New Constraints On Dust Content In The North Polar Layered Deposits, Mars From SHARAD Reflectivity.

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Introduction: The North Polar Layered Deposits (NPLD) is a formation of nearly pure water ice layers [1] up to 2 km thick and roughly centered on the north pole of Mars, in the Planum Boreum region. Although its age is unknown, it is likely no more than four million years old based on orbitally forced climate models [2]. The Shallow Radar (SHARAD) instrument on the Mars Reconnaissance Orbiter (MRO) has detected many subparallel reflectors within the NPLD [4], though the exact cause of these reflectors is a matter of debate. They are widely thought to result from variations in dust content with depth [4]. This variation has been linked to orbitally-forced insolation cycles, implying that these reflectors contain a climate proxy for late Amazonian Mars [5, 6, 7].

One potential cause of reflectors is the so-called “marker beds” identified in outcrop stratigraphy [7, 8]. Marker beds are thin layers characterized primarily by their resistance to erosion, which implies that they have a different composition than the surrounding ice. Previous research has failed to conclusively link specific marker beds to radar reflectors, but has shown that some genetic link is likely [8].

In this work, we map multiple SHARAD reflectors and measure their reflectivity using a method similar to Lauro et al. [9]. Notably, while previous efforts assumed a constant surface reflectivity, in this work we incorporate the measured surface reflectivity from Grima et al. [10]. This leads to more accurate estimates of subsurface reflectivity and better captures spatial variability within subsurface reflectors.

We then compare the measured subsurface reflectivity to a model approximating marker bed reflection. This model is similar to the one discussed in [9], but rather than simply modeling the response at a single frequency, in this work we model reflectivity across the full spectrum of the SHARAD chirp. This allows us to place better constraints on the composition of the modeled layers.

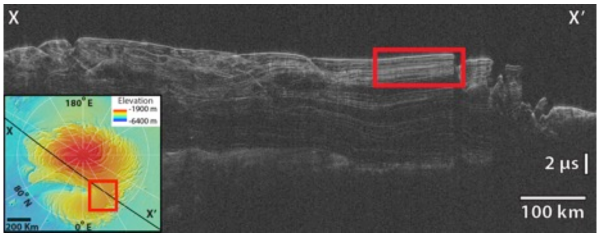

Figure 1: *SHARAD Radargram 1716901000 and inset MOLA elevation map of the NPLD for context. Red boxes indicate the study area.*

Data: Radar data were acquired using the SHARAD instrument on MRO. SHARAD is an orbital radar sounder that uses an 85 μs chirped pulse centered at 20 MHz with a 10 MHz bandwidth. It has a cross-track resolution of 3-6 km and an along-track resolution of 0.3-1 km achieved using synthetic aperture processing [11]. It has a nominal vertical resolution of 8.4 meters in water ice, though in practice this is closer to 10 meters. This work uses radargrams covering the so-called “saddle region” of the NPLD, which was chosen for its flat topography, resulting in very little surface clutter.

Reflectivity Measurement: Reflectivity for each reflector was measured using a modified version of the method from Lauro et al. [9]. Assuming a lossless medium, equal surface and subsurface roughness, and zero degree slopes, reflectivity can be calculated using the ratio of the power reflected by a subsurface reflector to the power reflected at the surface. In contrast to previous work [9, 12], surface reflectivity is not assumed to be constant over the mapped area. Instead, we use a previously generated map of SHARAD surface reflectivity [10] to determine the real surface reflectivity (R_s) at each radargram trace. This measured surface reflectivity is then inserted into Equation 1 below, along with the reflected power at the surface (P_s) and subsurface (P_{ss}) to calculate the reflectivity of the subsurface reflector (R_{ss}).

$$R_{SS} = \frac{P_{SS}}{P_S}\frac{R_S}{(1-R_S)^2} \qquad (1)$$

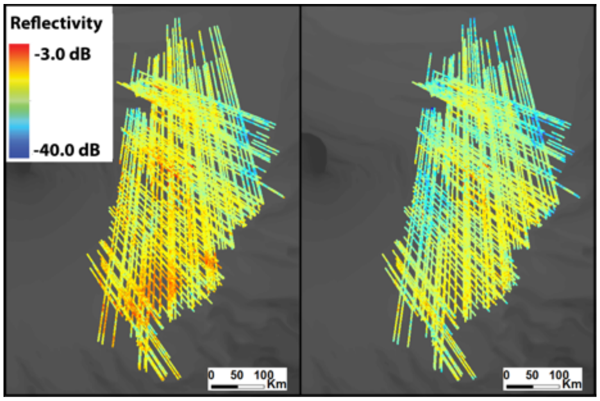

Figure 2: Left: *Map of subsurface reflectivity for reflector C as identified in [12] assuming constant surface reflectivity.* ***Right:*** *Same as top, but using variable, measured surface reflectivity [10] in Equation 1 instead of a constant value.*

