Cartography of the Soviet Lunokhods' Routes on the Moon

I. P. Karachevtseva, A. A. Kokhanov, N. A. Kozlova and Zh. F. Rodionova

Abstract Soviet missions Luna-17 (1971) and Luna-21 (1973) deployed the roving robotic vehicles Lunokhod-1 and Lunokhod-2 on the lunar surface. The Lunokhods (Moonwalkers) were the first extraterrestrial rovers that were operated remotely from Earth. Using Lunar Reconnaissance Orbiter (LRO) narrow-angle camera (NAC) (Robinson et al. 2010), the Lunokhods' routes have been reconstructed (Karachevtseva et al. 2013; 2017). Following the rover tracks that are visible on high-resolution LROC NAC images, we identified the exact rover traverses and compared them with data from archive topographic maps created during Soviet lunar missions. Derived LRO data (DEMs and orthomosaics) allowed us to analyze the topography of the Moon area at the local level and to map the Lunokhods' routes with more details.

Keywords Soviet Moon missions Luna-17 and Luna-21 · Lunar robotic vehicle (Lunokhod) · LROC NAC · DEM · Orthomosaic · Traverse reconstruction · Maps of Lunokhod-1 and Lunokhod-2 landing area

1 Introduction

The development of the theory and practice of Planetary Cartography is directly related to the progress in the field of space research beginning in the second half of the twentieth century. Russia has a long tradition in Planetary Cartography: Compilation of lunar maps began after the successful execution of the epochal space experiment to photograph the far side of the Moon by the Luna-3 mission in

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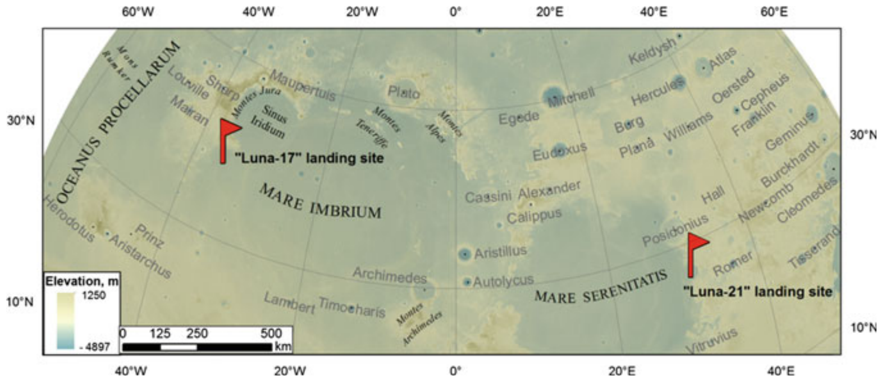


Fig. 1 Map of Lunokhods' landing sites: Luna-17 in Mare Imbrium and Luna-21 in Le Monnier crater, located on the eastern margin of the Serenitatis Basin (Mare Serenitatis)

1959 for the first time (Shevchenko et al. 2016). Later, Lunokhods, also for the first time, carried out detailed in situ exploration of large lunar surface areas remotely.

Luna-17 landed on November 17, 1970, in Mare Imbrium and Luna-21 landed on January 16, 1973, in Mare Serenitatis (Fig. 1). The goals of the missions were with the help of distantly controlled planetary vehicles to study the lunar topography, geology, and morphology (Vinogradov et al. 1971; Barsukov 1978), as well as mechanical conditions (Leonovich et al. 1971; 1978) and the chemical composition of the lunar surface (Kocharov and Viktorov 1974; Cherkasov and Shvarev 1975). The concept behind roving robotic vehicles was to support the human exploration of the Moon. It was anticipated that the rover would land and certify the site prior to human landings, examine the human lander after it landed, and transport the crew to a backup rover if necessary. Lunokhod-1 studied lunar mare (Florensky et al. 1978), and Lunokhod-2 focused on the transition area between mare and highlands (Florensky et al. 1976).

2 Lunokhods' Vehicles and Recent Remote Sensing Data

2.1 Lunokhods' Vehicles

The construction of Lunokhods was identical, but the total mass of Lunokhod-2 was 836 kg compared to 756 kg of Lunokhod-1 (Kemurdzhian et al. 1993).

