A RADARGRAMMETRIC CONTROL NETWORK AND CONTROLLED MINI-RF MOSAICS OF THE MOON'S NORTH POLE…AT LAST! R.L. Kirk[1], T.L. Becker[1], J. Shinaman[1], K.L. Edmundson[1], D. Cook[1], D.B.J. Bussey[2], [1]Astrogeology Science Center, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff AZ 86001 (rkirk@usgs.gov), [2]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723.

Introduction: This abstract is one in a series [1–3] describing our development of techniques for radargrammetry (analogous to photogrammetry but taking account of the principles by which radar images are formed) and their application to mapping the Moon with Mini-RF images. Our goals are twofold: 1) using radar stereopairs to produce digital topographic models (DTMs) of medium resolution and broad coverage; and 2) controlling large sets of images to produce image mosaics with greatly improved positional accuracy. The latter process is scientifically valuable because it enables radar observations obtained at various viewing geometries to be compared, corrected for slope effects, and correlated with other remote sensing data such as optical and thermal images and altimetry.

In [1] we described this overall program and the software developed to support it, and demonstrated the ability to control small numbers of images and make DTMs from them. Details of the software are given in [4]. In [2] we described the production of a DTM of Jackson crater from a targeted stereopair. Unexpected distortions in this DTM were traced to the details of modeling the spacecraft trajectory in [3], allowing us to demonstrate the production of regional DTMs and associated controlled mosaics of Constellation program regions of interest [5]. We also presented uncontrolled but orthorectified (i.e., projected onto a detailed topographic model to remove parallax distortions) mosaics of the lunar poles as a first step toward the production of the desired controlled mosaics. These uncontrolled mosaics have recently been archived in the NASA Planetary Data System (PDS).

In this abstract we describe how the remaining obstacles to production of controlled mosaics with hundreds to thousands of Mini-RF images have been overcome. We present a control solution and mosaics covering the zone 85–90°N latitude, and describe our plans to extend the project to 70°N and to the south polar region.

Source Data: NASA's Mini-RF investigation [6] consists of two synthetic aperture radar (SAR) imagers for lunar remote sensing: Mini-SAR on ISRO's Chandrayaan-1, and the Mini-RF on the NASA Lunar Reconnaissance Orbiter (LRO). Both are designed to record the full polarization state of the received signal: 4 parameters, which can be treated as a 4-band image and combined in various ways to yield quantities of interest such as the total backscattered power (S_1) and circular polarization ratio (CPR). Our software and techniques are applicable to data from either instrument, but the primary focus of this abstract is the coverage of the polar zones (to 70°N and S) obtained by LRO Mini-RF in June-July 2010. These images were obtained in "S Zoom" mode, with a radar wavelength of 12.6 cm (S Band) and 7.5 m pixel spacing (~15x30 m true resolution). Nearly complete coverage was obtained in both eastward and westward looking images, providing complementary views of surface slopes with illumination from the west and east respectively.

Other important datasets include X-band (4.2 cm) imaging of about 75% of the north pole by LRO in November-December 2010, including both Zoom and Baseline (75 m/pixel, 150 m resolution) images, additional LRO S-Zoom coverage of the south pole from 2009, and Mini-SAR S-band coverage of both poles to 80° at higher incidence angles.

Methodology: Stereo DTM production with Mini-RF images [1, 4] follows the same approach we have applied to the Magellan and Cassini radar imagers [7], using the commercial digital photogrammetric software SOCET SET (® BAE Systems) [8] with a "sensor model" (the transformation between pixel coordinates and ground coordinates) written by us, and the USGS software system ISIS [9] used to prepare the images in a form suitable for SOCET SET. Unlike Magellan and Cassini, for which images in native ("Level 1") geometry were not available, we have also developed the software and techniques to control, project, and mosaic thousands of Mini-RF images comprising hundreds of GB of data in ISIS. Implementing the sensor model transformation between pixels and ground coordinates in ISIS [4] was only the first step of this process. The others are as follows:

