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Laser altimetry data of Chang'E-1 and the global lunar DEM model

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The Laser AltiMeter (LAM), as one of the main payloads of Chang'E-1 probe, is used to measure the topography of the lunar surface. It performed the first measurement at 02:22 on November 28th, 2007. Up to December 4th 2008, the total number of measurements was approximately 9.12 million, covering the whole surface of the Moon. Using the LAM data, we constructed a global lunar Digtal Elevation Model (DEM) with 3 km spatial resolution. The model shows pronounced morphological characteristics, legible and vivid details of the lunar surface. The plane positioning accuracy of the DEM is 445 m (1σ), and the vertical accuracy is 60 m (1σ). From this DEM model, we measured the full range of the altitude difference on the lunar surface, which is about 19.807 km. The highest point is 10.629 km high, on a peak between crater Korolev and crater Dirichlet-Jackson at (158.656°W, 5.441°N) and the lowest point is −9.178 km in height, inside crater Antoniadi (172.413°W, 70.368°S) in the South Pole-Aitken Basin. By comparison, the DEM model of Chang'E-1 is better than the USA ULCN2005 in accuracy and resolution and is probably identical to the DEM of Japan SELENE, but the DEM of Chang'E-1 reveals a new lowest point, clearly lower than that of SELENE.

Chang'E-1, laser altimetry, lunar DEM, topographic tops of the Moon

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Chang'E-1 probe (CE-1) is the first lunar probe launched by China. At 18:05 on October 24th, 2007, Long March 3A carrier rocket successfully launched CE-1 into space, which served as a prelude to China's deep-space exploration. After six days' flight in phase meridian orbit around the Earth, CE-1 entered the lunar-bound orbit on October 31st, and was captured by the gravitational field on November 5th, thus entering the lunar orbit successfully. At 16:49 on November 20th, 2007, three line CCD stereoscopes on CE-1 began to work and obtained the first image of the Moon surface by China. At 02:22 on November 28th, Laser AltiMeter (LAM) began to work and obtained the first altimetry data from CE-1 to the Moon surface. Up to October 24th, 2008, CE-1 successfully carried out its designated tasks for the year in orbit; CCD stereoscope, LAM, and other scientific instruments had obtained a large amount of valuable science data and accomplished various tasks of scientific exploration. On March 1st, 2009, CE-1 was

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*Corresponding author (email: licl@nao.cas.cn) guided to crash the pre-designed regions of the Mare Fecunditatis of the Moon, thus successfully finishing China's first lunar orbiting project [1].

Here we analyze the data obtaining, processing, and preliminary exploration achievements of CE-1 LAM.

1 LAM and its data characteristics

Laser altimeter is an apparatus that calculates the distance from the reflector through the time difference of laser shot and succeeding reflection. CE-1 LAM is developed by Shanghai Institute of Technical Physics and is used to obtain the data of distance from CE-1 to the Moon surface, carry out the topographic mapping of the Moon surface, and aid the CCD stereoscope to draw the tridimensional image of the Moon surface.

CE-1 LAM consists of probe and electric cabinet. The probe consists mainly of laser emitter, receiving telescope, and laser exploration circuit. Among them, laser emitter emits narrow pulse laser beams to the Moon surface and the receiving telescope receives laser signals of back scattering of the Moon surface. Electric cabinet mainly includes such modules as center control circuit, distance measuring circuit, and laser control circuit, which are used to collect and store the exploration data (Figure 1). In Table 1, the main technical and performance parameters are listed.

Table 1 Main technical and performance parameters of LAM

Parameter	Numerical value
Distance measuring scope (km)	200±25
Size of footprint on the Moon surface	$<\phi 200$ m
Laser wave-length (nm)	1064
Laser energy (mJ)	150
Pulse width (ns)	5–7
Angle of laser divergence (mrad)	0.6
Laser repetition rate (Hz)	1
Caliber of receiving telescope (mm)	140
Caliber of emitting telescope (mm)	40
Telescope focal length (mm)	538
Distance resolution (m)	1
Distance measuring precision (m)	5

Based on the working principles of LAM, in the orbit of CE-1, the laser emitter emits narrow pulse laser beams to the Moon surface, the laser beams are reflected back to CE-1 when encountering the solid surface of the Moon, and the receiving telescope then receives the laser signals of the back scattering of the lunar surface. The distance from the orbiter to the lunar surface [2] can be calculated by measuring the time delay between emitting and reflecting laser pulses:

$$R = \frac{1}{2} c \times \Delta t, \tag{1}$$

here R is the distance from the orbiter to the laser reflection point of the Moon surface (sub-stellar point), Δt is the time difference between the laser signal emitting and reflection, and c is the light speed.

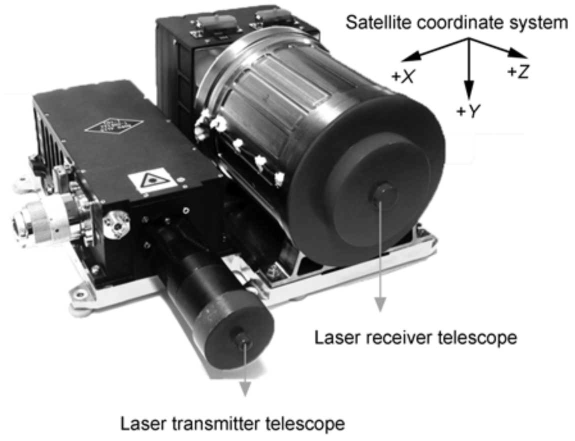

Figure 1 Schematic view of the external form of LAM.

Since there is a certain divergence angle of laser, light spot irradiated to the rugged Moon surface is actually a round curved surface. Angle of divergence of CE-1 LAM is 0.6 mrad, altitude of CE-1 is about 200 km, parameter of the laser footprint points is about 200 m, and therefore, every laser altimetry data actually represents the average altitude of the round region of the 200 m parameter of the lunar surface.

2 Time and spatial characteristics of CE-1 laser altimeter data

Laser altimeter is a main, effective payload on CE-1, and is used to measure the altitude of the whole Moon surface and aid CCD stereoscope to produce the tridimensional image of the Moon surface. LAM was first switched on at 02:22 on November 28th, 2007, and successfully obtained the altimetry data of the first orbit. Thanks to the overall arrangements of the flight track attitude and the technical experiment, the laser altimeter has not been continuously obtaining the altimetry data during more than one year working on orbit, but has carried out its work phase by phase. Up to December 4th, 2008, LAM has obtained data of over 1000 orbits, altogether 9.12 million original altimetry data covering the entire lunar surface. Laser footprint points of CE-1 are a series of scattered points arranged in chronological order in the direction of sub-stellar points on the lunar surface. Since CE-1 probe applies to the polar circular orbit, the orbit dip angle during the whole exploration period is 88.2°, the orbit retrace cycle is 2 [3], the track of sub-stellar points is basically parallel with the longitude in the middle and low latitudes, and the cross points are dense in the high latitude. The orbit altitude of CE-1 is about 200 km, and the altimetry frequency of LAM is 1 Hz. Therefore, the spacing of the laser altimetry data in the direction of the track of subs-stellar points (approximately the longitude direction) is about 1.4 km, while the spacing near the equator in the direction of the vertical track (approximately the latitude direction) is about 17.8 km (the sub-stellar point spacing of CE-1 is about 35.5 km and the orbit retrace cycle is 2). This data spacing decreases with the increase of latitude: it is about 3 km (in the latitude direction) near the south latitude and north latitude 60° and reaches 900 m (in the latitude direction) near south latitude and north latitude 80°.