Both Lunokhods carried laser retroreflectors—14 glass pyramids in one thermally insulated box—that were used for geodetic Lunar Laser Ranging (LLR) experiments in common with retroreflectors established on the lunar surface during Apollo Missions (a panel of 300 or 100 prisms). Since 1978, regular laser measurements of Lunokhod-2 are carried out providing data on the distance to the Moon with an accuracy of 25 cm (Kokurin 2003). Results from the LLR

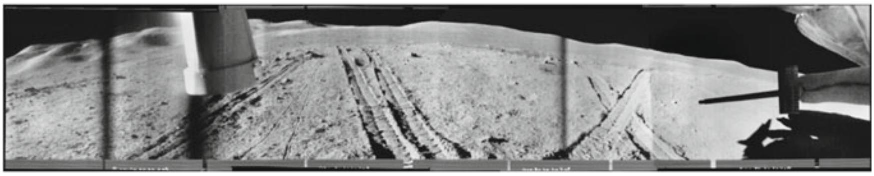


Fig. 2 New assembled archive panorama # 6-387 shows track of the rover and its ninth wheel

experiment (both Lunokhods and 3 Apollo reflectors) give us important insights concerning the dynamics and interior of the Moon (Dickey et al. 1994). In addition, with the reflector coordinates established to the cm level, the laser reflector stations mark important geodetic reference points that define the currently used lunar coordinate systems (Archinal et al. 2011).

At the time of the missions, there were no detailed maps or images of the landing sites. Therefore, it was impossible to plan the whole route beforehand; only main goals and directions were chosen. To save Lunokhod from dangerous craters and rock fragments, a special human crew was trained to control and operate the rovers from the Earth. For that purpose, Lunokhods had two television cameras for navigation (abbreviated as "MKTV"—the Russian abbreviation stands for "Small Frame Television System") mounted at a height of 950 mm above the surface. Due to the construction of cameras and considering signal delays, navigation images came to the Lunokhod driver every 6–10 s.

In order to conduct topographic and morphologic studies of the lunar surface, the rovers were also equipped with four panoramic TV scanning cameras: one horizontal and one vertical on each side (Selivanov et al. 1971). The design of the cameras allowed taking black and white panoramic images 360° × 30° (6000 lines × 500 samples) with an angular resolution of 0.06°. However as the cameras were mounted on the Lunokhod sides, horizontal cameras made panoramas with the width a bit more than 180° (Fig. 2). Therefore, stereo pairs at some selected sites were obtained by taking panoramas from two positions of Lunokhod. It allowed to determine the steepness and slopes inside craters with high level of details based on photogrammetric processing of stereo panoramas (Rodionov et al. 1971).

2.2 LROC Data: DEMs and Orthomosaics

As lunar landing sites, such as Luna-17 (Lunokhod-1) and Luna-21 (Lunokhod-2) working areas, have been LRO mission priority targets, stereo images with pixel size up to 0.3 m have been obtained for these regions. The orbiter is equipped with the LROCamera (LROC) system consisting of a wide-angle and two identical narrow-angle scanner cameras (NAC) for high-resolution (0.5 m/pixel) monochrome close-up views (Robinson et al. 2010). The panchromatic images are 5000 pixels wide and typically 50,000 pixels long. It provided possibilities to compare extraterrestrial in situ measurements with studies based on orbital remote sensing data. For this purpose, stereo processing of LROC NAC images for Lunokhods' activity areas was implemented (Karachevtseva et al. 2013; 2017).

Due to differences in the rovers routes, to study the Lunokhod-1 traverse only one stereo pair was used (see for details Karachevtseva et al. 2013) and about 60 stereo pairs were processed for research of Lunokhod-2 track (see for details Karachevtseva et al. 2017). 10 km^2 Lunokhod-1 area DEM with vertical accuracy ~0.1–0.5 m and 200 km^2 Lunokhod-2 area DEM with vertical accuracy 2–3 m were produced. The NAC geometric calibration and alignment information were taken from previously studied (Oberst et al. 2010) pre-launch measurements. LRO navigation data were derived from reconstructed orbit and pointing. A least-squares bundle block adjustment was carried out, following which the position and orientation of the NAC images improved. The PHOTOMOD implementation of the block adjustment is based on the RPC model (Grodecki and Dial 2003), which is characterized by an effectively reduced number of adjustment parameters (6 per image) providing a stable solution. The final 0.75 m DEM was shifted by 86 m laterally to fit the LLR-based coordinates of the Lunokhod-1 rover (Williams et al. 2013). All LRO data are provided in Mean Earth (ME) coordinate system, and LLR retroreflector array coordinates are also in the ME system (LGCWG and LRO Project 2008). Orthomosaics of the landing sites with the best visibility of the rover tracks were created using the DEMs. The results of photogrammetric image processing of LROC NAC stereo pairs—local DEMs and orthomosaics—provide a consistent coordinate base for mapping and studies of the routes, including variance of heights and slopes along the tracks.

3 Reconstruction of the Lunokhods' Routes

3.1 Identification of Lunokhod-1 Traverse

LRO NAC images show that the traverse of Lunokhod-1 can almost fully be recovered (~99%), except for few areas in shadow (<1%). Tracks appear dark in the images due to the disturbance of the surface by the wheels. In the available super resolution LROC NAC image (0.33 m/pixel), Lunokhod-1 tracks of left and right wheels can be seen clearly. Contrast is low on images taken at high Sun, and finding and following the rover wheel tracks are more difficult. Contrast enhancement was used to bring out image details. Analysis of surface brightness profiles across Lunokhod-1 tracks (Fig. 3) reveals that the brightness of the wheel tracks typically drops by ~1% with respect to the surrounding area. This is due to a change in the photometric properties of the surface once it has been disturbed. The brightness of the tracks is found to depend on solar elevation, but it also appears to depend on the azimuthal direction of rover motion (Figs. 4, 5, 6, and 7).

