

## PHOTOGRAMMETRIC REGISTRATION OF MOC IMAGERY TO MOLA PROFILE

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### ABSTRACT

The current Mars Global Survey (MGS) mission has been collecting high resolution digital images (MOC) and laser ranges (MOLA). The processing MOLA range data results in a global digital elevation model at ground spacings 1/64 degrees. However, many Mars exploration activities such as landing site selection, rover localization and site-specific studies require higher resolution topographic information. For this purpose, MOC images need to be processed based on photogrammetric principle along with MOLA data and other available ancillary data. As the first and also fundamental step, ground control needs to be selected for MOC images. This paper reports on our study on controlling MOC images by registering them to MOLA data. An approach is proposed which projects each MOLA footprint to MOC images using their exterior orientation parameters obtained from ancillary information about the time, location and orientation of the MOC images. Principles and technical details are presented. Using this approach, a stereopair of one of the selected candidate landing sites are associated to one MOLA profile. Consistent test results are obtained among the two images in the stereopair. Through this registration, further precision processing of MOC images is made possible.

### 1. INTRODUCTION

The surveying of Mars topography has been continuing for about three decades. The first Mars surveying missions could be dated back to Mariner 6 and 7 spacecrafts in early 1970's. This surveying was continuously updated as images from Mariner 9 and Viking Orbiters were obtained [Davies, et al, 1983; Zeitler et al, 1999]. As described by [Davies, 1999a], the first Mars control network is calculated by using nearly three thousand images along with trajectory and pointing data (the so called RAND network). Wu et al [1984] refine and augment the first results by using analytical photogrammetric triangulation. The refined control network (also called RAND-USGS network) is 3-D and has been used for the production of numerous Mars topographic products such as geometrically corrected Mars images, e.g., MDIM (Mosaicked Digital Image Model) 1.0 and 2.X [Kirk, et al, 2000], which are being used for many Mars related scientific investigations. To further refine the Mars control network, a joint effort from RAND and USGS recently started to recalculate the early control network with new sub-pixel image measurements from over four thousand MDIM images and precise reseau coordinates for correction of systematic image errors [Kirk et al, 1999; Davis, et al, 1999b]. Primary results of this RAND-USGS joint effort indicate that the estimated standard deviation of image measurements is 10.01  $\mu\text{m}$  [Davies, et al, 1999a] or  $\sim 200\text{m}$  on the Martian surface [Davies, et al, 1999b]. Similar effort is made by [Zeitler et al, 1999] for local Mars topography. A combined 3-D bundle adjustment of Pathfinder images reportedly improves the precision to an estimated  $\sim 740\text{m}$  in each coordinate component for the Pathfinder landing site. [Zeitler et al, 1999].

The next generation of Mars topographic surveying is recently made possible by Mars Global Surveyor (MGS). Since 1999, the mission started returning high resolution digital images and range measurements (<http://mars.jpl.nasa.gov/mgs/>). Orbiting at a polar and circular orbit of altitude  $\sim 400\text{km}$ , MGS contains a mapping payload of two types of equipment: MOLA (Mars

Orbital Laser Altimeter) and MOC (Mars Orbital Camera). MOLA calculates the range from MGS to Mars surface by measuring the round trip time a laser beam travels. Post processing of ranges based on orbital trajectory data and geodetic data can yield the three dimensional coordinates of the laser footprints [Neumann, 2001]. It is estimated that accuracy of elevations derived from MOLA data is  $\sim 30\text{-}40\text{m}$  [Smith et al, 1998]. Similar results are reported by [Zuber, et al, 1998] which indicate that MOLA elevation accuracy is  $\sim 5\text{-}30\text{m}$ , an increase of  $\sim 2$  orders of magnitude over the previous network. MOLA topography data has been used to analyze the Mars topography in the northern hemisphere [Smith, et al, 1998, 2001] and northern polar region [Zuber, et al, 1998]. In these efforts, a 1km grid MOLA DEM (Digital Elevation Model) has been generated to analyze the regional topography. The global Mars topography was not known until May 1999 when a  $1^\circ \times 1^\circ$  DEM with  $\sim 13\text{m}$  estimated elevation accuracy is released by [Smith et al, 1999]. Presently finer global DEMs up to  $1/256^\circ \times 1/256^\circ$  interval are being produced by the MOLA scientific team.