In order to calculate the lunar surface coverage of the LAM data, we divide the lunar surface into regular grids with equal spacing, and calculate the 9.12 million LAM data covering the entire lunar surface.

Figure 2(a) is the spatial coverage of original LAM altimetry data of the whole moon surface under the grid of 3 km. It shows the data coverage can reach to 51.6% of the

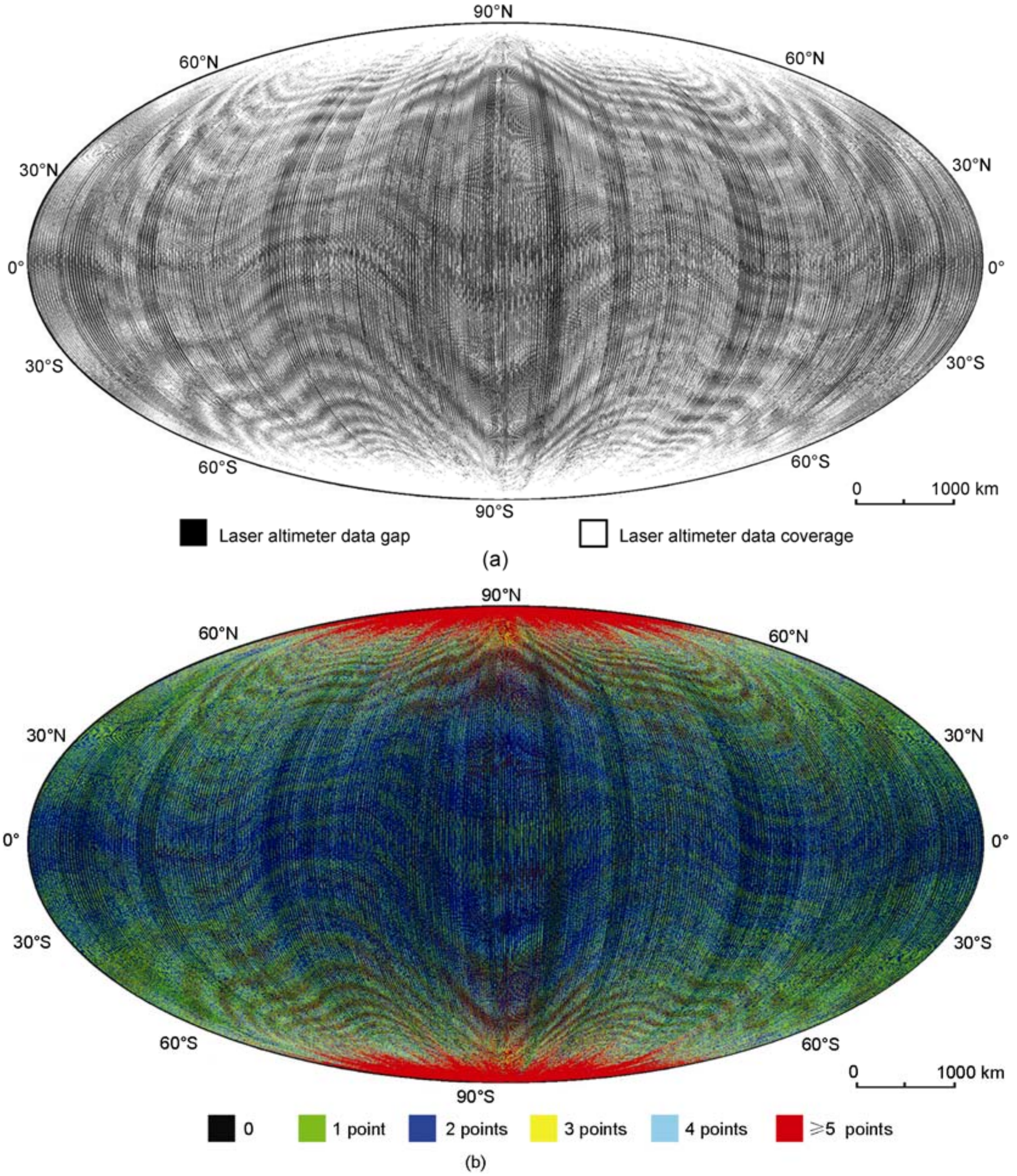

Figure 2 The spatial coverage analysis of LAM altimetry data under the grid of 3 km. This figure covers the global lunar range from 180°W to 180°E and from 90°S to 90°N, a total of 9.12 million original data. The projection adopts the Mollweide homalographic pseudocylindrical mode, and the central longitude is 270°W. (a) The distribution of spatial coverage: the black points represent the lunar surface region not covered by the original data, accounting for about 48.4%, while the white points represent the region with data coverage, accounting for about 51.6%. (b) The density distribution of the original altimetry data (amount) within the area of 3 km×3 km. The black color represents the absence of calculation data, accounting for about 48.4%; the green color represents presence of one set of calculation data, accounting for about 11.9%; the blue represents presence of two sets of calculation data, accounting for about 19.4%; the yellow represents three sets of calculation data, accounting for about 7.5%; the cyan represents four sets of calculation data, accounting for 6.2%; while the red represents five or more sets of calculation data, accounting for about 6.6%.

whole moon surface. From the distribution of the coverage density, we can see the density of data coverage is comparatively low in the low latitudes, and increases with the increase of latitude, and reaches the maximum in the two polar regions, which is determined by the CE-1 polar trajectory. Figure 2(b) is the density distribution resembling sinusoid in waveform stripes, and is caused by the distributing pattern of the CE-1 trajectory ascending node on the moon surface, while the density of the altimetry data is relatively high around the node of upward and downward trajectories. Additionally, there are some black banding stripes along the longitude in Figure 2 due to the discontinuity of the flight control and data sampling.

To further analyze the real coverage of the altimetry data and by considering the spacing of the laser footprint points is 1.4 km along the track of the sub-satellite points, we adopt 1.5 km×1.5 km grid (in the condition of continuous data, there is at least one altimetry data in every grid of the track of sub-satellite points) to analyze the coverage spacing changed with the latitudes as Figure 3 shows the results. The data spacing becomes less with the increase of the latitudes: in the equator, the uncovering spacing is 1.5 km at minimum and 24.0 km at maximum, and the average data is 5.2 km; in the polar regions, the minimum spacing is 130 m and the maximum is 2.2 km, and the average is 437 m; the maximum spacing of the whole moon surface is 34.4 km at 4.45°N and the minimum is 130 m at 85.00°S.

Figure 3 shows that the percentage of the same data spacing also increases with the latitude. The percentage of the data spacing less than 1.5 and 3 km reach 50% at 64.96°S/63.58°N and 59.87°S/54.08°N, respectively. Afterwards they increase distinctively with the latitudes; the percentages of all data spacing less than 4.5 km exceed 50% at all latitudes.

