ORBITAL RADAR ASSESSMENTS OF NON-POLAR ICE-RICH TERRAINS ON MARS. N. E. Putzig. Planetary Science Institute, 1546 Cole Blvd., Suite 120, Lakewood, Colorado 80401 USA. Contact: nathaniel@putzig.com.

Introduction: Two radar sounders now operating in Martian orbit have provided a wealth of information about the composition and internal structure of icy layers encompassing both polar regions. Beyond the polar layered deposits, three other terrain types yield subsurface radar returns believed to be associated with the presence of buried water ice. I will discuss the capabilities and limitations of the current radars and their findings in each of these terrains. These considerations inform the planning of future missions to explore and assess Martian near-surface ice that will be crucial for sustaining a human presence on the Red Planet.

Orbital Radar Sounders at Mars:

MARSIS. Since 2005, the Mars Advanced Radar for Subsurface and Ionosphere Sounding on Mars Express (MEX) has been obtaining sounding data from an elliptical orbit [1]. With a 1 MHz bandwidth, MARSIS provides a range (~vertical) resolution of 150 m in free space and 85 m in water ice. Coverage shifts seasonally as the MEX orbit periapsis precesses over time. MARSIS has had great success in mapping subsurface interfaces to depths of 4 km through polar ices and up to 2.5 km depth in non-polar terrains. With its relatively coarse range resolution, shallow subsurface features do not yield discernible reflections. Definitive detections of liquid water at greater depths have not been made, suggesting that the water table is either absent or much deeper than anticipated. Alternatively, there may be ubiquitous near-surface materials that are severely attenuating to the radar.

SHARAD. Since 2006, the Shallow Radar sounder on the Mars Reconnaissance Orbiter (MRO) has been obtaining sounding data from a near-circular orbit [2]. With a 10 MHz bandwidth, SHARAD provides a range resolution of 15 m in free space and 8.5 m in water ice.

Instrument	MARSIS	SHARAD
Orbit (km)	265–11550	255–320
Center freq. (MHz)	1.8, 3, 4, 5	20
Bandwidth (MHz)	1	10
Range res. (m)	150 $\epsilon_r^{-1/2}$	15 $\epsilon_r^{-1/2}$
Inline res. (km)	5–10	0.3–1
Crossline res. (km)	10–30	3–6

Table 1. Characteristics of Mars radar sounders.

However, the radar's ability to resolve very shallow interfaces (< ~20 m) is impaired by the presence of strong down-range sidelobes of the surface returns, an artifact of processing applied to band-limited signals. Coverage is very dense in the polar regions, allowing the construction of 3D data volumes that provide clear images of the structure of both polar caps to depths of 3 km [3]. Beyond the poles, SHARAD has obtained subsurface returns from several terrains known or suspected to contain high concentrations of water ice.

Terrains with Radar-inferred Buried Water Ice:

Debris-covered Glaciers. Landforms termed lobate debris aprons and lineated valley fill have been identified and mapped all across the mid-latitude regions of Mars, with larger and more widespread occurrences in Deuteronilus Mensae, Protonilus Mensae, and on the eastern rim of the Hellas impact basin. While the features exhibit morphologies clearly indicative of flow, debate over the relative fraction of ice was unsettled prior to MRO's arrival. SHARAD obtains strong reflections from the base these deposits in Deuteronilus [4] and eastern Hellas [5], indicating that they are largely composed of nearly pure water ice. While such basal reflections are rare in Protonilus, analysis of their surfaces indicates that roughness is likely causing the radar signals to scatter rather than there being an absence of ice at depth [6]. Although multiple periods of glacier formation and retreat have been hypothesized, there are typically no radar reflections found between the surface and basal returns. The lack of relatively shallow reflections following the surface returns suggests that the debris cover is thinner than the limit (~ 20 m) imposed by sidelobes of the surface returns.

