Radar Astronomy for Planetary Surface Studies

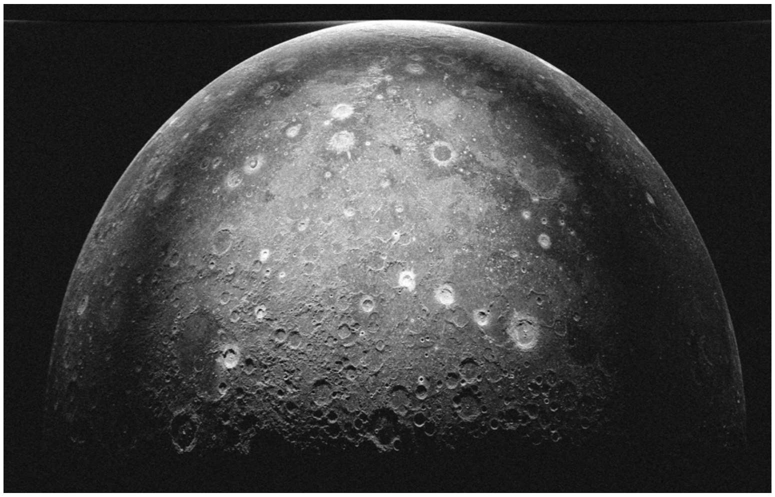
Bruce Campbell[1], Catherine Neish[2], Donald Campbell[3], Lynn Carter[4], Gareth Morgan[5], Michael Nolan[4], G. Wesley Patterson[6], Edgard Rivera-Valentin[7]; Patrick Taylor[7], Jennifer Whitten[8]
[1]Smithsonian Institution, Center for Earth and Planetary Studies; [2]Dept. of Earth Sciences, The University of Western Ontario; [3]Dept. of Astronomy, Cornell University; [4]Lunar and Planetary Laboratory, University of Arizona; [5]Planetary Science Institute; [6]Johns Hopkins University Applied Physics Lab; [7]Lunar and Planetary Institute; [8]Dept. of Earth and Environmental Sciences, Tulane University.

The radar systems at Arecibo Observatory have a fifty-year heritage of planetary surface studies, and the Green Bank Telescope has been used since 2001 for a number of planetary radar imaging experiments. More recently, the Goldstone Solar System Radar has been used to acquire image data for planetary surfaces, and to support the bistatic observations of the Mini-RF instrument on the Lunar Reconnaissance Orbiter (LRO). This paper addresses future applications of these facilities dealing with the surfaces of planets and satellites, leaving the fields of asteroid studies and planetary dynamics for separate papers.

1. Moon. Detailed imaging radar studies of the Moon date to the mid-1960's. Present studies with a bistatic Arecibo-Green Bank geometry allow polarimetric imaging at 12.6-cm (S-band) wavelength with as fine as 20 m spatial resolution [Campbell et al., 2006], and 70-cm (P-band) wavelength imaging at 200 m resolution [Campbell, 2016; Morgan and Campbell, 2016]. In both cases these resolutions are set by the bandwidth of the transmitter system. In particular, the Arecibo 430-MHz radar is limited to 1 MHz bandwidth. The X-band (3.5 cm) Goldstone Solar System Radar is capable of image resolutions in the ~10 m range for the lunar surface, and examples of interferometric topography derivation have been presented [Slade et al., 2011]. Both Arecibo and Goldstone have also been used as transmitters for bistatic observations of the lunar surface, using Mini-RF on LRO as the receiver [Patterson et al., 2017]. Their current and future availability as transmitters will be key to the continuation of this experiment during the LRO extended mission.

