

Positioning of the CE-1's impact site based on CCD image data photographed during the controlled impact on the Moon

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Up to now, many lunar explorations concluded their scientific mission through the impact on the lunar surface. The prediction and positioning of impact sites are based on the extrapolated orbiting data together with the real time orbiting data and observations from ground based telescope provided by TT & C System. As most lunar missions carried cameras onboard, a new method of positioning of CE-1 impact site is put forward. It is based on the CCD image data photographed during the controlled impact and the existing lunar terrain data. Test results from this new method also validate the published impact site position.

Chang'E-1, lunar impact, positioning

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In Xichang Satellite Launch Center at 18:05 on October 24, 2007, Chang'E-1 was successfully launched by Long March 3A Launch Vehicle, which started China's first lunar exploration project. After more than one year of operating on orbit, CE-1 performed the controlled impact on the Moon on March 1, 2009 and at 16:13 (Beijing Time) landed on the predetermined impact area of the Sea of fertility of the near side of the Moon [1].

Until now, many lunar exploration missions including Lunar Prospector, SMART-1, Chang'E-1, KAGUYA, and LCROSS have impacted the lunar surface. Their main purpose is to conduct the flight control experiment and to test whether there is water on the lunar surface and thus reduce the space debris on the moon orbit. It is a significant procedure to determine the impact site position during impacting the Moon, mainly through extrapolated orbiting data together with real time orbiting data and observations from

the ground-based telescope provided by TT & C system. Additionally, the time of the impact on the Moon is determined by the cutoff of the communication between the ground and satellite because of the broken hardware at the moment of impacting. And then the accurate impacting site is determined by combining the predicted and real time orbiting data. This is the common method of determining the impact site on the Moon by the satellite.

According to the report of European Space Agency (http://www.esa.int/esaSC/SEMWX03VRRE_index_0.html) [2], SMART-1 performed the impact on September 3, 2006, the satellite sent out its last signals to the earth at 05:42:21.759 (UTC), and the JIVE radio telescope from Hobart in Tasmania Australia measured a loss of signal at 05:42:22.394 (UTC). The actual impacting time is very similar to the SMART-1 dynamic prediction, i.e. at 05:42:20. The calculated impacting location at 46.20° West longitude and 34.4° South latitude is also very close to the infrared impact flash observed by Canada-France-Hawaii telescope (CFHT).

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According to the report of Japanese Aerospace Exploration Agency (JAXA) (http://www.kaguya.jaxa.jp/en/communication/position_e.htm), KAGUYA carried out the impact on the Moon at Japan local time 03:25 on June 11, 2009 at location 65.5° South latitude and 80.4° East longitude, just next to Gill Crater. The impact flash point on the lunar surface observed by Angola-Australia Telescope (AAT) in Australia and the infrared telescope near Mount Abu Observatory in India is in remarkable agreement with the reported time and position.

According to the report of National Aeronautics and Space Administration (NASA), LCROSS performed the impact on the Moon mission. Centaur Rocket landed on the predicted impacting point at 11:31:19 (UTC), of which the landing and impacting process was captured by the scientific apparatus on Shepherd spacecraft. And after 4 minutes at 11:35:45 (UTC), Shepherd spacecraft landed on the lunar surface through the same orbit and made the material analysis to the smoke produced by Centaur impact with the scientific apparatus onboard.

According to the report of Lunar Exploration and Aerospace Project Center (http://210.82.31.82/index.asp?modename=2009\zt_luoyue\index_zt_cely1), CE-1 carried out the mission to impact the Moon at 16:13:10 on March 1, 2009 (Beijing Time) at location 52.36° East longitude and 1.5° South latitude inside Mare Fecunditatis on the near side of the Moon. Unfortunately, however, because of the bad weather and the predicted impact site located on the lightning area, the impact flash around the impact site could not be observed on the earth ground and accordingly could not be verified through ground-based observations.

