Icarus 243 (2014) 173–190

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

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# The Miniature Radio Frequency instrument's (Mini-RF) global observations of Earth's Moon

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ARTICLE INFO

*Article history:*
Received 8 October 2013
Revised 18 April 2014
Accepted 15 July 2014
Available online 21 August 2014

*Keyword:*
Moon
Radar observations
Cratering
Volcanism

ABSTRACT

Radar provides a unique means to analyze the surface and subsurface physical properties of geologic deposits, including their wavelength-scale roughness, the relative depth of the deposits, and some limited compositional information. The NASA Lunar Reconnaissance Orbiter's (LRO) Miniature Radio Frequency (Mini-RF) instrument has enabled these analyses on the Moon at a global scale. Mini-RF has accumulated ~67% coverage of the lunar surface in S-band (12.6 cm) radar with a resolution of 30 m/pixel. Here we present new Mini-RF global orthorectified uncontrolled S-band maps of the Moon and use them for analysis of lunar surface physical properties. Reported here are readily apparent global- and regional-scale differences in lunar surface physical properties that suggest three distinct terranes, namely: a (1) Nearside Radar Dark Region; (2) Orientale basin and continuous ejecta; and the (3) Highlands Radar Bright Region. Integrating these observations with new data from LRO's Diviner Radiometer rock abundance maps, as well Clementine and Lunar Prospector derived compositional values show multiple distinct lunar surface terranes and sub-terranes based upon both physical and compositional surface properties. Previous geochemical investigations of the Moon suggested its crust is best divided into three to four basic crustal provinces or terranes (Feldspathic Highlands Terrane (-An and -Outer), Procellarum KREEP Terrane, and South Pole Aitken Terrane) that are distinct from one another. However, integration of these geochemical data sets with new geophysical data sets allows us to refine these terranes. The result shows a more complex view of these same crustal provinces and provides valuable scientific and hazard perspectives for future targeted human and robotic exploration.

## 1. Introduction

An important shift in our understanding of the lunar crust was the recognition that the regional-scale structure and distribution of materials on the Moon are dominated by lateral heterogeneities rather than on gross vertical stratigraphy (Jolliff et al., 2000; Wieczorek and Phillips, 2000). Our current understanding of the lunar crust suggests that it is divisible into distinct geologic terranes based primarily on compositional grounds. Yet physical properties of these same surface materials provide an independent means to help unravel lunar geologic history and assess their exploration potential. Due to limited amounts of data available prior to this point, these characteristics have not been fully integrated into our global view of the lunar crust. However, surface physical properties often play a determining factor in the distribution of volcanic and impact materials ultimately influencing spatial differences in surface and subsurface composition. In this context, synthetic aperture radar provides valuable insights regarding the surface and near subsurface physical character of lunar terranes. Here, we use radar data to more tightly integrate physical and compositional factors in global lunar geologic perspective.

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http://dx.doi.org/10.1016/j.icarus.2014.07.018
0019-1035/

Earth-based radar studies have focused on determining the physical character and depth of the lunar regolith for interpretation of lunar geologic history, resource characterization, landing site hazards, and evaluation of physical properties of the lunar surface (e.g., Thompson et al., 1974a; Ghent et al., 2005; Campbell et al., 2007). However, these data sets are limited by spatial resolution, changing observation geometries, and most importantly, to the lunar nearside, given the synchronous rotation of the Moon about the Earth. As a result, analyses of the lunar surface have been limited to relatively regional nearside localities. While there is significant merit to these studies, a more global analysis can bring to bear significant insight and additional context to these local analyses. In this regard, the suite of instruments carried aboard NASA's recent Lunar Reconnaissance Orbiter (LRO) are providing much needed global information regarding lunar surface physical properties such as surface roughness and rock abundance at both the surface and at modest depths into the regolith (Figs. 1–3). One of these instruments, and the dominant focus of this study, is the Mini-RF hybrid polarization synthetic aperture radar. Mini-RF has built upon its predecessor, Chandrayaan-1's Mini-SAR (which observed almost exclusively the lunar poles (Spudis et al., 2010)), by observing ~67% of the lunar surface at S-band (12.6 cm), including ~99% of the North and South polar regions (±70° to ±90°) (McAdam et al., 2011; Cahill et al., 2012; Spudis et al., 2013) (Figs. 2 and 3). This includes never before observed radar coverage of western Orientale, the farside Feldspathic Highlands Terrane (FHT), and the South Pole Aitken Terrane (SPA). These regions are at best only partially visible from Earth-based radar observatories (e.g., Campbell et al., 2007; Ghent et al., 2008). As a result, Mini-RF offers the first global radar perspective of the lunar surface and subsurface physical properties to integrate with other global lunar data sets.