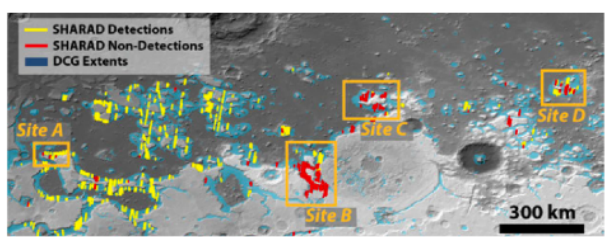

Fig. 1. Map of Deuteronilus and Protonilus Mensae with SHARAD detections and non-detections for basal reflectors in debris-covered glaciers. From [6].

Ground-ice Deposits. The presence of near-surface ground ice on Mars has been inferred for decades, and it was expected that the SHARAD sounder might detect this ice over much of the higher latitudes of Mars.

However, radar detections thought to be related to ground ice have been rather limited geographically, with a first mapping of subsurface returns at the Phoenix landing site at 68°N [7]. For those detections, no means to constrain the material properties has been found, so their relationship to ground ice is speculative, with the authors suggesting on the basis of thermal modeling that they are likely from the base of ground ice. At similar latitudes, radar detections of basal interfaces associated with pedestal craters support the idea that these features are a remnant of once more extensive deposits of ice-rich materials, although the results do not rule out non-ice origins [8]. Other near-surface returns extending down to ~38–40°N have since been found in broad areas of Arcadia Planitia [9] and Utopia Planitia [10], with constraints on dielectric properties (and thus ice content) inferred by relating the returns to terraces in craters and mesas, respectively. The authors inferred that the detections indicate ground ice far in excess of pore-filling. However, others have recently developed a means to constrain loss tangent (i.e., a measure of how reflection power attenuates with depth), and they find that the returns in these two regions are not consistent with massive ice deposits [11]. Even so, geomorphologic evidence and recent impacts have shown that ice is present in these regions at least in the shallow subsurface.

Medusae Fossae. Radar detections of interfaces at what appears to be the base of the widespread, near-equatorial Medusae Fossae Formation have been reported using MARSIS [12] and SHARAD [13]. In both cases, low dielectric constants (~3.0–3.6) were inferred that the authors suggested could be indicative of either extensive ground ice or dry materials with low density, such as volcanic ash deposits. Geological evidence and arguments for both types of material had been suggested previously. Models of ground ice stability and how it varies with latitude (e.g., [14]) have led most researchers to think ground ice could not be present at these low latitudes, and thus the volcanic ash explanation has been favored. However, recent reanalysis of neutron-spectrometer data [15] and the results of the SHARAD loss-tangent analysis [11] for these deposits both suggest the presence of water ice. This prospect of shallow, near-equatorial ice is exciting to consider for possible future human landing sites.

Discussion: To date, all radar detections associated with known or suspected ground ices are thought to be basal. The upper interfaces between dry regolith and massive ice or ice-bearing regolith is apparently too shallow (< ~20 m) to be resolved from the surface returns and their attendant sidelobes [7]. At the higher latitudes (~50–80°), neutron-spectrometer data [16] and thermal measurements indicate that ground ice is pervasive and within a meter or less of the surface. What remains unknown is how that depth to ice increases in more equatorial latitudes. Work is in progress to develop and apply advanced processing methods to the current radar datasets that should allow an improvement in both sidelobe suppression and overall vertical resolution [17], potentially reducing the limitation on SHARAD's ability to resolve shallow layers to depths of ~7-10 m. A favorable result here will narrow the detection gap between the radar and neutron/thermal methods. However, fully resolving this critical zone will require new instrumentation. There are several efforts underway to develop mapping radars (e.g., see Forum presentations by Campbell and Osinski for the 36th Mars Exploration Program Analysis group (MEPAG) Meeting, **https://mepag.jpl.nasa.gov/meetings.cfm?expand=m36**) that may be capable of broadly mapping ground ice in these zones. In each instance, the side-looking radar mapping is intended to be complemented by a "sounding mode" to better constrain the depth to ice where it is detected. As suggested in an earlier report [18], an alternative solution might be to fly a separate sounding radar, which would employ a greater bandwidth than that of SHARAD to resolve this shallow zone, but presumably using a lower center frequency than a mapping radar to avoid concerns about a limited depth of penetration and sensitivity to small-scale surface roughness that may preclude detections in many terrains.

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