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SPACE RESEARCHES IN KELDYSH INSTITUTE OF APPLIED MATHEMATICS OF RAS: PAST, PRESENT, FUTURE

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Summary. The article consists brief results of theoretical researches and the practical involvement of Keldysh Institute of Applied Mathematics (KIAM) workers in already realized, current and perspective projects of space researches and exploration using spacecrafts. The Institute (at present - Keldysh Institute of Applied Mathematics of RAS) was founded in 1953 to solve some vital problems facing the country with modern mathematical methods implementation. From the very beginning, KIAM actively participates in mission design and practical implementation in many space projects. Often the Institute's contribution to the ballistic design and ballistic-navigational support of spacecraft flights was decisive. At the initiative of S.P. Korolev and M.V. Keldysh, the Ballistic Center was established in the Institute, which, in close cooperation with S.P. Korolev Rocket and Space Corporation Energia, Lavochkin NPO, TsNIIMash and other industry organizations, successfully carried out the ballistic-navigational support for the flight control of automatic spacecrafts towards celestial bodies of the solar system, space devices within the framework of national programs of human space flights, the space system "Energia-Buran", flights of automatic space vehicles for astrophysical researches "Astron", "Granat", "Interball", "Spectr-R" and lot of other spacecrafts. The Institute also successfully carries out works on mission design of perspective spacecraft flights.

1 AT THE BEGINNING

October 4 2017 marked the 60th anniversary of the launch of the Russian R-7 rocket from the Baikonur Cosmodrome, which brought the world's first artificial earth satellite (AES) into its orbit. Lot of Soviet scientists and engineers worked on the creation of this spacecraft (Figure 1), among which SP Korolev, M.V. Keldysh and M.K. Tikhonravov should be highlighted. From this moment, the era of space exploration using spacecrafts (SC) was open.

Keldysh Institute of Applied Mathematics (further – the Institute) at all stages of its development and operation takes a direct part in the ballistic and navigation support in the design and implementation of spacecraft flights [1-22].

There are several periods directly related to the scientific and practical activities of Mstislav Vsevolodovich Keldysh in the formation of the Institute.

In 1944, at the V.A. Steklov' Mathematical Institute the Department of mechanics was formed by, the head of which stayed Mstislav Keldysh. Since then, M.V. Keldysh was engaged in rocket dynamics and applied celestial mechanics.

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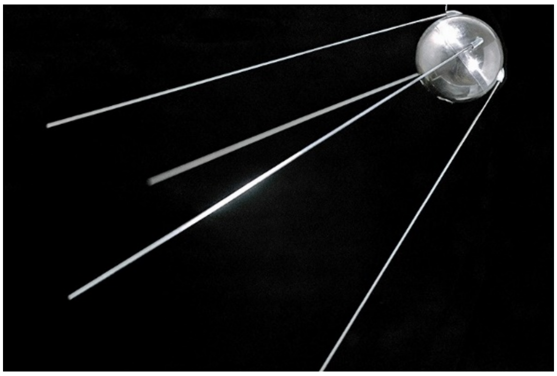


Figure 1. The first artificial Earth satellite. (Weight: 83.6 kg, diameter: 0.58 m. The radio transmitters operated at frequencies of 20 and 40 MHz (wavelengths of 15 and 7.5 m)

The creation history of the first artificial Earth satellite. On August, 30, 1955 the Commission on the development of the program of the launching of the satellite was established. Academician M.V. Keldysh was appointed Chairman of the Commission.

- September 14, 1956 meeting of the Presidium of the USSR Academy of Sciences chaired by academician. Nesmeyanov, which is considered the creation of the first satellite (object D).
- On November, 25, 1956 the design of the "Prosteyshiy Sputnik-1" satellite ("Elementary Satellite 1" in Russian) was started.
- On August, 21, 1957 successful flight of R-7 rocket tests.
- On August, 31, 1957 ground tests of the Prosteyshiy Sputnik-1 satellite with the R-7 rocket.
- On October, 04, 1957 at 22: 28: 34 DMV launch of the first satellite.

On November, 30, 1946, M.V. Keldysh was elected as a full member of the Academy of Sciences (academician). After that, he was appointed chief, and in August 1950 - scientific director of NII-1, which is currently the M.V. Keldysh Research Center. The NII-1 creation was supposed for solving problems in the rocketry. Since that time, the theory of the composite rockets movement, the introduction of liquid-jet and ramjet engines into aviation, unmanned missiles, control of the long-range missile flight have become the themes of the research of M.V. Keldysh and his team. M.V. Keldysh devoted about 15 years (from 1947 to 1960) to the development of air-jet engines and the creation in the Design Bureau of S.A. Lavochkin based on such an engine intercontinental cruise missile "Burya" ("Storm" in Russian). Flight tests of the "Burya" began in 1957. In in early 1960 the maximum range of its flight, 6500 km, allowed within the territory of the USSR, was achieved. At the same time, its deviation from the goal was less than 8 km, which was a very high result for that time. The "Burya" rocket carried out flights at altitudes of 18-25 km at a speed exceeding the sound speed by three times. For comparison: at the same time an American cruise missile, similar in characteristics, which was intended for approximately the same flight range, was not brought to flight samples.

The acquaintance of M.V. Keldysh with the Chief Designer of long-range missiles S.P. Korolev applies to 1947 and proceeds to the creative cooperation later.

Thus M.V. Keldysh led several teams that worked on various important directions for the country by 1953. In all applied works new methods of scientific research were required, and first of all, the rational mathematical calculations first of all. Their generation and implementation radically changed the scientific significance of computational mathematics. M.V. Keldysh, the author of many deep scientific ideas, was one of the first people, who was foreseeing the role of computational mathematics in the development of science and technology [5-9].

By the decree of the Council of Ministers of the USSR in 1953, the Department of Applied Mathematics (with the Rights of the Institute) was established at the Steklov' Mathematical Institute of the USSR Academy of Sciences, Academician M.V. Keldysh became the director of it. In 1966, this department was transformed into the Institute of Applied Mathematics of the USSR Academy of Sciences, which currently bears the name of the Keldysh Institute of Applied Mathematics of Russian Academy of Sciences (KIAM of RAS). Since the foundation of the Institute under the leadership of Mstislav Vsevolodovich, a broad job front has been conducted on rocket dynamics and applied celestial mechanics.

During the research period preceding the launch of the first artificial Earth satellite in 1957, main efforts of the Keldysh team were aimed at the intercontinental ballistic missile and the cruise missiles creating. The Institute's work on the composite missiles, on their structure, on the parameters and conditions determining the rocket shape, on the missile schemes, on the missiles movement control, on the fluid mobility in the tanks significantly influenced on the choice of the missiles design. In particular, in 1953, D.E. Okhotsimsky (later academician) solved the variational problem of determination of the optical characteristics of the package of missiles composite. These works helped S.P. Korolev to make the final choice of the scheme of the R-7 composite missile and seriously improved the flight characteristics of this missile.

In 1953, the Institute first proposed the ballistic descent method of a spacecraft from the orbit to Earth and demonstrated the possibility of its use in the implementation of human space flight. As a result of the application of this descent method, the space flight of Yu.A. Gagarin was completed by a successful landing (Figure 2).

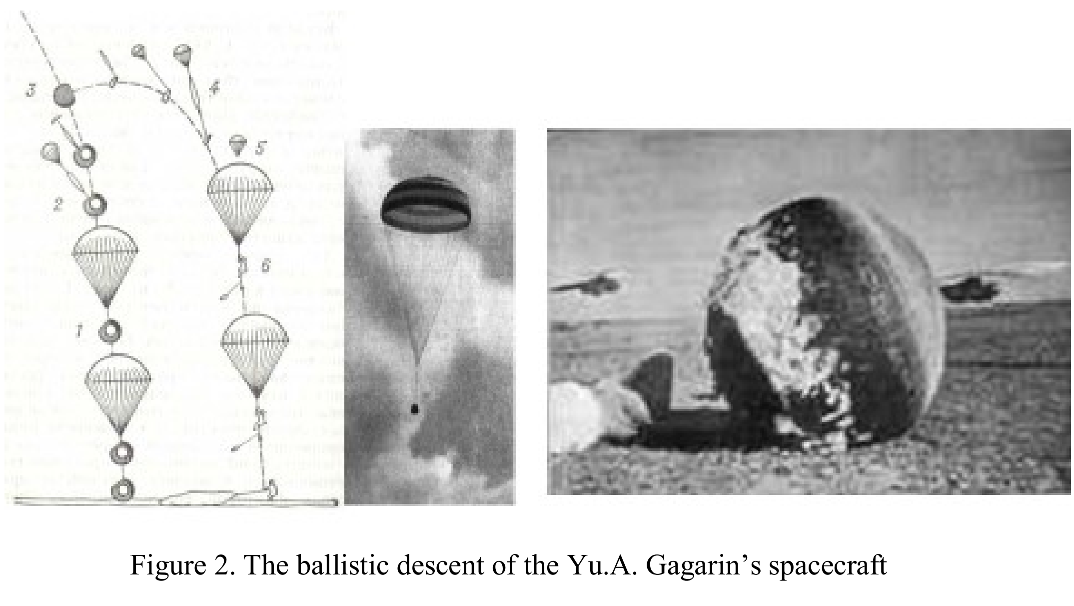


Figure 2. The ballistic descent of the Yu.A. Gagarin's spacecraft

In 1954, the Institute's team developed the first concrete version of the system of gravitational (passive) stabilization of an artificial satellite on the orbit and constructed the theory of such stabilization.