MOC consists of three pushbroom digital cameras: one blue and one red wide-angle (WA) low resolution camera, and one narrow angle (NA) high resolution camera. The MOC WA cameras take images at 230-500m pixel resolution, whereas the MOC NA camera provides images at 1-5m pixel resolution. More results have been reported recently on using MOC images for Mars topographic mapping. A photogrammetric approach or shape from shading is used by [Beyer and McEwen, 2002; Kirk et al, 2002] to analyze the topographic characteristics for the selected candidate landing sites of Mars Exploration Rover in 2003. Similar analyses are carried out by using stereo pairs based on photogrammetric principles [Kirk, et al, 2001b, 2001c; Kirk, et al, 2002; Ivanov and Lorre, 2002]. The first global mosaic is produced using MOC WA images as reported by [Caplinger, 2002].

A primary difficulty in Mars topographic surveying is the acquisition of precision ground control. Current efforts are

focused on associating existing results, such as DEM, MDIM, or the control network as well as newly collected MOC images to MOLA profile data, which provides accurate 3-D coordinates of discrete points on Mars surface. An early study shows local MOLA spots have a ~10-20km displacement in longitude from MDIM images [Smith et al, 1998]. Muller et al (1999) report a vertical offset up to ~1.8km between DEM generated from Viking Orbiter images and MOLA data. A link of Mars Pathfinder landing site images to the existing control network reveals a planimetric difference of ~4-5km [Zeitler, et al, 1999]. Despite all these discrepancies with previous studies, recent investigation suggests good consistency between MOC images and MOLA data. Anderson and Parker (2002), Ivanov and Lorre (2002), Kirk et al (2001a; 2001b, 2002), Soderblom et al (2002) report on the precision registration between MOC and MOLA data with focus on the selected candidate landing sites. The registration is achieved via a refined camera calibration model, instrument calibration parameters in SPICE kernel and trial and error studies. Archinal et al present (2002) their initial results on improving the RAND-USGS photogrammetric control network by using MOLA-derived radii and DIMs to improve control point absolute radii and horizontal positions. Using the extracted orientation information of MOC images from SPICE kernels, Kirk et al (2001b) generate high resolution DEMs over the selected candidate landing sites from MOC NA images. In addition, ortho images are produced for regional areas of interest using MOLA derived elevation data [Niedermaier, et al, 2002; Wählisch et al, 2002].

In this paper, we will present our current progress on precision registration of MOC images with MOLA ground profile. A new approach is proposed which projects each 3-D point in a MOLA profile onto the MOC images using pushbroom photogrammetric principals based on the extracted orientation information from SPICE kernels. The approach consists of several steps. First, information about MOC image acquisition is extracted based on their acquisition time. This information includes the location, orientation and scanning rate of MOC images. Second, corresponding MOLA range measurements are located from PEDR files and converted to 3-D coordinates referenced to the Mars surface (footprint). Third, these derived MOLA footprints are then projected onto MOC images using pushbroom photogrammetric principles so that the correspondence of each MOLA footprint to its MOC image point is determined. This process establishes a one-to-one correspondence between each MOLA footprint and its MOC image and provides the image coordinates for all MOLA footprints associated with the images. In this way, each MOLA footprint can be used as a ground control point and at least one MOLA profile with several dozens or about a hundred of footprints are associated with MOC images. This precision registration will allow us to carry out various geospatial processing of MOC images, including bundle adjustment, DEM and orthoimage generation, camera calibration, and the relative alignment of MOLA and MOC instruments.

The rest of the paper is organized as follows. Section 2 discusses the MOC imagery and the acquisition of its exterior orientation parameters from MOC image. Results are presented to show the information needed for subsequent photogrammetric processing. MOLA data is described in Section 3 where the approach to calculating ground elevation from MOLA range measurements is presented. MOLA footprints are overlaid with MOC image using existing tools developed by USGS. Section 4 proposes our approach that projects MOLA footprints on to MOC image using the derived

MOC orientation parameters, followed the presentation and analysis of the test results. Section 5 concludes the paper by summarising the major findings and prospecting future studies.

## 2. MOC IMAGE AND ITS ORIENTATION

As described earlier, two types of cameras are aboard the MGS spacecraft. Because of its high resolution of up to ~1m, only MOC NA camera images are used in this study. Like most satellite mapping systems, the position and orientation of the MOC NA camera are tracked and archived for later use. This information is stored in corresponding SPICE kernels sorted by orbit number and can be retrieved via calculation using the SPICE library. SPICE stands for S – Spacecraft, P – Planet, I – Instrument, C - "C-matrix" and E - Events and contains comprehensive data for the MGS mission, including MGS ephemeris, time and time offsets, camera rotation angles, instrument calibration constants, Mars ellipsoid parameters and many other necessary data needed for processing MOLA and MOC data. It is prepared and provided by NASA Navigation and Ancillary Information Facility (NAIF).

