The Russian Lunar Exploration Project

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Received February 24, 1999

Abstract—The Russian Lunar Exploration Project has the twin aims of establishing the internal structure of the Moon and determining the composition of the volatiles in a lunar polar region. The determination of the internal structure of the Moon, including an answer to the question of whether it has an iron core and of the size of such a core, is of crucial importance in choosing between the alternative mechanisms proposed to account for the formation of the Moon and the Earth. An analysis of volatiles *in situ* will pave the way not only to understanding the history of the Moon, but also the origin of the carbon–water material of the Earth. The research undertaken with the goal of solving these problems involved planning experiments, determining the composition of the instrument package and the contours of the spacecraft, and choosing the scenario of the space mission. Two seismic experiments are planned to achieve the main objective: the determination of the internal structure of the Moon. The first involves the use of two landers, spaced approximately 300 km apart and carrying wideband seismometers; the second involves the use of a small-aperture seismic array formed by positioning 10 seismometers on an area about 10 km in diameter, the seismometers having been delivered to the lunar surface by high-speed penetrators. It is proposed to land a polar station on the floor of a crater in the region of the south pole. The instrumentation complex of the polar station consists of a gamma-ray spectrometer, a neutron spectrometer, a mass spectrometer, a television camera, and several other instruments. The spacecraft is designed for use with launch vehicles of the *Molniya* or the *Soyuz-2-Fregat* type.

INTRODUCTION

A return to lunar exploration appears expedient for several reasons: (1) the factual material obtained in the 1960–1970s has been fully processed and interpreted; (2) new objectives, connected with advances in terrestrial geology and in cosmochemistry, have been formulated; (3) technologies and tools have appeared that make it possible to obtain new data with previously unattainable precision and particulars, and (4) projects have emerged for establishing stations on the Moon to utilize its resources, conduct astronomical observations, etc.

Studies of the Moon are of key importance in solving problems of fundamental geology. Just as investigations of the oceanic crust—above all, deep-sea drilling—have radically altered our notions of geotectonics and the dynamics of geological processes in recent decades, so the exploration of the Moon may be expected to lead to a new breakthrough in the Earth sciences. The Moon is in many respects a unique laboratory. Thanks to the absence of an atmosphere, its seismic stability, and the shielding of its farside from terrestrial radio noise, the Moon is an ideal location for deploying astrophysical stations and other such facilities. There are well-founded projects for using the Moon in future power generation. It is believed that terrestrial energy sources, including natural and nuclear fuels, will be unable to meet the needs of production by the middle of the 21st century. Two possible ways of solving this problem have been proposed, both of them involving the utilization of the Moon. The first is a project for the lunar-based production of ^{3}He and its delivery to Earth for use in thermonuclear fusion. This method would even today have economic advantages over the use of fossil fuels or uranium, if the technology of thermonuclear fusion and a corresponding infrastructure were in place. Secondly, a project has been developed and substantiated for establishing solar power plants on the Moon and transmitting the energy generated to Earth by microwave converters.

The Russian Lunar Exploration Project attaches priority to two goals. First, the determination of the internal structure of the Moon, including an answer to the question of whether it has a core and of the size of such a core; second, an analysis of the composition of the volatiles, including water, which could be concentrated in depressions at the lunar poles.

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PRIORITY OBJECTIVES OF LUNAR EXPLORATION

The Problem of the Origin of the Moon

In the area of lunar studies, there is a topical scientific problem, whose solution will lead to notable progress in the Earth sciences and planetology. The problem has arisen with advances in terrestrial geology. This is the problem of the origin of the Moon.

An understanding of the mechanism of the formation of the Moon furnishes a key to understanding the mechanism of the formation of the Earth. For its part, an understanding of the mechanism of the formation of the Earth and of its early geological history now ceases to be an academic problem of the natural sciences and is becoming one of the fundamental problems whose solution is relevant to the advancement of practical geology, environmental forecasting, etc.

The majority view at present is that the Moon formed as a result of a collision of the Earth with a large cosmic body, whose mass was about 0.1 that of the Earth, that is, it was the size of the planet Mars. The collision caused the ejection of material from the Earth's mantle into the Earth's orbit, and this material subsequently accreted to form a satellite. The Moon in this case inherited the chemical composition of the Earth's mantle, which accounts for its relatively low density and its lack of a massive iron core. The Moon's core cannot exceed 5% of its mass, whereas in the case of the Earth the iron core makes up 32% of its mass. This hypothesis was put forward by the American scientists Hartmann and Davis (1975) and Cameron and Ward (1976).

An alternative hypothesis, investigated by Galimov (1990; 1996), proposes that the Moon was formed not from terrestrial material but, like the Earth, from material of cosmic composition (the material closest to this composition is that of C1-type carbonaceous chondrites), that is, the formation of the Earth and the Moon was not consecutive but concurrent, with the loss of iron in the course of some high-temperature process.

There are also other versions of the formation of the Moon and the Earth from a common protoplanetary reservoir (Ruskol, 1975; Wasson and Warren, 1979; Weidenschilling *et. al.*, 1986). Although in some cases they contain fair criticism of the megaimpact theory (Boyarchuk *et al.*, 1998), they are not supported by arguments concerning material composition and, therefore, propose no material criteria that could be verified.

Whichever of these alternative hypotheses is correct, naturally, shapes our understanding of the early history of the Earth.

The purpose of our project is to determine those physicochemical parameters whose measurement could justify a reliable choice of one of the options of the formation of the Moon and the Earth–Moon system.

A geochemical analysis of the problem shows that such parameters exist. One of the key questions here is that of the refractory elements. At present there is no reliable estimate of the abundances of the refractory elements (Al, Ca, Ti, U, Th, Sr, the rare earths, and others) in the lunar material. An excess of refractory elements implies that a cosmic body had a high-temperature stage in its history. Laboratory experiments involving the evaporation of silicate melts in a vacuum show that an enrichment in refractory elements inevitably entails a loss of iron. The Moon, however, contains at least as much iron as does the Earth's mantle. Hence, if the Moon is enriched in refractory elements, it cannot have formed from material of the Earth's mantle.