Beginning in 1957, the scope of space subjects works has significantly expanded in the Institute. We note only some of these works, which was had fundamental importance for ballistic-navigation support for the design and implementation of spacecraft' missions. Already in 1957, a technique making it possible for the first time in our country to perform a computer-based determination of the orbit of an artificial satellite according to optical observations was developed. Soon the Institute the first in our country methods for determining and predicting the parameters of the space vehicle motion from ground-based radio-technical trajectory measurements developed. Later, according to an initiative of S.P. Korolev and M.V. Keldysh, the Institute created the Ballistic Center (BC), which became an integral part of the spacecraft control loop. E.L. Akim became the head of the KIAM BC.

2 ACHIEVEMENTS

The Institute conducted a wide range of fundamental research on the mechanics of motion of artificial and natural celestial bodies.

First of all, the problems of high-precision determination and prediction of the motion of the spacecraft' center of mass (CM) was considered. For this some methods and algorithms were developed for the joint determination solving of both parameter sets: of the CM motion and the parameters characterizing the influence of external forces on this motion. These methods have opened up the possibility for the first time to create a model of the gravitational field of the Moon along the trajectories of measurements of its artificial satellites [26]. The Institute carried out pioneering work for developing methods and algorithms of solving the problem of optimal target maneuvering of SC with multiple launching of onboard propulsion system.

The above methods and algorithms have found wide applications in missions design and their implementation.

The Institute team analyzed the possibility of a flight to Mars and Venus. Principal technical solutions were found and substantiated. These include, in particular: the scheme and method for SC' accelerating with an intermediate launch to an open AES orbit, which became later a universal method for SC accelerating; the operations management scheme of interplanetary flight spacecraft. Using these schemes, based on the revealed features and regularities of navigation, predicting the characteristics of the SC movement and optimal correction of orbits, it became possible to achieve maximum accuracy of flight control with minimum weighting costs for this control. The proposed schemes in their main features didn't need to upgrade over a long period of practice of space flights [1-3].

A wide range of fundamental results from the Institute's investigations was obtained. Thus, the theorem on the stability conditions for the relative equilibrium of a satellite in a gravitational field was proved. This result is used in the theory and practice of systems of passive gravitational stabilization of satellites. The theory of oscillations of a satellite at the elliptical orbit in a gravitational field was developed. A theory of the evolution of the rotation of satellites under the influence of disturbing moments of forces (gravitational, magnetic, aerodynamic, light pressure) was developed. The problem of determining the actual orientation of the satellite and the acting moments using on-board measurements was solved [1-3].

The theory of the orbital tether systems motion was developed in the Institute. A resonant theory of Generalized Cassini's laws of the rotation of natural and artificial celestial bodies is created. This theory, in particular, justifies the empirical laws of Giovanni Domenico Cassini (1693). The researches of N.G. Chetaev on the dynamics of systems with nonlinear velocities by constraints were advanced in the Institute. A theory of mechanical systems, controlled by superimposing of bond connections, was developed in the general case of nonlinear and non-ideal ones. The methods for transient processes constructing that impart the properties of attractors in the state space to servo-constraints were proposed. The problem of the material point motion with a constant velocity modulus in the central gravitational field was solved [1-3].

Works on the comprehensive ballistic design of a number of space flights were widely launched at the Institute: a man in near-Earth space; automatic spacecraft on the AES orbit, including those intended for servicing manned flights; automatic spacecraft to the Moon; interplanetary automatic spacecraft, etc.

The collective of the Institute and its BC successfully carried out the works assigned to it on ballistic and navigational support of the above-mentioned spacecraft missions.

2.1 Near Earth flights

An important role in the development of cosmonautics has historically been played by the creative community of two outstanding scientists - M.V. Keldysh and S.P. Korolev. The solution of the vital national challenge of rocket systems and manned SCs creation is directly connected with the names of the outstanding designer, academician S.P. Korolev and a number of the largest designers, the creators of numerous units and system. The outstanding scientist M.V. Keldysh and the leaded by him Institute made a great role in the solving of the theoretical and organizational aspects of the space flights challenge solving.

To the name of M.V. Keldysh was directly related the training and the flight execution on April 12, 1961 on the space ship "Vostok by the first Earth cosmonaut Yu.A. Gagarin. Mstislav Vsevolodovich much actively participated in the development of the space flights programs, the design of the ship and the life support systems. The Institute played an important role in the implementation of the entire subsequent flight programs of manned spacecraft and orbital stations, which provided our country with a number of priority achievements that made a significant contribution to the development of world cosmonautics.

The Institute has been directly involved in the implementation of all national manned space flight programs for almost four decades after the first manned flight into space. The work entrusted to it was carried out on the ballistic support of the flights of the component parts of the space stations in the orbits of AES: the Salyut type stations [10], the Mir stations (Figure 3). KIAM Ballistic Center carried out the ballistic-navigation support (BNS) work assigned to it to form the orbit of the satellite of the national segment as the germ of the international space station (ISS).

The pride of Russian cosmonautics - the Mir research complex - was existed since the launch of the Mir station in 1986 during 15 years. During this time, 5 scientific modules carried of the flights to the station and were docked with it (Kvant, Kvant-2, Kristall, Spectr and Priroda), as well as 31 Soyuz piloted spacecraft and 64 Progress cargo ships "Progress".

The trajectory measurements were promptly and regularly processed in the BC KIAM, the current orbit was determined, the prediction of future movement was performed, and the maneuvers parameters of each of these spacecraft were calculated. According to onboard measurements, a selective analysis of the dynamics of the orbital complex near the center of mass was carried out. The Institute's specialists participated in the selection of the scheme of the forced descent of the complex from orbit, analysis and preparation for possible emergency situations in the BNS implementation of the selected scheme. These final operations were unique in nature and were of extreme responsibility. Works on the BNS flight control of the Mir orbital complex were carried out jointly with TsNIIMash and RSC Energia.

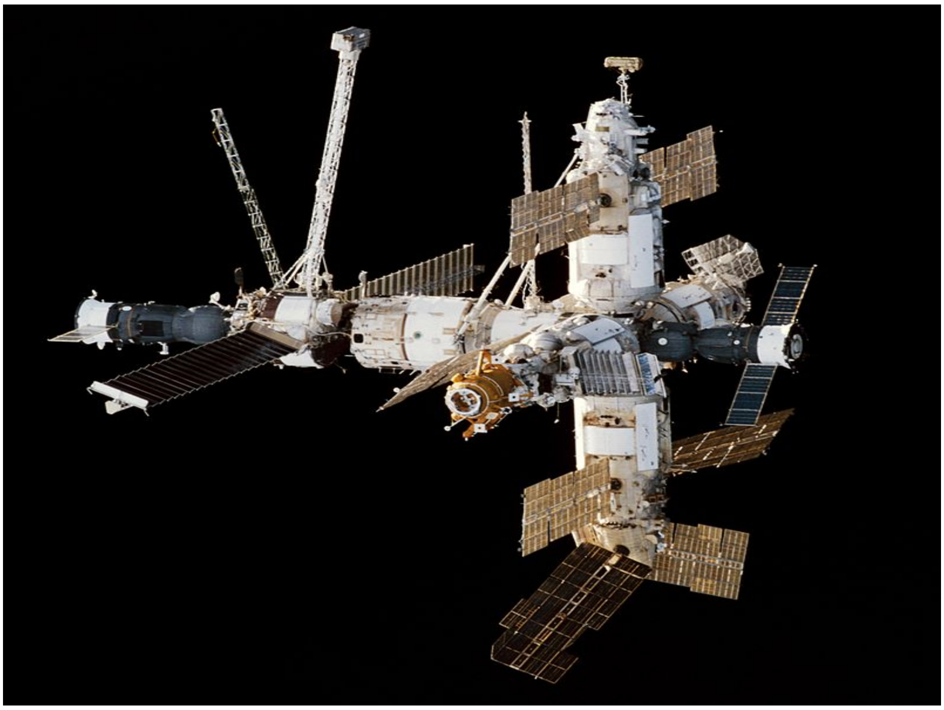


Figure 3. The "MIR" space station

The institute was involved in the work on the BNS of flights of the SC under international program. Particularly memorable was the flight of the Soviet and American ships under the ASTP program (Apollo–Soyuz Test Project) (Figure 4,5).

On July 15, 1975, the launch of the Soyuz-19 spacecraft in the USSR and the Apollo in the United States began the first in the history of mankind a joint space flight of spacecrafts from different countries. At the stages of preparation and implementation of this flight, the Institute took an active part. In the BC KIAM, methods and corresponding computer programs for calculating optimal maneuvering parameters (in terms of fuel costs) for the Soyuz spacecraft with several on-board engine inclusions were developed in order to form its trajectory by a specific time of docking with the Apollo spacecraft. These methods are currently used to form the trajectories of the satellites of celestial bodies.