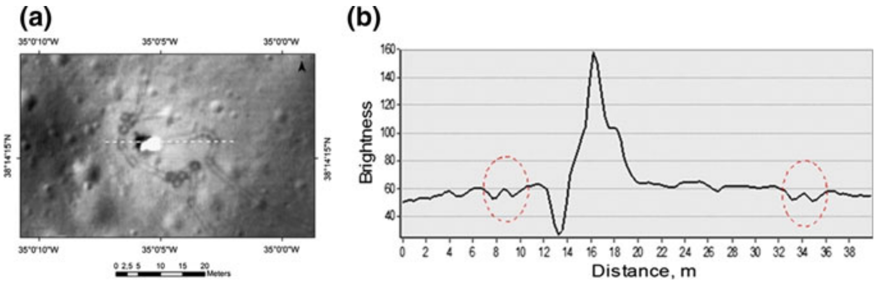


Fig. 3 Analysis of brightness of Lunokhod-1 wheel tracks: (a) LROC NAC image M175502049 with resolution 0.3 m/pixel; (b) corresponding profile of brightness along transect line with white dashed color on the image. *Note:* W-shaped pattern on the plot representing tracks of left and right rover wheels

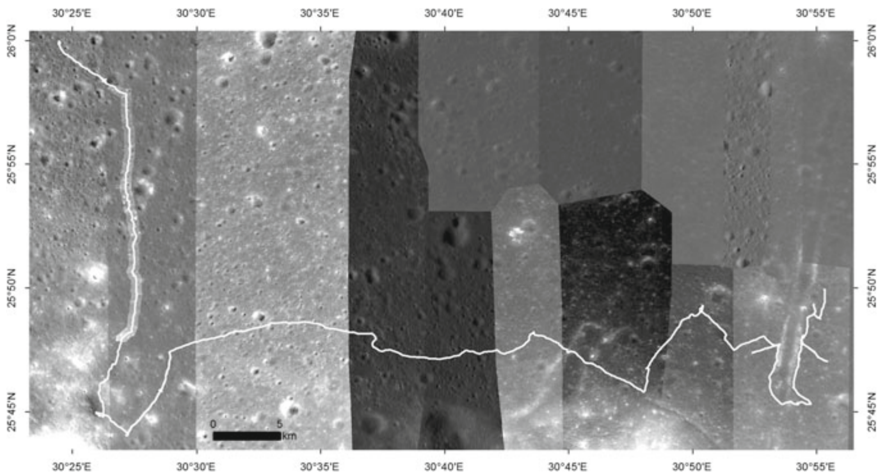


Fig. 4 Orthomosaic with high quality of visible track, produced to identify the route (equidistant cylindrical projection with center at study area—central meridian 30°40′, standard parallel 25°50′)

Poorly visible parts of the track, due to multiple crossing tracks or turning motion of the Lunokhod-1 (about $\sim$5% of the traverse length), were identified with the help of the archive topographic maps created during Luna-17 mission as a result of panorama processing (Abramova et al. 1978). To use the large-scale maps with resolution up to cm level (see below one example on Fig. 8a), the scales of the LROC NAC images were increased to 1:500, which approximately corresponds to the scale of the historic topographic plans.

The identified track was digitized and measured using ArcGIS software. Following identification of the track, the total length of the traverse is measured in GIS using equidistant along the meridian projection (due to meridional general orientation of traverse) as 9.93 km (Karachevtseva et al. 2013), that is shorter than

