Towards Albedo Reconstruction From Apollo Metric Camera Imagery.

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Orbital images contain rich information including the exposure time, sun and camera position at the time of the image capture. The goal of this research is to model the image formation process and extract the albedo information using digital elevation and surface reflectance models. This paper describes our preliminary results on Lunar albedo reconstruction from images captured by the Apollo missions. The method generalizes to both archival scanned and more recent digital images.

Introduction

Figure 1 shows an example of a scanned stereo image pair captured by the Apollo metric camera (AMC). These images are scanned at an approximate resolution of 20,000$\times$ 20000 pixels and have an average overlap of 75$\%$ between consecutive images [1]. The stereo pairs are used to generate high resolution digital terrain model (DTM) using the Ames Stereo Pipeline [2]. A robust bundle adjustment technique [3] refines the original estimates for the orientation and position of the AMC and co-registers the stereo image pairs into an accurate orbital image (Figure 2) and DTM Mosaic. It is important to note that the bundle adjustment algorithm does not guarantee that the matched DTM and pixel values in the co-registered images have the same value. The differences are due to the DTM computation errors and to the variation of surface reflectance and exposure time in consecutive overlapping images. Next section will describe our approach for extracting the estimate of the surface albedo from multiple overlapping images using the DTM, the sun and camera positions.

Figure 1: Apollo metric camera stereo pair.

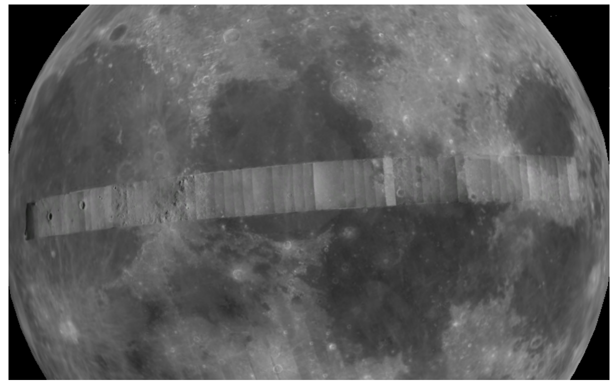

Figure 2: Apollo metric images from Orbit 33.

Image Formation Modeling and Reconstruction

Let $I_{ij}^k, A_{ij}, X_{ij}, R_{ij}^k, T^k$ be the observed image value, albedo, DTM, reflectance, and exposure time at pixel (i, j) and kth image. The goal of is paper is to determine the set $\tilde{A}_{ij}, \tilde{T}^k = \arg\min_{A_{ij},T^k} \mathbf{Q}$ where

$$\mathbf{Q} = \sum_k \sum_{ij} \left[(I_{ij}^k - \tilde{A}_{ij} T^k R_{ij}^k)^2 \right] \quad (1)$$

In the above equation the reflectance is computed using the Lunar-Lambertian model and is given by

$$R_{ij}^k = (1 - L(\alpha)) \cos(\mathbf{i}_{ij}^k) + L(\alpha) \frac{\cos(\mathbf{i}_{ij}^k)}{cos(\mathbf{i}^k) + \cos(\mathbf{e}_{ij}^k)} \quad (2)$$

where

$$L(\alpha) = \exp(-\frac{\alpha}{K_r}) \quad (3)$$

is a weighting factor between the Lunar and Lambertian reflectance models that depends on the phase angle (α) between the direction of the incident light and viewer's direction and a term K_r that depends on the surface characteristics. Often the value of this term is set $K_r = 60$ which is a good approximation for a large percentage of the Moon surface. The remaining terms in Equation 1 are determined by the following equations:

$$\cos \mathbf{i}_{ij}^k = \mathbf{n}_{ij} \mathbf{l}_{ij}^k \quad (4)$$

and

$$\cos \mathbf{e}_{ij}^k = \mathbf{n}_{ij} \mathbf{v}_{ij}^k \quad (5)$$

where $\mathbf{n}_{ij}$ is the surface normal computed from the DTM values, $\mathbf{v}_{ij}$ is the viewing direction between the DTM and the satellite position at the time the kth image was captured, and $\mathbf{l}_{ij}$ is the light direction between the DTM and the sun position at the time the kth image was captured. Determining the best albedo reconstruction from a set of images and the corresponding DTM is formulated as a cost minimization problem for all pixels ij and images k (Equation 1). An iterative solution to the above least square problem is given by the Gauss Newton updates described below.

