RESULTS OF THE MINI-SAR IMAGING RADAR, CHANDRAYAAN-1 MISSION TO THE MOON P. D. Spudis[1], D.B.J. Bussey[2], B. Butler[3], L. Carter[4], M. Chakraborty[5], J. Gillis-Davis[6], J. Goswami[7], E. Heggy[8], R. Kirk[9], C. Neish[2], S. Nozette[1], W. Patterson[2], M. Robinson[10], R. K. Raney[2], T. Thompson[8], B.J. Thomson[2], E. Ustinov[8] 1. Lunar and Planetary Institute, Houston TX 77058 (spudis@lpi.usra.edu) 2. Applied Physics Laboratory, Laurel MD 20723 3. NRAO, Siccorro NM 4. NASM, Washington DC 5. ISRO, Ahmedabad India 6. Univ. Hawaii, Honolulu HI 96822 7. PRL, Ahmedabad India 8. JPL, Pasadena CA 9. USGS, Flagstaff AZ 10. ASU, Tempe AZ

Mini-SAR is a small, low mass synthetic aperture radar that flew on the Indian Space Research Organization's Chandrayaan-1 mission to the Moon; a modified version of this instrument is aboard NASA's Lunar Reconnaissance Orbiter spacecraft [1]. Mini-SAR is designed to map the permanently dark areas of the lunar poles and characterize the nature of the deposits there.

The possible existence of ice in the polar cold traps of the Moon continues to be debated [2]. The Clementine spacecraft conducted a radar bistatic experiment in 1994, which supported the idea of an ice deposit within Shackleton crater, near the south pole [3]. However, this interpretation has been debated [4, 5] and there is still disagreement whether observed polarization anomalies are caused by the presence of water ice [6]. Despite this uncertainty, there is little argument related to the discovery by Lunar Prospector of enhanced hydrogen levels in the polar regions [7]. The question is whether this hydrogen is in the form of water ice [2]. By mapping the dark areas near the poles and determining the backscatter properties of these surface materials, we can help to constrain the nature and occurrence of water ice deposits on the Moon.

Mini-SAR uses an unusual analytical approach to look for ice [8]. Traditionally, the key parameter used to determine if ice is present is the circular polarization ratio (CPR) [6]. This quantity is defined to be the magnitude of the same sense (i.e., the left or right sense of the transmitted circular polarization) divided by the opposite sense polarization signals that are received. Volumetric water-ice reflections are known to have CPR greater than unity, while surface scattering from dry regolith has CPR less than unity [2]. Mini-SAR uses a hybrid dual polarization technique, transmitting a left-circular polarized signal and receiving coherently the linear Horizontal and Vertical polarization signals. This hybrid architecture preserves all of the information conveyed by the reflected signals [8]. From these data, all four Stokes parameters of the backscattered field are fully recoverable. Stokes parameters offer a very powerful tool to investigate the nature of lunar radar backscatter. In addition to calculating the magnitude of both circular polarizations, it will also be possible to ascertain other scattering properties such as the degree of linear polarization that will help to distinguish between multiple surface reflections versus volume scattering. These characterizations are critical to determine if the returned signal is caused by an ice-regolith mixture, or simply dry rocks on the lunar surface.

While no remote measurement can fully characterize the presence, phase, and stratigraphy of potential ice deposits at the lunar poles, an orbiting SAR provides the most robust method of obtaining a positive indication of ice deposits. The 6° inclination of the Moon's orbital plane around the Earth means that large areas of permanent shadow that might contain water ice can never be seen from Earth, and furthermore all polar areas that can be seen from Earth are viewed at high incidence angles, which reduces the coherent backscatter predicted for ice deposits. However all permanently shadowed regions can be imaged multiple times by an orbiting radar with incidence angles favorable for determining their scattering properties.