The problem of whether the Moon is enriched in refractory elements cannot be solved by analyzing lunar rock samples. The crustal rocks of the Moon are substantially enriched in Al, Ca, and Ti. On the other hand, the upper mantle, from which these rocks segregated, is characterized by low abundances of refractory elements (Fig. 1a). It is therefore estimates of the abundances of the refractory elements in the lower mantle that acquire a decisive importance. The rocks of the lower mantle cannot be studied directly. There is, however, a connection between the content of Al_2O_3 (Al is one of the principal refractory elements) and the elastic properties of rocks. At high abundances of Al_2O_3 in the lower mantle, its mineral composition (high content of garnet [22–28%] and magnesian character of olivine and pyroxene) corresponds to a definite range of possible seismic-wave velocities (Fig. 1b). Therefore, by obtaining a seismic-velocity profile for the interior of the Moon, it would be possible to answer the question of whether or not the Moon is enriched in refractory elements compared with the Earth.

Additionally, at an enhanced abundance of Al_2O_3 in the lower mantle, the observance of the constraints related to the known medium density and moment of inertia of the Moon requires the existence of an appreciable core of about 5% of the lunar mass (radius ~500 km) (Fig. 1c). On the contrary, if the abundances of the refractory elements on the Earth and the Moon are the same, the Moon should have a small core or none at all. It should be noted that the current interpretation of seismic data for the Moon (the Nakamura model) rather points to an enhanced abundance of Al_2O_3 (7–10%) in the lower mantle (Hood, 1986; Kuskov and Fabrichanaya, 1994). However, the available seismic data, based on experiments during the *Apollo* missions, are scant and do not justify final conclusions.

Another geochemical criterion of the conditions of the Moon's formation is associated with the character of the distribution of siderophile elements on the Moon and the Earth. The siderophile elements (Ni, Cd, W, P, Pt, Re, Te, and others) have an affinity for iron and, in the process of planetary core segregation, pass into the core, impoverishing the material of the mantle.

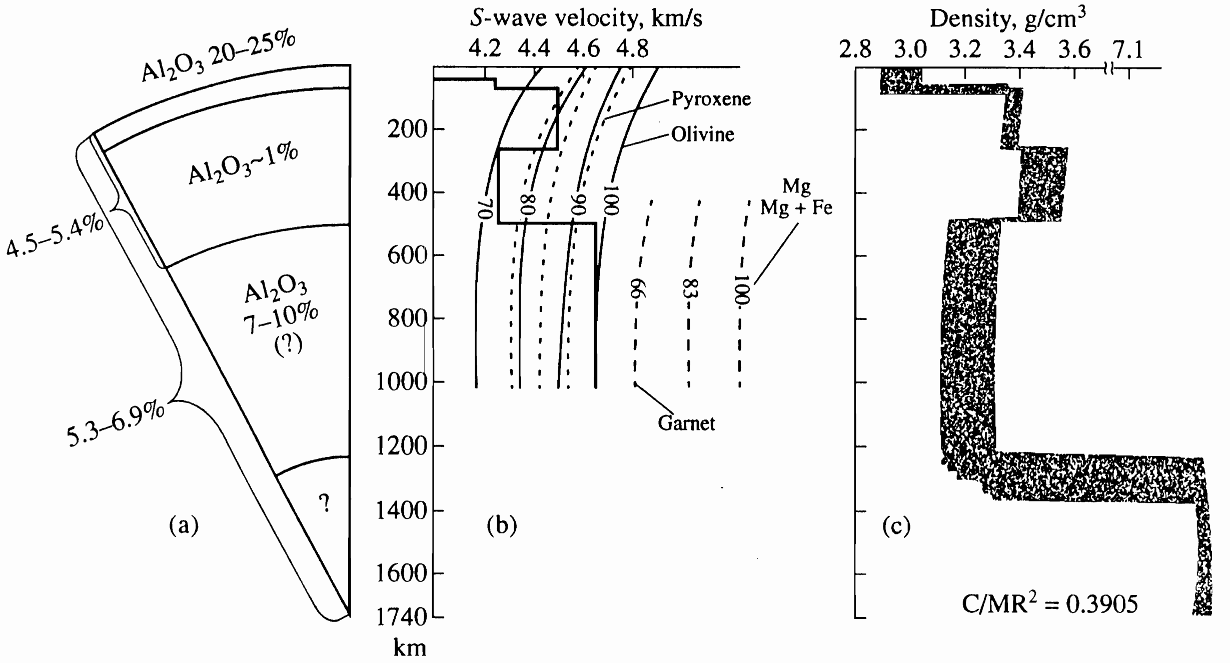

Fig. 1. Relationship between the chemical and the physical structure of the Moon. (a) Al_2O_3 distribution, known for the lunar crust and presumed for other shells of the Moon; (b) seismic profile (thick line) according to data of the *Apollo* missions (Nakamura, 1983) and computed curves of *S*-wave velocities for deep-seated minerals (Hood, 1986); (c) family of computed curves (Hood, 1986) describing the density stratification of the Moon that corresponds to an Al_2O_3-enriched lower mantle. In all cases the calculations point to the existence of a sizeable core (radius 300–500 km).

The degrees of siderophile impoverishment of the Earth's mantle and the Moon are fairly close, and this is a strong argument in support of the formation of the Moon from terrestrial mantle material. The similarity of the distribution of siderophile elements in the material of the Earth and the Moon suggests that the Moon should have no core or that, at any rate, it should not exceed 0.4% of the lunar mass. Otherwise there would be an excessive depletion of the Moon in siderophile elements relative to the Earth.

On the other hand, under certain conditions the observed distribution of siderophile elements could also have arisen if the Moon had formed from material of cosmic composition (Galimov, 1996). In that case, however, the core should have a mass of no less than 4.5–5.5% of the lunar mass.

It follows from this that the size of the core is of crucial importance in solving the problem of the origin of the Moon. The hypothesis of the formation of the Moon from material of the Earth's mantle can only be valid if the Moon has a very small core (0.4% of the lunar mass) or none at all. Conversely, the hypothesis of the formation of the Moon from material of solar composition calls for the existence of a core of 4.5–5.5% of the lunar mass (Galimov, 1996).

