MINI-SAR: AN IMAGING RADAR FOR THE CHANDRAYAAN 1 MISSION TO THE MOON.

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The debate on the presence of ice at the poles of the Moon continues. We will fly a small imaging radar on the Indian Chandrayaan mission to the Moon, to be launched in September, 2007. Mini-SAR will map the scattering properties of the lunar poles, determining the presence and extent of polar ice.

Introduction Although returned lunar samples show the Moon to be exceedingly dry [1], recent discoveries suggest that water ice may exist in the polar regions. Because its axis of rotation is perpendicular to the ecliptic plane, the poles of the Moon contain areas that are permanently dark. This results in the creation of “cold traps”, zones that, because they are never illuminated by the sun, may be as cold as 50–70 K [2,3]. Cometary debris and meteorites containing water-bearing minerals constantly bombard the Moon. Most of this water is lost to space, but if a water molecule finds its way into a cold trap, it is there forever – no physical process is known that can remove it. Over geological time, significant quantities of water could accumulate.

In 1994, the Clementine polar-orbiting spacecraft used its radio transmitter to “illuminate” these dark, cold trap areas; echoes were recorded by the radio antennas of the Earth-based Deep Space Network. Analysis of one series of data indicated that at least some of the dark regions near the south pole had reflections that mimicked the radio-scattering behavior of ice [4]. These data sparked a major controversy; Earth-based observations were interpreted to be both inconsistent with [5] and consistent with the presence of ice [6,7]. In addition, the authors of an alternate analysis of the Clementine bistatic data found no evidence for unusual reflection behavior at the south pole [8]. Subsequently, the orbiting Lunar Prospector spacecraft found large quantities of hydrogen in the polar regions [9,10], corresponding closely with large areas of permanent shadow [7], consistent with the presence of water ice. Nozette *et al.* [7] noted several procedural aspects of the data analysis in Simpson and Tyler [8] that could have resulted in the disparate results. The controversy over lunar polar ice continues to this day [11].

The existence of ice at the lunar poles is significant in two respects. First, these cold traps have existed for at least two billion years [12]; they contain a record of the impact of volatile components (mostly comets) in the inner solar system for that period of time. Such a record would tell us about the dynamic processes that perturb material from the outer into the inner solar system. Second, significant quantities of water ice could become useful for production of propellant and consumables to support future space activities there and in near-Earth space [13].

One way to obtain this information is to map ice deposits from orbit using an instrument designed to detect and elucidate the properties of the polar ice deposits. A radar system can operate as both a scatterometer and as a synthetic aperture radar imager. This multifunction capability has been demonstrated by previous space borne radar instruments (e.g. Pioneer-Venus, Magellan), but has not been applied to the Moon. In scatterometer mode, the system will be nadir pointing and measure the radar scattering properties along the ground track. Backscatter maps are of low resolution, but will yield a good regional view of the extent of the polar deposits and allow an estimate as to their total mass, currently estimated at ~ 10^{10} metric tonnes [10].

Chandrayaan Mission to the Moon. India plans to launch the Chandrayaan mission to the Moon in September, 2007. This 550 kg spacecraft will enter a polar orbit and map the Moon for 2 years [14]. It’s core payload includes monochrome imaging at ~ 5 m/pixel, a hyperspectral imager (color camera) that images the Moon at 80 m/pixel, a laser altimeter (1 Hz freq.) and an X-Ray fluorescence spectrometer to map the light elements (e.g., Si, Al) of the surface. In addition, an AO released by the ISRO last year invited proposals for additional international instruments. Of the over 20 proposals received, 5 were selected for flight in November, 2004; one of these was mini-SAR. We are currently seeking export-control approval for flight from the U.S. State Department.

Mini-SAR Instrument The mini-SAR will transmit Right Circular Polarization (RCP) and receive both Left Circular Polarization (LCP) and RCP. In scatterometer mode, the system will measure the RCP and LCP response in the altimetry footprint along the nadir groundtrack. The system will measure the surface RF emissivity, allowing a determination of the near normal incidence Fresnel reflectivity. Meter-scale surface roughness and circular polarization ratio (CPR) will also be determined for this footprint. This allows the characterization of the radar and physical properties of the lunar surface (e.g., dielectric constant, porosity) for a network of points. When directed off nadir the radar system will image a swath parallel to the orbital track by delay/Doppler methods (SAR mode) in both RCP and LCP.