In this study, we have successfully developed SPICE Library-based routines that access the corresponding SPICE kernels, and extract and calculate the necessary spacecraft locations and attitudes of MOC NA camera scan lines based on the acquisition time provided in the MOC image header. The calculation process involves the following steps. First, image acquisition time is converted to ephemeris time and spacecraft on-board time. A leapsecond kernel and a SPICE spacecraft clock kernel (SCLK) are used for this conversion. State vectors (position and velocity) of MGS relative to IAU-MARS frame are then calculated for each time epoch recorded in the MOC image header file by using ephemeris time and SPK kernels. The third step is to calculate the MOC orientations relative to Mars by using C-kernel and I-kernel. Once these quantities are obtained, the following collinearity equation can be established for each MOC scan line

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{Mars} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{MGS} + s \mathbf{R}_{MOC}^{Mars} \begin{bmatrix} x \\ y \\ -f \end{bmatrix}_{MOC} \quad (1)$$

where

$\begin{bmatrix} X & Y & Z \end{bmatrix}_{Mars}^T$  are the Mars ground coordinates in Mars fixed coordinate system;

$\begin{bmatrix} X & Y & Z \end{bmatrix}_{MGS}^T$  are the MGS coordinates in Mars fixed coordinate system;

$\begin{bmatrix} x & y & -f \end{bmatrix}_{MOC}^T$  are the image coordinates in MOC image space;

$f$ : focal length of MOC NA camera;

$s$ : scale factor associated with a Mars ground point;

$\mathbf{R}_{MOC}^{Mars}$ : the rotational matrix from MOC to Mars, which is represented as a sequential product of two rotational matrices

$$\mathbf{R}_{MOC}^{Mars} = \mathbf{R}_{MGS}^{Mars} \mathbf{R}_{MOC}^{MGS} \quad (2)$$

where

$\mathbf{R}_{MGS}^{Mars}$ : rotational matrix from MGS to Mars;

$\mathbf{R}_{MOC}^{MGS}$ : rotational matrix from MOC to MGS.

It should be noted that in Equation 1, the MGS coordinates, MOC image coordinates and the rotational matrix from MGS to Mars are time dependent, so each MOC scan line will have its own parameters. Such obtained parameters (location and orientation) are then used as exterior orientation elements in the subsequent photogrammetric processing of MOC images. Table 1 lists the calculated exterior orientation parameters for a MOC NA stereo pair.

Table 1. Exterior orientation parameters of a MOC stereopair

Ext. Orient.	Left image		Right image	
	Start line	End line	Start line	End line
X (km)	2638.162	2640.863	2743.679	2749.133
Y (km)	-2549.221	-2557.746	-2453.358	-2450.626
Z (km)	-891.875	-860.101	-895.114	-836.828
$\omega$ (deg)	-8.6296	-8.6392	11.3701	12.1810
$\phi$ (deg)	-75.9467	-75.9452	-75.9648	-76.8692
$\kappa$ (deg)	-124.5666	-124.5345	-126.576	-125.6728

The exterior orientation for the central scan line of the image is calculated. In this way, the exterior orientation elements for any scan line  $x_i$  is written as

$$\begin{aligned} X_i &= X_0 + k_1 x_i & \omega_i &= \omega_0 + k_4 x_i \\ Y_i &= Y_0 + k_2 x_i & \phi_i &= \phi_0 + k_5 x_i \\ Z_i &= Z_0 + k_3 x_i & \kappa_i &= \kappa_0 + k_6 x_i \end{aligned} \quad (3)$$

where,  $X_0$ ,  $Y_0$ ,  $Z_0$ ,  $\omega_0$ ,  $\phi_0$ ,  $\kappa_0$  are the exterior orientation of the centerline of a MOC image, and  $k_1 \dots k_6$  are the changing rates of exterior orientation in the image. Equation 1 and 2 will be used to determine the image location of MOLA footprints. In this way, MOC images will be registered with and controlled by MOLA data and further precision processing can be pursued.