In this work, we present an analysis of the Moon's global physical properties in the context of S-band radar and compare our results to optical and thermal data sets (e.g., the LROC Wide Angle Camera (WAC), the LRO Diviner Lunar Radiometer, Clementine near-infrared, and Lunar Prospector gamma-ray data products). The combination of these data sets impart additional insight regarding the surface properties of the various terranes defined based on composition (Jolliff et al., 2000). In general, individual lunar terranes represent a rock formation or group of rock formations that predominate and are discrete from adjacent groups of rock units. In this context, Jolliff et al. (2000) defined the three dominant lunar terranes: the Procellarum KREEP Terrane (PKT), the Feldspathic Highlands Terrane (FHT), and the South Pole-Aitken Terrane (SPAT). The Procellarum KREEP Terrane (PKT) is delineated on the basis of having thorium concentrations generally exceeding 3.5 ppm (Fig. 4a). For the most part, this coincides with the large volcanically resurfaced area on the nearside of the Moon. South Pole-Aitken Terrane is divided into (1) the inner topographic depression with the highest FeO concentrations (generally >8 wt.%) (Lucey et al., 2000a), and (2) the outer extent of the mafic anomaly corresponding to ejecta and degraded rim deposits (Fig. 4b and c). The Feldspathic Highlands Terrane (FHT) is defined as (1) the FHT-Anorthosite (-An), which consists of the FeO-poor (<5 wt.%) region on the northern-central farside of the Moon, and (2) the outer-FHT, which has been modified by volcanic deposits and basin impacts and their ejecta deposits (Jolliff et al., 2000).

Here, global observations of the Moon's S-band radar scattering properties are first examined independently from previous lunar geochemical terrane designations. We do this by simplifying Mini-RF scattering observations in much the same way the initial lunar terranes were classified, by de-emphasizing local effects in order to examine larger-scale variability. This broader perspective, in turn, is used to constrain regional-scale crustal differences that suggest the lunar surface can be differentiated into a modest number of regional terranes dominated by specific surface scattering regimes. We then integrate these observations (in addition to observations of rock abundance, maturity, and titanium) with Jolliff et al.'s (2000) initial compositional view of the lunar crust, and suggest specific refinements to these crustal divisions.

## 2. Mini-RF instrument and its analysis capabilities

Mini-RF is a hybrid-polarized, side-looking, synthetic aperture radar (SAR) that transmits in either S-band (12.6 cm) or X-band (4.2 cm) wavelengths and operates in either "baseline" mode (150 m resolution) or "zoom" mode (15 × 30 m resolution) (Raney, 2006; Chin et al., 2007; Nozette et al., 2010). Here, we concentrate our analysis on S-band zoom data products. These data are sensitive to centimeter to meter-sized scatterers (~0.1 to ~1.25 m in size) on the surface or in the near subsurface (roughly meters deep depending upon regolith composition). Mini-RF is unique in its capability to collect radar data from the entire lunar globe at a consistent and nearly unrestricted viewing geometry (Raney, 2006; Raney et al., 2012). This is a perspective that Earth-based imaging surveys cannot achieve due to the synchronous motion of the Moon about the Earth. This data is used to compute several additional parameters that provide complementary information about the lunar surface and near subsurface and are commonly utilized by ground-based radar astronomers.

## 3. Mini-RF derived data products and analysis method

Mini-RF transmits a circularly polarized signal, and measures returned signals in two orthogonal linear polarizations ($H$ and $V$) allowing for the calculation of all four Stokes parameters $S_1$, $S_2$, $S_3$, and $S_4$ (Raney, 2006; Raney et al., 2012) (Fig. 5a). These are calculated by,

$$S_1 = \langle |E_H|^2 + |E_V|^2 \rangle \quad (1)$$

$$S_2 = \langle |E_H|^2 - |E_V|^2 \rangle \quad (2)$$

$$S_3 = 2Re\langle E_H E_V^* \rangle \quad (3)$$

$$S_4 = -2Im\langle E_H E_V^* \rangle \quad (4)$$

where $E$ is the complex voltage in the subscripted polarization. These products are collected in strips consisting of 7.5 × 15 m pixels from an optimum LRO orbit of 50 km from the surface; this enables an effective resolution of 30 m/pixel. Global maps are constructed by down sampling and boxcar averaging these strips to an effective resolution of 100-m/pixel, to reduce speckle noise. Data strips are then orthorectified to a 128-pixel/deg Lunar Orbital Laser Altimeter (LOLA) digital terrain model (DTM) with a simple cylindrical projection. Orthorectified and projected strips are then combined to construct a 100-m/pixel global mosaic of each Stokes parameter. These global products are then down sampled and boxed car averaged once again to 30 pixels/deg consistent with other optical (e.g., Clementine, LROC WAC) and thermal infrared (i.e., Diviner) global ~1 km/pixel data products.

Decreasing our higher resolution data products to lower resolution products substantially reduces the multiplicative noise, which is determined by the number of statistically independent looks figured into the same scene. This is an inherent trait of synthetic aperture radar data sets and applies to all of Mini-RF's data products. Mini-RF has an effective multiplicative noise ($N_{eff}$) of 6.7, and reducing the spatial resolution by averaging reduces the error of the products used substantially (100 m/pix ~ 2.5%; 30 pix/deg < 2%).

The four Stokes parameters can be used to compute additional parameters that are commonly used for the analysis of radar data.