In this article, by utilizing the image data captured by CCD camera during controlled impact together with the published global lunar image data and terrain data, we measured the sizes of the impact craters on nearly 1500 km flying path and the times of flying over these craters, calculated the tangential velocity of the satellite on the lunar reference sphere under the lunar gravitation, and determined the coordinate of the impact site on the Moon.

1 Technical specifications of the camera & image data features during the impact

1.1 Main technical specifications

The optical payload onboard CE-1 is a push-broom camera with 512 pixels on every linear array and 11.89 f/s scanning velocity so that the continuous image data of the satellite at the orbit altitude of 200 km can be obtained. Refer to Table 1 for the main technical specifications of CCD camera [3].

1.2 Features of CCD image data during the impact on the Moon

According to the flight control plan, at 15:36 on March 1,

Table 1 Main technical specifications of CCD camera

Item	Index
Frame frequency (frame/s)	11.89
Spectral range (μm)	0.5–0.75
Quantitative level	8 bit
Exposure time (ms)	3.2, 7, 20, 84
Image width	60 km (@200 km orbit)
Pixel spatial resolution (Nadir point) (m)	120
Pixels on linear array	512
Pixel size	14 μm × 14 μm
Linear array	3
Intersection angle between linear (°)	16.7

2009, CE-1 began to brake and slowed down from south to north; at 15:58:08 the satellite stopped braking and began to land under the lunar gravitation to impact the lunar surface. The camera started to work at 15:58:06.858 (local time) as recorded by the timing code of image data downloaded by CE-1 and the time of the last image data is 16:13:06.463 (local time), so, during controlled impacting the Moon of CE-1, the total time of scanned imaging before impacting the surface is 14 min and 59.605 s.

Through linear array push-broom method and with fixed frame frequency (11.89 frame/s), CCD stereo camera design obtained the lunar surface images on the 200 km high orbit with 120 m spatial resolution. Such design of the CCD camera realizes the seamless and continuous coverage of the adjacent scanning lines on the lunar surface when operating on the 200 km high orbit. The visual angle, frame frequency, and pixel size of the camera cannot be changed, so the spatial resolution of the image increases when the orbit is becoming lower and the velocity of the satellite relative to the lunar surface also changes. At this moment the coverage of the adjacent two scanning lines on the lunar surface is not continuous any more along the track of the nadir points. The lower the orbit is, the higher the ground velocity of the satellite becomes. Thus, the larger the distance between the two scanning lines is, the larger the missing size of the scanning becomes.

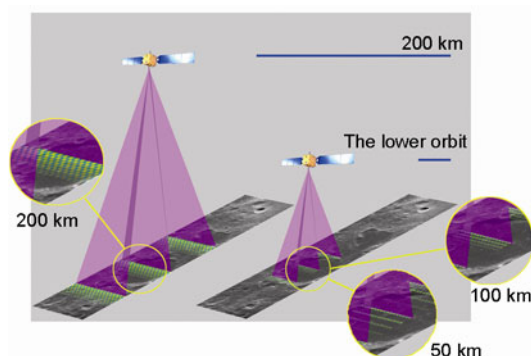
Therefore, the features of the CCD image data during impacting on the Moon are as follows (Figure 1, Table 2): (1) data in lines; (2) the adjacent lines are disconnected; the scanning coverage on the lunar surface is discontinuous, and the lower the orbit is, the larger the distance between the two scanning lines is; (3) the pixel resolution changes; and (4) the width changes.

2 Data processing method

The image data during the controlled impact on the Moon is apparently quite different from that on the 200 km high orbit. With the orbit height gets lower, the missing scanning becomes much more and image quality becomes worse, though the spatial resolution of the original image data is

Table 2 Imaging on typical height of CCD camera onboard CE-1

Orbit height (km)	Imaging width (km)	Resolution (m)	Imaging
200	60	120	Continuous imaging in lines
100	30	60	Imaging 1 line of every 2 lines
50	15	30	Imaging 1 line of every 4 lines
20	6	12	Imaging 1 line of every 10 lines

**Figure 1** Linear array scanning of CCD stereo camera onboard CE-1.

higher. The lunar surface texture is very difficult to distinguish when the satellite is getting close to the lunar surface.