The geochemical criteria of the lunar origin can thus be applied in geophysical experiments designed to investigate the internal structure of the Moon.

Seismic experiments on the Moon were conducted under the *Apollo* program. A more or less dependable seismic-velocity profile was obtained to depths of approximately 1000 km. However, the elastic properties of the interior of the Moon and the size of its core remain unknown.

Hence, the first objective of the project: staging a seismic experiment that would, using contemporary techniques, provide information on the internal structure of the Moon.

The Problem of the Origin of Water and Carbon

Questions about the origin and history of the most important volatiles of the Earth remain unanswered to this day. For example: did the ocean form as a result of outgassing the Earth's mantle, or was the water brought in material of the type of carbonaceous chondrites and comets that impacted the planetary body at the concluding stage of its formation? Why is the isotopic composition of the hydrogen of the World Ocean and the mantle so different? Could the carbon compounds observed in carbonaceous meteorites and comets have initiated the development of the Earth's biosphere?

The solution of these problems could be facilitated by investigations of the composition and evolution of the lunar volatiles (water, compounds of carbon, nitrogen, etc.). These constituents have not survived on the surface of the Moon or in the rocks of its crust. But

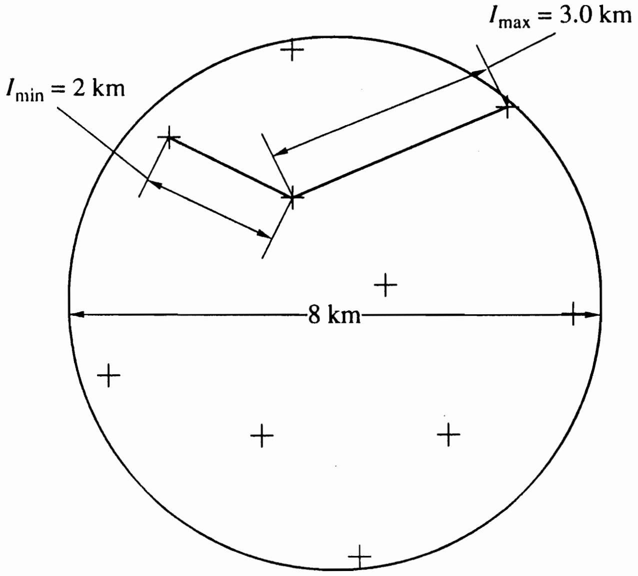

Fig. 2. Small-aperture seismic array.

since the lunar polar axis diverges from the normal to the ecliptic plane by a mere 1.5°, the depressed terrain in the region of the poles—for example, the floors of craters—may never have seen the Sun, with the result that the temperature there should be very low (~40 K). This would freeze the water and other volatiles that appeared on the surface of the Moon in the course of its outgassing or precipitation with comets and meteorites. Accumulation over geological time could lead to the condensation of considerable masses of ice in the regolith of the polar regions (Arnold, 1979).

Imaging from orbit by the American spacecraft *Clementine* in 1994 revealed a depression in the region of the south pole that has remained largely shadowed (Shoemaker *et al.*, 1994). According to observations by the American orbiter *Lunar Prospector*, there is indeed an enhanced concentration of hydrogen in the regions of both the south and the north pole of the Moon.

The condensation and preservation of water and carbon compounds in the lunar polar regions offers a unique chance of peering into the past and investigating the composition of the primitive carbon–water material of the Earth.

It would be extremely valuable if a soil sample from a polar region of the Moon were delivered to Earth. This would make possible its detailed investigation, including high-precision isotope analysis.

However, at the first stage, it would be expedient to conduct investigations *in situ* so as to confirm the existence of ice, assaying the composition of the soil and the concentration of water and other volatiles in it.

Studies of the soil in the permanently shadowed zone by landing a polar station there are regarded by us as the second priority of the project.

EXPERIMENTS PLANNED TO ACHIEVE THE PROJECT OBJECTIVES

In 1997, the Russian Space Agency allocated funds for research work under a lunar exploration project (code-name *Luna–Globe*), which made it possible to specify the character of the experiments planned, determine the contours of the spacecraft, and work out the scenario of the space mission.

The Seismic Experiment

Seismic studies to achieve the major objective—the determination of the internal structure of the Moon—are to be conducted by the parallel staging of seismic experiments of two types: (i) establishing a small-aperture seismic array, and (ii) using stations fitted with an extra-wideband seismic detector.

The experiment involving a small-aperture seismic array has been proposed by geophysicists at the Schmidt Institute of Physics of the Earth (O.B. Khavroshkin).

Preliminary calculations show that satisfactory results can be obtained with an array of ten seismic detectors mounted on high-speed penetrators piercing the lunar soil in an area approximately 10 km in diameter (Fig. 2) and spaced about 2–3 km apart.

Information on the internal structure of the Moon is to be obtained by processing the seismic data according to several seismic methods, including a transfer-function method and a modulation-effect method (Khavroshkin and Tsyplakov, 1996).

The gist of the method of transfer functions consists in jointly analyzing the entire totality of secondary multiple and exchange waves, and recasting the waveforms into a velocity profile. The method presupposes a knowledge of the exact cardinal-point orientation of horizontal-axis seismographs. In the case of an experiment with a group of penetrators that do not pierce the lunar soil simultaneously, the compressional waves generated by the incoming penetrators can be recorded by already operating instruments. At known coordinates of all the penetrators, the orientation of a horizontal-axis seismograph can be recorded with an accuracy higher than7°–10°, provided the seismograph succeeds in recording a compressional wave at least from a single penetrator.

The modulation effect makes it possible to identify long-period oscillations that modulate short-period oscillations and, in this way, register a signal of a very low frequency, using a relatively narrowband seismic detector sensitive to short-period oscillations. The range of the long-period oscillations registered will also cover the spectrum of the natural oscillations of the Moon, which should differ substantially, depending on whether it has a core or not.

