Co-registration of lunar topographic models derived from Chang'E-1, SELENE, and LRO laser altimeter data based on a novel surface matching method

Bo Wu, Jian Guo, Han Hu, Zhilin Li, Yongqi Chen

1. Introduction

Lunar topographic information is essential for lunar scientific investigations and lunar exploration missions. For example, high-resolution topographic data are critical for understanding the ring structures, mare fill, ejecta, and other crustal features of impact basins. They have major implications for determining the origin and evolution of the Moon. The Moon's crustal features have largely been established from a combination of satellite-altimetry-derived topography analyses and satellite observations of the lunar gravity field. The topographic information of lunar impact craters can provide fundamental insights into lunar crust properties, the role of volatiles, and the relative surface age and physics of the craters. Morphological characteristics are significant sources for scientific research. Surface slope measurements are reliable indicators of the importance of gravity-driven processes to a surface. Lunar topographic data also play a critical role in landing-site selection, precision landing, and ground science experiments in lander, vehicle/robot, astronaut, and outpost explorations.

Starting in the 1960s, various lunar topographic products have been created in the Apollo missions and the Clementine mission to fulfill geoscientist demand. Over the past several years, recent lunar exploration missions, such as the Chinese Chang'E-1, the Japanese SELENE/SELENE/Kaguya, and NASA's Lunar Reconnaissance Orbiter (LRO) have collected a vast amount of lunar topographic data. Laser altimeters and cameras onboard the Chang'E-1, SELENE, and LRO are the primary sensors for collecting lunar topographic information. They have different configurations providing elevation measurements with different characteristics. Variations in topographic models (DTMs) have been generated using the data from the Chang'E-1 Laser Altimeter (LAM), SELENE Laser ALTimeter (LALT), and LRO's Lunar Orbiter Laser Altimeter (LOLA). They provide great value to scientists who need DTMs for various lunar scientific investigations and explorations. However, among these lunar DTMs derived from different mission data, there are usually inconsistencies, such as translational.
shifts, angular rotations, or scale variations due to differences in sensor configurations, data acquisition periods, and production techniques. For example, Wu et al. (2011) found that there are small shifts (about 350 m and 1.5 km in horizontal and 150 m and 90 m in altitude at the Apollo 15 and 16 landing areas, respectively) between the DTMx derived from the Chang'E-1 LAM and SELENE LALT data. To obtain maximum value for science and exploration, the multi-resolution and multi-scale DTMs derived from different sensors must be co-registered in a common reference frame (Kirk et al., 2012). Only such an effort will ensure (1) the study of offsets, trends, and error analysis in various lunar topographic datasets, (2) the proper calibration and registration of the datasets, (3) the full comparative and synergistic use of the datasets, and (4) the generation of consistent and precise lunar topographic products.

Multiple lunar topographic datasets can be categorized into two co-registration types, including strategic and tactical co-registrations. Strategic co-registration must be performed globally and in a way that addresses internal errors and variations in the datasets. An a priori uncertainty analysis of each dataset is necessary to produce a combination with the highest possible accuracy. Tactical co-registration is related to the alignment of regional lunar topographic datasets from different sources. Over a relatively small regional area, any differences in coordinate definitions and the systematic varying errors of calibration are expected to appear as offsets and rotations and could be reduced by transforming the entire dataset.

This study focuses on the tactical co-registration of multiple lunar DTMs through a novel surface matching method to reduce the inconsistencies between them and, subsequently, to produce precise lunar topographic models. After presenting a literature review on lunar topographic products from various lunar missions and state-of-the-art co-registration methods between multiple datasets, an innovative surface matching method that incorporates feature points, lines, and surface patches interactively derived from the lunar topographic models is presented in detail. The DTMs derived from the Chang'E-1 LAM, SELENE LALT, and LRO LOLA data at two experimental sites (the Apollo 15 landing area and the Sinus Iridum area) are examined and analyzed. The performances of the proposed surface matching method are evaluated. Finally, concluding remarks are presented and discussed.

2. Related work

2.1. Lunar topographic models from earlier and recent missions

From earlier and recent lunar exploration missions, a vast amount of lunar topographic data has been produced using lunar surface images and elevation measurements collected by the cameras and laser altimeters onboard the spacecraft. In the Apollo era, a variety of photographic sources and laser altimeter measurements collected during the Apollo program were used for lunar topographic modeling. Lunar topographic maps at scales of 1:1,000,000 and 1:250,000 have been produced using metric camera photographs from the Apollo 15, 16, and 17 missions (Livingston, 1980; Mellberg, 1997). The laser altimeter attached to the metric camera systems onboard these three Apollo missions had a ground footprint of about 20 m and the laser altimeter data were used to constrain the bundle adjustment of the mapping camera data. The Clementine mission in 1994 provided the first near-global mapping of the Moon. The laser altimeter onboard the Clementine spacecraft collected elevation measurements of the lunar surface and the data were used to generate a topographic model of the Moon. The model had an absolute vertical accuracy of approximately 100 m and a spatial resolution of 2.5' (Smith et al., 1997). The United States Geological Survey (USGS) also generated a global digital image model (100 m/pixel) of the Moon using the images collected by the onboard ultraviolet–visible camera (Elison et al., 1999). In 2006, USGS released a Unified Lunar Control Network (ULCN) 2005 consisting of the 3D position of 272,931 points, which is based on a photogrammetric solution of 43,866 Clementine images and earlier data (Archinal et al., 2006).

