REPORT ON THE FINAL COMPLETION OF THE UNIFIED LUNAR CONTROL NETWORK 2005 AND LUNAR TOPOGRAPHIC MODEL.

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Introduction: In order to highlight this project to the extraterrestrial mapping community, we repeat here our earlier abstract [1], with a corrected Figure 2. A report describing the Unified Lunar Control Network 2005 and the files associated with that network is now available as an on-line USGS Open-File Report [2] at the location http://pubs.usgs.gov/of/2006/1367/. A "Readme" file describes the available files, including the report text, the original photogrammetric solution input and output files, derived files such as information on all the control point positions, the expected vertical precision (EVP) of the points and the solution residuals, and a directory containing global DEMs derived from the point positions. While a paper providing further details about the solution is in preparation, we provide some useful additional information about the solution and possible uses for it here.

The Solution: The ULCN 2005 includes the determination of the 3-D positions of 272,931 points on the lunar surface and the correction of the camera angles for 43,866 Clementine images, using 546,126 tie point measurements. The solution RMS is 20 μm (= 0.9 pixels) in the image plane, with the largest residual of 6.4 pixels. The 7 iteration solution took ~40 hours for completion on a ~2 GHz system. There is an average of 46 km^2/point and therefore ~6.8 km between points. This photogrammetric network solution is the largest planetary control network ever completed. Other details of the solution are given in Table 1.

As described in [2], this network is derived from two earlier networks, the ULCN [3] and the Clementine Lunar Control Network (CLCN) [4]. The new network includes the slightly constrained (1°) solution of the camera angles (dropping duplicates), the 3D positions of the CLCN points, and the constrained 3D positions of 1,261 of the ULCN points that could be measured in Clementine images. Since the point positions are no longer constrained to a sphere and due to the loose constraints on the camera angles and ULCN point positions, we believe we have largely corrected the several km horizontal errors that exist in the CLCN solution. The 3D positions of the control points also provide a global topographic model for the Moon that is denser than that provided from Clementine LIDAR and of apparently similar accuracy. (Figure 1).

Accuracy: The Open-File Report [2] discusses in more detail what we have been able to determine about the accuracy of the ULCN 2005. Because of the lack of any other sources of more accurate data, such characterization is quite difficult. However, if one assumes that the a priori (mission measured) spacecraft/camera orientation angles were all entirely correct (their quoted accuracy is 0.03°[5]), then the maximum 3σ error due to camera angle changes is about 5.1 km, while the vast majority of the camera angle changes reflect horizontal errors of several hundred meters or less.

The radial errors in control point positions are primarily influenced by the EVP for any given pair of image measures of a point, which vary widely from the meter to the several hundred meters to the many km level (or even hundreds of km for a few points with poor geometry). The radial position of a few ULCN (1994) points with only one image measurement and of points with poor geometry is determined mostly from a priori values determined from ULCN, LIDAR, or polar stereo data [6], or influenced through the solution by nearby points with better EVP. There is also an inherent uncertainty of about 100 m for the Clementine spacecraft orbits [7]. So the vast majority of the points would appear to have radial uncertainties of several hundred meters. However, for individual points of interest the EVP values should be examined to see if they are better – or far worse – than average. When the ULCN 2005 solution radii of all 272,931 control points are compared to the a priori radii derived from an interpolation of a combination of Clementine LIDAR and polar Clementine stereo data [6], the differences are not significant so the radii must therefore be of similar accuracy. The mean absolute difference of the solution radii from their a priori values is 137 m, with a standard deviation of 219 m.

Uses of the ULCN 2005: The original reason for doing a solution that combined the ULCN (1994) and CLCN was primarily to remove the large horizontal errors known to be present in the CLCN, and thus allow for the possible option of generating an improved Clementine Basemap Mosaic (CBM)[8] and other Clementine mosaics[9,10]. Indeed, that option still exists, although we have been unable to obtain funding to carry it out. However, as part of a funded PG&G task to generate an initial Lunar GIS, we are creating an improved version of the CBM by warping the mosaic based on the change in point coordinates from the CLCN to the ULCN 2005. We are excited to report initial tests show better results than we hoped for. We tested 3, 6, and 12 parameter polynomial warps and have settled on a 6 parameter warp. Using a 30°x30° test area and more that 7400 vectors, we successfully obtained RMS errors of <110 meters. But more importantly, a visual inspection of the registration is also impressive (Figure 2 – corrected from reference [1]). We will continue to use 30°x30° tiles for entire global dataset. This process will be completed using the ESRI© Arc/Info Workstation warping routines. The most difficult part of this task will be merging the tiles back together. To aid in this step before warping we will first buffer 1° on all sides of the image and then clip back before merging or blending. This is not intended as a replacement for a full "redo" of the CBM, but will provide a somewhat improved version of the CBM in the meantime.

