PROGRESS IN RADARGRAMMETRIC ANALYSIS OF MINI-RF LUNAR IMAGES. 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[3], 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, [3]Boston University, Boston, MA 02215

Introduction: This abstract is one of a series describing 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 described the software tools we have developed [1, 2], 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. In [3] we described the production of a DTM of Jackson crater from a targeted stereopair. Although this model had good horizontal resolution and vertical precision, it was found to contain severe long-wavelength distortion. Here, we report for the first time the cause of the problem and show how it can be avoided by minor software changes. Our revised Jackson DTM is free of distortions and has significantly improved resolution compared to the earlier result, opening the way for further stereomapping.

The Mini-RF transmitter stopped operating in December, 2010 before additional targeted stereo observations could be obtained, but the large set of images with standard incidence angle (described below) include numerous overlaps giving fortuitous stereo coverage. These stereo overlaps occupy a "sweet spot" in resolution and swath width intermediate between the Narrow- and Wide-Angle Lunar Reconnaissance Orbiter Cameras (LROC NAC and WAC) [4], making them highly effective for filling in the gaps (on the order of kilometers at low latitudes) between LOLA laser altimetry profiles [5] and supporting scientific investigations of those areas for which they are available. We are producing additional DTMs and controlled image mosaics in the equatorial zone, focusing on several of the regions of interest identified by the Constellation program [6] with the densest Mini-RF coverage. In addition, we have started the substantial task of controlling the large set of images covering the lunar poles, with the goal of producing seam-free and distortion-corrected radar mosaics that will register precisely to other datasets such as LOLA and LOLA-controlled NAC mosaics.

Instruments and datasets: NASA's Mini-RF investigation [7] 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 [8], and the Mini-RF technology demonstration, which was launched on the NASA Lunar Reconnaissance Orbiter (LRO) in June 2009. The software and techniques described below are applicable to data from either instrument. 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 (baseline) and 30 m (zoom mode) resolutions. Most observations to date have been obtained in S-zoom mode. Coverage of part of the south polar zone in support of the LCROSS mission [9] 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-band baseline imaging of the north pole, yielding >75% coverage poleward of 80° before the instrument stopped transmitting. Substantial coverage of non-polar latitudes was also acquired, with >66% of the lunar surface covered in S band during 1.5 years of operations.

Technical Approach: Our approach to radargrammetric processing of Mini-RF images [1, 2] follows the methods we have applied to numerous optical sensors and to the Magellan and Cassini radar imagers [11–13]. In particular, we use the USGS in-house cartographic software system ISIS 3 [14] 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 [15] for DTM production by automated matching and for interactive editing of DTMs using its stereo display capability. We have written software needed to translate the images in "Level 1" geometry [10] and supporting information from ISIS to SOCET SET formats. In addition, we have written sensor model software to calculate the transformation between ground and pixel coordinates (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 for outside researchers to make their own DTMs from released data [16]

Targeted stereo at Jackson crater: 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°. This imaging strategy yielded strong stereo convergence across the full width of the image swath, in contrast to the overlaps between images with similar look angle (e.g., fortuitous overlaps between images in the polar and equatorial mapping campaigns), for which stereo strength decreases as the amount of overlap increases. Each observation was obtained in four segments, corresponding to the changing target elevation; our DTM production has focused on the segment overlapping the crater.

Our initial analysis of this dataset was described in [2a]. Because of substantial overall discrepancies in shape between the stereomodel and the LOLA DTM used as a control source, we used only a single control point to tie the former to the latter. Automated stereomatching yielded a 25 m/post DTM requiring relatively little editing compared to other planetary radar datasets [13]. Features as small as 50–100 m across were resolved in some areas, particularly the crater floor and walls, but a horizontal resolution on the order of 500 m typified most of the model. This nevertheless represented a substantial advance over the LOLA dataset, which at that time contained only a single altimetry track within the ~10 km width of the DTM. Comparison of the stereo results with LOLA grid data revealed (in addition to the resolution difference) a discrepancy with a peak-to-peak amplitude of nearly 4000 m and a smooth, almost parabolic variation along track. Smaller variations (but larger than seen with Chandrayaan-1 Mini-SAR data in [1]) were seen in the control net residuals.