In order to improve the image quality, the image data should be processed with radiometric and geometric corrections and especially the missing scanning areas of the lunar surface should be pieced out to regain the lunar surface texture. During the controlled impacting and landing on the Moon with the orbit height getting lower, the processing method of obtaining the image data is very similar to that on the 200 km high orbit but special requirements are also needed. Data processing methods mainly include radiometric correction, photometric correction, line piecing-out, geometric correction, etc. After processing the image data of impact on the Moon together with the published global lunar image data and DEM data [4, 5], pick out the homonymous craters and analyze the impact site of CE-1.

2.1 Image data processing

Regarding the image data obtained during the controlled impact on the Moon, the following processing has been conducted:

(1) Radiometric correction: the relative calibration coefficient obtained through ground calibration test is used for relative calibration processing for image.

(2) Photometric correction: calculate the photometric correction parameter of every linear array by utilizing the ephemeris data provided by TT & C System. Carry out photometric correction for every pixel by adopting Lommel-Seeliger model [6, 7], and then normalize the radiation values of all pixels under the same lightening condition.

(3) Line piecing-out: calculate the number of missing

lines according to the distance on the lunar surface between two adjacent scanning lines and whence the lunar surface spatial resolution. Regarding the pixel value of every missing line, calculate the gray-scale value of every pixel value of the missing lines according to the corresponding gray-scale value of adjacent lines by adopting the second Lagrange interpolation. At the same time, calculate the timing code information of every line by calculus of interpolation through the same method. The procedures mainly include distance calculation of missing scanning, spatial resolution calculation, and line piecing-out etc.

(4) Geometric correction: calculate the corresponding position of pixel on the lunar surface by use of the camera parameters, the orbit and attitude data and with consideration of the transformation among the rotation, shape and coordinate system of the Moon, to determine the relative position; and then apply the above-mentioned processed image registration to the published base map of the global lunar image data.

2.2 Longitude and latitude calculation of the impact site

2.2.1 Extract crater information

The identification and measurement of craters are the most important information that can be used to extrapolate the flying height, velocity, and nadir points of CE-1. We can extract the crater information by utilizing the image of impacting the Moon that has been imagery processed. The identified craters can be used for two purposes: the first is to calculate the velocities along the longitude and latitude on the reference sphere and the second is to determine the origin of the coordinate system of impact site.

The extraction of the crater information includes identifying the crater edges, extracting the crater diameter along the orbit direction, finding out the corresponding image data lines of the crater edge and the ends of diameter, so that the timing code information of this line obtained by satellite can be determined.

In identifying the crater edge, crater with a regular shape that can be clearly distinguished from the image of landing orbit is chosen. The excircle of this crater is considered as the edge of this crater. By adopting the DEM and image data stacking method, extract the cross section of the crater and make the crater excircle on the highest terrain of the crater edge, and then measure the diameter of this excircle along the flying direction and find out the corresponding number of the image data lines according to the intersection point of this diameter (flying direction) and the excircle (points of tangency A & B). In this way, the timing code information of this data line obtained by satellite can be concluded (Figure 2). We choose two craters (Table 3) to calculate and verify the velocity under unpowered phase during the controlled impact on the Moon of CE-1.

