SURFACE ROUGHNESS PREVENTS SHARAD PENETRATION OF SOME MARTIAN DEBRIS-COVERED GLACIERS: A FRAC TAL ANALYSIS OF HI RISE DTMS  

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**Introduction:** Debris-covered glaciers (DCG) are numerous in the mid-latitudes of Mars and are targets of high interest for in-situ resource utilization of water ice, as well as a record of Amazonian climate [1-5].

The Shallow Radar (SHARAD) sounding instrument on board Mars Reconnaissance Orbiter (MRO) detects the base of many DCG and has been used in previous studies [3,4] to constrain their bulk composition (>80% water ice with surface debris 1-10 m thick). A recent expanded survey in the region of Deuteronilus Mensae showed that these results are consistent for 87% of DCG surveyed, while the remaining 13% lacked detection of the base or interior of DCG (Figures 1-2) [6].

One possible explanation is the rough sublimation pit textures that are typically found on DCG surfaces [7]. DCG with exceptionally rough surfaces may scatter the incident radar signal such that any reflection from basal or interior interfaces is reduced to below SHARAD’s noise level.

In this study we quantify DCG surface roughness using a fractal model applied to high resolution digital terrain models (DTMs).

**Methods:** The High Resolution Imaging Science Experiment (HiRISE) is a visible and near infrared imager on board MRO capable of resolutions up to 25 cm. The resolution of HiRISE allows us to accurately quantify topography on the scales relevant to SHARAD. We produced digital terrain models (DTMs) at 1 m resolution from stereo HiRISE imaging at five DCG sites using the open source NASA Ames Stereo Pipeline [8,9].

For each DTM that was produced, patches were extracted that correspond to the effective footprint of individual SHARAD observations (Figures 3, 4a). These patches thus represent the surface roughness relevant to each observation, whether it produced a detection or non-detection of subsurface signal.

We then employed a fractal model developed by [10] to quantify DCG surface roughness for each of these footprints using the rms surface slope parameter \(s(\Delta x)\):

\[
s(\Delta x) = \sqrt{\langle [z(x) - z(x + \Delta x)]^2 \rangle} \quad (1)
\]

Where \(z\) is detrended surface slope and \(x\) the horizontal location along any profile. The rms surface slope is dependent upon horizontal scale \(\Delta x\) and follows an exponential form dependent upon an anchoring rms slope at the scale of the radar wavelength \(s_\lambda\) as well as the hurst exponent H:

\[
s(\Delta x) = s_\lambda (\frac{\Delta x}{\lambda})^{H-1} \quad (2)
\]

\(s_\lambda\) is arguably the most important parameter, while H (values between 0 and 1) describes how roughness increases at greater lengths scales. A least-squares fit of the form shown in Eqn. 2 was then applied to solve for H (Figure 4).

The radar backscattering coefficient is derived:

\[
\sigma_0(H) = 16\pi^3 \rho \int_{r=0}^{\infty} \exp[-4\pi^2 s_\lambda r^{2H} \cos^2 \theta] r^2 \times J_0(4\pi r \sin(\theta)) \, dr \quad (3)
\]

Where \(\rho\) is the assumed surface reflectivity and \(\theta\) the incidence angle.

**Results:** The rms slope \(s(\Delta x)\) for each SHARAD footprint was fit well by equation 2, with all fits featuring \(R^2 > 0.91\). H ranges between 0.24 and 0.62, while \(s_\lambda\) ranges between 2.6° and 5.6°—corresponding to rms height of 0.4-1.0 m. The difference in roughness between DCG surfaces is a result of glacial and periglacial...
textures including sublimation pits (strong effect on $s_\lambda$) and flow lineations/troughs (strong effect on H).

SHARAD observations that were mapped as non-detections generally exhibit values of $s_\lambda > 3.75^\circ$, while detections tend to have values lower than $3.75^\circ$ (Figure 5). Non-detections with lower values of $s_\lambda$ tend to exhibit higher H values. The dividing line in H-$s_\lambda$ parameter space between detections and non-detections roughly follows the contour of $\sigma_0 = 60$ dB.

**Discussion and Conclusions:** There is a strong correlation between surface roughness and the detectability of the subsurface in SHARAD data over DCG. Surfaces with a theoretical backscatter $\sigma_0 > 60$ dB are nearly all non-detections while surfaces with $\sigma_0 < 60$ dB are nearly all detections. This work thus shows that surface roughness alone is sufficient to explain the differences in SHARAD detectability of DCG interiors.

The morphologies controlling DCG surface roughness have been linked to glacial and periglacial processes [11]. This line of evidence, and the similar gross morphology between DCG with and without SHARAD detections, leads us to interpret these features as equivalent in terms of internal composition (>80% water ice).


Figure 3: Context map for Site A (Location in Fig. 1) showing the location of the stereo HiRISE DTM and overlapping SHARAD Fresnel zones corresponding to detections of the glacier interior. Example Fresnel zone shown in Figure 4 is highlighted in green.

Figure 4: Example profile analysis of topography within a Fresnel zone sample of the stereo HiRISE DTM. (a) HiRISE image of Fresnel zone; red line indicates the location of the (b) detrended elevation profile. (c) RMS surface slope $\tan^{-1} s_\lambda$ as a function of $\Delta x$; fractal concepts have been applied to solve for the hurst exponent H.

Figure 5: Hurst exponent H plotted against the rms surface slope $\tan^{-1} s_\lambda$ to present the results of fractal surface roughness analysis for all SHARAD Fresnel zones overlapping HiRISE DTMs in Sites A-E. Detections of the glacier basal interface tend to correspond with surfaces less rough in $\tan^{-1} s_\lambda$, H, or both while non-detections correspond to rougher surfaces. Contours indicate the theoretical backscattering coefficient $\sigma_0$ for surfaces with these values of $\tan^{-1} s_\lambda$ and H (Eqn. 3).