Three-dimensional radar imaging of structures within the north polar cap of Mars. Nathaniel E. Putzig[1], Frederick J. Foss II[2], and Bruce A. Campbell[3]. [1]Southwest Research Institute, Boulder, CO (nathaniel@putzig.com); [2]Freestyle Analytical & Quantitive Services, LLC, Longmont, CO; [3]Smithsonian Institution, Washington, DC.

Introduction: We present a new three-dimensional (3-D) volume of radar data from observations taken by the Shallow Radar (SHARAD) instrument on 2311 orbits of the Mars Reconnaissance Orbiter (MRO). This volume encompasses the entirety of Planum Boreum, the dome of ice-rich deposits that forms the north polar cap of Mars (Fig. 1), and it provides a greatly improved view of the cap's internal structure from the surface to the base of the deposits at depths of ~2–3 km.

SHARAD Observations: With a 10-MHz bandwidth centered at 20 MHz, SHARAD has a range resolution of 15 m in free space, ~8 m in nearly pure water ice (expected in the Planum Boreum layered deposits [*Picardi et al., 2005; Phillips et al., 2008*]), and still finer in ice with more lithic inclusions (expected in the basal deposits [*Plaut et al., 2012*]). From MRO's ~300 km orbit altitude, SHARAD's lateral resolution at the surface is ~3–6 km, reducible along track to 0.3–1.0 km with synthetic-aperture processing [*Seu et al., 2007*]. High-power returns from the surface and subsurface interfaces indicate a strong contrast in the dielectric properties of materials. In the polar terrains, the reflections likely arise from different degrees of dust or other lithic loading between adjacent ice layers [*Phillips et al., 2008; Putzig et al., 2009; Nunes and Phillips, 2006*].

Off-nadir returns. Surface features such as crater walls and polar troughs located beyond the spacecraft's nadir point yield reflections, termed *clutter*, that can be difficult to distinguish from nadir returns. Internal structure (e.g., dipping layers) may result in the mislocation of features in 2-D radargrams (images of returned power along track vs. delay time). While 2-D synthetic-aperture processing correctly positions reflectors in time delay, the relationship of delay to 3-D physical location differs among nadir and off-nadir surface and subsurface interfaces. In addition, the signal-to-noise ratio (SNR) can be low when material properties lead to substantial scattering or absorption.

SHARAD studies often use elevation data from other instruments (typically MOLA, the Mars Orbiter Laser Altimeter) to simulate surface clutter for comparison to 2-D radargrams [*e.g., Putzig et al., 2009; Holt et al., 2008*], but this technique does not mitigate clutter obfuscation of nadir subsurface returns, mis-positioning of internal structures, and signal losses. With sufficient density of coverage, each of these issues can be alleviated with 3-D migration processing when treating the data as a single volume.

Time delays. Prior to applying migration processing, the along-track data must be corrected for any relative time delay introduced by the variable orbit altitude and the Martian ionosphere. While accurate ephemeris data enables a straightforward altitude correction, we found that the ionospheric delay varies significantly along track and from one orbit to another. A substantial effort produced an accurate method for correcting ionospheric phase distortion and estimating the delays [*Campbell et al., 2014*], but residual delays up to ~0.2 µs remain. Investigation of a means to further reduce these time delays is ongoing.

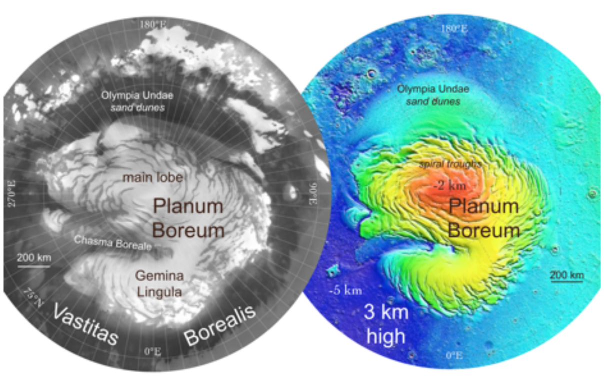

Figure 1. Two views of the north polar region of Mars, showing the high-standing icy layered deposits in a mosaic of Mars Orbiter Camera images (left) and a color-coded (red=high, blue=low) shaded relief map from the Mars Orbiter Laser Altimeter (MOLA).

