Methods and means of measuring information exchange among the spacecraft on the laser connection line

I N Kartsan[1], Yu N Malanina[2], A O Zhukov[3, 4, 5], R Yu Tsarev[6], and S V Efremova[1]

[1]Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russia
[2]Irkutsk State Transport University, Irkutsk, Russia
[3] Institute of Astronomy of the Russian Academy of Sciences, 48, street Pyatnitskaya, Moscow, 119017, Russia
[4] Sternberg Astronomical Institute, 13, Universitetsky pr., Moscow, 119234, Russia
[5] Russian Technological University, 78, Vernadskogo Av., Moscow, 119454, Russia
[6] Siberian Federal University, 82/6 Svobodny pr., 660041 Krasnoyarsk, Russia

E-mail: kartsan2003@mail.ru

Abstract. The article deals with the methods and means of using the inter-satellite measurements on the laser communication lines for high-precision temporary support of the GLONASS system spacecrafts. There is given the justification of the principles of measuring and exchange information among the spacecrafts via the laser navigation and communication lines for mutual synchronization of the on-board time scales of the GLONASS system spacecrafts.

1. Introduction

At present, the orbital grouping of spacecrafts equipped with the on-board inter-satellite measurements is being deployed, which will soon provide experimental confirmation of the effectiveness of using inter-satellite measurements via the laser communication channel.

The satisfaction of future requirements on the accuracy characteristics of ephemeris-temporary information for the spacecraft of space navigation systems at long intervals of autonomous operation is associated with a significant reduction of the errors of radio-technical measuring instruments in determining the distances between spacecrafts in the orbital grouping, as well as between spacecrafts and ground measuring devices. However, the radio measuring devices cannot fully provide the solution to the task of achieving future accuracy characteristics of ephemeris-temporary information [1].

In addition, there are certain problems caused by the difficulties of further improving the accuracy characteristics of the onboard frequency standards.

There is a need for a significant change in the technology of executing the ephemeris-temporary task in comparison with those currently implemented in the GLONASS space navigation system through the use of laser communication lines to measure navigation parameters and information transmission between spacecrafts, as well as between spacecrafts and the ground-based laser devices.

The solution of the ephemeris-temporary task in the GLONASS system to ensure high accuracy of ephemeris-temporary information transmitted to consumers in the navigation frame and the need for metrological provision of ephemeris-temporary information of spacecrafts, the radio onboard and the ground measuring equipment is possible with the technology based on use of distance measurements between spacecrafts, but between the spacecrafts and the ground-based equipment with the help of laser systems equipment.

Laser systems can also play an independent role in providing the required accuracy characteristics of ephemeris-temporary support to consumers. In particular, the use of ground-based laser facilities for high-precision laser range measurements at any time of the day will significantly increase the number of measurements and, therefore, arrange a stable technological cycle for ephemeris-temporary support to achieve high accuracy characteristics of the GLONASS spacecrafts and, accordingly accuracy of navigation definitions of consumers, which is of fundamental importance for ensuring the competitiveness of the GLONASS system.

In this regard, the task of using laser communication lines for regular on-line refinement of the time-frequency correction of the onboard time scale and mutual synchronization of the onboard time scale, bringing the time-frequency corrections to the onboard time scale of the spacecraft to the orbital group time scale of the GLONASS system is very urgent.

The use of laser systems for conducting high-precision measurements of the range between the spacecrafts and the divergence of the onboard time scales of spacecrafts will improve the accuracy characteristics of navigation definitions and increase the interval of autonomous operation.

The use of laser systems for inter-satellite ranging measurements with an error of no more than 10 cm will allow to determine the relative shifts of the spacecraft onboard time scales with an error of no more than 1 nanosecond.

The main functions of the onboard laser systems are:

- measuring inter-satellite distances with centimeter accuracy;
- transfer of measuring and any other information between the spacecrafts;
- synchronization of the spacecraft onboard time scales systems with nanosecond accuracy;
- calibration of the spacecraft onboard electronic equipment.

The physical principles of measurements carried out by the on-board laser system and the ground laser system provide potentially high accuracy characteristics for measuring the range between spacecrafts and determining the divergence in their on-board time scales.

