Orbital Photogrammetry of Selected Relief Elements with Evidences of Geological Activity in Aitken Crater on the Far Side of the Moon

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Abstract. Achievements in the field of lunar research over the past 10-15 years have brought a lot of important information about the Moon and its interior. In particular, a high-resolution orbital survey performed from low lunar orbit by the Lunar Reconnaissance Orbiter (LRO) station has revealed details of the structure of impact craters, which were not even suspected before. For example, rivers and non-frozen lakes of molten lunar soil in the area of Tycho crater. Another impressive example is the glacier-like tongues of lunar rocks flowing from the central peaks of young impact craters. Or the unexpectedly high frequency of meteorite impacts on the lunar surface. Results of this kind can significantly affect future plans for the exploration of the Moon by automatic weapons and expeditions with a crew. They can also make a noticeable contribution to fundamental research. In this work, using a specific example of the Aitken crater, the possibilities of studying the relief in young impact craters based on photogrammetric processing of orbital images of the lunar surface are shown. The problems of a computational nature in the creation of 3D-models of the lunar relief and their referencing to the selenocentric coordinate system are also considered.

1. Introduction

Aitken crater is located in the central part of the far side of the Moon. Selenographic coordinates of the crater: 173° E, 17° S.

The crater was named after the American astronomer Robert Grant Aitken (1984-1951), known in world science for his achievements in the study of binary stars.

Among tens of thousands of lunar craters, Aitken has long attracted the attention of scientists. The increased interest is due to the properties of the crater, as well as its position on the lunar territory. It is an impact crater with a diameter of 130 km, the wall of which is almost untouched by traces of later falls (see figures 1, 2). The crater has an unusual central peak stretching from north to south. The floor of the crater is covered with material, which includes areas with anomalous reflective properties. In addition, isolated mountain peaks are observed in the bottom area to the west of its central peak, the nature of which raises many questions. The eastern part of the floor keeps fresh traces of young impact craters with atypical floor topography, and the floor areas near the foot of the inner slope of the eastern part of the crater wall are covered with fresh melts of lunar matter (see figures 4, 5).
The selenographic position of Aitken crater has one more important feature. This crater, unlike many others, lies on the edge of a huge deep lowland on the far side of the Moon known as the South Pole-Aitken basin.

2. Orbital images of Aitken crater

The first orbital images of Aitken were obtained by the American satellites "Lunar Orbiter" in 1966-1968 during the preparation of sites for landing people on the Moon under the "Apollo" program [1]. Unfortunately, despite the high resolution, the “Lunar Orbiter” images were made using phototelevision technology, which did not allow for their accurate photogrammetric processing.

The first images of Aitken crater, taken with a metric camera, were taken from the board Soviet spacecraft “Zond-8” in 1970, when it made another flight around the Moon without a crew. These images covered the area of the far side of the Moon from the Mare Orientale to the middle of the far hemisphere, including the Aitken crater and its surroundings.

It is important to note the historical significance of the photographs taken from the “Zond-6” (1968) and “Zond-8” (1970) spacecraft. These were the first in the history of space exploration photographs of another celestial body made at close range and delivered to Earth. The film was delivered to Earth in a special descent vehicle.

Another historically important aspect of the flight of the aforementioned spacecrafts is that it was the photographs of the “Zond-6” and “Zond-8” spacecraft which led to the discovery of a large previously unknown lowland on the far side of the Moon, called by the authors of the discovery “South-West sea” [2]. Further studies of the far side of the Moon established that the “South-West sea” is the central part of a large multi-ring impact basin on the far side of the Moon, and the basin itself received the working name “South Pole – Aitken” (SPA) [4, 5].

Following the “Zond” spacecraft, high quality photographs of the far side of the Moon were made on film by the crews of the “Apollo-15, -16, -17” spacecrafts. The “Apollo-17” crew managed to survey the Aitken crater with two cameras in several revolutions from low orbit and deliver the film to Earth.