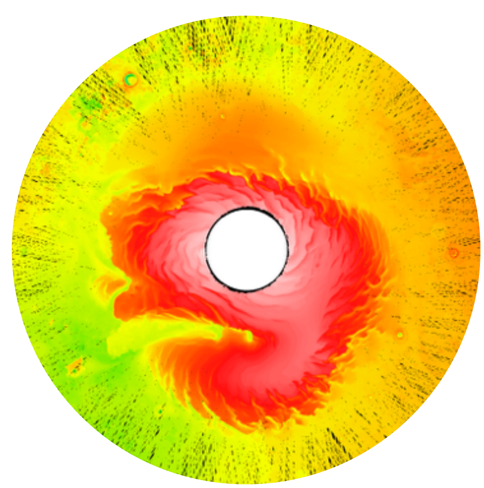

Figure 2. Map of current SHARAD coverage poleward of 75°N, binned at 3 km per pixel (~1 SHARAD Fresnel zone) and colored by MOLA elevation. About 3000 orbital tracks over Planum Boreum enable 3-D processing. A coverage void poleward of ~87.4°N results from the inclination of MRO's near-polar orbit.

Migration Processing: The occurrence in seismic data of the geometric and loss concerns discussed above led to the development of migration processing, a mathematical inversion that converts the recorded seismic image to one in which subsurface features appear in their proper position both laterally and vertically [*Claerbout, 1985; Yilmaz, 1987*]. Migration processing also improves resolution by collapsing backscattered wave-field energy to the scattering point. Many migration algorithms have been developed to account for various degrees of subsurface complexity [*Stolt, 1978; Gazdag, 1978; Gray et al., 2001; Bednar, 2005*]. As applied here, 3-D migration addresses many limitations of 2-D radargrams. For example, clutter returns are useful signals in 3-D space, enhancing the resulting image when repositioned to their source locations. Interfering returns are unraveled and internal structures are properly positioned. In addition, SNR improves by a combination of band-limited, spatial-domain processing and incoherent summation of reflectors seen in adjacent and crossing orbit tracks.

Previous 2-D Results: Collective analysis of SHARAD radargrams has revealed a repeated sequence of broadly continuous layers in Planum Boreum, likely linked to ~1-Ma obliquity cycles [*Phillips et al., 2008; Putzig et al., 2009*]. Enormous spiral troughs evident at the surface were mapped into the interior along trough-bounding surfaces visible in radargrams as layering discontinuities. Analysis of these features shows them to be giant aeolian bedforms that have been translating poleward since the layered deposits were about half their present thickness [*Smith et al., 2013*]. Similarly, Chasma Boreale, which separates the main lobe of layered deposits from the Gemina Lingula lobe, has been shown to be a constructional rather than an erosional feature [*Holt et al., 2010*]. In addition, a completely buried chasma of similar scale to that of Chasma Boreale was discovered by mapping unconformities and deep structure below the region east of the topographic saddle that separates Gemina Lingula from the main lobe [*Holt et al., 2010*]. Deeper still, diffuse returns extend down to the level where the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) obtains strong returns from the bottom of a basal unit that underlies about two-thirds of Planum Boreum [*Brothers et al., 2015; Selvans et al., 2010; Tanaka et al., 2008*].

