CO_2 ice (a porous material with 1.4 real part of permittivity) at 1 MHz.

Materials and geology

Lalich et al.[1] state that the results of their simulations, combined with other papers (presumably: Smith et al.[6] and Bierson et al.[7]; not directly cited in the Matters Arising), question the liquid brines interpretation. We point out that interpretations of the bright basal reflections as caused by alternative materials have been already examined and critiqued by Schroeder and Steinbrügge[8], and that our own laboratory experiments (Mattei et al.,[9]) demonstrate that clays and hydrated salts do not have dielectric properties consistent with the magnitude of the MARSIS reflections observed at Ultimi Scopuli.

Lalich et al.[1] also mention that the location of the bright reflections is not consistent with locations predicted by calculations of the hydraulic potential at the base of the SPLD[10]. This issue has been already extensively discussed by Lauro et al.[3] though some essential points are worth repeating here. Arnold et al.[10] used the subsurface echo time delay data by Orosei et al.[2] to reconstruct the basal topography around the wet area detected by MARSIS. They then used the resulting SPLD bed elevations to calculate the subglacial hydraulic potential surface. They concluded that the high reflectivity area does not match any location predicted by the hydraulic model, and therefore the bright reflector should be a hydraulically isolated patch of liquid water rather than a subglacial lake. This conclusion is based on a well-established methodology, but we note that it depends critically on the accuracy of the basal topography estimation, a point also clearly made by Arnold et. al.[10]. The large size of the MARSIS footprint and the diffuse nature of basal echoes outside the bright reflectors prevent a detailed and accurate reconstruction of the basal topography: the simple averaging of echo time delays in overlapping footprints, which was used to estimate subglacial topography by Orosei et al.[2] and Arnold et al.[10] improves neither horizontal nor vertical resolutions. Assuming the vertical resolution of MARSIS (~55 m in ice) as the nominal uncertainty on the basal topography, the corresponding uncertainty in the hydraulic potential is about 1 MPa (see Supplementary Fig. 2 in Lauro et al.,[3]), which is larger than the local variation of hydraulic potential across the area surrounding the bright reflector (thus affecting the reliability of the model).

A permanent CO_2 ice layer has not been detected at Ultimi Scopuli. However, because Lalich et al.[1] also discuss simulations with a layer of CO_2 ice at the top of the SPLD, we comment on such issue. These authors assume that the southern Residual Ice Cap unit (RIC; Api unit in Kolb and Tanaka,[11]) covers the Ultimi Scopuli region, instead of the Seasonal Ice Cap unit (SIC). According to literature and data, the southern RIC is inferred to be composed by CO_2 ice, with some amount of H_2O ice [12-15] and to be stable at least over centuries[16]. Thus, it can be considered as a permanent ice-cap a few meters thick[17,18] in semi-equilibrium with the present day Martian environment. However, the RIC is centred near 87°S – 315 E° (it is offset from the rotational pole[19]) and it has a maximum diameter of about 400 km. Thus, it is very far from the Ultimi Scopuli region and the location of the bright basal reflections (centred at 81°S).
The southern SIC is formed by seasonal deposition, starting from late summer to early autumn (its maximum extension is during the winter), of a thin and discontinuous layer of CO_2 ice (up to 1-2 meters thick[20]). It is centred around the geographic pole and extends up to ~65 S. So, it only seasonally covers parts of Ultimi Scopuli, and its physical and rheological characteristics can be expected to be completely different than those of the RIC, used by Lalich et al.[1] in their models.

Final remarks

Based on our analysis of the constructive interference model proposed by Lalich et al.[1], we can conclude that such model is not able to reproduce the real dataset collected by MARSIS at Ultimi Scopuli. The main advantage of MARSIS sounder it is the use of three frequencies (3, 4, and 5 MHz) to investigate a subsurface area. The results reported in Ultimi Scopuli regard an area largely covered by MARSIS data, collected several times in different seasons and years, and different directions of the orbits. Therefore, the dataset is very large and provides results that are consistent among frequencies. Any model dedicated to reproducing MARSIS outcomes should consider the results concurrently obtained at all frequencies and be validated at 3, 4 and 5 MHz at the same time.

Data availability

MARSIS data are available through the Zenodo research data repository doi: 10.5281/zenodo.1285179.

Competing interests

The authors declare no competing interests.

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