Advances In The Use Of Radar Reflectivity As A Climate Proxy In The North Polar Layered Deposits.

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Introduction: The North Polar Layered Deposits (NPLD) are a formation of nearly pure water ice layers [1] up to 2 km thick and 1000 km across roughly centered on the north pole of Mars, in the Planum Boreum region. Although their precise age is unknown, it is likely no more than four million years old based on orbitally forced climate models [2, 3]. In addition to layering visible in outcrop imagery, the Shallow Radar (SHARAD) instrument on the Mars Reconnaissance Orbiter (MRO) has detected many subparallel reflectors within the NPLD [4]. Reflectors are organized into four groups or "packets," separated by reflection-free zones. The exact source of these reflectors is a matter of debate, but they are generally thought to result from variations in dust content with depth [4, 5]. Previous work linked layers and reflectors to orbitally-forced insolation cycles, implying that reflectors could act as a climate proxy for late Amazonian Mars [6, 7, 8, 9].

One hypothesis for the source of radar reflectors is that they are caused by the so-called "marker beds" identified in outcrop stratigraphy [8, 10]. Marker beds are thin layers characterized primarily by their relative 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 [10].

By assuming SHARAD reflectors are caused by an enhancement in dust content within marker bed layers, Lalich et al. [11] were able to use reflectivity measurements to place constraints on layer composition. However, they were forced to make a number of simplifying assumptions and limited their analysis to ten small study sites around the NPLD. In this work we seek to extend that analysis through a combination of more extensive reflector mapping, the consideration of other types of reflector-causing stratigraphy, and the application of recently developed SHARAD processing techniques.

Data and Study Area: 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. SHARAD has a cross-track resolution of 3-6 km and an along-track resolution of 0.3-1 km achieved using synthetic aperture processing [12]. It has a nominal range resolution of 8.4 meters in water ice.

In addition to standard radargrams, we also make use of data produced using a processing technique known as "super resolution," which has recently been adapted for SHARAD [13]. Combined with targeted interference suppression, we are able to enhance the range resolution of SHARAD by a factor of three, and increase the signal-to-noise ratio by ~3 dB [13]. Previously, uncertainty in subsurface layer thickness hindered efforts to use SHARAD reflectivity as a proxy for ice composition [11], and analysis of "split chirp" radargrams suggested that what appeared as single reflectors in SHARAD data might instead be the result of multiple thin layers [14]. Using super resolution radargrams, we can place tighter constraints on layer thickness and more accurately discriminate between individual reflectors, dramatically increasing our ability to interpret reflectivity measurements.

For this work we have selected the "saddle region" of the NPLD as our study area. The region's flat topography virtually eliminates lateral clutter which can sometimes make SHARAD radargrams difficult to interpret. Our selection also facilitates comparisons to previous studies, which also focused on the saddle region [11, 15]. Unlike those previous studies, we aim to extend our analysis beyond the top packet of reflectors (~500 m depth) and therefore explore a longer period of time.

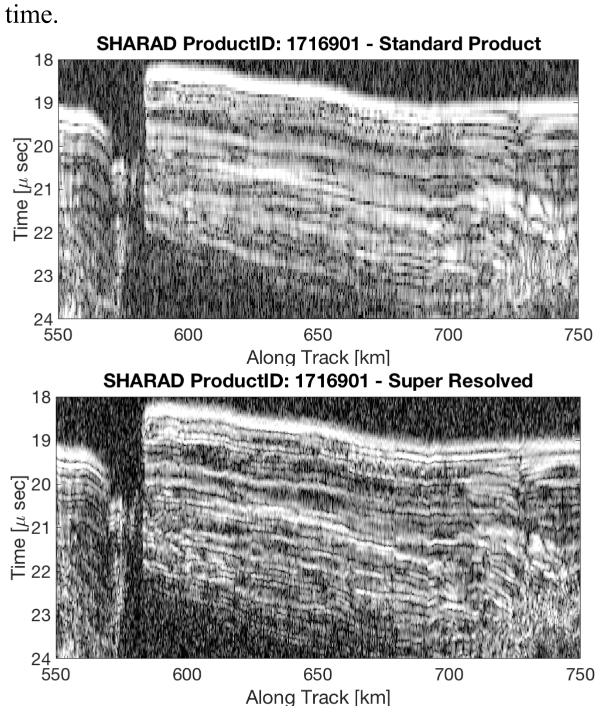

Figure 1: Top: Standard SHARAD radargram over the saddle region. **Bottom:** Same observation with super resolution processing.

Measuring SHARAD Reflectivity: Reflectivity for each mapped reflector is measured using a modified version of the method from Lauro et al. [16]. Assuming equal surface and subsurface roughness and negligible slope, reflectivity can be calculated using the ratio of the power reflected by a subsurface reflector (P_{ss}) to the power reflected at the surface (P_s):

$$R_{ss} = \frac{P_{ss}}{P_s}\frac{R_s e^{2\delta kz}}{(1-R_s)^2} \tag{1}$$

Where R_s is the surface reflectivity, δ is the loss tangent, k is the wavenumber, and z is the depth to the subsurface reflector. In keeping with previous work [11], surface reflectivity is not assumed to be constant over the mapped area. Instead, we will use a previously generated map of SHARAD surface reflectivity to determine the local surface reflectivity at each radargram trace [17]. For δ we adopt the bulk value calculated by Grima et al. [1].

Using Reflectivity to Constrain Composition: To first order, the radar reflectivity of a material is dependent on its permittivity. In practice, however, SHARAD is not able to resolve individual layer interfaces, and thus observed reflectivity is also dependent on layer thickness and/or the total number of layers responsible for a single resolvable reflector. In order to use SHARAD to estimate layer composition, Lalich et al. [11] assumed that reflectors were caused by single marker beds, modeled reflectivity as a function of marker bed thickness and dust content, and then compared measured reflectivities to their model. We will follow the same basic procedure for this study. However, while there is some evidence linking marker beds and SHARAD reflectors, it is still possible that at least some reflectors are caused by multiple layers too thin to resolve even using super resolution processing [14].

To account for this, we will use a new model for estimating subsurface reflectivity (and thus composition) that allows for multi-layer scenarios [18]. While it would normally be unrealistic to consider every possible permutation of reflector-causing layer sets, the super resolution data discussed earlier will allow us to limit the likely scenarios to a manageable number.

Future Work: While the saddle region makes for an ideal first study area, reflectivity can vary substantially over the NPLD [11, 15]. In the future, expanded radar mapping could help disentangle the effects of local and mesoscale climate conditions from the global signal present in the polar cap. Layered ice deposits are also present outside the PLD themselves, notably in Korolev crater. Similar reflectivity analyses of these deposits could reveal much about the Martian polar and global climate systems.

Integrating radar and visible stratigraphy could also enhance scientific returns from each dataset. Previous efforts to match reflectors with specific outcrop layers were unsuccessful [10], but it is possible that a similar effort may yield better results with the advent of super resolution processing.

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