3 Data processing of LAM

After measuring the emitting and receiving time in the satellite orbit, LAM switches the data to the distance values, so the original data of LAM is the distance value of the satellite relative to the solid moon surface. However, if we want the original measuring data to have "altitude" significance, a series of data processing is needed, mainly including eliminating invalid data, systematic correction, geometrical positioning, and altitude calculating.

(1) Eliminating invalid and redundant data. According to the orbit design and real orbit measuring data, the height of the CE-1 orbit ranges 200±25 km and the topographic relief on the lunar surface is 20 km, so the reasonable measuring values of LAM should also be within this range. Some altimetry values exceed this range because of the abnormal signals, moon surface noises, uneven topography, and low signal-to-noise ratio etc. We consider these values irrational numbers that need to be eliminated. Besides, to test the correctness of the altimetry data, LAM carries out three samplings for every laser altimetry (every laser emitting and receiving); thus two redundant values should be eliminated for every measurement.

(2) Systematic correction. Before the launch of CE-1, LAM ground verification testing determined the systematic correction parameter of the altimetry data (quantization error caused by crystal oscillating) and the systematic correction parameter (systematic errors caused by electronic system delay). These correction parameters are needed to systematically correct the original altimetry values.

(3) Geometrical positioning and altitude calculation of LAM data. LAM altimetry data is a data point with spatial significance. Its spatial position should be calculated by constructing the observation equation [4] with the parameters of the instrument, satellite, and selenodesy systems. Parameters related to LAM data spatial positioning mainly include satellite orbit data, satellite attitude parameters, equipment geometric parameters, equipment installation data, and moon rotating and pointing parameters at the moment of acquiring the data. CE-1 orbit data adopts geocenter J2000 system; the attitude data is the orbital coordinate system; the geometric parameter of the altimeter installation

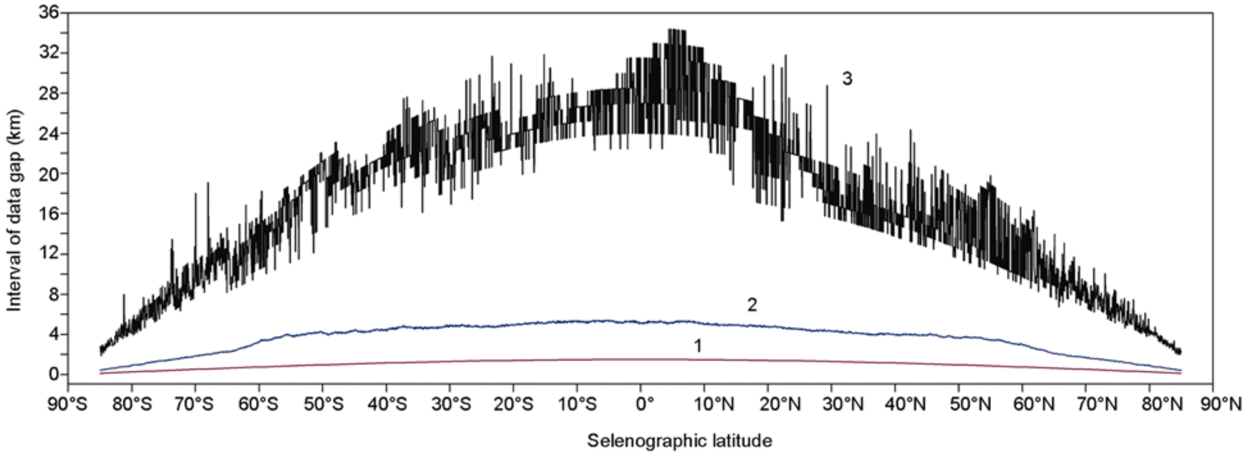

Figure 3 The LAM data spatial spacing of CE-1 on the whole Moon surface varies with the latitudes under 1.5 km×1.5 km grid. Line 1 represents the minimum value, line 2 the average value, and line 3 the maximum value.

adopts the coordinate system of the satellite. The measuring values of all coordinate systems are converted to the moon-fixed coordinate system, and the spatial positions of the laser footprint points are calculated. And then we convert the data of the moon surface footprint points from the moon-fixed coordinate system to the geodetic coordinate system. Finally we can obtain the moon surface geographic coordinate system and the altitude values of the LAM data. According to IAU/IAG suggestions, the selenodesy system uses the spherical moon-fixed coordinate system; the reference ellipsoid is spheroid with 1737400 m semi-diameter and the meridional in the center of vision (central bay) on the front moon surface; the definition of latitude and longitude is identical to that of the Earth [5]. By now, CE-1 laser altimetry data has already been converted from the original altimetry data to the longitude and latitude values of the moon-fixed coordinate system and the altitude value relative to the 1737400 m front moon surface.

4 Accuracy analysis of LAM data

From the observation equation of LAM data, the main factors influencing the moon surface coordinate system of the laser footprint points and the accuracy of altitude value mainly include the accuracy of the distance from the satellite to the footprint points (equipment altimetry value), the accuracy of satellite vector (orbit measuring values), and the measuring accuracy of the equipment observation direction (determined by the attitude measuring values and equipment installation parameters etc.). Besides, the noise of the equipment system and topographic relief on the moon surface can also cause certain effects on the laser altimetry data. Table 2 shows the various error sources and error magnitude of the CE-1 altimetry data calculated according to CE-1 and the measurement and control data.

Table 2 shows that the measurement accuracy of satellite orbit and attitude is the main factor that influences the accuracy of LAM. According to the law of error propagation, the final calculating errors of CE-1 laser altimetry data are as follows.

When the TT & C data was enough, the altitude error of LAM is 21 m (1σ) and plane position error is 224 m (1σ).

When the TT & C data was ineffective, the altitude error of LAM is 60 m (1σ) and plane surface position error is 445 m (1σ).

Since most of the LAM data is obtained during the orbital arc of the ineffective TT & C data, we choose the accuracy under such circumstance for the CE-1 LAM data error, that is, the altitude error is 60 m (1σ) and plane position error is 445 m (1σ).

5 Global lunar DEM processing and topographic mapping

The main DEM models consist of regular grid model, irregular triangular model, and contour line model. Other models, such as sectional model, scattering model, and hybrid model [6, 7] are rarely adopted. Moon surface digital altitude model (DEM) is a digital modeling process of the lunar topography. We choose the 9.12 million LAM data obtained from November 28th, 2007 to December 4th, 2008 and make the global lunar DEM by adopting the regular grid model. The global lunar DEM data processing experience mainly three steps: data filtering, spatial resolution analysis, and interpolation and mapping.

5.1 LAM altitude data filtering

Because of the errors in the measurements of the equipment system noise, topographic relief on moon surface, satellite orbit and attitude and so on, the original LAM altimetry data inevitably contains errors. From the original data to DEM processing data, the errors are propagated and magnified, resulted in the obvious altitude singular point in the altimetry data and even severe distortion [8].