The flight under the ASTP program was successful thanks to the coordinated work of the Soviet cosmonauts and American astronauts also the effective work of the involved ground services of the USSR and the USA.

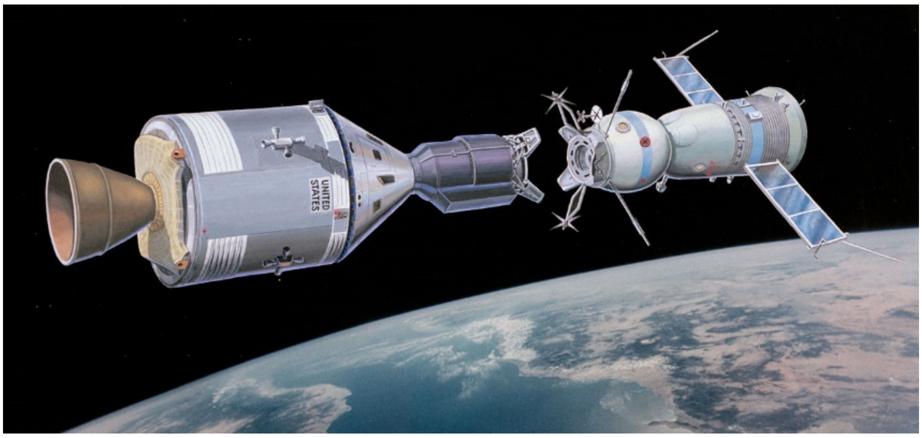


Figure 4. Space flight of the "Soyuz" — "Apollo" ASTP space vehicles

Figure 5. Left to right: ASTP cosmonauts Slayton, Stafford, Brand, Leonov, Kubasov

The most outstanding result of the joint activities of our rocket and aviation industry in the past years was the creation and flight of the universal reusable transport space system (MTKS) "Energia-Buran" on November, 15, 1988. The current year marks 30 years of this unique event.

The «Energia-Buran» Soviet space system is one from two's was realized MTKS systems over the World. It was a response to a similar multi-purpose civilian-military NASA "Space Shuttle" program. As a result of researches executed in KIAM and RSC «Energia» in 1971-1975 the necessity of the national MTKS establishing was detected and proved as a means of deterring a potential adversary. As a result of the commissioning of its reusable Space Shuttle systems, the USA could have a decisive military advantage in terms of delivering a preemptive strike.

The orbital ship (OS) «Buran» executed it's first and the single flight in November, 15, 1988. It was launched to the AES' orbit from the Baikonur Cosmodrome by the «Energia» launch vehicle. The time of flight lasted 205 minutes, OS implemented two orbits around the Earth and executed the landing. Not manned spacecraft' flight was fully automatically using the Soviet onboard computer and software. It should be noted that the US Shuttle had possibilities landing on the Earth only in manned manual mode. The OS' space flight fact (really space flyer) and its landing in automatic mode, under the control of the onboard computer - entered the Guinness Book of Records.

Figure 6. MTKS Energia-Buran on the launch

The Institute took an active part of the system "Energia-Buran» creation works (Figure 6). Work was carried out on scientific support for the development of onboard control complex (OCC) algorithms for the OS motion in the area of irreversible operations - the descent of an orbital spacecraft in the atmosphere, from 100 km before landing on the airfield. The Institute participated together with industry organizations in the developing of the control algorithms for the OS on the descent and landing site, carried out mathematical modeling of the OS total motion, semi-natural motion simulation, visual inspection of the descending onboard software. The Institute developed computational models of aerodynamic characteristics of the Buran air complex, used by all project participants. Other works were also carried out. General mathematical software was developed for the OS onboard computer complex and for the ground automatic system preparation of the start-up of the Energy-Buran system and its conduct.

The Institute carried out modeling of the work of the OCC during the flight of the Energia launch vehicle at the stages of its development in order for the errors detecting and elimination of deficiencies.

BC KIAM has successfully implemented a ballistic-navigation support for all segments of the Energy – Buran system's flight, including the active site, the orbital segment and the OS landing area.

Along with the implementation of work on manned flight programs, the Institute was directly involved in the work on the BNS of flights of SCs in other space projects. First of all, we should mention the international projects "Astron" (conducting astrophysical studies of galactic and extragalactic sources of cosmic radiation), "Granat" (orbital observatory) and "Interball" (studying the interaction of the Earth's magnetosphere with the solar wind). The SCs of these projects performed their flights in the orbits significantly different from circular ones. The SC of the Granat project and one of the Interbol SCs flew in highly elliptical orbits and reached about 200,000 km from the Earth in the apocenter.

In conclusion of this section it should be noted that along with development execution on the program of manned flights, the design S.P. Korolev bureau conducted developments on the creation of an automatic probes for the research of the Moon and the Earth nearest planets (Venus, Mars). As part of the years of testing until the mid-60s of the last century, there were implemented several probe launches to the Moon, Venus, Mars, in which the KIAM specialists took part in the preparation and realization. However, later developments on the topic of flights to the Moon, planets and other bodies of the Solar system were assigned to the Lavochkin NPO. This is due to two circumstances: large loading of KB of S.P. Korolev by developments by manned programs and the readiness of the Lavochkin NPO collective for this implementation of developments. The talented scientist and organizer Georgy Nikolayevich Babakin [4,11] became the chief designer on this topic. M.V. Keldysh and G.N. Babakin marked the beginning of close creative trusting cooperation between KIAM and Lavochkin NPO, which has been fruitfully continuing for more than half a century [11].

2.2 Flights to the Moon

Initially, the main efforts were aimed at solving the problem of achieving the Moon and researches of cis-lunar space [1-4,11]. An example of successful developments from the "Moon" projects cycle was the selection of trajectories for photographs and photographing of an invisible from the Earth "Far side of the Moon" for the" Luna-3 "probe (Figure 7). Here, for the first time in world practice, a "gravity assist maneuver" was proposed and successfully realized - a purposeful change of the trajectory probe as a result of disturbances in its motion by the gravitational celestial body (the Moon).

The Institute carried out and implemented the design studies related to the navigation support for the flights to the Moon of all national lunar probes (Figure 8).

Of particular note are the stations: "Luna-9" (Figure 9), which for the first time in the world made a soft landing on the surface of the Moon; "Luna-10" - the first artificial satellite of the Moon; "Luna-16" - the first automatic spacecraft that carried out the collection and delivery of samples of the lunar soil to the Earth; Luna-17 is the first automatic spacecraft that delivered the Lunokhod to the surface of the Moon, which was controlled by the commands of a specially trained operator on Earth.

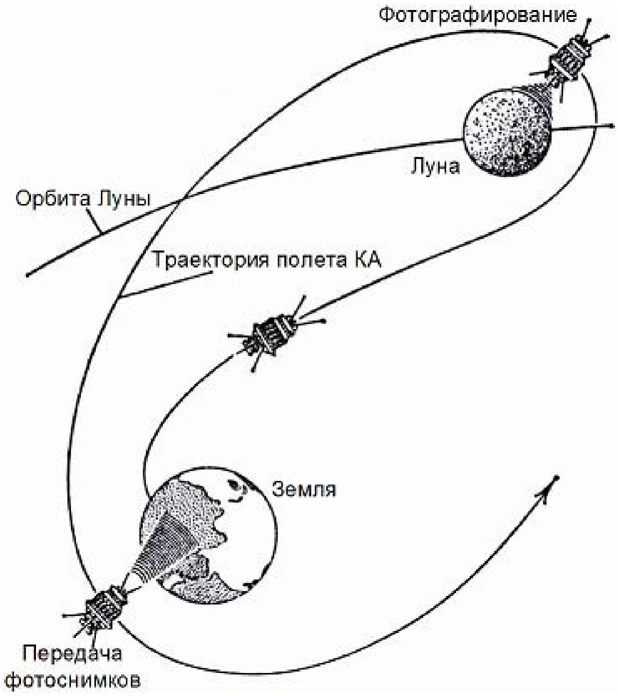


Figure 7. Moon flyby of the" Luna-3 "probe and its photographing of an invisible from the Earth Far side of the Moon