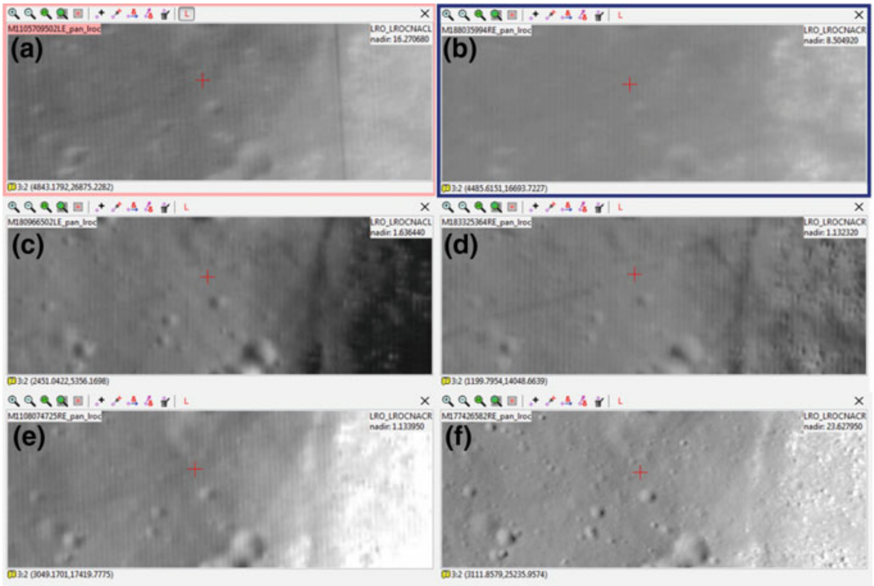


Fig. 5 Traverse visibility on different LROC NAC images: (a) M1105709502LE, (b) M188035994RE, (c) M180966502LE, (d) M183325364RE, (e) M1108074725RE, (f) M177426582RE

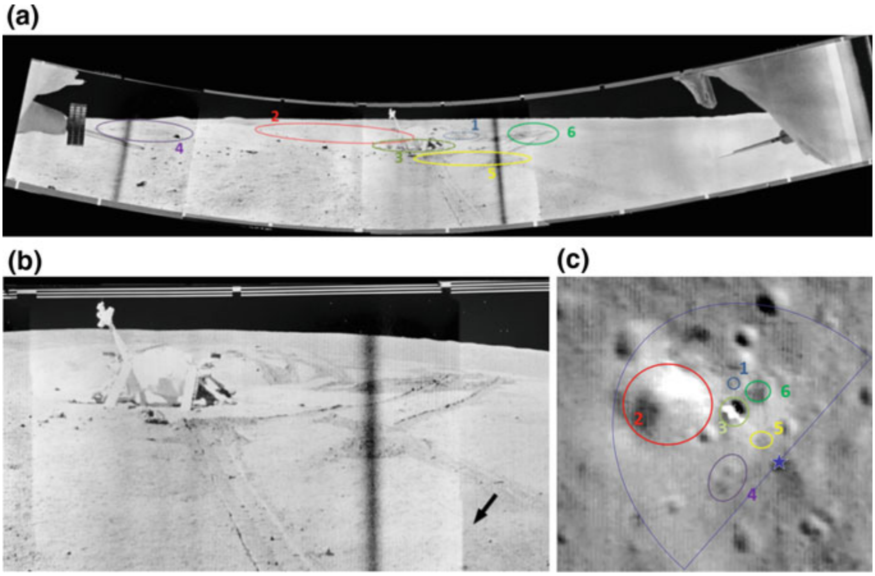


Fig. 6 Implementation of Lunokhod panoramic images for identification of the wheel tracks: (a) Lunokhod-2 panorama #6-375 with marked prominent features that are also visible in LROC NAC orthoimage; (b) zoomed in fragment of the panorama—the ninth wheel track is marked by an arrow; (c) LROC NAC orthoimage of the landing site, observation point of the panorama is marked with a star