It is proposed to use an improved version of the seismometer developed for the *Mars-96* spacecraft as the seismic detector element of the small-aperture array (Fig. 3).

speed penetrator has the following rated parameters:

Total mass	12 kg,
Including seismic instrumentation	3 kg
Seismometer recording range	0.5–40 Hz
Sensitivity	10^{-10} cm/Hz
Radiotelemetry unit and control unit	1 kg
Buffer memory capacity	20 mb
Power unit (lithium batteries)	3 kg
Active lifetime	1 yr
Acceptable g-forces	up to 10 000 g;
Dimensions:	
(a) diameter	12 cm
(b) length in different modifications	1–2 m
Soil-piercing angle	not < than 75°
Angle of attack	3°–7°

It is a distinctive feature of the seismic experiment involving the establishment of a small-aperture array that the penetrators are dropped from an approach trajectory and pierce the ground at a high speed. In the limiting case—in the absence of braking thrust—this is a speed of 2.5 km/s, and the penetrators may be expected to pierce the regolith to a depth of 10–15 m. The penetrator body is shaped so as to reduce the g-force effects on the scientific instrumentation. Although the available data show that the serviceability of the instruments can be preserved under these harsh conditions, further tests may necessitate a reduction of the insertion speed of the penetrators. The consequent increase of propellant consumption makes the orbital studies optional and may minimize the instrumentation of a polar station.

It is desirable that the small-aperture array be deployed on the Moon in an area with a low seismicity and a thick regolith layer. On the nearside of the Moon, it is the eastern part of the southern hemisphere that is calmest seismically (Lammlein, 1977). The regolith is thicker in the highlands, but the dissected topography makes a landing there riskier. The researchers who have been choosing a landing site (headed by V.V. Shevchenko) consider the southern part of Mare Fecunditatis, centered at18° S and 52° E, to be the optimal location for deploying the small-aperture array (Fig. 4).

The second type of seismic experiment involves the use of a seismic station that includes a wideband seismic detector.

A wideband seismometer that is sensitive enough in the region of long-period oscillations is needed because of the distinctive elastic properties of the Moon.

Investigations of the interior of the Moon are hampered by relatively high attenuation (low values of the quality factor Q) at depths exceeding 1000 km (Lognonne and Mosser, 1993). The value of Q diminishes from 1500 in the lower parts of the lunar upper mantle to less than 300 at depths of 800–1000 km. Attenuation increases especially rapidly at higher frequencies. While at a frequency of 1 Hz the increase is 50-fold, at 0.5 Hz it is 8-fold, and at 0.125 Hz, a mere 2-fold.

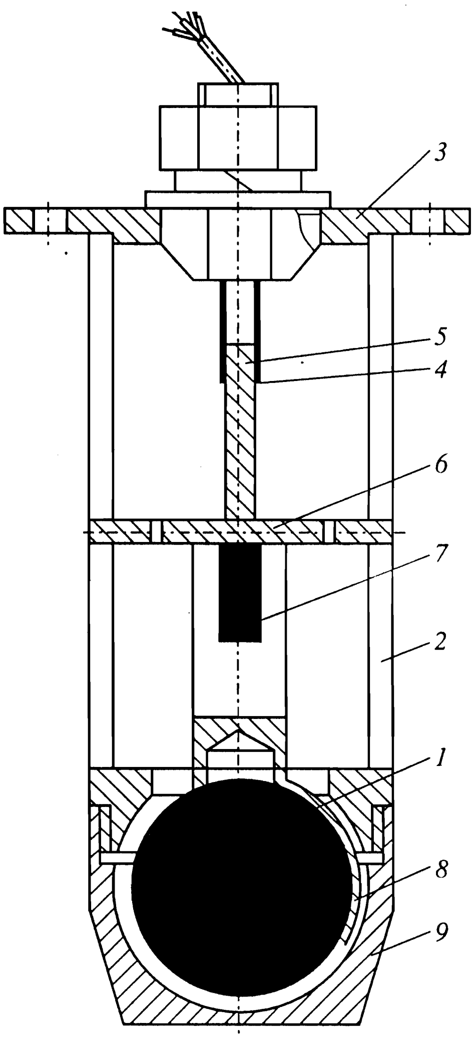

Fig. 3. Seismic detector developed for penetrator of the *Mars-96* project: (*1*) spherical mass; (*2*) body; (*3*) lid; (*4*) flexible-element tail; (*5*, *6*) adapter; (*7*) piezoelectric sensor; (*8*) leaf spring; (*9*) bottom trap.

Hence the importance of developing a seismometer that is highly sensitive in the region of low frequencies (Fig. 5).

An example of such an instrument is the French wideband triaxial seismic detector of the Q type, designed for the *Mars-96* mission. Its sensitivity is nearly two orders of magnitude higher than that of the seismometer used in the *Apollo* project in the region of frequencies below 1 Hz. A modified version of the seismometer is capable of withstanding g-forces of the order of 1000*g*.

It is proposed to employ two landers carrying wideband seismometers of this type.

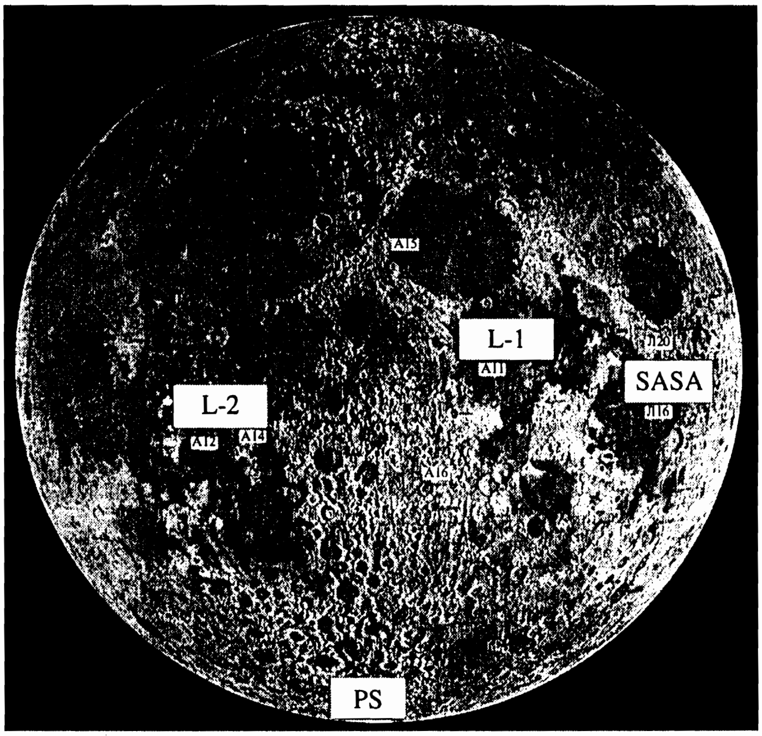

Fig. 4. Location of landers delivered to the Moon in the course of the planned experiment: SASA—small-aperture seismic array (18° S, 52° E); L-1—lander with wideband seismic detector (7° N, 23.5° E); L-2—same (3° N, 23.4° W); PS—polar station (87.5° S, 38° E).