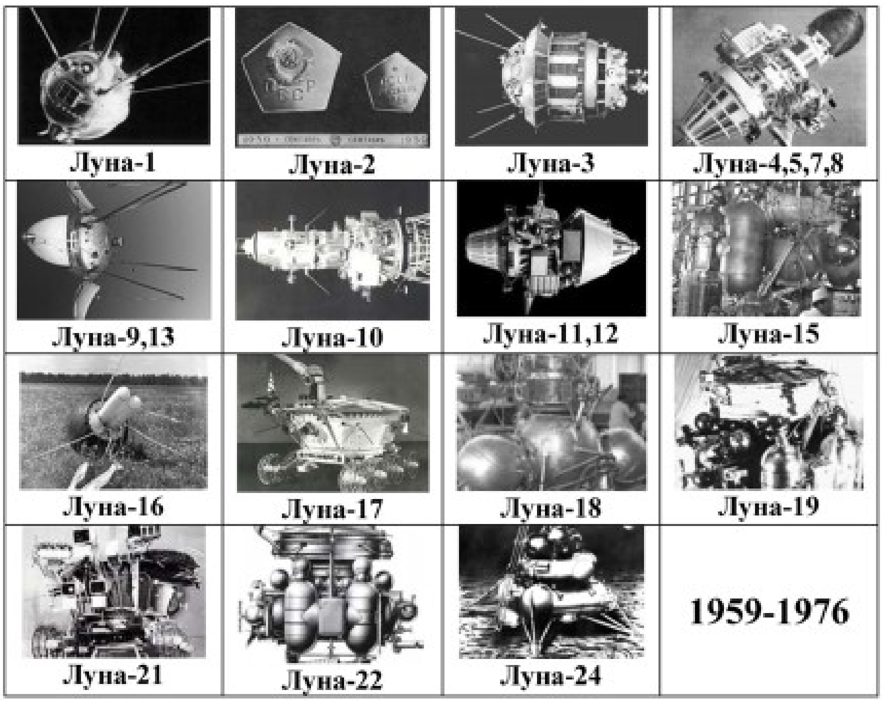


Figure 8. Soviet spacecrafts that explored the Moon

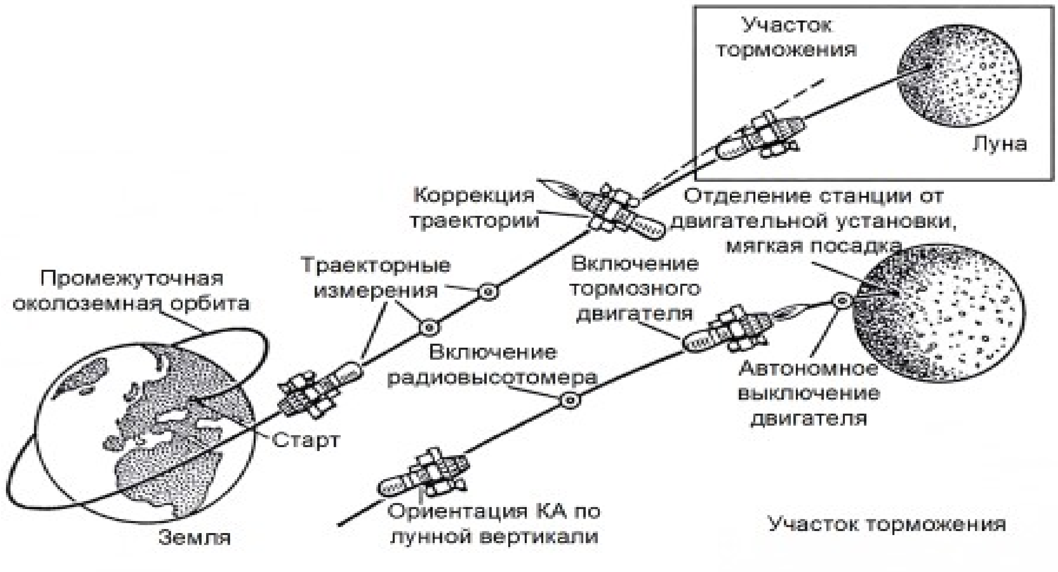


Figure 9. The first soft landing on the Moon's surface (the "Luna-9" station). 3, October, 1966

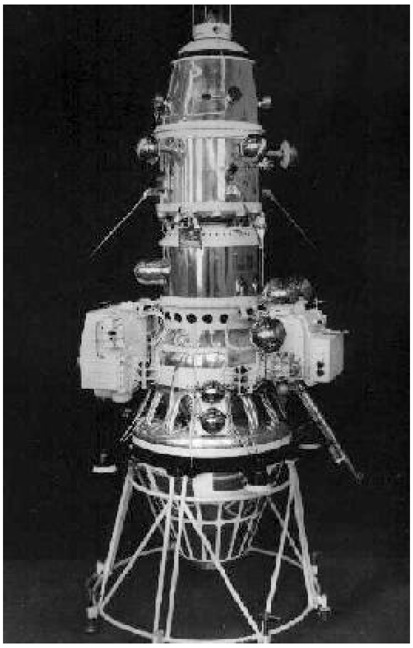
In order to deliver the returning vehicle with lunar soil to a given national landfill, it was necessary to land the Luna-16 probe on the lunar surface with a given accuracy. A new high-precision trajectory measurement system was created and debugged at the Institute. By observing the movement of the AMS "Luna-10" (Figure 10), "Luna-11, 12 and 14" the model of the lunar gravity field was created. The results of these works made it possible to successfully solve the problem of collecting and delivering lunar soil to the Earth on all lunar spacecrafts intended for this purpose. In the indicated figure, in a fixed for some point in time, the selenographic coordinates system is the magnitude of the change in the longitude of the ascending node ($\Delta\Omega$) and the argument of the latitude of the pericenter ($\Delta\omega$) for 460 revolutions of the Luna-10 AMS. These noticeable changes in the AMS orbit parameters are mainly due to the noncentrality of the Moon's gravity. In Figure 11 the container with lunar soil returned to Earth is shown.

2.3 Flight to Venus

Sixteen Soviet Venusian automatic probes were launched toward the Venus: "Venera-1,2,..., 16" (Figure 12).

First in the world probe "Venera-3" reached the planet atmosphere. Regretfully, the connection with this probe was lost approximately a fortnight before it entered the planet atmosphere planet.

It should be noted, as successful, the flight probe "Venera-4", from the board of which the measurements of atmosphere of another planet were directly obtained for the Earth directly. This happened in October 1967. Another series of probes of the Venera-4 type were combined and smooth descents in the atmosphere of Venus over various areas of its surface (probe Venera-5, 6). They reached the atmosphere of the planet in May 1969.



Start of mission	
Launch date	March 31, 1966, 10:48:00 UTC
Rocket	Molniya-M 8K78M
Launch site	Baikonur 31/6
End of mission	
Last contact	May 30, 1966
Orbital parameters	
Reference system	Selenocentric
Semi-major axis	2,413.0 kilometres (1,499.4 mi)
Eccentricity	0.14
Periselene	2,088 kilometres (1,297 mi)
Aposelene	2,738 kilometres (1,701 mi)
Inclination	71.9 degrees
Period	178.05 minutes
Lunar orbiter	
Orbital insertion	April 3, 1966, 18:44 UTC

Figure 10. The Moon gravity field influence on the AMS «Luna-10» motion. Disturbances caused by the non-centrality of the Moon gravitational field $\Delta\Omega = -7.7^{\circ}, \Delta\omega = -11.7^{\circ}$

Figure 11. Container with lunar soil

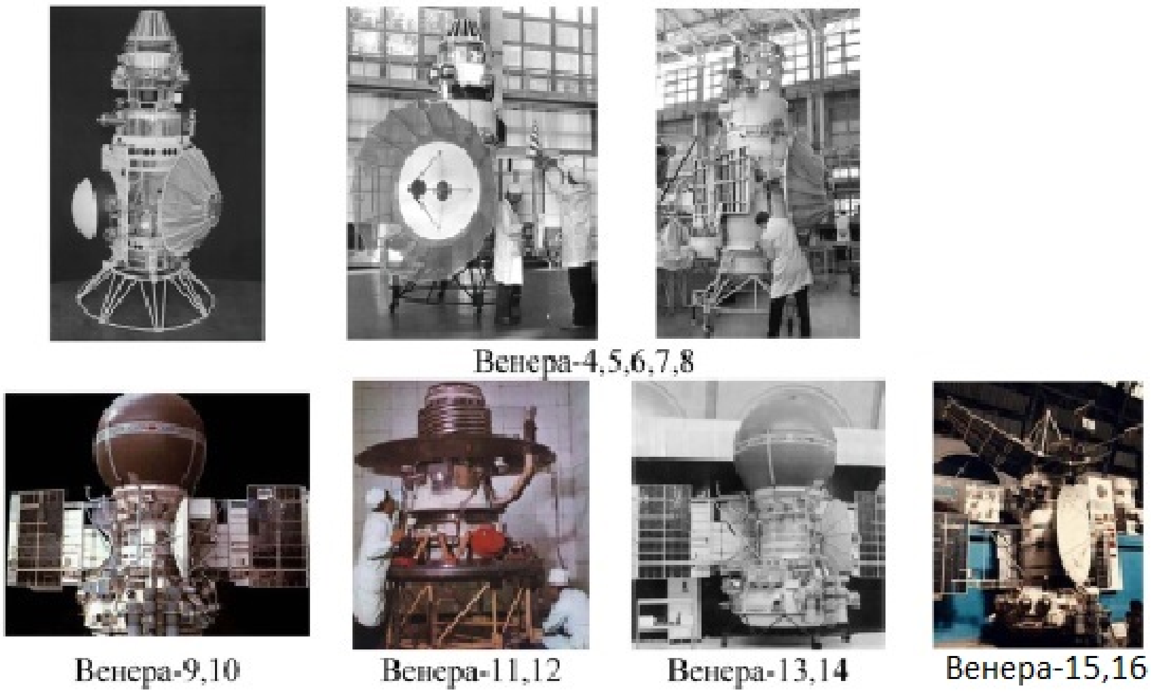


Figure 12. Spacecrafts «Venera 4, 5, …, 16»

In December 1970, probe ("Venera-7") for the first time in the history of mankind made a soft landing on the another planet surface and transmitted telemetric data on the Earth. The probe landing occurred on the night side of the planet.