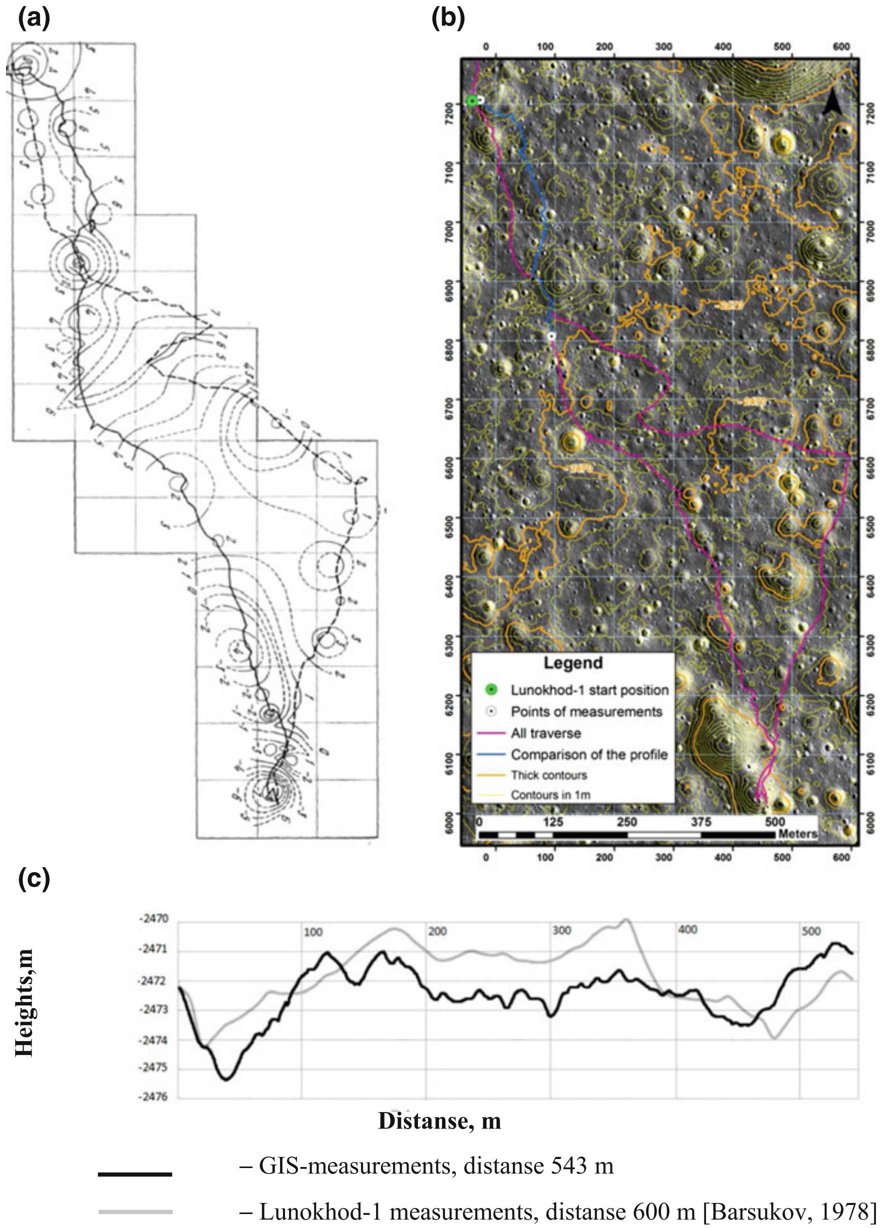


Fig. 7 Topography for the southern part of the Lunokhod-1 traverse area: (a) topographic map from Leonovich et al. (1978); (b) contour map, derived from LROC NAC data; and (c) comparison of profiles for the part of traverse (blue line at the contour map)

the previously published significantly (10%) longer path of 10.54 km (Ivanov et al. 1978). Studies of the traverse sections indicate similar differences in estimates of the track length for each lunar day. This discrepancy is probably due to wheel slippage, which would artificially increase the travelled distance. Wheel slippage is a common problem on both Lunokhods and Mars Exploration Rovers. The odometer measurements, expected to check against wheel slippage, had an accuracy of not more than 7% (Leonovich et al. 1978), which may partly explain the discrepancy.

3.2 Identification of Lunokhod-2 Traverse

The Lunokhod-2 route was primarily west to east (contrary to Lunokhod-1, which moved south to north), and Lunokhod-2 travelled a distance four times longer than Lunokhod-1 did. Hence, several sets of LROC NAC images were required to cover the Lunokhod-2 study area. These images were acquired over several different LRO mission phases and have various lighting conditions (Fig. 4).

For track identification, images taken under complementary illumination and the highest-resolution were used (pixel scales ~0.5–1.0 m). Figure 5 and Table 1 show examples of traverse visibility on different space images.

The lengths of individual parts of the Lunokhod-2 traverse from different lunar days were determined using GIS tools and equidistant projection with the main parallel crossing the most part of the route to reduce linear distortions. The total length of the traverse was measured as 39.1 km, significantly longer (~2 km) than the previously published result of 37 km, which was based on the onboard odometer measurements. The big discrepancy between historic and recent distance measurements of the Lunokhod-2 route probably has multiple causes: (1) mistakes based on odometer measurements (ninth wheel) as mentioned above for Lunokhod-1 and (2) accumulation of errors along the longer path.

3.3 Implementation of Panoramic and MKTV Images

Surface panoramas and MKTV images also were useful in local identification and refinement of the Lunokhods' traverses. For this purpose, archive analog panoramas as scanned image fragments were re-assembled in digital form (Kozlova et al. 2014) with the help of specially developed software (Zubarev et al. 2016).

Observation points for panoramas were determined on the route (Kozlova et al. 2016) using the identification of the same craters in newly processed archive panoramas (Fig. 6a) and in high-resolution LROC NAC orthoimages (Fig. 6c). One of the first panoramas taken by Lunokhod-2 captures the landing module and the beginning of the route: Wheel tracks are clearly visible, including the track of the ninth wheel (Fig. 6b).

4 Comparisons with Archive Traverse Data

Of course, the differences in recent measurements for both Lunokhods' routes also depend on two various methods implemented for estimation of the path: (1) calculation from odometer based on "in situ" data from lunar surface provided by the ninth wheel and (2) digitizing tracks using orbital images. To analyze the discrepancies, archive topographic schemas and maps produced during Luna-17 and Luna-21 missions were used.

4.1 Lunokhod-1 Archive Data

The contours at Lunokhod-1 topographic schema and profiles (Fig. 7a) published after the mission (Rodionov et al. 1971; Leonovich et al. 1978) were compared with contour map derived from DEM produced using LROC NAC stereo pairs (Fig. 7b). While the total height range in both representations is in agreement, only approximate matching of slopes and topographic trends was found. Based on available 600-m length traverse archive profile, a comparison with a traverse profile taken from the LROC DEM reveals that the basic features (e.g., point of lowest elevation) match well, while the magnitude of the topography is grossly misrepresented (Fig. 7c).