The landers are to be deployed at a considerable distance (no less than 300 km) from each other in the equatorial zone. It is expedient to do this at the *Apollo* landing sites . The sites chosen have the geographical coordinates 0.7° N, 23.5° E and 3° N, 23.4° W, which correspond to the landing sites of *Apollo 11* and *Apollo 12*, respectively.

The technical potential of present-day seismic sounding allows for a depth error of ±20 km in determining the boundaries of the lunar core and the lower mantle. If, however, the degree of horizontal inhomogeneity in the transition zone is high, the uncertainty of the determination can rise to 40–80 km. This is satisfactory for achieving the aims of the seismic experiment.

Analysis of the Soil in the Permanently Shadowed Zone

To study the composition of the soil in a polar crater where there may be frozen water, it is planned to land a station containing instruments for soil sampling and investigation in the region of the south pole.

The scientific instruments installed in the polar station and their purpose and principal characteristics are listed in the table. Most of the instruments can, in this or that measure, provide information on the presence of volatiles, specifically water, in the lunar soil at the landing site of the station. These instruments include a television camera, a neutron detector, a gamma-ray and a mass spectrometer.

The TV camera is intended for obtaining a panoramic picture of the landing site of the station and measuring the physical characteristics of the soil. It can also be used to form an opinion on the presence of frozen volatiles on the basis of several parameters: (i) the albedo value; (ii) the reflective properties of the soil in imaging in different wavebands, and (iii) the reflectance characteristic of the surface under illumination at different angles. Because the landing area is shadowed, it is proposed to use artificial light sources (flares, flash bulbs, and spectrum-selective light-emitting diodes). The TV experiment could yield the following information: (i) a panoramic picture of the crater; (ii) a picture of the surface 2–50 m in radius for evaluating the geological conditions in the landing area, and (iii) a picture of the surface 1–2 m in radius for studying the soil structure.

The TV camera has eight lenses, which provide it with a 360° horizontal and a 45° vertical viewing angle. The surface resolution is 2 mm at a distance of 0.7 m. The spectral operating range is 0.4–0.9 μm.

The neutron detector is intended to detect water (ice) in the lunar soil. It consists of two uncooled silicon charged-particle detectors, between which there is a LiF-based converter. When the soil is irradiated with neutrons from a Cf^{252} source, the neutrons are slowed and enter the converter, in which the exoenergetic reaction 6Li + n = 4He + 3H + 4.78 MeV takes place. The energy of the neutron is converted to the energy of charged particles (α-particles and tritium nuclei), which are simultaneously registered by the silicon detectors. The signals from them are summated and fed into a pulse height analyzer. The sensitive surface of the detector has an area of 5 cm^2. The lower limit of water (ice) detection is 0.5–1.0% by mass.

The gamma-ray spectrometer. The irradiation of rocks with cosmic rays gives rise to secondary neutrons, whose interactions with hydrogen produce gamma-ray photons of 2.223 MeV energy.

Since the temperature in the zone of the polar station is always low, a high-resolution semiconducting detector of extrapure Ge with a low operating temperature (below 130 K) can be used without artificial cooling.

The detector efficiency at an energy of 1.33 MeV is ~20% of the efficiency of the NaI(Tl) detector, the energy resolution at this energy is ~2–2.5 keV, the number of channels of the pulse height analyzer is 8096, and the channel capacity is 2^{16} pulses. In the operational mode, the spectrometer detector is positioned at a distance of 1.0–1.5 m from the body of the station.

Theoretical estimates and experimental modeling show that the limit of water detection is ~1% by mass.

The mass spectrometer. The composition of the gaseous component of the lunar surface rocks is to be investigated using a hyperboloid mass spectrometer. The rock to be analyzed is sampled by a miniature ground-sampler and placed in the sample admission vessel, which is connected to the operating volume of the

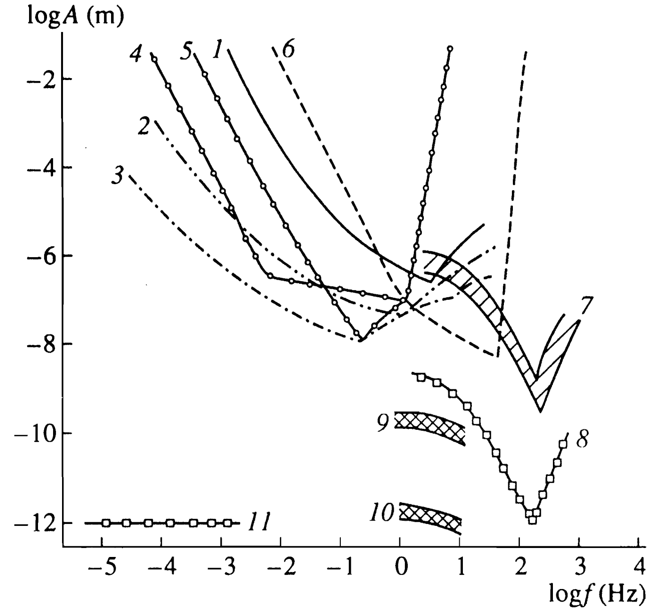

Fig. 5. Sensitivity of seismic instruments in space projects: (*1*) *Viking*; (*2*) *Optimism* (passive mode); (*3*) *Optimism* (active mode); (*4*, *5*) *Apollo*, long-period seismometers; (*6*) *Apollo*, short-period seismometer; (*7*) *Mars-96*, penetrator; (*8*) *Mars-96*, modified version; (*9*, *10*) maximum and minimum noise of the Moon, respectively; (*11*) *Luna–Globe* modulation method.

