Aerospace engineering experience and on-board software projects of satellite navigation systems

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Abstract. The main stages of creating global space navigation systems of the first generation are discussed in the article. The authors give a description of the scope and content of work, stages and timing of this work, and also give the main characteristics of the satellites and on-board software testing processes of these space navigation systems. The list and sequence of technological stages of the on-board software testing process are defined in the description of the methodology for guaranteeing the quality of development and maintenance of the on-board software of communication and navigation satellites.

1. Introduction

The possibility of using artificial earth satellites as mobile radio landmarks to determine the location attracted attention of specialists after their first successful launches. Satellite radio navigation has a number of significant advantages over traditional methods using celestial bodies or ground-based radio beacons as landmarks. First of all, the globality of the service, the independence of navigation support from the time of the year, day, weather conditions, the efficiency and accuracy of users’ determination of their location, speed and time should be noted [1-4].

Historically, since the beginning of the development of domestic satellite navigation systems, JSC “Academician M F Reshetnev Information satellite systems” (JSC “ISS” earlier OKB-10, KB PM, NPO of Applied Mechanics) at the government level was determined as the head in the cooperation of developers, responsible not only for the space segments of these systems, but also for the systems in general, including their main characteristics: accuracy, availability, integrity, etc. Since the mid-1960s, cooperation with the leading role of JSC “ISS” has developed and created satellite radio navigation systems of two generations, differing in the principles of construction, methods, efficiency and accuracy of navigation determinations, orbital alignment, service area, etc. [5-9].
2. Satellite navigation systems of the first generation

The necessity to create a navigation satellite system was primarily due to the requirement to achieve parity in the naval component of the triad of nuclear weapons of the USSR and the USA. A satellite navigation system called NNSS (Navy Navigational Satellite System), consisting of four Transit satellites in low (1000 km) polar orbits, ground control and monitoring system and shipborne receiver-indicator equipment had already deployed by that time (in 1962) and in 1964 put into service the Navy in the United States.

The NNSS was developed by the Applied Physics Laboratory of J. Hopkins University commissioned by the US Navy for submarines armed with Polaris ballistic missiles as part of a unified program with the creation of missiles and the construction of submarine missile carriers. But already in 1967, at the international level, it was announced that it would be possible to use the NNSS by civilian vessels, and not only belonging to the United States, but also to other countries (except for socialist countries). Each Transit satellite emitted two coherent phase-shift keyed navigation signals with carrier frequencies of 150 and 400 MHz, containing navigation (ephemeris of the corresponding satellite), time (digitized time stamps) and telemetric (on the state of onboard systems) information.

The scientific research carried out and the fragmentary information about the American Transit satellites available in OKB-10 in the early 1960s indicated the relevance of creating a similar domestic satellite navigation system to ensure parity with the United States as a security of accurate delivery of warheads to targets. Therefore, in 1963, OKB-10, which by that time had created an integrated launch vehicle (ILV) “Kosmos-3M” and the first domestic communication satellites “Strela-1” and “Strela-2”, which were put by this carrier into circular orbits up to 1500 km [5] came out with an initiative to develop a system similar to NNSS. While recognizing its relevance, it was necessary to simultaneously admit that the tasks of satellite radio navigation were not taken into account in the current execution documents on rocket and space topics. It was necessary to look for a solution within the space programs already planned by the execution documents.

One of such space programs was the program for the creation, in the interests of the Navy, of a satellite radio communication system using the spacecraft (SC) “Molniya-2” in circular orbits with an altitude of about 800 km. Looking for solutions, the idea of increasing the efficiency of the combat use of naval vessels, primarily missile submarines, by combining the functions of a communication repeater and a navigational beacon within a single type satellite “Molniya-2”, started up. So that in one float to the periscope position, submarines would have the opportunity to simultaneously carry out both a two-way radiotelegraph communication session with coastal control points and determine both their position and course, as the azimuth of a fixed direction for aiming missiles.

