Enhanced Subsurface Analysis of the Martian Cryosphere Afforded by Three-Dimensional Radar Imaging.
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Introduction. Ice-rich regions in the mid-latitudes of Mars are a high-value scientific target as well as a source of potential *in situ* resources for future human exploration [1]. Using terrestrial seismic 3D imaging techniques adapted for Mars Reconnaissance Orbiter (MRO) Shallow Radar (SHARAD) observations [2], we produced the first 3D radar image of a 10°x10° region of Deuteronilus Mensae, marking an important step forward in fully characterizing the ice content of mid-latitude debris-covered glaciers [3]. In this presentation, we will review the development and enhancements made using 3D imaging techniques and argue for their application to mid-latitude targets of interest, especially in locations that are being considered for potential human exploration.

SHARAD emits a "chirped" pulse, downswept from 25 MHz to 15 MHz, that yields a 15-m free-space range (vertical) resolution. After synthetic-aperture processing, the along-track resolution is set to 463 m (128 pixels per degree). SHARAD 3D images, available at https://sharad.psi.edu/3D, have 475-m x 475-m bins.

Enhanced 3D Imaging. The adaptation and application of terrestrial seismic 3D imaging techniques to work with SHARAD observations marked an important milestone in the evolution of planetary radar science [4]. When analyzing SHARAD data using standard along-track profile views ("2D radargrams"), off-nadir surface returns ("clutter") often obfuscate subsurface reflections in regions of complex topography. By imaging the data in 3D, radar returns are repositioned to their points of origin, thereby greatly reducing clutter interference within the 3D radargram while removing other geometric distortions. The first application of SHAREAD 3D imaging proved quite effective [5], albeit with a few shortcomings attributable to inconsistencies in processing and residual ionospheric effects on the radar signals.

To address the limitations of the original 3D images, the input 2D radargrams were treated with an advanced ionospheric correction algorithm and were co-registered with the predicted surface returns from clutter simulations, resulting in new 3D images that effectively retain the original vertical resolution of the 2D radargrams [5].

Deuteronilus Mensae. Using the workflow developed for the enhanced Planum Boreum 3D image [2, 4], we carried out a pilot study of a 10°x10° region in Deuteronilus Mensae to assess how well these 3D imaging techniques would work in an area with a lower density of SHARAD coverage. Along-track and cross-track spacing within an imaged area determine how well the slopes of topographic features will be resolved and how well the imaged data will reflect reality. Deuteronilus Mensae is one of the most densely observed regions on Mars outside of the polar regions and stood as a great proving ground for the application of this technology in the mid-latitudes. **Figure 1** shows a comparison of the thickness of ice between analysis completed using standard 2D radargrams and that with 3D imaging. It is apparent from comparing these two mapping results that analysis using the 3D radargrams is able to identify more basal reflections in areas not mappable with the standard 2D radargrams.

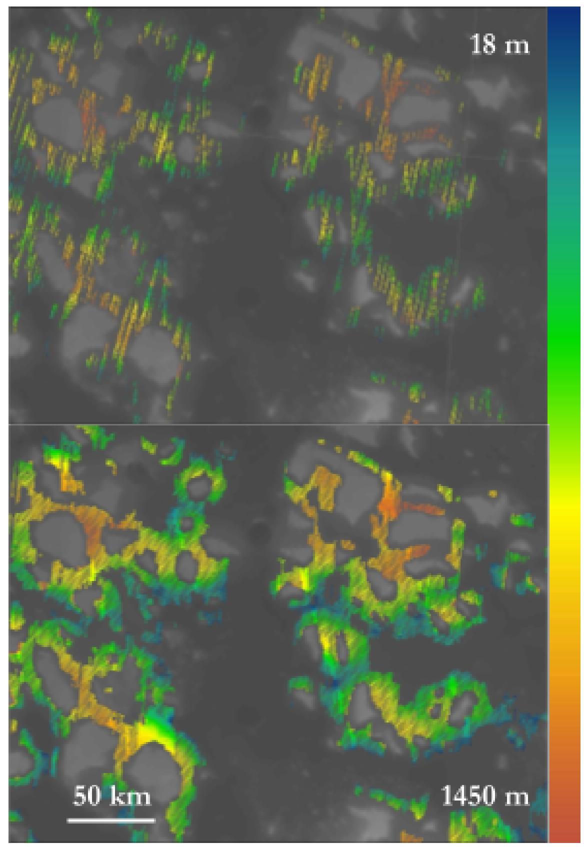

Figure 1. Map thickness to base of ice in a portion of Deuteronilus Mensae using standard 2D radargrams (top panel) andusing the 3D radargram (bottom panel). Color indicates ice thickness assuming a dielectric constant of pure water ice (3.15).

Phlegra Montes. To evaluate the ice content of debris-covered glaciers in Phlegra Montes, we conducted a pilot study using SHARAD data. We examined 922 2D radargrams using Geophysics by SeisWare (commercial analysis software). Phlegra Montes is topographically complex, which results in a high degree of clutter in the 2D radargrams.