### 3. MOLA PROFILE AND ALIGNMENT WITH MOC

MOLA measures ranges from MGS to Mars ground surface at ground spacing  $\sim 340\text{m}$  along MGS orbit. Based on orbit trajectory data, initial post-processing of the original measurements can yield orthometric heights for Mars. The parameters used to compute Mars elevations is provided by the MOLA team in the form of PEDR (precision experiment data record) volumes. The PEDR includes the raw shot planetary radii (distance from Mars center of mass to MOLA range point on surface of Mars), the areoid radii (radius of reference areoid with 3396 km mean equatorial radius), the areocentric latitude and longitude of the frame mid-point on the Mars surface (along with deltas to calculate position of each MOLA shot), and associated correction factors (e.g., crossover residuals for planetary radii). The elevation of each MOLA shot, after all corrections have been applied, is

$$h = \text{plrad} - \text{areoid} \quad (4)$$

$h$ : elevation of MOLA footprint or ground track  
 $\text{plrad}$ : shot planetary radius (corrected)  
 $\text{areoid}$ : areoid radius

Computer routines are developed based on existing tools by using the SPICE Library, PEDR accumulative index, PEDR

reader. With these routines, we are able to find the corresponding MOLA PEDR file associated with a MOC image, calculate the areodetic coordinates (longitude, latitude, height) of MOLA ground track and convert them to Cartesian areocentric coordinates ( $X$ ,  $Y$ ,  $Z$ ) for use in controlling MOC images. Table 2 shows a portion of extracted and calculated areocentric coordinates of MOLA footprints (ground track). The coordinates were computed by extracting the latitude, longitude, and elevation coordinates into an ASCII table using the PEDR2TAB utility, and then converting the coordinates to Cartesian format using the SPICE Library routine GEOREC.

Table 2. Cartesian areocentric coordinates of MOLA footprints

X (km)	Y (km)	Z (km)
2469.471	-2191.971	-792.691
2469.504	-2192.054	-792.363
2469.540	-2192.134	-792.035
2469.596	-2192.310	-791.380
2469.625	-2192.397	-791.052
2469.659	-2192.479	-790.724
2469.701	-2192.552	-790.395
2469.764	-2192.720	-789.740
2469.845	-2192.987	-788.758
2469.876	-2193.071	-788.430

In order to acquire the most MOLA data to obtain sufficient control for MOC images, an exhaustive search is carried out to find all MOLA profiles that are associated with a MOC image. This effort turns out to be a success. For the stereopair of Eos Chasma, one of the selected candidate landing sites, two MOLA tracks located were found. As a primary check on the consistency of MOLA and MOC data, the MOLA profile is overlaid with the MOC images. This is accomplished using the USGS developed ISIS (Integrated Software for Imagers and Spectrometers) package. ISIS recomputes the latitude and longitude of the MOLA ground coordinates using the same SPICE kernels used in the geometric processing of the MOC image to obtain consistency. The characteristics of this approach have been studied and its potential needs to be further explored. The initial overlay of MOLA elevation profile and MOC image is shown below in Figure 1, where the fine green line shows the elevation and the circular dots indicate the MOLA footprints.

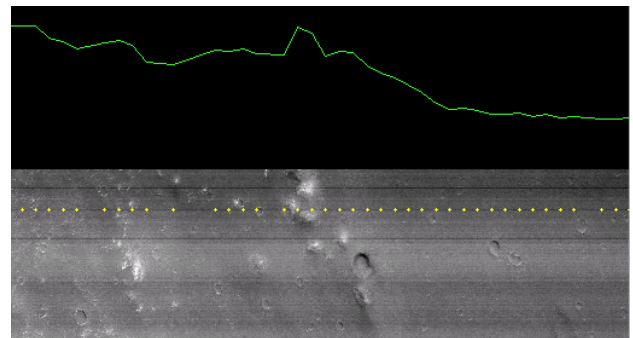


Figure 1. MOLA profile overlaid with a MOC image (Eos Chasma. The image is 90 degree rotated and only a portion is shown in a zoomed-in mode.)

### 4. PHOTOGRAMMETRIC REGISTRATION

The purpose of MOLA and MOC registration is to determine the location of a MOLA footprint on the MOC image. In this way, every MOLA point can then be used as ground control point for the subsequent MOC photogrammetric processing. To

do so, we design and implement an iterative approach that projects a MOLA footprint to the MOC image. For each MOLA footprint, we first treat MOC as a frame camera with constant exterior orientation parameters. This set of parameters is taken from the ones for the central scan line of the MOC image. A MOLA footprint is then projected onto MOC image using this initial exterior orientation with Equation 5. The  $x$  coordinate along the flight direction is then used to update the exterior orientation parameters with Equation 3. In the next step, the updated exterior orientation is used to calculate the image coordinate correction  $dx$  with Equation 5. This process stops once the correction  $dx$  coordinate approaches zero. This calculation steps are shown as below.

