

### Three-dimensional imaging of the Martian polar ice caps from orbit with the MRO Shallow Radar sounder.

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**Introduction:** SHARAD, the Shallow Radar sounder on the Mars Reconnaissance Orbiter (MRO), has obtained a large quantity of closely sampled sub-surface sounding data in several locations on Mars. While three-dimensional (3-D) subsurface sounding is performed routinely at the Earth's surface using both radar and seismic techniques, orbit-based observations of this type remain rare. In fact, there is no terrestrial data set with the geographic extent and coverage that SHARAD has obtained for the Martian polar regions. We have created a 3-D radar volume from SHARAD observations of Planum Boreum, a dome of ice-rich deposits that forms the north polar cap of Mars, and are in the process of testing a 3-D imaging process. We are also formulating plans to apply the same process to SHARAD observations of Planum Australe, a similar stack of icy layers at the south pole of Mars.

Interpreting orbital surface-penetrating radar data relies on discriminating between signals returned from surface and subsurface features directly below the spacecraft and signals scattered back toward the spacecraft from off-nadir features (*clutter*). Also, 3-D geometries—such as dipping or folded layering—may result in the mislocation of features when they are imaged solely with 2-D methods. The synthetic-aperture focusing typically applied to radar data compresses returns from along-track scatterers but not those from cross-track scatterers, potentially leaving a structural blur in the data. In addition, the signal-to-noise ratio (SNR) can be quite low for single observations when material properties lead to substantial scattering or absorption. For terrestrial radar and active-source seismic surveys, a imaging technique known as *migration* has been developed over the last few decades to address such geometric and loss problems. 3-D acquisition, often involving many sources and receivers spread over a large area, is now routinely employed in terrestrial studies, and 3-D migration often largely corrects geometric distortion by placing structures in their proper location in 3-D space while improving SNR.

Migration of the 3-D volume of SHARAD data should alleviate the strong off-nadir interference from pervasive troughs that cut the surface of Planum Boreum while correcting structural relationships and enhancing faint returns. These improvements will allow much greater accuracy and confidence in the interpretation of structural and stratigraphic features of both the finely layered, ice-rich units in the upper part of the section and the more coarsely layered units at

the base that likely contain a higher fraction of lithic materials. Clarifying these features will in turn allow major advancements toward the overarching goal of linking the geologic history of the polar layered deposits to climate processes and their history.

**Background:** SHARAD is a chirped-pulse sounding radar with a 10-MHz bandwidth centered at 20 MHz. Range (~vertical) resolution is 15 m in free space and ~10 m in the subsurface, depending on the material properties. For nearly pure water ice with a real permittivity of 3.15 as is expected for the Planum Boreum layered deposits (1-3), the range resolution is ~8 m. A greater proportion of lithic inclusions, as is likely the case for the Planum Boreum basal deposits, will increase the real permittivity and thereby yield a finer range resolution. In the case of CO<sub>2</sub> ice, which typically has a lower real permittivity (~2.1), the radar will yield a coarser range resolution of ~10 m, insufficient to resolve the perennial CO<sub>2</sub>-ice and water-ice layers of the ~5-m thick south polar residual cap (4) but capable of resolving the recently discovered thick deposits of CO<sub>2</sub> ice that underlie them (5). With the MRO orbit at an altitude of 250–320 km, the lateral resolution at the surface is ~3–6 km (1–2 Fresnel zones), reducible in the along-track direction to 0.3–1.0 km with synthetic-aperture focusing (6). Bright returns in a radargram typically indicate a strong contrast in the dielectric properties of materials at a geologic interface. In the polar terrain of Mars, the reflections likely arise from dielectric differences between ice layers with different degrees of dust or lithic loading (e.g., 7, 2, 3). In Planum Australe, dielectric contrasts may also be related to boundaries between layers of CO<sub>2</sub> ice and water ice (5).

Seismic surveys are typically designed to sample the subsurface in either a large cross-sectional area (i.e., 2-D acquisition with sources and receivers deployed in a line) or a volume (i.e., 3-D acquisition with sources and receivers deployed in a given area). The complexity of the recorded image depends on the distribution, geometry, and magnitude of acoustic impedance boundaries, which may include horizontal and dipping interfaces of geological formations, faults, intrusive bodies, edge or point scatterers, and pore-filling fluids. Because of such complexity, certain processes are often applied to seismic data to increase its interpretability, and migration has become a routine part of the processing sequence. Migration is a mathematical inversion process whereby the seismic image