Furthermore, MOLA coverage is poor in this region, and thus clutter simulations do not capture all of the sources of clutter seen by SHARAD, making disambiguating clutter from actual subsurface returns much more difficult. To assist with our interpretation, we converted the two-way delay time radargrams to depth using a two-layer model of free space (ε'=1.0) above the surface and pure water ice (ε'=3.15) below the surface. Using this type of dielectric model is useful for detecting the base of LDAs, as it flattens the returns from the base of the glaciers, aligning their bases with the outlying terrain. Despite the number of radargrams analyzed and the appearance of many glacial landforms in Phlegra Montes in HiRISE and CTX data, we were only able to identify reflectors with high confidence in 31 radargrams (**Figure 2**). We also identified ambiguous reflectors in 16 other radargrams and flat-lying reflectors associated with surface-clutter returns in an additional 26 radargrams.

While the density of SHARAD coverage over Phlegra Montes is continuing to increase, our understanding of the total ice content within Phlegra Montes is at a standstill due to the amount of clutter in the 2D radargrams. Application of the 3D imaging technology to the SHARAD observations in this area would clarify the resulting images and greatly reduce clutter, enabling a better assessment of the ice content in this region using a 3D radar image.

Regions of Interest. There are various topographically complex, ice-rich regions on Mars that would benefit greatly from application of the 3D imaging techniques discussed above. Paramount among these are the remainder of Deuteronilus Mensae, Phlegra Montes (discussed above), and the eastern rim of Hellas basin, where numerous debris-covered glaciers and lineated valley fills have been previously identified [6], but clutter makes detection of subsurface interfaces difficult to interpret. Furthermore, regions on Mars that host various volcanic deposits, some of which exhibit multiple subsurface radar reflections [7], could benefit from similar processing. Application of the 3D imaging techniques in these regions would assist in the interpretation of the structural relationship between lava flows and their total volumes, increasing our understanding of the evolution of the Martian landscape during their emplacement.

Conclusion. In an age when sending humans to Mars is a distinct possibility, technological advances in data processing must be applied to regions of potential resources that are being considered for a human presence. The methods discussed herein stand to further our knowledge of the presence and abundance of ice in the subsurface, the evolution of the climate, and the total reservoir of volatile on Mars.

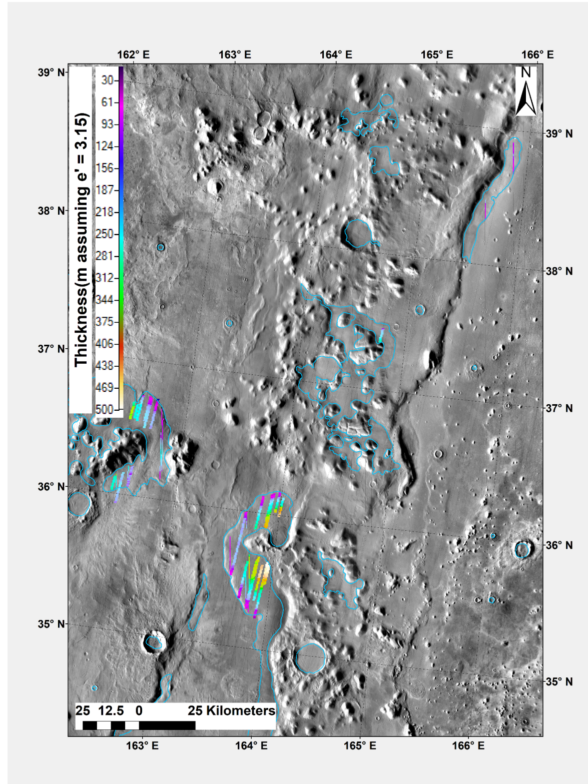

Figure 2: Ice-thickness assuming a dielectric value of pure water ice (3.15) of LDAs based on the high-confidence subsurface reflectors identified in 31 2D radargrams.

Data Availability. The new Planum Boreum and the Deuteronilus Mensae SHARAD 3D radargrams are publicly available in SEG-Y Rev. 2 data format at https://sharad.psi.edu/3D, and delivery to NASA's Planetary Data System Geosciences node is in progress. Access to the Colorado Shallow Radar Processing System (CO-SHARPS) can be requested at https://sharad.psi.edu/cosharps.php.

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References: [1] Putzig et al. (2022) LPSC 53. [2] Seu et al. (2007) JGR: Planets 112.E5. [3] Russell et al. (2021) AGU P35G-2213. [4] Foss et al. (2017) TLE 36.1. [5] Putzig et al. (2018) Icarus. [5] Putzig et al., *in prep*. [6] Holt et al. (2008) Sci. 322(5905) [7] Morgan et al. (2013) 340 (6132).