In October 2007, China launched Chang'E-1, its first lunar probe (Ouyang et al., 2010). The LAM onboard the Chang'E-1 spacecraft collected more than 9 million range measurements covering the entire Moon, of which about 3.2 million were useful for topographic modeling (Li et al., 2010). The Chang'E-1 LAM data had spacing resolutions of 1.4 km for the along-track direction and 7 km for the cross-track direction (at the equator). A global lunar digital elevation model (DEM) with a 3-km spatial resolution was produced using the LAM data. The plane positioning accuracy of the DEM was 445 m, and the vertical accuracy was 60 m (Li et al., 2010). The CCD camera onboard the Chang'E-1 spacecraft returned 1098 orbiter images with a spatial resolution of 120 m. A global DEM with 500 m grid spacing was also produced using these images (Liu et al., 2009). Regional DEMs with 360-m grid spacing were generated at the Apollo 15 and 16 landing areas by integrating the Chang'E-1 LAM and image data (Wu et al., 2011). The Chang’E-1 data are currently publically available in Planetary Data System (PDS) format through the Lunar Exploration Data Release System (http://159.226.88.59:7779/CE1OutENGWeb/step.jsp). China’s second lunar probe, Chang’E-2, was launched in October 2010. Chang’E-2 carried a similar suite of instruments to Chang’E-1, but the laser altimeter and CCD camera were both improved. The Chang-E-2 imagery had global 7 m/pixel coverage and regional coverage of Sinus Iridum at 1.5 m/pixel. Regional lunar topographic models were produced using the Chang’E-2 data (Di et al., 2012; Zou et al., 2012).

The Japanese lunar explorer SELENE was launched in September 2007 (Noda et al., 2009). Its onboard LALT collected more than 20 million range measurements, of which 10 million had high-quality orbital data and were used for topographic modeling (Araki et al., 2009). The SELENE LALT data covered the entire region of the Moon with a height resolution of 5 m at a sampling interval smaller than 2 km. A global lunar topographic map with a spatial resolution of 0.5' was derived from the SELENE LALT data (Araki et al., 2009). SELENE also acquired stereoscopic images with 10-m resolution using its push-broom Terrain Camera, which covered almost the entire surface of the Moon. A global DTM mosaic with 10-m spatial resolution was produced from the camera imagery (Haruyama et al., 2012). The SELENE data are publically available in the SELENE Data Archive (http://l2db.selene.darts.isas.jaxa.jp/index.html.en).

NASA successfully launched its LRO to the Moon in June 2009. The LOLA onboard the LRO is a pulse detection altimeter that incorporates a five-spot X-pattern, measuring the distance to the lunar surface at five spots simultaneously (Smith et al., 2010). LOLA has so far collected more than 5.5 billion valid range measurements (Kirk et al., 2012). The five-spot pattern provides five adjacent profiles for each track, 10–12 m apart over a 50– to 60-m swath, with combined measurements in the along-track direction every 10–12 m. The across-track resolution depends on the spacecraft’s number of orbits, and after one year of operation is approximately 0.04' (about 1.2 km at the equator) (Smith et al., 2010). A topographic map of the near side of the Moon has been generated using 1 billion LOLA measurements at a spatial resolution of 20 m along track and a 0.1' ground-track spacing (Riris et al., 2010). The wide-angle cameras (WACs) and narrow-angle cameras (NACs) onboard LRO have collected lunar images at resolutions of 100 m/pixel and 50 cm/pixel, respectively. The WAC images have proven global coverage, and a near-global DTM GLD100 with a pixel spacing of 100 m has been produced from the WAC images.
Co-registration of multiple topographic models

For surface comparison or co-registration between different topographic models, vast efforts have been exerted on Earth topographic datasets in the past. Williams et al. (1999) studied the registration of three-dimensional datasets with rigid motions. The registration process comprises two steps: correspondence selection and motion estimation. Besl and McKay (1992) presented an iterative closest point (ICP) algorithm for surface matching. The key function of the ICP algorithm is to search for pairs of the closest points in the two datasets, estimating the rigid transformation and iteratively refining the transformation by repeatedly generating pairs of closest points on the two sets by minimizing an error metric. However, the ICP algorithm has several drawbacks: (1) it is time consuming due to the exhaustive search for the closest points; (2) good initial approximations of the closest points are required for the convergence of the iteration calculations; (3) the closest point pairs are sometimes unreliable, especially for topographic models with low spatial resolutions; and (4) possible errors in point selection will lead to unfavorable surface matching results. Li et al. (2001) presented a surface matching technique to detect the local deformation of a surface using a least-median-of-squares estimator. Gruen and Akca (2005) described a least squares 3D surface matching method. This method is able to estimate the 3D transformation parameters between two or more surface patches using the generalized Gauss–Markov model by minimizing the sum of the Euclidean distance squares between the surfaces. However, good initial approximations of the transformation parameters are required in their method. Streutker et al. (2011) presented a slope-based method for the co-registration of overlapping elevation surfaces. This method is used to realign the flight lines of light detection and ranging (LiDAR) datasets, and results show that the decimeter offsets between different LiDAR flight lines can be reduced. However, this method may perform poorly if the initial offsets between the two surfaces are relatively large.

Few studies have emphasized the co-registration of multiple lunar topographic models. Rosiek et al. (2001) described a method to co-register the Clementine images with the Clementine laser altimeter data, in which the Clementine global mosaic was used to establish horizontal control and Clementine laser altimeter points were used for vertical control. However, due to the marginal overlap between stereo models, the geometry of the photogrammetric network was weak and resulted in stereo models that did not align with each other. Di et al. (2010) presented a co-registration method of lunar DTMs derived from the Chang‘E-1 stereo images and the laser altimeter data to reduce the inconsistencies between them. In their method, a DTM is generated first from the stereo images, and then the DTM is registered to the LAM data through surface matching using an ICP algorithm (Besl and McKay, 1992). Through surface matching, a 3D rigid transformation model (with three rotation and three translation parameters) between the DTMs can be obtained, from which the exterior orientation (EO) parameters of the images are adjusted so that the images and laser altimeter data are co-registered. Di et al. (2012) further examined the crossover adjustment of the Chang’E-1 laser altimeter data, and then used the ICP algorithm to co-register the Chang’E-1 stereo images with the refined laser altimeter data. Wu et al. (2011) developed a bundle adjustment approach to integrate the Chang’E-1 imagery and laser altimeter data for precision lunar topographic modeling. The bundle adjustment model involves the laser altimeter points, image EO parameters, and tie points collected from the stereo images. The output of the adjustment is the refined image EO parameters and laser ground points. After the bundle adjustment process, the misregistrations between the Chang’E-1 imagery and the laser altimeter data are reduced from as large as 18 pixels to about 1 pixel in image space. Guo and Wu (2012) examined the co-registration between the DTMs derived from the Chang’E-1 and SELENE laser altimeter data using a least squares surface matching method based on tie points identified from the DTMs. Seven transformation parameters (one scale factor, three rotations, and three translations) are employed in this co-registration method. Results show that small shifts between these two datasets are reduced after co-registration. Beyer et al. (2010, 2011) and Rosiek et al. (2012) presented some initial results of comparison of LRO NAC DTMs.