![Figure 1. View of Aitken crater in orbital images from the LRO station. Top left is a composite of WAC LRO camera images (resolution about 100 m/px). Top right is a fragment of M149411565LE image from NAC LRO camera, which captures material flows in the area of the floor marked in the left image with a white arrow. Bottom is an oblique image of the NAC LRO camera showing a close-up view of the southern half of the central peak, craters with bulbous floor structure and material flows from the named craters towards the foot of the inner slope of the eastern part of the Aitken wall. At the very bottom of the oblique image, a glacier-like tongue "crawling out" from the southwestern slope of the central peak is visible.](image-url)
3. Some results of the Aitken crater study

Scientists first noticed the Aitken crater on the images of orbital observations from the “Lunar Orbiter” series satellites. This was reported in 1970 in a NASA report [1]. Authors of the report L.J. Kosofsky and F. El-Baz described the view of the crater in the central part of the reverse hemisphere as “The crater ... (about 150 kilometers in diameter), whose floor is incompletely flooded with dark mare material, is an exceptional feature in this highland region of light-toned surface material”.

The materials of the orbital survey of the “Apollo-17” spacecraft made it possible for the first time to create a topographic map of the Aitken crater area. This 1: 250000 scale map, known as LTO, contains information about the topography of the crater's surface in the form of isohypses, plotted with a step of 100 meters [6, 7]. The photogrammetric coordinate system used as the basis for the LTO map is based on images of the metric and stellar cameras installed on board the “Apollo-17” spacecraft. Apparently, this coordinate system became the first precise coordinate system in the Aitken crater area. The coordinates of the reference craters of this system were used to construct the “Zond-8” [8] selenocentric coordinate system, which covered a significant area of the far side of the Moon from the Mare Orientale to Aitken crater and its environs. Later, the “Zond-8” coordinate system, known among specialists as the TsNIIGAiK catalog, was used as the reference coordinate system when the extension of control points of the TsNIIGAiK catalog on the territory of the Aitken crater [9].

![Figure 2. Aitken Crater in two views on 3D-model built by the authors. Above view of the crater from the north side, below - from the east.](image)

The construction of the lunar coordinate system allows you to get an idea of the geometry of the crater and the elements of its relief, such as the central peak, the crater floor and its wall. So the authors of the paper [10] constructed the height profiles of the Aitken crater cross-sections passing through the center of the crater in two directions: from northwest to southeast and from northeast to southwest. The constructed profiles established the size of the central peak in height above the level of the crater floor, as well as the relative elevation marks of the crater wall in the above sections.

The successful arrangement of the orbits of the “Zond-8” and “Apollo-17” spacecrafts made it possible to find areas of overlap between the images of the two mentioned missions just in the area of the Aitken crater. The authors of [11] used this circumstance to compose stereopairs from images obtained from different orbits, which allowed them for the first time to construct a discrete model of the Aitken crater from images of two different cameras.
One of the most interesting results related to the Aitken crater concerns the problem of the ages of lunar craters. Studying the structure of young impact craters using the example of Aitken and Tsiolkovsky craters, and also taking into account the provisions of the Barenbaum galactocentric paradigm [12, 13], the authors of publications [14-17] come to a fundamental conclusion about the age of the lunar surface. They argue that the age of the Moon itself and the age of its surface should be considered as two different independent characteristics. So, if the age of the Moon, according to generally accepted estimates, is more than 4 billion years, then the age of its surface is determined by two or three last comet bombardments. The decisive contribution in this case belongs to galactic comets, which periodically completely plow over all of the surface layer of the Moon [15].

It is also interesting to note that Aitken crater was included in the list of the most promising regions for upcoming expeditions within the framework of the well-known space program "Constellation" (the space program for the development of manned astronautics in the United States [18]).

4. The task of constructing 3D-models of lunar relief elements
Classical photogrammetry algorithms are mainly aimed at creating discrete digital elevation models, while the practical needs of the exploration of the Moon increasingly lead researchers to the task of
constructing textured models. That is, such 3D-models that would allow examining the structure of the relief in different, and preferably in arbitrary, angles, while maintaining the resolution at the level of the original photographs or slightly lower. Such a survey potentially carries the possibility of detecting in the structure of relief elements details that are simply not visible, or are not clearly visible on single images of which such a textured model consists. When it comes to building relief models in areas of the Earth's territory, then in this case it is most often possible to check the presence of certain relief details in nature. In the case of constructing models on sections of the lunar surface, the problem acquires a different meaning, since new angles of objects that can be viewed with the help of the constructed model are revealed to the observer for the first time and there is no other way to verify their reality. Thus, there is an element of absolute novelty in the lunar version of modeling, which entails the potential to discover previously unknown new details of the relief structure in the study area. All of the above gives the task of constructing 3D-models of lunar relief elements a clearly expressed exploratory research character.