Measuring sessions between the on-board laser system and the ground-based laser system, using the results of laser range measurements and information exchange to solve ephemeris-temporary problems will improve the accuracy characteristics of the spacecraft ephemerides and the frequency-time corrections to the on-board time scales relative to the space navigation system time scale.

Measurements of the range between the spacecraft onboard laser systems can provide with nanosecond accuracy the determination of discrepancies between the true values of the spacecraft onboard time scale and the predicted values.

Inter-satellite measurements also make it possible to overcome the reduction of the spacecraft observability zone at the regional location of ground-based measuring points, to ensure the exchange of any information between the spacecrafts and to increase the interval duration of the space navigation system autonomous operation while maintaining the required accuracy characteristics of the navigation field of the system [1].

2. Organizational principle justification of measurement and information exchange between spacecrafts via the laser communication line for mutual synchronization of onboard time scales of spacecrafts of GLONASS space navigation system

The choice of method and scheme of interaction between the spacecrafts for measuring and information exchanging via an inter-satellite laser navigation communication line for mutual synchronization of the onboard time scales the spacecraft should take into account the following factors:

- fulfillment of the specified requirements for the accuracy of mutual synchronization of the spacecraft onboard time scales;
- ensuring the maximum interval between successive corrections of the spacecraft onboard time scale by inter-satellite laser measurements of the spacecraft navigation parameters;
- planning of inter-satellite laser measurements taking into account the requirements for the sequence of inter-satellite laser measurements and of information exchange between spacecrafts via the laser communication line and the actual state of the onboard facilities and instructions from the system control center in a case of possible emergency situations;
- the interaction of the onboard laser systems with ground-based equipment should mainly be informational;
- the functioning of the system for its intended purpose should not depend on the performance of individual spacecraft or ground-based facilities, in case of failure in certain sessions of interaction plans of the onboard laser systems;
- the technological cycle of time information correction on board the spacecraft should provide for the availability of backup schemes for measuring and exchange information on the inter-satellite laser communication line for executing tasks of temporary support with specified accuracy characteristics;
- the exchange of information on the inter-satellite laser line between the spacecrafts on the state of the orbital grouping, individual spacecraft and ground-based facilities;
- transfer of information on the laser communication line from the onboard laser system to the ground-based laser system and back;
- use for the intended purpose of the spacecraft with the failed some kits of the on-board laser system;
- restoring of information on board the spacecraft required for executing the temporary task by transmitting it via a laser communication line from the ground-based laser system to the onboard laser system or via an inter-satellite laser communication line;
- execution of the technological cycle operations of temporary support for spacecraft in minimum time;
- using the minimum amount of RAM onboard digital computer of the spacecraft for the operation of onboard software systems that interact with the onboard laser system.

The time scale synchronization principles of the space navigation system for inter-satellite measuring and information exchange using onboard software system should be selected for:

- providing the required accuracy characteristics of synchronization of all time scales of the space navigation system at the specified intervals of autonomous operation of the spacecraft for the intended purpose□;
- reliability and survivability of the space navigation system in abnormal situations with minimal recovery synchronization of the time scales taking into account the implementation features of these requirements when the onboard laser system equipment on the spacecraft is being installed as well as using ground-based laser facilities.

One of the main factors determining the method of spacecraft onboard time scale synchronization by inter-satellite laser measuring of navigation parameters by the onboard laser system equipment is the regular and operational planning of the technological cycle of interaction of the onboard laser system using both the ground control complex and onboard facilities.

When planning, the sequence of mutual targeting of the onboard laser system is determined with a minimum time of re-targeting of the onboard laser system, providing, in particular, the maintaining of position preservation of the support-rotary device from the current session as the initial for the next session.

According to the results of the interaction sessions in the space navigation system, a single phase and frequency of the group “orbital” time keeper are established at a given time. The group "orbital" time scale is the "weighted average" sum of frequencies and phases of all onboard time keepers of the system, with the exception of the spacecraft onboard time scale drift due to relativistic effects in the frequency-time corrections calculated in the main communication control center.

The group orbital time scale is the reference time scale of the system, with respect to which the frequency-time corrections to the spacecraft onboard time scale are determined.

The deviation of the spacecraft onboard time scale from the group orbital time scale at laser measuring time is an assessment of the frequency-time corrections to the onboard time scale relative to the group orbital time scale.