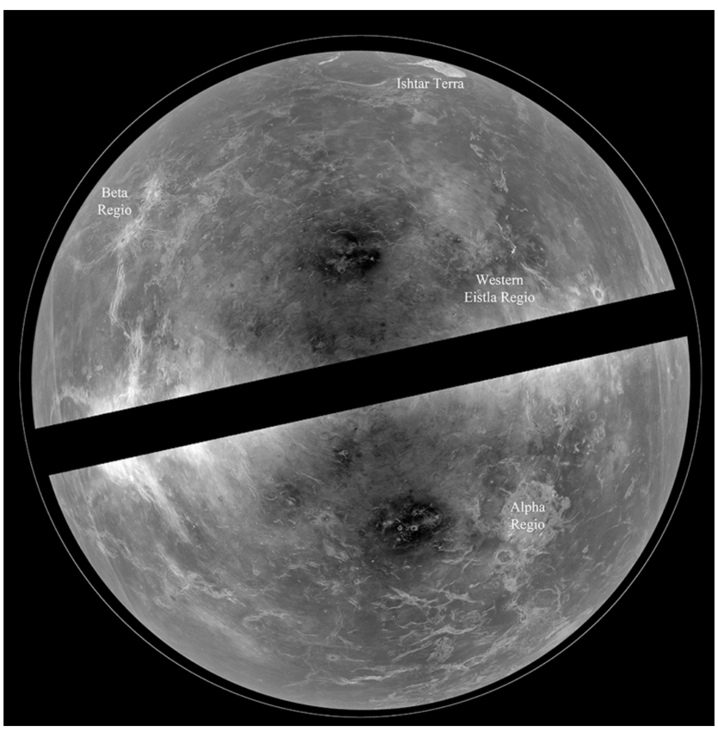
Earth-based radar studies of the Moon at X-band and S-band are being supplanted by spacecraft orbital observations. The Chandrayaan-1 and Lunar Reconnaissance Orbiter Mini-RF radars collected images for large regions at X- and S-band, though their calibration is problematic and, to date, the Earth-based data are the more robust polarimetric measurement [Carter et al., 2016]. An upcoming orbital mission, ISRO's Chandrayaan-2, will include polarimetric S-band and L-band (~24 cm) wavelength radars. The launch of this spacecraft is expected in April 2019. From that point forward, Earth-based S-band observations may provide limited support through different viewing geometries and polarimetric calibration. However, observations at X- and P-Band will still remain limited to Earth-based facilities.

A scientific rationale remains for Earth-based 70-cm observations, since the depth of penetration in the regolith exceeds that of the planned L-band radar. In order to truly complement orbital maps, the Arecibo transmitter must be upgraded to a minimum of 4 MHz bandwidth. This new transmitter would allow a single radar "look" at 50-m spatial resolution during each observing day (about 2.5 hours as the Moon passes above Arecibo), with a total of 6-8 such looks comprising a final image of quite large areas on the lunar surface [Campbell et al., 2014]. This would allow for more robust comparisons with the higher-resolution S-Band data of the Moon. A higher-power, higher-bandwidth P-band system would also allow improved observations of Venus and near-Earth asteroids.



70-cm wavelength Arecibo-GBT radar image of the Moon. North pole is at lower center. Younger craters have radar-bright interiors and surroundings due to abundant rocks formed during the impacts. Mare lava flows range from relatively bright radar echoes to very dark returns linked with high abundance of titanium-bearing minerals.

2. Venus. Earth-based imaging of Venus continues to be of interest beyond the Magellan mission in the early 1990's. The major advantage of the Earth-based datasets are their dual-polarization measurements, which allows for a more complete view of surface properties and mantling deposits [Carter et al., 2004; 2006]. The same-sense circular polarization (SC) is much more sensitive to the presence of fine-grained surface mantling deposits than the Magellan observations. New data were acquired in 2012, 2015, and 2017, and summing of these looks much improves the signal-to-noise ratio of the important SC return.



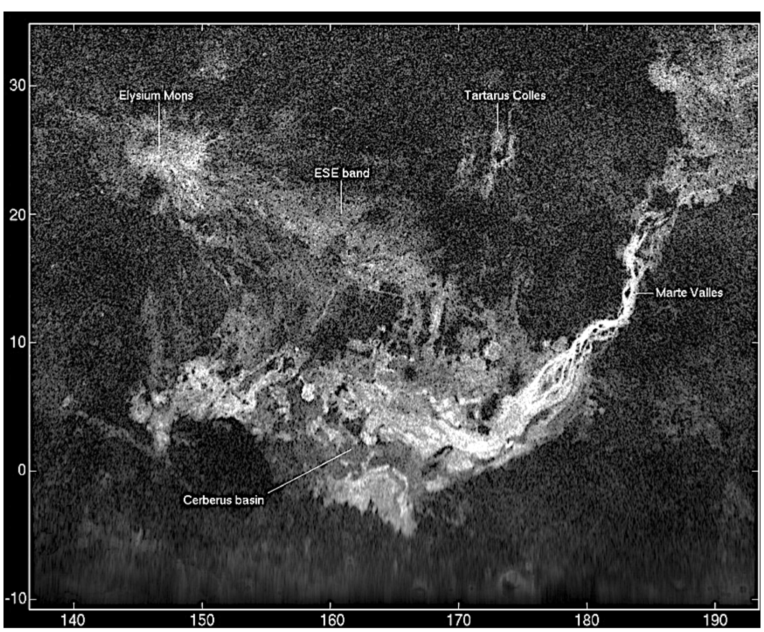
Earth-based 12.6-cm radar image of Venus from the 2012 conjunction. Very low radar-return areas near the center of the north and south hemispheres are broad areas covered by fine-grained material formed by impact cratering. Very bright features are volcanoes and mountain ranges.

