CHARACTERIZING THE GEOMETRIC DISTORTION OF THE LUNAR RECONNAISSANCE ORBITER WIDE ANGLE CAMERA. E. Speyerer[1], R. Wagner[1], M. Robinson[1], K. Becker[2], J. Anderson[2], P. Thomas[3], and S. Brylow[4]. [1]Lunar Reconnaissance Orbiter Camera Science Operation Center, Arizona State University, [2]United States Geologic Survey, [3]Cornell University, [4]Malin Space Science Systems. (espeyerer@ser.asu.edu)

Instrument Description: The Wide Angle Camera (WAC) is part of the Lunar Reconnaissance Orbiter Camera (LROC) system that is currently acquiring synoptic views of nearly the entire Moon each month [1]. The WAC is a push frame imager capable of providing images in seven different color bands. The WAC uses a CCD with seven narrow-band interference filters bonded over the detector array. There are two ultraviolet filters (UV: 321 and 360 nm) and five visible filters (VIS: 415, 566, 604, 643, and 689 nm). The WAC consists of two sets of optics, one for the visible wavelengths and a separate lens for the UV bands. However, there is only one CCD image array in the WAC. Therefore, light though the UV optics is redirected over the CCD using a prism.

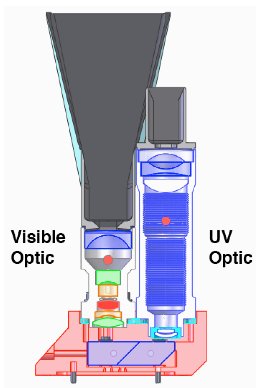

Figure 0- Diagram of WAC

The camera is designed to operate in two modes: monochrome and color. In the monochrome mode (nominally the 643nm band) the WAC acquires framelets that have 1024 samples and 14 lines. In color mode, the WAC acquires framelets for all seven bands, however due to limitations in the readout rate of the CCD array, only the center 704 samples are read out for each 14 line visible band. For the UV framelets, the center 512 samples are read out of the UV portion of the array. During the read out, the 512 samples and 16 lines are summed in 4 × 4 pixel boxes resulting in a 128 × 4 pixel framelet, which increases the signal to noise ratio for the UV bands.

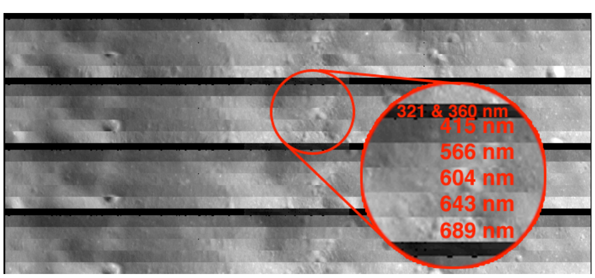

Figure 1- Section of a level 1 WAC color image highlighting the various wavelengths available.

All framelets imaged simultaneously are stored as one frame. The WAC repeatedly acquires frames at a rate such that each of the narrow framelet overlaps provides continuous coverage for each color band. Typical WAC observations contain 36 to 1,800 evenly spaced framelets. In addition, unlike the Narrow Angle Camera (NAC), which images manually targeted locations, the WAC acquires images constantly (except for short periods when the image is being read out of the buffer) while in view of illuminated terrain.

Both optics have a short focal length providing a wide field of view (FOV). In the monochrome mode the WAC has a 91.9° FOV and has a 61.4° FOV in color mode for the visible bands (UV 59.0° FOV). The nadir pointing pixels have a pixel scale of 74.9 meters for the visible bands from an altitude of 50 km, while UV bands have a pixel scale of 383.5 meters from the same altitude. On 11 December 2011 LROC entered a 30 by 216 km frozen orbit with the periapsis over the south pole. This configuration results in higher resolution images in the southern hemisphere and lower resolution (but broader coverage) in the northern hemisphere.

Pre-Flight Geometric Calibration: Before the launch of Lunar Reconnaissance Orbiter (LRO), the WAC was calibrated post assembly at Malin Space Science Systems (MSSS). The camera was mounted on an Ultradex rotary stage that provided "azimuthal" control in one-degree steps with an accuracy of one arc second. The elevation of the instrument was controlled separately on another rotary stage with continuous variability and lower accuracy than the Ulradex stage. In front of the WAC was a projected image of a collimated spot of selectable size. A Quartz Tungsten Halogen lamp (visible bands) and a Xenon lamp (UV bands) was used to illuminate the pinhole. To identify distortions in the WAC optics, the WAC imaged the spot at a range of azimuth and elevations. The pixel coordinates of the spot centroid in each image was identified and translated to physical locations on the CCD. By knowing the position of the camera with respect to the collimated spot (azimuth and elevations) a radial function was identified that was able to undistort the WAC images (see section on radial model).

