Interpretation of the Moon Probing Signals During Landing Using Laser Scanning Systems

Igor Kulikov[1*] | Boris Kryuchkov[1]
[1] "Yu.A. Gagarin R&T CTC" FSBO, Star City, Moscow Region, Russia
inkul1963@gmail.com, B.Kryuchrov@gctc.ru

Abstract

The paper deals with the issues of determining the current spatial position of the landing space module relative to the surface of the Moon. The novelty and relevance of the proposal is to implement the technology of a scanning lidar or a laser scanner as a spatial data source. Currently, this innovative technology finds wide and effective application in various spheres on Earth. The use of a matrix-type laser scanner is depended on the feature of the trajectory of the space module at the final stage of landing, which has a long vertical section.

The high spatial resolution of laser shooting, the speed of obtaining and using digital information and other characteristics of the scanner allow us to offer it as a basic element of the lunar landing module's vision system. The prompt receiving of the planet surface sounding signals in the format of digital terrain models with a given spatial resolution based on laser shooting is the basis for the formation of a safe pre-landing maneuver and landing of a space module on the surface of the Moon. The proposed method is of interest both for using manned and unmanned space technology.

Keywords
Surface sounding signals, laser scanning, lidar, digital terrain model, lunar landing

Introduction

An important element of space exploration programs is the direct study of the surface of the Solar System's cosmic bodies and planets by automatic and manned spacecraft including the rovers and arranging human on-planet activity. A general analysis of national lunar exploration programs shows that the main consecutive stages of exploring other planets are [1 — 4]:

- Study of the planet's surface using low-orbit space stations (universal and dedicated);
- Performance of automatic and manned missions of transport spacecraft to the orbit of the target planet (cosmic body);
- Building of long-term manned orbital stations;
- Lunar-landing of cosmonauts and exploration of the Moon using as well robotically operated rovers;
- Building and use of fixed lunar bases to provide regular scientific studies and industrial development of the planet's resources.

* *Corresponding author

In order to perform a vigorous on-planet activity it is necessary to have reliable data on the location and state of environmental objects. The data should include the spatial-technical information on the relief, locality, natural entities, and artifacts. The efficiency, accuracy, and relevance of the said data should not depend on characteristics of space environment, lunar day or night time, real topology of an object, etc.

These requirements can be successfully met by using specialized space laser scanning systems (LSS) that have the wide spread and are effectively realized in a large number of technical applications on the Earth. The studies given below show that the use of LSSs will ensure the success and safety of lunar missions both during landing and take-off of MSC and during the movement of cosmonauts on the planet's surface.

Materials and Methods

The lidar method implemented in air, ground and mobile laser scanning technologies shows high accuracy and reliability of the spatial data obtained. By the successful technical adaptation of it for solving research problems on the surface of the Moon, it can become the basis of a multi-channel vision system. The use of scanning laser devices could significantly expand its capabilities, which are now based on the characteristics of television, radar and infrared sensors.

During professional discussions on the implementation of the proposed method in the moon landing support system, the need to study the following issues was revealed, they are:

- laser propagation of the scanner during operation of the space module's landing engine;
- adaptation of industrial lidar technology for use under space vacuum conditions;
- determination of the optimal operation parameters of the on-board computer and selection of an effective method for calculating the DEM under limited landing maneuver time.

Results

As a rule, landing on the Moon where there is no atmosphere is related to the transit from an elliptical orbit to the design point located close to the lunar surface with a near-zero horizontal velocity and a subsequent vertical descent to the design landing point with the deceleration of the lunar landing complex (LC) at the maneuver end (Fig. 1) [5 — 7].

The generation of control signals for issuing a deceleration impulse as well as the calculation and optimization of the vertical trajectory of pre-landing descent directly depends on the actual height of the LC and characteristics of the underlying lunar surface.

The choice of the LC's path to the specified cis-lunar space which ensures the needed conditions for its landing is realized by controlling the spacecraft in orbit according to the data of navigation systems. Information on the space vehicle altitude just above the Moon at the pre-landing maneuver stage can be obtained using signals of existing radar systems, radio altimeters, laser altimeters, autonomous optical navigation systems and others [8 — 10].

