

3-D Processing of SHARAD Data

An Overview for Planetary Data System Users

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Summary

This document provides an overview of Mars Reconnaissance Orbiter (MRO) Shallow Radar (SHARAD) observations of Mars and of the processing steps that went into producing three-dimensional (3-D) radargrams from portions of that data, such as that of the north and south polar regions and various locations in the midlatitudes. A description of the initial 3-D processing procedure can be found in the article by Foss et al. [2017] published by the Society of Exploration Geophysicists in *The Leading Edge* and featured on the cover of the January 2017 issue. Discussion of results emerging from those first polar 3-D radargrams can be found in the article by Putzig et al. [2018] in a special issue of *Icarus* that features results of recent studies of the polar regions of Mars. One conclusion from those first polar data volumes was that delay-time offsets between SHARAD observations along individual orbit segments were not completely removed from the dataset, so a new effort was made to correct that problem. The correction involved the use of surface-clutter simulations for each observation and the adjustment of the first arrivals in the radargrams to match those predicted by the simulations. This new procedure was first applied for the north polar region, and first science results are described by Putzig et al. [2024]. The method was then applied in the midlatitudes for the first time for a region of debris-covered glaciers in East Deuteronilus Mensae and demonstrated to be successful [Perry et al., 2024]. A thorough discussion of the original and revised processing procedures is provided by Foss et al. [2024].

SHARAD observations

SHARAD is a chirped-pulse sounding radar with a 10-MHz bandwidth centered at 20 MHz. The radar wavelength is 15 m, which sets the range (~vertical) resolution in free space. The range resolution becomes finer in the subsurface, depending on the material properties [Seu et al., 2007]. For nearly pure water ice with real permittivity $\epsilon' = 3.15$ as is inferred for the north polar layered deposits [Picardi et al., 2005; Phillips et al., 2008; Grima et al., 2009], the nominal range resolution is reduced to ~8 m. A greater proportion of lithic inclusions, thought to be the case for Planum Boreum basal units in the north and portions of Planum Australe in the south, will increase the real permittivity and thereby yield a still finer range resolution. A greater fraction of pore space or a different composition (e.g., CO₂ ice, such as in the zones of low radar reflectivity near the south pole; see Bierson et al. [2016]) may result in a decrease of real permittivity and a coarser range resolution than that in pure water ice. However, the range resolution is impacted by subsequent processing aimed at reducing signal sidelobe energy such that the effective vertical resolution in the subsurface remains about 15 m [Putzig et al., 2024]. With the MRO orbit at an altitude of 250–320 km, the lateral resolution (set by the signal's Fresnel zone) at the surface is ~3–6 km, reducible in the along-track direction to 0.3–1.0 km in focused processing [Seu et al., 2007].

SHARAD records contain reflections from all terrain within a large area illuminated by the antenna beam, and additional processing is used to narrow the contributing region. Along-track resolution is greatly improved by focused Doppler processing of a suite of pulses recorded as the spacecraft moves along track. Returns from several seconds of observation are used to form a synthetic aperture in which the reflections from the desired region are isolated in time delay and Doppler frequency shift, then summed to improve the signal-to-noise ratio (SNR). Side-by-side stacking of progressive focused return signals spaced at 300–500 m along track creates a 2-D radargram (i.e., a profile image of returned radar power with distance along track on the horizontal axis and range delay time—sometimes converted to depth—along the vertical axis). For details of the 2-D radar processing methods that preceded the 3-D processing applied to the data volumes, see the documentation for the U.S. SHARAD derived data products and references therein [Campbell and Phillips, 2014].

Bright returns in a radargram indicate strong contrasts in the dielectric properties of materials at geologic interfaces, providing geometric information that reveals subsurface structure. Some mineralogical components may strongly attenuate radar waves, and changes in return strength along a dipping horizon can be used to characterize the loss properties [e.g., Campbell et al., 2008; Watters et al., 2007]. In the polar layered deposits of Mars, reflections likely arise from dielectric contrasts between ice layers with different compositions (H_2O or CO_2) or degrees of dust or lithic loading [e.g., Nunes and Phillips, 2006; Grima et al., 2009; Putzig et al., 2009].