Scientific instruments of the polar station

Instrument	Mass, kg	Power consumption, W	Purpose
TV camera	1.5	5	Obtaining a panoramic picture of the landing area. Assessing the mineral composition of the rock. Detecting ice
Neutron detector	0.4	2.7	Determining water content in the rock from ~0.5%
gamma-ray spectrometer	2.5	3.0	Determining the abundances of H_2O and CO_2 in the rock Determining the abundances of U, Th, and K Determining the abundances of the rock-forming elements Mg, Al, Si, Cf, Ti, and Fe
Mass spectrometer	1.5	5.0	Determining the abundances of volatiles, including H_2O, in the rock
α-*p*-X spectrometers + multichannel pulse-height analyzer	1.1	2.1	Determining the contents of the light elements O, Na, Mg, Al, Si, and others in the rock
Magnetometer	0.4	1	Measuring the local magnetic field
Thermograph	0.3	2	Measuring the ground temperature
Accelerometer	0.2	0.2	Measuring g-forces during insertion into the ground

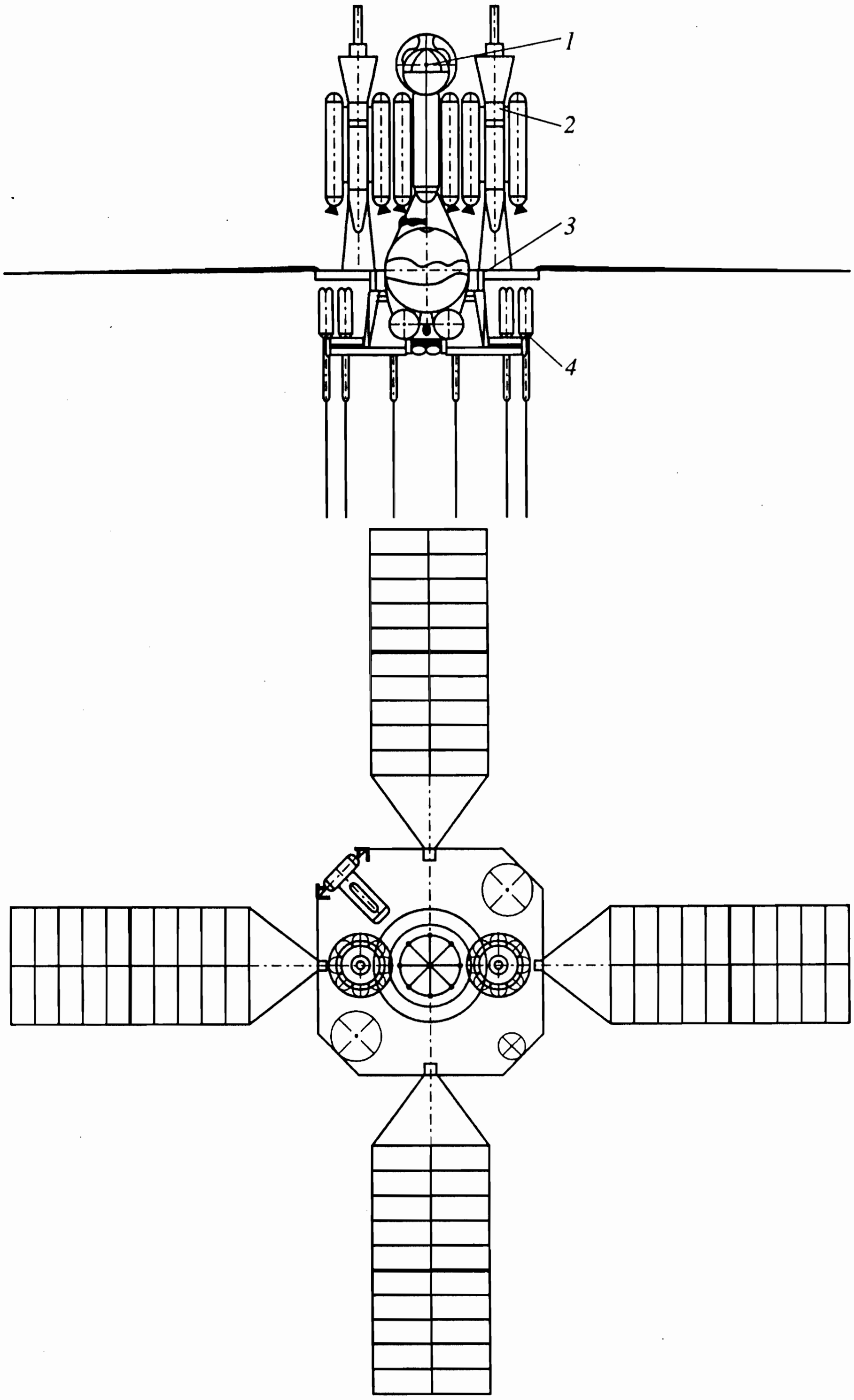

Fig. 6. General view of the *Luna–Globe* spacecraft: (*1*) polar station; (*2*) landers with wideband seismometer; (*3*) flight module; (*4*) carrier with SASA high-speed penetrators.

mass spectrometer analyzer through an inlet tube of a small cross section. For the maintenance of the required vacuum, the analyzer tube has an outlet into "outer" space. The admission vessel is fitted with a heater. The heating of the rock material in the admission vessel sends the gaseous products along the inlet into the mass analyzer tube, from which, after their composition has been studied, they are removed into space via the outlet.

Range of masses recorded	1–50 amu
Dynamic range (for peak at 28 amu)	10^5
Sensitivity	10^3 cm^3
Resolution at 0.1 level (for 44 amu peak)	over 1 amu

Other instruments that are to be installed in the polar station (α-p-X spectrometers, a magnetometer, a thermograph, and an accelerometer) are intended for determining the elementary composition and physical properties of the soil.