It is not the first time that Kazan Federal University (KFU) has addressed the problem of creating 3D-models of the lunar relief. The first three-dimensional model of the Aitken crater was built and published in 2015 by student at Kazan Federal University Ilya Akhmanov [19]. Akhmanov's result concerns not only the Aitken crater itself, but also its surroundings. It includes territories to the east and west of the crater along route 14 and 15 of “Apollo-17” orbit. Due to this, Akhmanov's model includes a significant number of images, but the resolution of the images used was not high, since they used images from the set of an educational laboratory workshop, where the volume of each image did not exceed 12-13 megabytes. As a result, despite the large coverage area, the image of the relief on the model loses in quality and a detailed full-fledged comparison with our models cannot be made. In general, Akhmanov's model and our models are very similar to each other. Such a result was to be expected, since the models were constructed based on the materials of the same survey using the same computer program Agisoft Photoscan, developed by the Russian “Geoscan” company [20].

![Figure 5. View of the glacier-like tongue in Aitken crater on fragments of the 3D-model constructed by the authors. The upper part of the figure shows the tongue from its frontal part, the lower part of the figure shows the tongue from its rear part.](image-url)
New attempt to construct 3D-model of the Aitken crater was made by us two years later, when powerful photogrammetric stations appeared at the disposal of the authors. Now the task was to create a high quality model based on images of the metric and panoramic cameras of the “Apollo-17” spacecraft. If a metric camera provides a resolution of about 10-15 meters on the lunar surface, then the resolution of panoramic camera reaches one meter! The use of photogrammetric stations made it possible to construct the high-resolution 3D-model and for the first time [21] examine the structure of the glacier-like tongue from different sides (see figures 5, 6). It is curious to note that such high resolution was obtained already 50 years ago, but images of the “Apollo” panoramic camera became available to researchers outside the United States relatively recently, after 2010, when they began to be digitized on the photogrammetric scanner [22].

Figure 6. The frontal part of the glacier-like "tongue" in close-up on the fragment of the ultra-high resolution image M1095365439RE of the LRO station. In the central part of the image, the area from which numerous boulders were thrown out is clearly visible. (Credit: NASA / GSFC / Arizona State University).

Building a textured model of a crater from high-resolution images is a rather laborious task, since it involves pixel-by-pixel processing of several images, each of which is 16-bit graphic file of more than one gigabyte in size. For example, 3D-model of the entire Aitken crater based on three orbital images of the metric camera takes 10-20 hours of computer time at one photogrammetric station. Connecting images of the panoramic camera takes the time to build 3D-model even more, despite the fact that only fragments of panoramic images are included in the building process. It is not possible to include panoramic images in 3D-model as a whole, since the size of one such image in digital form is about 14 Gigabytes. Considering the above, the authors made attempt to create 3D-model of the Aitken crater when several photogrammetric stations are simultaneously involved in the processing of images. Such attempt helped the authors understand how effective the use of computational cluster can be in the task of building 3D-model. The results of the described attempt are presented in Table 1. As follows from the comparison of the computer time costs, building the model in the computational cluster mode reduces the time spent by about 10 times in the case when the cluster consists of three photogrammetric stations. The calculations were carried out in the course of building model of the entire Aitken crater using four images. Each of the images was presented as 16-bit black-and-white
image in the form of a graphic file of about 1.2 Gigabytes in size. The images were taken with metric film camera in one orbit, delivered to Earth by the “Apollo-17” crew, and digitized with a photogrammetric scanner.

Table 1. Expenditures of computer time for building the same model on one computer (graph - normal calculation) and on a computing cluster of three computers (graph - cluster calculation).

| Steps of 3D-analysis images | Time spent for one computer (min) | Time spent per cluster calculation (min) |
|-----------------------------|----------------------------------|----------------------------------------|
| Alignment pictures          | 23                               | 3                                      |
| Building dense point clouds | 136                              | 14                                     |
| Building a 3D-model         | 69                               | 8                                      |
| Building texture            | 17                               | 1                                      |
| Total:                      | 245                              | 26                                     |

5. The problem of referencing 3D-model of lunar craters

Further analysis of the Aitken crater model constructed by us provides for its coordinate reference to the lunar coordinate system. A linked 3D-model would allow numerical estimates of the areas and volumes of various landforms in the Aitken crater. In particular, to estimate the volumes of isolated mountain peaks to the west of the central peak of the crater, the sizes and volumes of details of the central peak itself, as well as the glacier-like tongue.