- Calculation of the partial derivatives of the sensor model with respect to the spacecraft trajectory, needed in the control adjustment calculation.
- Implementation of a special version of the ISIS adjustment program *jigsaw* [10] that uses the Mini-RF sensor model. We hope in the future to integrate adjustment of radar and optical images in a single program.
- Enhancement of the way *jigsaw* models the spacecraft trajectory. The existing approach, using second order polynomials in time, cannot accurately represent an orbit arc of more than a few degrees. Jigsaw can now model trajectories as the sum of a fixed *a priori* part that is spline-interpolated from a set of waypoints (the standard form of a NAIF SPICE SPK kernel [11]) and an adjustable polynomial of arbitrary order. This enhancement will also be useful for controlling long-arc pushbroom images, e.g., from the Mars Express HRSC.
- Adaptation and testing of a faster interpolation method for projecting images [12] to the radar sensor model.
- Selection of the required images based on latitude and look direction, discussed at greater length below.
- Development of effective procedures for automated collection of the majority of the image-to-image tiepoints needed in the control calculation.
- Development of manual procedures for collecting the critical ties between images with opposite look direction and between images and ground control data.
- Determination of appropriate weighting for the adjustable parameters of the trajectory.
- Automation of processing (apart from the control adjustment) with testing on a single workstation and production on the Astrogeology high performance computing cluster.

Identifying images that cover the region of interest (70–90° N or S latitude) is straightforward, based on maximum and minimum latitudes stored in the labels. Handling image look direction is more complex. The side-looking images pass both right and left of each pole, forming a pattern reminiscent of the spokes of a bicycle wheel. Our goal is to control all of these images simultaneously, producing a geometrically strong network because of the many crisscrossing image overlaps, but then to produce separate mosaics containing only the east- and west-looking coverage respectively. The illumination direction will then be relatively uniform within each mosaic. Most image files contain purely east- or west-looking data, but those that pass closest to the pole reverse their look direction at the top of the orbit. We use the ISIS application *phocube* to map the sub-spacecraft ground azimuth (relative to north) at every pixel of each image. This lets us identify the "mixed" images for inclusion in both mosaics and also lets us mask them so that only the pixels with appropriate look direction for that mosaic are used.

Initial north polar control network and test mosaics: The images covering the 70–90°N zone number 1140, about equally divided between east- and west-looking, with 359 mixed files. To control these images, we are working outward from the pole, starting with the 85–90°N zone. All images overlapping this zone were included in tiepoint collection and adjustment, but a subset of 455 images that lie entirely within this zone were used to construct test mosaics to verify the control solution. Because the image strips converge toward the pole and overlap manyfold, this subset sufficed to produce mosaics with only minor gaps (Figure 1).

Automated tiepoint measurement by the ISIS program *coreg* proved highly effective when applied only to images with similar look (and therefore illumination) direction. About 6000 points were measured in this way, with an average of 5 images successfully matched per point. The 359 mixed images were matched to images of both looks, effectively providing bridges between the sub-networks. Unfortunately, the success rate for automated matching of opposite-look images was low (a problem that is being addressed through the implementation of more advanced matching algorithms [13]). About 25 additional tiepoints were therefore measured manually and 17 ground control points used in the 86–90°N LROC-NAC mosaic were transferred to the Mini-RF images; an average of 10 images was measured at each of these points. A *jigsaw* control calculation based on these inputs converged successfully but issues with the scaling of the results back to pixel units prevent us from reporting meaningful RMS residuals at this time. Our confidence in the validity of the solution therefore rests on the controlled test mosaics produced. Blink comparison of the east- and west-looking mosaics shows no discrepancies visible at the pixel level, except in limited areas where additional ground control may be needed. Figure 2 compares the consistency of the test mosaics with the uncontrolled mosaics [3], which contain kilometer-scale offsets.

Future work: Expansion of the north polar control network and mosaics to 70°N is underway, with a new control solution computed as points for each 5° latitude zone become available. The divergence of the image strips will result in a decreasing number of automatically measured same-side points per zone, so an increasing number of manually measured east-west and image-ground ties will be needed. We nevertheless see no fundamental obstacles to completing this mosaic. Funding to produce the south polar S-Zoom mosaic has been approved by the NASA Planetary Geology & Geophysics program. When complete, both mosaics will be archived in the PDS. This will provide shadow-free, 4-polarization and 2-look coverage of both poles in support of future research and exploration planning, as well as basemaps to which other observations (higher incidence, X-band, and even Arecibo-to-LRO bistatic images) can be controlled if suitable funding can be identified.