When developing methods and algorithms, it is necessary to assess the accuracy characteristics of the group orbital time scale in real-life operating conditions at long intervals of autonomous operation (when replacing the onboard frequency standard or changing its characteristics).

In the systems of synchronization of onboard time scales using the onboard laser system the prompt adjustment of the means interaction plan should be provided, in particular, an automatic selection of the reference onboard frequency standard of the spacecraft instead of the failed one.

The peculiarities of mutual synchronization of time scales are also determined by the chosen direction of signal transmission and the method of information exchange between the synchronized objects.

Currently, the space navigation system implements the principle of directional synchronization, which provides for synchronization of the spacecraft onboard time scales relative to the scale of the reference lead time keeper, which is the central synchronizer.

In the future, the principle of directional synchronization can be implemented by a ground based laser system.

The ground based laser system should solve the following tasks:

- measuring the range between the ground station and the spacecraft equipped with the onboard laser system;
- determination of discrepancies between the spacecraft onboard time scales and the Central station time scale;
- exchange of information from the spacecraft (via the onboard laser system) in order to clarify the frequency-time corrections to the spacecraft onboard time scales and to form a group orbital time scale of the system.

If the intersatellite measurements of the navigation device are used to synchronize the spacecraft onboard time scale, then the reference time keeper of the system can be the onboard frequency standard of one of the spacecraft.

Thus, the principle of directional synchronization in one direction from the reference time keepers to the followers is implemented.

It is possible to implement a hierarchical interaction structure of laser tools in which the led time keepers of a higher level (synchronized directly from the lead time keeper) are the reference time keepers for the led time keepers of a lower synchronization level.

When synchronizing the time scales through the hierarchy stages, there is an accumulation of errors in the mutual synchronization of the spacecraft time scales. Therefore, to reduce the errors, it is necessary to strive for single-level structures of directional synchronization.

For the spacecrafts equipped with onboard laser systems, the principle of mutual synchronization is considered, in which there is no leading time keeper, although it is possible that during the measuring process one of the onboard time keepers will be chosen as a working support.

The spacecraft onboard time scales are synchronized with each other.

In this case, the principle of directional synchronization will also be applied to link the group orbital time scale to the time scale of the central synchronizer.

When carrying out without-demand measuring of navigation parameters between the pairs of spacecrafts, measurements results are exchanged, which allows each spacecraft to determine the mutual discrepancy between their onboard time scales.

It is known that the task of synchronization of time scales in the space navigation system is to establish unambiguous phase and frequency relationship between the synchronized objects.

According to the method of information exchange there are distinguished:

- a one-way method of synchronization of the onboard time scales, implemented for consumers of the space navigation systems;
- a two-way method in which information is exchanged between the synchronized objects of the space navigation system. This method is used in both directional and mutual synchronization systems, when the synchronized objects should have information about the discrepancy between their own time and the frequency scale relative to the time and frequency scale of the other objects.

3. Synchronization of spacecraft on-board time scales relative to the onboard time scale of the spacecraft

The synchronization of the on-board time scale of the spacecrafts relative to the on-board time scale of the spacecraft implements the principle of directional synchronization with two-way information exchange via a laser communication line among the spacecrafts, the time scales of which are synchronized during the correction phase and frequency relations between the onboard time scales.

The scheme of measuring and information exchange among the spacecraft of the space navigation system via the inter-satellite laser communication line is shown in figure 1.

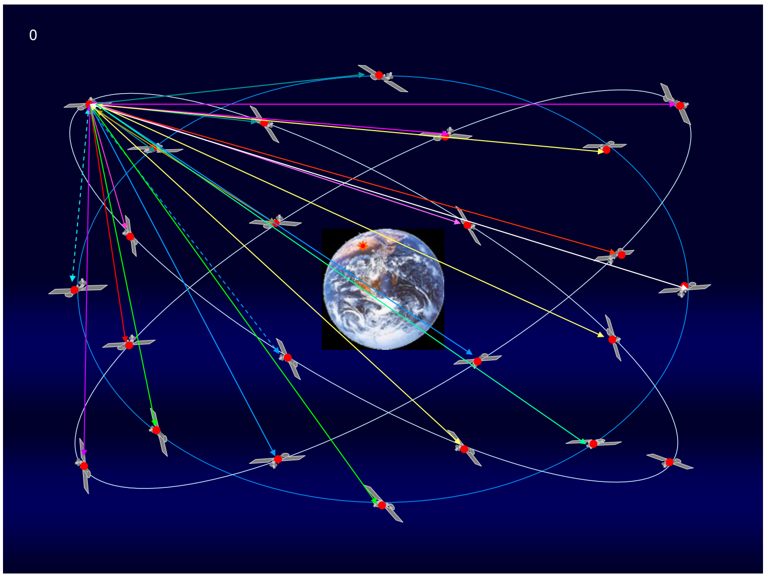

Figure 1. Scheme of measuring and information exchange among the spacecraft space navigation system via the inter-satellite laser communication line.