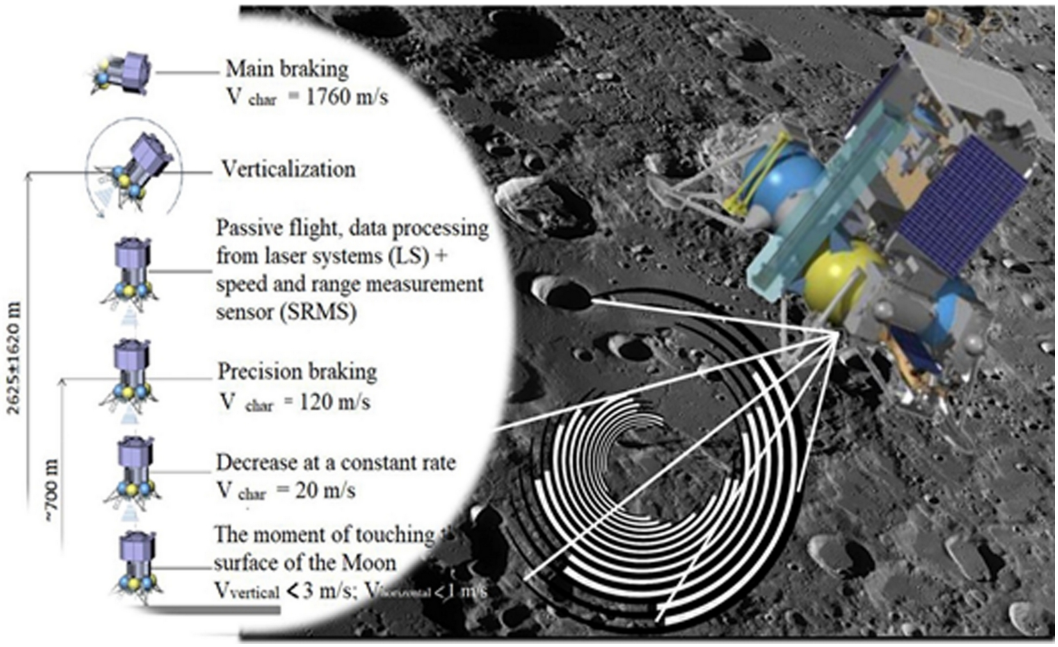


Fig. 1. Parameters of the pre-landing maneuver of the LC

The special problem consists in providing the optimal landing path for the LC and placing it at the safe lunar-landing point (landing site). The landing site is considered safe when the terrain slope is less than 20º with the average distance between the landing legs of existing LCs of ~3 m, when there are no stones and other land roughness of more than ~0.2 m high. Under these conditions the supports or the bottom of the descent module can rest safely [11 — 13].

At present, different technologies of lunar landing of the LC at the post-"verticalization" descent stage are being considered. The key technologies consist in using: the Doppler velocity and range meter (DVRM), tele (video) control, radiolocation, laser range finder, etc. [14 — 18]. An application of these systems does not exclude risks that occurred during Apollo (USA) and Luna (USSR) missions [19 — 24]. It should be noted that some of the said technologies can be used only in the hand control mode by cosmonauts who have a high operator qualification.

Prompt, actual and detailed information on spatial characteristics of the underlying surface as a digital terrain model (DTM) can be obtained by an air laser scanning (ALS) method [25 — 28]. When flying over the lunar surface with some horizontal velocity it is possible to use the space-adapted classic ALS equipment or the scanning lidar technology [29 — 39]. At the post - "verticalization" descent stage, the application of this technology is ineffective due to the absence of the forward motion of MSC relating the Moon and impossibility to generate the spatial sweeping of laser beams.

The most reasonable way to tackle this task is the use of matrix-type laser scanning systems; there are two up-to-date options (Fig. 2).

The spatial laser beams sweep in the rectangular matrix ("Flash Lidar" system) is realized by using the estimated quantity of non-parallel individual radiators and stochastic physical oscillation of the LC relative to the vertical axis at the stage of its descent [40 — 42]. The format of the spiral sweep of the rotating radiators system depends on the number of radiators and the speed of their rotation.