Work based on the new data reveals surprising patterns of crater ejecta preservation in the Venus highlands, where pristine surface conditions are crucial for landed geological studies [Campbell et al., 2015; Whitten and Campbell, 2016]. New discoveries have also emerged on explosive volcanic deposits that are likely the youngest features on the planet [Campbell et al., 2017]. Long-term observations (1988-2017) are being used to measure the average rotation rate of Venus, another major issue in using Magellan-era maps to plan future landing sites.

There will be no spacecraft radar system for Venus until the mid-2020's or later, so Earth-based work is still of high value. The Arecibo monostatic geometry offers the best performance, as tests in 2012 with the Arecibo-GBT configuration were not encouraging. New data, starting with the 2020 conjunction, will continue to increase the SNR for polarimetric studies, extend the time baseline for spin-rate estimation, and enable a search for newly erupted volcanic deposits.

3. Mars and Mercury. Mars presents a more challenging radar imaging target than the Moon or Venus due to its greater distance and higher spin rate. Spatial resolution at S-band is limited to a few kilometers and depends upon a long-code correlation technique to overcome the intrinsic ambiguity in frequency [Harmon et al., 2012]. Arecibo provides the best configuration for signal-to-noise performance, and the long round-trip travel time allows for dual-polarization measurements not feasible for the Moon. The opposition of 2020 may permit a new round of imaging in support of a number of science topics. This would be of particular interest for obtaining polarimetric information of various features on Mars, such as lava flows, for roughness determination and comparison to similar features on the Moon. Past observations have also been used in landing site planning [e.g., Putzig et al., 2016].

The same long-code technique has been successfully applied for Mercury S-band imaging [Harmon et al., 2011]. Potential follow-on observations might focus on acquiring enough looks to achieve useful SC echoes from the broad Mercury plains regions for comparison to similar features on the Moon, comparable to the work done for rayed craters [Neish et al., 2013]. It would also help to constrain the distribution of volatiles in Mercury's polar regions [Chabot et al., 2013]. Studies of this type are particularly timely, given the new remote sensing data available from the MESSENGER mission, and the upcoming Bepi-Colombo mission. Note that neither spacecraft had a radar instrument, nor are there plans for one in the future.



Arecibo 12.6-cm radar image of lava flows and channel deposits in the Elysium region of Mars. Data from Harmon et al. [2012]. The brightest features running from right to lower center are rough lava flows that fill more ancient water-carved channels.

4. Jovian Satellites

The satellites of Jupiter will be visible from Arecibo each fall in the 2023-2027 period. Dual-polarization S-band images have been used in the past to make coarse-resolution maps and to study the scattering properties of their icy surfaces [Black et al., 2001; Ostro and Shoemaker, 1990]. The major driver for new observations comes from the RIME and REASON sounder instruments on the JUICE and Europa Clipper spacecraft. Both spacecraft will be in the Jovian system by about 2029, so the radar observations could focus on improved surface properties maps as a guide to potential smooth and rugged regions.

References

Black, G.J., D.B. Campbell, and S.J. Ostro, Icy Galilean Satellites: 70 cm Radar Results from Arecibo. *Icarus*, 151, 160-166, doi:10.1006/icar.2001.6615, 2001.

Campbell, B.A., G.A. Morgan, J.L. Whitten, L.M. Carter, D.B. Campbell, and L.S. Glaze, Pyroclastic flow deposits on Venus as indicators of renewed magmatic activity, *J. Geophys. Res., 122,* 1580-1596, doi:10.1002/2017JE005299, 2017.

Campbell, B.A., Planetary Geology with Imaging Radar: Insights from Earth-Based Lunar Studies, 2001 to 2015, *Pub. Astron. Soc. Pacific, 128:062001*, doi:10.1088/1538-3873/128/964/062001, 2016.