To implement the synchronization method on board the leading spacecraft and the guided spacecrafts with the onboard laser system, the following basic steps are performed according to the standard scheme:

- the pre-processing by computing means of the on-board laser system on the reference spacecraft for the **first** level of synchronization (hereinafter referred to as $\mathbf{SC_{on}}$) of the measuring information obtained from the inter-satellite laser line and the determination of the pseudo range values up to the led spacecraft;
- the transmission via the inter-satellite laser line for the guided spacecraft measurement results of the pseudo range obtained in a special computing device of $\mathbf{SC_{on}}$;
– reception via the inter-satellite laser line on the guided spacecraft the pseudo range measurement results obtained by a special computing device of $\mathbf{SC_{on}}$;
– calculation by computing means of the on-board laser systems of divergence of the onboard time scale of the guided spacecraft relative to the onboard time scale of $\mathbf{SC_{on}}$;

– forming the data bank of frequency-time corrections on the leading spacecraft with the results of the divergence of the onboard time scales of all guided spacecrafts relative to the onboard scale of spacecrafts $\mathbf{SC_{оп}}$;

– transferring the data bank of time-frequency corrections via the inter-satellite laser line from $\mathbf{SC_{оп}}$ to all guided spacecrafts;

– according to the information available in the data bank of frequency-time corrections, the on-board digital computer of each spacecraft forms a group orbital time scale, relative to which the time-frequency corrections to its on-board time scale are determined.

The reference for the spacecraft of the second synchronization level (hereinafter referred to as $\mathbf{SC_{2оп}}$) can be assigned to any of the spacecrafts from the first synchronization level, which can interact via a laser line with the spacecraft of the second synchronization level and has the highest accuracy characteristics.

The technology of spacecraft interaction with the spacecraft $\mathbf{SC_{2оп}}$ coincides with the above with the following addition: $\mathbf{SC_{2оп}}$, in addition to its own information, exchanges information with the guided spacecrafts of the second level synchronization, the results are transmitted to the time-frequency correction data bank, which will thus contain full information about the on-board time scales of all spacecrafts of the system.

Ensuring the high accuracy of mutual synchronization of the spacecraft on-board time scales depends on the completeness of the orbital grouping and the performance of both intra-plane and inter-plane measuring of navigation parameters between the spacecrafts carried out on the laser communication line at almost identical times. This method is the most effective one for organizing inter-satellite measurements to determine the mutual divergence of the onboard time scales, to form the orbital group time scales for all spacecrafts and to determine the corrections to the on-board time scales relative to the orbital group time scale and to control the accuracy of their formation.

Of course, the initial frequency-time corrections to the spacecraft on-board time scales are not initially included in the process of formation of the system onboard time scale, as it is formed by the results of measurements of only ground-based radio measuring instruments. After determining the mutual divergence of the on-board time scale according the results of inter-satellite laser measurements, the original time-frequency correction is made. When moving from the system reference time scale of the to the orbital group time scale, the frequency-time corrections to the on-board time scale should be formed relative to the orbital group time scale.

At present, the accuracy characteristics of the on-board frequency standard are worse than the ground reference frequency standards, however, with the joint processing of synchronous measuring of the mutual divergence of the onboard time scales carried out by the onboard laser systems, it can be expected that the group orbital time scale formed as a group average time scale based on the on-board time scales of all spacecrafts in its accuracy characteristics will approach the time scale of the system formed on the basis of the time scales of the ground frequency standards [2-11].

4. Conclusion

The interaction of the onboard laser systems with the ground-based laser facilities will allow to increase the number of high-precision range measurements, as well as covert transmission of the information necessary for forming high-precision time-frequency information for navigation frame.

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