According to the error characteristics, the original altimetry data errors can be divided into accidental error (random noise), systematic error, and gross error (mistakes). The systematic errors, related to the LAM hardware, have regular effects on the altimetry results, and are corrected by the systematic correction during data preprocessing phase.

Table 2 Error analysis of LAM measurement of the Moon surface altimetry

Error source	Measurement equipment	Measurement accuracy	Error calculation result	
			Selenocentric (altitude) direction	Plane surface
Orbit measurement error	USB & VLBI joint survey	Data with segmental arc observation	20 (1σ)	179.6 (1σ)
		Data without segmental arc observation	60 (1σ)	424 (1σ)
Attitude measurement error	Star sensor	Orbital coordinate system, better than 0.15° (3σ)	<1	129 (1σ)
Time measurement error	Clock of the satellite	5 ms	1 (1σ)	8 (1σ)
Measurement error of equipment installation	Optical collimator	Installation error 20″ (3σ)	<1 (1σ)	14 (1σ)
Equipment altimetry error	LAM	5 m (1σ)	5 (1σ)	1 (1σ)

Gross error is the wrong output caused by abnormal working state of the equipment, and has already been eliminated as invalid data during the preprocessing of LAM data. The existence of gross error is the reason of severe distortion in DEM topography reconstruction. Random error, caused by random factors of lunar topographic relief and unstable satellite platform during data collection, has no regular effects on the observation results. The altimetry data with random errors can be processed by filtering.

The effect of altitude data filtering has a direct relation with the degree of topographic relief. The moon surface can be divided into two main geographic units [9]: lunar mare and lunar terra (also called lunar highlands). The density of craters in lunar mare area is relatively low. The topography is, on the whole, with little change. The craters in lunar terra region are relatively high in density and big in topographic change especially on the boundary of lunar mare and terra and on the edge of big craters with great topographic relief. In order to effectively filter the singular point data in the altitude scattering points, we divide the whole moon surface into four regions: South Pole (60°–90°S), North Pole (60°–90°N), lunar mare at medium latitudes (70°–70°N, 95°–95°E), and lunar terra at medium latitudes (70°–70°N, 180°–85°W, 85°–180°E) by using different altitude threshold values to filter.

The filtering is accomplished by two processes: single track filtering and region filtering. Single track filtering adopts geoscience statistical method [10]: counting point by point the altitude difference and standard difference between altitude points and the data points forward and backward.

$$\bar{h} = \frac{1}{N}\sum_{i=1}^{N} h_i, \tag{3}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(h_i - \bar{h})^2}{N-1}}, \tag{4}$$

where $\bar{h}$ is the average value of altitude, σ is the standard difference, N is the number of altitude points in the set of points (N=5), and h_i is the altitude value of the moon surface. If the footprint point can meet the condition of the following eq. (5), this point will be eliminated as a singular point.

$$\left|h_i - \bar{h}\right| > M\sigma, \tag{5}$$

where M is the setup parameter of altitude threshold value. According to the filtering efficiency determined by the lab results, M=2 in lunar mare region and M=4 in the highlands.

After the single track is filtered, the altitude data is merged with altitude scattering data. And then the region filtering is conducted. The region filtering is accomplished in two steps by adopting the moving curved surface fitting method [11]. First, by adopting the least squares fitting method, take the DEM grid point as the center and use the altitude points setting within a certain semi-diameter to determine the minimum least squares surface, that is, the initial fitting surface, to calculate the fitting altitude value of every point and the altitude standard difference of the initial fitting surface. Judge whether the difference between every altitude value and fitting altitude value can meet the requirement of the threshold value in order to eliminate the altitude singular point. And then determine the least squares surface of second degree that has already been elimination processed through the least squares principle, and calculate the altitude standard difference of the fitting curved surface. If the difference between the altitude value of certain point and the fitting altitude value exceeds the given threshold value, this point should be eliminated. The setup of altitude threshold value is consistent with the single track filtering principle, that is, twice of the altitude standard differences is taken as the threshold value in the lunar mare region while 4 times of that in the lunar terra region.

The calculation formula is as follows:

$$h_i = a_0 + a_1 x_i + a_2 y_i, \tag{6}$$

$$h_i = b_0 + b_1 x_i + b_2 y_i + b_3 x_i^2 + b_4 x_i y_i + b_5 y_i^2, \tag{7}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(h_i - \hat{h}_i)^2}{N-1}}, \tag{8}$$

where h_i is the Moon surface altitude value of the altitude point in the points setting; a_0–a_2 are the coefficient values of least squares surface; b_0–b_5 are the coefficients of least squares curved surface; (x_i, y_i) is the position of altitude point; $\hat{h}_i$ is the fitting altitude value obtained from eqs. (6) or (7), and σ is the altitude standard difference. If the footprint point altitude can meet the conditions of the following formula, this point will be eliminated as a singular point.

$$\left|h_i - \hat{h}_i\right| > M\sigma. \tag{9}$$

The setup of altitude threshold value is consistent with the single track filtering principle. With reference to the filtering efficiency determined by the lab results, take twice of the altitude standard difference as the threshold value in lunar mare region and four times of that in lunar terra region.

5.2 Data interpolation

After the above filtering, the singular points of laser altimetry data are eliminated and the altitude data is ready for the interpolating and DEM mapping of the whole moon regular grid.

The algorithm concerning DEM model consists mainly of Kriging, inverse distance weighted (IDW), least curvature, irregular triangular grid [12] and so on. We conduct experiment and make comparisons on inner accuracy-compliant [13], altitude render view and topographic section of various interpolating. The result shows the inner accuracy-compliant of Kriging can attain less than 200 m, which is the best for LAM data application on CE-1. Therefore, we adopt Kriging interpolation [14] to process the global lunar LAM data.

5.3 The size of DEM grid and its accuracy analysis

To analyze the mapping capability of CE-1 laser altimetry data and determine the whole moon DEM spatial resolution, we conduct experiment on the measurement errors of altitude data and DEM accuracy with different sizes of grids. Table 3 is the probability statistics with or without measurement data and DEM accuracy errors under the whole Moon surface in different grid sizes. It shows that the probability of real measurement data in grid is more than 50% if the grid size is over 3 km, and the DEM altitude error is better than 58.6 m (1σ) and less than the real altitude measurement error 60 m (1σ) on altimeter, so taking the grid size of 3 km to conduct the whole moon DEM mapping can satisfy the error of altitude measurement.

To test the effects of data coverage rate on DEM spatial resolution [15], we analyze the relativity of altitude values and value errors under data coverage rate 30%, 50%, and 100% respectively in three lab regions: high latitude region in the south hemisphere, equator region and high latitude region in the north hemisphere. The results from the three lab regions are identical. Figure 4 shows the lab results around the equator region.

