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# Chapter 14

# Space Autonomous Navigation System of Soviet Project for Manned Flyby of Moon*

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## Abstract

The onboard space navigation system, Alpha, for the USSR** Project L-1 of the manned flyby of the Moon is described in this chapter. The system was developed by the Institute of Applied Mathematics of the USSR Academy of Sciences and by the Central Design Bureau for Experimental Machine-Building, in the years 1966–1968. A sextant was used to obtain the onboard measuring information; it allowed cosmonauts a manual receiving of the optical measurements of the angular elevations of the known stars above the horizons of Earth and the Moon. The principal properties of the ballistic navigation algorithm are presented. This algorithm provided determination of the spacecraft orbit and correction velocity impulses for all the flight stages to ensure the safe spacecraft re-

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** Union of Soviet Socialist Republics, or Soviet Union (1922–1991).

entry into Earth's atmosphere. The problems that were connected with implementing the algorithm in the onboard computer are shown. This autonomous navigation system was successfully tested at the ground test complex for the flyby of the Moon with the unmanned variant of flight (spacecrafts *Zond 5—Zond 8*) from 1968 until 1970. The tests have shown that this onboard navigation system has met all the time and accuracy conditions in determination of the orbit parameters and correction velocity impulses.

## Introduction

Soviet Project L-1 for the manned and unmanned automatic flyby of the Moon was developed in the USSR in the 1960s.[1–5] The leading company of the project was the Special Design Bureau-1 (OKB-1, here and hereafter the Russian abbreviations are used) headed by academician S. P. Korolev[6] as Chief Designer. Further this enterprise was named the Central Design Bureau of Experimental Machine-Building (TsKB EM). Later it was the S. P. Korolev Rocket and Space Corporation Energia (S. P. Korolev RKK Energia).[7]

Some special works were performed for the project, in particular:

- *Spacecraft* with systems for manned and unmanned automatic flyby of the Moon was developed on the basis of the spacecraft Soyuz.[8] It was made by OKB-1 (TsKB EM)—O. G. Makarov, G. Ju. Maximov,[9] N. P. Beresnev, V. D. Blagov, L. I. Dul'nev, et al.;
- An analysis of *space trajectories* for flyby of the Moon with return to Earth, by gently sloping reentry to Earth's atmosphere, with the osculating perigee altitude of about 50 km was performed. It was made by OKB-1 (TsKB EM) and by the Institute of Applied Mathematics of the USSR Academy of Sciences (IPM AN SSSR).[10] Now the last institute is the M. V. Keldysh Institute of Applied Mathematics, Russian Academy of Sciences (Keldysh IPM RAN);
- A *ground navigation system* was developed on the basis of ground radio measurements facilities (by the Research and Development Institute-885 (NII-885)[11]—academician M. S. Ryazansky,[12] et al.);
- An *autonomous navigation system* was developed by TsKB EM and IPM AN SSSR. It was made on the basis of an onboard computer developed by the Research and Development Institute of Micro-Instruments—NII Mikropriborov (NII MP) and by TsKB EM. A sextant developed by the Kiev enterprise, Arsenal, was used as a measuring instrument;

- A *flight control system*, in particular, a control system for descent in Earth atmosphere at returning from Moon to Earth with about the second cosmic (escape) velocity, was developed. It was made by the Research and Development Institute of Automatics and Instrument Engineering—NII Avtomatiki i Priborostroeniya (NII AP)[13]—academician N. A. Pilyugin,[14] et al; by the IPM AN SSSR—academician D. E. Okhotsimsky, et al.[15]; by Professor N. E. Zhukovsky Central Aero-Hydro-Dynamic Institute (TsAGI)—academician V. A. Yaroshevsky,[16] et al.