Unlike probe Venera-7, the next identical probe Venera-8 is made a soft landing on the planets on the day side. With the probe, data was received on the parameters of the atmosphere of the planet and a series of data on the composition of the rocks on the planet surface at the site of the landing of the apparatus. probe landing on the surface Venus was carried out in July 1972.

Since SC «Venera-9» the SC construction was consisted from the service module and the descent module. The service module provided a retransmission to the Earth information from the apparatus. The service module could go on the orbit of the AVS or remain on the flyby trajectory. Researches carried out by the descending apparatus on its surface (obtaining a panorama of the surface area of the landing region), required translations of big beams of science information on the Earth. The designing of new scheme of the near-planet operations solved this complex problem. According the planned scheme before two days until the conditional pericenter of flyby hyperbola the separation of the SC in two parts was executed: the entry module (EM) and the orbiter module (OM). The remove maneuver was executed in the Venusian sphere of action. It provided a translation of OM to the hyperbolic flyby trajectory over the landing EM areas on the planet (flyby-descent scheme). In the case of the existence of a maneuver, it was inhibition, which deduced the orbital-descent scheme. Unlike all previous flights to Venus, information from the EM was transmitted to Earth not directly, but by retransmission through an orbiter. This made it possible to obtain a high informational content of the radio link EM - Earth with a sufficiently low weight of radio equipment and power sources of the EM.

The orbital-descent scheme was implemented for the first time on the spacecraft Venera-9 and Venera-10. It ensured the high accuracy of the EM's penetration of these stations into specified areas of Venus's surface, the introduction of the first artificial satellites of the planet to the venerocentric orbit, the synchronous operation of OM and EM during EM descent in the atmosphere and during its work on the surface, laboratories. The high performance of the spacecraft Venera-9 and Venera-10, one of the main tasks of which was to conduct research of the cloudless atmosphere and to obtain a panorama of the planet's surface, was largely achieved by choosing a new flight pattern in the near-planet region. This scheme allowed, in particular, to significantly increasing the weight of scientific equipment in the total weight of the EM. The landing module received and transmitted the first panoramas from the surface of the planet through orbiters to Earth. The soft landing of DMs of the Venera-9 and Venera-10 probes was implemented in October 1975.

Spacecraft flights to Venus in 1978 and 1981 required significantly higher energy costs compared to the flight in 1975. This is the reason for the absence of an orbital-descent scheme implementation in them. During the implementation of the "Venera-11" - "Venera-14" flyby-descent flight scheme was successfully implemented. KIAM specialists took an active part in the development and implementation of this flight pattern. The soft landing of descent modules Venera-11 and Venera-12 was realized in December 1978, and by Venera-13 and Venera-14 probes in March 1982.

Artificial satellites of the planet Venus ("Venera-15" and "Venera-16") provided radar mapping of the northern part of the planet from 30 degrees north latitude to the pole with a resolution of 1 - 2 km. The obtained information allowed creating the first atlas of Venus (Figure 13). The launch of the Venera-15 and Venera-16 probes at the interplanetary trajectories to Venus took place in June 1983. The orbits of artificial satellites of Venus were formed in October 1983. KIAM provided the definition the orbit determination necessary to construct the first map of Venus.

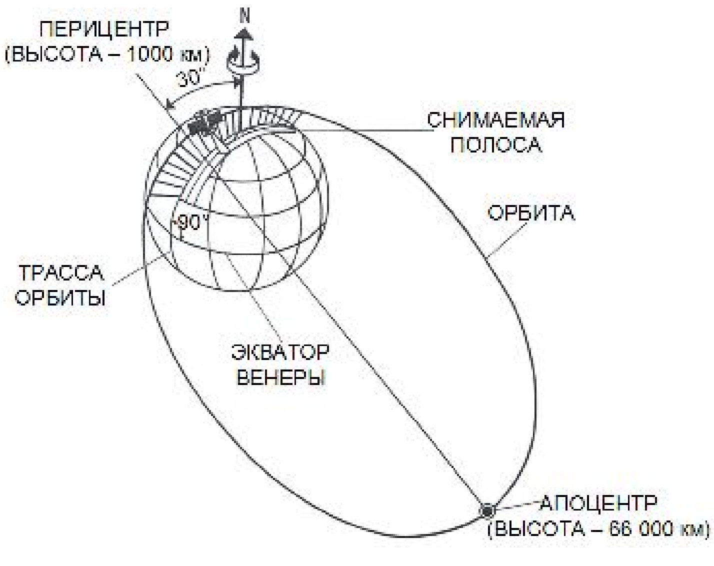


Figure 13. Orbits of probes "Venera-15" - "Venera-16"

The Institute collective took an active part in BNS in designing and realization these spacecrafts flights to the planet Venus. The Institute provided the ballistic data on the interpretation of scientific information of the planet Venus obtained via telemetry.

Space missions toward the Solar system planets made high demands on the accuracy of knowledge of the geocentric coordinates of the planets. Astronomical theories of planetary motion, constructed using only traditional optical angular measurements, could not provide the required accuracy. Therefore, the work of the Institute on specifying the ephemeris of the planets, based on the radar measurements of the planets and high-precision radio-technical observations of the movement of their artificial satellites, was of fundamental importance. One point that arose during the approach to the planet of the spacecraft "Venera-4". Due to the large error in the prediction of the position of Venus, obtained using the classical astronomical theory of Newcomb, a large error appeared in the prediction of the Doppler frequency shift, due to which unique information about the planet could be lost. M.V. Keldysh, who participated in the Deep Space Communications Center (Evpatoria) in conducting this final communication session of the Venera-4 spacecraft with the Earth, set the task of building a theory of the movement of the planets using spacecrafts data and radar data. After a relatively short time, a high-precision theory of the motion of the Earth and Venus was constructed according to radar measurements, optical observations and observations of the motion of the Venera-9,10 probes along the orbit of the satellite of Venus. The geocentric coordinates of Venus were refined by more than an order of magnitude.

In the interests of the Venus mapping project, the first definition of the dynamic compression of Venus from observations of the spacecraft Venera-9 and Venera-10 was performed. According to the data of radar and optical observations of Mercury, Venus and Mars, the KIAM experts, together with co-authors, constructed a relativistic theory of the motion of the inner planets. The problem of the high-precision navigation of the Venera-15,16 probes was solved, which made it possible to build images of the planet and its relief. According to the spacecrafts Venera-15 and Venera-16 data, the period of rotation of Venus and the direction of its axis of rotation were specified.

2.4 Flights to the Mars planet

For the purpose of research of the planet Mars, the launches of seven national spacecrafts were implemented: "Mars-1, 2,..., 7". For each of these probes the trajectory of approach to the Mars crossed its sphere of action.

Unfortunately, for various reasons, each of these spacecrafts only partially fulfilled the provided flight program. But, in the aggregate, the scientific and trajectory information obtained from these spacecrafts allowed directly or indirectly expanding the concept of Mars and its spatial motion.

For the first time in the history of mankind, using the Mars-2 probe, an attempt was made to deliver the so-called landing module (LM) to the surface of Mars. Alas, the LM crashed. In addition, the Mars-2 spacecraft turned out to be the second spacecraft put into orbit of an artificial Martian satellite (AMAS) 10 days later than the American spacecraft Mariner-9. The rapprochement of the LM with the surface of the planet and the transfer of the spacecraft on the AMAS orbit took place in May 1971. All scientific data from the Mars-2 probe has been lost due to the poor quality of telemetry.

As compared to the probe Mars-2, the Mars-5 and Mars-6 missions were much more successful in terms of obtaining scientific information. The first of them was launched into AMAS orbit and produced 22 revolutions around the planet during his active existence. According to the data of AMAS on Earth, images of the surface (in the southern hemisphere) of Mars and such important parameters for science and technology as the content of water vapor in the atmosphere, the temperature of the planet's upper atmosphere, the characteristics of the magnetic field of Mars, etc. were obtained. Another probes (Mars-6) delivered the DM to the surface of Mars. For the first time in the world from the EM direct measurements of Mars atmosphere parameters (temperature, pressure, etc.) were produced. The launches of Mars-5 and Mars-6 probes took place in 1973, respectively, in July and August. The transfer of the Mars-5 orbiter to the AMAS orbit took place in February 1974. The Mars-6 spacecraft landed on the Martian surface in March 1974.

The KIAM collective took an active part in the BNS to design and implement these flights of spacecraft to the planet Mars and provided the ballistic data for the interpretation of the scientific information received.

