Compact Polarimetry at the Moon: The Mini-RF Radars

R. Keith Raney[1], Paul Spudis[2], Ben Bussey[1], J. Robert Jensen[1], Bill Marinelli[3], Priscilla McKerracher[1], Ron Schulze[1], Herman Sequeira[1], and Helene Winters[1]

[1]Johns Hopkins University APL
[2]Lunar and Planetary Institute
[3]NASA Headquarters

1. INTRODUCTION

The Mini-RF radar aboard India's lunar Chandrayaan-1 satellite [1] (2008-9) was the first polarimetric synthetic aperture radar (SAR) outside of Earth orbit. The architecture of that radar—and of its more advanced two-frequency sibling on NASA's Lunar Reconnaissance Orbiter [2] (2009-)—is hybrid dual-polarimetric [3][4]. This architecture is a form of compact polarimetry [5] in which the dual-received data are orthogonal linear polarizations, in contrast to the transmitted polarization which is circular. The Mini-RF radars, as the pioneers for this new class of radar, illustrate the value of hybrid-polarity for lunar and planetary applications.

2. EVOLUTION TO HYBRID POLARITY

The design studies for the Mini-RF lunar radars looked carefully at alternative architectures, within the stipulated science and implementation constraints. The implementation requirements included minimal mass and power, and accommodation for the dual-linearly-polarized (H and V) antenna design that had been stipulated as part of the technology demonstration that was a parallel theme of the mission. The first-order science requirement was measurement of the circular-polarization ratio, defined as the power ratio of the same-sense (SC) to the opposite-sense (OC) of circularly polarized backscatter, relative to the sense of the transmitted circular polarization. This measurement requires transmission of circular polarization. It also suggests that the receiver must be (dual-) circularly polarized, but that turns out to be a false conclusion.

The original concept for these radars was conventional, transmitting right- (or left-) circular polarization, and receiving both senses of circular polarization, resulting in SC and OC image pairs [6]. Circularly polarized transmission may be realized by transmitting H and V polarizations simultaneously, 90-degrees out of phase. These signals are generated by running the output of the transmitter through a 90-degree hybrid. If the radar were required to be circularly polarized on receive as well as on transmission, then the H and V signal sequences from the antenna each would have to go through another 90-degree hybrid, from which the outputs would be combined to generate signals at both senses of circular polarization, thus realizing a circularly polarized dual-channel receiver.

The conventional circularly-polarized approach was simplified by keeping the H- and V-polarized data received at the antenna in their linear polarizations all the way through the receiver and the processor, thus removing the need for two 90-degree hybrids in the receive paths [3]. This simplification not only reduced the mass of the radar, but also improved the receiver's noise figure. The simpler linearly polarized receiver concept was justified through a paradigm shift in radar design. Rather than imagery, the primary data product of the Mini-RF radars was defined to be the 2x2 coherency matrix of the backscattered field. This new perspective implied that the receiver must maintain the relative phase between the H and V signals as well as their magnitudes. Under the constraint that the data product is the coherency matrix, the polarization basis of the receiver becomes irrelevant. The measurements from a linearly dual-polarized receiver are equivalent to those from a circularly dual-polarized receiver, since the 4-element Stokes vector calculated from the coherency matrix does not depend on the polarization basis in which the data are observed. Further, the Stokes vector captures all of the information available in the backscattered field, hence it offers more measurement options than the usual SC and OC image pairs. The resulting hybrid-polarity architecture is an ideal response to the requirements for the lunar Mini-RF SARs; maximal science provided through minimal hardware.

3. CALIBRATION

Polarimetric measurements imply more stringent calibration of the radar than required by a single channel system. Hybrid-polarimetric architecture has the unique and appealing property that it is self-calibrating. The relative phase and magnitude balance of the receive channels may be observed and corrected, as needed, without recourse to an *in situ* reference such as a corner reflector. The trick is to average the returns collected at vertical incidence (over a random nominally horizontal surface). If the radar is known to be transmitting high-quality (near-unity aspect ratio) circular polarization, then nadir illumination is necessary and sufficient for polarimetric relative calibration. This is true, because in this case (1) the received data should be circularly polarized in the opposite sense, and (2) data observed through the H and V channels should be identical statistically to first and second order. Discrepancies can be measured, and turned into calibration coefficients, thus balancing the receiver's phase and amplitude properties, antenna-to-end. The technique is especially appealing for polarimetric radars designed for lunar or planetary observations, for which *in situ* corner reflector calibration references would be impractical.

The radar's transmitted polarization for the Mini-RF radars was imperfect, having an axial ratio on the order of 2.4 dB. Relative calibration under this constraint requires external resources. The receive channels were characterized by illumination from the Arecibo radio telescope, a circularly polarized source of known high quality. The resulting data, combined with nadir backscattering data, were sufficient to characterize the polarization of the radar's transmitted field. In addition, the transmitted polarization was observed directly by illuminating the Green Bank Radio Telescope. The results were in agreement between the nadir-viewing and direct observation methods of characterizing the transmitted polarization.

4. RESULTS

The hybrid-polarimetric Mini-RF radars offer the same suite of polarimetric information from lunar orbit as state-of-the-art Earth-based radar astronomy, most elegantly illustrated by the Arecibo-Green Bank combination. In particular, the Mini-RF data support determination of the circular polarization ratio (CPR) which is known to be anomalously large for backscatter from volumetric ice, or from surface structures dominated by "double-bounce" reflections, such as fresh impact crater ejecta [7]. CPR mappings from the Mini-RF lunar observations of the permanently shadowed interior of several polar craters are consistent with the signals that correspond to ice deposits.

5. REFERENCES

[1] Spudis, P., Nozette, S., Bussey, D. B. J., Raney, R. K., Winters, H. L., Lichtenburg, C. L., Marinelli, B., Crusan, J. C., & Gates, M. M. (2009). Mini-SAR: an imaging radar experiment for the Chandrayaan-1 mission to the Moon. *Current Science, Indian Academy of Sciences, 96*(4), 533-539.

[2] Chin, G., Brylow, S., Foote, M., Garvin, J., Kasper, J., Keller, J., Litvak, M., Mitrofanov, I., Paige, D., Raney, K., Robinson, M., Sanin, A., Smith, D., Spence, H., Spudis, P., Stern, S. A., & Zuber, M. T. (2007). Lunar Reconnaissance Orbiter overview: The instrument suite and mission. *Space Science Review, 129*, 391-419.

[3] Raney, R. K. (2006). Dual-polarized SAR and Stokes parameters. *IEEE Geoscience and Remote Sensing Letters, 3*(3).

[4] Raney, R. K. (2007). Hybrid-polarity SAR architecture. *IEEE Transactions on Geoscience and Remote Sensing, 45*(11), 3397-3404.

[5] Nord, M. E., Ainsworth, T. L., Lee, J.-S., & Stacy, N. J. S. (2009). Comparison of compact polarimetric synthetic aperture radar modes. *IEEE Transactions on Geoscience and Remote Sensing, 47*(1, Part 1), 174-188.

[6] Spudis, P. D., Lichtenberg, C. L., Marinelli, B., & Nozette, S. (2005). Mini-SAR: An imaging radar for the Chandrayaan-1 mission to the Moon, Paper 1153. *Proceedings, Lunar and Planetary Science XXXVI, Houston, TX*.

[7] Ostro, S. J. (2002). Planetary radar astronomy. *The Encyclopedia of Physical Science and Technology, 3rd Edition.* R. A. Meyers, Academic Press. **12:** 295-328.