Co-registration of multiple topographic models has been examined for Mars topographic datasets. Anderson and Parker (2002) examined the precision registration between Mars orbiter camera (MOC) imagery and Mars orbiter laser altimeter (MOLA) data at selected candidate landing sites. Yoon and Shan (2005) presented a combined adjustment method to process the MOC imagery and MOLA data and indicated that the large misregistration between the two datasets could be corrected to a certain extent. Spiegel (2007) developed a high-resolution stereo camera (HRSC) imagery bundle adjustment technique, in which a sparse stereo point cloud is adjusted to optimize its fit to a surface interpolated from the MOLA data. This adjustment is now standard in the production of controlled orthorectified HRSC products. Lin et al. (2010) developed a co-registration process to align Mars DTMs derived from the MOLA, HRSC, and high-resolution imaging science experiment (HiRISE). The base algorithm for co-registration is a 3D conformal co-ordinate transformation including seven parameters (three translations, three rotations, and one scale factor). Instead of simply taking the closest point pairs on the DTMs for the transformation parameter solution, an enclosing surface patch is used for better approximation of corresponding points. Delaunay triangulations of the DTMs are constructed. They are used to find the enclosing triangles of point pairs in the triangulations, which enables a better height value to be interpolated than if only the single closest point is used. Lin et al. (2010) also presented an assessment of surface matching parameters for the co-registration of multi-resolution Mars DTMs.

Based on previous studies, this study presents a novel surface matching method for the co-registration of multiple lunar topographic models. This method incorporates feature points, lines, and surface patches into the surface matching to guarantee robust surface correspondence, which is hard to achieve from the traditional point-based surface matching method. Strict mathematical models of using feature lines and surface patches for surface matching have been developed, which to our knowledge are new in the field of surface matching. It should be noted that while the focus of this study is the co-registration of lunar DTMs derived from the Chang‘E-1 LAM, SELENE LALT, and LRO LOLA laser altimeter data, the developed method can also be used for the co-registration of lunar DTMs derived from various sources, e.g., lunar laser altimeter data and lunar orbiter images.
3. A novel surface matching method based on multiple features

3.1. Overview of the approach

For two lunar DTMs derived from different sources of laser altimeter data, one is treated as a reference DTM (e.g., DTM 1) and the other as a matching DTM (e.g., DTM 2). Feature points, lines, and surface patches are identified on both DTMs for surface matching. The feature points are normally the centers of craters or other terrain feature points. The feature lines are the ridge or valley lines detected from the DTMs. To obtain feature surface patches, the DTMs are segmented through triangulations, and the triangles that share surface normals are merged to form local surface patches. The feature points, lines, and surface patches are then used as inputs in the combined adjustment model. The outputs comprise seven transformation parameters (one scale factor, three rotations, and three translations), from which the matching DTM can be co-registered to the referencing DTM. Fig. 1 shows the overview of the approach.

It should be noted that if the spatial resolutions of the two DTMs are different, then the DTM with a higher resolution will be resampled to a new DTM with the same resolution. Surface matching is carried out between the two equal-resolution DTMs, while the obtained transformation parameters are applied to the original DTMs for further co-registration and analysis.

3.2. Combined adjustment model

For the co-registration of multiple DTMs using point pairs, the relationship between a point \( P(X_P, Y_P, Z_P)^T \) on the reference DTM and a point \( P'(X'_P, Y'_P, Z'_P)^T \) on the matching DTM can be represented using the following equation (Mills et al., 2003):

\[
P = sR^T + T
\]  

(1)

where \( s \) is a scale factor denoting the magnification or contraction between the two DTMs, \( R \) is a rotation matrix that is determined entirely by three Euler rotation angles \((\phi, \omega, \kappa)\), and \( T=(T_X, T_Y, T_Z)^T \) is a 3D translation vector between the two DTMs. In Eq. (1), the seven parameters \( s, (\phi, \omega, \kappa) \) and \((T_X, T_Y, T_Z)\) are all unknowns that need to be solved. Each point pair generates three observation equations.

The following describes the mathematical model of using line pairs for surface matching. As shown in Fig. 2, a line pair \((L, L')\) is identified on the two DTMs. \( P_1 \) and \( P_2 \) are on line \( L \) on the reference DTM and \( P_3 \) and \( P_4 \) are on line \( L' \) on the matching DTM. If the seven transformation parameters are perfectly accurate, the corresponding points of \( P_3' \) and \( P_4' \), which are \( P_3 \) and \( P_4 \), should be collinear with points \( P_1 \) and \( P_2 \). Therefore, the distance from point \( P_3 \) (or \( P_3' \)) to line \( L \) should be 0 in the ideal situation. A mathematical model that uses line pairs for surface matching is built based on this observation.

Assuming a 3D line \( L \) is determined by points \( P_1 \) and \( P_2 \), it can be mathematically modeled by the intersection of two space planes as shown in the following equation:

\[
L = \begin{align*}
    m_{11}x + m_{12}y + m_{13}z &= b_1 \\
    m_{21}x + m_{22}y + m_{23}z &= b_2 
\end{align*}
\]  

(2)

Eq. (2) can be expressed in matrix form as

\[
MX = B
\]  

(3)

where

\[
M = \begin{pmatrix}
    m_{11} & m_{12} & m_{13} \\
    m_{21} & m_{22} & m_{23}
\end{pmatrix}, \quad B = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}, \quad X = (x \ y \ z)^T,
\]

forming the line equation.