2.5 Flights to the small celestial bodies of the Solar system

Provided that Phobos (natural satellite of the Mars) is considered as a small body, only four national probes were launched to small bodies: two - to the comet of Halley's Comet - "VEGA-1, 2" and two – to the Phobos - "Phobos-1, 2 ".

The "VEGA-1" and "VEGA-2" probes structurally practically do not differ from each other and differ little in the tasks they solve. Launch of two (rather than one) of such probes in December 1984 is primarily due to the increased reliability of Halley's Comet study and researches of the Venus neighborhood, with which the probe first comes together for a realization of the gravitational maneuver for the purpose of its transfer to a trajectory flight to a comet.

Flight of both probes "VEGA-1, 2" passed successfully: large amount of information about the atmosphere and soil of Venus was obtained, the necessary gravitational maneuver of each probe was performed, after which they continued the flight to the comet. The encounter probes "VEGA-1" and "VEGA-2" with a comet occurred in 1986 on March 6 and March 9, respectively. The Institute scientists performed the full scope of developments on BNS complex flights probe "VEGA-1, 2".

The computational algorithms allowing quickly determining the current motion parameters of the comet, taking into account its observation by television cameras installed on board of the probes "VEGA-1, 2", and trajectory measurements of this probes were designed in the Institute. These algorithms allowed clarifying the ephemeris of Halley's Comet and timely transmitting them to the European Space Agency for using in precise shaping of the Giotto probe approach trajectory to this comet. This provided flyby of the Giotto in the second decade of March 1986 at a distance of 605 km from the nucleus of the specified comet.

In July 1988, the probes "Phobos-1" and "Phobos-2" were launched consistently towards Mars. Along with other tasks, each of this probes should have been output to a quasi-synchronous orbit (QSO), with which they should have executed descent (landing) of the Long-lived autonomous station (LAS) on the Phobos surface. At the beginning the probe transferred at the QSO, which has the name QSO-1, then it is transferred to the pre landing QSO named QSO-2. During the probe flight at the QSO-1, its distance from Phobos oscillates approximately from 200 km to 600 km. With a probe flight over QSO-2, its distance from the Phobos was less than at the flight over QSO-1 and oscillates approximately between 50 km and 200 km. LAS was descended with a distance of approximately 50 km. The flight of the probe at the QSO-1 was near 20 days. During this time, Phobos makes near 63 revolutions around the Mars.

At the QSO-1 the measurements of the direction coordinates of the Phobos-probe should have been executed as well as the television imaging of the satellite. With using this data on the Earth, the position of the probe relative to the Phobos body was refined and the parameters of the maneuvers were calculated to translate the probe with QSO-1 to QSO-2. After realization of this maneuver with a probability close to one, probe with Phobos should not collide for a certain time (at least until the scheduled time of LAS separation from probe).

Unfortunately, probe "Phobos-1" was lost on the way from Earth to Mars. The second probe ("Phobos-2") was launched on the AMAS orbit on January 30, 1989, and then, after a series of maneuvers, on March 21, 1989 it was launched to QSO-1. However, at the stage of preparation for the probe transfer to QSO-2, on March 29, 1989 it was lost. However, measurements taken in KIAM helped to clarify the theory of motion Phobos. BC KIAM in a timely manner and qualitatively implemented the job according all the developments assigned to it by BNS training and realization of the flights probes "Phobos-1" and "Phobos-2".

At the Institute effective computational algorithms were designed which allow quickly determine the current motion parameters of Phobos using the images of Phobos by television cameras installed on board of SC, and its ground trajectory measurements.

During preparation for the probe flight "Phobos-1, 2", The Institute designed a general algorithm for calculating the probability of performing constraints on the motion of a spacecraft relative to a celestial body [12]. Based on this algorithm for the BNS of the Phobos-1,2 missions using, KIAM specialists designed the algorithm for calculating the estimate of safe flight of an artificial satellite of the planet in the vicinity of its natural satellite [13].

3 PRESENT AND PREDICTED FUTURE

Currently, KIAM of the RAS is actively involved in developments in the preparation and realization of Russian and international projects. First of all, it should highlight the developments of the Institute of BNS for projects "RadioAstron", "ExoMars", Moon exploration program, "Laplace", "Spectr-RG".

3.1 Project «RadioAstron»

Currently the Institute is conducting work on the BNS of the "Spectr-RG" SC flight of the RadioAstron project and its scientific program.

The launch of the Spectr-R spacecraft on the flight path around the Earth took place on July 18, 2011. This spacecraft performs the functions of an international orbital astrophysical observatory (Figure 14). A radio telescope was installed aboard the Spektr-R spacecraft to conduct basic astronomical research in conjunction with ground-based radio telescopes. The orbit of the Spectr-R spacecraft was chosen so as to ensure the operation of the Earth – Cosmos interferometer with a base size much larger than the diameter of the Earth. Directly the BNO of the flight "Spectr-R" is carried out by the BC KIAM [14-16,21].

It can be considered that the RadioAstron project to study the Universe is one of the most successful scientific space projects implemented in the 21st century.

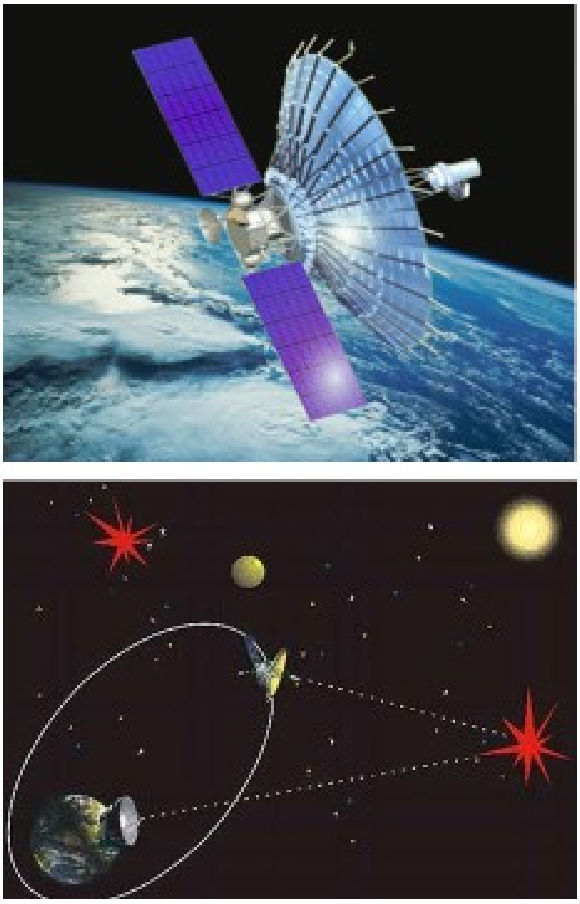


Figure 14. International Astrophysical Observatory of the RadioAstron Project

The main task of the project is the execution of radio interferometry observations with very-long bases with using complex of science devices of Astro Space Center of P.N. Lebedev Physics Institute (ASC LPI). Space radio telescope with a diameter of 10 m aboard the SC Spectr-R is the ground-space element of the interferometer outputted relative to the ground radio telescopes at a distance limited by the apogee of SC orbits. The largest radio telescopes of the world are used as ground elements of the interferometer. The evolution of orbits SC "Spectr-R" allows during the flight to observe the sections of the celestial sphere in certain modes to solve science problems of the project.

SC "Spectr-R" was created in Lavochkin NPO based on the space of the Navigator platform, successfully operated at SC "Elektro–L". Also in Lavochkin NPO a space radio telescope of unique construction was created.

The management of the space complex "Spectr-R" is carried out by the main operational control group, created on the basis of Lavochkin NPO, with the participation of specialists from organizations of the on-board system design, involving ground control stations and ground science complex. The calculation of the target designations (by SC) of the ground control stations and ground measure stations, the development of the results of orbits measurement parameters, reconstruction of SC orbit and prediction, calculation of ballistic parameters of the SC trajectory, correction and monitoring of SC ballistic existence and the shading degree SC by the Earth and the Moon - all this is provided by BC KIAM.

Along with the works in operational BNS of the "Spectr-R" SC control, KIAM in close cooperation with ASC LPI, participates in the realization of the science program of the SC motion required for the science information processing. To solve this very complex task, in addition to the ground-based trajectory measurements, the Doppler measurements of the high-information radio line (HIRL), distance laser measurements, made by national and foreign laser location stations, are used, and, along with the trajectory information, are used as part of the incoming from the SC telemetry information. To determine the parameters of the SC trajectory according to the specified information, a special technique being designed in KIAM is used.

Preparations for the BNS works of flight SC "Spectr-R" began several years before its launch. Implementing a priori estimate of the fidelity of determining the parameters of SC motion under conditions of periodic unloading of engine flywheels, a typical program was proposed for conducting the measurements of current navigation parameters. In the design program, the requirements to the trajectory SC were taken into account, which ensure high-quality processing of the data from the ground-space interferometer: the errors in position determination, SC's full speed and full acceleration should not exceed, respectively, $600\,m, 0.02\,m/\sec$ and $10^{-8}m/\sec^2$.

