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# Radargrammetry with Chandrayaan-1 and LRO Mini-RF images of the Moon: Controlled mosaics and DTMs

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## 1. Introduction

The Mini-RF investigation [1] consists of two synthetic aperture radar (SAR) imagers for lunar remote sensing: Mini-SAR (also known as "Forerunner"), which was flown on the ISRO Chandrayaan-1 orbiter in November 2008, and the Mini-RF technology demonstration, which was flown on the NASA Lunar Reconnaissance Orbiter (LRO) in June 2009. A key objective for both instruments was to investigate the possible presence of water ice in permanently shadowed areas near the lunar poles [2]. Not only can these imagers "see in the dark" by providing their own illumination, they measure the full polarization characteristics of the reflected signal for circularly polarized transmitted radiation [3], allowing ice to be recognized by its polarization signature [4]. Mini-SAR obtained nearly complete image coverage of both lunar poles to 80° latitude with a resolution of 150 m and radar wavelength of 12.6 cm (S band), as well as images of 15 non-polar targets for comparison purposes. LRO Mini-RF is capable of imaging in both S-band and and "X-band" (actually 3 cm C-band) wavelengths and at 150 m and 30 m (zoom mode) resolutions. Most of its observations to date have been obtained in S-Band zoom mode, and include both right- and left-looking coverage of much of the south polar zone in support of the LCROSS mission [5] as well as extensive and rapidly growing non-polar coverage.

In this abstract we describe the software and techniques we have developed for radargrammetric analysis of the Mini-RF images, enabling us to make controlled image mosaics with precision and accuracy improved by at least an order of magnitude compared to uncontrolled products, as well as digital topographic models (DTMs), from which orthoimages (images from which topographic parallax distortions have been removed), slope maps, and other products can be generated. A primary motivation for both types of processing is to coregister the radar images as closely as possible to one another and to other datasets [6], so that detailed analyses can be made. Targets of interest include candidate ice-rich craters [7], pyroclastic deposits [8], and the LCROSS impact site (mapped in this abstract). Mini-RF zoom-mode data, with resolution and coverage intermediate between the LROC narrow- and wide-angle cameras, could also be useful for systematic topographic mapping of the low latitudes of the Moon to fill in the kilometre-scale gaps between LOLA altimetry profiles [9].

## 2. Radargrammetry

Radargrammetry is the art and science of making geometric measurements based on radar images, and is precisely analogous to photogrammetry but takes account of the different principles by which a radar image is formed. The fundamental tool in both cases is a *sensor model*, which allows one to calculate the image coordinates (line and sample) of any point whose latitude, longitude, and elevation are specified, or the latitude and longitude of any image pixel provided the elevation is specified. The sensor model is needed to transform image pixels into their appropriate locations in map coordinates. It is also used to make controlled image mosaics that have improved accuracy by *bundle adjustment*, in which the spacecraft positions are adjusted to achieve the best least-squares agreement between the positions of features in overlapping images and between the images and pre-existing ground control. Finally, the sensor model is used to turn a dense set of feature correspondences between a pair of images, obtained either by automated image matching or interactively, into a DTM.

Our approach to radargrammetric processing of Mini-RF images follows that which we have applied to numerous optical sensors and to the Magellan and Cassini radar imagers [10–12]. In particular, we use the USGS in-house cartographic software system ISIS [13] to ingest and prepare the data, project images onto a known reference surface (sphere, ellipsoid, or DTM), and perform a variety of general image analysis and enhancement tasks. We use a commercial digital photogrammetric workstation running SOCET SET (® BAE Systems) software [14] for DTM production by automated matching and for interactive editing of DTMs using its stereo display capability. Using this commercial system with a given data set requires not only an appropriate sensor model, but also software to translate the images and supporting information from ISIS to SOCET SET formats. Our Mini-RF software could be simplified compared to that for Magellan and Cassini because the images [15] are available in "Level 1" coordinates (similar but not identical to the geometry of a pushbroom camera) as well as in "Level 2" map coordinates [16]. Thus, it is not necessary to begin our calculations by undoing the map projection process.