For a point \( P \) (e.g., \( P_3 \) or \( P_3' \)) on line \( L' \), the distance from its corresponding point \( P_3' \) (or \( P_3 \)) to line \( L \) can be determined by the following equation:

\[
d = \sqrt{(B-MP)^T(MM^T)^{-1}(B-MP)}
\]  

(4)

In the ideal situation, the distance \( d \) should be 0. The constraint \( d=0 \) is then used for line correspondence in the adjustment model. The matrices \( B \) and \( M \) in Eq. (4) are related to line \( L \) and determined by points \( P_1 \) and \( P_2 \). \( P \) (e.g., \( P_3 \) or \( P_3' \)) in Eq. (4) is determined by point \( P \) (or \( P_3' \)) through Eq. (1). For each line correspondence, two distance constraints can be generated independently, as two points are determinants for a line. Therefore, each line correspondence will produce two observation equations.

From the preceding discussion, it can be seen that there is no point correspondence (e.g., correspondence of line end points) requirement in the line-matching adjustment model. Two corresponding lines, each determined by any two points, can be used for line matching, even though the lengths of the two lines could vary. This line-matching strategy provides more robust correspondence compared with point pairs.

For the correspondence between two surface patches, the normal vectors of the surface patches are used for surface matching. As
shown in Fig. 3, the relationship between a surface patch \( M \) and its corresponding surface patch \( M' \) can be determined by their surface normals \( n(n_x, n_y, n_z)^T \) and \( n'(n'_x, n'_y, n'_z)^T \) through the following equation:

\[
n = Rn',
\]

where \( R \) is the rotation matrix determined by the rotation angles \((\phi, \omega, \kappa)\), as described previously in Eq. (1). For each corresponding surface (normal vector), three observation equations can be generated that are related only to the rotation matrix.

After linearizing Eqs. (1), (4) and (5) with respect to the seven unknown transformation parameters, the observation equations for the combined adjustment can be represented in matrix form as

\[
V = AX - LP
\]

where \( X \) is the unknown vector to be solved containing the transformation parameters \((s, R, T)\), \( L \) is the observation vector, \( A \) is the coefficient matrix containing the partial derivatives from each observation, and \( P \) is the \( a \ priori \) weight matrix of the observations that reflects the measurement quality and the contribution of the observation to the final result. In particular, the combined adjustment in this method includes the following three parts for the three different types of observations:

\[
V_1 = A_1X_1 + B_1X_2 + C_1X_3 - L_1P_1 \\
V_2 = B_2X_2 - L_2P_2 \\
V_3 = A_3X_1 + B_3X_2 + C_3X_3 - L_3P_3
\]

The first equation in Eq. (7) is the observation equation for the point correspondence, in which \( X_1 \) is the unknown scale parameter, \( X_2 \) represents the vector of unknown rotation angles \((\phi, \omega, \kappa)\), and \( X_3 \) is the vector of unknown translation parameters. The coefficient matrix \( A \) in Eq. (6) is divided into \( A_1, A_2, \) and \( A_3 \) for different types of unknown parameters. The second equation represents the observation residuals of normal vectors of the corresponding surface patches. As denoted in this equation, the surface normal is only related with the unknown rotation angles. The third equation is the observation equation for line correspondence after applying the distance constraint \( d=0 \). For different types of observation equations, different weights \( P_i (i=1–3) \) are assigned (details discussed in Section 3.4).

Since this study focuses on co-registration of multiple lunar topographic models in local regions, the geometric centroid of the study area is used as the rotation origin. The seven unknown transformation parameters are calculated through a least squares minimization of difference between the matching surface and the reference surface based on Eq. (7). It should be noted that this adjustment model has the flexibility to use individual types of feature points, lines, and surface patches or any combination of the three for surface matching, depending on the types of features that can be detected from the DTMs. If only the surface patches are used, only the three rotation angles can be determined. Feature lines or points are necessary to determine the translation parameters and the scale factor.

3.3. Determination of multiple features

3.3.1. Feature point determination

Co-registration of multiple DTMs from feature points is the most common and easiest method. Popular approaches are largely based on the ICP algorithm (Besl and McKay, 1992). However, as discussed previously, the ICP algorithm has several drawbacks, and even the closest points derived through the iterative calculations in the ICP algorithm do not necessarily have to be the exact corresponding points on both DTMs. This is especially true for lunar DTMs derived from different sources; they usually have low spatial resolutions of several hundred meters or kilometers, and there are usually...
inconsistencies between them. A tiny discrepancy in the point pairs will lead to large variations in the transformation parameters.

Only feature points that can be clearly identified on the DTMs, such as the centers of craters or other terrain feature points, are used in the adjustment model. 2D DTM gray-scale maps (e.g., Fig. 4(a)) are used to determine the crater centers. The circles or ellipses that best fit the boundaries of the craters in the 2D gray-scale maps are determined, and the centers of the circles or ellipses are selected as the planar locations of the crater centers. The altitudes of the crater centers are derived from the DTMs based on their planar locations. To determine the terrain feature points, skeleton lines (ridge or valley lines) are first extracted on the DTMs based on a terrain analysis algorithm (Tarboton, 1997), and the intersection points of the skeleton lines with similar patterns in the local regions (e.g., point 3 in Fig. 7(a) and (b)) are selected as the terrain feature points. Their 3D coordinates can be derived from the DTMs. The matches of these feature points are performed interactively. These feature points have low priority in the adjustment model compared with feature lines and surface patches due to the possible uncertainties in determining them. As such, fewer feature points are used and they are assigned smaller weights in the adjustment model.

3.3.2. Feature line determination

The feature lines are the important skeleton lines (ridge or valley lines) on the DTM. As mentioned above, a terrain analysis algorithm (Tarboton, 1997) was used in this study to extract feature lines from multiple lunar DTMs. Fig. 4 shows an example of the feature line extraction. Fig. 4(a) is a DTM interpolated from the LRO LOLA data in the Apollo 15 landing area, in which light colors represent higher elevation areas and darker colors represent lower elevation areas. Fig. 4(b) shows the results of feature line extraction. It is apparent that a large number of feature lines can be successfully extracted from the DTM. After the feature lines were extracted from multiple DTMs, those common line segments that could be clearly identified were used in the adjustment model to determine the transformation parameters.

