Combining lunar photogrammetric topographic data with Clementine LIDAR data. M. R. Rosiek, R. Kirk, and E. Howington-Kraus United States Geological Survey, Astrogeology Team, Flagstaff AZ 86001 (e-mail: mrosiek@usgs.gov).

Introduction: During the Clementine Mission both oblique and vertical multispectral images were collected. The oblique and vertical images from a single spectral band collected during the same orbit form a stereo pair that can be used to derive the topography. These stereo pairs were used to derive the topography of an area surrounding the lunar South Pole (90°S - 64°S latitude) and North Pole (90°N - 64°N latitude). In addition, during the Clementine mission laser altimeter data were collected. A goal was to match the photogrammetric topographic data to the topographic data collected by the laser altimeter. This required developing some innovative techniques to deal with mismatches between the photogrammetric topographic data set and the laser altimetry topographic data. [1,2]

Clementine Data: In 1994, the Clementine spacecraft acquired digital images of the Moon at visible and near infrared wavelengths [3]. Stereo pairs consisting of oblique and vertical images were obtained with the ultraviolet-visible (UVVIS) camera. The UVVIS camera image size was 384x288 pixels with five spectral bands and one broad band. The 750 nm band stereo pairs are the image source for this study. The ground sample distance (GSD) for oblique images ranges from 300 to 400 meters. The GSD for the vertical images, acquired at the end of an orbit, is slightly larger and ranges from 325 to 450 meters. Using the formula for stereo height accuracy [4] an estimate of height accuracy is 180 m. This formula is $IFOV_{max}/(K \cdot B/H)$ with $IFOV_{max}$ defined as Maximum Instantaneous Field of View, B/H is the base-to-height ratio, and K is an estimate of pixel measurement accuracy on the imagery.

The Clementine laser altimeter (LIDAR) data were used previously to produce a global topographic model of the Moon [5]. The model has a vertical accuracy of approximately 100 m and a spatial resolution of 2.5°. Altimetry data were collected between 79°S - 81°N [5].

A global image mosaic of the Moon was produced from the 750 nm Clementine data [6,7]. The mosaic includes high resolution, oblique and vertical images. Match points were picked to tie the imagery together, and the camera pointing angles were adjusted to align the imagery. This produced a seamless image mosaic with latitude and longitude information but no information on the elevation [6,7]. The control net developed in support of the global image mosaic was produced by RAND Corporation. The control net consisted of 543,246 measurements of 271,635 points on 43,871 images. An estimate of the error in the solution is provided by the a posteriori standard deviation of unit weight of 7.7 micron, in the Clementine sensor image plane; this means there is about 1/3 pixel of measurement error in the solution [8].

Analytical Aerotriangulation: Topographic data can be extracted from Clementine digital images utilizing a digital photogrammetric workstation (BAE Systems SOCET SET software) [9]. SPICE data associated with the Clementine images contain support information that can be used to estimate the camera position and angles for each image. The imagery and support information were downloaded to our digital photogrammetric workstation from the Integrated Software for Imagers and Spectrometers (ISIS) system [10]. Match points used to produce the image mosaic also were downloaded.

The match point latitude and longitude from the global image mosaic were used for an initial estimate of the horizontal position. The elevations of the match points were estimated from the altimetry data. Weights for the elevations are varied depending on the horizontal distance to a Clementine laser altimeter point: match points within 2000 m of a Clementine laser altimeter point are given a high weight; match points between 2000 m and 5000 m from a Clementine laser altimeter point are given a medium weight; and match points greater than 5000 m from a Clementine laser altimeter point are given a low weight. Normally, this would hold the solution to be close to the altimetry data.

In forming the Clementine Mosaic, over 3,600 images and 29,000 match points were used in the southern polar region, an area defined as 64˚S to 90˚S. A subset of images (983 images) and the match points (973 control points) were selected for processing. Additional tie points were picked with the criteria that each image should have nine match or tie points distributed throughout the image. This process added 1,226 tie points. Tie points have estimates for their ground location based on the position and previously estimated attitude of the camera.

For the adjustment procedure an iterative least squares solution is used; this allows the camera angles and match point ground locations to change during the adjustment. The final root mean square (RMS) error of the match point measurements is 0.68 pixel. Generally, a value of below one pixel should be acceptable.

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The SOCET SET software provides an automated routine to extract elevation data. For every stereo model, a correlation point was determined every 1 km in ground distance.

Initial Results: Data were collected from 572 stereo models using imagery from 50 different orbits. The DEM collected from one stereo model was compared to an adjacent DEM collected from a stereo model within the same orbit. The results of those comparisons are summarized on the "Models" line of Table 1. The DEMs within an orbit were merged into a single DEM. A merged DEM from one orbit was compared to a merged DEM from an adjacent orbit and those results are shown on the "Orbits" line of Table 1. Errors were summarized by number of points, RMS, standard deviation, bias, and percentage of points that were blunders (Table 1). For overlapping models within an orbit, the RMS and bias error are similar. For elevation errors in overlapping orbits, the bias error drops to 104 m.

Table 1 - Average of errors (Models: n=572, Orbits: n=50)

	Points	RMS	St. Dev.	Bias	% Blunders
Models	1801	836m	155m	812m	1.8%
Orbits	20073	314m	292m	104m	2.2%

We initially believed that the biases between stereo models were caused by tilts in the models, but, in general, triangulation errors do not result in DEMs that are tilted in the flight direction. While editing and merging the elevation data, we realized that the bias errors have an extremely systematic pattern: within pairs of overlapping models, within an orbit, the one closer to the pole is invariably higher. Furthermore, the magnitude of the bias is nearly identical in overlaps within different orbits but at the same latitude. The merged set of all DEMs therefore contains concentric "cliffs" corresponding to the latitudes where individual models join.

