INVESTIGATING ENGLACIAL DEBRIS BANDS ON MARS WITH SHARAD, USING HIGH RESOLUTION CLUTTER SIMULATIONS AND SLOPE RESOLVABILITY ANALYSIS

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Introduction: Debris-covered glacial landforms at the mid latitudes of Mars preserve ice accumulated in episodes of high obliquity during the Amazonian age (i.e., [300 to 800 Ma]) [1-3]. The presence of debris layers in outcrops and the distribution of boulder bands on the surface, as observed with HiRISE (High Resolution Imaging Experiment, 25 cm/px), indicate the existence of internal debris layers that may have formed during glacial ablation episodes [4-5] and help elucidate glacier evolution and paleoclimate.

Intriguingly, the SHARAD (Shallow Radar) instrument has provided scant evidence of englacial debris bands. These reflectors have been identified with SHARAD in only a few locations, including a lobate debris apron (LDA) complex in eastern Hellas Planitia [6], and a glacial composite system in Phlegra Montes. The latter consists of an LDA fed by a lineated valley fill (LVF) [7].

One reason for the limited detection of englacial debris bands could be the potential signal loss from sloped interfaces during synthetic aperture processing due to destructive interference. Due to refraction, the maximum resolvable slope of a layer decreases when the ray path travels from free air to ice. Consequently, the detection of sloped internal layers is more constrained than a sloped surface [8, 9].

There is also an uncertainty in confirming internal reflectors with clutter simulations ("cluttergrams") using a MOLA (Mars Orbiter Laser Altimeter) DEMs (digital elevation model). Surface clutter can be missing from the simulations due to the low spatial resolution of the DEM (MOLA 463 m/px) compared to the wavelength of SHARAD in free air (~15 m) [10].

This study aims to understand the detectability of englacial debris bands with SHARAD. We employ our model in the south-facing slope of an LDA in Euripus Mons (44.82°S 105.18°E), where internal reflectors have been observed [6]. We present two methods for this validation: 1) high-resolution clutter simulations based on a CTX (Context Camera, 6 m/px) DEM and 2) slope resolvability analysis.

Fig 1. Results for SHARAD orbits 1061401 (top) and 894601 (bottom). Locations are indicated as a-a’ and b-b’ in Fig 2, respectively (a, d): Radargrams (in time delay) showing internal reflectors coherent with englacial debris bands (red) and surface clutter (yellow). (b, e): MOLA DEM cluttergrams retrieved from the Planetary Data System (PDS). (c, f): CTX DEM cluttergrams

Fig 2. Hillshade of the CTX DEM mosaic over Euripus Mons. SHARAD ground tracks 1061401 (a-a’, Fig 1a) and 894601 (b-b’, Fig 1b). Ground tracks of elevation profile (c-c’, Fig 4).

Methodology:

High-resolution cluttergrams: We created a DEM mosaic (Fig 2) from four different CTX stereo pairs to cover the LDA surrounding Euripus Mons. We preprocessed the images with ISIS (Integrated Software for Imagers and Spectrometers) version 3. Then, we used ASP (Ames Stereo Pipeline) version 3.3.0 for stereo processing, mosaicking, and alignment with MOLA DEM. The resulting product is a CTX DEM (12 m/px), which is an input for the clutter simulator [10]. Examples of CTX DEM cluttergrams are shown in Fig 1c and Fig 1f.
Fig 3. Schematic of the idealized setup used to derive the maximum resolvable slope of an internal layer, with the radar beam normal at the nadir point. Δx is the displacement of the radar beam between pulses (Vt/PRF), h is the spacecraft altitude, d is the ice thickness between the surface and the englacial debris band (h >> d), θ is the slope angle of the englacial debris band (γ) relative to the surface (β), and α is the refraction angle.

Model for slope resolvability analysis: We adapted a model for englacial layers on terrestrial ice sheets with airborne sounding radar [9]. Given that the radar is not directional and the spacecraft is further away from the surface than the airborne system, our model assumes that the radar beam from SHARAD is perpendicular at the nadir point (Fig 3). Thus, the slope angle θ is the internal reflector (γ) relative to the surface (β). The maximum resolvable slope of an englacial debris band can be expressed as

\[ \theta_{\text{max}} = \arcsin\left(\frac{c \text{ PRF} \Delta \phi}{4\pi f V_t P n_i}\right) \]

where c is the speed of light, Δφ is the phase shift (set to 180° for consistency with [11]), PRF is the pulse repetition frequency (700.28 Hz), f is the center frequency (20 MHz), Vt is the tangential velocity (~3400 m/s), P is the presum factor (8, default in US SHARAD products) [11, 12], and ni is the refraction index between free air and ice (1.79, with a dielectric constant of 3.2 [3]). With these values, the maximum resolvable slope for englacial debris bands θ_{\text{max}} is 3°.

Discussion:

Qualitative analysis of cluttergrams: In radargram 1061401 (Fig 1a), the internal reflectors (red arrows) within the LDA don’t have a clutter source associated with either cluttergram. The only possible source of clutter is outside the LDA. In radargram 894601 (Fig 1b), there is a source of clutter within the LDA that is enhanced in the CTX-based clutter simulation. However, two internal reflectors don’t have an associated source of clutter.

Therefore, both radargrams in Fig 1 have reflectors that can potentially be englacial debris bands.

Slope resolvability: From the elevation profile shown in Fig 4, we calculated the average slope angle of the surface (β = 2.5°) and the internal layer (γ = 0.4°). This results in a relative slope angle (θ = 2.1°) that falls within the resolvability range (θ < θ_{\text{max}}).

Fig 4. Elevation plot retrieved from [6]. It was generated from manual interpretations on SHARAD radargrams and interpolated with an Inverse Distance Weighted (IDW) algorithm. LDA surface (blue), internal reflector (yellow), basal reflector (purple). Location is indicated in c-c’ (Fig 2). Projected in the coordinate system Mars 2000.

We see two scenarios in which internal reflectors in other Martian glacial landforms may not be resolvable by SHARAD due to an increase in the angle θ: 1) steeper surfaces, or 2) spoon-shaped dipping reflectors. The latter has been observed with ground penetrating radar (GPR) in the cirque of Galena Creek Rock Glacier, a Mars-analog glacier located in Wyoming, USA [13]. GPR imaged internal reflectors that intersect the surface with an angle θ of 26° (β ≈ 11°, γ ≈ -15°). On Mars, such subsurface geometry, even with internal layers at lower dip angles over less steep terrains, may still exceed the maximum resolvability range.