A second significant current use of the ULCN 2005 is that we are tying the global Lunar Orbiter digital mosaic to that network [11]. This will place the LO mosaic in the most accurate known lunar coordinate frame, including the projection of the LO images onto the ULCN 2005 topography. Although still sparse and with hundreds of meters uncertainty in radii, such an orthoprojection of the images will still be a vast improvement over projection onto a sphere (as was done with the CBM).

Similar to the "warping" of the CBM mosaic above, the same information can also be used to "warp" coordinates themselves from the CLCN to values compatible with the ULCN 2005 solution. The great value of this is that users can measure coordinates on the CBM or other Clementine mosaics, and then use this process to determine updated coordinates in the ULCN 2005, which can then be used for operational planning such as orbital image collection and landing/impact targeting.

The other obvious significant use of the ULCN 2005 data is as a global topographic model. Included in the distribution files [2] are two gridded topographic models for the Moon, in various common GIS formats. Users are cautioned though that the available topographic information is still sparse and that the EVP of the radii of the control points from which the available DEMs have been derived are not at all uniform. For the best possible results in a given area investigators may wish to use the control point coordinates and EVP information and their own filtering, interpolation, and smoothing algorithms for deriving topographic models.

We finally note that a particular example of the use of the ULCN 2005 has been to register previously created Clementine stereo DEM tiles from over the entire surface of the Moon. See [12] for more information on this process.

Future Work: As described in [2] we had intended to further improve the ULCN 2005, by directly adding image measures from Mariner 10, Galileo, and Lunar Orbiter images, thus improving the density of points, and strengthening the solution geometrically (with the larger Galileo and LO images) to create a "ULCN 2007." That effort is now however on hold due to budget cuts. We still hope to complete such an effort if funding can be found. In the near term, it would provide further coordinate system improvements that would be useful for targeting or planning in upcoming missions. In the long term, this effort is still needed because it will directly connect these significant legacy datasets to each other and to future datasets. Also, in the long term we hope to use one or more of the planned altimeter datasets (e.g. LOLA) to form a stable coordinate frame, that these and all of the future mission datasets can be tied to. However, as we have pointed out elsewhere [13], there appear to be no plans by or funding available from NASA to undertake this critical work.

References: [1] Archinal, B. A., et al. (2007). LPS, XXXVIII, 1904. [2] Archinal, B. A., et al. (2006). U. S. Geological Survey Open-File Report 2006-1367, 21 p. *pubs.usgs.gov/of/2006/1367/*. [3] Davies, et al. (1994) *JGR*, 99, E11, 23,211. [4] Edwards, et al. (1996) LPS, XXVII, 335. [5] Nozette, S., et al. (1994) *Science*, 266, 1835. [6] Rosiek, M. R., et al. (2001) Planetary Mapping 2001, at http://astrogeology.usgs.gov/Projects/ISPRS/MEETINGS/Flagstaff2001. [7] Zuber, M. T., et al. (1994) *Science*, 266, 1839. [8] USGS (1997) USA_NASA_PDS_CL_30xx, NASA PDS. [9] USGS (1999) USA_NASA_PDS_CL_40xx, NASA PDS; Eliason, et al. (1999) LPS, XXX, 1933. [10] USGS, in preparation; Eliason, et al. (2003) LPS, XXXIV, 2093. [11] Weller, L., et al. (2007). LPS, XXXVIII, 2092. [12] Rosiek, M., et al., (2007). LPS, XXXVIII, 2297. [13] Kirk, R. L., et al. (2006) Int. Arch. Photogram. Rem. Sen. & Spatial Inf. Sci, XXXVI, Part 4, Goa.

