GEOMETRIC CALIBRATION OF THE CLEMENTINE UVVIS CAMERA. E. J. Speyerer[1], R. V. Wagner[1], and M. S. Robinson[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ.

Introduction: The Clementine spacecraft launched in 1994 as part of a joint program between the Strategic Defense Initiative Organization and NASA [1]. During the mission, the Ultraviolet/Visible (UVVIS) camera [2,3] collected over half a million images of the lunar surface, which were later reduced into a global multispectral mosaic and a series of mineralogy and maturity maps [4-8].

To facilitate mapping exercises, efforts were made to geodetically control the images into a global control network. Specifically, in the late 1990's, the United States Geologic Survey (USGS) and the RAND Corporation used over 500,000 match points to systematically control 43,871 images used in the 750 nm global basemap [3,4,9] to derive the Clementine Lunar Control Network (CLCN). However, this triangulation ignored topographic effects (i.e. assumed a spherical Moon with a radius of 1737.4 km) that resulted in scale and positional errors. Later investigations showed the existence of 8 to 10-km horizontal offsets in the resulting maps due to extreme "corrections" in camera orientations [10].

Later work improved upon this initial control network, with the creation of the Unified Lunar Control Network (ULCN) 2005 produced by the USGS [11]. While the ULCN 2005 included the local radius of the Moon during image triangulation, significant offsets (mean = 1.09 km; median = 1.59 km) remain when compared to the current lunar reference frame.

For this study, we are using images acquired by the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) to update the Clementine UVVIS internal and external orientation parameters to enable precise and accurate map products that align with the latest geodetic reference frame.

Clementine UVVIS Camera: The Clementine UVVIS framing camera was capable of acquiring images in five different narrow bandpasses (415, 750, 900, 950, and 1000 nm) as well as a single broadband filter (400-1000 nm) using a filter wheel. The 5.6° × 4.2° field of view and 384 × 288 pixel CCD enabled the UVVIS camera to acquire images with a ground sampling distance of 115 m from an altitude of 425 km (although the point spread function of the optics reduces the true resolution).

LROC Wide Angle Camera: The LROC WAC is a push frame camera capable of providing images in seven different color bands (321, 360, 415, 566, 604, 643, and 689 nm) [12]. The WAC has a 90° field of view in monochrome mode and a 60° field of view in multispectral mode. From an altitude of 50 km, the WAC acquires images with a nadir pixel scale of 75 meters for the visible filters (384 meters for the UV filters). The WAC images almost the entire Moon each month, capturing the lunar surface under a variety of lighting conditions over time. Using the latest LRO ephemeris provided by the Lunar Orbiter Laser Altimeter (LOLA) and Gravity Recovery and Interior Laboratory (GRAIL) teams and the refined LROC camera model parameters, WAC images have a geodetic accuracy of better than 45 m [13].

Controlling UVVIS and WAC Images: In order to improve the observational geometry of each Clementine UVVIS image, we first identified LROC WAC images acquired under similar lighting conditions (i.e. difference in sub-solar point between observations < 5°) that cover the UVVIS field of view. In many cases, a single Clementine image may match multiple WAC observations due to significant overlap at higher latitudes and the extensive temporal coverage resulting from over 7.5 years of WAC observations.

After radiometric calibration and photometric correction, each WAC image is map projected to the surface using a global DTM (GLD100) [14]. These procedures are carried out using Integrated Software for Imagers and Spectrometers (ISIS) [15], which is developed and maintained by the USGS. The odd and even WAC framelets are mosaicked into a single mapped image. The mapped WAC image is then transformed back into the UVVIS camera space using an ISIS utility called *map2cam*. This enables each feature in the UVVIS image to be tied to a unique line and sample in the WAC observation.

The UVVIS/WAC image pairs are then coregistered using a series of control points automatically derived using an ISIS utility called *findfeatures* that applies feature-based matching algorithms. The software takes advantage of the OpenCV framework, which allows the user to select from a broad range of feature detectors, extractors, and matchers [16].

Geometric Calibration of the UVVIS Camera: The interior and exterior orientation parameters used by ISIS and NASA's Navigation and Ancillary Information Facility (NAIF) are stored in a series of SPICE kernels. As part of this investigation, we are updating the interior and exterior orientation parameters archived in the Clementine UVVIS Instrument Kernel (IK), the C-Matrix Kernel (CK) and the Frames Kernel (FK). In addition we will be assessing the quality of a series of independently derived ephemeris kernels (SPKs) from Goddard Space Flight Center (derived in 1994), Navel Research Laboratory (1994) and Jet Propulsion Laboratory (2007).

Interior Orientation. From the output of *findfeatures*, we have collected thousands of UVVIS line and sample coordinates tied to points on the lunar surface (latitude, longitude, and radius) using coordinates of the corresponding feature identified in the WAC image(s). Using procedures developed for in-flight calibration of the LROC WAC [13], we are able to derive a precise focal length, optical boresight (line and sample), and accurately describe optical distortion of the UVVIS camera. Preliminary results showed evidence of lateral chromatic aberration in the UVVIS optics. The aberration introduces a 0.14% difference in magnification or 0.7 pixel error corner to corner when comparing the 415 nm band images to images acquired with the 1000 nm filter. Due to this band dependent distortion, we derived optical distortion parameters for each band and included radial and tangential distortion terms:

$$x_d = x_c\left(1+k_2r^2\right)+\left(P_2\left(r^2+2x_c^2\right)+2P_1x_cy_c\right)$$

$$y_d = y_c\left(1+k_2r^2\right)+\left(P_1\left(r^2+2y_c^2\right)+2P_2x_cy_c\right)$$

where (x_d,y_d) are the observed, distorted pixel coordinates, (x_c,y_c) are the ideal pixel coordinates, k_2 is the radial distortion coefficient, r is the radius of the ideal pixels from the boresight, and P_1 and P_2 are tangential distortion terms (Table 1).