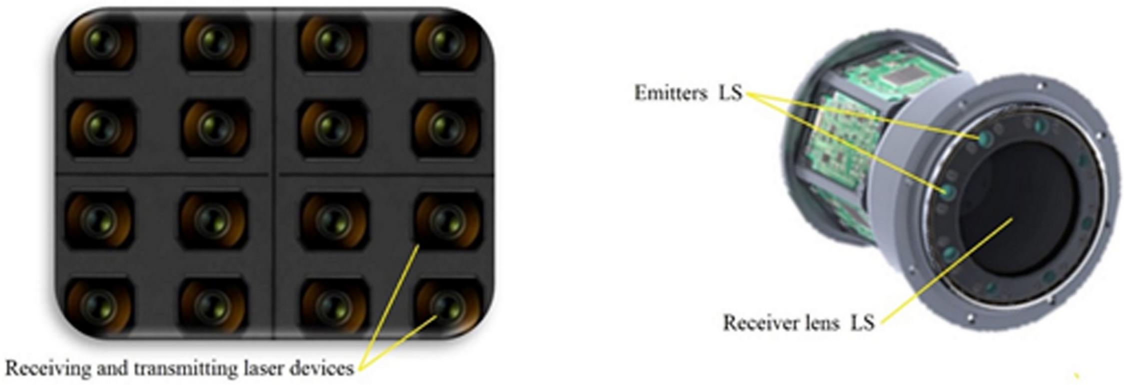


Fig. 2. Technical design options of scanning laser systems for lunar landing (rectangular matrix – «Flash Lidar» system and a rotating radiator system)

In both cases, the frequency of the pulsed radiation of laser sensors as well as the present height of the LC which determines the accuracy of instrumental measurements of range (height), the initial size of the scanning area, and the laser spot diameter – the signal generated as a laser reflection point (LRP) on the planet's surfaces are of particular importance.

A priory, the rotating radiators system has a simpler technical solution, high-density of single measurements on an initial area, more uniform distribution of LRPs over the lunar surface (spatial resolution of shooting) as well as a possibility of enhancing the LSSs by increasing the number of individual laser sensors and the rotation speed of radiators.

Fig. 3 shows the spatial sweep scheme and some characteristics of the matrix-type scanning lidars available in existing industrial prototypes of civil use.

Due to the absence of an atmosphere on the Moon the said parameters of LSSs can objectively be better [43 — 46].

