

NEW L-BAND RADAR OBSERVATIONS OF INA FEATURE ON THE MOON. S. S. Bhiravarasu¹, J. D. Stopar², E. G. Rivera-Valentín³, G. A. Morgan⁴, G. M. Wolff², C. D. Neish⁵, J. T. S. Cahill³, T. Chakraborty¹, D. Pandey¹, A. Das¹, D. Putrevu¹; ¹Space Applications Centre, ISRO, Ahmedabad, India (sriram.saran@sac.isro.gov.in), ²Lunar and Planetary Institute, USRA, Houston, TX, ³Johns Hopkins University Applied Physics Laboratory, Laurel MD, ⁴Planetary Science Institute, Tucson AZ, ⁵Western University, London, Ontario

Introduction: Irregular mare patches (IMPs) on the Moon are characterized by their distinct, sharp morphology and texture, are relatively small and appear anomalously young, compared to the surrounding maria [e.g., 1-3]. Due to the unusual and complex characteristics of IMPs, their origin and specific formation mechanism is one of the most debated topics of lunar volcanism and geological evolution history [3, 4]. The enigmatic Ina formation (3 km, 18.65°N, 5.30°E), first discovered during the Apollo era [5], was later analyzed in detail using remote sensing observations at multiple wavelengths to understand its formation mechanism, and physical and chemical properties [1-4, 6]. Although numerous formation mechanisms have been proposed, the origin and age of Ina, remain unresolved [3, 4].

Radar is a powerful tool to study the physical properties of volcanic settings because scattering is dependent on composition, near-surface roughness, and the presence of subsurface scatterers or layering [e.g., 7, 8]. In this work, we seek to understand the radar scattering properties of the Ina formation with respect to its surrounding maria using the new L-band radar data obtained from the Dual-Frequency SAR (DFSAR) instrument onboard Chandryaan-2 [8]. In particular, we analyze the interior of Ina to further characterize its physical properties and morphology.

DFSAR data: The DFSAR is a monostatic SAR system, operating at 24 cm (L-band) and 12 cm (S-band) wavelengths [8]. The Ina feature has been imaged in L-band fully polarimetric mode at an incidence angle of 20° and at a slant range resolution of $\sim 0.5 \times 9.6$ m in azimuth and range directions respectively. Further processing (i.e., multi-looking and orthorectification) of this dataset produced 30 m/pixel spacing images, as shown in Figure 1.

Previous observations: Ina is located on a broad, ~ 22 -km-diameter shield volcano [9]. Previous monostatic S-band radar observations from the LRO Mini-RF instrument indicated that Ina has enhanced circular polarization ratio (CPR) at the depression edges and blocky areas, but shows CPR values similar to the surrounding maria at the smooth units [7]. The range of CPR values observed imply that no pyroclastics are evident, and if any are present, they must be very thin or intermixed with regolith such that they are no longer visible to S-band radar [7]. In their work, [10] suggested that Ina has similar meter scale roughness but different decimeter scale roughness properties when compared to some impact melt deposits on the Moon. Reflectance

spectra observations of Ina are further consistent with either the absence of significant amounts of Fe-bearing volcanic glass, or very thin intermixed pyroclastics [11].

New L-band radar observations: The DFSAR co-polarized (HH, Fig. 1a) image distinctly highlights the numerous mounds within Ina due to their varying slopes, along with the edges that appear radar-bright likely due to mass wasting from the walls. In contrast, the cross-polarized (HV, Fig. 1b) image is relatively unaffected by the terrain slopes and highlights the blocky terrain towards the south, as described in [2]. The mounds and the lower unit that extends from and surrounds the margins of the mounds have very low L-band CPR values (<0.2 , Fig. 1c) and appear blue in the Van zyl polarimetric decomposition image (Fig. 1d), which indicates a dominant surface scattering regime from smooth material in these units. Towards the south, areas with blocks and boulders up to widths of ~ 1 to 5 m [2] are radar-bright in both HH- and HV-pol data (Fig. 1a, b). The CPR values associated with these blocky units are not elevated (<0.5), as typically expected from rocky regions such as fresh impact ejecta (e.g., 7, 8) and appear as predominantly green (diffuse/volume scattering) in the corresponding decomposition image (Fig. 1c, d). As evident from Fig. 1c, the CPR values in most parts of the Ina interior are on the order of 0.1, very similar to those observed from the smooth portions of surrounding maria. These values are slightly lower than observed by [7, 10] at S-band, which could be due to either a smaller (cm-scale) block-size distribution within the Ina or the effect of different incidence angles of observation (20° of DFSAR vs. 49° of Mini-RF). Moreover, the HV-pol and decomposition images (Fig. 1b, d) suggest that the upper meter of the central portion of Ina is composed of fine-grained, less consolidated, and/or block-poor material.