Project L-1 was realized in 1968–1970 by the automatic flights of spacecrafts (SC) *Zond 5–8*. The rocket Proton, with the additional fourth stage, was used to launch SC *Zond*s.[17]

It was SC *Zond-5* (15 September 1968 – 22 September 1968) that for the first time in the world performed after flyby of Moon returning to Earth with the second cosmic (escape) velocity. Live creatures (animals)—turtles—were launched to the Moon and returned to Earth for the first time in the world.[18] Spacecrafts *Zond-6* (10 November 1968 – 17 November 1968) and *Zond-7* (8 August 1969 – 14 August 1969) performed the controlled descent in Soviet territory.[19] Returning SC *Zond-8* (20 October 1970 – 27 October 1970) was performed from the north direction after flyby of the Moon.[20] Figure 14–1 shows SC *Zond*s *5–8*.[21]

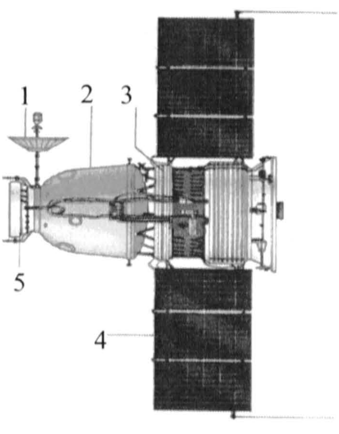


**Figure 14–1**: Spacecraft *Zonds 5–8*: 1—sharp-direction antenna; 2—descent module; 3—engine module; 4—solar panels; 5—instrumental module.

Figure 14–2 gives the trajectory of *Zond-6*.[22] Figure 14–3 gives the scheme of the *Zond-6* descent in the Earth atmosphere.[23]

Initial variant of Project L-1 had no autonomous navigation system. But analysis showed insufficient reliability of navigation for the "south" spacecraft reentry to the Earth atmosphere from the Moon with the second cosmic (escape) velocity.

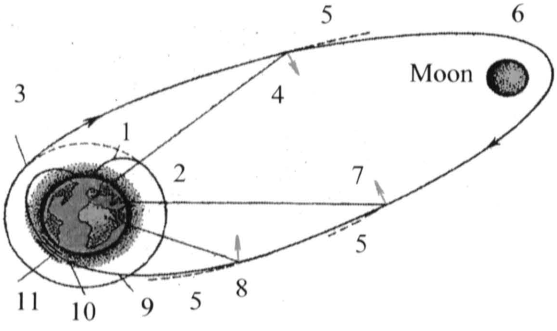


**Figure 14–2**: Scheme of flight for *Zond-6* with flyby of Moon: 1—launch to parking orbit; 2—parking orbit; 3—start to Moon; 4—the first correction, at distance from Earth $r_{c1}$≈246,000 km, with correction velocity impulse $\Delta V_{c1}$; 5—uncorrected motion; 6—flyby of Moon; 7—the second correction, $r_{c2}$≈236,000 km, $\Delta V_{c2}$; 8—the third correction, $r_{c3}$≈120,000 km, $\Delta V_{c3}$; 9—separation of descent module; 10—descent in air; 11—reentry interval.

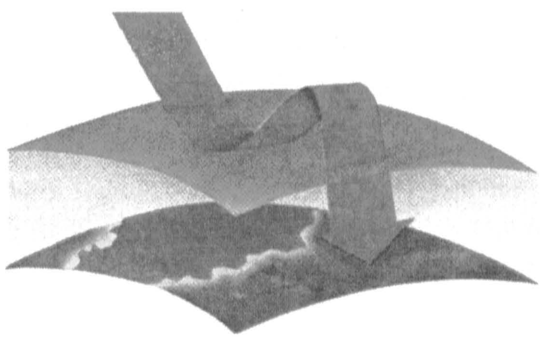

**Figure 14–3**: Descent of *Zonds 6–7* in Earth's atmosphere.

The cause was that at the initial step of the project, the ground radio navigation system did not ensure a proper reliability concerning the necessary accuracy in determination of the osculating orbit perigee altitude before the spacecraft reentry to the Earth atmosphere (with necessary reentry interval 45±10 km). After suggestions of the OKB-1 and IPM AN SSSR and taking into account the big experience base of Soviet rocketry and cosmonautics in autonomous optical navigation and also the principal importance of autonomous navigation,[24] the development of the onboard computer and the autonomous navigation system was incorporated into the project in about 1966.

The *autonomous navigation system* included the following elements:

- Cosmonaut (astronaut);
- Measuring instrument–sextant; it allowed cosmonauts to measure the angles of the known star elevations above the horizons of Earth and the Moon;
- Onboard Digital Calculating Computer (BTsVM)—onboard computer. It provided the capability to perform manual input of the measured angles and measurements times into the computer working memory RAM, to process the measurements and determine the spacecraft orbit elements, to calculate the correction velocity impulses and, on this base, to define parameters to the flight control system for correction execution; and
- Timekeeper and navigation journal.