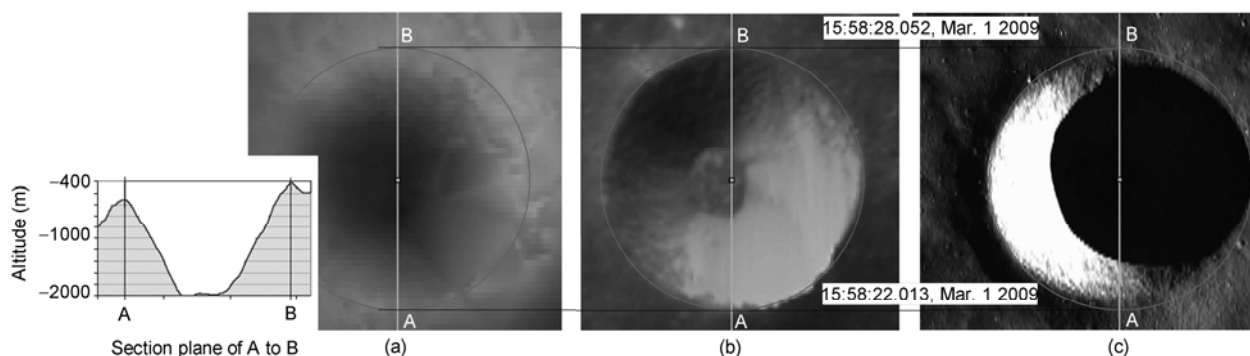


Figure 2 Extracting and measuring picture of the crater information. (a) The DEM data around the crater; (b) the image obtained on 200 km high orbit; (c) the image of impacting the Moon. A and B are lower edge and upper edge respectively.

Table 3 Crater information for velocity calculation

No.	Timing code		Name of crater	Longitude & latitude of crater center	No. of corresponding line		Diameter ^{a)} (m)
	Lower edge	Upper edge			Lower edge	Upper edge	
1	2009-03-01	2009-03-01	Watt E	55.068°E, 49.865°S	902	1261	9800
	15:58:22.013	15:58:28.052					
2	2009-03-01	2009-03-01	Rheita G	54.305°E, 40.820°S	11510	12140	14449
	16:01:11.273	16:01:20.103					

a) The diameter is the distance between the highest points of the crater intersection edge measured by DEM.

In order to calculate, locate, and track the nadir point positions during the CE-1's controlled impact on the Moon and finally determine its impact site, we compare the impacting image with the global lunar image obtained on the 200 km high orbit, find out all the identifiable homonymous craters, and extract the corresponding longitude, latitude, and timing code of the crater center. Twenty-seven homonymous craters have been identified during the controlled impact on the Moon (Table 4), and their positions and timing information are used to track the nadir point pathways of CE-1 and calculate the coordinate system of the impact site.

2.2.2 Calculation of satellite tangential velocity on reference sphere

From the two craters of the first type, we get the satellite tangential velocity on the lunar surface, make reduction to the lunar reference sphere, and resolve into the velocity respectively along the longitude and latitude directions.

(1) Calculate the satellite velocity on the real lunar surface according to the crater diameter and the time of nadir points crossing the crater, using the following formula:

$$v = \frac{D}{\Delta t}, \quad (1)$$

where D is the crater diameter along the nadir point pathway; Δt is the time of nadir points crossing the crater.

With the data shown in Table 3, the CE-1 velocities when crossing the two craters are respectively 1.6228 and

Table 4 Positions & timing code information of the homonymous craters

No. of craters	Longitude of crater center (E)	Latitude of crater center (S)	Corresponding timing code info.	Crater diameter (m)
1	53.339°	25.081°	16:06:03.345	650
2	53.386°	24.697°	16:06:10.410	836
3	53.218°	23.718°	16:06:28.835	1398
4	53.327°	23.546°	16:06:31.333	1215
5	53.180°	23.045°	16:06:40.205	1130
6	53.050°	20.608°	16:07:24.821	800
7	53.043°	19.463°	16:07:46.694	733
8	53.009°	18.973°	16:07:54.606	533
9	52.976°	18.337°	16:08:06.194	1273
10	52.976°	17.794°	16:08:16.065	1066
11	52.879°	16.554°	16:08:39.266	713
12	52.869°	15.483°	16:08:58.105	562
13	52.847°	15.419°	16:08:59.283	350
14	52.853°	14.736°	16:09:11.359	766
15	52.770°	14.201°	16:09:21.331	9000
16	52.754°	13.970°	16:09:25.489	859
17	52.741°	12.298°	16:09:56.753	899
18	52.718°	12.232°	16:09:57.025	1036
19	52.715°	12.233°	16:09:57.138	1200
20	52.720°	11.555°	16:10:09.000	2342
21	52.684°	11.281°	16:10:14.300	918
22	52.680°	11.062°	16:10:18.028	385
23	52.647°	10.641°	16:10:26.136	1334
24	52.542°	8.153°	16:11:10.168	566
25	52.504°	7.628°	16:11:20.245	1583
26	52.530°	7.453°	16:11:23.000	333
27	52.411°	6.337°	16:11:43.625	300

1.6364 km/s.