Table 3 Coverage statistics of real LAM data points under different grid sizes of the whole moon surface

	8 km grid	7 km grid	6 km grid	5 km grid	4 km grid	3 km grid	2 km grid
Altimetry data coverage (%)	90.3	86.3	81.0	73.6	64.1	51.6	34.0
DEM altitude error (1σ) (m)	35.2	40.3	42.1	48.3	55.3	58.6	234.2

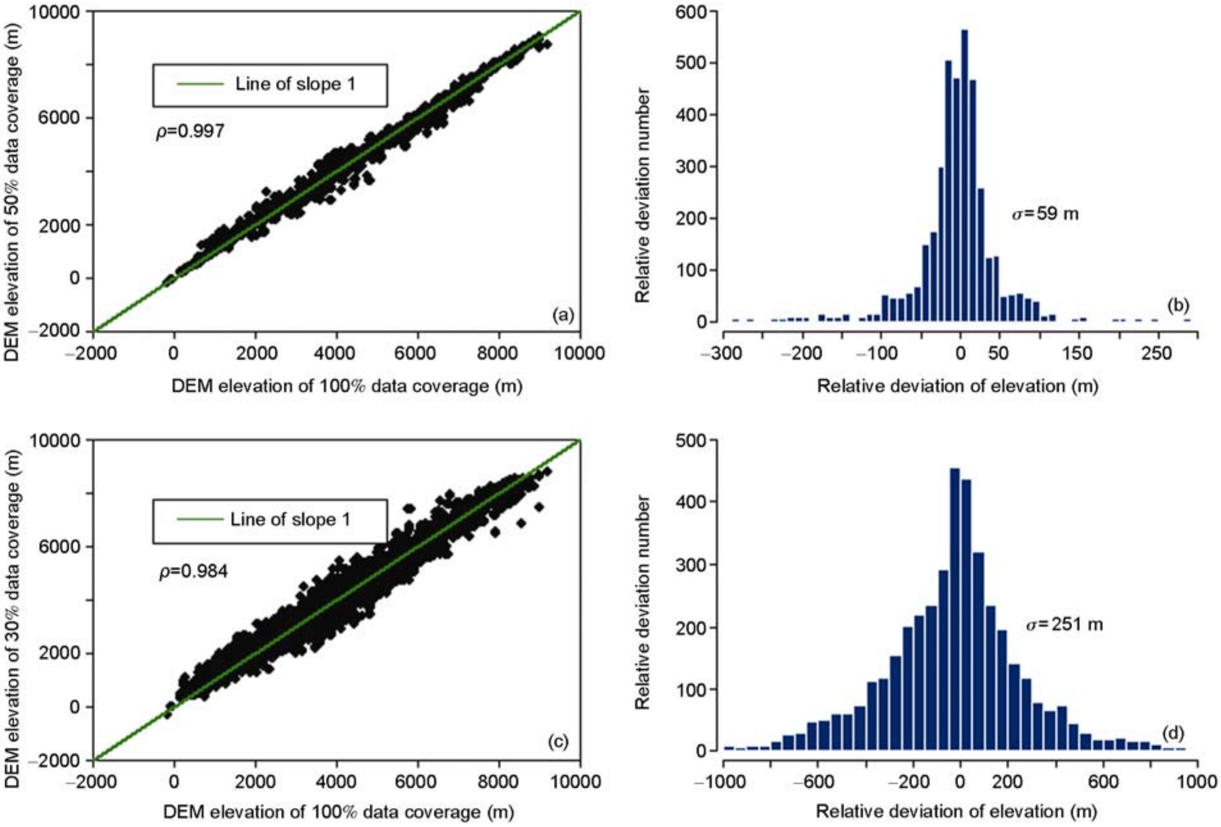

Figure 4 Analysis of altitude measurement results of lunar DEM model (3 km grid) under various altimetry data coverage rate. The longitudinal coordinates are the altitude values of all grids on DEM model made at certain coverage rate, while the horizontal coordinates are the altitude values of all grids on DEM model made at 100% coverage rate. The analytic region of this figure is located around 178.5°E and 157.5°W and 10.5°N and 10.5°N with approximate area 367802 km^2.

The number of the original altimetry data is 49467. The figure only shows the lab results at 30%, 50%, and 100% coverage rates. Figure 4(a) and (b) shows the state at 50% coverage rate with 25567 sampling number, the correlation coefficient ρ=0.997, the altitude measurement error range −976–654 m relative to the 100% coverage rate, the arithmetic average value −10 m, and the standard difference σ=59 m. Figure 4(c) and (d) shows the state at 30% coverage rate with 16749 sampling number, the correlation coefficient ρ=0.984, the altitude measurement error range −1737–1603 m relative to the 100% coverage rate, the arithmetic average value −50 m, and standard difference σ=251 m.

Through the lab analysis of Figure 4, the altitude error caused by 30% data coverage rate reaches 251 m (1σ), which exceeds the altitude measurement error (60 m, 1σ) of LAM far more, while the altitude error caused by 50% data coverage rate is 58.6 m (1σ), less than the altitude measurement error of LAM. Therefore, when the lunar surface regional data coverage rate of laser footprint points exceeds 50%, the accuracy of DEM model can meet the lunar surface altitude measurement accuracy of LAM. Figure 2 shows that the global lunar data coverage is 51.6% under 3 km grid, so LAM data on CE-1 can be used to map the whole lunar DEM model with 3 km spatial resolution.

When mapping the global lunar DEM topography, we still adopt the strategy as we do the filtering. We divide the lunar surface into four regions according to the topographic features: South Pole (60°–90°S), North Pole (60°–90°N), lunar mare at medium latitudes (70°–70°N, 95°–95°E), and lunar terra at medium latitudes (70°–70°N, 180°–85°W, 85°–180°E) and interpolate the altitude data respectively into regular grid DEM models with 3 km spatial resolution. After inlaying the data from the four regions, we get the global lunar DEM model of 3 km spatial resolution (refer to Figure 5(a) and (b)).

5.4 Quality analysis and comparison of DEM data

To compare the DEM quality of CE-1 with that of ULCN2005 and SELENE, we make the tridimensional image (refer to Figure 6(a)–(c)) of the same region on the lunar surface and the wash-off relief map of the middle and low latitude (refer to Figure 7(a)–(c)).

The data coverage range, the coordinate systems, altitude standards and projections are completely consistent in Figures 6 and 7. Therefore, the DEM model of CE-1 shows a similar data precision and spatial resolution to the SELENE. Obviously, it is also better than the ULCN2005, which can distinguish the main topographic unit of more than 100 km, but cannot determine the details of the topography. For this reason, we consider DEM model data of LAM obtained by CE-1 and SELENE is the best in accuracy and resolution among the similar type of data.

6 Analysis and comparison of the altitude extremes on the global lunar

The DEM model of CE-1 LAM displays that the highest point, the lowest point on the lunar surface are located on the back side of the Moon. The highest point is on the peak of Crater Korolev and Dirichlet-Jackson Basin along the east edge of Engel'gardt Crater (refer to Figure 8) at (158.656°W, 5.441°N, 10.629 km). The lowest point is located on the bottom of the three craters inside Crater Antoniadi of the South Pole-Aitken Basin (refer to Figure 8) at (172.413°W, 70.368°S, −9.178 km); the second lowest point is on the bottom of crater near the southeast edge at (163.717°W, 61.009°S, −8.973 km); the third lowest point is on the bottom of Crater F of Crater Lemaître at (148.483°W, 61.543°S, −8.748 km). The maximum altitude difference of the global lunar is 19.807 km.