Ballistic algorithm of navigation was a basis of the mathematical software for the navigation system.

## Ballistic Algorithm of Navigation

### Requirements to the Navigation Algorithm

Some requirements were stated to the algorithm of the onboard navigation:

- Requirements from onboard computer;
- Requirements from measuring system;
- Time requirements of the project;
- Accuracy requirements of the project.

### Onboard Digital Calculating Computer (BTsVM)

Onboard computer, *Salyut-1,* was used for the navigation system. It was the first Soviet onboard computer made with microchips. The computer was developed by the Research and Development Institute of Micro-Instruments (NII Micro-Priborov—NII MP), Zelenograd, Moscow Region (I. N. Bukreev, A. S. Florovsky, G. Ja. Gus'kov,[25] et al.), and the TsKB EM teams of K. K. Chernyshev and G. V. Noskin. This computer had very limited capabilities. Its main characteristics were the following:

- Working memory RAM had 64 32-bit registers;
- Read-only memory ROM (for programs and constants) had 4,096 17-bit registers;
- Arithmetic had a fixed point;

- Average speed was equal to about 100 operations/s (500 short operations/s, 10 long (multiplication, division) operations /s);
- Mass was about 14 kg (with a console);
- Dimensions of the computer were about 45 × 14 × 14 cm; ones of the console were about 22 × 12 × 6 cm.

Figure 14–4 gives a photo of the computer with the console and a slide rule (for scaling). Characteristics of 514 stars with magnitude *m* to 4 were kept in the computer memory. Cosmonauts were provided with the Star Catalogue given in the Navigation Journal.

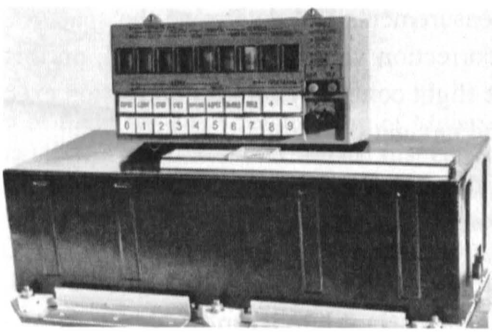

**Figure 14–4**: Photo of onboard computer, *Salyut-1,* with the console and a slide rule.

## Autonomous Navigation Measurements

A sextant was used to obtain the measurement information. It provided cosmonauts with the onboard optical measurements of angles for known stars elevations above horizons of Earth and the Moon, as it is shown in Figure 14–5.

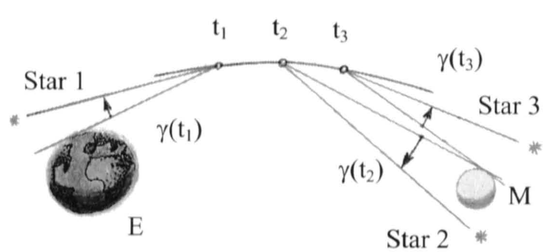


**Figure 14–5**: Measurements of angles for the stars elevations above Earth and Moon horizons: E—Earth; M—Moon.

## Orbit Determination in Keplerian Approximation

Universal algorithm of navigation was developed by the IPM AN SSSR. The algorithm satisfied the requirements shown and provided determination of the spacecraft orbit elements and calculation of the trajectory correction on the basis of the onboard measurements for all the flight stages.

To increase the calculation speed, the orbit was determined by loop-within-loop method. An inner loop (with main number of iterations) determined the orbit with calculating all the quantities and derivatives by formulas of the Kepler two-body problem. An outer loop (with a small number of iterations) gave small corrections to the orbit elements; they took into account the perturbations and determined the orbit for a full enough field model with gravity of Earth, Moon, Sun, and Earth's oblateness.

The following orbital elements $\mathbf{q}=\{q_l\ (l=1, 2, \ldots, 6)\}$ were used in the algorithm: $h$ ($=V^2-2\mu/r$, energy constant, $V$—velocity, $r$—distance to a gravity center, $\mu$—gravitational parameter), $\varphi_1$ ($=e \sin\omega$, $e$—eccentricity, $\omega$—argument of pericenter), $\varphi_2$ ($=e \cos \omega$), $i$ (inclination), $\Omega$ (ascending node), and $T_u$ (time of the ascending node passing). They correspond to the geocentric or selenocentric spacecraft motion.