After the issuance of execution documents, OKB-10 began to create the world’s first combined navigation and communication satellite complex “Cyclone”. Satellite navigation by the means of first generation space systems used the radial-velocity (Doppler) method of navigational sighting by naval users, regardless of departmental affiliation, and, in addition, goniometric and distance measuring method was used for special users. Carrying out radial-velocity and distance measurements in one session, in addition to determining the azimuth, significantly increased the accuracy, reliability and, most importantly, noise immunity of spacecraft observations, since the goniometric and distance signal was received by a narrow-beam antenna with an opening angle of the scanning directional pattern of 1.2 degrees.

According to the navigation signals of a low-orbit satellite, the consumer could determine only two of his horizontal coordinates and only on the surface of the Earth, which is generally acceptable only for naval users, with a relatively low, especially at the initial stages, positioning accuracy (up to 1000 ... 1500 m) and with a frequency 1.5… 2.0 hours at equatorial and middle latitudes. Such a periodicity of possible observations of satellites and the globality of the navigation field formed by them are determined by the altitude and inclination of orbits (circular, circumpolar with an altitude of ~ 1000 km)
and the number of satellites in the orbital structure (4–6). Moreover, the orbital altitude is the result of a compromise between the diameter of the radio coverage area, the minimum required duration of the observation session, and the energy of radio lines.

Not only the satellites themselves, but practically all the elements of the system underwent modernization: the command and measurement radio line was transferred from the meter to the decimeter range, new sets of ship navigation equipment were developed, and the hardware and software equipment of the command post of the system was completed.

At the time of commissioning, the system “Parus” provided the determination of two horizontal coordinates with a root-mean-square error of 250 ... 300 meters, which was almost four times less than the specified one. This improvement in accuracy became possible due to a number of measures to improve the accuracy of determining and predicting orbital parameters, proposed methodically developed by OKB-10 enterprise (choosing the optimal scheme for conducting radio monitoring of the orbit, determining the duration of the measured interval required to achieve the highest accuracy of daily forecasting of orbital parameters, using original numerical and analytical methods for integrating the parameters of navigation spacecraft motion, for specifying the value of the so-called ballistic coefficient for these satellites, which takes into account their atmospheric deceleration). These measures were introduced into the practice of ballistic-ephemeris support in the ballistic center of the system.

Further development of low-orbit domestic navigation went towards the creation on the basis of the system “Parus” of the single-purpose navigation system “Cicada”, and later on, on its basis, the domestic part of the space segment of the international satellite system for detecting and determining the geographic coordinates of ships and aircraft in distress (COSPAS-SARSAT). In the USSR the need to develop and create a single-purpose, navigation satellite system, by analogy with the American NNSS with satellites “Transit”, became obvious even before the end of the 1960s, since the navigation-communication satellites “Cyclone-B” (“Parus”), both already mentioned above, due to the integration of navigation and radio communication tasks within a single satellite, had restrictions on the cycle duration of the radiation of navigation radio signals. Of course, such integration significantly increased the effectiveness of the combat use of the system, especially with underwater nuclear missile carriers, but it was precisely this that caused these restrictions due to the lack of energy resources on satellites. At the same time, for the massive, unrequired free use of the navigation signal by an unlimited number of civil (and military as well) vessels in any area of the World Ocean, it was required to ensure continuous emission of navigation signals by each satellite in the satellite system at each loop and during the entire period of active existence.

In the course of the development of the navigation system “Cicada”, on the initiative and with the participation of NPO AM, the work to determine a matching model for the movement of satellites in "navigation" (1000 km, 83°) orbits by studying the movement of two geodetic satellites "Sphera" (Cosmos-842 and Cosmos-911) was also carried out. The collection of measurement information was carried out by a network of special observation points and five oceanographic vessels of the Navy, equipped with radio-geodetic measuring equipment. The introduction of such a matching model into the ballistic-ephemeris support of the first generation navigation satellites has increased the accuracy of positioning based on their radio signals by three times: from 250 ... 300 m (1976) to 80 ... 100 m (1979).