Exterior Orientation. The exterior orientation parameters are stored in the C-Matrix Kernel (CK), Spacecraft Position or Ephemeris Kernel (SPK), and a Frames Kernel (FK). The CK stores the relative orientation of the spacecraft with respect to a base reference frame such as J2000. The FK contains the fixed angular offset of the UVVIS camera with respect to to the spacecraft. This information along with the spacecraft position or ephemeris data stored in the SPK can be used to fully describe the location and orientation of the camera for each observation.

To adjust for offsets in the placement of UVVIS images on the lunar surface, the orientation (CK and FK) and/or spacecraft location (SPK) can be corrected. An adjustment to the spacecraft location or orientation will cause the image to shift along the surface when projected (Fig. 1). Adjusting the CK can introduce a small distortion that causes pixels on one side of the frame to be translated further than pixels on the opposite side (Fig. 1b). However, these effects are small given the offset observed in UVVIS images and the altitude at which the images were acquired (Fig. 1c). Therefore, we are only adjusting the orientation of the UVVIS camera. Any systematic offsets will be compensated for with a fixed change in the FK while the remaining offsets will be accounted for in the CK that stores orientation information for each UVVIS observation.

SPICE updates: Once the exterior orientation parameters are refined for each UVVIS image, a new IK, FK, and CK will be generated and released via NAIF and included in an upcoming ISIS distribution. With these new kernels, images can be map projected with sub-pixel accuracy to the geodetic grid defined by the LRO mission, thus enabling quick cross-mission analysis without the need to manually align the datasets.

References: [1] Nozette et al. (1994) *Science*, 266, 1835–9. [2] Kordas et al. (1995) *SPIE Proceedings*, 2478, 175–186. [3] McEwen and Robinson (1997) Adv. Sp. Res., 19, 1523–1533. [4] Edwards et al. (1996) *LPS XXVII*, Abstract #1168. [5] Lucey et al. (1998) *JGR,* 103, 3679. [6] Robinson et al. (1999) *LPS XXX,* Abstact #1931 [7] Lucey et al. (2000) *JGR.,* 105, 20297. [8] Lucey et al. (2000) *JGR,* 105, 20377 [9] Davies et al. (1996) *Int. Moon Workshop* [10] Cook et al. (2002) *AGU Fall Meeting*, Abstract #P22D-09 [11] Archinal et al. (2006) *USGS Open-File Report 2006-1367*, 1-12 [12] Robinson et al. (2010) *Space Sci. Rev.*, 150, 81–124. [13] Speyerer et al. (2016) *Space Sci. Rev.,* 200, 357–392. [14] Scholten et al. (2012) *JGR*, 117, E00H17. [15] Anderson et al. (2004) *LPS XXXV,* Abstract #2039. [16] Garcia et al. (2016) *Learning Image Processing with OpenCV*, 232.

Table 1- UVVIS interior orientation parameters

	fl (mm)	k_2	P_1	P_2
415 nm	89.8728	3.62e-5	-2.94e-5	5.26e-5
750 nm	89.9758	4.16e-5	-2.47e-5	3.99e-5
900 nm	89.0011	4.40e-5	-2.51e-5	4.56e-5
950 nm	89.9944	4.17e-5	-2.50e-5	4.93e-5
1000 nm	89.9926	4.27e-5	-2.92e-5	4.79e-5

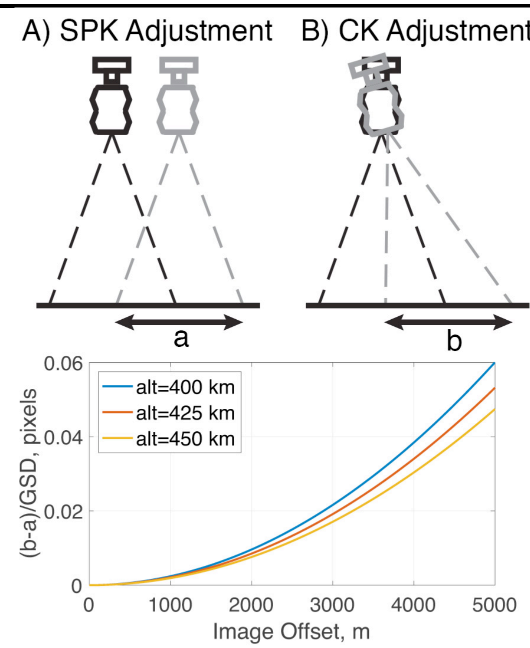

Fig. 1- Image distortion due to SPK vs. CK adjustments. The difference (b-a) normalized to the altitude dependent ground sampling distance (GSD) of the UVVIS camera indicates that adjusting just one of the parameters will result in a precise solution (error < 0.01 pixel for typical orientation adjustments).