A DECADE OF RADAR SOUNDING AT MARS. J. J. Plaut. Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, plaut@jpl.nasa.gov

Introduction: The past 17 years have been a truly golden era of Mars exploration, with a flotilla of orbital and landed spacecraft acquiring data that have revolutionized our view of the planet. Remote sensing observations from orbit span the electromagnetic spectrum. For nearly 10 years, the surface, subsurface and ionosphere of Mars have been probed by orbital radar sounders, the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) on ESA's Mars Express, and the SHAllow RADar (SHARAD) on NASA's Mars Reconnaissance Orbiter. Both experiments have been unqualified successes, and are still going strong as of mid-2014. This paper reviews the key findings from the Mars radar sounders, which have provided new insight into many aspects of the history and current environment of the planet.

MARSIS and SHARAD are sister instruments that operate in the same general fashion but with complementary characteristics. MARSIS operates in multiple frequencies, in the range of 1.3-5.5 MHz (55-230 m wavelength) using a dipole antenna 40 m in length [1]. The low frequencies of MARSIS allow for deep penetration into the subsurface, at the expense of vertical resolution, which is a function of the transmitted signal bandwidth (1 MHz). SHARAD operates at a single central frequency of 20 MHz (15 m wavelength; 10 m antenna) with a 10 MHz bandwidth, providing higher vertical resolution at the expense of penetration capability [2]. Both sounders use a "chirp" pulse technique and synthetic aperture processing to optimize sensitivity and resolution. The MARSIS footprint is 5-10 km by 10-30 km, with a vertical resolution of 150 m in free space. The SHARAD footprint is 0.3-1 km by 3-6 km, with a vertical resolution of 15 m in free space. MARSIS has made robust subsurface detections in the range of depths of 200-3700 m; SHARAD has made robust subsurface detections in the range of depths of 20-2700 m. MARSIS also can operate in a stepped-frequency mode in the frequency range 0.1-5.5 MHz for sounding of the topside of the ionosphere.

Polar layered deposits (PLD): The PLD have proven to be ideal targets for radar sounding. The full thickness of the polar plateaus (Plana Boreum and Australe) are typically penetrated by MARSIS, including the lower "basal unit" in the north [3-5]. This allows mapping of topography on the basal contact (presumably where the icy PLD overlies lithic crust); the contact has substantial relief in the south [4] and is relatively flat in the north [5]. MARSIS mapping has allowed new estimates of the volume of the PLD and hence the size of the H2O reservoirs. In terms of global equivalent water layer, the MARSIS-based values are 10-12 m for the south [4] and 8-10 m for the north [5]. The bulk composition of the polar plateaus is constrained by the interaction with the radar signals. The position of basal reflections in time delay is consistent with the continuation of the surrounding terrain under the PLD in both the north and south, and this observation leads to the determination of the dielectric constant (or refractive index), which within errors is indistinguishable from that of pure ice [3-7]. Further constraints on composition are obtained from the strength of deep reflections, which again show indications of only minor impurities in the ice. Estimates of the mass fraction of impurities are generally <10%, with values <5% considered likely [3,4,7]. The high vertical resolution of SHARAD, about 9 m in ice, allows detailed studies of the internal stratigraphy, structure and history of the PLD. Typical SHARAD PLD radargrams show numerous reflective horizons, typically continuous over 100s of km [6,8]. Groupings of these reflectors into packets is suggestive of cyclical episodes of deposition, possibly tied to orbitally-driven climate cycles [6,9]. Stratigraphic and structural relationships were used to resolve long-standing questions on the origin of features such as Chasma Boreale [10] and the spiral troughs [11]; both studies suggested long-termed structural stability of the NPLD, and hence argued against any significant role for ice flow. A low radar wave velocity zone was identified in the upper SPLD, whose properties were consistent with a large buried reservoir of CO2 ice, the volume of which is comparable to the present atmospheric CO2 reservoir [12]. The lack of deflection of the basal interfaces under the PLD imply a thick elastic lithosphere, and heat flow values at the lower end of previously suggested ranges [3,6].

Associated polar terrains: The unit surrounding the SPLD known as the Hesperian Dorsa Argentea Formation [13] contains a reflective horizon in MARSIS data over much of its mapped occurrence [14]. The reflectors are observed at time delays consistent with a maximum depth between 500 and 1000 m. The relatively strong returns and the morphology of surface features both suggest an ice-rich layer overlying a lithic substrate. This implies the presence of a substantial additional H2O reservoir, consisting of ice that may be the oldest yet detected on Mars.

Remnant glaciers: Features in the mid-latitudes first described as lobate debris aprons (LDAs) were targeted with SHARAD and observed to frequently be penetrated to their base [15,16]. The most prominent occurrences were east of the Hellas Basin [15] and at the dichotomy boundary in Deuteronilus Mensae [16]. Time delay and reflector intensity measurements indicate that the bulk of the LDAs in these areas consist primarily of ice, with a lithic component no more than 10%. Associated terrains such as lineated valley fill and concentric crater fill show similar radar characteristics. Based on SHARAD observations, these features are now characterized as remnant glaciers protected from sublimation by a surface debris lag ~10 m thick. The presence of these large volumes of ice in the temperate zone implies substantial changes in climate during the Amazonian, and also provides tantalizing targets for further in situ exploration and utilization. Putative remnant mountain glaciers in the Tharsis region [17] are not penetrated by radar sounding.