In 1979, the navigation system “Cikada” consisting of four spacecraft of the same name, a ground control complex (common with the GCC of the system “Parus”) and ship (marine) navigation equipment was put into operation for navigation support of ships of the Navy, other law enforcement agencies, as well as civilian vessels. The use of navigation satellites in the system of timely notification of the fact and coordinates of a disaster is extremely important in saving human lives and emergency objects (ships, aircraft, etc.) [10].

The beginning of international cooperation on the creation of a satellite system for detecting and locating ships and aircraft that suffered an accident was laid at a bilateral (USSR and USA) meeting held in Washington in March 1977. In November 1979, in Leningrad, representatives of the USSR, the
USA, France and Canada signed a Memorandum confirming the desire of the parties to cooperate in a joint project to create a satellite search and rescue system "COSPAS-SARSAT", consisting of two complementary and technically compatible radio technical subsystems: COSPAS (created by the Soviet Union) and SARSAT (created by the USA, France and Canada) [3, 10].

To solve the rescue problem, the vehicle (sea, air) is equipped with an emergency buoy, which is automatically or forcibly switched on at the time of the accident and continuously (up to two days) transmits signals on one of two frequencies: 121.5 and 406 MHz or both at the same time. These signals at 1544.5 MHz are relayed via satellite to a ground navigation center, which allocates the Doppler frequency increment and determines the coordinates of the emergency buoy. In Russia, ground navigation centers are located in the following cities: Moscow, Arkhangelsk, Novosibirsk, Vladivostok, and the system control center is located in Moscow. The satellite also provides a mode for processing and storing the signal received from the buoy at a frequency of 406 MHz with its subsequent retransmission to the ground navigation center when the satellite enters the center's radio visibility zone. This expands the scope of the system to a global one. The received information is transmitted to the Center of the international system "COSPAS-SARSAT", which, through the appropriate search and rescue services, organizes work on the release of rescue equipment to the disaster area and providing assistance.

Due to the modernization options provided for in the development, some navigation satellites "Cicada", in order to create the space segment of the international system, began to be equipped with emergency signal repeaters, while performing the functions of emitting dual-frequency navigation signals as part of the system “Cicada”. Such satellites were called “Cikada-N” or simply “Nadezhda”. The first SV "Nadezhda", manufactured by IA "Polet", was launched into navigation orbit from the Plesetsk cosmodrome by the launch vehicle “Cosmos-3M” in 1982, and already in September 1982 from this satellite (at that time the only one in the system COSPAS-SARSAT), the signals of the emergency radio beacon of a Canadian aircraft that crashed in the mountains of British Columbia were relayed, which ensured the prompt detection and rescue of three people. With a given service life of two years, this satellite actually operated until March 1988 (almost 6 years). The system “COSPAS-SARSAT” (two domestic and two American satellites) was fully deployed by the end of 1984 and its full-scale operation began in 1985.

According to expert estimates, the satellite system “COSPAS-SARSAT” substantially (by 10 times or more) allows reducing the search time for a mobile object (vehicle) in distress, which is equipped with an emergency radio beacon. This is especially important for those who move in sparsely populated and extreme climatic conditions (these include the northern tundra, taiga, the Arctic Ocean, deserts), where every extra hour of stay without help for seriously wounded or overcooled people is fraught with death. On the whole, this system accounts for tens of thousands of saved human lives.

The international system is approved by the international organizations IMO (maritime) and ICAO (civil aviation), which made decisions on its mandatory use by sea vessels (since 1995) and aircraft (since 2005). Satellite navigation systems of the 1st generation (“Parus” and “Cikada”) by the end of the 1970s provided data on two planned coordinates of the object's location with an accuracy within a hundred meters. In the process of creating first generation satellite navigation systems, the basic configuration of the satellite was developed, which served as the basis for the spacecraft of the unified series (KAUR-1) [1].

3. Issue of system testing of onboard software for navigation satellites

3.1. Retrospective analysis
The advances in system testing discussed in this section are based on the principles outlined in the article cited below [11-13]. One of the most important tasks in the development of onboard software for
satellites is to ensure its quality. A large contribution to ensuring the required level of onboard software (OBS) quality is made by the stages of system testing and OBS confirmation. In JSC "ISS" named after M.F. Reshetnev in the development of OBS for navigation satellites, the effectiveness of these stages is ensured by using a number of principles considered below in the development technology of OBS [14-18].