As discussed previously, surface matching based on feature lines is more robust than the point-based method. Feature lines are particularly useful in determining the translation parameters between the multiple DTMs. In theory, two pairs of feature lines are enough to determine the three translation parameters. More feature lines can be used to refine the results through a least squares adjustment. Because feature lines may have relatively

![Fig. 6. Chang'E-1 LAM, LRO LOLA, and SELENE LALT data and DTMs in the Apollo 15 landing area.](image)

![Fig. 7. Feature points, lines, and surface patches determined on the Chang'E-1 and LRO DTMs in the Apollo 15 landing area.](image)
weak control in determining the rotation angles between the multiple DTMs, surface patches are employed in this approach to determine rotation transformation parameters. This is described in the following subsection.

3.3.3. Feature surface patch determination

Feature surface patches are normally planar sub-surface patches on the DTM. Corresponding surface patches on multiple DTMs can provide robust rotation transformations between the DTMs. To obtain feature surface patches on the DTM, first, a triangulation of the DTM is performed by dividing each grid in the DTM into two triangles. Next, a surface normal is calculated for each triangle, which is a vector originating at the triangle center that points to the outer side and is perpendicular to the triangle plane. Starting from any triangle in the triangulation, a merging process is performed to merge its neighbor triangles into a surface patch by comparing the differences in the triangulation, a merging process is performed to merge its neighbor triangles into a surface patch by comparing the differences in the triangulation. This merging process is continued until all of the triangles can be considered to share the same surface location. If the value is close to 1, the surface normals for the surface patch. It is notable that only surface normals belonging to surface patches are indicated with black. After surface patches on the DTMs are selected, the average surface normal of the triangles within each surface patch are calculated and used as the surface normal for the surface patch. It is notable that only surface patches that can be clearly identified on both the DTMs are used in the adjustment model. They are usually relatively large surface patches, such as those marked with 1, 2, and 3 in Fig. 5(b).

It should be noted that we developed automatic software programs to extract feature points, lines, and surface patches from the DTMs. The matching of these features in multiple DTMs must be performed interactively at this stage.

3.4. Weight determination in the adjustment model

The adjustment model employs pseudo-observation equations constructed from the participants (feature points, lines, and surface patches). Though this is a useful and common treatment in adjustment methodology because it provides the flexibility to properly weight the participants in the adjustment (Mikhail et al., 2001), it also introduces difficulties in how to assign appropriate weights to the adjustment model participants. The weights are determined by both the different magnitudes of order across different units and the a priori measured accuracies of the participants. In general, the more accurate and reliable participants will have higher weights in the adjustment.

For the three types of participants (feature points, lines, and surface patches) used in this approach, the feature surface patches are determined through the cluster of triangulations based on the local-area terrain trends, which contribute to the calculation of the three rotation parameters in the surface matching. The feature lines are identified according to similar feature terrain line segments, providing robust determination of the three translation parameters and also contributing to the calculation of other transformation parameters. The feature lines and surface patches are considered the most accurate measurements in the adjustment model. Therefore, a unit weight is assigned to all of the surface normals and feature lines. The feature points are identified mostly at the centers of craters or other terrain feature points, which are considered to be the relatively less reliable measurements in the adjustment model. In addition, the point correspondences are more sensitive to noises in the DTM. These noises cause disturbances around the points that can be eliminated in the line detection and surface growing process. The feature points are assigned a weight much smaller than the unit weight based on their a priori variance. It is apparent from previous experience in photogrammetry (Yoon and Shan, 2005) that the adjustment model is less sensitive to weight assignments. Moderate changes in weight magnitude yield similar results.

4. Co-registration of multiple lunar DTMs derived from Chang‘E-1 LAM, SELENE LALT, and LRO LOLA data

The developed multi-feature-based surface matching method was used to co-register the multiple DTMs derived from the Chang‘E-1 LAM, SELENE LALT, and LRO LOLA data in the Apollo 15 landing area and the Sinus Iridum area. The details are described in the following subsections.

<table>
<thead>
<tr>
<th>Transformation parameters</th>
<th>Multi-feature-based method</th>
<th>Point-based method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>0.9978</td>
<td>0.9986</td>
</tr>
<tr>
<td>Δx (longitude)</td>
<td>–1.92 m</td>
<td>110.77 m</td>
</tr>
<tr>
<td>Δy (latitude)</td>
<td>24.44 m</td>
<td>43.39 m</td>
</tr>
<tr>
<td>Δz (altitude)</td>
<td>–217.63 m</td>
<td>–883.15 m</td>
</tr>
<tr>
<td>Δϕ (roll)</td>
<td>0.014°</td>
<td>0.036°</td>
</tr>
<tr>
<td>Δθ (pitch)</td>
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<td>–0.0005°</td>
</tr>
<tr>
<td>Δκ (yaw)</td>
<td>–0.001</td>
<td>0.0043°</td>
</tr>
</tbody>
</table>

Table 1: Transformation parameters between the Chang‘E-1 and LRO DTMs in the Apollo 15 landing area.
4.1. Co-registration of multiple lunar DTM in the Apollo 15 landing area

The Apollo 15 landing site is located at (3.66° E, 26.08° N) at the foot of the Apennine Mountain range. The experimental area in this study covered a region of 0.5–8° E and 21–32° N, including diverse terrain features such as the Apennine Mountain, Autolycus Crater, and Hadley Rille. The maximum elevation difference is about 8 km, from the peak of the Apennine Mountain to the bottom of the Autolycus Crater. Fig. 6 shows the distributions of

Fig. 9. Profiles derived from the LRO and Chang’E-1 DTM in the Apollo 15 landing area. (a) Profiles for reference line 1 using multi-feature based co-registration, (b) profiles for line 1 using point based co-registration, (c) profiles for line 2 using multi-feature based co-registration, (d) profiles for line 2 using point based co-registration, (e) profiles for line 3 using multi-feature based co-registration, (f) profiles for line 3 using point based co-registration, (g) profiles for line 4 using multi-feature based co-registration and (h) profiles for line 4 using point based co-registration. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
the laser altimeter points from Chang’E-1 LAM, LRO LOLA, and SELENE LALT at the study area. There were 9683, 1,132,676, and 11,595 points from Chang’E-1 LAM, LRO LOLA, and SELENE LALT, respectively. DTMs sharing a 0.02° grid spacing resolution (about 600 m in latitude and 400 m in longitude) were interpolated from the laser altimeter points, respectively. The points were overlaid on their corresponding DTMs as illustrated in Fig. 6(a), (c), and (e). Fig. 6(b), (d), and (f) show the 3D view of the DTMs.