It is planned to land the polar station in a shadowed region near the south pole. The proposed site is centered at 88° S and 38° E (V.V. Shevchenko and coworkers). The site corresponds to a crater about 56 km in diameter. Its advantages are a relatively large area, old age, and a position shifted somewhat toward the hemisphere visible from the Earth. The landing precision is ±15 km.

The determination of the rock chemical composition by the α-p-X spectrometer and the gamma-ray spectrometer should substantially improve the calibration of the instrument, thereby reducing the limits of water detection to 0.2–0.5% by mass.

SPACE ROCKET COMPLEX

Spacecraft

In accordance with the technical assignment of the RAS Vernadsky Institute of Geochemistry and Analytical Chemistry, the Lavochkin Research and Production Association (S.D. Kulikov, R.S. Kremnev, K.M. Pichkhadze, V.A. Dolgopolov, G.N. Rogovskii, and others) accomplished the work of determining the parameters and packaging of the spacecraft, and the flight scenario necessary to perform the stipulated scientific experiments.

Two variants of the spacecraft were considered: (i) using the *Molniya* launch vehicle and (ii) using the *Soyuz* launch vehicle with the *Fregat* booster.

The spacecraft consists of (Fig. 6): (i) the flight module; (ii) the high-speed penetrator carriers; (iii) the polar station, and (iv) two landers.

The high-speed penetrators are arranged along the perimeter of the carrier ring. The carrier is provided with a sequence timer, a storage battery, and powder thrusters. At a preset time the carrier separates from the spacecraft and is spun-up by the symmetrically arranged powder thrusters.

The polar station consists of a retrorocket engine and a lander module.

The retrorocket engine effects the first braking when the polar station deorbits and the second braking to reduce its vertical speed.

The g-forces on impacting the lunar surface must not exceed $500G$.

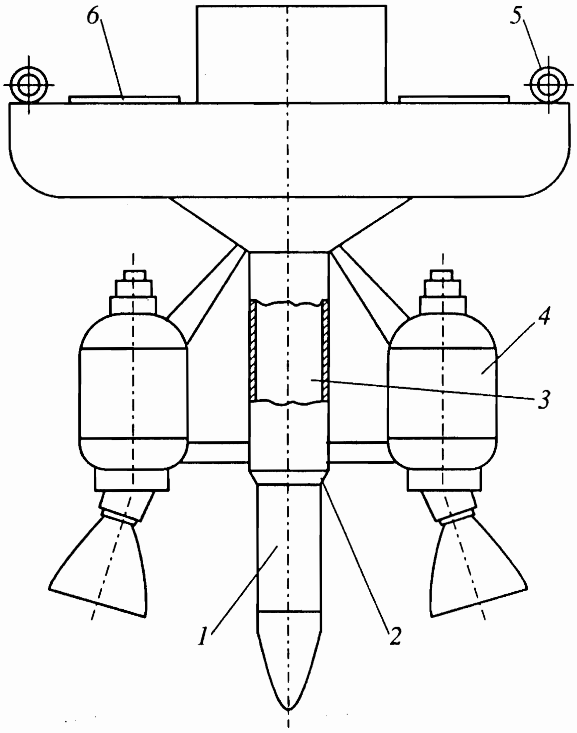

Fig. 7. Lander: (*1*) nose cone; (2) body; (*3*) instrument compartment; (*4*) retroengine; (*5*) spin thruster; (*6*) descent control unit.

The landers are intended for delivering and deploying the seismic stations, which contain the wideband seismometers (Fig. 7).

A lander consists of the retrofire module and a penetrator.

The powder thrusters brake the penetrator to a ground-insertion speed of about 80 ± 20 m/s.

The spin-up thrusters serve to spin up the lander.

The g-forces acting on the instrumentation when the penetrator pierces the lunar surface do not exceed $500G$.

In addition to scientific instruments, the penetrator carries electrical-power and thermal-regulation systems, a radio transmitter, a control unit, and an antenna unit.

The flight module contains engine units, control, attitude-control, and electrical-power systems, telescopic booms with solar panels, and actuator mechanisms. Besides service systems, the flight module carries scientific instruments for studies of the Moon from lunar orbit.

Translunar Injection of Spacecraft. Flight and Landing Scenario

The spacecraft is to be launched by a *Molniya* or *Soyuz* launch vehicle.