SHARAD processing

Here we provide an overview of the procedures used by Foss et al. [2017], Putzig et al. [2022], and Perry et al. [2024] to take the SHARAD observations from collections of 2-D profiles to geometrically corrected 3-D radargrams. More details are available from Foss et al. [2024] and other cited references.

A critical element for focused processing of orbital radar data is an accurate representation of the spacecraft velocity and the local surface slope. Horizontal reflectors directly below the spacecraft typically yield the strongest surface and subsurface returns. As an interface dips away from horizontal, the focusing becomes less effective, and signal returns may disappear entirely for interfaces at high slope angles, due to the geometric limitation imposed by SHARAD's 135- μs range window. Clutter, i.e., signals from features off the nadir track of the spacecraft (e.g., crater and mesa walls, polar troughs), is often difficult to uniquely identify in a single radargram since it may focus well in 2-D. A useful discriminator between clutter and subsurface returns is their relative “move-out.” Typically, the time delay of returns from off-nadir surface features will shift much more between nearby, parallel ground tracks than that of near-horizontal reflectors at nadir. This method of analysis was demonstrated with data from the Apollo Lunar Sounder Experiment [Maxwell and Phillips, 1978; Peeples et

al., 1978] using a graphical approach. For current sounders such as SHARAD, elevation data and a model of the radar are typically used to produce synthetic radargrams for identifying clutter [Choudhary et al., 2016; Christoffersen et al., 2021].

Over the course of the MRO mission, the coverage density of SHARAD observations in some areas, especially the polar regions and a few select areas of the midlatitudes, has increased to the point where it has become feasible to treat these portions of the dataset as 3-D data rather than as a collection of 2-D profiles. This approach provides several advantages. At orbit crossings, data from multiple observations may be summed to improve the SNR proportionally to the square root of the number of overlapping data values (demonstrated with 2-D profiles by Campbell et al. [2015]; see also Whitten and Campbell [2018]). The 3-D imaging relies on a technique referred to as “migration” in seismic data processing (note that this usage differs in substantive ways from that employed in the field of radar processing). Where features are well sampled by the radar, 3-D migration processing can unravel interfering nadir and off-nadir (clutter) returns, effectively treating the latter as useful information on the geometry of off-nadir topography with respect to the nadir ground track.

Terrestrial active-source seismic surveys are designed to sample the subsurface in either a cross-sectional area (2-D acquisition with sources and receivers deployed in a line) or a volume (3-D acquisition with sources and receivers deployed in a grid). A fraction of the energy emitted by the sources that passes into the subsurface is reflected upward and recorded at receivers. The clarity of the recorded image depends on the acquisition parameters and the seismic complexity of the subsurface. In seismically complex areas, it is often necessary to apply certain processes to the data to correct geometric effects. To this end, migration has become a routine part of seismic data processing. 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 wave field [French, 1974; Claerbout, 1985; Yilmaz, 1987; Yilmaz et al., 1987a; Yilmaz et al., 1987b]. Migration converts the input seismic image to one in which subsurface features appear in their proper position laterally and vertically. In addition, migration improves resolution of the image by collapsing backscattered wave-field energy to the scattering point. Many migration algorithms have been developed and implemented to account for subsurface seismic complexity of various degrees [Stolt, 1978; Gazdag, 1978; Gray et al., 2001; Bednar, 2005].