recorded at or near the surface is re-imaged to appear as if it were recorded directly above the subsurface points sampled by the propagating wave field (8-11), thereby placing subsurface features in their proper position both laterally and vertically (in time or depth). Migration also improves resolution by collapsing backscattered wave-field energy to the scattering point. Over the last several decades, there have been many migration algorithms developed and implemented to account for various degrees of subsurface seismic complexity (12-14). Most migration algorithms require *zero-offset* data, with co-located sources and receivers. However, zero-offset seismic surveys are not typical in practice because sources (e.g., dynamite, airguns) are generally destructive. Processing steps are applied to create a pseudo-zero-offset 3-D volume from nonzero-offset data. For SHARAD, since the transmit and receive modes use the same antenna and Doppler processing accounts for the relative motion between the spacecraft and the Martian surface, collections of 2-D radargrams already are zero-offset 3-D volumes. With 3-D migration, off-nadir clutter treated as noise in 2-D become useful signal by enhancing the resulting image when repositioned to its source location. In addition, SNR is improved by a combination of band-limited, spatial-domain processing and incoherent stacking of reflectors seen in multiple SHARAD tracks.

**Previous Work:** Analysis of early-mission SHARAD data from Planum Boreum (2) and subsequent mapping with more extensive coverage (3) revealed a pervasive, broadly continuous stack of layers, with packets of finely spaced layers overlying relatively homogeneous inter-packet zones (Fig. 1). Comparison to results from climate models (16, 17) suggests that each sequence may correspond to a ~1-My obliquity or eccentricity cycle. A low degree of basal deflection (< 100 m) indicates either a transient state of compensation in the mantle (unlikely) or a much thicker (~300-km) elastic lithosphere than had previously been considered. Later work by Holt et al. (18) delineated unconformities and mapped a buried chasma to the east of the topographic saddle that separates Gemina Lingula from the main lobe of Planum Boreum. Beneath the finely layered deposits, the SHARAD data show diffuse returns (Unit B in Fig. 4a) that extend down to the level where the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) obtained a strong return from a basal unit (19). Operating at a lower frequency, MARSIS is capable of sounding to greater depths than SHARAD but with about tenfold more coarse vertical resolution. The diffuse zone appears to correspond to geologic units at the base of the finely layered deposits identified previously in image data (20-22).

**Preliminary Results:** We selected a set of 540 SHARAD observations with ground tracks crossing the Planum Boreum saddle region for use in testing 3-D binning, signal-enhancement processing, and migration (Fig. 2). We have successfully created a 3-D volume from this saddle-region subset. Coverage in the 500-m  $\times$  500-m bins ranges from 0 to 33, highest at the ground-track tangent latitudes near 87°N. Relatively large coverage gaps exist toward the periphery of the subset (Fig. 2 inset), so we applied a spatial interpolation prior to 3-D signal-enhancement and migration tests, which are currently underway. Figure 3 presents

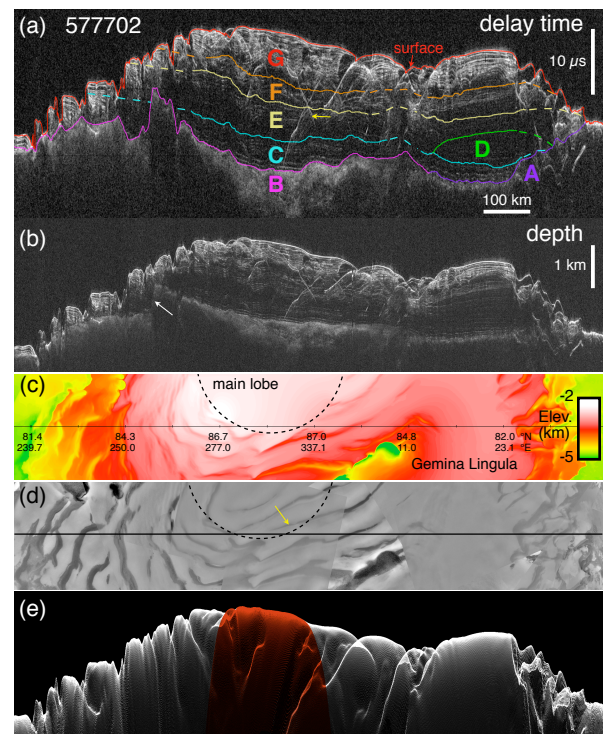


Figure 1. Radargrams for SHARAD observation 577702 in (a) delay time and (b) depth across Planum Boreum. Bounds for radar Units A–G are dashed where extrapolated. Depth version assumes a subsurface real permittivity of 3.15 (nearly pure ice). Vertical exaggeration ~100:1. (c) MOLA elevation map and (d) Viking MDIM mosaic show location of ground track. (e) Simulated delay radargram from MOLA data and an incoherent scattering model (Holt et al., 2006) identifies as surface clutter many returns with steep apparent dip. Some returns (e.g., arrow in a) that do not appear in the simulation are attributable to troughs (e.g., arrow in d) poleward of the ~87°N limit of the MOLA data (dashed black semicircles). Red shading in (e) shows region affected by the MOLA no-data zone. White arrow in (b) identifies a large elevation anomaly at top of Unit B, which the 3-D volume will help to resolve. From Putzig et al. (2009).



