Peculiarities of precision space platform design for navigation satellites

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Abstract. Space radio navigation combines the latest achievements of computer and telecommunication technologies. The symbiosis of navigation satellite system, modern radio communication and electronic cartography allows to determine the location and speed of a moving vehicle, calculate distances, develop efficient routes, monitor compliance, get information about cartographic objects. There are now two systems available: GPS (US) and GLONASS (Russia). Using both systems ensures more accurate determination of the coordinates of moving objects. The article deals with the issues related to the creation of a new type of space platform for navigation spacecrafts, namely, a precision space platform. The design requirements for precision space platforms of the navigation satellite are considered. The principles of designing the elements of precision platform that meet the requirements of a navigation satellite in terms of accuracy are determined. Finally, the dynamics of changes in the parameters of a precision space platform of navigation satellites that enhance the accuracy characteristics of the GLONASS system is shown.

1. Introduction
Space radio navigation is the application of radio frequencies to determine the parameters of the moving objects [1, 2]. Currently, only two global navigation satellite systems (GNSS) are used by the international community: GPS and GLONASS. Compass and Galileo are still being developed [3].

In 1993, the system, now consisting of 12 satellites, was formally declared operational and in December 1995 it was brought to a fully operational constellation of 24 satellites and offered for international exploitation together with GPS [1, 2].

The Global Navigation System target federal program for 2002–2011 was adopted by the Russian government in 2001. The purpose of this program was to modernize the Global Navigation Satellite System (GLONASS). Throughout this federal program the following results were achieved: developed and launched GLONASS-M satellite, featuring unpressurized configuration, better signal characteristics and a design lifetime of seven years; developed and launched GLONASS-K satellite having unpressurized configuration, better signal characteristics and an increased design lifetime of ten years; the orbital constellation was extended to 24 satellites [4, 5].

GLONASS sustainment, development and use are carried out under the Federal GLONASS Program for 2012-2020. Within the frameworks of this target program it is necessary to develop and launch flight testing of a new generation satellite GLONASS-K2 with improved tactical and technical characteristics and enhanced functionality. The purpose of this research is to develop a new space platform with precision characteristics.
2. The peculiarities of navigation satellites exploitation

The Global Navigation Satellite System is a radio navigation system using regular time signals transmitted from satellites with known position. The constellation configuration provides for continuous, global coverage of the Earth’s surface and the near-Earth space. The navigational radio signal is used by consumers to measure the distance and the radial rate of its change, and also to obtain trajectory data, which describe the motion of a satellite for each measurement moment (ephemerides) and digital scale of satellite (airborne) time [1-3].

The radio navigation signal in the measuring loop must have high stability of frequency and phase and exclude distortions when passing through ionosphere and troposphere, and through antenna feeder devices of the satellite and those of a consumer, i.e. to maintain the phase relationships in the radio navigation signal. The use of a dual-frequency navigation signal makes it possible to reduce or remove ionosphere-induced errors.

Navigation antennas should form a diagram that covers the Earth’s surface and the near-Earth space (the global diagram) and be positioned in a way that their phase center is at a minimum distance from the longitudinal axis of the satellite that coincides with the mass center and the orbital radius vector. The shift of the antenna phase center from the satellite longitudinal axis introduces an error which cannot be taken into account because of the arbitrary angular misalignment of the user and the satellite and thus do not allow receivers to calculate and display accurate location, speed, and time information.

Navigation support for the satellite is assigned to the ground control complex and consists in measuring the orbital parameters of the satellite and predicting its motion (ephemeris), as well as in measuring the difference between the on-board and ground time scales and predicting this divergence [6].

A high-precision systematic time scale formed by ground and satellite time keepers and reference parameters of the satellite orbit provided by the ground control system make the basis for the ephemeris time provision of the satellite. The onboard time keepers of the satellite are atomic frequency standards providing high daily stability. For proper functioning of the atomic frequency standards on the satellite there should be created comfortable operating conditions and provided shielding against magnetic field. The sensitivity of the atomic frequency standards to temperature fluctuations dictated its precise thermal stabilization relative to the performance point.