The Mission: The Mini-SAR was launched on the Chandrayaan-1 mission on October 22, 2008 [9] and operated for the following nine months. The principal goal of Mini-SAR on Chandrayaan-1 was to systematically map the surface polewards of 80° latitude for both poles. Mini-SAR uses S-band (2380 MHz, 12.6 cm wavelength), has an illumination incidence angle of 35°, and image strips have spatial resolution of 75 meters per pixel. During polar mapping, it imaged both poles in SAR mode every 2-hr orbit, covering both polar regions in a single 28 day mapping window from mid-February to mid-April, 2009. Because the instrument looks off-nadir, there is a gap in SAR coverage within a couple of degrees of latitude around both poles. Portions of these gaps in coverage were partly filled by high-incidence angle SAR on Chandrayaan-1, but we hope to fill in some of those coverage gaps during the Mini-RF instrument on the LRO spacecraft.

Our data products include complete maps of both polar regions of the Moon at 75 m/pixel. These images will consist of opposite sense image mosaics (to reveal the terrain of the dark areas near the poles), images of Stokes parameters, and derived maps of CPR and other Stokes "daughter" products, including degree of linear polarization [8]. All raw data as well as processed data including higher order products such as mosaics will be made available to the scientific community, both through the international portal of the Indian Space Science Data Center and through the Geosciences node of the NASA Planetary Data System.

Results: The Mini-SAR instrument operated nearly continuously for the two month period planned and collected SAR data for over 90% of both lunar poles as well as selected test and calibration strips of several non-polar targets of a variety of terrains around the Moon. Data quality is excellent (Fig. 1) and preliminary results are presented here and in several companion abstracts.

Polar deposits. Both poles were well covered by Chandrayaan data. The north polar region displays backscatter properties typical for the Moon, with circular polarization ratio (CPR) values in the range of 0.1-0.3, increasing to > 1.0 for young primary impact craters. These high CPR values likely reflect a high degree of surface roughness associated with these fresh features. We have identified a group of craters in the north polar region that show elevated CPR (between 0.6 and 1.7) in their interiors, but no enhanced CPR in deposits exterior to their rims (typical CPR values ~0.2 to 0.4; Fig. 1). Almost all of these features are in permanent sun shadow and correlate with proposed locations of polar ice modeled on the basis of Lunar Prospector neutron data [10]. These relations are consistent with deposits of water ice in these craters [11]. The south polar region shows similar relations, except that it has more extensive low CPR terrain and fewer anomalous high-CPR interior craters. Massifs that make up the rim of the South Pole-Aitken basin show high CPR, similar to results seen in basin massifs in the near-equatorial Apennine mountain range. These results are somewhat unexpected; lunar massifs are some of the oldest terrain on the Moon and are expected to be covered with thick, fine-grained regolith. Downslope movement has apparently removed much of this material, exposing an abundance of decimeter-scale blocks. Small areas of high CPR are found in some south pole craters, notably Shoemaker and Faustini; these areas might be deposits of water ice.

Non-polar CPR properties. We obtained several SAR strips covering a wide variety of lunar geological units at low latitudes for both calibration and to create a catalog of the backscatter properties of geological units [12]. Initial results are congruent with measurements from Earth-based radar; from our SAR data, the smooth, fine-grained pyroclastic deposits near Sulpicius Gallus have CPR on the order of 0.179 ± 0.055, agreeing closely with the value measured from Arecibo radar (0.18 ± 0.05; [13]). Fresh craters such as Aratus and Aristarchus have high CPR values while the average combined CPR of mare and highland terrain is ~0.32 ± 0.11. Other geologically interesting targets were covered and we will study their backscatter properties in detail to compare with the polar data and to derive their surface properties.

LCROSS support and LRO planning. The Mini-SAR team supported the selection of the LCROSS landing site by mapping the south pole with both Chandrayaan and LRO radar; the Mini-RF experiment has a high resolution mode, roughly a factor of 5 higher than Mini-SAR. We found the proposed Cabaeus impact site to be very low in CPR, on the order of 0.24 ± 0.12 [14]. This result suggests that massive, pure water ice deposits do not exist in this region of the Moon, a supposition apparently confirmed by the LCROSS results, which indicate water concentrations of a few percent at most.

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Fig. 1 – Small permanently shadowed crater on the floor of Rozhdestvensky showing high CPR inside the crater but low CPR outside.