Determination of the orbit has been planned to be performed after a session of onboard measurements by iterative way using least-squares technique.

A system of normal equations[26] for corrections of the elements $\Delta \boldsymbol{q}_j^{(i)}$

$$\mathbf{A}_j^{(i)}\, \Delta\mathbf{q}_j^{(i)}=\mathbf{B}_j^{(i)}$$

has been constructed on the basis of angle measurements $\gamma^{(o)}(t_k)$, their correction via the perturbations, and values of the elements for previous iteration $\mathbf{q}_j^{(i)} = \{h_j, \varphi_{1j}, \varphi_{2j}, i_j, \Omega_j, T_{uj}\}^{(i)}$ (here $j$ is a number of the iteration for the outer loop, $i$ is a number of the iteration for the inner loop).

Having solved this system, corrections of elements $\Delta\mathbf{q}_j^{(i)}$ for this iteration were received. After entire inner Kepler loop, the corrected orbital elements were obtained.

## Accounting Perturbations for Orbit Determination

"Exact" trajectory of spacecraft was determined by numerical integration of a system of differential equations for the spacecraft motion using Encke's method.[27] Calculating values of the measured angles $\gamma^{(c)}(t_k)$ are defined for both "exact" and "Keplerian" trajectories. That allowed finding the reduction of the measurements due to the perturbations. Usually, the number of iterations in the outer loop (and also a number of the integrations) was small enough (about 2–3).

## Calculation of Orbit Correction

Calculating the correction velocity impulses was performed in two steps similarly to determination of the orbit elements: (a) the first one was performed for the model of the Kepler field in a two-body problem; (b) the second one was made with taking into account the perturbations. This was performed similarly to the definition of the orbit from measurements.

Four corrections were planned in the algorithm: (1) before Moon's sphere of influence; (2) in the Moon's sphere of influence; (3) after flyby of Moon; and 4) before reentry to Earth's atmosphere. For the first three cases, a correction velocity impulse was calculated to go after it at the given time to the aim point (this point usually was constructed on the basis of the nominal trajectory). The orbit after the correction was defined by two spacecraft positions—the position for the correction and the aim position, that is, by solving the Lambert problem, in fact. For the last, "cleaning" correction, the final osculating perigee altitude was corrected.

The analysis has shown high methodical accuracy of this method for the correction calculation.

## Peculiarities of Algorithm

Some peculiarities of the algorithm developed should be noted:

- There were developed and used such algorithm, calculation sequence, and codes, which provided capability to match all the algorithm (with integration) and necessary measurements using very small RAM in the onboard computer (64 registers only);
- All the quantities in the algorithm were scaled, and their values were not greater than one (1.0), taking into account that arithmetic had a fixed point;
- Calculations were made such that their accuracy was not reduced and their speed was not slowed;
- In particular, to increase the speed, the developed scheme of algorithm used a small number of integration, nevertheless providing high enough accuracy in the orbit determination;
- Algorithm had a special structure. Its main functional parts were made in the form of separate units. This simplified the codes preparing, their debugging, and implementing in the onboard computer.

## Navigation Algorithm Implementation in Onboard Computer and Its Debugging

Navigation algorithm was then implemented in the onboard computer *Salyut-1*—by TsKB EM. It should be noted that the TsKB EM not only took part in creation of this computer at the Research and Development Institute of Micro-

Instruments (NII MP) but also developed all the software (PMO) for the onboard computer. The software included the operation system and standard programs, and also the special program complex (Instrumental PMO) for debugging onboard software at the ground Universal Digital Calculation Computers (UTsVM) similar to the Soviet universal computer of that time—M-20.

For debugging and testing the navigation system and for training the crews, a special test complex was designed and created in TsKB EM. It consisted of the real onboard computer *Salyut-1* with the console and a program model (made on the UTsVM like M-20) of spaceflight for the SC L-1, and a model of simulated onboard measurements. In particular, a special program complex was created for debugging of navigation algorithm and the onboard computer at this test complex. Debugging the navigation algorithm at the onboard computer *Salyut-1* has been performed jointly—by the TsKB EM and by the IPM AN SSSR.