Detailed modeling of gravitational forces exerted by the Earth, the Moon, the Sun and forces of non-gravitational nature (reactive forces, light pressure, transmitter radiation, etc.) will allow to achieve a highly accurate prediction of the satellite motion for a long period (several days). Some regular factors should be modeled when predicting the motion of the satellite (for example, transmitter’s session). Factors that have random effects and cannot be modeled should be limited. The magnitude of the residual unmodeled acceleration from disturbing forces should be reduced to an acceptable level.

This requires the implementation of certain measures when designing and manufacturing navigation satellites and their on-board systems, including the prohibition imposed on use of reactive systems for specified satellites during their lifetime. Moreover, in order to ensure high stability of the GNSS orbital structure, it is necessary to hold mutual displacements on the latitude argument within acceptable limits without reaction-control correction during the satellites lifetime.

As a result, the navigation satellite as a whole and its components should meet special requirements that ensure its accuracy characteristics, which dictates the necessary to create a new type of space platform - precision one.

3. Design requirements for precision space platforms

3.1. Orientation and stabilization system

In nominal yaw attitude of navigation satellite, the orientation of navigation antennas axis, parallel longitudinal axis of the satellite OX to the Earth and the orientation of the photo-voltaic arrays to the Sun are provided by turning the satellite and the photo-voltaic arrays relative to the longitudinal axis.
of the satellite until the normal to the photo-voltaic arrays is aligned with the "Sun-Satellite-Earth" plane and rotation of the photo-voltaic arrays around the axis of rotation OZ, perpendicular to the longitudinal axis of the satellite OX, until the normal to the photo-voltaic arrays is aligned to the Sun. This orientation scheme allows to form stable and comfortable operating conditions for on-board equipment as light does not affect the console of the satellite ± OZ and + OY, and also to obtain a relatively steady heat flux from the space vehicle. The resulting satellite attitude maneuvers around OX are permissible due to the global diagram of navigation antennas. The re-orientations of transverse axes (OY, OZ) relative to the velocity vector are permissible due to the prohibition imposed on use of reactive systems for orbit correction and generation of control moments [2].

Requirements that satisfy the conditions of minimizing unmodeled acceleration from disturbing forces should be met when creating the orientation and stabilization system of the navigation satellite. These requirements include: high accuracy of photo-voltaic arrays orientation to the Sun (1...2°); the use of an electromagnetic system for generation of control moments to offload reactive wheels in the normal mode of space vehicles operation.

For the chosen orientation scheme on shadow orbits, significant uncertainties in the orientation of the satellite to the Sun in the zone of small and large persistent organic pollutants angles due to high angular velocities of tracking which exceed the capabilities of the executive elements. Therefore, within the specified intervals of the orbit, covering the intervals of uncertainty in the satellite orientation on the satellite's shadow orbits and located symmetrically relative to the maximum and minimum measures of the persistent organic pollutants angles, independent proactive program attitude maneuvers are made around the satellite axes OX and OZ for the calculated value with an intermediate confinement of the given orientation.

3.2. Correction system

When choosing the type of propulsion system for the navigation satellite correction system, it is necessary to take into account a number of additional requirements [2], such as:

- faithful realization of final correction pulses that allow to hold mutual displacements of satellites on the latitude argument within acceptable limits during their entire lifetime;
- ensuring high tightness when the propulsion system is deenergized during the satellite lifetime by using sequence shut-off valves in the hydraulic circuit.

In the process of fuel depletion, the spacecraft center of mass changes its location, and, as a consequence, there occurs change in the position of the antenna phase centers, which introduces an additional error in the measured distance to the space vehicle. When using two fuel containers, these shifts are minimized due to their symmetrical placement and simultaneous fuel depletion. In only one tank is used, it is recommended to place a correction system near the center of mass of the space vehicle.

3.3. Thermal control system

Navigation satellites with a pressurized instrumentation module, are equipped with a single-circuit (gas) thermal control system that transfers heat from the device to the radiator - the surface of the sealed container, partially shielded (if necessary) by the shutter doors. To minimize the magnitude of unmodeled acceleration from disturbing forces, there can be created a model for the shutter doors operation or designed shielding from solar radiation pressure. Precision thermal stabilization of atomic frequency standards is ensured by designing a separate circuit for air purging and providing it with controlled electric heaters [2].