In-Flight Geometric Calibration: After launch of LRO, it was observed that there were some small discrepancies (0-0.5 pixels) between multiple map-projected WAC color bands acquired during the same observation. In addition, the accuracy of the pre-flight distortion model near the edge of the CCD had residual displacements near 1-2 pixels in some bands. This latter displacement was noticeable in monochrome images, which span the entire 1024 pixel CCD array. To improve on the pre-flight distortion model, the placements of map-projected WAC pixels were compared to map projected images provided by the NACs, which have a much narrower field of view (2.85°) and much smaller geometric distortion making them a good proxy for absolute positions on the surface.

To compare the images, WAC and NAC observations covering the same geologic terrain under similar lighting environments were identified. We chose the relatively flat Mare Imbrium deposit to reduce registration errors due to topographic variations. The NAC images were calibrated, reduced, and map projected at a pixel scale of twenty-five meters. Next, overlapping WAC images were map projected at a pixel scale of twenty-five meters over each NAC observation. The map-projected image was then trimmed so that both the NAC and WAC images were the same dimensions and covered the same geologic terrain. ISIS [2] was then used to automatically register the NAC and WAC image pairs. The pixel coordinates of the coregistered spots in the WAC were converted back to the (unprojected) line and sample to identify the position of the original distorted WAC pixel. The pixel coordinates recorded for the NAC image were also converted back to raw coordinates in the WAC image and thus provide a corrected pixel location. Using these distorted and corrected pixel locations, further refinement to the WAC distortion model was derived.

Geometric Distortion Models: Due to the wide-angle field of view, the WAC optics distort the position of pixels across the CCD array progressively outward from the boresight. To correct for this geometric distortion a model is used to shift the pixels from their distorted pixel coordinates (x_d, y_d) back to their undistorted locations (x_c, y_c).

Radial model. From the pre-flight calibration, a radial model was chosen. In this model the line and sample are converted into mm, with respect to its location on the CCD array and the distance from the optical boresight is calculated:

$$r = \sqrt{\left(x_d - x_o\right)^2 + \left(y_d - y_o\right)^2}$$

where x_0 and y_0 are the coordinates of the instrument's boresight and r is the distance the distorted pixel is away from that point. This radius value is then used to calculate the position of the undistorted pixel:

$$x_c = x_d \Big/ \left(1 + k_1 r^2 + k_2 r^3\right)$$

$$y_c = y_d \Big/ \left(1 + k_1 r^2 + k_2 r^3\right)$$

Radial + Taylor Series. The radial model alone cannot correct all the distortion present in the WAC optics. Likewise, a Taylor series alone cannot accurately describe the barrel distortion. However, together they can correct for the barrel and residual distortions. To use this model, the barrel distortion is removed using the equation above and the output is fed into a 2D Taylor series that removes the small remaining residuals.

Brown's Distortion Model. An alternative way to describe the geometric distortion is with Brown's distortion model which accounts for radial distortion, decentering of the optics, and tilt of the CCD array [3,4]. Below is the adaptation of the Brown's model that we are using to characterize the geometric distortion of the WAC:

$$x_c = x_d + \left(x_d - x_0\right)\left(k_2 r^2 + k_3 r^3 + k_4 r^4\right) + \ldots$$

$$p_1\left(r^2 + 2\left(x_d - x_0\right)^2\right) + 2p_2\left(x_d - x_0\right)\left(y_d - y_0\right) + s_1 r^2$$

$$y_c = y_d + \left(y_d - y_0\right)\left(k_2 r^2 + k_3 r^3 + k_4 r^4\right) + \ldots$$

$$p_2\left(r^2 + 2\left(y_d - y_0\right)^2\right) + 2p_1\left(x_d - x_0\right)\left(y_d - y_0\right) + s_2 r^2$$

where p_1 and p_2 are the decentering and s_1 and s_2 are the tilting distortion parameters.

Results and Current Status: From the pre-flight calibration, radial distortion coefficients were derived (k_1=-0.0099 k_2=-0.0005 for the visible and k_1=-0.024 k_2=-0.0070 for the UV optics). This model and coefficients removed most of the optical distortion, but small residuals still remain. In-flight calibration measurements and improved distortion models reduce the residual offsets present in the radial model. While the radial and Taylor series can be used to undistort WAC images, high order Taylor series coefficients in the cross-track direction are required to remove most of the residuals. Higher order Taylor series are also prone to describe outliers present in the coregistration data and therefore may not provide the best distortion model. Unlike removing the residuals with the Taylor series, Brown's model has coefficients that physically relate to the geometry of the optics and image array. We are currently deriving a set of distortion coefficients (x_0, y_0, k_2, k_3, k_4, p_1, p_2, s_1, *and* s_2) that model the distortions present in the visible and UV optics. Initial parameters are yielding RMS errors of 0.622 pixels (from in-flight coregistration data) for the visible bands. An improved distortion model will be included in an upcoming release to the PDS (IK and FK) and ISIS (camera model implementation).

References: [1] Robinson et al. (2010), , *Space Sci. Rev*., 150, 81-124. [2] Anderson, J. A., et al. (2004), LPSC. XXXV, abstract 2039. [3] Brown (1966), *Photogrammetric Engr*., 7, 444-462. [4] Brown (1971), *Photogrammetric Engr*., 8, 855-866.