3.1.1. Architectural decomposition of OBS. The first key to effective testing and validation of a OBS is its architectural decomposition. The architectural decomposition, in the aspect under consideration, assumes that, firstly, the OBS functionally and structurally decomposes into the software of subsystems, and, secondly, that the software of all subsystems is built on the basis of the tools provided by the software of the on-board satellite control complex (OBSCC), and, thirdly, that the integral issues of OBS functioning are resolved in the OBSCC software.

Such a decomposition provides an efficient distribution of responsibility for the functionality of the OBS and determines the composition of the typical schedule for system testing and development of the OBS, which ensures the required degree of OBS development with minimal costs.

3.1.2. Software modeling. The second key to effective testing and confirmation of the OBS is the use of software models of the OBSCC satellite hardware and models of the behavior of the satellite subsystems in system testing.

The listed models are part of the Ground Debugging Complex of the OBS (GDC, the name has a historical origin), which is the main tool for system testing of the OBS.

The models of behavior of satellite subsystems are considered as components of the software testing procedures for the corresponding subsystems, and the departments that develop software for the corresponding subsystems are responsible for their creation.

3.1.3. High-level unified user interface. The GDC OBS not only allows testing the OBS on the entire set of functional capabilities of the OBS, but also, thanks to the automated test system and telemetry processing included in it, provides a unified user interface for system testing [19]. The proposed interface is based on a graphical formalized language for describing procedures and testing options. This is the language of cyclograms.

The high level of this interface allows the designers to design and conduct system testing directly for the designers of the logic of the functioning of the satellite subsystems and the satellite as a whole.

The unification of this interface allows it to be used at all test workplaces of engineering products and satellites of JSC "ISS". In addition, the persistence of this interface facilitates the transfer and accumulation of experience and greatly simplifies the maintenance of the OBS.

A formal graphical language for describing test sequences and tools for preparing cyclograms provided by an automated test system make it possible to visually describe test procedures, automate retesting and create prerequisites for solving the problem of automated test generation.

3.1.4. Confirmation within subsystems. The cornerstone principle of effective testing and confirmation of the satellite is the principle of the development of the satellite as built-in (in the technical system) software, structurally consisting of a set of software of satellite subsystems functionally included in these subsystems.

This approach not only makes transparent responsibility for the functionality of the BPO, but also significantly simplifies the procedure for confirming the OBS to the customer, since the confirmation of the functional requirements for the OBS breaks down into the confirmation of the functional requirements for the software of the subsystems, which are determined at the level of these subsystems and are confirmed at their working off.

Accordingly, this approach leads to a significant reduction in the cost of confirming the OBS.
3.1.5. **An efficient typical work schedule.** The principles listed above allow for the creation of an effective standard schedule for system testing and validation of OBS [20]. The use of the term "complex debugging" (CD) in the names of stages, instead of the modern term "system testing", has historical roots [21].

Confirmation of the OBS is carried out within the framework shown on the schedule for the development of technological products and the satellite as a whole. At the same time, there are some objective dependencies between the stages of system testing and the stages of confirmation of subsystems.

3.1.6. **Additional approach bonuses.** As an additional bonus, the use of software models of OBS for system testing is the possibility, against the background of system testing, of "deep" debugging of OBS components in terms of the programming language used (Module-2). Another bonus is the ability to create a satellite program model for satellite simulators based on the program models. In this case, the software models are only supplemented with a small number of functions that are not needed for system testing of the OBS, but are provided for by the operational documentation for the satellite.

In addition, the OBSCC, without any modifications, can be used for preliminary working out of the cyclograms of testing subsystems on technological products and the satellite as a whole. This possibility is ensured by the use of unified test automation tools at the test workplaces and OBSCC.

3.2. **BPO-OBS verification and confirmation technology**
The list and sequence of technological stages are determined when describing the methodology for guaranteeing the quality of development and maintenance of BPO-OBS [22]. Let us consider them in more detail.