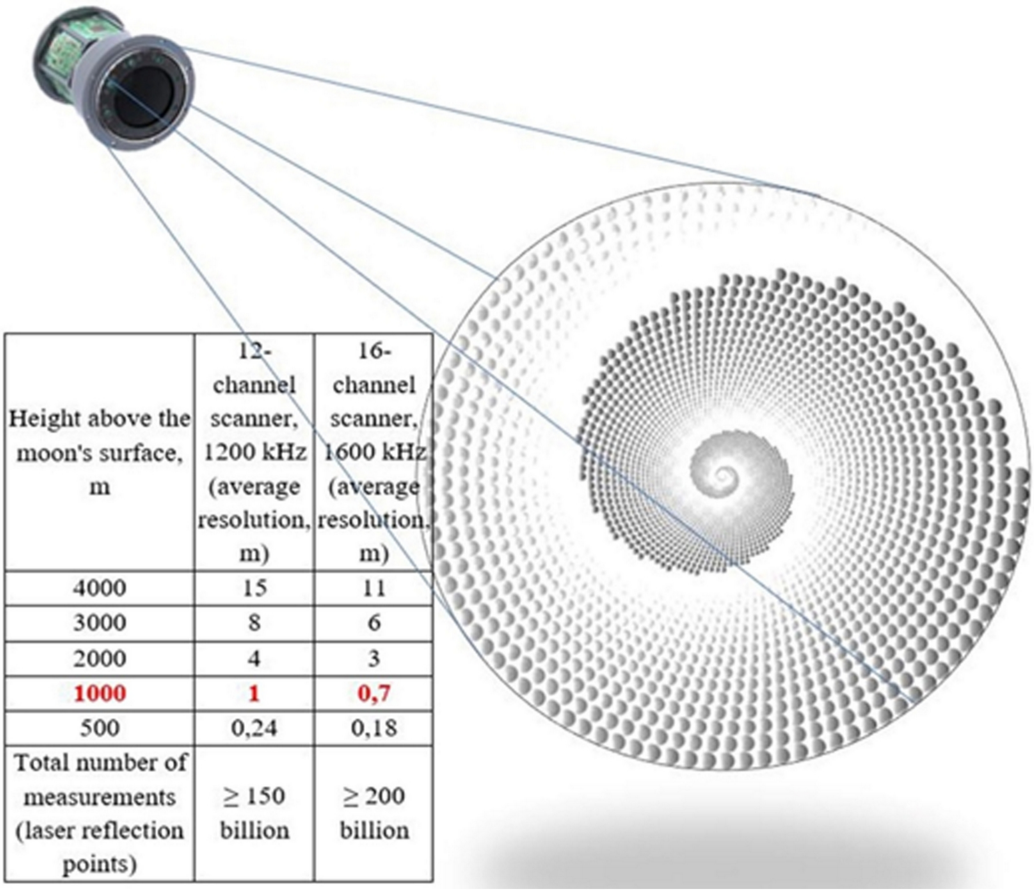
As the calculations show (see Table 3), up to the height of precision deceleration of the LC the laser system provides information on the planet's surface with one meter resolution over a total area of from 18 km^2 to 1.5 km^2. From the height of less than 1 km it is possible to obtain data for performing prompt modelling and using the DTM with spatial resolution of less than 1 m.

As the LC descents the number of points of laser reflection (LRP) per unit of the landing area increases up to the point density (LRP per 1 m^2) helping to reveal (detect) dangerous geometric obstacles (objects) of 15-20 cm high on the planet's surface what ensures solving any special navigation tasks in an automatic mode as well, such as:

- Re-directing of the LC on the new landing pad;
- Spatial orientation, selection of the most rational position of the LC before landing considering the real relief of an underlying surface, position of the Sun, occurrence of obstacles, etc.;
- Calculation and maintaining of the specified vertical descent velocity of the LC;
- High-precision determination of the height (range) to generate a deceleration pulse, etc.

Starting from the height of 500 m and having the reserve of time for descent of more than 30 sec, the effective selection of an optimal lunar-landing site is ensured taking into account all the above said landing safety requirements. It should be noted that applying this technology of lunar-landing the total quantity of single measurements of height (range) at the specified landing site after the "verticalization" of the LC is 150…200 billion that is impossible to ensure by other known ways.

The scanning lidar proposed for use while lunar-landing is per se an adaptive option of ALS. When integrating a scanner radiator into the LC design, it is necessary to take into account the possibility of shading it by external elements of the landing module what can be compensated by installing several radiators or by placing them outside the module dimensions.



Height above the moon's surface, m	12-channel scanner, 1200 kHz (average resolution, m)	16-channel scanner, 1600 kHz (average resolution, m)
4000	15	11
3000	8	6
2000	4	3
1000	**1**	**0,7**
500	0,24	0,18
Total number of measurements (laser reflection points)	≥ 150 billion	≥ 200 billion

Fig. 3. Spatial resolution characteristics of the laser scanner at the pre-landing descent stage

In addition to maintaining the specified operating temperature profile for the lidar as well as taking into account its mass-volume and energy characteristics, the key requirement for adapting ALS to lunar conditions that are subjected to the special study is the evaluation of radiation impact of the landing engine unit on the conditions for passaging a laser pulse signal. Disturbances provoked by the permanent jet flame of the landing engines can impact laser scanning systems what is particularly dangerous at the final stage of lunar-landing which is about one minute.