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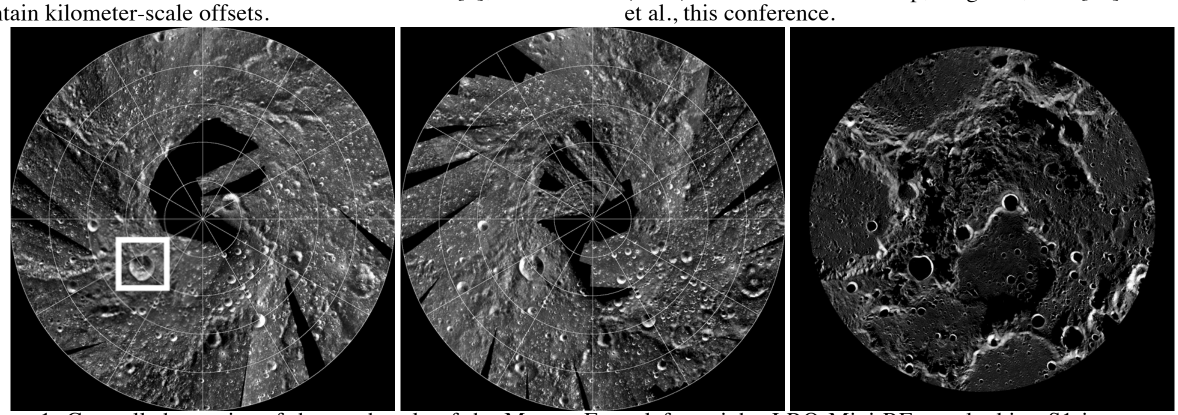

Figure 1. Controlled mosaics of the north pole of the Moon. From left to right, LRO Mini-RF east-looking S1 images; west-looking S1 images; LROC NAC images. Polar stereographic projection, 85-90°N (NAC data begins at 86°N), 0° lon at bottom. Grid spacing 1° lat x 30°lon. Box shows area enlarged in Fig. 2.

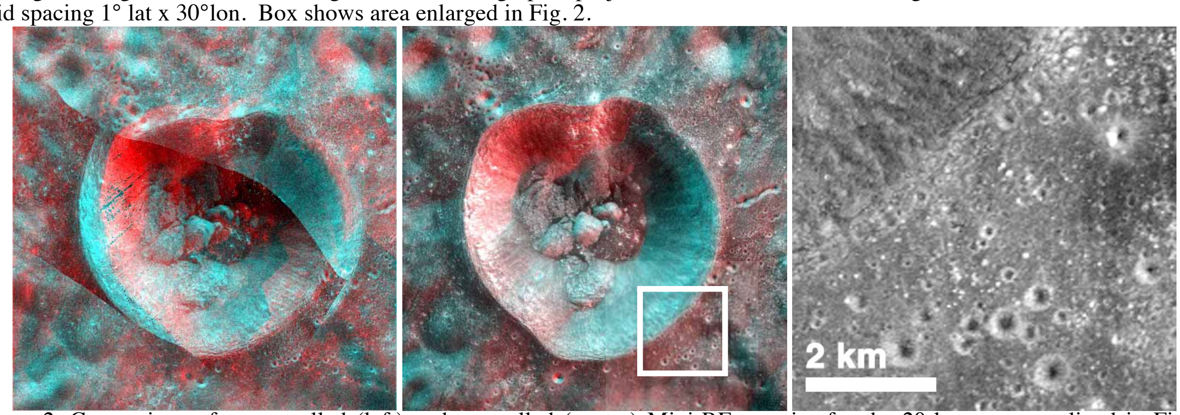

Figure 2. Comparison of uncontrolled (left) and controlled (center) Mini-RF mosaics for the 20-km crater outlined in Fig. 1. East-looking mosaic is shown in cyan, west-looking in red. Image-to-image and look-to-look mismatches are in the range of 1-3 km uncontrolled, 30 m or less after control adjustment. At right, a further enlargement of the crater rim shows the high signal to noise ratio achieved by averaging multiple overlapping images in the mosaic.