Navigation satellites with an unpressurized instrumentation module are built on the passive elements (thermal insulation, optical coatings, conductive heat-removal system, etc.), supplemented with heat pipes and electric heaters. The most part of the heat-generating equipment is installed on the inner skin of the honeycomb panels, which is not affected by the Sun. Compensation heating is used to compensate seasonal variation of the solar flux on the outer surfaces of the satellite and to compensate heat dissipation of equipment in a powered down state. As a result, the heat fluxes of the satellite
stabilize and the accuracy of modeling the disturbing forces from uneven thermal radiation increases [2].

Precision thermal stabilization of atomic frequency standards is ensured by designing a separate temperature stabilized zone on a honeycomb panel with built-in current transformers and precision heaters on the basis of hyper thermal conductive structures controlled by electric heaters with high-precision temperature sensors.

3.4. Design requirements
To reduce unmodeled acceleration from disturbing forces, the following measures are implemented [2]:
- high tightness of closed structures;
- materials with low mass-loss rates are used on the outer surfaces;
- high stability of the satellite configuration is supported during its lifetime;
- a model for reducing optical coefficients of the satellite outer surfaces and photo-voltaic arrays is developed.

4. Nomenclature of precision space platforms
The characteristics of precision space platforms for navigational satellites were determined on the basis of requirements from navigation system, i.e. implementation of accuracy characteristics. These characteristics include an equivalent pseudo-range error due to the error of the ephemeris-time provision and the user measurement error [1-3].

The rate of the equivalent pseudo-range error depends on the daily instability of atomic frequency standards and the accuracy of their thermal stabilization, as well as permissible magnitude of unmodeled accelerations, which in turn depend on a variety of factors, including the accuracy of orientation to the Earth and the Sun.

The rate of the equivalent pseudo-range error due to the user measurement error depends on the error of the radio line, the instrumental errors and the errors in defining the position of the satellite antennas phase centers relative to the spacecraft center of mass, taking into account that the center of mass changes its position during the mission period.

Efforts to improve the quality of precision spacecrafts, when it comes to the equivalent pseudo-range error have been taken from the very beginning of the first GLONASS navigation satellite development (table 1).

| Name of the characteristic | Glonass | Glonass-M | Glonass-K | Glonass-K2 (13) | Glonass-K2 (24) |
|----------------------------|---------|-----------|-----------|----------------|----------------|
| Spacecraft mass, kg,       | 1415    | 1415      | 995       | 1673           | 1673           |
| Transmit power, W          | 50      | 100       | 140       | 300            | 300            |
| Daily instability of atomic frequency standards | 5·10⁻¹³ | 1·10⁻¹³ | 5·10⁻¹⁴ | 1·10⁻¹⁴ | 5·10⁻¹⁵ |
| Accuracy of temperature stabilization of atomic frequency standards, deg | 5.0 | 1.0 | 0.5 | 0.1 | 0.01 |
| Orientation error, deg:    |         |           |           |                |                |
| to the Earth               | 0.5     | 0.5       | 0.5       | 0.25           | 0.2            |
| to the Sun                 | 5.0     | 2.0       | 1.0       | 1.0            | 1.0            |
| Error of antennas reference phase centers, m | – | – | – | – | – |
| The magnitude of unmodeled accelerations, m/c² | 5·10⁻¹⁰ | 5·10⁻¹¹ | 1·10⁻¹¹ | 1·10⁻¹¹ | 1·10⁻¹¹ |
| The equivalent pseudo-range error, m | 5.0 | 1.4 | 0.5 | 0.3 | 0.3 |
5. Conclusion
The data presented in the table confirmed the effectiveness of measures developed for the implementation of precision space platforms of navigation satellites that enhance the accuracy characteristics of the GLONASS system.

The authors reviewed the features of the specified navigation satellite and developed special requirements for a new type of space platform - precision one.

The principles of designing the elements of precision platform that meet the requirements of navigation satellite in terms of accuracy were determined.

The dynamics of changes in the parameters of a precision space platform of navigation satellites that enhance the accuracy characteristics of the GLONASS system is shown.

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