Interpretation of the moon sounding signals using LSS is performed in both automatic and manual LC landing modes. In both cases, processing laser pulses reflected from the Moon's surface result in obtaining the DTM (Digital Terrain Model). This model is a peculiar digital twin of the real landing site relief. Depending on the signal processing method aboard the LC using a highly productive computer the GRID-model or TIN-model of the surface of the Earth's natural satellite is generated [47 — 50]. Besides, it is possible to apply other LS data processing methods. The use of them is limited by the requirements for the size, operability, accuracy, detail, and reliability of the

DTM generation.

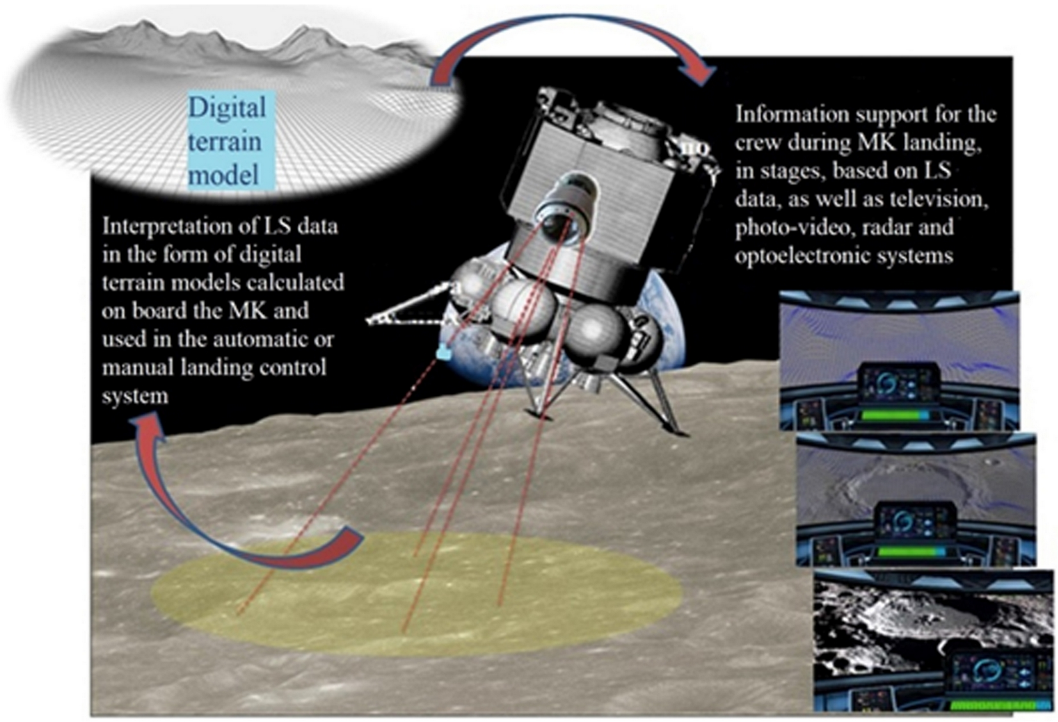


Fig. 4. The use of laser scanning data at the stages of landing of the Lunar Complex

While descending, the LC's computer constantly specifies the design landing point (site) and generates the control signals to turn on/off the LC's engine unit on the basis of continuous processing the spatial information contained in the DTM using navigational algorithms for landing. At the same time, the said information in any format is displayed for cosmonauts on the screen which visualized the area specified for landing together with data from optoelectronic, radio-electronic, and other subsystems against the Lunar map or the initial cartographic underlay of the seleno-information system.

If the automatic landing control system fails, data from the scanning lidar as a basic information module together with data from other sensors will allow landing in the director or manual mode regardless of eventual optical occurrences such as dust clouds that make worse the direct visual contact of cosmonauts with the Moon.

The proposed above landing technology, which is used for the spacecraft's vision system and the use of data from the LSS, is based on the interpretation of the moon sounding signals – the direct active high precision measurement of the spatial characteristics of sets of lunar surface points and the intelligent processing of obtained digital images – and can be effective for ensuring safety of space missions. Due to the objective necessity to use the lidar survey data promptly during high-dynamic stages of lunar-landing, the processing of this data in an external circuit (digital cloud) is not possible but should be performed using a highly productive computer complex directly on board the LC [51 — 53].

