NEXT STEPS IN RADARGRAMMETRY OF THE MOON: TARGETED STEREO OBSERVATIONS AND CONTROLLED MOSAIC PRODUCTION. R.L. Kirk[1], E. Howington-Kraus[1], T.L. Becker[1], D. Cook[1], J.M. Barrett[1], C.D. Neish[2], B.J. Thomson[2], D.B.J. Bussey[2] and the Mini-RF Team. [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 of a series about our research and development of techniques for radargrammetry (the art and science of making geometric measurements based on radar images, analogous to photogrammetry but taking account of the different principles by which a radar image is formed). We previously [1, 2] described the software tools we have developed, which allow us to make controlled image mosaics with positional accuracy more than an order of magnitude better than uncontrolled products, and to create high resolution digital topographic models (DTMs) from radar stereopairs even in areas not illuminated by the sun. In this abstract, we describe the acquisition and processing of a targeted stereo observation of the equatorial zone, yielding a DTM of part of Jackson crater with very high horizontal resolution and vertical precision. Such targeted imaging would be highly effective for filling in the gaps (currently on the order of kilometers) between LOLA laser altimetry profiles [3] at the low latitudes, because the resolution and swath width of the radar images occupy a "sweet spot" intermediate between the Narrow- and Wide-Angle Lunar Reconnaissance Orbiter Cameras [4].

Our mapping of Jackson crater revealed significant long-wavelength geometric distortions in the DTM. Given the principles by which radar images are formed, such distortions cannot simply be instrument effects (like the optical distortions to which camera lenses are subject) but must arise from errors in the spacecraft trajectory data. We therefore report on our efforts to assess both the severity and frequency of these errors. This assessment is the first step toward identifying the cause of the problem and developing strategies both to correct the existing data and to ensure that future observations are affected as little as possible. Fortunately, one of the most effective ways to assess distortions in the majority of Mini-RF images simultaneously is by constructing the radargrammetric control network that would in any case be needed in order to produce controlled mosaics.

Instruments and Data Sets: NASA's Mini-RF investigation [5] consists of two synthetic aperture radar (SAR) imagers for lunar remote sensing: Mini-SAR (also known as "Forerunner"), which was launched on the ISRO Chandrayaan-1 orbiter in October 2008 [6], and the Mini-RF technology demonstration, which was launched on the NASA Lunar Reconnaissance Orbiter (LRO) in June 2009. 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 non-polar targets for comparison purposes. LRO Mini-RF is capable of imaging in both S-Band and X-band (4.2 cm) wavelengths and at 150 m and 30 m (zoom mode) resolutions. Most observations to date have been obtained in S-zoom mode. A combination of west- and east-looking coverage of part of the south polar zone in support of the LCROSS mission [7] was obtained in June-September 2009. Systematic S-zoom mosaics of both poles were obtained in June-July 2010. A second polar imaging campaign in November-December 2010 focused on X-baseline imaging of the north pole in expectation that the eventual transition of LRO to an elliptical orbit would make northern hemisphere imaging difficult or impossible. Substantial coverage of non-polar latitudes has also been acquired, with >46% of the lunar surface covered in S band during the first year of observations.

A key feature of the Mini-RF investigation is that all observations are available as unprojected images, known as "Level 1" products [8], as well as after projection into "Level 2" map coordinates based on trajectory and topographic models that may later be superseded.

Technical Approach: Our approach to radargrammetric processing of Mini-RF images [1, 2] follows that which we have applied to numerous optical sensors and to the Magellan and Cassini radar imagers [9–11]. In particular, we use the USGS in-house cartographic software system ISIS [12] to ingest and prepare the data, project images onto a known reference surface, and perform general image analysis and enhancement tasks. We use a commercial digital photogrammetric workstation running SOCET SET (® BAE Systems) software [13] for DTM production by automated matching and for interactive editing of DTMs using its stereo display capability. We have written the software needed to translate the images and supporting information from ISIS to SOCET SET formats. In addition, we have written sensor model software (which allows one to calculate the line and sample image coordinates of any point whose latitude, longitude, and elevation are specified, or the latitude and longitude of any image pixel provided the elevation is specified; see [2] for details) for both ISIS and SOCET SET. As a result, we can use either system to perform a bundle adjustment that improves the registration of Mini-RF images to one another and to ground control, and to project the images onto a topographic surface, and have verified [1, 2] that consistent results are obtained. The tools needed to create DTMs are, however, unique to SOCET SET. This commercial software package is relatively expensive, but the USGS makes it available as a guest facility at which outside researchers can make their own DTMs from released data [14].

Targeted Stereo: Stereo imaging with radar is subject to a fundamental constraint that does not apply to optical imaging: because the instrument supplies its own illumination, increasing the geometric convergence angle between images not only strengthens the stereo but also introduces illumination differences. Opposite-side imaging (e.g., [1]) yields strong stereo but differences in the appearance of the images can reduce the effectiveness of automated matching and increase the amount of manual DTM editing required. On the other hand, if images are obtained from the same side at a consistent look angle, there is a tradeoff between stereo strength and degree of overlap. If the images overlap completely, the viewing angles are identical and no height information is obtained. One solution to this dilemma is to change the look angle of the entire radar beam relative to nadir, in order to obtain two images of the same target with different viewing geometries. This is analogous to optical stereo imaging with a single camera, in which the spacecraft is rolled to take a second image of a target at an off-nominal angle [15]. In this way, it is possible to obtain near-complete overlap, acceptably strong stereo geometry, and reasonably compatible illumination simultaneously.