(2) With the height difference Δh between the lunar surface measured by DEM and reference sphere, we can get the velocity v reduction to the reference sphere with radius R (Figure 3), using the following formula:

$$\frac{v}{v_h} = \frac{R + \Delta h}{R}, \quad (2)$$

where v is the velocity of satellite on the real lunar surface; v_h is the velocity of satellite on the reference sphere; R is the radius of the reference sphere ($R=1737.4$ km); Δh is the height difference between the lunar surface and the reference sphere.

From the calculating results of the two craters shown in Table 3, we get the velocities of CE-1 on the reference sphere ($R=1737.4$ km) are 1.6238 and 1.6374 km/s respectively, and the average value of which is $v_h=1.6306$ km/s.

(3) During the CE-1's controlled impacting the Moon of flying from south to north, the orbit inclination angel provided by TT&C system is 91.1° . Therefore, the velocity components of satellite on the reference sphere along the longitude and latitude (Figure 4) can be obtained using the following formula:

$$v_{x0} = v_h \cdot \sin i, \quad v_{y0} = v_h \cdot \cos i, \quad (3)$$

where v_{x0} is the velocity along the latitude on the reference sphere; v_{y0} is the velocity along the longitude on the reference sphere; v_h is the velocity of the nadir points on the reference sphere;

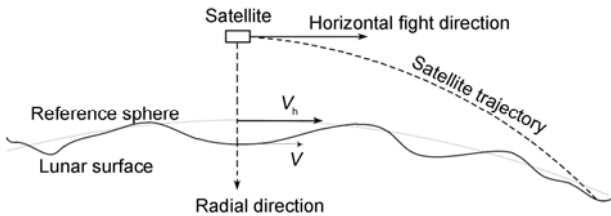


Figure 3 Velocities diagram of satellite on difference heights.

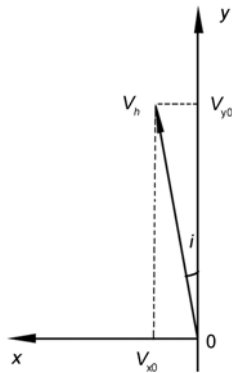


Figure 4 Velocities resolutions of satellite on the reference sphere. x axis points at the west along the latitude; y axis points at the north along the longitude.

reference sphere; $i=1.1^\circ$ is the intersection angle between the orbital plane and the latitude direction of the reference sphere.

From the results, the velocity along the latitude is $v_{x0}=0.0313$ km/s when CE-1 crossed over this crater, the velocity along longitude $v_{y0}=1.6303$ km/s.

2.2.3 Resolution of the longitude and latitude of the impact site

The process of impacting the Moon can be considered as the horizontal projectile motion with an initial velocity. Velocities v_{x0} and v_{y0} of the nadir points on the reference sphere remain unchanged. The following is the theoretical displacement along the latitude and longitude on the reference sphere in a certain period:

$$s_x = v_{x0} \cdot \Delta t, \quad s_y = v_{y0} \cdot \Delta t, \quad (4)$$

where s_x and s_y are the displacements respectively along the latitude and longitude on the reference sphere.

With the influence of the lunar rotation, the impact site will have some deviation during impacting the Moon and needs correcting to amend the longitude and latitude of the impact site. According to the satellite dynamical equation of the x and y axis, we can calculate the landing deviation along the x and y axis caused by Coriolis force [8]. Below is the deviation formula:

$$\begin{cases} \Delta x = -\frac{1}{3} g \omega t^3 \cos \theta - \omega v_{y0} \sin \theta t^2, \\ \Delta y = v_{x0} \omega t^2 \sin \theta. \end{cases} \quad (5)$$