Author contributions: I.K. developed the idea of using a laser scanner with a rotating matrix. B.K. proposed to use this laser scanner in the lunar space module’s landing system. Both authors have read and approved the final version of the paper.

Funding: This research received no external funding.

Data availability statement: The data presented in this study are openly available. The authors' open materials on this topic were previously published in [29, 42]. The paper was prepared in May 2023.

Conflicts of interest: The authors declare no conflict of interest.

References

1. The strategy of the Russian manned cosmonautics until 2035. – GC "Roscosmos", 2022. – 35 p.
2. The concept of Russian manned cosmonautics. – GC "Roscosmos", 2022. – 18 p.
3. The Russian Lunar program. – URL: https://руни.рф/index.php/Российская_лунная_программа (accessed date: 28. 04. 2023).
4. Russian Lunar exploration Program. – URL: https://topwar.ru/121142-rossiyskaya-programma-osvoeniya-luny.html (accessed: 04/28/2023)
5. E.S. Gordienko, A.V. Simonov, P.A. Khudorozhkov. Ballistic Planning of Missions for the Delivery of Lunar Soil Samples to the Earth // Engineering Journal: Science and Innovations, №3, 2020. P. 1–22.
6. Spacecraft Motion Control While Landing on the Moon Surface. B.I. Zhukov, V.N. Likhachyov, P.E. Rozin, Yu.G. Sikharulidze, A.G. Tuchin, D.A. Tuchin. // Bulletin of R&PA named after S.A. Lavochkin №4 (54), 2021. P. 22–30.
7. E.A. Mikrin. Scientific and Technical Problems of Implementing the “Manned Space Systems and Complexes” Project // Space Engineering and Technologies, №3 (26) 2019. P. 5–19.

8. Satellite Navigation of Circulunar Spacecraft and Objects on the Moon Surface. E.A. Mikrin, M.V. Mikhailov, I.V. Orlovsky, S.N. Rozhkov, I.A. Krasnopolsky. // Gyroscopy and Navigation, Vol. 27, № 1 (104), 2019. P. 22–32.
9. Gordienko, E.S., Ivashkin, V.V., and Simonov, A.V., Analyzing stability of orbits of artificial satellites of the moon and choosing the configuration of the lunar navigation satellite system, Vestnik NPO im. S.A. Lavochkina, 2016, no. 4 (34), pp. 40–54.
10. On the possibility of using astronomical navigation methods to ensure manned flights to the Moon. A.I. Kondrat, A.A. Mitina, G.D. Oreshkin, A.I. Shurov / Proceedings of the Ninth International Aerospace Congress IAC'18 dedicated to the 30th anniversary of the successful flight of the Buran orbiter. Abstracts of reports of Lomonosov Moscow State University (August 28-31, 2018. Moscow, Russia). pp. 428-429.
11. Where to land: which landing sites on the moon were chosen for NASA astronauts. – URL:https://rtraveler.ru/universe/kuda-prilunitsya-kakie-mesta-vysadki-na-lune-vybrali-dlya-astronavtov-nasa / (accessed: 04/28/2023)
12. Ivanov M.A., Abdrakhimov A.M., Bazilevsky A.T., etc. The geological context of the potential landing site of the Luna-Globe expedition. - Astronomical Bulletin. 2014. vol. 48, No. 6. pp. 423-435.
13. Ivanov M.A., Marov M.Ya., Bazilevsky A.T. et al. Boguslavsky crater on the Moon: choosing a landing site for the LUNA-GLOBE mission lander. - Bulletin of FSUE NPO named after S.A. Lavochkin, 2017. No.2. pp. 44-51.
14. B.S. Zhukov, I.V. Polyansky, S.N. Zhukov. Autonomous Optical Navigation in Lunar Orbit and While Lunar Landing Using a Superwide-Angle Camera. // Current Problems of Remote Sounding of the Earth from Space. 2017. Vol. 14. № 2. P. 24–35.
15. Huang Yichong. Optimal control of the maneuver of the lunar vehicle to the selected soft landing point between hovers. - Proceedings of MAI, 2016, No. 4: - URL: http://trudymai.ru/published.php?ID=74747 (accessed: 04/28/2023)
16. Shirenin A.M., Mazurova E.M., Bagrov A.V. Construction of a high-precision selenodesic coordinate system on the physical surface of the Moon using LED beacons located on its surface // Space Research. 2016. vol. 54, No. 6. pp. 493-498.
17. Bagrov A.V., Dmitriev A.O., Leonov V.A. and others. Global positioning system for the Moon based on active light beacons // Bulletin of S.A. Lavochkin NPO. 2017. No. 4. pp. 5-10.