## Autonomous Navigation System Testing and Crews Training

After debugging codes and algorithms, before flights of unmanned spacecraft L-1 (*Zond*s *5–8*), on the test complex, there were performed testing and developing the system with participation of TsKB EM, IPM AN SSSR and cosmonauts, who were the candidates to the flight at the manned spacecraft L-1 (Oleg G. Makarov, Alexey A. Leonov, Nikolay N. Rukavishnikov, Valery F. Bykovsky, Vitaly I. Sevast'yanov, and Pavel R. Popovich).[28] A special navigational journal (onboard journal) for the navigation system was created. Figure 14–6 demonstrates a picture for the onboard journal of system Alpha.

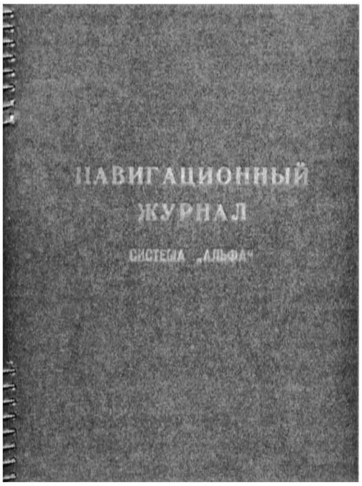


**Figure 14–6**: Picture of the onboard journal for navigation system Alpha.

The journal was used for testing the system, training the cosmonauts in determination of the orbit elements, and calculation of the correction velocity impulses and planned to be used for solving these problems in the real flight. The star catalog and all the forms required for solving the navigation problems were placed in this journal.

Figure 14–7 shows a page of the journal from its Form Alpha 2 with a fragment of the star catalog. The stars Capella, Polaris, Betelgeuse, Sirius, and Canopus are seen there.

Форма Альфа 2

**Каталог звезд**

| № п/п | Звездная величина m | Спектр | Долгота градусы, минуты | Широта градусы, минуты | Название звезд ( ) — номер по каталогу С-I |
|---|---|---|---|---|---|
| 101 | 3,2 | B | 079 02 | +18 17 | η Возничего |
| 102 | 2,8 | G | 079 15 | -43 55 | β Зайца |
| 103 | 3,4 | B | 079 44 | -25 32 | η Ориона |
| 104 | 1,6 | B | 080 32 | -16 49 | γ Ориона (16) |
| 105 | 2,6 | F | 080 58 | -41 04 | α Зайца |
| 106 | 0,1 | G | 081 26 | +22 52 | α Возничего (Капелла) |
| 107 | 2,6 | B | 081 45 | -57 23 | α Голубя (36) |
| 108 | 2,2 | O | 081 57 | -23 33 | δ Ориона |
| 109 | 3,8 | A | 082 07 | -74 26 | β Живописца |
| 110 | 1,6 | B | 082 09 | +05 23 | β Тельца |
| 111 | 2,8 | O | 082 35 | -29 12 | ι Ориона |
| 112 | 1,7 | B | 083 03 | -24 31 | ε Ориона |
| 113 | 3,4 | O | 083 17 | -13 22 | λ Ориона |
| 114 | 3,8 | O | 083 41 | -25 56 | σ Ориона |
| 115 | 1,7 | B | 084 16 | -25 18 | ζ Ориона |
| 116 | 3,0 | B | 084 22 | -02 12 | ζ Тельца |
| 117 | 3,6 | F | 084 26 | -45 49 | γ Зайца |
| 118 | 3,6 | A | 085 34 | -38 13 | ζ Зайца |
| 119 | 2,0 | B | 085 59 | -33 04 | κ Ориона |
| 120 | 3,1 | K | 086 00 | -59 11 | β Голубя |
| 121 | 3,8 | G | 086 45 | -44 18 | δ Зайца |
| 122 | 2,0 | F | 088 09 | +66 06 | α Малой Медведицы (Полярная) |
| 123 | 0,8 | M | 088 20 | -16 02 | α Ориона (Бетельгейзе) (04) |
| 124 | 3,7 | F | 088 29 | -37 37 | η Зайца |
| 125 | 4,0 | K | 089 12 | -66 15 | η Голубя |
| 126 | 1,9 | A | 089 30 | +21 30 | β Возничего (25) |
| 127 | 3,7 | G | 089 30 | +30 51 | δ Возничего |
| 128 | 2,7 | A | 089 31 | +13 46 | θ Возничего |
| 129 | 3,1 -3,9 | M | 093 01 | -00 54 | η Близнецов |
| 130 | 4,0 | K | 093 50 | -29 40 | γ Единорога |
| 131 | 3,0 | M | 094 53 | 00 49 | μ Близнецов |
| 132 | 2,0 | B | 096 46 | -41 15 | β Большого Пса |
| 133 | 3,0 | B | 096 58 | -53 23 | ζ Большого Пса |
| 134 | 3,8 | B | 097 52 | -30 16 | β Единорога |
| 135 | 3,8 | G | 098 00 | -56 43 | δ Голубя |
| 136 | 1,9 | A | 098 41 | -06 45 | γ Близнецов |
| 137 | 3,1 | G | 099 31 | +02 04 | ε Близнецов |
| 138 | 3,6 | A | 100 42 | +11 02 | θ Близнецов |
| 139 | 3,4 | F | 100 47 | -10 06 | ξ Близнецов |
| 140 | 4,0 | K | 101 19 | -42 20 | ν2 Большого Пса |
| 141 | -1,5 | A | 103 40 | -39 36 | α Большого Пса (Сириус) (00) |
| 142 | -0,7 | F | 104 33 | -75 50 | α Киля (Канопус) (01) |
| 143 | 3,7-4,5 | G | 104 34 | -02 03 | ζ Близнецов |
| 144 | 3,2 | B | 106 44 | -66 05 | ν Кормы |
| 145 | 3,8 | K | 107 45 | -46 47 | o1 Большого Пса |
| 146 | 3,5 | A | 108 06 | -00 11 | δ Близнецов |
| 147 | 4,0 | B | 108 09 | -55 09 | κ Большого Пса |
| 148 | 3,6 | A | 108 22 | -05 38 | λ Близнецов |
| 149 | 3,8 | G | 108 32 | +05 45 | ι Близнецов |
| 150 | 1,6 | A | 109 49 | +10 06 | α Близнецов (Кастор) |