3.2.1. **Verification of requirements.** The software requirements are considered by the relevant personnel when developing and approving the document "Initial data (ID) on BPO - OBS" for compliance with the requirements of the technical assignment (TOR) or specifications for systems, for the absence of conflicts when using OBSCC resources and taking into account all warranty requirements quality.

Verification of requirements is provided by the established procedure for issuing and approving the document "Initial data (ID) on BPO - OBS" and the availability of a standardized set of unified OBS interfaces.

3.2.2. **Verification of an architectural project.** The documents of the architectural project are reviewed by the relevant personnel when agreeing to assess the implementation of functional and non-functional requirements for the software-Software system, as well as for the resources used.

In the documents of the architectural project, using the traceability matrix, it is shown that all the requirements are reflected in the corresponding components of the software-Software systems.

Verification of architectural design documents is ensured by the established procedure for their release and approval, a standardized set of unified software interfaces for the Software of OBSCC and reviews.

3.2.3. **Verification of development and testing tools for onboard software.** This stage is intended to confirm the software interpreter of the on board computer commands and the software models of OBSCC devices used as part of the OBS development and testing tools. To solve this problem, the Laboratory Development Complex (LOC) is used, which includes a real sample of the on-board computer.

3.2.4. **Verification of a detailed design.** The detailed design of the system software component is considered by the developer of the architectural project during the step-by-step approval of the specification for the component defined by the architectural design document, as well as for the fulfillment of the established design and technological requirements and agreements.
3.2.5. **Code verification.** The program code is reviewed by the appropriate personnel as the assignment is signed to ensure the complete and efficient implementation of the detailed project in the programming language. At the same time, compliance with the established requirements for coding, commenting and the use of unified interfaces and libraries must be met.

A step-by-step process of checking the code and detailed design for compliance with each other and the document is essential during the parallel development of the detailed design and code.

3.2.6. **Offline testing.** Autonomous testing of a program is carried out independently of other programs in accordance with the method of autonomous testing.

The methodology is developed simultaneously with the design of the program as part of a detailed project.

Offline testing should ensure that:

- all program operators were executed, all decisions at the selection points were made, and the program behavior corresponds to its detailed design;
- the program was executed over the entire range of critical values of input data and settings, namely: at nominal and boundary values, as well as at unacceptable values, and the program behavior corresponds to the architectural and detailed designs;
- the program meets the resource requirements of the architectural project, the time characteristics of the program are calculated for the minimum, nominal and maximum variants of the program runtime.

The reliability of the results of autonomous testing is ensured by using the appropriate debugging tools for the cross-programming system (PCS) Modula-2. These tools provide automatic evaluation of the listed criteria and help to achieve them.

3.2.7. **Testing OBS of navigation satellites integration.** During the integration testing process, the compliance of the interfaces and resource characteristics of the programs is checked.

Integration testing should ensure that:

- all external interfaces of the OBS modules components are closed;
- the absolute OBS module meets all characteristics in terms of location, memory and external names;
- resource characteristics of OBS components correspond to the requirements of the architectural design.

Integration testing is carried out by KSP Modula-2 at each build of the Software system and OBS.

3.2.8. **System testing of OBS on the Ground Debugging Complex.** The goal of OBS system testing at GDC is to confirm that all functional and quantitative requirements defined by the design documentation are being met.

System testing is carried out at three levels:

- at the system software level in system modes;
- at the system software level in navigation satellite modes;
- at the OBS level in general.

At the levels of the system software, verification of the fulfillment of all functional and quantitative requirements for the system software in the requirements documents and architectural design from the system side is carried out.
At the OBS level, verification of the integral requirements for the system software by OBS and the logic of the satellite functioning as a whole, reflected in the requirements documents and the architectural design, is carried out.

System testing of the system software is performed in accordance with the system software testing methodology. In this document, using a traceability matrix, it is shown how a set of requirements for an architectural design and the document "Initial data - ID on OBS" in the software part of this system is covered by a set of tests.