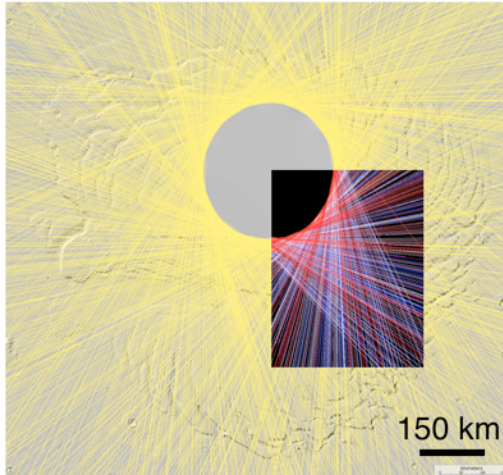


Figure 2. SHARAD ground tracks (yellow) over Planum Boreum as of March 2011 (1480 orbits). Inset shows subset of tracks over saddle-region (540 orbits) used in 3-D binning (Fig. 3) and imaging tests. Basemap is MOLA shaded relief.

some views of the infilled subset 3-D volume. Even with this relatively sparse, unmigrated 3-D volume, features such as the internal trough-migration paths of Smith and Holt (23), the buried chasma of Holt et al. (18), and the basal-unit boundary mapped by Putzig et al. (3) are revealed in surprising detail. 3-D signal-enhancement processing and migration will sharpen these and other previously mapped structures, and inclusion of the full data set in this process will allow the delineation of many new features throughout Planum Boreum.

**Discussion:** While efforts to correlate radar reflections in the Martian polar layered deposits to layering seen in image data have met with some success (e.g., 24, 25, 26), tracking individual reflectors or packets of reflectors to their intersections with either the walls of incised troughs or the periphery of the deposits is often hampered by loss of signal due to some combination of interference, scattering, and attenuation. In many cases, the geometry of surface undulations and troughs is likely the cause of these issues (e.g., see dashed colored lines in Fig. 1a). Synthetic radargrams created from elevation data (Fig 1e) are useful in identifying the sources of interfering returns and avoiding the misinterpretation of features. The application of