To test the correctness of the highest and lowest points, we re-check the DEM model and the original altimetry data together with the image data. The laser altimetry data, which is reserved efficiently during the filtering process, was obtained at 19:51.727 on December 22nd, 2007. The original altitude value of this data is 10.632 km and the corresponding position on the interpolated DEM model is 10.629 km. The altitudes of the two footprint points on the track of the same sub-stellar point observed continuously before and after this highest point are successively 10.345, 10.528, 10.597, and 10.513 km. Among another set of data measured at the closest point (about 5 km), the altitude of the footprint point of this highest point is 10.619 km. Obviously, the highest point discovered in this article is the real altimetry data of the lunar surface rather than the data singular point.

The lowest point data was obtained at 13:52:29.778 on July 15th, 2008. It is proved not to be a singular point but the real altimetry data by the same testing process as the highest point.

To further test the data correctness of the highest and lowest points, we overlay the data on the CCD image from CE-1 for inspection. They are identical with the topographic features of the lunar surface, so we conclude that the positions of the two extreme points are correct.

Up to now, only USA's Clementine, Apollo 15, Apollo 16, Apollo 17, Japan's SELENE, and China's CE-1 have conducted the laser altimetry on the lunar surface. Among them, only the laser altimetry data of SELENE and CE-1 has covered the entire lunar surface and mapped the global lunar DEM model. Archinal and his team [17] used Clementine laser altimeter and UVVIS image data to make a global DEM model, that is, ULCN2005 DEM model. Table 4 lists the altitude extreme points data obtained from

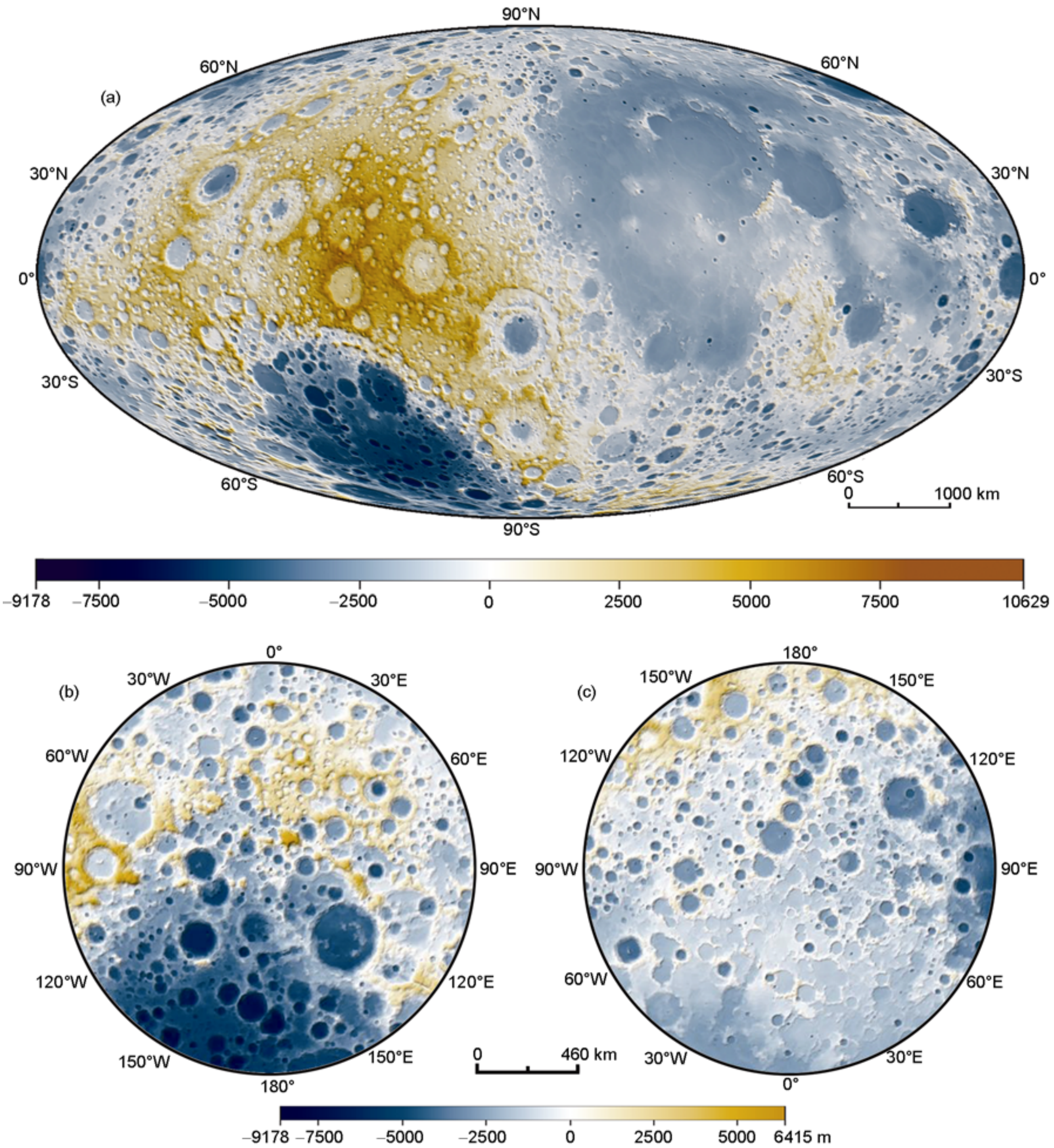

Figure 5 The global lunar DEM model mapped with CE-1 LAM data (a) the DEM model of two lunar poles mapped with LAM data on CE-1 ((b), (c)). The number of the original data obtained from November 28th, 2007 to December 4th, 2008 is approximately 9.12 million, covering 180°W–180°E and 90°S–90°N. The projection adopts the Mollweide homalographic pseudocylindrical mode, and the central meridian adopts 270°W with the left side as the back of the Moon and the right side as the front of the Moon. The coordinate system of the Moon uses that of the mean ground polar axis, and the altitude reference plane uses the front Moon surface of 1737.4 km semi-diameter with the Moon mass center as the reference origin point and with 3 km spatial resolution. The maximum altimetry difference of the global lunar is 19.807 km with its highest point at (158.656°W, 5.441°N, 10.629 km) on a peak between Crater Korolev and Crater Dirichlet-Jackson and the lowest point at (172.413°W, 70.368°S, –9.178 km) in the South Pole-Aitken Basin. Figure 5(b) is the DEM model of lunar surface around the South Polar region 60°–90°S, while the right Figure 5(c) is that around the North Polar region 60°–90°N. The projection adopts the polar sphere isometric mode with the pole as the center and latitude 70° as distortion isogam. The coordinate system of the moon, the altitude reference plane, and the reference origin point are identical with Figure 5(a) and also with spatial resolution 3 km.