4.1.1. Co-registration of Chang’E-1 and LRO DTMs in the Apollo 15 landing area

The developed multi-feature-based surface matching method was used to co-register the Chang’E-1 DTM to the LRO DTM. Feature points, lines, and surface patches were detected from both of the DTMs using the methods described in Section 3.3. Finally, three point pairs (two crater centers and one mountain peak) and six line pairs were identified from the two DTMs as illustrated in Fig. 7(a) and (b). Three pairs of surface patches were also identified from the two DTMs as shown in Fig. 7(c) and (d). They were then used as inputs in the adjustment model for surface matching.

After surface matching using the developed method, seven transformation parameters including one scale factor, three translations, and three rotations were obtained. They are listed in Table 1. The results show that for the DTMs derived from the Chang’E-1 LAM and LRO LOLA data in the Apollo 15 landing area, there are about 25 m offset between these two datasets in the horizontal direction, and the LRO data are about 218 m higher than the Chang’E-1 data. The deviations in rotations between these two datasets are small, and the scales are very similar.

Another point-based-surface matching method was also tested. In this method, several point pairs were identified from the DTMs, and a similar strategy with the ICP algorithm was employed to obtain the closest points based on the initial identified point pairs. After that, the closest points were used as inputs in an adjustment model based on Eq. (1). Similarly, the geometric centroid of the study area was used as the rotation origin and seven transformation parameters were finally obtained. Twelve point pairs including the three used in the previous method were used for the Chang’E-1 and LRO DTMs in the Apollo 15 landing area, and the obtained transformation parameters are also listed in Table 1.

The obtained transformation parameters were used to transform the Chang’E-1 LAM point set to a new frame, and a new DTM was interpolated from the new point set. This co-registration process brought the new Chang’E-1 DTM into alignment with the LRO DTM. To evaluate the co-registration method performances, four reference lines were selected for profile comparison analysis as shown in Fig. 8, of which lines 1 and 2 are along the north–south direction and lines 3 and 4 are along the east–west direction.

Three profiles were derived for each reference line, including a profile derived from the LRO DTM, a profile derived from the original Chang’E-1 DTM, and a profile derived from the Chang’E-1 DTM after co-registration. Fig. 9(a), (c), (e) and (g) show the results from the multi-feature-based co-registration, and Fig. 9(b), (d), (f) and (h) show the results from the point-based co-registration.

Fig. 9 shows that the general trends among these profiles are consistent for the four reference lines in this study area. The profiles derived from the Chang’E-1 DTMs show relatively smooth topography compared with the profiles derived from the LRO DTM. This is because the Chang’E-1 DTMs were interpolated from the relatively sparse Chang’E-1 LAM points and may not be sufficient to represent the actual topography in this area. Fig. 9 also shows obvious offsets between the profiles derived from the original Chang’E-1 DTMs (cyan lines) and the profiles from the LRO DTM (blue lines). After co-registration using the multi-feature-based method, the profiles derived from the co-registered Chang’E-1 DTM (red lines) are quite consistent with the LRO profiles for all the four reference lines as shown in Fig. 9(a), (c), (e) and (g). Although the profiles derived from the co-registered Chang’E-1 DTM using the point-based method (purple lines) are closer to the LRO profiles after co-registration, there are still obvious offsets between the profiles, as shown in Fig. 9(b), (d), (f) and (h).
The absolute elevation differences of the profiles were calculated and the statistics including the average, maximum, minimum, and standard deviation were obtained. They are shown in Table 2. The results indicate that the multi-feature-based co-registration method performed much better than the point-based method.

### 4.1.2. Co-registration of SELENE and LRO DTMs in the Apollo 15 landing area

Similar processes were used to co-register the DTM derived from the SELENE LALT data with the DTM derived from the LRO LOLA data in the Apollo 15 landing area. The results from the point-based co-registration method are omitted here. Table 3 lists the seven transformation parameters of the SELENE and LRO DTMs obtained using the multi-feature-based co-registration method. There is about a 40 m offset between the SELENE and LRO DTMs in the horizontal direction, and the SELENE data are generally about 164 m higher than the LRO data. The rotation deviations between the two datasets are small, and their scales are very similar.

**Fig. 10** shows the profiles for the same four reference lines illustrated in **Fig. 8**, including profiles derived from the LRO DTM, the original SELENE DTM, and the SELENE DTM after multi-feature-based co-registration. **Table 4** lists the statistics of the absolute elevation differences of these profiles.

**Fig. 10** and **Table 4** show that the SELENE and LRO profiles along the north–south direction are quite consistent. The averages of the absolute elevation differences between the profiles derived from the original SELENE DTM and LRO DTM are 31.98 m for reference line 1 and 40.22 m for line 2. For the profiles along the east–west direction (reference lines 3 and 4), the differences are much larger, showing...
averages of 189.29 m for reference line 3 and 91.57 m for line 4. In comparing the profiles at reference line 3, it can be seen that the original SELENE data are clearly higher than the LRO data in the upper-right part of the study area. After applying multi-feature-based co-registration, the differences are reduced significantly for all four reference lines.