## 3. ISIS Software

Given the availability of Mini-RF data in Level 1 coordinates, we have implemented a sensor model for the ISIS 3 system, based on the physical principals of SAR image formation. We have verified that map-projecting Level 1 images with this sensor model yields results consistent with the Level 2 products from the Mini-RF processing pipeline developed by Vexcel Corporation. This apparently redundant capability is valuable for several reasons. First, image projection in ISIS can potentially make use of improved spacecraft trajectory data in the form of SPICE kernels [17] and improved topographic models onto which to project the images as these become available. Second, we have also incorporated the Mini-RF sensor model into the ISIS bundle-adjustment program "jigsaw" so that images can be controlled to yield even higher accuracy. Finally, the ISIS software (unlike either SOCET SET or the Vexcel SAR processor) is freely available and can be used by anyone to make controlled mosaics and other products from Mini-RF images. The system includes software needed to ingest both Level 1 and Level 2 data products archived in NASA Planetary Data System (PDS) format. All software elements are compatible with both Chandrayaan-1 and LRO images.

# 4. SOCET SET

We have also implemented a Mini-RF sensor model for SOCET SET, as well as the software needed to translate images and spacecraft trajectory data (in SPICE SPK format) to SOCET formats. With these tools, all SOCET SET functions are available for Chandrayaan-1 and LRO Mini-RF images in combination with one another or, if desired, with any other supported images. The bundle adjustment capability of SOCET SET provides a useful check of the validity of results from ISIS "jigsaw" but the main application is DTM production by a combination of automatic image matching and interactive editing. The commercial software and special display hardware it uses are relatively expensive, but several planetary investigators have SOCET workstations at their home institutions (see, e.g., [18]). The USGS has several such workstations used for mapping under the NASA Planetary Cartography program and various flight programs, and one that is operated as a guest facility at which outside researchers can make their own DTMs from publically available data [19].

# 5. Test Data, Results, and Prospects

The properties of stereo DTMs depend on the resolution and viewing directions of the source imagery. By far the most extensive sets of overlapping SAR images are in the areas poleward of 80° north and south. Forerunner images covering >90% of these regions were obtained. LRO Mini-RF S-zoom mode images cover a smaller but still appreciable fraction of the south polar zone at higher resolution [5]. Both datasets provide a mixture of eastward and westward viewing and illumination direction; although the look direction (left or right of the ground track) is constant for each image strip, the compass directions of illumination on the ascending and descending sides of the orbit are opposite. Standard formulas of radargrammetry indicate that the expected vertical precision (EP) for opposite-look S-zoom images is on the order of 10 m, if image matching is precise to half the resolution as we have found to be the case for Cassini radar [11]. Same-side image pairs would have EP at least a factor of two worse but are easier to stereomatch because of the consistent illumination. Horizontal resolution of the DTM can be expected to be a few times the resolution at best, or on the order of 50-100 m in either case. Same-side images from LRO and Chandrayaan-1, which have incidence angles of 47.6° and 33.5° respectively, could be used but the relatively weak geometry and worse resolution of Forerunner would lead to an EP of ~120 m and horizontal resolution of at least 500 m. Finally, by deliberately targeting two LRO S-zoom images with different look angles from the same side, it should be possible to optimize illumination, EP, and image overlap simultaneously. An image pair of this type covering the crater Jackson was recently obtained.

Initial tests of both mosaic and DTM production were made with S-zoom images covering part of the crater Cabeus (including the LCROSS impact point) near the south pole. Three images with eastward and three with westward look direction were bundle adjusted together. The RMS mismatch at control points was reduced from 150 m to 12 m, confirming that residuals smaller than the image resolution of 15x30 m could be obtained. A stereo DTM was constructed by matching the images in pairs with opposite viewing direction. This DTM shows excellent agreement with Kaguya altimetry (used as the control base) and LOLA altimetry, but is substantially more detailed, resolving features as small as about 200 m across.

In the near future we will test a new version of the SOCET SET image matching algorithm intended specifically for radar imagery to see if DTM resolution and accuracy can be improved further, and will compare results for opposite-side, same-side, and stereo targeted same-side image pairs.

# 6. Summary and Conclusions

We have implemented a series of radargrammetric tools for processing Chandrayaan-1 and LRO Mini-RF radar images of the Moon. These tools will be used within the Mini-RF team to make high-precision controlled mosaics and digital topographic models. Through the open release of ISIS software and the USGS/NASA Planetary Photogrammetry Guest Facility, the same capabilities will soon be available to the entire planetary research community.

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