Migration algorithms often require zero-offset data, wherein sources and receivers are nominally co-located. True zero-offset seismic surveys are not typical in practice because seismic sources (e.g., dynamite, airguns) are destructive, so additional processing steps are taken to produce pseudo-zero-offset data. For SHARAD, the same antenna transmits and receives the signals, with the spacecraft typically moving less than 10 m and Doppler processing accounting for the relative motion between the

spacecraft and the surface, so the polar grids of 2-D radargrams are already effective zero-offset 3-D surveys. Thus, it was possible to use zero-offset seismic processing methods to treat the SHARAD data over each polar region as a single 3-D reflectivity volume [Foss et al., 2017]. As implemented, 3-D migration addresses many of the limitations of interpreting single 2-D radargrams in areas of complex topography. For example, clutter returns in 2-D are “moved” in the 3-D image to better align these returns with the surface topography from which they were reflected. In addition, the 3-D processing further improves the SNR largely through incoherent stacking of reflectors seen in multiple tracks. At the same time, artifacts may be introduced by the migration process in areas containing concentration of high-power noise (“spikes”) or incomplete coverage of surface or subsurface structures. Due to the hyperbolic nature of the migration operator, these artifacts may appear as bowl-shaped features that could be mistaken for impact craters [Putzig et al., 2018].

Prior to carrying out the 3-D processing, it is necessary to correct ionospheric distortions and delays affecting the radar returns that vary in time and space. The dense grid of SHARAD coverage proved very useful in assessing and removing the relative ionospheric delays between tracks and along each track, a critical correction aimed at preserving the range resolution of the input data. As implemented for the standard U.S. processing of SHARAD data [Campbell and Phillips, 2014], these corrections are carried out in an autofocusing process [Campbell et al., 2014]. For the standard U.S. products in the PDS, a constant set of processing parameters are in use to provide an optimal set of 2-D radargrams for the global dataset. Steps applied include the ionospheric compensation and autofocusing with a relatively modest aperture duration (8.774 s) that provides clutter suppression and a relatively broad multi-look Doppler frequency bandwidth (0.4 Hz) that reduces speckle while improving feature continuity. Because the migration process addresses the clutter in a 3-D sense while providing SNR and continuity improvements, Foss et al. [2017] modified the 2-D processing applied to the input data for the 3-D radargrams to use a longer aperture (38.019 s) and a narrower multi-look Doppler frequency bandwidth (0.2 Hz). All other parameters remain the same as those applied to the standard U.S. products [Campbell and Phillips, 2014].

In preparation for the 3-D imaging, Foss et al. [2017] applied a so-called “demigration” process to each 2-D radargram that redistributes each data value along a hyperbolic 2-D diffraction curve. This step has the effect of repositioning reflectors to their zero-offset positions, resulting in a product that is similar to an unfocused radargram. Next, they assembled all 2-D radargrams (2300 in the north and 2100 in the south for the first two polar volumes delivered to the PDS in 2021) into a 3-D binning grid, wherein the grid size (475 m) was chosen close to the input 2-D frame interval (463 m) (where a frame is the set of data values in delay time for a given location). While spatial aliasing is theoretically possible at these bin sizes [e.g., see p. 191-196 of Liner, 2016], the data are effectively anti-aliased along-track in the 2-D pre-processing. Subsequent

to the 3-D binning, they applied a spatial interpolation to fill coverage gaps—largest on the polar-cap periphery where tracks diverge—prior to further processing that culminates in the 3-D migration step, which “moves” reflectors from the locations where they were recorded to their true subsurface positions.

Subsequent to the production of the first two polar 3-D radargrams (product version 1, with “V1” in the file names), it was realized that an effective loss of vertical resolution by a factor of ~ 2 had occurred, and this was attributed to incomplete removal of the ionosphere-induced delays between the input 2-D radargrams. To address this problem for subsequent 3-D radargrams, a new procedure was developed whereby the delay times of first arrivals in each 2-D radargram are adjusted to match those of corresponding clutter simulations. This step is carried out prior to the demigration described above, and before the 3-D imaging is carried out. The results largely corrected the problem [see Putzig et al., 2022], providing a superior 3-D radargram product. See Foss et al. [2024] for a thorough overview of the original and modified processing procedures.

