REGIONAL LROC NAC CONTROLLED MOSAICS AND ABSOLUTE ACCURACY ASSESEMENT.

M. R. Henriksen[1], D. Gojic[1], P. E. Gray[1], R. V. Wagner[1], M. S. Robinson[1], and the LROC Team[1] [1]School of Earth and Space Exploration, Arizona State University, 1100 S. Cady, Tempe, AZ 85287 – (mhenriksen@ser.asu.edu)

Introduction: High-resolution (0.5 – 2 m pixel scale) Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) [1] images of key features have been bundle-adjusted and mosaicked to provide seamless and geodetically accurate data sources for a variety of science and engineering studies [2]. These mosaics are typically composed of 2-10 NAC image pairs, specifically targeted on sequential orbits to have similar illumination. To ensure overlapping coverage, the images toward the outside of the targeted, or featured, mosaics can be slewed up to 30°.

As well as providing crucial scientific data, regional NAC controlled mosaics can also be used to assess the effectiveness of a bundle adjustment in improving NAC images' positional accuracy. A review of the literature on planetary controlled mosaics concludes that this is an error assessment that is has not been performed. NAC images' positional accuracy is well-characterized and highly precise due to the presence of retroreflectors and other human hardware on the Moon, as well as a highly accurate global geodetic Lunar Orbiter Laser Altimeter (LOLA) dataset with Gravity Recovery And Interior Laboratory (GRAIL) improvements to refine pointing parameters [3]. In addition, NAC regional mosaics are much smaller than the typical controlled mosaic. This makes them efficient, both in terms of resources and time, to use for testing the effects of various ground sources, radius sources, and bundle adjustment parameters on the positional accuracy of the resulting controlled mosaics.

Orientation parameters for each NAC image are described in a series of binary- and text-based Spacecraft, Planet, Instrument, C-Matrix and Events (SPICE) kernels [4]. LOLA smithed, or reconstructed, Spacecraft Position Kernels (SPKs) with GRAIL gravity model improvements [5] are available for NAC images acquired before June 20, 2014, providing location data that is accurate to within 20 meters [4]. Theoretically, then, a regional mosiac's positional accuracy could be improved by slightly adjusting image locations while simultaneously eliminating visible seams. Existing work shows that unless *apriori* point sigmas and bundle adjustment parameters are very tightly constrained, the control network bundle adjustment solutions displace images by larger distances than pointing uncertainties would suggest necessary, while decreasing overall accuracy with measured offsets up to 40 m [2].

Control Network Development: To mitigate any errors in the resulting controlled mosaics, control networks, consisting of tie points between overlapping images, ground points between the images and a 'ground truth,' and the associated point *apriori* sigma values, are carefully constructed. In addition to the images in the targeted featured mosaic, additional nadir-pointing, like-illumination images taken prior to June 20, 2014, and therefore having highly accurate spacecraft position and pointing, are included in the control network so that each ground point and tie point includes as many measures as possible (Table 1).

Table 1: Control Network Summary

Images	Points	Measures	Ground Points
32	9114	25383	120

Ground and radius sources are also selected to maximize accuracy. Ideally, highly controlled NAC digital terrain models (DTMs) and the DTM-derived orthophotos, or other highly accurate ground and radius sources, would be used exclusively for control. However, complete DTM coverage of a featured mosaic region is rarely possible due to the limited number of stereo observations. Therefore, ground sources are typically constructed by layering map-projected nadir pointing images with smithed SPKs underneath any available NAC DTM [6] orthophotos of the region to provide full ground coverage for the mosaic. If there is no coverage by a NAC DTM radius source for a particular ground point, the radius for that point defaults to the GLD100 [7].

Apriori sigma values are assigned to each ground point based on the known accuracies of the ground and radius sources. When a DTM orthophoto is available, estimated latitude and longitude errors are used as the horizontal values. If only a map-projected image is available, an uncertainty of 15 m is used instead. The *apriori* radius value is assigned three times the root mean square (RMS) error of the offset between the NAC DTM and LOLA tracks. If a point uses the GLD100 as a radius source, an *apriori* sigma value of 40 m is used, based on the GLD100's reported uncertainty [7].