DEM models. ULCN2005's global lunar DEM model is provided by ULCN2005 lunar control network (http://pubs.usgs.gov/of/2006/1367). The global lunar DEM model data of Japan SELENE has not been released, but part of it has been stated in the article by Araki et al. [16]. According to Table 4, the position and altitude data of the highest point in this article is rearly identical with that of Japan SELENE, but quite different from that of Clementine. "The highest point" in ref. [18] is close to that in this article and the SELENE's results, but "the lowest point" similar to the third lowest point in this article is not the real extreme point position. Both CE-1 and SELENE adopt 1 Hz altimetry

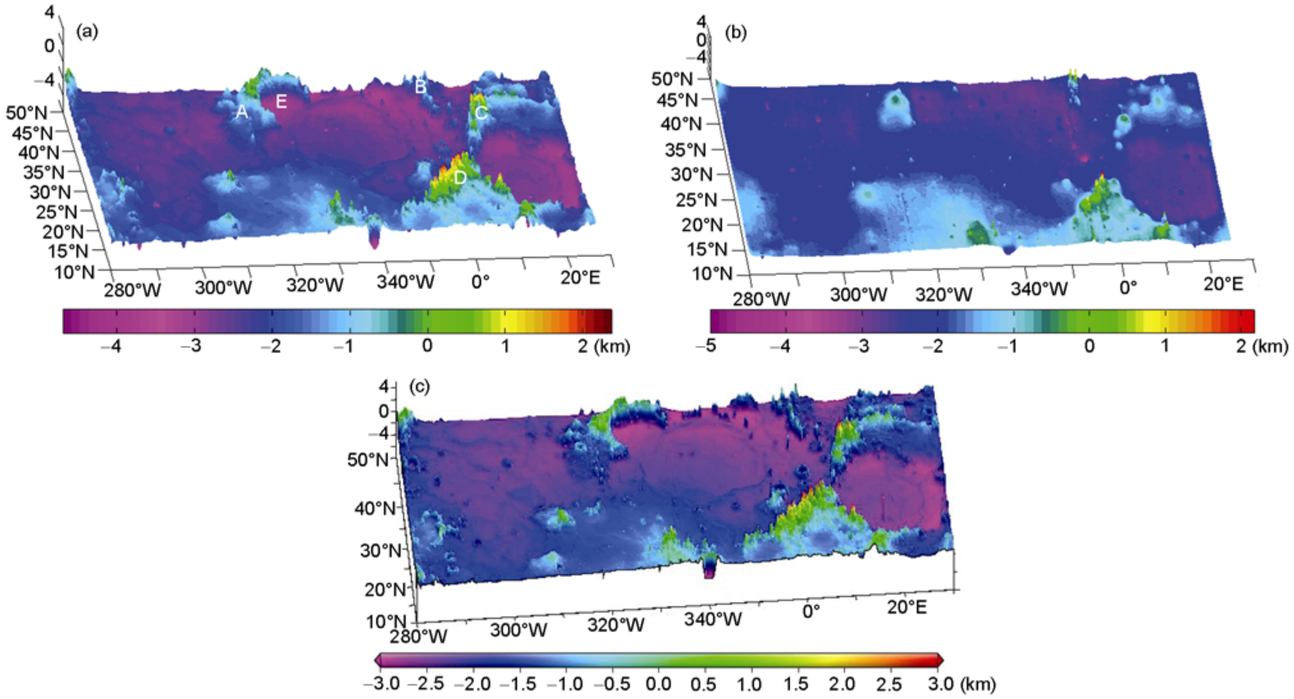

Figure 6 Tridimensional images of oceanus procellarum-mare imbrium-mare serenitatis mapped with laser altimetry DEM data respectively of CE-1, ULCN2005 and SELENE. (a) CE-1 data mapping; (b) ULCN2005 data mapping of the lunar surface control network; (c) SELENE data mapping [16]. A: Jura Maintains; B: the Alps; C: Caucasus; D: Apennines; E: Sinus Iridium.

Table 4 Comparisons of the highest and the lowest points and maximum altitude difference[a)]

Data source	Highest point of the Moon surface			Lowest point of the Moon surface			Max. altitude difference (km)
	Latitude (W)	Longitude (N)	Altitude (km)	Latitude (W)	Longitude (S)	Altitude (km)	
CE-1 (this article)	158.656°	5.441°	10.629	172.413°	70.368°	–9.178	19.807
SELENE (Japan) [16]	158.64°	5.44°	10.75	172.58°	70.43°	–9.06	19.81
CE-1 (SHAO) [18]	158.625°	5.375°	10.44	148.625°	61.375°	–8.63	19.07
ULCN2005 DEM [17]	160.656°	3.344°	7.939	169.719°	69.781°	–8.910	16.849

a) The altitude values are all referenced to spherical object with 1737.4 km semi-diameter.

frequency, and the spacing of their measuring points' orbits are very close (around 17.8 and 15 km respectively), so the coverage resolution ratios of the two altimetry data are similar, but the difference of their highest point data is 121 m and the difference of the plane position is about 484 m. Given the altimetry accuracy 60 m (1σ) of CE-1 laser altimetry data and plane position error 445 m (1σ), the altitude data difference between the two highest points of CE-1 and SELENE is equivalent to twice of the standard difference of CE-1 altitude data error and one time of the plane data error, so it is difficult to distinguish between them, or they may be the data of the same measuring point (the difference may be caused by the measuring error) or data of two very close altimetry points.

The plane position difference between the lowest points detected by CE-1 and SELENE is approximately 5.38 km, which exceeds the measuring error, so the two lowest points detected by the two models should be the measuring data from two different positions. The lowest point of CE-1 model in this article is 118 m lower than that of SELENE, and still within the standard twice of the CE-1 altitude data error, but it is most probable that the position of CE-1 laser footprint point is quite close to (or it is) the lowest position on the lunar surface.

7 Conclusions

(1) CE-1 accomplished its scientific exploration during the one year and four months detection on track. LAM obtained about 1000 multiple track data and approximately 9.12 million valid original altimetry data covering the entire lunar surface in space.

(2) The altitude measuring accuracy and the plane position accuracy of the lunar surface footprint points of CE-1 LAM are 60 m (1σ) and 445 m (1σ) respectively.

(3) Under global lunar 3 km grid, the spatial coverage ratio of CE-1 LAM altimetry data can reach 51.6%. With the DEM altimetry error less than the original data measurement error, the LAM possesses the independently made

