PHOTOMETRIC LUNAR SURFACE RECONSTRUCTION

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ABSTRACT

Accurate photometric reconstruction of the Lunar surface is important in the context of upcoming NASA robotic missions to the Moon and in giving a more accurate understanding of the Lunar soil composition. This paper describes a novel approach for joint estimation of Lunar albedo, camera exposure time, and photometric parameters that utilizes an accurate Lunar-Lambertian reflectance model and previously derived Lunar topography of the area visualized during the Apollo missions. The method introduced here is used in creating the largest Lunar albedo map (16% of the Lunar surface) at the resolution of 10 meters/pixel.

1. INTRODUCTION

High resolution and accurate albedo maps of planetary surfaces in general, and the Lunar surface in particular, are used in landing site selection, mission planning, understanding soil composition, and as educational resources. Accurate albedo maps effectively support landing operations as they are used to estimate the landing site appearance under the illumination conditions (Sun and spacecraft position) at landing time. In planetary science the albedo maps advance our understanding of soil porosity, surface composition and formation through correlations with terrain models and other data mapping (multi-spectral, mineralogical) products.

This paper describes a method for albedo map reconstruction using imagery retrieved by the Apollo 15, 16 and 17 missions. The Apollo Metric Camera was flown on an orbit at approximately 100 km above the Lunar surface. It was a wide field of view (75°) orbital mapping camera that photographed consecutive images with approximately 80% overlap. The digital scans of these film images [9, 3] capture the full dynamic range and resolution of the original film, resulting in digital images of size 22,000 × 22,000 pixels, representing a resolution of 10 meters/pixel and covering approximately 16% of the Lunar surface. Each pixel of the Apollo Metric Camera images was formed by a combination of many factors, including albedo, terrain slope, exposure time, shadowing, and viewing and illumination angles. The goal of albedo reconstruction is to separate the contributions of these factors. This is possible in part because of redundancy in the data; specifically, the same surface location is often observed in multiple overlapping images. The albedo reconstruction technique includes all of the above quantities in an image formation model and re-estimates them from the existing imagery. The overall system is shown in Figure 1. The components of this block diagram are explained in more detail in the following sections.

2. PHOTOMETRIC MODEL

Starting with the first images from the Apollo missions, a large number of Lunar reflectance models were studied [6, 7, 8]. In this work the reflectance is derived from the Lunar-Lambertian model [6, 5]. As shown in Figure 2, we define the following unit vectors: n is the local surface normal, and l and v are directed at the locations of the Sun and the spacecraft, respectively, at the time when the image was captured. We further define the angles i separating n from l, e separating n from v, and the phase angle α separating l from v.

The reflectance model used in our approach is given by

\[
R^k_{ij} = (e^{-c_1 \alpha} + c_2) \left[ (1 - L(\alpha)) \cos(\iota^k_{ij}) + 2L(\alpha) \frac{\cos(\iota^k_{ij})}{\cos(\iota^k_{ij}) + \cos(\epsilon^k_{ij})} \right] \tag{1}
\]

where \( L(\alpha) \) is a weighting factor between the Lunar and Lambertian reflectance models [2] that depends on the phase angle and surface properties. \( R \) is a photometric function that depends on the angles \( \alpha, \iota \) and \( \epsilon \). The parameters \( c_1 \) and \( c_2 \) play a significant role in modeling the surface reflectance at low phase angles. This can be noticed in the reduction of the banding artifacts in Figure 8 on the top right.
3. PARAMETER ESTIMATION

The computation of the reflectance (“R Map” in Figure 1) using Equation 1 is central to our albedo reconstruction technique. Let $I_{ij}, A_{ij}, R_{ij}$ be the Apollo Metric Camera image value, albedo and reflectance at pixel $ij$, and $T$ be a variable proportional to the exposure time of the image. Then

$$I_{ij} = T A_{ij} R_{ij}. \quad (2)$$

Note that the image formation model described in Equation 2 does not take into consideration the camera transfer function since the influence of the non-linearities of the camera transfer function plays a secondary role in the image formation model [2]. From Equation 2 it can be seen that when the observed pixel value, exposure time, and reflectance value are known, the image formation model in Equation 2 provides a unique albedo value. However, these observed values are subject to errors arising from measurement (exposure time), image scanning process (image value) and stereo modeling errors (reflectance), resulting in imprecise albedo calculations. The method presented here mitigates these errors by reconstructing the albedo of the Lunar surface from all the overlapping images, along with their corresponding exposure times and DTM information. The albedo reconstruction is formulated as the least squares problem that minimizes the following cost function $Q$:

$$Q = \sum_k \sum_{ij} \left[(I_{ij}^k - A_{ij}^k R_{ij}^k)^2 S_{ij}^k w_{ij}^k \right] \quad (3)$$

where the superscript $k$ denotes the variables associated with the $k$-th image and $S_{ij}^k$ is a shadow binary variable, $S_{ij}^k = 1$ when the pixel is in shadow and 0 otherwise. The weights $w_{ij}^k$ are chosen such that for each image $k$ they have linearly decreasing values from the center of the image ($w_{ij}^k = 1$) to the image boundaries ($w_{ij}^k = 0$). The choice of these weights insures that the reconstructed albedo mosaic is seamless. The $S_{ij}^k$ values play an important role in accurate albedo estimation by discarding image pixels that are in shadow and for which the DTM and the reflectance models are unreliable [1, 4]. The DTM used in computing the reflectance value $R_{ij}^k$ at each pixel is obtained by a weighted average (using the above weighting coefficients) of the DTM generated using stereo from all pairs of consecutive Apollo Metric Camera images. Figure 3 shows the DTM before and after the weighted DTM averaging and denoising process. It can be seen that the noise artifacts in the original DTM are reduced in the averaged DTM while the edges of the large craters and mountain regions are well-preserved. The color shaded averaged DTM of the Apollo 15, 16 and 17 missions is shown in Figure 4 over the image mosaic of the Clementine mission.

$$\{\tilde{A}_{ij}, \tilde{T}^k, \tilde{c}_i\} = \arg \min_{A_{ij}, T^k, c_i} Q \quad (4)$$

for all pixels $ij$ and images $k$, where $Q$ is the cost function in Equation 3. An iterative solution to the above least square problem is given by the Gauss-Newton updates given below.

**Step 1 (initialization):** Compute the enhanced DTM as described earlier and the weights. Normalize the weights so that the sum of weights over all images is 1 at each pixel. Initialize the exposure time as inversely proportional to the average image reflectance. Initialize the phase coefficients $c_1$ and $c_2$ to some reasonable values. Initialize the albedo as the arg min of the cost function $Q$ for fixed exposure time and phase coefficients

$$A_{ij} = \frac{\sum_k I_{ij}^k T^k R_{ij}^k S_{ij}^k w_{ij}^k}{\sum_k (T^k R_{ij}^k)^2 S_{ij}^k w_{ij}^k} \quad (5)$$
Figure 7 (top-left), and the contour of crater showing the ejecta artifacts in the input imagery. Note the shadow removal effect in due to the irregular terrain shape.

Each pixel the local emission and incidence angles are non-zero the Clementine images do not describe a true albedo map since at our approach can recover the average albedo intensity. However, ground Clementine data is practically seamless demonstrating that images have an average intensity close to the average albedo. Note craft were rather high in the sky above the terrain making these incidence and emission angles (that is, both the Sun and the space-tine mission at 500 meters/pixel resolution were taken at very low tine mission image mosaic. The images captured by the Clemen-
ing the processing of this data significantly more challenging.

Captured on film by the Apollo missions have more noise artifacts compared to imagery obtained from more recent missions, the images nar traverse and are due to the small fraction of overlap between images taken in adjacent orbits compared to the overlap between consecutive images within the same orbit.

The Lunar albedo and the corresponding error map files can be accessed in GeoTiff tile format from

https://byss.arc.nasa.gov/albedo/albedo.html

and

https://byss.arc.nasa.gov/albedo/error.html
Fig. 7. Image mosaic of the Apollo zone (left), and the reconstructed albedo (right).

Fig. 8. Image mosaic of the Apollo zone (left), and the reconstructed albedo (right).

respectively. The albedo in KML format (viewable in Google Earth) can be accessed at

https://byss.arc.nasa.gov/albedo/albedo.kml

5. CONCLUSIONS AND FUTURE WORK

This work introduces a method for photometric reconstruction of the Lunar surface from archival images taken during the Apollo 15, 16 and 17 missions. The reconstructed area covers approximately 16% of the Lunar surface at an unprecedented resolution of 10 meters/pixel for this coverage. The proposed method jointly estimates the surface albedo and camera exposure time, and refines the Lunar photometric parameters using a weighted least squares method. The reconstructed albedo and reconstruction error are made publicly available, and it is hoped that they will help planetary scientists and mission planners in current and future NASA missions. The methods introduced in this paper also enable future research in robust surface reconstruction and shape-from-shading techniques that will further increase the resolution of current terrain models.

6. REFERENCES