Campbell, B.A., D.B. Campbell, G.A. Morgan, L.M. Carter, M.C. Nolan, and J.F. Chandler, Evidence for Crater Ejecta on Venus Tessera Terrain from Earth-Based Radar Images, *Icarus*, doi:10.1016/j.icarus.2014.11.025, 2015.

Campbell, B.A., B.R. Hawke, G.A. Morgan, L.M. Carter, D.B. Campbell, and M. Nolan, Improved discrimination of volcanic complexes, tectonic features, and regolith properties in Mare Serenitatis from Earth-based radar mapping, *J. Geophys. Res*., 119, doi:10.1002/2013JE004486, 2014.

Campbell, D.B., B.A. Campbell, L.M. Carter, J.L. Margot, and N.J.S. Stacy, Lunar polar ice: No evidence for thick deposits at the south pole, Nature, 443, 835-837, 2006.

Carter, L.M., B.A. Campbell, C.D. Neish, M.C. Nolan, G.W. Patterson, J.R. Jensen, and D.B.J. Bussey, A comparison of radar polarimetry data of the Moon from the LRO Mini-RF instrument and Earth-based systems, *IEEE Trans. Geosci. Rem. Sensing, 55, 1915-1927,* doi:10.1109/TGRS.2016.2631144, 2017.

Carter, L.M., D.B. Campbell, and B.A. Campbell, Volcanic deposits in shield fields and highland regions on Venus: Surface properties from radar polarimetry, *J. Geophys. Res*., 111, doi: 10.1029/2005JE002519, 2006.

Carter, L.M., D.B. Campbell, and B.A. Campbell, Impact crater related surficial deposits on Venus: Multi-polarization radar observations with Arecibo, *J. Geophys. Res*., *109, E06009*, DOI 10.1029/2003JE002227, 2004.

Chabot, N. L., Ernst, C., Harmon, J. K., Murchie, S. L., Solomon, S. C., Blewett, D. T., Denevi, B. W., Craters hosting radar-bright deposits in Mercury's north polar region: Areas of persistent shadow determined from MESSENGER images. *Journal of Geophysical Research*, *118*, doi:10.1029/2012JE004172, 2013.

Harmon, J. K., Slade, M. A., Rice, M. S., Radar imagery of Mercury's putative polar ice: 1999-2005 Arecibo results. *Icarus*, *211*, 37–50, doi:10.1016/j.icarus.2010.08.007, 2011.

Harmon, J.K., M.C. Nolan, D.I. Husmann, and B.A. Campbell, Arecibo radar imagery of Mars: The major volcanic provinces, Icarus, 220, 990-1030, doi:10.1016/j.icarus.2012.06.030, 2012.

Morgan, G.A., B.A. Campbell, B.R. Hawke, and D.B. Campbell, Investigating the stratigraphy of Mare Imbrium flow emplacement with Earth-based radar, *J. Geophys. Res., 121, 1498-1513,* doi:10.1002/2016JE005041, 2016.

Neish, C. D., Blewett, D. T., Harmon, J. K., Coman, E. I., Cahill, J. T. S., Ernst, C. M., A comparison of rayed craters on the Moon and Mercury. *Journal of Geophysical Research-Planets*, *118*, 2247–2261, doi:10.1002/jgre.20166, 2013.

Putzig, N.A., G.A. Morgan, B.A. Campbell, C. Grima, I.B. Smith, R.J. Phillips, and M. Golombek, Radar-derived properties of the InSight landing site in Western Elysium Planitia on Mars, *Space Sci. Rev., doi:10.1007/s11214-016-0322-8*, 2016.

Slade, M.A., L.A.M. Benner, and A. Silva, Goldstone Solar System Radar Observatory: Earth-based planetary mission support and unique science results, Proc. IEEE, 99, 757-769, 2011.

Ostro, S.J., and E.M. Shoemaker, The extraordinary radar echoes from Europa, Ganymede, and Callisto: A geological perspective, Icarus, 85, 335-345, doi:10.1016/0019-1035(90)90121-O, 1990.

Patterson, G.W., et al., Bistatic radar observations of the Moon using Mini-RF on LRO and the Arecibo Observatory. *Icarus, 283, 2-19*, doi:10.1016/j.icarus.2016.05.017, 2017.

Whitten, J.L., and B.A. Campbell, Recent volcanic resurfacing of Venusian craters, *Geology, 44,* 519-512, doi:10.1130/G37681.1, 2016.