During the preparatory of works, it turned out that the measurements of slant range and radial speed, implemented by two command-measure stations in Bear Lakes and Ussuriysk, Doppler signal measurements from stations in Pushchino and Green Bank, cannot provide the precise of determination of the parameters of motion required for the data processing of ground-space interferometer. Therefore, it was decided to install on-board SC "Spectr-R" corner reflectors for laser ranging. A cycle of organizational measures was also implemented to prepare for operating of ground laser ranging stations network with SC "Spectr-R".

A month before the launch of the Spectr-R spacecraft, Lavochkin NPO organized and carried out an adjustment of the command-measuring stations in Ussuriysk and Bear Lakes by SCs in geostationary orbit, which revealed and eliminated a number of deficiencies in the transmission of target indications and measurements of current navigation parameters.

The joint work of specialists of Lavochkin NPO and KIAM of RAS in the field of ballistics and navigation provided radio interferometric observations with very-long bases.

Currently, Spectr-R, after seven years after launch, is successfully operating.

For the successful flight of the SC, the necessary corrections were made for the trajectory of his flight, the parameters of which were calculated by BC KIAM specialists. The choice of the trajectory of the following SC flight (after correction) under the conditions of its repeated encounters with the Moon's sphere of influence or even "immersion" in this SC area is realized by scientists from The Institute and ASC LPI. From the set of trajectories offered by BC KIAM, ASC LPI specialists select the most acceptable trajectory with point and view of implementation of the science program of the project RadioAstron [16,28].

3.2 Project «ExoMars»

Project "ExoMars" is a joint Russian-European project for the Mars exploring, within the framework of which it is planned to solve principal new science problems. It is performed in two stages-missions with probe launches in 2016 and 2020th.

In "ExoMars-2016" mission SC was consisted of the orbital module TGO (Trace Gas Orbiter), designed to study small gas impurities of atmosphere and water ice distribution in the soil of Mars, and the descent module EDM (Entry, Descent and Landing Demonstrator Module), which must enter into the Mars atmosphere for the landing on the planet's surface. The descent module, after separation from SC and to landing on the surface Mars descent module keeps in touch with the orbital module. Orbital module by carrying out the maneuvers transferred to the Mars artificial satellite orbit. The results of realization of the missions: the descent module could not reach normally the Mars surface – according to the European Space Agency (ESA) it crashed; the orbital module on October 16, 2016 successfully transferred to an elliptical orbit relative to Mars.

In 2020 Mission (as in Mission 2016), it is assumed that the composition of the SC includes the orbital module TGO and EDM descent module. However, within the framework of the mission, with help of the descent module developed in Russia, it is planned to deliver the Mars Rover ESS near 300 kg. The objectives of the Rover are geological research and search for traces of life in the subsurface layer of Mars near the landing place. After the Rover's descent with the landing platform, the next day it will begin its science mission as a long-lived stationary platform. The planned launch date is April-May 2020.

Important aspects of the project are the creation of a ground data acquisition complex with ESA and the management of interplanetary missions and the integration of the experience of Roscosmos and ESA with design technologies for interplanetary missions. The project can be considered as a stage of preparation for the development of Mars (exploration of landing areas, the search for subsurface water, monitoring of the radiation situation). The Space Research Institute of RAS (SRI) is responsible for the creation and operation of the Russian science device, which is a part of the spacecrafts, also for the ground science complex.

KIAM is actively involved in the project "ExoMars". In the interests of the operation of the ground control complex (GCC), BC KIAM, together with other industry organizations, should be ready for the timely implementation of the BNS flights SC project.

3.3 The Moon exploration program projects

The Space Research Institute (SRI of RAS) on behalf of Roscosmos has drawn up a phased program of Moon research [25]. At the first stage, it is proposed to begin research using automatic stations. By means of them, a place will be chosen for the future lunar station and the resources necessary to secure the future base will be discovered. Planned missions are the next: Luna-25 Glob (Figure 15), Luna-26 Resource, Luna-27 Resource, and Luna-28 Grunt. In addition, it is planned to begin preliminary design of the automatic research stations of a new generation, which will be able to begin exploring the moon in the second half of the next ten years and after 2030.

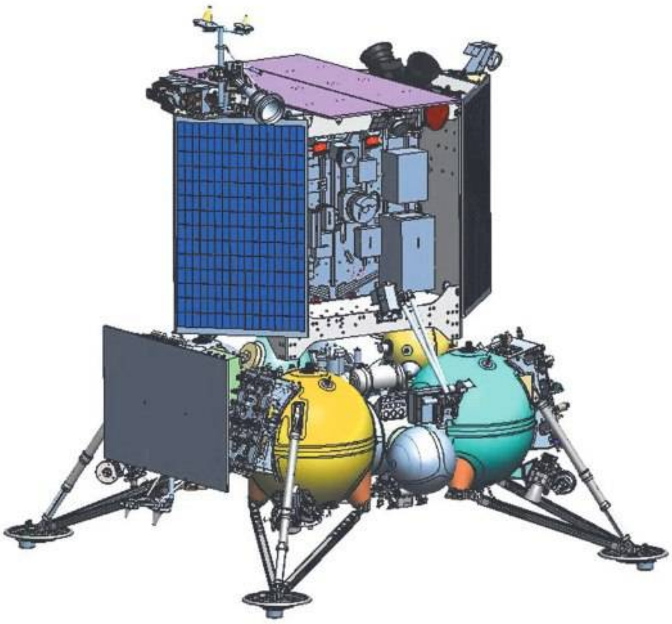


Figure 15. Spacecraft «Luna-Glob»

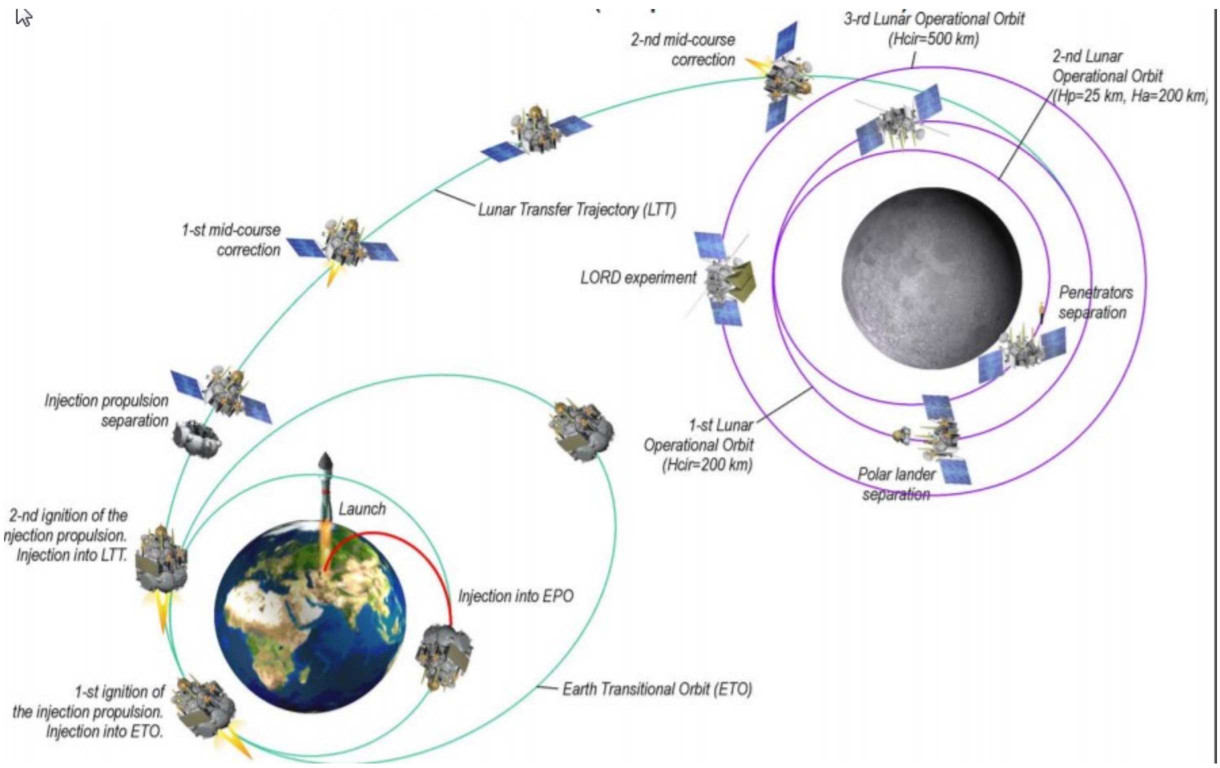


Figure 16. Scheme of the Moon probe flight

Compact experimental station for the soft landing developing at the Moon's polar region will be provide to adapt the soft landing technology and to learn regolith in the Moon' polar region. On the Figure 16 displayed the scheme of flight probe «Luna-25». The project designed in Lavochkin NPO. Duration of the mission is one year.