**Figure 14–7**: Picture of a page from onboard journal.

We must note that the cosmonauts have appreciated very highly the capabilities and characteristics of the autonomous navigation system Alpha. They took part in this work with great wish and enthusiasm.

The testing gave good results. The type of the angular measurements taken allowed determination of the spacecraft orbit very well; the orbit was defined quickly and accurately enough, taking into consideration the full and saving structure of the algorithm. So, the system and the cosmonauts were ready for the flights of the SC L-1—*Zond*s *5–8*.

For the flights of the automatic unmanned spacecraft L-1 (*Zond*s *5–8*, September 1968 – October 1970) the operation of the autonomous navigational system was simulated at the ground test complex in parallel with the operation of general Mission Control Center.

The simulation showed that the autonomous navigation system did not practically yield to the general ground Mission Control Center—both in the rate and in the accuracy. All the operations in the measurements processing, the orbit determination, and the correction velocity impulse calculation lasted about two hours. So, the system and the cosmonauts were ready for the manned flights of spacecraft L-1.

Unfortunately, the flight of spacecraft L-1 has been realized in unmanned automatic variant only; and the autonomous navigation system Alpha has not operated in conditions of real manned flight to the Moon and back.

Nevertheless, the results of the performed testing and ground simulation gave weighty enough arguments to conclude that the autonomous navigation system developed had potentially high characteristics.

## Conclusions

The experience in creating the autonomous navigation system Alpha of the spacecraft L-1 for the manned flyby of the Moon showed good prospects of the onboard navigation systems. Even for restricted enough capabilities of the onboard computer in the 1960s, this system has demonstrated high characteristics in rate and accuracy, which were practically not worse than ones for the ground Mission Control Center. Autonomous navigation systems have a good future in cosmonautics in modern conditions of miniaturization for information–computer technology.

There was quite a big team that took part in the creation of the system. Besides the authors, these were some experts from IPM AN SSSR (Professor V. A. Egorov, N. I. Zolotukhina, G. R. Sazykin, V. A. Zlatoustov, E. R. Smolyakov), TsKB EM (Dr. G. V. Noskin, Dr. K. K. Chernyshev, V. M. Shutenko, Ju. V. Stishev, Dr. Ju. N. Zybin, and Dr. E. V. Gaushus); NII MP (for the onboard computer—I. N. Bukreev, A. S. Florovsky, G. Ja. Gus'kov,[29] et al.); KB Arsenal (for the sextant). Academicians S. P. Korolev, B. E. Chertok, B. V. Raushenbakh, M.

V. Keldysh, D. E. Okhotsimsky[30] gave a lot attention and support to the system creation.

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