The authors carried out the first experiment of coordinate referencing on the basis of the Sitdikova’s catalog [9], built in the coordinate system of the TsNIIGAiK catalog. Sitdikova's catalog was built specifically to carry out educational and research work on orbital images in the Aitken crater. For this, the author included more than 100 small-diameter craters densely covering the territory of the Aitken crater. To bind the model, 15 reference craters were selected, the images of which were clearly visible on the constructed model. Unfortunately, the accuracy of this first attempt turned out to be rather modest, since the errors at the control points were at the level of 1.0-1.5 km [23]. With such an accuracy of the binding, the above expected estimates of sizes, areas, and volumes are of no practical interest.

Figure 7. Scheme of coverage of small area in Aitken crater near the southern end of the central peak with fragments of panoramic images of the “Apolon-17” spacecraft included in the 3D-model built by the authors on the basis of “Agisoft Methashape” technology [24].
Figure 8. Arrangement of groups of control points for coordinate reference of our 3D-model. In each group, outlined by red ovals, several control points were selected, the images of which could be confidently identified on the QuickMap [25]. The images of the reference points themselves in this figure are barely visible due to their small size.

Figure 9. The stage of placing the reference point pickets on the fragment of 3D-model. In the foreground there is a small fragment of the rear part of the tongue, in the lower right corner you can see a piece of the south-western slope of the central peak (view from the south-eastern side). Two groups of control points are shown, designated in figure 8 by numbers 6 and 7, each of which has 4 control points.

Then we turned to the new digital QuickMap, created taking into account the latest lunar missions, including LRO data. The name "map" in relation to QuickMap is rather arbitrary, since this digital software product contains all the information available today about the lunar relief obtained by the
world's leading space agencies for many years. Thus, it would not be an exaggeration to call the Quick Map not a map, but a kind of "Electronic Moon" or "Digitized Moon".

For referencing, we selected a small area of the Aitken crater floor, approximately 20 x 15 km in size (see figure 7, 8). This size of the site was dictated by the fact that the laboratory with photogrammetric stations was closed for six months (from March to September 2020) due to the coronavirus pandemic. The authors had to be content with modeling and binding the model in this part of the research with an ordinary household laptop. Despite the limited computer power, the authors built the model for the above-described area. The main difference from the previous method of binding the model was that the authors built a new catalog of control points, the coordinates of which were taken from the QuickMap (see figures 8, 9). The accuracy of the heights of points on the lunar surface on the QuickMap is 2-3 orders of magnitude higher than in the Sitdikova catalog, since the height data of the Quick Map is based on high-precision measurements of the LOLA laser altimeter. As a result, the errors of the model positioning within the described area at the control points were reduced to the level of 5-10 meters in the plan and up to 4 meters in height! 3D-model with such errors allows the authors to count on obtaining reliable numerical estimates for the above relief elements in the Aitken crater.

Figure 10. View of the young multi-ring impact Orientale basin in the central part of the western hemisphere of the Moon from the LRO orbit [26]. The results of the interaction of objects falling on it in the entire conceivable range of their sizes, masses and speeds are presented on the Moon: from the icy cores of galactic comets, circumsolar comets and asteroids to metallic meteorites. The first orbital photographs of the Mare Orientale on film were taken from the Soviet “Zond-8” spacecraft and delivered to Earth in 1970 [27, 28].

6. Conclusion
The craters of the Moon along with its seas represent the most common elements of the lunar relief. They keep the traces of impact events for hundreds and thousands of years, thus making up a kind of archaeological monument to the very process of crater formation. The results of this process are perfectly visible from Earth even with small telescopes. Orbital observations of the lunar surface present us with lunar craters in all their magnificence and variety (see figure 10). Here are the results of the interaction of objects falling on the Moon in the entire conceivable range of their sizes, masses,
velocities and compositions: from the icy cores of galactic comets, circumsolar comets and asteroids to metallic meteorites.

If we take into account the mechanism and nature of the interaction of objects falling on the Moon with its surface, it becomes obvious that the material of lunar craters is formed under conditions of extreme temperatures and pressures. Moreover, the energy of interaction is such that it is not possible to reproduce it ever on Earth.

Thus, lunar craters can be viewed as a unique natural laboratory near the Earth, where the problems of physics of extreme states of matter can be studied. Building 3D-models of the lunar topography based on high-resolution orbital images is another step towards creating such laboratory.

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