Also, comparisons between crater morphologies from the published archive topographic contour map and the LRO NAC image and DEM were made (Fig. 8). The earlier contour map has been derived by photogrammetric processing of Lunokhod-1 stereo panoramas (Abramova et al. 1978). Since the goal of mapping was to represent all recognized relief features with its characteristics, special system of cartographic signs has been developed (Shingareva and Burba 1978). Lunar relief objects shown on the archive maps were divided into three groups: (1) elements with closed outline (craters, hills, boulders); (2) linear elements (grooves, ridge, lineaments); and (3) spatial elements (fields of craters and boulders).

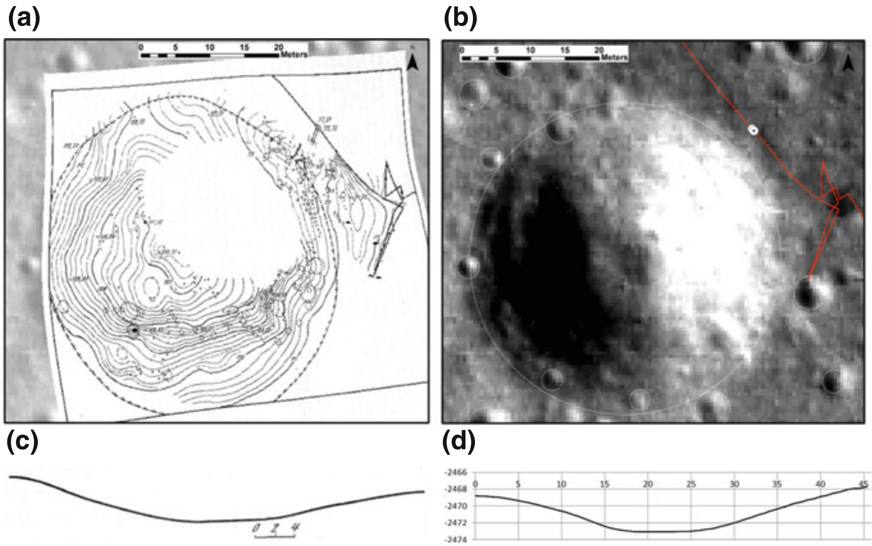
Considering the different nature of the archive and recent data sets, the overall agreement in size, depth, and shape of the crater is good (Fig. 8c, d).

4.2 Lunokhod-2 Archive Data

During Lunokhod-2 mission, operation route map, which original is currently held by the Lavochkin Research and Production Association Museum,[1] was compiled.

Also, various individual topographic maps of small study areas derived from operative panorama processing based on coordinate observations and navigation measurements were produced (Rodionov et al. 1973), including a topographic map

[1]http://www.laspace.ru/rus/museum.php.



D=40.0 m; H=4.5 m D=45.3 m; H=5.5 m

Fig. 8 Comparison of archive Lunokhod-1 data and recent GIS measurements: (a) topographic map of a small crater (map# 3 from Abramova et al. 1978) referenced to the LROC NAC orthoimage; (b) the same crater identified on LROC NAC orthoimage and a part of rover track identified using the archive map; (c) height profile through the crater from the map # 3; (d) height profile obtained from high-resolution LROC NAC DEM

Table 1 Illumination conditions on LROC NAC images

M1105709502LE Resolution 1.25 Emission angle 17.57 Incidence angle 45.29 Phase angle 31.5 Solar longitude 334.3	**M188035994RE** Resolution 1.40 Emission angle 9.17 Incidence angle 29.04 Phase angle 25.06 Solar longitude 123.05
M180966502LE Resolution 1.41 Emission angle 1.78 Incidence angle 70.57 Phase angle 72.32 Solar longitude 37.28	**M183325364RE** Resolution 1.40 Emission angle 1.2 Incidence angle 46.39 Phase angle 45.29 Solar longitude 65.84
M1108074725RE Resolution 1.36 Emission angle 1.2 Incidence angle 67.48 Phase angle 66.33 Solar longitude 3.13	**M177426582RE** Resolution 0.49 Emission angle 24.13 Incidence angle 71.52 Phase angle 47.93 Solar longitude 354.88