Other complimentary results: This interpretation is comparable to that of Wolff et al. 2023 [LPSC this volume], who using S-band Mini-RF, also found radar evidence for ~ 1 -2 m of fine-grained materials in the center of Ina, on portions of both mounds and adjacent lower units. This is further consistent with one of the observations by [4], who showed that most units (portions of both the lower unit and smooth mounds) within the center of Ina exhibit anomalously higher H-parameter values that could be consistent with abundant low thermal inertia material (e.g., pyroclastics or the surface deposits of a magmatic foam). From analyses of craters superposed on the mound units (which range in

height from 5 to 25 m), there is support for more than 5m of fine-grained materials or regolith-like materials at the surface in many locations [12, 13]

Conclusions: Our radar analysis supports the idea that the formation mechanism of Ina included a fine-grained or unconsolidated component. This could be consistent with pyroclastic debris; however, if so, then it must not be high in Fe-rich glass content [e.g., 11]. It has been proposed that the eruption of a magmatic foam could simultaneously produce a fine-grained regolith as vesicles undergo rapid expansion at the surface [14]; yet must not have a high glass content to be consistent with reflectance spectra observations by [11]. Another mechanism that is potentially consistent with a meters-thick, fine-grained but glass-poor deposit in the center of Ina is a redistributed regolith. Such a deposit might be the residual materials left from regolith drainage into subsurface voids [15] or from fine-grained materials redistributed and accumulated during outgassing from the Moon's interior [6].

While the DFSAR L-band results do not directly support or refute any of the suggested Ina formation models, they do provide new and important constraints to further refine the models. We plan to acquire additional L- and S-band radar data of various IMPs using DFSAR in the upcoming imaging seasons. These data can be complemented with Arecibo (S-band) and Mini-RF (S- and X-band) data, to further understand the origin and evolution of the IMPs.

References: [1] Braden, S. E. et al. (2014) *Nature Geoscience* 7, 787–791. [2] Garry, W. B. et al. (2012) *JGRP* 117. [3] Qiao, L. et al. (2020) *JGRP* 125. [4] Byron, B. D. et al. (2022) *JGRP* 127. [5] Whitaker, E. A. (1972) *NASA SP-289*, 2584–2585. [6] Schultz, P. H. et al. (2006) *Nature* 444, 184–186. [7] Carter, L. M. et al. (2013) *LPSC Abs.* 2146. [8] Bhiravarasu, S. S. et al. (2021) *PSJ* 2, 134. [9] Qiao, L. et al. (2019) *JGRP* 124. [10] Neish, C. D. et al. (2017) *Icarus* 281. [11] Vannier, H. et al. (2022) *LPSC Abs.* 2678. [12] Stopar, J. et al. (2017) *LPSC Abs.* 1792. [13] Basilevsky, A. T. and Michael, G. G. (2021) *SSR* 55 [14] Head, J. W. and Wilson, L. (2020) *GRL* 47. [15] Qiao, L. et al. (2021) *PSJ* 2, 66.

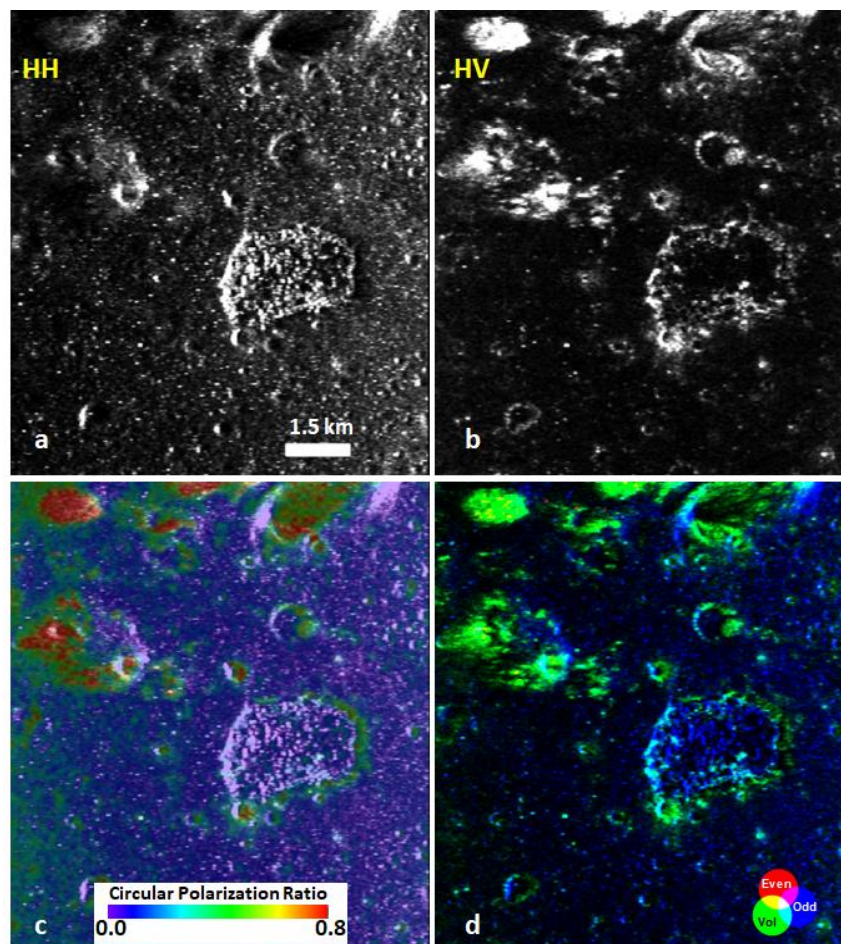


Figure 1. DFSAR L-band radar images of Ina feature shown here in (a) HH, (b) HV polarizations, and (c) CPR, (d) Van Zyl non-negative Eigenvalue Decomposition images. The CPR is stretched to a color scale and overlaid on HH polarization image. The color wheel in the polarimetric decomposition image highlights the colors for each scattering regime (red: even bounce; blue: single (odd) bounce; green: volume scattering).