To conduct system testing of software systems and OBS as a whole at GDC OBS, software models of the OBSCC of satellite equipment and models of behavior of satellite systems are being developed as part of the complex.

3.2.9. Confirmation of OBS. Confirmation and acceptance of systems software and OBS as a whole is carried out within the framework of testing and acceptance of systems and the product as a whole. Confirmation is performed on development and flight products.

3.3. Major advances in verification and validation technology of OBS

- Development of unified programs within the framework of the "Program Description" document simultaneously with the development of the "Autonomous Testing Methodology" document for a typical scenario, which guarantees high-quality verification of the detailed design and code.
- Automatic evaluation of program performance and test completeness criteria. Programs are admitted to the integration process only after 100% achievement of the test completeness criteria and confirmation of full compliance with the design requirements.
- Use of verified software models of the onboard processor, OBSCC device models, satellite subsystems behavior models as part of testing tools, which allow fully autonomous and system testing of OBS without the use of real equipment.
- A positive side effect of this approach is the "forced" thorough study of the logic of the hardware and its interfaces by OBS designers and programmers.
- High level of user interface of testing tools, which allows system testing directly to designers of the logic of functioning of satellite subsystems and the satellite as a whole.
- Full preservation of user interfaces of testing tools for different computing platforms and the use of a unified user interface for all testing and testing tools in system testing tools.
- Using not only interactive testing and debugging tools, but also languages and tools for batch testing and debugging, allowing you to design and program tests using the same technology as the tested programs of OBS.
- The use of test suites allows you to automate regression testing and continually improve the test suite, while the portability of OBS components and the consistency of test tool interfaces keep test archives up to date for new products and during long-term maintenance. Using a special language for system testing allows you to automate not only test run, but also the assessment of test results.
- Organization of system testing in accordance with the architectural decomposition of OBS. This approach ensures effective allocation of responsibility for consistency and levels of system testing. In the current technology, system testing is carried out sequentially at five levels:
  - the level of the software functioning environment (operating system level),
  - level of software control environment,
  - at the subsystem software level in system modes,
  - at the software level of the subsystem in the spacecraft modes,
  - at the OBS level as a whole (at the level of integrated control macro programs).
Thus, for the first generation of navigation satellite systems, methods and means of verification and confirmation of OBS have been developed, which guarantee its compliance with all established functional and non-functional requirements throughout the entire life cycle of the OBS. The proposed OBS verification and confirmation technology has been fully implemented in JSC "ISS" named after academician M.F. Reshetnev. The developed methods and means were first applied in the development of domestic communication and navigation satellites [19-22].

4. Conclusion

The successful operation of the first generation of satellite navigation systems has attracted widespread attention from other potential customers. It became necessary to create a second-generation satellite navigation system, common for all types of consumers: land, sea, air and space, in the interests of both the country's defense and the national economy. Satellite navigation systems of the second generation must provide operational (in real time) high-precision three-coordinate (in latitude, longitude and altitude) determination of the location and three components of the user's velocity vector, corrections to the user's local time relative to the State Standard and relative to UT-1 universal time associated with uneven rotation of the Earth globally over the earth's surface, in the air and near-earth space. In addition, the system must also provide for the determination of the heading correction (azimuth of a fixed direction) in the polar and circumpolar regions of the Northern hemisphere. It is not possible to fulfill the listed requirements using low orbit navigation systems due to the principles underlying their construction.

The use of the principles discussed above in the development technology of OBS satellites allows not only to create software in the required quantity, in the required time frame and with the required level of quality, but significantly reduces the cost of its development. This fact was confirmed in the framework of many programs and projects implemented by JSC "ISS", including the development of OBS communication satellites of the Express-AM series, navigation satellites of the Glonass system and the geodetic satellite GEO-IK.

In conclusion, it can be stated that the domestic space navigation was created in stages, through the efforts of military and civilian specialists from various organizations and enterprises of the Russian Federation. In the process of implementing such a large-scale project, many scientific and technical problems have been overcome and many technical solutions have been obtained, protected by copyright certificates and patents.

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