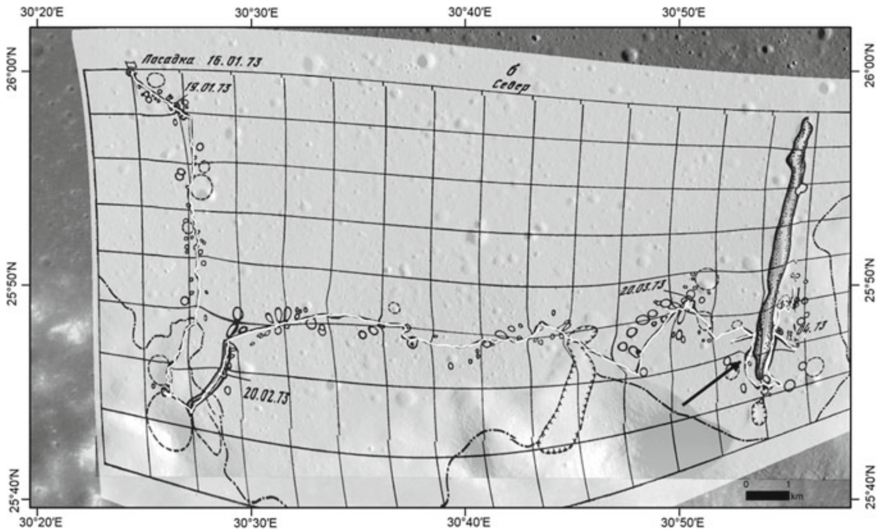


Fig. 9 Differences between Lunokhod-2 route, digitized in GIS (white), and the route from transformed historic topographic schema (black), produced as the result of analysis and mapping after Luna-21 mission (maximal discrepancy, marked with arrow, is about 80 m)

of the southwest part of the route, a relief map of an intensively studied small crater, and a topographic sketch map of the entire working area.

Archive Lunokhod-2 route maps were used for comparison with recent traverse reconstruction. For this about 50 corresponding tie points on the route from archive map and new traverse were picked. Then archive map was rubber stretched to match the new traverse recognized on LRO orthomosaic. Judging from the distortion of the map grid significant long-wavelength displacements was identified in the archive map, up to the 100-m level (Fig. 9). However, on small-scale, the historic, and the LROC NAC-based representation of traverses show excellent qualitative agreement.

5 Recent Cartography of Lunokhods' Activity Area

Lunokhods for the first time carried out detailed in situ exploration of large lunar surface areas remotely. Lunokhod-1 travelled on a typical lunar mare region, while Lunokhod-2 investigated a transition area from mare into highlands. Despite the fact that so much time has passed since the missions, these areas are still of great scientific interest, for example, for morphometric measurements (Basilevsky et al. 2014), and the archive Lunokhod data is still valuable and suitable for further research using recent technologies (Kaydash and Shkuratov 2014).