Discussion: We believe that the systematic elevation errors just described are a result of the relatively weak geometry of the image set, which limits the success of our analytical triangulation. Successive stereo models within each orbit generally overlap as noted, but the region of overlap is extremely narrow, so that match points chosen in the overlap region are nearly collinear. When initial estimates for camera pointing come from the adjustment used to make the Clementine global mosaic, initial elevation values for the tie points tend to be lower near the pole than away from it. When initial pointing angles are taken from before the adjustment for the global mosaic, initial elevation values for the tie points are higher near the pole. The least squares weighting scheme can be set to have the adjusted tie points elevation close to the altimetry data, yet the systematic bias is still in the data.

The systematic and significant biases between adjacent DEMs provide strong evidence of what the correct elevation relation between these models is, even if the triangulation process is inadequate to derive camera angles consistent with this result. We initially thought that adjustment of the overlapping DEMs to minimize the biases between them would yield a correct (as far as that is possible) DEM for the polar region.

One can readily imagine a simple, ad hoc method of reducing offsets in the merged DEM: starting at some latitude in each orbit (e.g., 71°S, where confidence in both the altimetry data and the stereo geometry is high) and working inward and outward, add or subtract a constant elevation from the adjacent DEM to bring it into agreement with the starting model. Then adjust the elevation of the third model to bring it into agreement with the second, and so on. Because the latitudinal offsets are similar from one orbit to the next, adjusting each orbit independently in this way should yield reasonably good agreement between as well as within orbits. This is similar to the approach employed by Cook [11]. Given the presence of other error sources in the DEMs, however, a better approach is to determine a vertical correction for every individual DEM in the polar region simultaneously, in such a way as to minimize the sum-squared offsets both within and between orbits. Software to perform this calculation is available in ISIS: the program EQUALIZER is designed to give a simultaneous least-squares estimate of the best brightness and contrast corrections to images in a mosaic, based on their relative brightness and contrast where they overlap. Treating the DEM segments as images (so that "elevation" becomes "brightness"), this program performs the needed calculation. The result is a mosaic of images with equalized brightness (i.e., a composite DEM with equalized elevations).

When the DEMs were adjusted using the EQUALIZER software and then mosaicked together, the resulting composite DEM had a bowl shape. The elevation values near the pole were lower than the elevation values at the edge. Between 70°S and 72°S the composite DEM was close to the altimetry data, from 64°S to 70°S the composite DEM was higher than the altimetry data, and southward from 72°S, where altimetry data existed, the composite DEM was lower than the altimetry data. Measurements were taken along meridian lines on features that appeared flat, bottom of craters and mare areas. The elevations from the composite DEM were compared to a gridded product based on the altimetry points along these meridian lines. There was a systematic slope of 1 km per degree shown by this data.

The individual DEM for each stereo model was detilted by this amount and then ran through the EQUALIZER software. The resulting composite DEM was in agreement with the altimetry data. The detilted individual DEMs were combined using the SOCET SET software. This software provides a method to average and feather the individual DEMs into a composite DEM. There is a limit of 50 DEMs per run, so the DEMs were merged first by orbit number, then grouped into eight groups and orbits within the group were merged, and then the eight groups were merged into one DEM.

Work on extracting topographic data for the north pole followed a similar path. Images and support data were downloaded from ISIS to the photogrammetric workstation along with match point data. Additional tie points were selected. The altimetry data were used to estimate elevation values to tie the solution to the altimetry data. When the individual DEMs were extracted and mosiacked together they exhibited the same concentric “cliffs” as the south pole DEMs. Data for the north pole was equalized and the tilt was measured. For the north pole the tilt was 800 meters per degree. After the DEMs were detilted and merged together there was a new small error between the composite DEM and altimetry data that was not seen in the south pole DEMs.

The north pole composite data was higher than the altimetry data on one side and lower than altimetry data on the other side. This tilt in the composite DEM did not appear to be symmetrical about any particular point. To remove this error instead of simultaneously solving for the vertical offset of the individual DEMs, the EQUALIZER software was run in a pairwise fashion between an individual DEM and the altimetry data. The EQUALIZER software looks at the contrast ratio between the data and if this ratio is outside of certain boundaries, the data will not be adjusted. Not all the DEMs that overlay the altimetry data could be adjusted because the contrast ratio was out of bounds for some DEMs. The DEMs that could be adjusted were mosaicked together into a new DEM. The individual DEMs were run through the EQUALIZER software in a pairwise fashion against this new DEM. This process continued until about 50 DEMs remained to be equalized. Then a simultaneous run was made using the individual DEMs, the new surface and the altimetry data. This resulted in a composite DEM that did not exhibit a systematic tilt compared to the altimetry data. This pairwise procedure of running the EQUALIZER software was tried with the south pole data. This improved the fit of the south pole composite DEM with the altimetry data.

Summary: Topographic data were collected using oblique and vertical images from the Clementine Mission. The Clementine global mosaic was used to establish horizontal control and Clementine laser altimeter points were used for vertical control. Due to marginal overlap between stereo models, the geometry of the photogrammetry match and tie points was weak and resulted in stereo models that did not align with each other. A method was found to align the stereo models and combine the photogrammetry stereo DEMs with a DEM based on the Clementine laser altimeter points. This combined DEM will be used to produce topographic color-coded maps of the Moon.

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