3-D SUBSURFACE IMAGING OF PLANUM BOREUM WITH SHARAD DATA. N. E. Putzig[1], F. J. Foss II[2], B. A. Campbell[3], and R. J. Phillips[1]. [1] Southwest Research Institute, 1050 Walnut St, Suite 300, Boulder, CO 80302 (nathaniel@putzig.com); [2] Freestyle Analytical & Quantitative Services, LLC, 2210 Parkview Dr, Longmont, CO 80504; [3] Smithsonian Institution, MRC 315, PO Box 37012, Washington, DC 20013.

Introduction: We describe work currently underway that will transform the large collection of observations of Planum Boreum by the Mars Reconnaissance Orbiter's Shallow Radar (SHARAD) instrument into a geometrically corrected 3-D subsurface volume.

A major goal of Mars exploration has been to explain the nature and timing of the polar layered deposits that occur at both poles. The idea that the sequence of layers is linked to climatological cycles holds the promise of decoding past climate by determining the processes controlling the rates of accumulation and erosion of these materials [1,2,3]. SHARAD has provided windows into the interiors of Planum Boreum [4,5,6,7] and Planum Australe [7,8,9], but seeing clearly through those windows to the structure and stratigraphy below is limited by our ability to reconstruct an accurate image from the returned radar signals.

Conventional radar analysis: Currently, we present and analyze SHARAD observations as radargrams, which are 2-D profiles with distance along track horizontally and power vs. delay time (sometimes converted to depth) vertically in an image format [Fig. 1]. 3-D features are characterized by taking a series of observations and "connecting the dots" to map out radar returns from the surface and subsurface interfaces. While the pictures thereby produced are clearer in some areas (e.g. Planum Boreum) than in others (e.g., Planum Australe), even in the best cases, our understanding is obfuscated by "clutter," which is signals returned from features that lie outside of the spacecraft's nadir track that interfere with those from the subsurface below it. Clutter is typically generated by topographic rises or depressions at the surface with facets oriented toward the spacecraft. Current efforts to distinguish the clutter from nadir subsurface returns are limited to the generation of synthetic radargrams from topographic models of the surface. Any returned signal appearing in the SHARAD data that has a corresponding feature in the synthetic is deemed to be a return from the surface and is dismissed as "noise". In some cases, off-nadir returns may actually arise from subsurface interfaces (e.g., [10]). In other cases, no nadir returns at all are obtained due to the surface being sloped away from spacecraft. These problems all arise from the attempt to produce a 2-D cross-section of a 3-D object using an inherently 3-D signal.

3-D radar analysis: To clarify the picture, radar signals returned from off-nadir need to be repositioned to their actual source locations, but identifying unique source locations is typically not possible within a single observation. With multiple observations from a range of lateral offsets, one can begin to partition nadir and off-nadir signals, and thus promote the clutter from noise to signal. On Earth, densely sampled subsurface sounding is performed routinely for industrial and scientific purposes using both radar and seismic methods, and 3-D imaging techniques (often referred to as "migration") are applied routinely to these data sets.

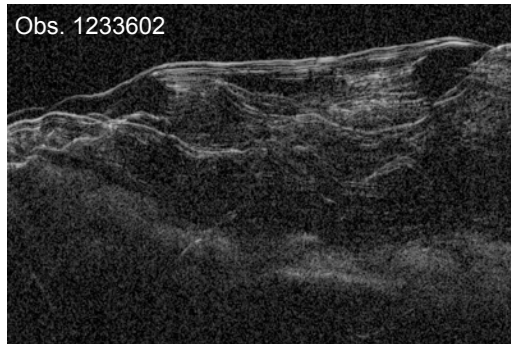

Figure 1. SHARAD radargram from a portion of Planum Boreum showing coincident returns from off-nadir features and subsurface interfaces.

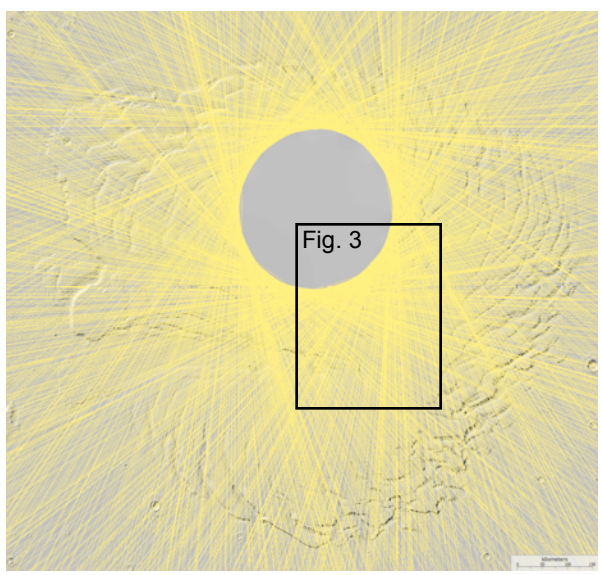

Figure 2. Yellow lines show SHARAD groundtracks over Planum Boreum from 1480 orbits, as of March 2011. Basemap is MOLA shaded relief.