3-D Radargram Data Value Properties

It is important to note that the 3-D migration process itself doesn't introduce any radiometric bias to signals returned from horizontal interfaces and that it attenuates signals returned from dipping interfaces by $\sqrt{1-\sin^2\theta}$ where θ is the slope of the interface. In practice, this is not a significant issue, because the range of slopes from which reflections are recordable is limited by the physical antenna beam pattern as a function of the orbital recording aperture. However, the data values in the 3-D radargrams are not immediately suitable for radiometric analysis due to the fact that each frame in the input 2-D radargrams was converted to so-called "reflection strength" by taking the square root of the instantaneous power values. In addition, for the first two polar data volumes (product version 1), the data values were debiased by subtracting the mean of the resulting non-zero data values over the entire frame. These steps were taken to make the radargrams available for use in 3-D processing more suitable for the 3-D processing algorithms, which expect oscillating wavefield amplitude data rather than non-negative instantaneous power data. It was later determined that the debiasing step is not necessary, and the processing of subsequent products (version 2 or higher) does not include this step.

While these adjustments are not fully invertible after 3-D processing, one may approximately invert these steps with the following procedure. For the debiased data volumes, end users may wish to add the per-frame mean value determined prior to the 3-D processing to each data value in each frame of the volume. The EXTRAS/SURFACES directory in the archive contains files with those mean values for the affected volumes. For all data volumes delivered in reflection strength, end users may wish to square all data values subsequent to any rebiasing. The resulting power

data will then be suitable for radiometric analysis and comparison to the power values of the 2-D U.S. SHARAD standard products. Note that a small number of zero and negative values may remain in the 3-D data products, and each of these should be replaced with the smallest positive value prior to any conversion to decibels.

References

- Bednar, J.B., 2005. A brief history of seismic migration. *Geophysics* 70, 3MJ–20MJ, doi:10.1190/1.1926579.
- Bierson, C.J., Phillips, R.J., Smith, I.B., Wood, S.E., Putzig, N.E., Nunes, D., and Byrne, S., 2016. Stratigraphy and evolution of the buried CO₂ deposit in the Martian south polar cap. *Geophys. Res. Lett.* 43, 4172–4179.
- Campbell, B., Carter, L., Phillips, R., Plaut, J., Putzig, N., Safaeinili, A., Seu, R., Biccari, D., Egan, A., and Orosei, R., 2008. SHARAD radar sounding of the Vastitas Borealis Formation in Amazonis Planitia. *J. Geophys. Res.* 113, E12010, doi:10.1029/2008JE003177.
- Campbell, B.A., and Phillips, R.J., 2014. Mars Reconnaissance Orbiter Shallow Radar Radargram Data. NASA Planetary Data System, MRO-M-SHARAD-5-RADARGRAM-V1.0. http://pds-geosciences.wustl.edu/mro/mro-m-sharad-5-radargram-v1/mrosh_2001/
- Campbell, B.A., Putzig, N.E., Foss II, F.J., and Phillips, R.J., 2014. SHARAD Signal Attenuation and Delay Offsets Due to the Martian Ionosphere. *IEEE Geosci. Remote Sens. Lett.* 11, 632–635, doi:10.1109/LGRS.2013.2273396.
- Campbell, B.A., Morgan, G.A., Putzig, N.E., Whitten, J.L., Holt, J.W., and Phillips, R.J., 2015. Enhanced Radar Visualization of Structure in the South Polar Deposits of Mars. *Lunar Planet. Sci. XLVI*, Abstract 2366.
- Choudhary, P., Holt, J.W., and Kempf, S.D., 2016. Surface Clutter and Echo Location Analysis for the Interpretation of SHARAD Data From Mars. *IEEE Geosci. Remote Sensing Lett.* 13, 1285–1289, doi:10.1109/LGRS.2016.2581799.
- Christoffersen, M.S., Holt, J.W., Kempf, S.D., O’Connell, J.D., Aguilar, R., 2021. MRO SHARAD Clutter Simulations Data Products, Browse Products, and Documentation. NASA Planetary Data System. <https://doi.org/10.17189/NBDH-2K53>
- Claerbout, J.F., 1985. *Imaging the Earth’s Interior*. Blackwell Scientific Publications, Oxford, UK, 398 p.
- Foss, F.J., Putzig, N.E., Campbell, B.A., Levin, S.A., Perry, M.R., Holt, J.W., Christoffersen, M.S., Smith, I.B., Morgan, G.A., Russell, A.T., 2024. Producing 3D radargrams from orbital radar sounding data at Mars: History, results, methods, lessons and plans. *Icarus* 419, doi:10.1016/j.icarus.2023.115793.