To test this idea, stereo observations of the 71-km crater Jackson were targeted on 25 April 2010. On orbit 3821, latitudes 7.5°S to 40°N near longitude 196°E were imaged with the normal off-nadir look angle, resulting in a centerline incidence angle of 44°–48°. On the following orbit, the same area was imaged at a reduced incidence angle of 24°–29°. Each observation was obtained in four segments, corresponding to the changing target elevation. We restricted our processing to the first segment of each image, which covers the crater (Figure 1). Controlling the images was difficult because of substantial overall discrepancies in elevation between the stereo model and the LOLA DTM used as a control source. We resorted to a solution tied to LOLA by only a single well-defined ground point on the northern crater rim, with tie points distributed along the image strip. This was sufficient for stereo matching to proceed very effectively, yielding a DTM at 25 m/post grid spacing. Only minor editing was required, mostly near the image edges; the normalized editing time of ~0.8 hours per million DTM points compares favorably with HiRISE images [15] and is dramatically less than required for other radar data [11]. The DTM reveals details of crater morphology such as the central peak and terracing of the inner wall down to ~50 m in horizontal scale (Figure 2).

Comparison of the stereo DTM with ~250 m/post LOLA data revealed (in addition to dramatically greater detail) a very smooth discrepancy that varied almost quadratically with latitude and had a peak-to-peak amplitude of nearly 4000 m. In addition, the bundle adjustment residuals in the north-south direction were ~3x higher than for the Cabeus data set [2] and these residuals also varied systematically as a smooth, almost cubic function of latitude having a peak-to-peak amplitude of 6 pixels (~90 m). Because radar images are formed by measuring the location of features in relation to the spacecraft trajectory (i.e., time of zero Doppler shift and range at that time) these distortions and discrepancies in the calculated ground coordinates must come from errors in the trajectory data used at some stage in processing.

Next Steps: Determining how widespread such trajectory errors are, what causes them, how they can be avoided, and whether and how they can be mitigated for images already taken will be a major focus of our research in the near future. Four lines of investigation will address this issue

1) Comparison of the Jackson targeted stereo images with independent data (e.g., LROC NAC or other images of suitable resolution) in a new control adjustment that should provide information about the degree to which each Mini-RF image is distorted, rather than merely the difference between them.
2) Acquisition and processing of one or more additional targeted stereopairs, in an attempt to determine whether this is an effect peculiar to the nonstandard spacecraft pointing used for such observations.
3) Construction of control networks for the large sets of images covering the polar regions. This would in any case be the next step toward production of controlled mosaics, which will make the radar data much more useful for comparative studies by registering them to one another and to other geophysical data sets. A simultaneous bundle adjustment of all the images is also the most efficient way to "screen" the entire data set to find an (assumed) minority of problem images.
4) Controlling and mosaicking of non-polar images. Because these do not form a large contiguous block like the polar image sets, we will do spot checks to assess how often and where large distortions occur.

Correlating the results of these investigations with spacecraft and instrument operational modes and other significant events may provide clues to the cause of the image distortions first seen at Jackson crater. Hopefully, such an identification of the cause will allow us to avoid obtaining distorted images in the future (as has been the case for severe "jitter" distortions of MRO HiRISE images [16]). Even if a specific cause is not determined, however, it should be possible to correct for the relatively smooth distortions of the images by using the ISIS bundle adjustment program "jigsaw." The main disadvantage of this approach is that a relatively dense set of ground control points per image will be required, and that such points must at present be measured manually.

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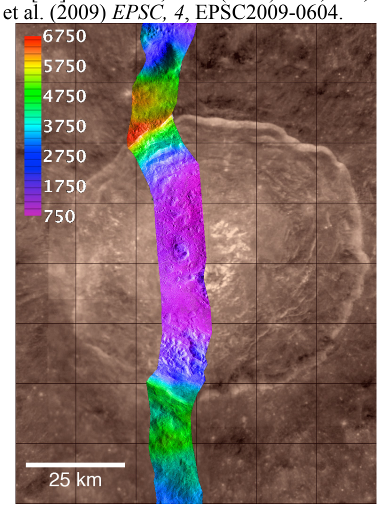

Figure 1. Orthorectified S-zoom image of part of Jackson crater, color-coded with elevation from targeted same-side stereopair. Stereo-derived elevations have been adjusted to match LOLA altimetry over distances >10 km, as described in text. Backdrop is Clementine UVVIS base mosaic, tinted brown to distinguish it from the radar imagery. Simple Cylindrical projection, 195°–198°E, 20°–22°N.

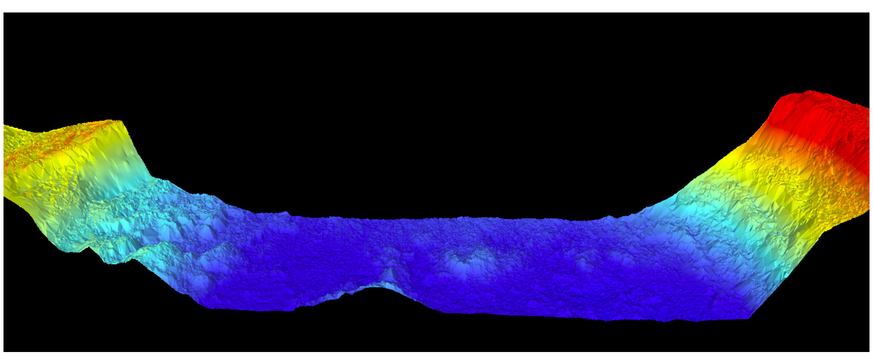

Figure 2. Perspective view of part of the Jackson stereo DTM showing the crater interior as shaded relief color-coded from blue (low) to red (high). Topographic features as small as 50 m across are visible, including slump terraces on the inner walls of the crater. Vertical precision is estimated to be ~6 m. View from the east with 2x vertical exaggeration.