4.2. Co-registration of multiple lunar DTMs in the Sinus Iridum area

Sinus Iridum is a plain of basaltic lava that forms a northwestern extension to the Mare Imbrium. The Chinese first lunar lander/rover Chang’E-3 is planned to land on the Sinus Iridum landing area in 2013. In this study, the Sinus Iridum area covered a region of 26–38°W and 40–50°N, including a large flat area surrounded by mountains. The maximum elevation difference is about 5 km. Fig. 11 shows the distributions of the laser altimeter points from Chang’E-1 LAM, LRO LOLA, and SELENE LALT at the study area. There were 15,581, 1,428,761, and 18,379 points from Chang’E-1 LAM, LRO LOLA, and SELENE LALT, respectively. DTMs with the same spatial resolution, 0.02° grid spacing (about 600 m in latitude and 400 m in longitude), were interpolated from the laser altimeter points, respectively. The points were overlaid on their corresponding DTMs as illustrated in Fig. 11(a), (c), and (e). Fig. 11(b), (d), and (f) show the 3D view of the DTMs.

4.2.1. Co-registration of Chang’E-1 and SELENE DTMs in the Sinus Iridum area

In the Sinus Iridum area, the developed multi-feature-based surface matching method was used to co-register the Chang’E-1
DTM to the SELENE DTM. Three point pairs (two crater centers and one feature point) and six line pairs were identified from the two DTMs as illustrated in Fig. 12(a) and (b). Four pairs of surface patches were also identified from the two DTMs as shown in Fig. 12(c) and (d). They were then used as inputs in the adjustment model for surface matching.

After surface matching using the multi-feature-based method, seven transformation parameters were obtained. They are listed in Table 5. The results show that for the DTMs derived from the Chang’E-1 LAM and SELENE LALT data in the Sinus Iridum area, there were about 470 m offset between the two datasets in the horizontal direction, and the SELENE data were about 230 m higher than the Chang’E-1 data. The point-based surface matching method was also tested for the Chang’E-1 and SELENE DTMs in the Sinus Iridum area. Thirteen point pairs including the three used in the previous method were used, and the obtained transformation parameters are also listed in Table 5.

The obtained transformation parameters were used to co-register the Chang’E-1 DTM to the SELENE DTM. To evaluate the performances of the co-registration method, four reference lines were selected for profile comparison analysis as shown in Fig. 13, of which lines 1 and 2 are along the north–south direction and lines 3 and 4 are along the east–west direction.

Three profiles were derived for each reference line, including a profile derived from the SELENE DTM, a profile interpolated from the original Chang’E-1 DTM, and a profile interpolated from the Chang’E-1 DTM after co-registering to the SELENE DTM. Fig. 14(a), (c), (e) and (g) show the results from the multi-feature-based co-registration, and Fig. 14(b), (d), (f) and (h) show the results from

Table 5
Transformation parameters between the Chang’E-1 and SELENE DTMs in the Sinus Iridum area.

<table>
<thead>
<tr>
<th>Transformation parameters</th>
<th>Multi-feature-based method</th>
<th>Point-based method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>1.0024</td>
<td>1.0027</td>
</tr>
<tr>
<td>ΔX (longitude)</td>
<td>−301.18 m</td>
<td>−403.69 m</td>
</tr>
<tr>
<td>ΔY (latitude)</td>
<td>−357.18 m</td>
<td>−380.80 m</td>
</tr>
<tr>
<td>ΔZ (altitude)</td>
<td>−230.91 m</td>
<td>−799.42 m</td>
</tr>
<tr>
<td>Δα (roll)</td>
<td>0.0071</td>
<td>0.022</td>
</tr>
<tr>
<td>Δβ (pitch)</td>
<td>0.0028</td>
<td>−0.0009</td>
</tr>
<tr>
<td>Δγ (yaw)</td>
<td>−0.0072</td>
<td>−0.0095</td>
</tr>
</tbody>
</table>
Fig. 14. Profiles derived from the SELENE and Chang'E-1 DTMs in the Sinus Iridum area. (a) Profiles for reference line 1 using multi-feature based co-registration, (b) profiles for line 1 using point based co-registration, (c) profiles for line 2 using multi-feature based co-registration, (d) profiles for line 2 using point based co-registration, (e) profiles for line 3 using multi-feature based co-registration, (f) profiles for line 3 using point based co-registration, (g) profiles for line 4 using multi-feature based co-registration and (h) profiles for line 4 using point based co-registration. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
the point-based co-registration. Fig. 14 shows that the general trends among these profiles are consistent for all the four reference lines in this study area. There are obvious offsets between the profiles derived from the original Chang'E-1 DTMs (cyan lines) and the profiles from the SELENE DTMs (blue lines). After co-registration using the multi-feature-based method, the profiles derived from the co-registered Chang'E-1 DTM (red lines) are closely attached to the SELENE profiles for the four reference lines as shown in Fig. 14(a), (c), (e) and (g). Although the profiles derived from the co-registered Chang'E-1 DTM using the point-based method (purple lines) are closer to the SELENE profiles compared with the profiles before co-registration, there are still obvious offsets between the profiles, as shown in Fig. 14(b), (d), (f) and (h).

The absolute elevation differences of the profiles were calculated and the statistics are given in Table 6. The results show that there are about 56 m offset between the SELENE and LRO DTMs in the horizontal direction, and the elevations of the two datasets are fairly consistent in the study area. The rotation deviations and scale differences between the two datasets are all very small.

Fig. 15 shows the profiles for the same four reference lines illustrated in Fig. 13, including profiles derived from the LRO DTM, the original SELENE DTM, and the SELENE DTM after multi-feature-based co-registration. Table 8 lists the statistics of the absolute elevation differences of these profiles.

As mentioned previously, one of the benefits of multiple DTM co-registration is the full synergistic use of multiple datasets and generation of consistent and better lunar topographic products. After the SELENE and Chang'E-1 DTMs were co-registered to the LRO DTM using the multi-feature-based method, the derived transformation parameters were used to bring the SELENE LALT and Chang'E-1 LAM datasets into alignment with the LRO LOLA. The DTMs with 0.01° grid spacing resolutions (about 300 m in latitude and 200 m in longitude) were generated using all of the laser altimeter points at the Apollo 15 landing area and the Sinus Iridum area. Fig. 16 shows a side-by-side visualization of the original DTMs derived from the LRO LOLA data and the new DTMs, indicating that the latter provides finer and more detailed topographic information. The yellow boxes marked in Fig. 16(b) and (d) show obvious examples.