- Foss, F.J., II, Putzig, N.E., Campbell, B.A., and Phillips, R.J., 2017. 3-D Imaging of Mars' Polar Ice Caps Using Orbital Radar Data. *The Leading Edge* 36, 43–57, doi:10.1190/tle36010043.1.
- French, W.S., 1974. Two-dimensional and three-dimensional migration of model-experiment reflection profiles. *Geophysics* 39, 265–277, doi:10.1190/1.1440426.
- Gazdag, J., 1978. Wave equation migration with the phase-shift method. *Geophysics* 43, 1342–1351.
- Gray, S.H., Etgen, J., Dellinger, J., and Whitmore, D., 2001. Seismic migration problems and solutions. *Geophysics* 66, 1622–1640.
- Grima, C., Kofman, W., Mouginot, J., Phillips, R.J., Hérique, A., Biccari, D., Seu, R., and Cutigni, M., 2009. North polar deposits of Mars: Extreme purity of the water ice. *Geophys. Res. Lett.* 36, L03203, doi:10.1029/2008GL036236, 4 p.
- Liner, C., 2016. *Elements of 3D Seismology*. Society of Exploration Geophysicists, Tulsa, OK, 362 p.
- Maxwell, T.A., and Phillips, R.J., 1978. Stratigraphic correlation of the radar-detected subsurface interface in Mare Crisium. *Geophys. Res. Lett.* 5, 811–814.
- Nunes, D.C., and Phillips, R.J., 2006. Radar subsurface mapping of the polar layered deposits on Mars. *J. Geophys. Res.* 111, E06S21, doi:10.1029/2005JE002609.
- Peebles, W.J., Sill, W.R., May, T.W., Ward, S.H., Phillips, R.J., Jordan, R.L., Abbott, E.A., and Killpack, T.J., 1978. Orbital radar evidence for lunar subsurface layering in Maria Serenitatis and Crisium. *J. Geophys. Res.* 83, 3459–3468.
- Perry, M.R., Russell, A.T., Russell, M.B., Foss, F.J., Chuang, F.C., Morgan, G.A., Bain, Z.M., Campbell, B.A., Putzig, N.E., 2024. Three-dimensional imaging of martian glaciated terrain using Mars Reconnaissance Orbiter Shallow Radar (SHARAD) observations. *Icarus* 419, doi:10.1016/j.icarus.2023.115716.
- Phillips, R.J., Zuber, M.T., Smrekar, S.E., Mellon, M.T., Head, J.W., Tanaka, K.L., Putzig, N.E., Milkovich, S.M., Campbell, B.A., Plaut, J.J., Safaeinili, A., Seu, R., Biccari, D., Carter, L.M., Picardi, G., Orosei, R., Mohit, P.S., Heggy, E., Zurek, R.W., Egan, A.F., Giacomoni, E., Russo, F., Cutigni, M., Pettinelli, E., Holt, J.W., Leuschen, C.J., and Marinangeli, L., 2008. Mars north polar deposits: stratigraphy, age, and geodynamical response. *Science* 320, 1182–1185, doi:10.1126/science.1157546.
- Picardi, G., Plaut, J.J., Biccari, D., Bombaci, O., Calabrese, D., Cartacci, M., Cicchetti, A., Clifford, S.M., Edenhofer, P., Farrell, W.M., Federico, C., Frigeri, A., Gurnett, D.A., Hagfors, T., Heggy, E., Hérique, A., Huff, R.L., Ivanov, A.B., Johnson, W.T.K., Jordan, R.L., Kirchner, D.L., Kofman, W., Leuschen, C.J., Nielsen, E., Orosei, R., Pettinelli, E., Phillips, R.J., Plettemeier, D., Safaeinili, A., Seu, R., Stofan, E.R., Vannaroni, G., Watters, T.R., and Zampolini, E., 2005. Radar Soundings of the Subsurface of Mars. *Science* 310, 1925–1928.