Because ice in concentration exhibits the Coherent Backscatter Opposition Effect (CBOE), which causes an increase in radar echo reflectivity and CPR enhancement along the backscatter direction [4,6], mini-SAR will allow extensive data to be collected on the location and distribution of lunar ice deposits. At S-band, CBOE is sensitive to 1-10 meter-scale ice deposits covered by up to 40 cm of dry lunar regolith. The technical parameters of the instrument are summarized in Table 1.

Table 1. Radar System Parameters

Frequency	2.5 GHz
Antenna Gain (min)	24.97 dBi
Peak RF Power	20 W (max)
Polarization	Transmit RCP Receive RCP, LCP
Incidence Angle	45°
Spacecraft Orbital Height	100 km
SAR Mission Duration (max/orbit)	< 10 minutes
Specific radar cross section	–30 dB at 45° angle of incidence
	140 m ground range resolution
Independent looks	16
Nominal Signal to Noise	10 dB

The Chandrayaan laser altimeter [14] will collect new topographic data over both poles, providing a topographic control network for the polar regions of the Moon. It has been pointed out [15] that such a control network, combined with long-lived baseline shadow mapping, will enable much more precise determination of the location and extent of the permanently shadowed terrain, allowing for seasonal and topographic corrections. Such information will allow a more precise estimate of the extent and location of the polar cold traps and hence, ice deposits. This information is important to evaluating the habitability of the lunar poles.

Imaging of the lunar surface by the SAR mapper precludes the imaging of the Moon by the other Chandrayaan-1 sensors, including the medium and high resolution imaging cameras. This is because the high data rates produced by both instruments precludes simultaneous operation. However, the Chandrayaan imaging campaign has a built-in hiatus every six months [14], permitting the two to operate in sequence, alleviating this problem. In addition, spacecraft power limitations preclude other instrument operation during the brief SAR passes. No SAR passes are anticipated during eclipse. Because the Moon rotates very slowly (~ 0.5 degree longitude per hour) and the Chandrayaan spacecraft is in a 2-hr mapping orbit [14], we do not have to take SAR image data on every orbit. A SAR swath taken every 3rd orbit will compile a complete polar mosaic (80° poleward) in about 2 weeks of mapping.

Data products from mini-SAR include maps of lunar surface scattering properties, including maps of CPR, indicative of ice. The polar backscatter maps will have a typical resolution of 1-2 km/pixel. In addition, we will obtain complete SAR mosaics in both RCP and LCP of the polar regions at about 150 m/pixel. These images will display the locations of polar ice and the topography and morphology of the permanently dark regions around both lunar poles. Our experiment should answer to first order the broad questions about lunar polar ice, its extent and purity.

If Chandrayaan lasts for an extended time in lunar orbit (nominal mission end is August, 2009), we hope to conduct a bistatic imaging experiment with the US Lunar Reconnaissance Orbiter (Fig. 1). By transmitting RCP from the Chandrayaan mini-SAR and receiving RCP and LCP on the LRO, we can image the polar deposits through the beta (phase) angle, providing definitive evidence for the presence of water ice at the poles. Monostatic radar can only image the deposits at zero phase ($\beta=0$) and thus, there is always an ambiguity as to the high back scattering being caused by roughness (surface) or ice (volume) scattering. Bistatic imaging can eliminate this ambiguity. Coordinated radar observations from Chandrayaan and LRO should be a high priority for these mission operations.

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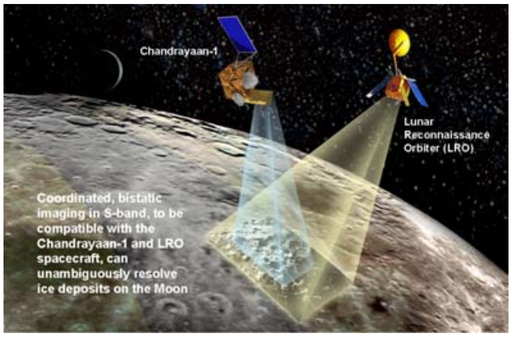

Fig.1 Coordinated bistatic imaging of the lunar poles distinguishes surface (roughness) from volume (ice) scattering.