Step1. Let  $X_i = X_0, Y_i = Y_0, Z_i = Z_0,$

$\omega_i = \omega_0, \varphi_i = \varphi_0, \kappa_i = \kappa_0$

Step 2. Calculate  $(x, y)$  coordinates using the collinearity equation

$$\begin{aligned} x &= -f \frac{a_1(X-X_i)+b_1(Y-Y_i)+c_1(Z-Z_i)}{a_3(X-X_i)+b_3(Y-Y_i)+c_3(Z-Z_i)} \\ y &= -f \frac{a_2(X-X_i)+b_2(Y-Y_i)+c_2(Z-Z_i)}{a_3(X-X_i)+b_3(Y-Y_i)+c_3(Z-Z_i)} \end{aligned} \quad (5)$$

Step 3. Update the exterior orientation parameters using Equation 3.

Step 4. Use Equation 5 to calculate the  $x$  coordinate correction ( $dx$ ) with the updated orientation parameters.

Step 5. Update the  $x$  approximate coordinate  $x=x+dx$ , if  $dx$  is beyond a given threshold, then return to step 3; otherwise the iteration terminates.

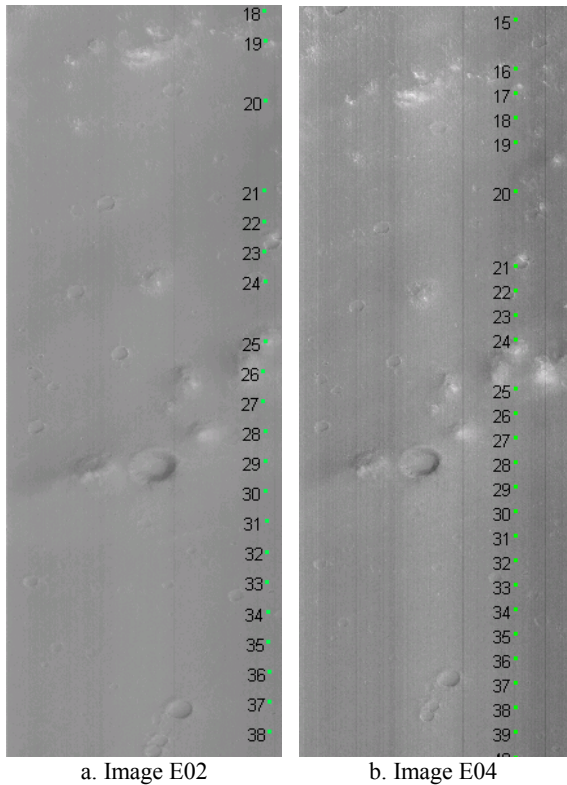


Figure 2. One MOLA profile (green dots) overlaid on a MOC stereopair (Eos Chasma area. Only a portion is shown in a zoomed-in mode. The labelled numbers are MOLA footprint number.)

Using the above approach, one MOLA profile is projected to two images of Eos Chasma area, one from E02 and one from E04 extended missions. The results are presented in Figure 2, with MOLA footprint numbers labelled beside its location. As can be seen from this figure, the projections of the MOLA profile are in general consistent. Initial visual check suggests the discrepancy of the two projections is at  $\sim 1-2$  MOLA footprint spacing. Since the two projections are obtained independently using the exterior orientation parameters of the two images, this result also reveals the good consistence of orbital trajectory data (SPICE kernels) based on which the exterior orientation of the images is derived. It should be noted that this registration is conducted for the original MOLA footprint 3-D coordinates calculated using SPICE and PEDR. Every MOLA footprint is found its corresponding locations on the MOC images and therefore can be used as ground control for subsequent MOC image processing. Another distinction of this approach is that no knowledge on MOC and MOC instrument (internal) alignment is needed. This is made possible because of the use of precision photogrammetric geometry and the available exterior orientation. Taking advantage of this, an analytical approach may be developed to determine this alignment via in-flight self-calibration. Despite the aforementioned distinctions, this approach depends on the precision interior orientation of the MOC camera. In our initial tests, only normal focal length and aspect ratio are used. Further study will consider lens distortion and other calibrated values if available.

## 5. CONCLUSION

Accurate and sufficient ground control is of a necessity for using MOC images to generate DEM and control network. By using trajectory data and sensor geometry, MOC images can be registered to a MOLA profile at a precision of  $\sim 1-2$  MOLA footprint spacing. This in turn suggests the good consistence of trajectory data. Through the use of the proposed approach, every MOLA footprint can be used as a ground control point in subsequent MOC image photogrammetric reduction, which is our current and future research focus.

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