3-D Processing Workflow: To produce 3-D volumes with SHARAD observations, we begin with 2-D radar processing wherein we apply an autofocusing method that includes synthetic-aperture and Doppler processing to enhance the along-track resolution and account for the effects of spacecraft motion relative to the surface [*Campbell et al., 2011*]. This method includes a means to correct phase distortions and estimate the time delays introduced by passage of the signals through the Martian ionosphere [*Campbell et al., 2014*]. Standard practice for generating radargrams intended for 2-D analysis (see the derived data products on the Planetary Data System (PDS) at http://pds-geosciences.wustl.edu/missions/mro/sharad.htm) uses apertures and Doppler bandwidths tuned to suppress clutter signals (e.g., PDS U.S. products use an aperture of 9 s and a bandwidth of 0.4 Hz). In preprocessing for 3-D volumes, we choose a longer aperture (18 s) and a wider Doppler bandwidth (0.8 Hz) because clutter suppression is no longer desired. It proved impractical to omit the conversion to power and the 2-D focusing from the preprocessing, so upon reading the data into Landmark Graphics ProMAX SeisSpace software, we apply a DC shift to yield pseudo-amplitude and a demigration process to remove the 2-D focusing. Subsequently, the data are placed into a rectilinear binning grid, summing together data from multiple tracks that may occur in any given bin and interpolating to fill any empty bins. The preprocessing registers the data to a Martian equipotential surface (areoid), so we reregister it to the average spacecraft radius, as the 3-D imaging algorithms we employ require that the input datum be near the acquisition point. At this stage, one may perform full 3-D migration processing of the data, but the ~300 km elevation of the spacecraft makes this step very compute intensive and a burden for data storage. To alleviate these resource constraints, Stewart Levin of Stanford University kindly offered to develop 3-D downward continuation code that reconstructs the data as it would have been recorded from a level much closer to the surface [*Levin and Foss, 2014*]. This interim step allows us to apply the 3-D migration process from the near-surface datum, saving time and resources. Because the SHARAD dataset is effectively a zero-offset volume and the polar layered deposits largely represent a constant-velocity subsurface, the highly efficient Stolt algorithm [*Stolt, 1978*] for 3-D migration processing is sufficiently accurate for our purposes.

3-D Results. In a preliminary study, we constructed a 3-D data volume from SHARAD observations on 540 orbital passes over eastern Planum Boreum, with a lateral bin size of 500 m × 500 m and no migration processing [*Putzig et al., 2012*]. Despite these limitations, the volume readily shows features such as the trough-bounding surfaces, the buried chasma, and the basal-unit boundary that previously required painstaking effort to map with 2-D radargrams. This work facilitated advances in the mitigation of ionospheric effects [*Campbell et al., 2014*] and other preprocessing concerns. With these improvements and full geographic coverage of Planum Boreum from 1579 orbit passes, a first 3-D volume encompassing the entire cap was produced, to which we also applied migration processing. The new, more extensive volume revealed major structural features that were largely hidden in the 2-D radargrams (Fig. 3), and provided the first indication of buried impact craters within the icy layered deposits [*Putzig et al., 2014*].

To demonstrate the efficacy of the 3-D processing, we selected a 2-D single-orbit SHARAD radargram for comparison to a nearly coincident inline track (constant X value in the polar projection) extracted from the 1579-orbit 3-D volume before and after migration (Fig. 3), and we include a constant-delay-time slice through the volume along a swath centered on the same track. The views of gross internal features such as the trough-bounding surfaces, the buried chasma, the basal-unit boundary, and the diffuse basal unit itself are significantly sharpened by migration processing. In addition, previously hidden features are revealed, such as the shallow sloping reflector in Fig. 2d that appears to be a major unconformity. Elsewhere in the 3-D volume, known impact craters that are partially buried within the polar layered deposits have distinctive, bowl-shaped signatures. Similar features in other portions of the volume have no surface expression but may also be impact craters.