- Putzig, N.E., Seu, R., Morgan, G.A., Smith, I.B., Campbell, B.A., Perry, M.R., Mastrogiuseppe, M., 2024. Science results from sixteen years of MRO SHARAD operations. *Icarus* 419, doi:10.1016/j.icarus.2023.115715.
- Putzig, N.E., Foss II, F.J., Campbell, B.A., Holt, J.W., Perry, M.R., Smith, I.B., Russell, A.T., Nerozzi, S., Christoffersen, M.S., Mueller, I.H., Sava, P.C., 2022. New Views of the Internal Structure of Planum Boreum from Enhanced 3D Imaging of Mars Reconnaissance Orbiter Shallow Radar Data. *Planet. Sci. J.* 3:259, 14 pp. doi:10.3847/PSJ/ac9d3b.
- Putzig, N.E., Smith, I.B., Perry, M.R., Foss, F.J., II, Campbell, B.A., Phillips, R.J., and Seu, R., 2018. Three-dimensional radar imaging of structures and craters in the Martian polar caps. *Icarus* 308, 138-147, doi:10.1016/j.icarus.2017.09.023.
- Putzig, N.E., Phillips, R.J., Campbell, B.A., Holt, J.W., Plaut, J.J., Carter, L.M., Egan, A.F., Bernardini, F., Safaeinili, A., and Seu, R., 2009. Subsurface structure of Planum Boreum from Mars Reconnaissance Orbiter Shallow Radar soundings. *Icarus* 204, 443–457, doi:10.1016/j.icarus.2009.07.034.
- Seu, R., Phillips, R.J., Biccari, D., Orosei, R., Masdea, A., Picardi, G., Safaeinili, A., Campbell, B.A., Plaut, J.J., Marinangeli, L., Smrekar, S.E., and Nunes, D.C., 2007. SHARAD sounding radar on the Mars Reconnaissance Orbiter. *J. Geophys. Res.* 112, E05S05, doi:10.1029/2006JE002745.
- Stolt, R.H., 1978. Migration by Fourier transform. *Geophysics* 43, 23–48.
- Watters, T.R., Campbell, B., Carter, L., Leuschen, C.J., Plaut, J.J., Picardi, G., Orosei, R., Safaeinili, A., Clifford, S.M., and Farrell, W.M., 2007. Radar Sounding of the Medusae Fossae Formation Mars: Equatorial Ice or Dry, Low-Density Deposits? *Science* 318, 1125.
- Whitten, J.L., and Campbell, B.A., 2018. Lateral continuity of layering in the Mars South Polar Layered Deposits from SHARAD sounding data. *J. Geophys. Res.* 123, 1541–1554, doi:10.1029/2018JE005578.
- Yilmaz, O., 1987. *Seismic Data Processing*. Society of Exploration Geophysics, Tulsa, OK, 526 p.
- Yilmaz, O., Chambers, R., Nichols, D., and Abma, R., 1987a. Fundamentals of 3-D migration: Part 1. *Geophysics: The Leading Edge of Exploration* 6, 22–30.
- Yilmaz, O., Chambers, R., Nichols, D., and Abma, R., 1987b. Fundamentals of 3-D migration: Part 2. *Geophysics: The Leading Edge of Exploration* 6, 26–33.