As of this writing, SHARAD has acquired observations on over 1500 orbits across Planum Boreum (Fig. 2) and 1200 across Planum Australe since operations began in 2006, and these large volumes of closely sampled subsurface sounding data are amenable to 3-D imaging. Subsurface returns from Planum Boreum are substantially more consistent than those from Planum Australe (cf. [4] and [7]), so we began our effort to apply 3-D imaging methods to the SHARAD data from the former region, and we will describe our methods and initial results at the 5th International Conference on Mars Polar Science and Exploration.

Datum corrections and 3-D binning: In order to allow the use of existing 3-D imaging technologies, all observations need to be referenced to a common datum (i.e., aligned vertically in range delay), and the data needs to "binned", i.e. emplaced into a regular lateral grid. The imaging process is highly compute-intensive and its effectiveness is dependent on the details of the binning scheme. We therefore have chosen a representative subset of the Planum Boreum observations on which to test various binning schemes and migration algorithms, where we will vary the bin size and geometry (e.g., bins defined by rectangular, polar, and pseudo-polar geometry, where the latter is closely aligned to either the ascending or descending branch of the orbit tracks). Figure 3 shows the ground tracks for the chosen subset of data, which is centered over the topographic saddle between the main lobe and the Gemina Lingula lobe of Planum Boreum. SHARAD observations over this region show a regular sequence of quasi-parallel layers that are largely flat-lying but include enough structure to evaluate the quality of imaging results from different migration algorithms.

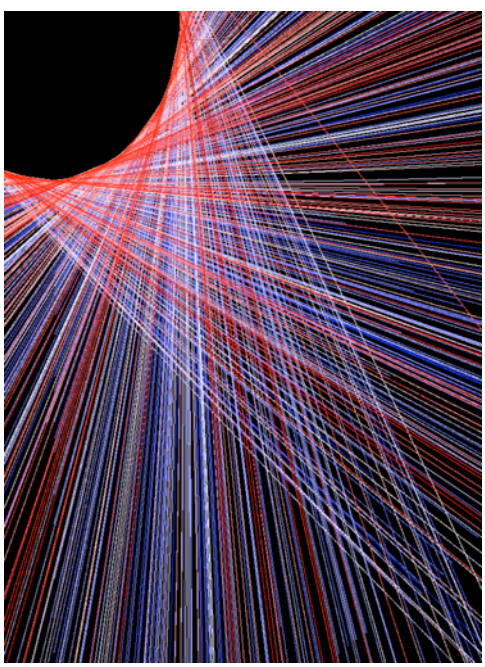

Figure 3. Colored lines show SHARAD groundtracks over the saddle region of Planum Boreum from 540 orbits. Blue, white, and red correspond to early, intermediate, and late orbits.

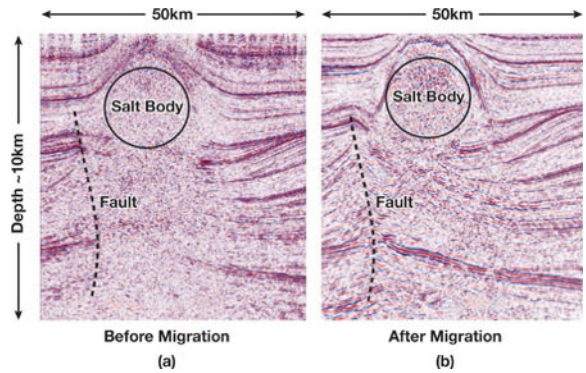

Figure 4. A terrestrial example of the effectiveness of 3-D migration, applied here to a seismic data set that was acquired over a salt body on Earth. Image is from the web site http://developer.nvidia.com/node/195/.

3-D imaging considerations: Doppler processing that is applied to the SHARAD data prior to the binning will account for the motion of the spacecraft that occurs between the time when a signal is transmitted and when it is received, and the data may thus be treated as zero-offset (i.e., co-located source and receiver) going into the migration process. A number of different migration algorithms have been developed and implemented over the last several decades to account for various types of subsurface geologic complexity (e.g., see Fig. 4). Earlier analysis has established that the polar layered deposits are very ice-rich [4,11], so the radar propagation velocity within Planum Boreum is essentially constant, whereas seismic velocities in typical terrestrial studies are much more variable. Thus, we will likely be able to use very fast and accurate imaging methods, such as 3-D frequency-wavenumber migration [12].

References: [1] Clifford S. M. et al. (2000) *Icarus 144*, 210–242. [2] Fishbaugh K. E., Head J. W. (2005) *Icarus 174*, 444–474. [3] Tanaka K. L. et al. (2008) *Icarus 196*, 318–358. [4] Phillips R. J. et al. (2008) *Science 320*, 1182–1185. [5] Putzig N. E. et al. (2009) *Icarus 204*, 443–457. [6] Holt J. W. et al (2010) *Nature 465*, 446-449. [7] Smith I. B. and Holt J. W. (2010) *Nature 465*, 450–453. [7] Seu R. et al. (2007) *Science 317*, 1715–1718. [8] Phillips R. J. et al. (2009) *LPS XL*, Abstract #2007. [9] Phillips R. J. et al. (2011) *Science 332*, 838–841. [10] Plaut J. J. et al. (2010) *LPS XLI*, Abstract #2454. [11] Nunes D. C., Phillips R. J. (2006) *JGR 111*, E03002. [12] Stolt, R. H. (1978) *Geophysics* 43, 23–48.