18. Bobronnikov V.T., Kozorez D.A., Krasilshchikov M.N. et al. Statistical dynamics and optimization of aircraft control. - M.: Alliance, 2013. - 468 p.
19. The magazine "All about space". The Apollo 15 mission. – URL: https://aboutspacejornal.net (accessed: 04/28/2023)
20. B.I. Kryuchkov, B.V. Burdin, A.V. Solodnikov. The experience of the USSR and the USA in preparing cosmonauts and astronauts for landing on the Moon // Manned space flights, №1 (34). - 2020. Pp. 86-103.
21. "Luna-15". – URL: https://epizodsspace.airbase.ru/e2/foto-e2/l-15/l15.html (accessed: 04/28/2023)
22. Kazmerchuk P.V., Martynov M.B., Moskatinev I.V., etc. The LUNA-25 spacecraft is the basis for new lunar exploration. - Bulletin of S.A. Lavochkin FSUE NPO, 2016. No.4. pp. 9 — 19.
23. Compton, William David Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions. - p.139. NASA (1989)
24. Lindsay, Hamish Apollo 11. The First Men Jn The Moon. A Tribute to Honeysuckle Greek Tracking Station. – URL: https://honeysucklecreek.net/msfn_missions/Apollo_11_mission / hl_apollo11.html (accessed: 04/28/2023)
25. Komissarov A.V. Theory and technology of laser scanning for spatial modeling of territories. Dissertation for the degree of Doctor of Technical Sciences // Komissarov Alexander Vladimirovich. Siberian State University of Geosystems and Technologies (SSUGiT). Novosibirsk, 2015 – 278 p.
26. Laser location of the earth and forests: A textbook / Medvedev E.M., Danilin I.M., Melnikov S.R.− 2nd ed., reprint. and additional − M.: Geoskosmos; Krasnoyarsk: V. N. Sukachev Institute of Forest SB RAS, 2007. − 230 p.
27. A. Ulrich. Information content of the point cloud during aerial laser scanning. - URL: http://лазер.рф/2019/11/28/14842 / (accessed: 04/28/2023)
28. Ground laser scanning: monograph // V.A. Seredovich et al. - Novosibirsk: SGGA, 2009. – 261 p.
29. Kulikov I.N. Laser scanning devices and their use in promising Lunar missions // Manned flights into space, No. 4 - 2021. pp. 57-74.
30. Starovoitov E.I., Zubov N.E. The use of a laser altimeter as a backup meter when approaching spacecraft in lunar orbit. - Space Engineering and Technologies, 2015, No.

3(10), pp. 60-67.