- **Step 1:Initialization**: Compute the average DTM from the overlapping set of images, initialize the exposure times and initialize the albedo by averaging over the overlapping pixels. Initialize the exposure time to compensate for the average image reflectance.

- **Step 2**: Re-estimate the albedo using Equation 6.

$$\tilde{A}_{ij} = A_{ij} + \frac{\sum_k (I_{ij}^k - T^k A_{ij} R_{ij}^k) T^k R_{ij}^k}{\sum_k (T^k R_{ij}^k)^2} \tag{6}$$

- **Step 3**: Re-estimate the exposure time using Equation 7.

$$\tilde{T}^k = T^k + \frac{\sum_{ij} (I_{ij}^k - T^k A_{ij} R_{ij}^k) A_{ij} R_{ij}^k}{\sum_{ij} (A_{ij} R_{ij}^k)^2} \tag{7}$$

- **Step 4**: Compute the error cost function $\mathbf{Q}$ for the re-estimated values of the albedo and exposure time

- **Convergence**: If the convergence error between consecutive iterations falls below a fixed threshold then stop iterations and the re-estimated albedo is the optimal reconstructed albedo surface. Otherwise return to step 2.

The albedo reconstruction results are shown in Figure 3. It can be seen by comparison with Figure 2 that most of the artifacts from overlapping images global variations in brightness are reduced.

Conclusions and Future Work

This paper introduced an albedo reconstruction and exposure time compensation for orbital images. The system has been successfully tested on the Orbit 33 set images from the Apollo Metric camera. Future work will focus on masking out pixels in shadow from the albedo and exposure time calculations, and the use of robust cost function to replace the current least square approach. Furthermore, we will investigate the use of "shape from shading" approaches to correct the DTM values.

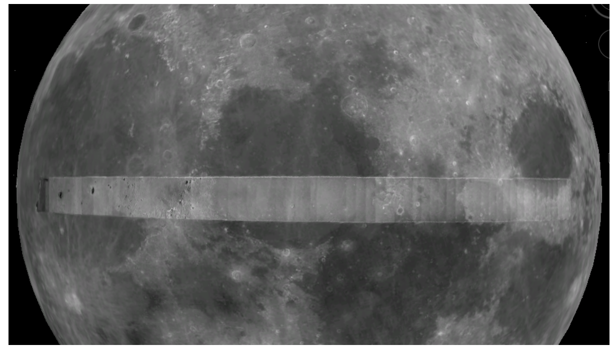

Figure 3: Albedo estimation from Apollo metric camera.

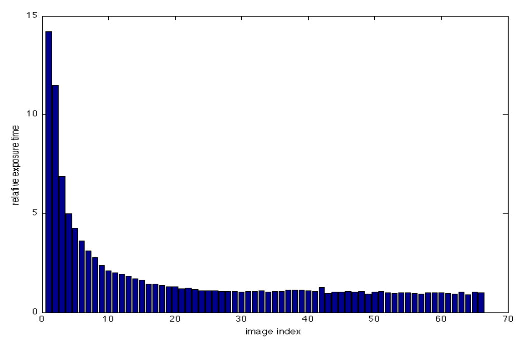

Figure 4: Estimated relative exposure times for Orbit 33 images.

References

[1] M. J. Broxton, Z. M. Moratto, A. Nefian, M. Bunte, and M. S. Robinson. Preliminary Stereo Reconstruction from Apollo 15 Metric Camera Imagery. *40th Lunar and Planetary Science Conference*, 2009.

[2] Ara V. Nefian, Kyle Husmann, Michael J. Broxton, Vinh To, Michael Lundy, and Matthew Hancher. A Bayesian Formulation for Sub-pixel Refinement in Stereo Orbital Imagery. *IEEE International Conference on Image Processing*, 85, November 2009.

[3] Michael J. Broxton, Ara V. Nefian, Zachary Moratto, Taemin Kim, Michael Lundy, and Aleksandr V. Segal. 3D Lunar Terrain Reconstruction from Apollo Images. *International Symposium on Visual Computing*, 2009.