The control network is bundle-adjusted using the Integrated Software for Imagers and Spectrometers (ISIS) application *jigsaw* [8,9]. While a solution with smaller residuals and better convergence (indicated by the *Sigma0* output [2,9]) can be achieved by solving over the existing pointing polynomials and by solving for position, velocity, and acceleration for both spacecraft position and camera pointing, we have found that the mosaic is more accurate when solving for only a few parameters. Therefore, spacecraft position, camera angles and camera velocities are the only positioning and pointing options typically used for our solutions. Additional parameters (*overhermite* and *overexisting*) that utilize the current camera pointing and spacecraft position as *apriori* values are included as well, as these have been found to slightly improve both the overall bundle adjustment solution *Sigma0* value and the absolute accuracy (Table 2).

Error Analysis: In addition to analyzing the output from the bundle adjustment solution, the estimated absolute accuracy of the ground coordinates is assessed. An automated version of the method described in [10] is used to calculate the true ground coordinate. Selected ground coordinates from a completed, map-projected mosaic are input, and the pixels at those ground coordinates are matched to line and sample values in overlapping NAC images with smithed SPKs (accuracy of +/- 20 m). The ground coordinates are then averaged to provide a single 'ground truth' coordinate to compare to the controlled mosaic [10]. We would therefore expect the corresponding point in a mosaic with an accurate bundle adjustment to be within 20 m of this 'ground truth' coordinate.

Controlled Mosaics of Apollo 17 Landing Site. Apollo landing sites make good test candidates for confirming the accuracy of NAC controlled mosaics because the locations of the anthropogenic objects (lunar module (LM), Lunar Roving Vehicles (LRV), and retroreflectors) are both well characterized [10] and identifiable in the mosaics. Furthermore, high-resolution NAC DTMs are available for all the landing sites. Several versions of the Apollo 17 landing site controlled mosaic (3 NAC pairs) were made in order to characterize the effects of varying solve parameters and radius sources on absolute accuracy. To control for the effects of point accuracy distribution, the same control network was used for all the mosaics (Table 1), varying only the *apriori* values based on whether the NAC DTM or the GLD100 was used as the radius source.

Of the test mosaics made, the most accurate were those created using NAC DTMs as radius sources and solving for a minimal number of tightly constrained jigsaw parameters, using the original pointing as *apriori* values as described above (Table 3). When the NAC DTM was not used or the *apriori* pointing parameters were loosened, the recorded errors showed that the pointing accuracy actually decreased as a result of the bundle adjustment, despite an improvement in visible seams (Table 3).

Conclusion and Future Work: Currently, the construction of highly accurate and seamless controlled mosaics is possible as long as highly accurate ground and radius sources exist, and the point uncertainties, bundle adjustment parameters and number of parameters are very tightly constrained. Disconcertingly, however, any relaxation of these constraints results in larger offsets over some portions of an image than the pointing uncertainties would suggest necessary, especially as the offsets continue to increase with relaxation of parameters and point uncertainties. In light of this observation, it becomes difficult to trust even those displacements with magnitudes within the pointing accuracy. Future work, then, will necessarily involve further characterizing the effect of various bundle adjustments on the absolute accuracy of LROC NAC controlled mosaics. Production of highly accurate and well-controlled mosaics of key features of interest for release to the PDS will continue as well.

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Table 2: Bundle Adjustment Parameters (subset)

	Minimal Parameter Set	Full Parameter Set	Relaxed Minimal Parameter Set
camera pointing parameters	velocities	accelerations	velocities
spacecraft position parameters	position	accelerations	position
overexisting/ overhermite	yes	yes	yes
Spacecraft position sigma	20	30	100
Spacecraft acceleration sigma	N/A	1	N/A
twist	no	yes	no
Camera angles sigma	0.01	0.01	0.01
Camera angular velocity sigma	0.01	0.01	0.01
Camera angular acceleration sigma	N/A	0.001	N/A
radius	yes	yes	yes

Table 3: Solution Error Analysis (subset)

	1	2	3	4
Radius Source	NAC DTM	NAC DTM	NAC DTM	GLD100
Parameter Set	Minimal	Full	Relaxed Minimal	Minimal
Sigma0	0.563	0.530	0.532	0.594
Residual Std. Dev. (pixels)	0.180	0.135	0.150	0.252
Maximum Residual (pixels)	4.012	3.99	3.97	3.81
Mean Offset (meters)	9.792	11.988	13.462	31.286
Maximum Latitude Offset (meters)	16.906	23.912	29.904	39.015
Maximum Longitude Offset (meters)	-9.382	-12.790	-9.760	-20.035