The project "Luna-Resurs" provides for the launch of two SCs: "Luna-Resurs-OA" (orbiter) and "Luna-Resurs-LM" (lander). SC "Luna-Resurs-LM" is intended for researches surface Moon. SC "Luna-Resurs-OA" is intended for range researches surface moon with polar orbits AMS. Ballistic design of this missions developed in cooperation with Lavochkin NPO and KIAM of RAS.

3.4 The Moon exploration program projects

The national Jovian probe mission «Laplace» is considered. The project proposes the landing implementation on one of the Jupiter's Galilean satellites. In connection with this a lot of gravity assists near the Jovian Galilean moons executing required. This project is developing by specialists of SRI of RAS, Lavochkin NPO, SINP MSU (Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University), KIAM of RAS.

KIAM of RAS was developed the Jupiter's system exploration project using the gravity assist maneuvers near Galilean satellites. With using real ephemeris heuristic search algorithm of a series of gravity assists of the probe executed in Jovian system for the purpose of converging it with one of its satellites was realized. If the total produced radiation dose (TID) exceeds some cost, the way cross the "upper corridor" of the Tisserand-Poincare graph is implemented. At the same time, low-cost reduction of the asymptotic velocity SC, necessary for the encounter with the Jovian moon, is carried out. Optimal scenarios are constructed - the sequence of passage of the celestial bodies and the development of the conditions of their execution. Examples are considered using such passages of the celestial bodies for the development of specific variants of the missions "Laplace P" [18-20].

3.5 The "Spectr-RG" project – flight в in the vicinity of L2 Lagrange point of the Sun-Earth system

The flight of the SC "Spectr-RG" is planned. The main task of the mission is to survey the entire sky in X-ray and other ranges in order to search for clusters of galaxies, to study black holes, neutron stars, outbreaks of supernovas and galactic nuclei. The "Spectr-RG" SC will be placed in the vicinity of the L_2 Lagrange point of the Sun-Earth system (Figure 17-19).

In KIAM conducted a ballistic design of a spacecraft flight to the vicinity of the L_2 Lagrange point and the subsequent spacecraft's entry into the halo-orbit. A method has been developed for calculating the trajectories of single-pulse Earth-halo-orbit flights with and without using the lunar gravity assist. A universal algorithm was constructed that allows finding the halo-orbits in the vicinity of the L_2 libration point of the Sun-Earth system with given geometric characteristics and calculating the flight trajectories to the halo-orbit from a low near-earth orbit [22,29].

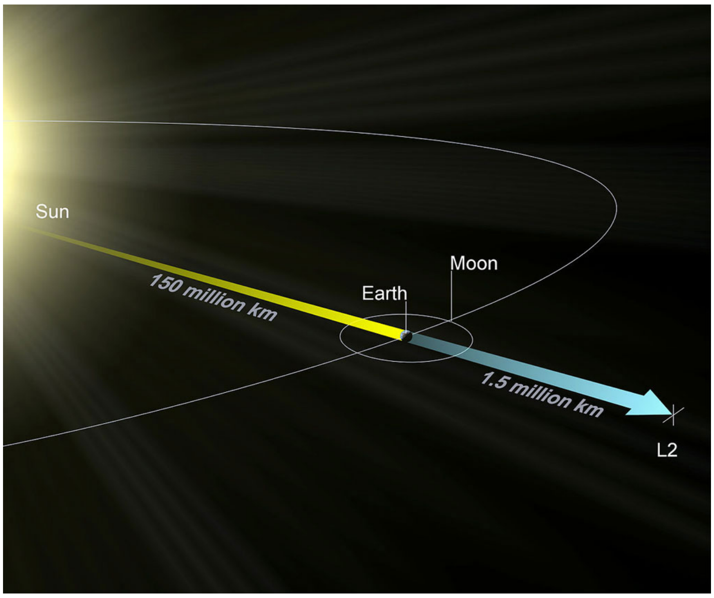


Figure 17. Position of L_2 Lagrange point of the Sun-Earth system

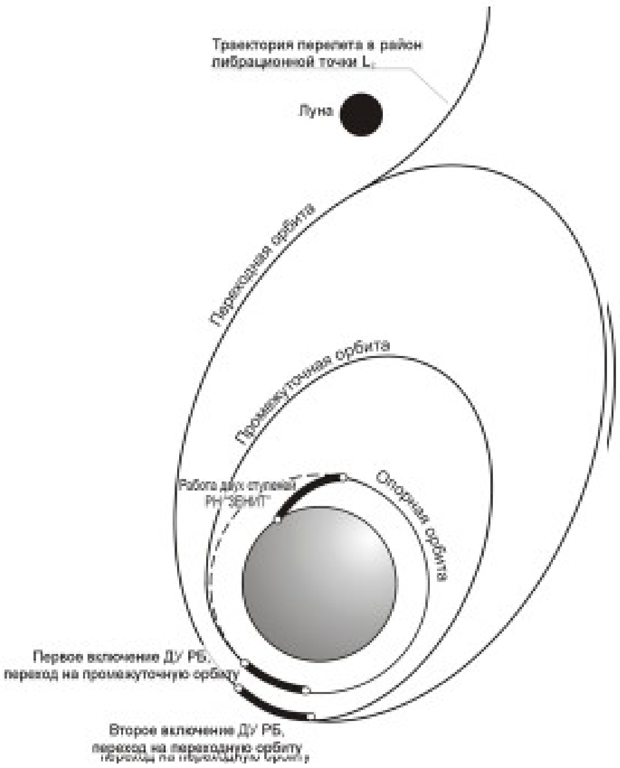


Figure 18. The SC «Spectr-RG» project trajectory to the L_2 Lagrange point of the Sun-Earth system with the Moon's flyby

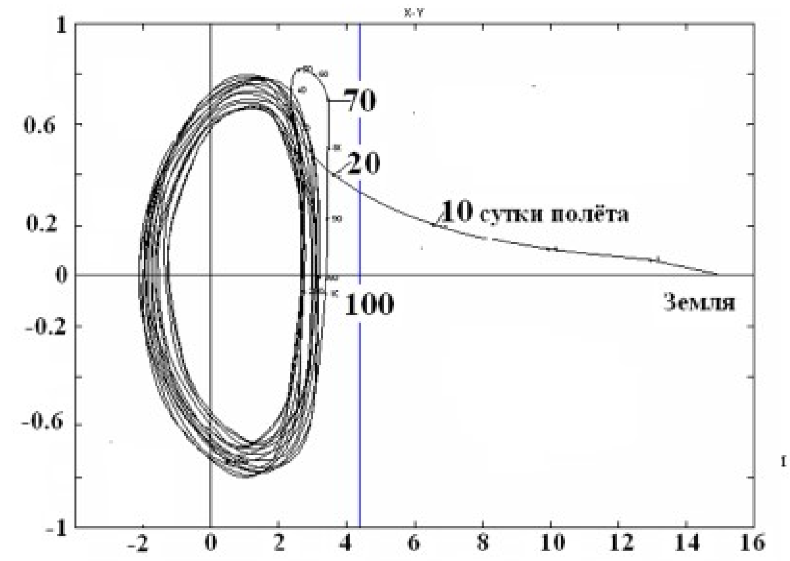


Figure 19. Transfer to halo orbit without Moon gravity assist: trajectory projection on OXY plane of L_2-centred rotating reference plane. Trajectory flight and halo-orbits around L_2 point. All axis units are presented in 10^8 km

3.6 The «Venera-D» project

The "Venera-D" international project for the Venus studying supposed to be realized after 2024 by dint of the Russian automatic interplanetary station of Venusian series. Its goal is to continue the fundamental researches of planets, started in the 60-80th of the XX century by USSR and USA. Although there was obtained a large amount of data about the planet before, many issues remain that are associated with the Venus evolution. The project "Venera-D" should provide a qualitatively new level of researches by simultaneously examining Venusian natural phenomena from the orbits of the AVS, subsatellite and from Venusian surface. Unlike previous Venusian missions, the landing of the module "Venera-D" will not execute the landing blindly, but in a terrain with a known geological context, by dint of using a radar measurement of Venera 15,16 probes and the "Magellan" probe. In [27] the change in the resurfacing regimes of Venus and probable ways of forming the terrain types that make up the surface of the planet is learned. The interpretation of the nature of the terrain types and their morphologic features allows characterizing facilities of concrete surface regions for the possibility of the "Venera D" landing operations. Such a technically complex space project will be implemented for the first time using national and international developments in space engineering technology, creating miniature measuring instruments and improving the quality of space radio communications.

KIAM experts already developed ballistic design of flights to Venus in 2021–2036 epoch with the aim of the spacecraft entering the orbit of the satellite of Venus and for the landing the descent module at a given point on its surface [23,24].

4. CONCLUSION

Now, in conclusion, it can be noted that from the very beginning of the space researches KIAM actively involved in many space projects, and often his contribution to the ballistic-navigation support of SC flights was decisive. The collective of the Institute values the name of Mstislav Vsevolodovich Keldysh, with which a whole epoch in the formation and development of space flights is connected. KIAM has major achievements, traditions, beautiful collective. He has the potential and the desire to continue to successfully solve theoretical and applied problems in the field of Space researches.

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