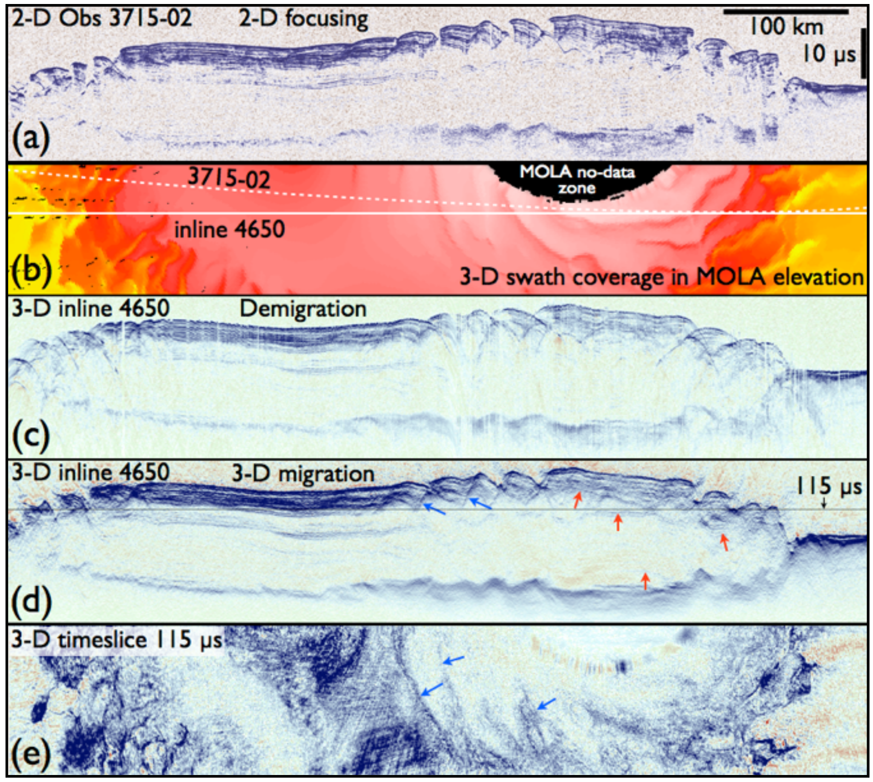

Figure 3. 3-D processing reveals new features within Planum Boreum. (a) 2-D radargram for SHARAD observation 3715-02 shows radar return power (blue high, red low), extending left to right across eastern Gemina Lingula, the main lobe, and into Olympia Planum. Subsurface reflectors are often obfuscated by interfering returns from off-nadir features and scattering losses, especially below trough-rich areas. (b) Map of SHARAD coverage at 3-km per pixel over a 3-D swath from the 1579-orbit volume (yellow-red-white colors are low-to-high elevations from MOLA), showing ground tracks for the radargram in (a) and the 3-D inline in (c) and (d). (c) Radargram for 3-D inline 4650 after demigration to recover hyperbolic move-out of off-nadir returns. Residual timing differences discussed in text are discernible. (d) Radargram for 3-D inline 4650 after 3-D migration. Surface and subsurface geometry, including that of trough-bounding surfaces (blue arrows), is corrected, and formerly hidden reflectors (red arrows) are revealed in areas most affected by off-nadir returns. (e) Timeslice at 115 μs from migrated 3-D radar swath. Trough-bounding surfaces (blue arrows), structural boundaries, and other features are sharpened.

Most recently, we have further tuned the ionospheric corrections, adjusted data scaling to improve dynamic resolution, reduced the bin size, and incorporated the latest data to produce a new migrated volume from SHARAD observations collected on 2311 MRO orbits. Coverage in the smaller 475×475-m bins ranges from 0 to ~50 tracks per bin, highest at the orbital tangent latitudes near 87°N. The additional coverage and the scaling improvements provides increased resolution and better dynamic range in this latest volume, which will be featured at the 3-D Symposium.

Validation and mapping of the crater-like features throughout the volume may provide a new means to constrain the age of the polar layered deposits that is independent of climate models. In general, the clearer views of the Planum Boreum interior provided by 3-D processing are advancing our understanding of the geologic history of the polar layered deposits and promising to yield new insights into the evolution of Martian climate throughout the late Amazonian period.

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