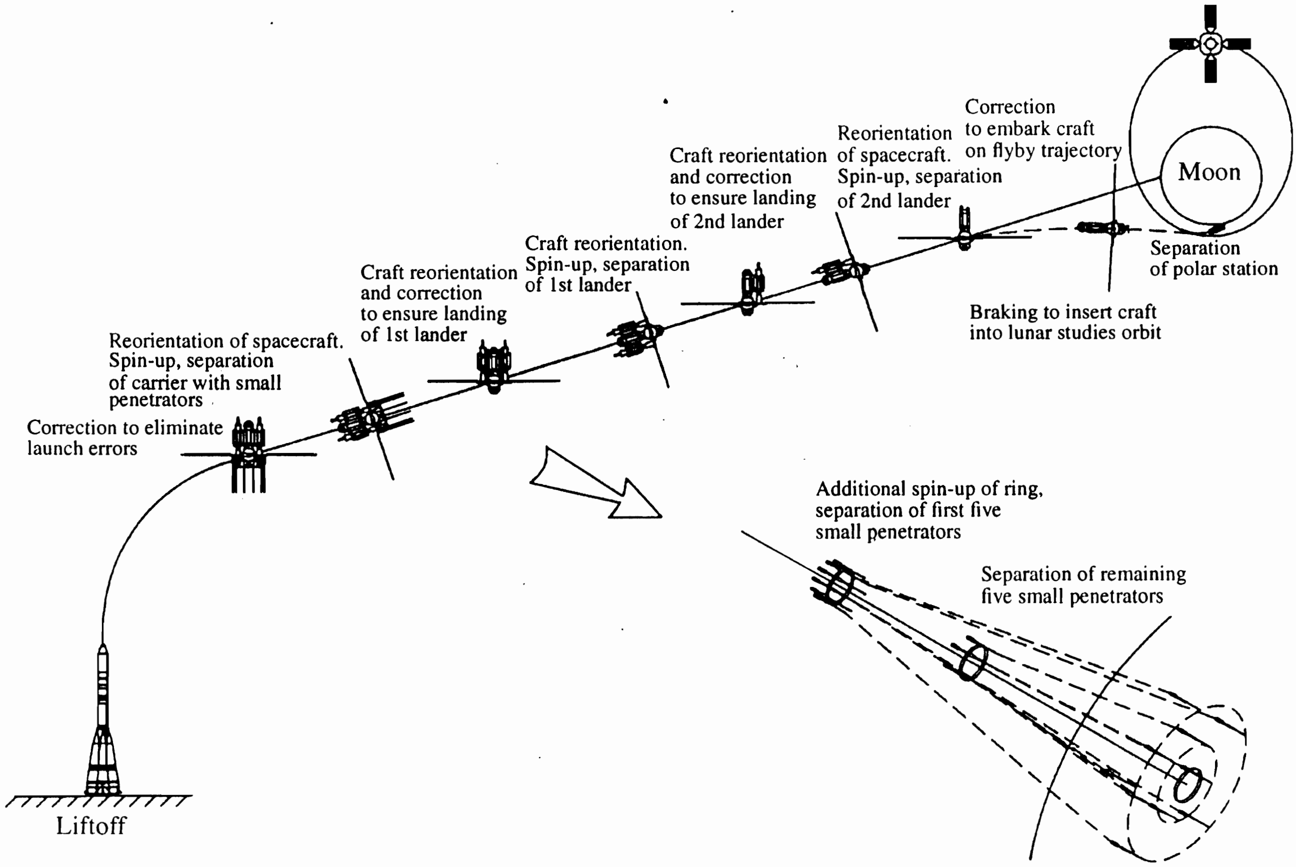

Fig. 8. Scenario of spacecraft flight to the Moon.

The *Molniya* launch vehicle consists of four stages. It is 43.4 m long and has a maximum diameter of 10 m. Its takeoff mass is 320 t. Three stages of the vehicle enable it to lift about 7000 kg into a circular orbit 200 km high. The boost stage (fourth stage) serves to transfer the spacecraft from the intermediate to the target orbit.

The scenario of the flight to the Moon is shown in Fig. 8. The flight time is approximately 4.5 days. The first course correction—to eliminate launching errors—is scheduled for 32–38 h after takeoff (at a distance of 210 000–260 000 km from the Earth). Approximately 29 h before the spacecraft reaches the Moon, a 14-hour countdown is activated. During the first hour, the spacecraft is reoriented, the carrier with the penetrators is separated, and it is spun-up. This is followed, consecutively, by spacecraft reorientation, the spin-up and separation of the first lander, and then the second.

After separation from the spacecraft, the penetrator carrier and the two landers function as follows.

The penetrator carrier flies along an impact trajectory, spinning at a rate of 3 rad/s. At an altitude of 700 km, the spinning rate is increased to 20 rad/s and five penetrators separate. Travelling at a lateral velocity of 20 m/s and a vertical velocity of 2.6 km/s, the penetrators, during their approach to the Moon (250 s), fly asunder to the circumference of a circle about 10 km in diameter. At an altitude of 350 km, the remaining five penetrators separate and, during their descent, manage to fly asunder to a circumference about 5 km in diameter.

If experiments reveal a need to reduce impact loads, an intermediate operation will be introduced to brake the penetrator carrier.

The landers, after separating from the spacecraft, travel along an impact trajectory. At an altitude of 2 km from the lunar surface, a powder retroburn slashes their speed from 2.6 km/s to zero. After this, the retroengine is jettisoned and the free-falling penetrator impacts the ground at a speed of 60–120 m/s.

On approaching the Moon, the spacecraft is transferred into lunar orbit. An orbital correction is performed to make sure that the orbital plane passes through the landing site chosen for the small (polar) station in the region of the south pole and that the perigee of the orbit is situated over the landing site.

The polar station separates from the spacecraft and its orbital velocity (~2 km/s) is reduced to zero. The station is in free fall from an altitude of about 500 km. At an altitude of 2 km a retroburn reduces the velocity of the station to zero. Following this, the retroengine is jettisoned and the station falls to the surface at a speed of approximately ~80 m/s.

The orbiter is needed to relay the signal received from the polar station to Earth. The polar orbit of the lunar orbiter provides the conditions for the global mapping of the Moon. The scenario provides for a fairly high orbit (about 500 km). Should further studies reveal that a lower orbit can be used, it will be expedient to map the Moon with a gamma-ray and a neutron spectrometer, instruments designed and made for the *Mars-96* mission. Radar sensing in the meter-range are of substantial interest, since they could make possible an estimate of the thickness of the lunar regolith. However, the possibility of such investigations depends on whether there will still be reserves of mass after the priority experiments.

CONCLUSIONS

The accomplishment of the tasks formulated in the project could lead to a most significant advance in geosciences and planetology.

At the same time the project is but a first step in the new phase that is now beginning in the exploration and utilization of the Moon.

Should the presence of water and other volatiles in the polar region be confirmed, soil samples from that region will have to be delivered to Earth.

The problem of the utilization of the Moon will undoubtedly become topical in the 21st century, above all in connection with energy problems on Earth. As mentioned in the foregoing, a challenging prospect in this context is that of utilizing the resources of lunar ^{3}He. This will necessitate extensive and prolonged research, geological exploration, and mining work on the Moon. The country that develops the required technology will become a global technological leader.

The setback with the *Mars-96* project prompted a revision of the program and strategy of planetary exploration.

In this context, a return to lunar exploration appears most timely and expedient.

Lunar exploration projects, apart from their great scientific value, have a number of other advantages:

1. they are economical and can be implemented using medium-class launch vehicles of the *Molniya* or *Soyuz* types, or "defense-conversion rockets" with an additional booster stage;

2. they can be prepared at short notice, since they are based on experience gained by the country in exploring the Moon with unmanned probes;

3. they are not tied to rigid launch dates, and their implementation and careful preparation are not jeopardized by inadequate or irregular funding, and

4. they can be used for the thorough preparation of more expensive missions to remote bodies of the Solar System.

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