31. Russian space-based lidar of the BALKANS. Zuev V.E., Balin Yu.S., Tikhomirov A.A., Znamensky I.V., Melnikov V.E. // Space science and technology. No.3 (1), 1997, pp. 16-25.
32. Baturin Yu.M., Kryuchkov B.I., Leonov A.V. Virtual 3D modeling of real PKCS in the interests of historical and technical research and preservation of scientific and technical information about objects. // Manned space flights. No. 3 (28), 2018, pp. 97 – 116.
33. Laser on the ISS to combat space debris. - URL: http://www.dailytechinfo.org/space/6946-lazer-kosmicheskiy-musor.html (accessed: 04/28/2023)
34. Laser communication in space. - URL: https://ru.qaz.wiki/wiki/Laser_ communication_in_space (accessed: 04/28/2023)
35. Laser weapons in space. Features of operation and technical problems. - URL: https://topwar.ru/171444-lazernoe-oruzhie-v-kosmose-osobennosti-jekspluatacii-i-tehnicheskie-problemy.html (accessed: 04/28/2023)
36. Russian light in space (Laser rangefinders). - URL: http://space.hobby.ru/projects/slr.html (accessed: 04/28/2023)
37. The choice of lasers to increase the range of onboard location systems of spacecraft. Starovoitov E. I., Savchuk D. V., Zubov N. E. // Scientific edition of Bauman Moscow State Technical University, issue No. 08, 2013. - URL: http://cyberleninka.ru/article/n/vybor-lazerov-dlya-uvelicheniya-dalnosti-bortovyh-lokatsionnyh-sistem-kosmicheskih-apparatov (accessed: 04/28/2023)
38. Lidar in space. - URL: https://www.spar3d.com/blogs/the-other-dimension/lidar-in-space-2 / (accessed: 04/28/2023)
39. The Perseverance rover scans the rocks of Mars with a "singing laser". You can listen to it. - URL: https:// www.bbc.com/russian/features-56363527 / (accessed: 04/28/2023)
40. Flash Lidar performance with real-time image enhancement algorithms to prevent landing hazards. Farzin Amzajerdyan, Paul Brewster, Byron Meadows, Rafia Haq. NASA Langley Research Center, Hampton, Virginia 23681, USA. 2015 - 14 p.
41. Lidar ZENMUSE L1. – URL: https://www.dji.com/ru/zenmuse-l1 (accessed: 04/28/2023)
42. Kryuchkov B.I., Kulikov I.N., Burdin B.V. On information support of the crew's actions using a scanning lidar during the landing of a manned lunar module // In the book: Manned flights into space. Materials of the XIV International Scientific and Practical conference of the FSBI "Research Institute of the Central Research Institute named after Yu.A. Gagarin",

November 2021. pp. 20-22.

43. H. Yichong. Motion control of a spacecraft making a soft landing on the moon according to the hovering scheme. Huang Yichong. Moscow Aviation Institute (National Research University), 2018.- 133 p.
44. A.E. Potter, T.H. Morgan (1988). Discovery of Sodium and Potassium Vapor in the Atmosphere of the Moon Archive copy dated June 21, 2008 on Wayback Machine Science 241 p. – URL: https://www.science.org/doi/abs/10.1126/science.241.4866.675 (accessed: 04/28/2023)
45. V.D. Krotikov, V.S. Troitsky. Radio emission and the nature of the Moon. – URL: https://ufn.ru/ufn63/ufn63_12/Russian/r6312a.pdf (accessed: 04/28/2023)
46. The use of laser (optical) communication in space on Earth. – URL: https://intellect.icu/ispolzovanie-lazernoj-opticheskoj-svyazi-v-kosmose-na-zemle-9322 (accessed: 04/28/2023)
47. Novakovsky B.A., Permyakov R.V. Complex geoinformation and photogrammetric modeling of relief: Textbook. – M.: Publishing House of MIIGAiK, 2019 – 175 p.
48. Using GRID and TIN for analysis and modeling of spatial objects, processes and phenomena. – URL: https://geo.bsu.by/images/pres/soil/gisopt/gisopt05.pdf (accessed: 04/28/2023)
49. PHOTOMOD digital photogrammetric system. Version 7.0. User Manual. Creation of a digital relief model. -M.: Publishing house "JSC firm "Rakurs", 2020 - 301 p.
50. Digital relief model by tin. – URL: https://topogis.ru/tsifrovaya-model-rel-yefa-po-tin.php (accessed: 04/28/2023)
51. GR740 Next Generation Microprocessor Flight Models. – URL: https://indico.esa.int/event/373/contributions/6118/attachments/4194/6283/0900%20-%20Presentation%20-%20GR740.pdf (accessed: 04/28/2023)
52. Pavel Osipenko. Microprocessors for space applications. – URL: https://russianelectronics.ru/mikroproczessory-dlya-kosmicheskih-primenenij/ (accessed: 04/28/2023)
53. High-performance Space Computing (HPSC). – URL: https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/HPSC (accessed: 04/28/2023)