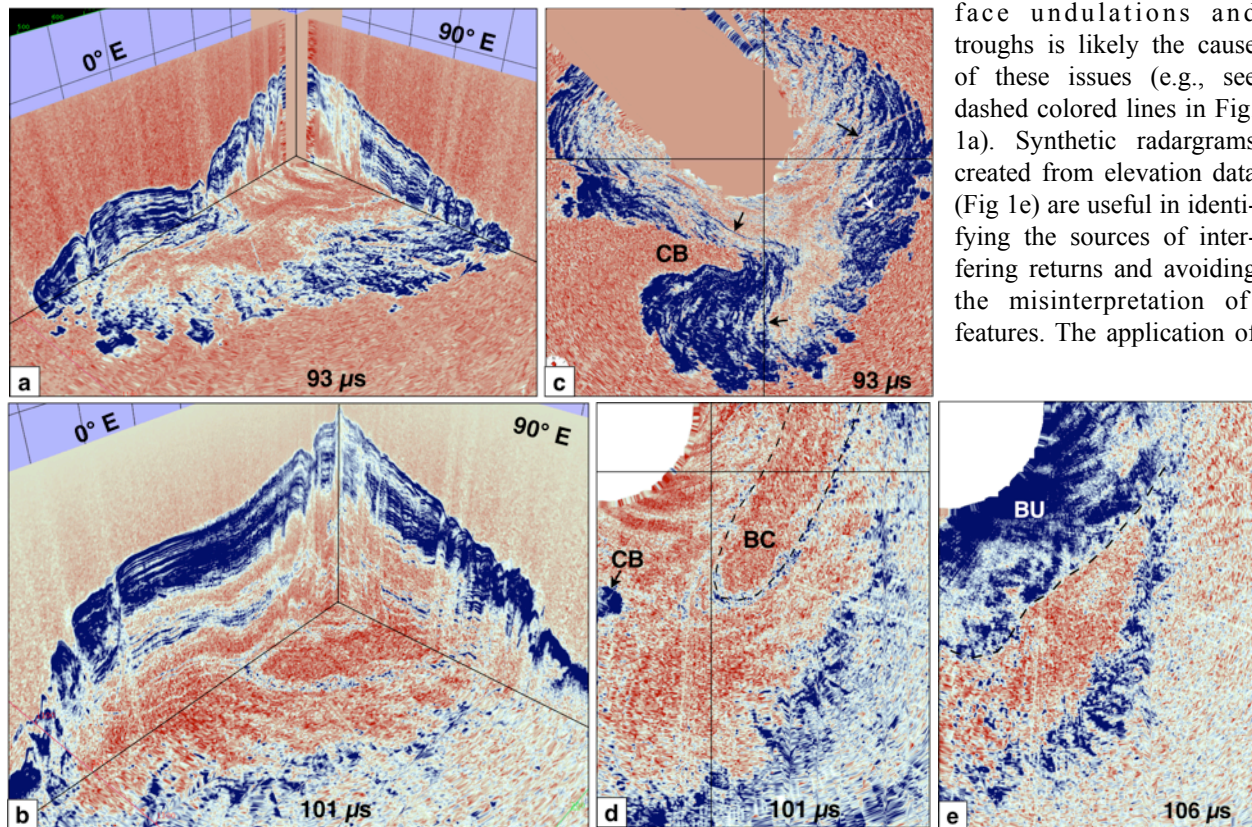


Figure 3. Cut-away views (a, b) and timeslices at constant delay (c–e) taken from the infilled 3-D volume produced from the subset of SHARAD tracks (with full ~8-fold bin coverage only in the saddle region; see Fig. 2 inset). Views show the radar return power (blue high, red low) from the interior of Planum Boreum. Interior trough migration paths are visible in the 93- $\mu$ s timeslice (a, c) in and beyond the region where they were mapped by Smith and Holt (23) (at arrows in c). A buried chasma (BC) first identified by Holt et al. (15) appears in the 101- $\mu$ s timeslice (b, d) as a horse-shoe feature (dashed line in d) across the saddle from Chasma Boreale (CB); adjacent timeslices (not shown) confirm its synclinal structure. Near the base of the layered deposits, the timeslice at 106  $\mu$ s (e) show in unprecedented detail the boundary (dashed line) of the basal unit (BU) where it is buried beneath the saddle region.

a 3-D migration process will take such analysis a step further, largely unraveling the interfering signals and allowing much greater confidence in our interpretation of subsurface structure as it is imaged by the radar data, thus expanding our ability to track reflection events and identify their terminations in regions where jumbled signals are currently indecipherable.

In Planum Australe, SHARAD data has a broadly different character (27). While the radar does show a thick stack of layers in some regions (25), in many other areas layering is obscured or absent altogether. In any case, there is likely no direct correspondence to the layers in the north, since the surface cratering record of Planum Australe suggests an age of ~10 Ma (28, 29), over twice the age of the entire stack of layers in Planum Boreum based on models of ice stability (17). The south also contains striking near-surface zones devoid of reflections above the noise level that occur in several areas. Phillips et al. (5) mapped four such reflection-free zones (RFZs) and found geometries for one in the perennial CO<sub>2</sub> cap region at the pole that allowed them to constrain the real permittivity, finding values consistent with a massive, shallowly buried deposit of CO<sub>2</sub> ice. If sublimated, this deposit would nearly double Mars' atmospheric pressure. At present, geometries in the SHARAD 2-D data have not allowed a constraint on the permittivity of the outlying RFZs, which may be of a different nature. With 3-D binning, signal-enhancement processing, and migration, our ability to map these deposits in detail and perhaps constrain their composition may be much improved.

Any effort to perform a similar 3-D imaging of ice sheets on the Earth will pose new and different challenges. At Mars, there is only a remanent magnetic field, the CO<sub>2</sub> atmosphere is thin and dry (at most, a few 10s of mm of precipitable water), and the polar deposits are extremely cold (~200 K) and believed to be nearly devoid of interstitial liquid water through to their base. In contrast, the Earth's active magnetic field produces a stronger and more variable ionosphere, and the higher moisture content in both the atmosphere and within the ice sheets would introduce much greater distortion and absorption for an orbital radar sounder using comparable wavelengths. A more likely terrestrial application of 3-D migration to subsurface radar would be for data acquired from airborne radars using a different range of frequencies.

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