The following is the displacement along the latitude caused by the lunar rotation during the impact on the Moon:

$$\Delta s = R \omega t \cos(\phi), \quad (6)$$

where Δx and Δy respectively represent the landing deviation along x and y axis caused by Coriolis force. Δs is the displacement of x axis caused by lunar rotation during the landing; v_{x0} and v_{y0} are the initial velocities of x and y axis; θ is the absolute value of the latitude at the starting point; ω is the lunar rotation angle velocity with 2.66×10^{-6} rad/s; g is the gravity acceleration of the Moon with 1.62 m/s²; t is the time between the starting point and the impacting site while the time of the starting point is determined by the starting crater and the impacting time is calculated through the timing code recorded by the last frame of image data downloaded by the satellite, the time being 16:13:06.463 on March 1, 2009 (Beijing Time).

(1) Latitude of the impact site

$$\phi = \phi_0 + \frac{s_y - \Delta y}{R}. \quad (7)$$

where ϕ_0 is the starting point of the latitude.

(2) Longitude of the impact site

$$\lambda = \lambda_0 - \Delta \lambda, \quad (8)$$

where λ_0 is the starting point of the longitude; $\Delta\lambda = (s_x - \Delta x + \Delta l_s) / (R \cdot \cos \varphi)$; $\Delta\lambda$ is the longitude correction.

By utilizing the above 27 homonymous craters and considering them respectively as the starting longitude and latitude, the “o” shows the calculation of the coordinate system of the impact site (Figure 5).

2.2.4 Correction of the impact site

Theoretically, all the impact sites obtained from calculation should have the same coordinate. But with change of the starting points and starting time, the distribution of longitudes and latitudes of the impact site presents an error cumulative trend, that is, the further the starting point from the impact site is and the more the accumulated time will be, the larger deviation the impact sites relative to published position have. The main error comes from the measurement error of the initial velocity.

(1) There are statistical errors of the total corresponding image lines of the crater's upper and lower edges. The terrain change of the two craters is around 1 to 1.5 km, which has caused the error in the statistics of the total image lines.

(2) The measurement of the crater's diameter adopts DEM data with 3 km resolution and image data with 120 m resolution, and there are some errors in this process.

(3) During the reduction of the real lunar velocity to the reference ellipsoid velocity, the height difference Δh is calculated from the average value of the crater's heights. There are some errors during this reduction.

(4) The reference ellipsoid velocity is the average value of two measurements. The adjustment to the two initial velocities is about 6.8 m/s and the accumulated time from the first starting crater to the impact site is about 7 min, which may cause 3 km position deviation.

In order to reduce the cumulative error, we calculated that the impact site is $x=52.229^\circ \pm 0.071^\circ$, $y=-1.800^\circ \pm 0.040^\circ$ by means of least-square procedure and statistical analysis to the longitude and latitude of the impact site obtained through the calculation of all the starting points. The coor-

dinate correction of the impact site is respectively $\Delta x = 0.00138\Delta t$ and $\Delta y = 0.00134\Delta t$ (Figure 5).

3 Discussion of positioning the impact site

Based on the tracking observations of radio ranges and VLBI delays of Chang'E-1 (CE-1) satellite during the controlled landing on the Moon on March 1, 2009, Li et al. [9] determined the landing trajectory and the coordinates of the landing point. It is shown that the landing epoch (the emission epoch of the last signal) of CE-1 satellite on the Moon was at UTC8h13m6.51s. The lunar longitude, latitude, and surface height of the landing point in the lunar primary axes frame are respectively 52.2732°E , 1.6440°S , and -3.56 km (the reference lunar radius is 1738 km). The uncertainties are 0.0040° , 0.0168° , and 0.18 km. The corresponding uncertainty in the tangential direction of the lunar surface is 0.52 km and the three-dimensional positioning uncertainty is 0.55 km (Table 5).