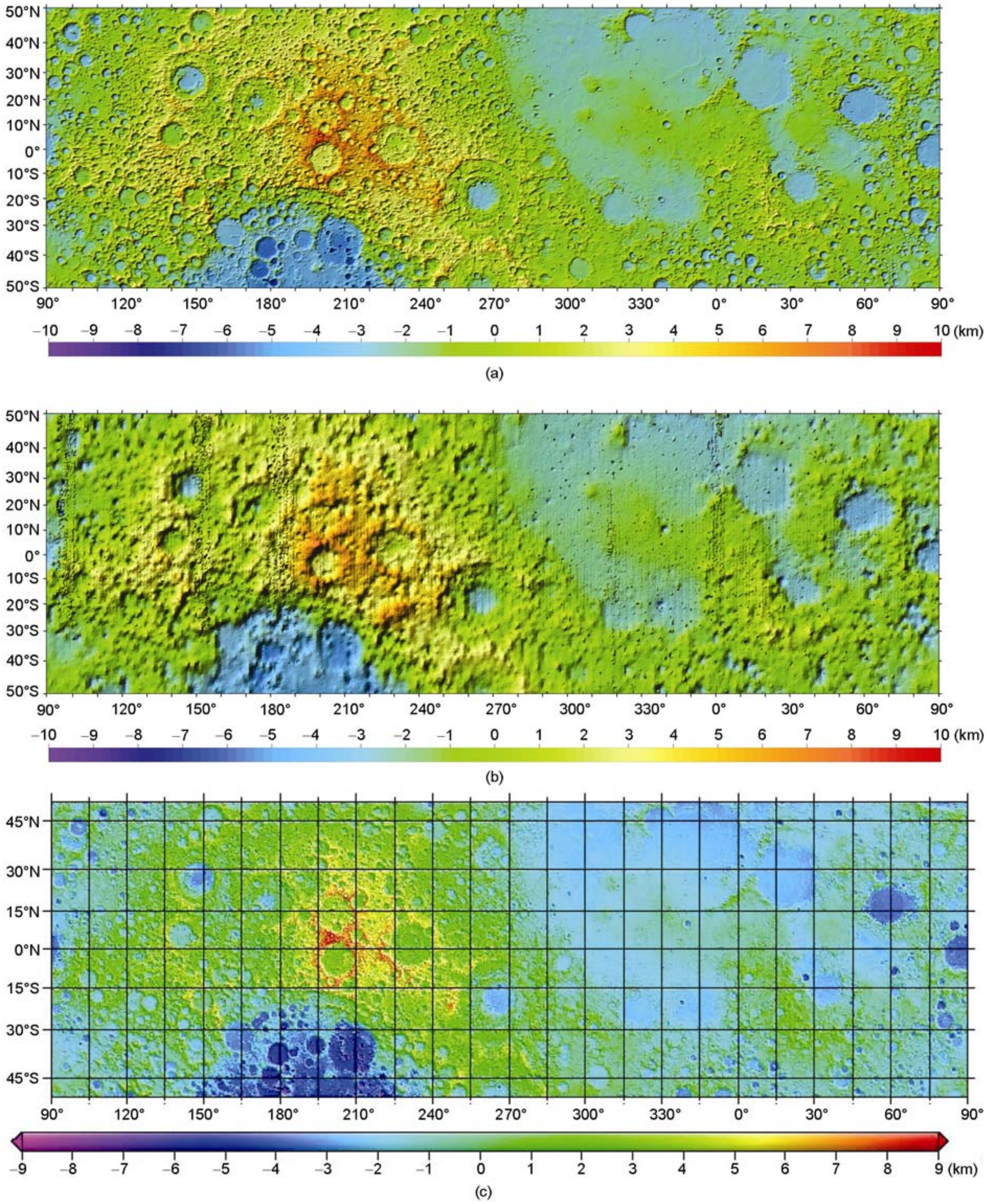

Figure 7 Comparison of wash-off relief maps in the middle and low latitude on lunar surface with laser altimetry DEM data respectively from CE-1, ULCN2005 and SELENE. (a) CE-1 data mapping; (b) ULCN2005 data mapping of moon surface control network [17]; (c) SELENE data mapping [16].

global lunar DEM model with spatial ratio of 3 km.

(4) During the data processing, the single track filtering adopts geoscience statistical method while the region filtering adopts moving curved surface filtering method, both of which effectively eliminate the random errors. The data interpolation adopts Kriging method with the inner accuracy-compliant within 200 m, effectively reserving the original altimetry value.

(5) The global lunar DEM model made by CE-1 LAM shows a vivid and legible topography of the lunar surface, identical with SELENE model, but obviously better than the DEM model of ULCN2005. The SELENE model can also

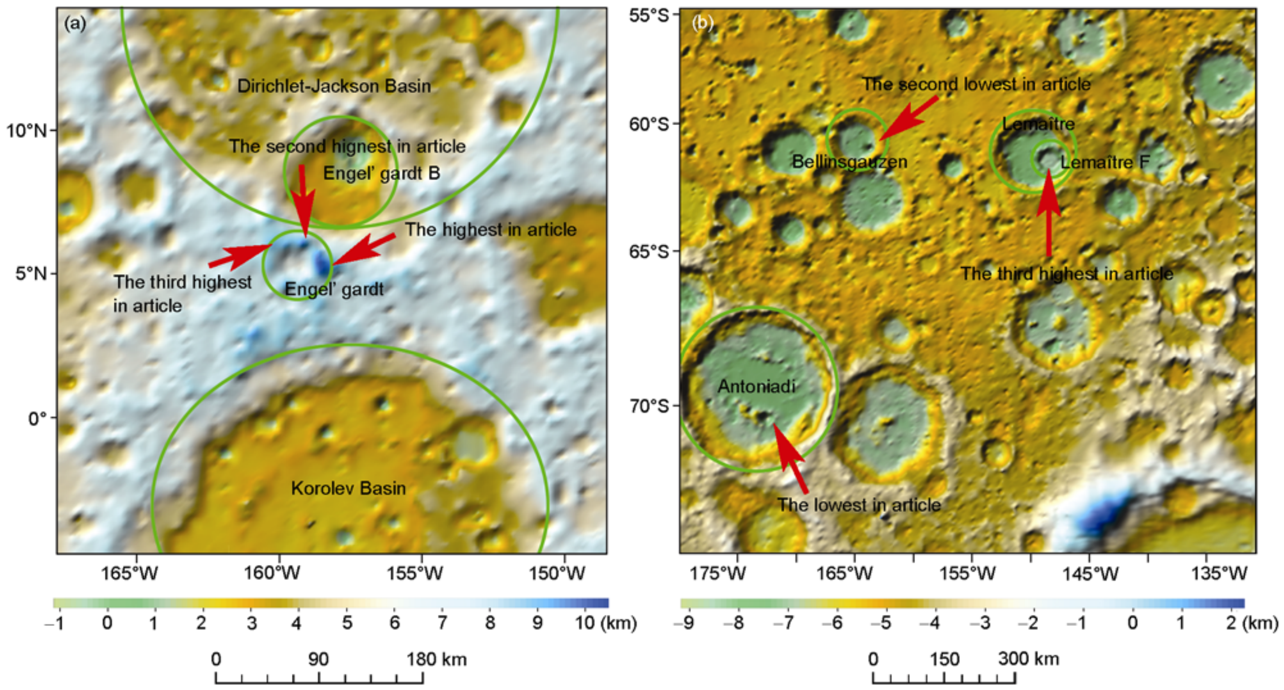

Figure 8 Topographic mapping of the highest point (a) and the lowest point (b).

show the same data with good accuracy and high resolution.

(6) The maximum altitude difference of the global lunar detected by DEM model of CE-1 LAM is 19.807 km. The highest point on moon is on the peak of Crater Korolev and Dirichlet-Jackson Basin along the east edge of Engel'gardt Crater at (158.656°W, 5.441°N, 10.629 km), and the lowest point is located in the bottom of the three craters inside Crater Antoniadi of the South Pole-Aitken Basin at (172.413°W, 70.368°S, –9.178 km), identical with the SELENE DEM results with only subtle difference about the highest point. The lowest points are similar, but the plane position difference is about 5.38 km, so they should be points in different positions.

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