Widespread ice in the northern plains: Several large areas in the northern plains, in Arcadia and Utopia Planitiae, show reflectors in SHARAD data at depths up to 100 m [18,19]. Periglacial surface features, terraced craters and shallow ice exhumed by recent impacts in these areas imply a role of ice in the radar transparent layer [20]. SHARAD observations at the Phoenix landing site reveal a similar, but less extensive reflector, suggested to represent the base of the near-surface ice-rich regolith sampled by Phoenix [21]. Global mapping of the near-surface dielectric constant using MARSIS found a consistently lower value on the northern plains than on other terrains [22,23]. This is consistent with a widespread component of ground ice in the upper ~70 m, but could also be caused be low density sediments.

Medusae Fossae Formation (MFF): The equatorial MFF showed deep reflectors in both MARSIS and SHARAD data [24,25]. Geometric constraints allowed determination of the dielectric constant to be near 3, which would be consistent with a low density or high porosity lithic deposit such as ash or dust, or with ice (or a combination of these). MARSIS reflectors were seen as deep as 2 km, SHARAD up to 580 m. The lack of pervasive multiple internal reflectors argues against a PLD-like stratigraphy for the MFF; as does the absence of periglacial morphology in surface imagery.

Young lava flows: Areas of relatively recent lava flows are penetrated by SHARAD to maximum depths of ~100 m in ELysium and Amazonis Planitiae and among the large Tharsis volcanoes [26-28]. A complex set of reflectors in the Elysium region reveals interplay between fluvial and magmatic episodes, including the burial of large fluvial outflow channels by later lava flows [28].

Liquid water: At the outset, a goal for both MARSIS and SHARAD was to detect liquid water in the subsurface. No such detection has been made. The reasons for this lack of detection are not entirely clear, but are likely the result of one or a combination of factors [29]. Among these are the possibility that there may be no subsurface liquid reservoirs in the upper several km of the subsurface. The lower heat flow values inferred from minimal deflection of the PLD mean that the melting temperature of ice may not be reached in the upper several km, although the presence of brines in a putative aquifer could counteract this effect. Alternatively liquid water may be hosted at shallow depths, but beneath crustal rocks that are impervious to the current radar sounder signals. Penetration of dense, ice-free rock is consistently seen only in young lava flows, to depths of about 100 m. Older rock units, which may host lossy hydrated minerals, are not readily penetrated by SHARAD [30]. Small aquifers may exist in the shallow subsurface but their presence may not be obvious in the radargrams due to their limited lateral extent. Finally, if the upper boundaries of aquifers are transitional in filled porosity, the dielectric contrast may not be sufficiently sharp to produce a detectable echo.

References: [1] Jordan, R. et al. (2009) PSS 57, 1975. [2] Seu, R. et al. (2007) JGR 112, E05S05. [3] Picardi, G. et al. (2005) Science 310, 1925. [4] Plaut, J.J. et al. (2007) Science 315, 92. [5] Selvans, M.M. et al. (2010) JGR 115, E09003. [6] Phillips, R.J. et al. (2008) Science 320, 1182. [7] Grima, C. et al. (2009) GRL 36, L03203. [8] Seu, R. et al. (2007) Science 317, 1715. [9] Putzig, N.E. (2009) Icarus 204, 443. [10] Holt, J.W. (2010) Nature 465, 446. [11] Smith, I.B. and J.W. Holt (2010) Nature 465, 450. [12] Phillips, R.J. et al (2011) Science 332, 838. [13] Tanaka, K.L. and D.H. Scott (1987) USGS I-1802-C. [14] Plaut, J.J et al. (2007) LPSC 38, 2144. [15] Holt, J.W. et al. (2008) Science 322, 125. [16] Plaut, J.J. et al., (2009) GRL 36, L02203. [17] Head, J.W. and Marchant, D.R., (2003) Geology 31, 641. [18] Plaut, J.J. et al. (2009) LPSC 40. [19] Nunes, D.C. (2010) JGR 115, E10004. [20] Bramson, A. et al. (2013) LPSC 44. [21] Putzig, N.E. et al. (2014) submitted. [22] Mouginot, J. et al. (2010) Icarus 210, 612. [23] Mouginot, J. et al. (2012) GRL 39, L02202. [24] Watters, T.R. et al. (2007) Science 318, 1125. [25] Carter, L. et al. (2009) GRL 36, L23204. [26] Campbell, B.A. (2008) JGR 113, E12010. [28] Morgan, G. et al. (2013) Science. [27] Carter, L.M. et al. (2008) Icarus 199, 295. [29] Clifford, S. et al. (2010) JGR 115, E7001. [30] Stillman, D.E. and R.E. Grimm (2011) JGR 116, E03001.