The specific cause of these distortions was unknown, but the spacecraft trajectory information was strongly implicated because spacecraft pointing plays no role in the process of forming radar images. To determine whether the problem lay in the physical trajectory, the mission-provided trajectory data (NAIF SPICE SPK kernel [17]), or our handling of the information, we started collecting tiepoint information to control additional images and make further DTMs. We also compared the results of controlling and projecting the images in ISIS and in SOCET SET. These tests showed that SOCET SET was interpolating the sparse trajectory points as a piecewise linear function rather than a smooth curve, leading to multi-km position errors between points. When SOCET SET was supplied a dense set of trajectory points (estimated by smooth spline interpolation in ISIS), (a) the stereomodel conformed to LOLA data and was easily controlled with multiple ground control points; (b) the distortion of the DTM relative to LOLA was eliminated; (c) the number of errors in the DTM requiring manual editing was further reduced; and (d) the resolution of the DTM was improved by a factor of several compared to the initial version. This improvement was partly the result of enhancements to the stereomatching algorithm in the intervening year, and partly the result of being able to use the LOLA DTM as a "seed" to initialize the matching process.

Nonpolar controlled mosaics and DTMs: To constrain the problem of choosing fortuitously overlapping images in the low and mid latitudes for mapping, we elected to focus on the 50 Constellation regions of interest [6], which were chosen for their interest scientifically, as potential landing sites, or both. Many have been mapped with LROC NAC data, so they are likely to remain the focus of ongoing research. The Apollo Basin (APB), Gruithuisen Domes (GRT), King crater (KNG) and Orientale region 2 (OR2) sites were selected as having the best Mini-RF image coverage and overlap for mapping, based on visual inspection of footprint plots. Images overlapping the 40-km wide outer boundary of each region of interest were then selected. Because the images are elongated in the orbit direction, this results in extensive coverage north and south of each region but not to the east and west. Apollo was the first site mapped (Fig. 1), and provided several lessons. (Mapping of the other sites is in progress and will be reported in our presentation.) First, the actual coverage of the images is affected by topographic parallax, since radar images are oblique, and can differ significantly from the nominal footprints based only on the image corner coordinates. The result can be unexpected gaps in the image and especially DTM coverage. Second, although same-side stereo coverage is preferred, useful DTMs can be compiled from opposite-look images, with low error rates but somewhat poorer resolution than was obtained for Jackson crater. As expected, the use of a dense set of trajectory points prevented the DTM from being distorted. We conclude from this experience that it would be useful to compute more detailed and accurate Mini-RF image footprints by projecting additional points on the image boundary onto a global topographic model, and to incorporate these footprints into the USGS Uniform Planetary Coordinates database [18] so that its PILOT interface [19] can be used to identify the most useful images for mapping. Enhancing PILOT with a tool for evaluating the quality and coverage of stereopairs would be especially valuable for planning future DTM production.

Polar control networks and mosaics: Selection of the best images and stereopairs is not an issue in the polar regions (roughly 70°–90° N and S) because nearly seamless mosaics could be made by using all available images, and because the dense LOLA coverage precludes the need for stereo DTMs. Instead, the main challenge is the sheer volume of data to be processed, consisting of hundreds of images per pole with on the order of 10^8 pixels per image. Once controlled, these images could be orthorectified by projection onto the LOLA surface, removing parallax distortions. They would then align with one another (yielding seamless mosaics), with LOLA, and with other datasets, significantly enhancing the science return from LRO.