Marker Bed Model: We use the model for thin layer reflection from MacGregor et al. [13] to approximate marker bed reflection, as marker beds are generally thinner than SHARAD's vertical resolution and thus can not be modeled as simple interfaces [14].

$$R = \left| r_{01} + t_{10} r_{12} t_{01} \left(\frac{e^{-2ik_1\delta}}{1 - r_{12} r_{10} e^{-2ik_1\delta}} \right) \right|^2 \qquad (2)$$

Here, r and t are the complex Fresnel amplitude reflection coefficients at each interface, k_1 is the propagation constant in the thin layer, and δ is the thickness of that layer. The first subscript of r and t refers to the medium through which the wave is currently travelling, while the second subscript denotes the medium the wave is travelling into. For the purpose of computing individual Fresnel reflection coefficients, we assume a dust-ice mixture between two layers of nearly pure ice.

Instead of modeling reflectivity solely at SHARAD's center frequency, as previous work has done [12], here we model reflectivity over the full SHARAD chirp, thus obtaining reflectivity as a function of frequency for each dust content-thickness pair. We then multiply this reflectivity by the Fourier transform of the SHARAD chirp, which acts as an energy density function, and integrate over all frequencies in order to obtain a total SHARAD reflectivity estimate for each value of dust content and layer thickness.

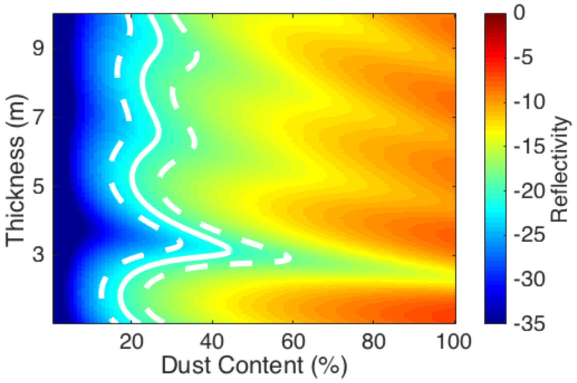

Figure 3: *Model of SHARAD reflectivity for layer thicknesses between 1 and 10 meters and dust contents from 0% to 100%. The solid white line is a contour of the median measured reflectivity of the mapped reflector shown in Figure 1. The dashed white lines are the 25th and 75th percentile contours.*

Results: As seen in Figure 2, incorporating the measured surface reflectivity has a significant impact on the estimated subsurface reflectivity. Some regional differences have been dampened, while others have been accentuated. Overall, the spatial reflectivity variations appear smoother, but the magnitude of variation between the brightest and dimmest regions remains large resulting from a combination of dust content and layer thickness.

Previous work hypothesized that SHARAD reflectivity is more of a proxy for layer thickness than dust content [12]. However, after extending the marker bed reflectivity model to include the full SHARAD frequency range, it appears that the opposite may be true. As shown in Figure 3, the reflectivity of the mapped reflector is constrained to a narrow band of dust contents for most layer thickness values. Modeled reflectivity does not seem to depend on layer thickness outside of a narrow range between 3 and 4 meters. This indicates that the variations mapped in Figure 2 may be due to changes in ice impurity content rather than layer thickness, and thus SHARAD reflectivity is acting primarily as a proxy for dust content.

Future Work: SHARAD reflectivity will be mapped for multiple reflectors at different locations within the NPLD. By comparing mapped reflectivities to the marker bed model described here, we can estimate changes in dust content as a function of depth within the polar cap, and attempt to match any observed patterns to those predicted by climate-driven accumulation models [7]. This will allow us to track changes in the processes responsible for ice and dust deposition and ablation throughout the history of the NPLD, effectively using SHARAD reflectivity as a climate record for the past 4 million years.

References: [1] Grima C. et al. *GRL 36,* (2009). [2] Levrard, B. et al. *JGR: Planets 112,* (2007) [3] Greve, R., and Mahajan, R.A., *Icarus 174,* (2005) [4] Phillips, R. J. et al. *Science 320,* (2008). [5] Cutts, J. A. & Lewis, B. H., *Icarus 50*, (1982). [6] Toon, O.B. et al., *Icarus 44*, (1980). [7] Hvidberg, C. S. et al., *Icarus 221*, (2012). [8] Christian, S. et al., *Icarus 226*, (2013). [9] Lauro, S.E. et al., *Icarus 219*, (2012). [10] Grima, C. et al. *Icarus 220,* (2012). [11] Seu, R. et al. *JGR: Planets 112* (2007). [12] Lalich, D.E., and Holt, J.W., *GRL,* (2016). [13] MacGregor, J. et al., *Journal of Glaciology 57*, (2011). [14] Milkovich, S. M. & Head, J. W. *JGR: Planets 110***,** (2005).