Table 1: Additional Statistics of the ULCN 2005 solution

Point info	Point name	Lat. (°)	Long. (°) E	radius (km)	EVP (m)
Northern	IL5504B	89.96N	234.66	1737.92	708
Southern	EJ0122C	89.97S	43.89	1737.41	740
Highest	JE5549A	13.91N	97.68	1747.49	2260
Next Highest	HS2243B	3.05N	200.10	1745.50	469
Lowest (error?)	KN2183C	48.90N	3.83	1724.64	612
Next Lowest	CT0705B	69.71S	190.05	1727.97	430

Radius range (next highest to next lowest): 17.53 km
Mean lunar radius: 1736.93 km, σ=2.1 km, n=272,931

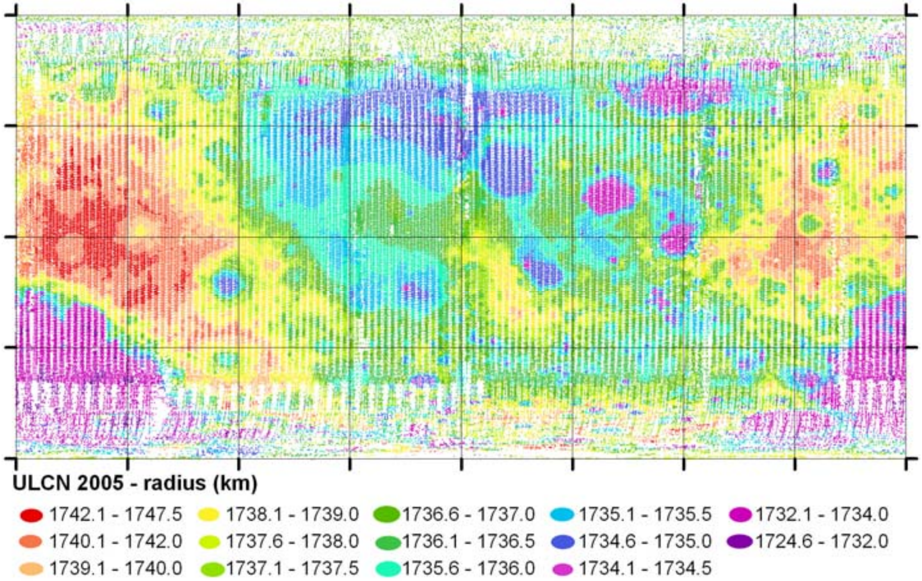

Figure 1: The 272,931 control points of the Unified Lunar Control Network 2005, color coded by radius. Simple cylindrical projection of the entire Moon, with north up and east to the right.

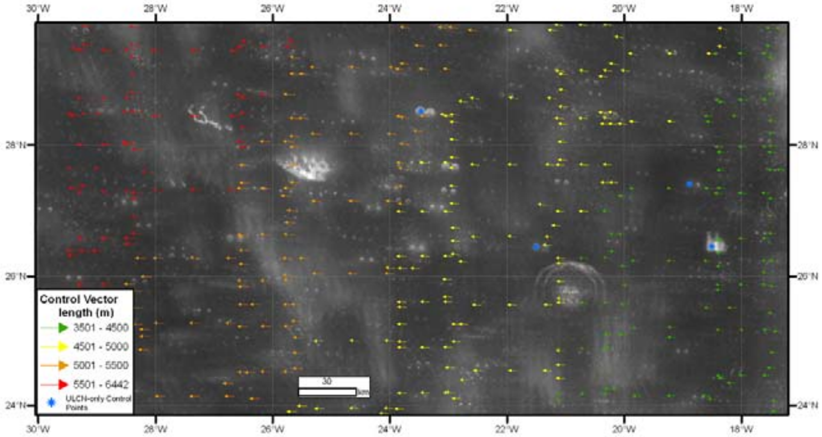

Figure 2: This image shows the pre-warped Clementine 750nm (CBM) tile and the final warped image with a 50% transparency for both, thus showing the offset between the CLCN and ULCN 2005 positions. The control point change vectors are colored by offset length in meters. Blue points are ULCN 2005 only. The crater Lambert is at right. Simple cylindrical projection, with north up and east to the right.