Using USB and VLBI tracking data, Cao et al. [10] determined the location of the impact crater by statistical orbit determination. The tracking data before last control are processed to investigate data quality, and the ranging system error and solar radiation pressure coefficient are also determined for the use of the last arc. The results show that the landing epoch of CE-1 satellite on the Moon was at 08:13:07.02 (UTC). The lunar longitude, latitude, and surface height of the landing point in the lunar primary axes frame are respectively 52.255°E , 1.657°S , and -2562 m (the reference lunar radius is 1738 km). The three-dimensional positioning inaccuracy is better than 300 m.

Combining the USB ranging data with the VLBI delay and delay rate data, Li et al. [11] determined the location of the impact crater by five-order polynomial function. The results indicate that the landing epoch of CE-1 satellite on the Moon was at 08:13:07.02 (UTC) (Table 5). The lunar longitude, latitude, and surface height of the landing point in the lunar primary axes frame are respectively 52.2549°E , 1.63091°S , and -2575.4 m (the reference lunar radius is 1738 km).

By means of comparative analysis, there are the following reasons for differences in coordinates:

(1) Since the time difference between the impact time in this method and the newly published time is 3.5 s, this 3.5 s flying time causes 5.7 km (about 0.19°) position deviation; (2) the two-dimensional location accuracy of the base map of the global lunar image data is from -100 m to 1.5 km (about 0.003° to 0.05°) [4]; and (3) there were inconsecutive image data captured by a push-broom camera during controlled impact. The extraction and measurement of craters are uncertain, so are the satellite velocity, positions, and timing code information of the homonymous craters. The result is that the maximum difference in longitude and lati-

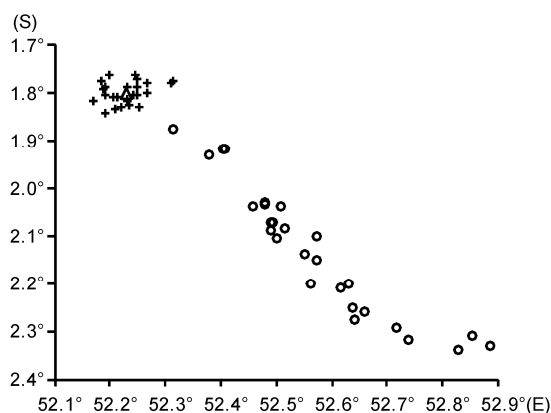


Figure 5 Coordinate of the impact site. o, The uncorrected coordinate of the impact site; +, the corrected coordinate of the impact site; Δ, the final coordinate of the impact site.

Table 5 Coordinates analysis of the impacting site of CE-1 satellite on the Moon

	This paper	Li et al. [9]	Cao et al. [10]	Li et al. [11]	News report
Time	BT 16:13:06.463	UTC 8:13:06.514	UTC 8:13:07.020	UTC 8:13:07.020	BT 16:13:10
Longitude	52.229° ±0.071°E	52.2732° ±0.0040°E	52.255°E	52.2549°E	52.36°E
Latitude	1.800° ±0.040°S	1.6440° ±0.0091°S	1.657°S	1.63091°S	1.50°S

tude of the impacting site is 0.071° and 0.04°.

The impacting time on the Moon in this method was at 16:13:06.463 (Beijing Time). The lunar longitude and latitude of the impacting site are respectively 52.229°E and 1.800°S. These deviations are within the error analysis of the above impact site, which demonstrates it is feasible to determine the impact site of CE-1 by using the image data.

4 Conclusions

Many lunar explorations concluded their scientific mission through the impact on the lunar surface. The extrapolated orbiting data together with the real time orbiting data and observations from ground-based telescope provided by TT & C System are used for the prediction and positioning of impact sites. As most lunar missions carried cameras onboard, a new method of positioning of CE-1 impact site is put forward. It is based on CCD image data photographed during the controlled impact and the existing lunar terrain data. The test results from this new method also validate the published impact site position.

In the second stage of the CLEP, Chang'E-3 lander and rover will survey on the lunar surface. It will be necessary to precisely position the landing site. Combining the ranging data and VLBI tracking data with the landing camera data and high-accuracy lunar image and topographic map, we can improve the positioning precision of the landing site by determination of the landing trajectory and the coordinate analysis of the landing point on the Moon.

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