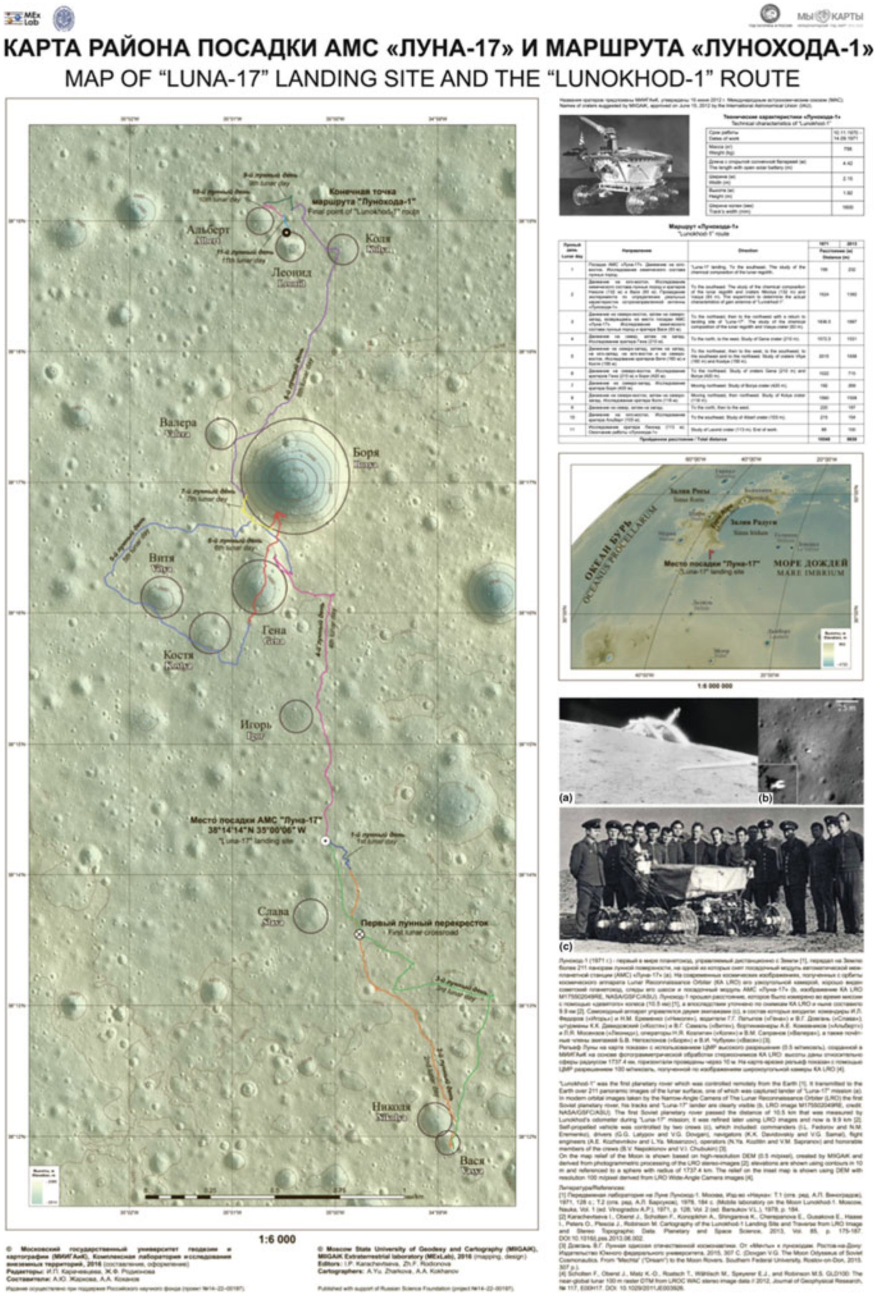


Fig. 10 Map of the Lunokhod-1 route (Karachevtseva et al. 2016). Original size of map sheet is 594 × 841 mm. Colors of route parts show distance travelled through single lunar day

To present the results of the study, Lunokhod route maps—1:60000 for the Lunokhod-1 and 1:25000 for the Lunokhod-2—were compiled (Fig. 10). The geographical basis for mapping is orthomosaic of high-resolution images, which shows the smallest craters at the defined scale. Maps are compiled in equidistant cylindrical projection, to minimize linear distortion for distance measurements. The main parallel of the projection for the Lunokhod-1 map is 35°N, and for the Lunokhod-2, it is 25.8°N (the center of mapped territory).

Since these maps constitute one series, a uniform design was developed: One gradient color scale is used for relief visualization both on the main maps and the insertion maps. Also, local relief on the main maps is shown by contours. Different contour intervals were selected depending on the minimal and maximum heights inside the mapped territory: 10 m for the Lunokhod-1 and 50 m for the Lunokhod-2 map.

The sign of traverse was drawn as a centerline between two visible tracks. As the Lunokhods worked several lunar days, each section of traverse, passed during single day, is shown in a separate color and labeled by the day's number. Both maps contain reference information, including technical characteristics of the rovers, description of routes by lunar days with comparison of old and recent distance measurements and brief historical overview. The Lunokhods' maps are presented in A1 size and give a fresh look at the history of the Soviet lunar exploration program.

GIS-supported files are available via the MIIGAiK Extraterrestrial Laboratory Geoportal.[2]

6 Summary

As lunar landing sites such as the Luna-17 (Lunokhod-1) and Luna-21 (Lunokhod-2) operation areas have been the priority targets of the LRO mission, this provided an opportunity to compare extraterrestrial in situ measurements with studies based on orbital remote sensing data. For this purpose, stereo processing of LROC NAC images for Lunokhods' activity areas was implemented. Based on LRO data and GIS, we reconstructed Lunokhods' traverses and gave new insights into Soviet lunar mission achievements.

Bringing archive data into modern spatial context provides excellent opportunities for detailed comparative analysis with new data. It provides a new view on past and recent lunar missions as, for example, studies of Lunokhod-1 and Yutu working areas (Basilevsky et al. 2015), including morphometric and geologic assessment, estimations of boulder types and densities, crater classes, and regolith structure. Moreover, the well-studied lunar regions can be used for future missions as an analog for testing and calibration of different instruments and techniques.

[2] http://cartsrv.mexlab.ru/geoportal (short URL: goo.gl/ffycQb).

For example, high-resolution DEMs and orthomosaics of the Lunokhod-1 and Lunokhod-2 areas support morphometric and safety assessments for the selection of the candidate Luna-25 (Luna-Glob) landing sites. There is a considerable amount of shadow in polar areas, and there is no opportunity to obtain good quality stereo pairs for photogrammetrically processed DEMs. Therefore, a method of estimating the distribution of slopes in portions of shaded areas measured in the images acquired at different solar incidence angles was suggested (Abdrakhimov et al. 2015). This method was calibrated on analog regions in Lunokhod-1 and Lunokhod-2 areas where we have images with various illumination conditions as well as detailed DEMs. Furthermore, the LLR coordinates of the Lunokhod-1 and Lunokhod-2 rover positions provide high absolute accuracy of the created DEMs that can be used as a reference area to control calibration of the stereo camera for planned Russian Moon projects and to perform refinement of the spacecraft trajectory during the future orbital mission Luna-26 (Luna-Resource).

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