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. We are currently focusing on a subset of images close to the north pole in order to develop and test the procedures for collecting the necessary data. Automated matching techniques are being used to collect image-to-image ties. Where these are sparse (we anticipate this mainly where images have opposite look directions) these will be supplemented by manually measured tiepoints. Ground control points will also be measured manually, based on the LOLA DTM and the LOLA-controlled NAC image mosaic recently produced at USGS.

Although all images will be controlled as part of a single network, separate mosaics will be produced, containing only image sections with eastward and westward illumination/look direction respectively. Because the look direction changes within a single orbit as the spacecraft passes the pole, the images will be masked pixel-by-pixel based on the local azimuth to the spacecraft.

References: [1] Kirk, R.L. et al. (2010) *LPS XLI*, 2428. [2] Kirk, R.L., et al. (2010) *IAPRSSIS*, *38*(4), 43, online at http://www.asprs.org/publications/proceedings/orlando2010/files/KIRK.PDF. [3] Kirk, R.L., et al. (2011) *LPS XLII*, 2392. [4] Robinson, M.S. et al. (2010) *Space Sci Rev, 150,* 81-124. [5] Smith, D.E. et al. (2009) *Space Sci Rev* doi:10.1017/s11214-009-9512-y. [6] Lucey, P.G. et al. (2009) *LPI Contrib. 1483*, 6922. [7] Nozette, S. et al. (2010) *Space Sci Rev*, *150*, 285. [8] Spudis, P.D. et al. (2010) *GRL*, *37*, L06204. [9] Colaprete, A., et al. (2010) *Science*, *330*, 463. [10] Batson, R.M. (1990) in *Planetary Cartography*, 60–95. [11] Howington-Kraus, E. et al. (2002) *LPS XXXIII*, 1986. [12] Kirk, R.L. et al. (2012) *Icarus*, in revision. [13] Kirk, R.L. et al. (2008) *IAPRSSIS XXXVII*(4), 973. [14] Anderson, J.A. et al. (2004) *LPS XXXV*, 2039. [15] Miller, S.B., and A.S. Walker (1993) *ACSM/ASPRS Ann. Conv. 3*, 256; — (1995) *Z. Phot. Fern. 63*(1) 4. [16] Kirk, R.L. et al. (2009) *LPS XL*, 1414. [17] Acton, C.H. (1999) *LPS XXX*, 1233. [18] Akins, S.W. et al. (2009) LPSC XL, 2002. [19] Bailen, M.S. et al. (2011) *LPS XLII*, 2214.

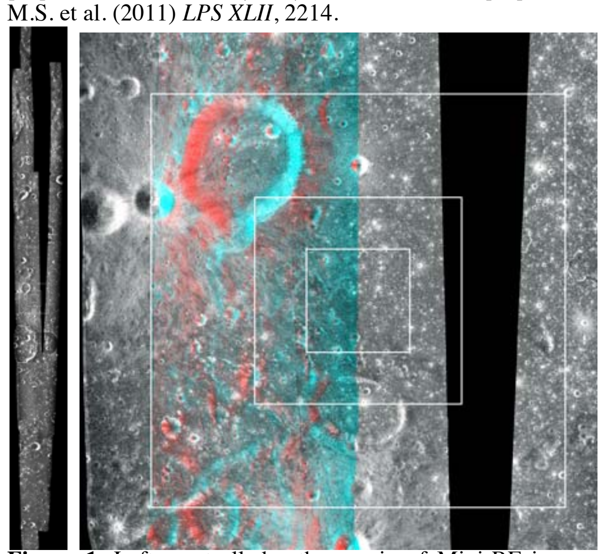

Figure 1. Left, controlled orthomosaic of Mini-RF images centered on the Constellation Region of Interest Apollo Basin (APB, 37° S -154° E). Right, enlargement of the portion of the mosaic covering the ROI. Outermost box is 40x40 km in size. Overlapping images with opposite look direction, used for stereo DTM production, are shown as an anaglyph. Equirectangular projection with north at top.