Table 6
Statistics of the absolute elevation differences between the profiles derived from the Chang'E-1 and SELENE DTMs in the Sinus Iridum area.

<table>
<thead>
<tr>
<th>Reference line</th>
<th>Average (m)</th>
<th>Maximum (m)</th>
<th>Minimum (m)</th>
<th>Standard deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference line 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (original)</td>
<td>176.80</td>
<td>734.17</td>
<td>1.41</td>
<td>233.35</td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (multi-feature-based method)</td>
<td>15.18</td>
<td>521.28</td>
<td>0.07</td>
<td>124.74</td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (point-based method)</td>
<td>34.97</td>
<td>724.29</td>
<td>0.30</td>
<td>114.96</td>
</tr>
<tr>
<td>Reference line 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (original)</td>
<td>154.78</td>
<td>520.44</td>
<td>2.02</td>
<td>74.17</td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (multi-feature-based method)</td>
<td>15.72</td>
<td>276.47</td>
<td>0.91</td>
<td>68.16</td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (point-based method)</td>
<td>39.76</td>
<td>256.97</td>
<td>0.24</td>
<td>49.38</td>
</tr>
<tr>
<td>Reference line 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (original)</td>
<td>192.86</td>
<td>1244.5</td>
<td>0.60</td>
<td>300.26</td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (multi-feature-based method)</td>
<td>29.76</td>
<td>1118.9</td>
<td>0.50</td>
<td>230.40</td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (point-based method)</td>
<td>73.11</td>
<td>1152.70</td>
<td>0.70</td>
<td>253.05</td>
</tr>
<tr>
<td>Reference line 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (original)</td>
<td>149.55</td>
<td>607.50</td>
<td>0.80</td>
<td>123.97</td>
</tr>
<tr>
<td>SELENE profile–Chang'E-1 profile (multi-feature-based method)</td>
<td>17.78</td>
<td>402.80</td>
<td>0.00</td>
<td>9.48</td>
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<tr>
<td>SELENE profile–Chang'E-1 profile (point-based method)</td>
<td>61.28</td>
<td>664.10</td>
<td>0.20</td>
<td>74.34</td>
</tr>
</tbody>
</table>

Table 7
Transformation parameters between the SELENE and LRO DTMs in the Sinus Iridum area.

<table>
<thead>
<tr>
<th>Transformation parameters</th>
<th>Multi-feature-based method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>0.9989</td>
</tr>
<tr>
<td>ΔX (longitude)</td>
<td>–22.87 m</td>
</tr>
<tr>
<td>ΔY (latitude)</td>
<td>51.42 m</td>
</tr>
<tr>
<td>ΔZ (altitude)</td>
<td>7.74 m</td>
</tr>
<tr>
<td>Δφ (roll)</td>
<td>–0.0003</td>
</tr>
<tr>
<td>Δθ (pitch)</td>
<td>0.000008</td>
</tr>
<tr>
<td>Δκ (yaw)</td>
<td>0.00014</td>
</tr>
</tbody>
</table>

4.2.2. Co-registration of SELENE and LRO DTMs in the Sinus Iridum area

Similar processes were performed to co-register the DTM derived from the SELENE LALT data with the DTM derived from the LRO LOLA data in the Sinus Iridum area. Table 7 lists the seven transformation parameters of the SELENE and LRO DTMs obtained using the multi-feature-based co-registration method. The results show that there are about 56 m offset between the SELENE and LRO DTMs in the horizontal direction, and the elevations of the two datasets are fairly consistent in the study area. The rotation deviations and scale differences between the two datasets are all very small.

5. Conclusions and discussion

This study presents a multi-feature-based surface matching method and applies it to the co-registration of multiple lunar DTMs derived from Chang'E-1, SELENE, and LRO laser altimeter data. The experimental analysis that used the datasets in the
Apollo 15 landing area and the Sinus Iridum area leads to the following conclusions.

(1) In the Apollo 15 landing area, the LRO LOLA data are about 218 m higher than the Chang‘E-1 LAM data, and there are about 25 m offset between the two datasets in the horizontal direction. For the SELENE LALT and LRO LOLA datasets, the SELENE data are generally about 164 m higher than the LRO data, and there are about 40 m offset between them in the horizontal direction. In the Sinus Iridum area, the SELENE LALT data are about 230 m higher than the Chang‘E-1 LAM data, and there are about 470 m offset between them in the horizontal direction. There are about 56 m offset between the SELENE LALT and LRO LOLA datasets in the horizontal direction, and their elevations are fairly consistent in the study area.

(2) The multi-feature-based surface matching method is able to effectively co-register multiple lunar DTMs. After applying the co-registration method to the multiple DTMs, the differences among them could be significantly reduced in both the Apollo 15 landing area and the Sinus Iridum area. The multi-feature-based surface matching method performed much better than the point-based method. The multi-feature-based surface matching method developed in this study was able to effectively co-register multiple lunar DTMs derived from the data from different sensors in different missions to produce consistent and precise lunar topographic models. It could also be used to co-register other similar datasets. For example, it could be used to align LiDAR datasets and remove the offsets usually seen in adjacent LiDAR flight lines. It should be noted that the matching of feature points, lines, and surface patches must be done interactively in the current method. Future studies should...
Fig. 16. Side by side visualization of the DTM results. (a) The original LOLA DTM in the Apollo 15 landing area, (b) the DTM derived by using all the aligned laser altimeter points in the Apollo 15 landing area, (c) the original LOLA DTM in the Sinus Iridum area, and (d) the DTM derived by using all the aligned laser altimeter points in the Sinus Iridum area. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

examine the automatic matching of these features so that the surface matching method can be fully automatic.

Acknowledgments

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