DOI: 10.17725/rensit.2023.15.367

Method for determining spacecraft motion parameters based on ultra-long-baseline radio interferometric measurements

Igor L. Afonin, Alexander L. Polyakov, Yuri N. Tyschuk, Vladislav V. Golovin, Gennadiy V. Slyozkin

Sevastopol State Technical University, http://www.sevsu.ru/
Sevastopol 299053, Russian Federetion
E-mail: igor_afonin@inbox.ru, al_polyakov@inbox.ru, y.tyschuk@gmail.com, v_golovin@mail.ru, g.slyozkin@mail.ru

Received August 14, 2023, peer-reviewed August 21, 2023, accepted August 28, 2023, published December 06, 2023.

Abstract: **The proposed method for measuring current navigational parameters of spacecrafts makes it possible to control them to a certain extent using a single ground-based automated station. With this the following specifics of a single-station control are taken into account: location of spacecraft spatial-time monitoring stations, geometrical interpretation of these measurements, difficulties in processing of the received information and proper selection of radio equipment required for performing such measurements. The proposed method for trajectory tracking is based on the ultra-long-baseline interferometry. Measuring base here is the distance between a ground-based radio complex and onboard radio complex of the reference spacecraft that is constantly visible by the ground-based monitoring station. Onboard radio complex can include an array of spacecrafts traveling either along elongated elliptical orbit with an apogee height of more than twenty thousand kilometers or along a 36000 km high geostationary orbit. Application of the proposed method will help extend capabilities of the space monitoring system in terms of prompt clarification of public and private catalogues of spacecrafts orbiting the Earth.**

Keywords: **navigation, ballistic-navigational support, spacecraft, space source, radio system, trajectory tracking, radio interferometer**

UDC 656.61.052:621.396

For citation: Igor L. Afonin, Alexander L. Polyakov, Yuri N. Tyschuk, Vladislav V. Golovin, Gennadiy V. Slyozkin. Method for determining spacecraft motion parameters based on ultra-long-baseline radio interferometric measurements. *RENSIT: Radioelectronics. Nanosystems. Information Technologies,* 2023, 15(4):367-376e. DOI: 10.17725/rensit.2023.15.367.

Contents

1. INTRODUCTION

When developing highly complex systems, a number of fundamental issues arise, the solution of which determines the appearance of the system and ways to further enhance it. Developing a trajectory radio interferometric system involves the following fundamental steps: elaboration of the trajectory tracking method for spacecrafts (SC); due consideration of specifics associated with gathering and processing information about current navigational parameters (ICNP) of spacecrafts; ensuring synchronization of remote time scales at the radio interferometer monitoring stations.

Synchronization of time scales in the proposed method is achieved by the use of a geostationary SC in order to reduce the errors associated with the movement of the SC relative to the reference points.

Signal exchange procedure is to be structured in such a way as to mainly eliminate the delays associated with the formation and propagation of signals. In this case, the synchronization accuracy will depend on the parameters of the onboard radio complex (RC), type of signal, and accuracy of time interval measurements.

Signal exchanged between the stations of an ultra-long baseline interferometer (ULBI) must be a broadband noise-like signal (BNLS) synchronized with frequency and time reference standards.

Stability of onboard RC oscillators the ground-based RC oscillators shall ensure such coherent accumulation time at the output of the ground-based RC receiver that would achieve the desired signal-to-noise ratio.

Time delays of the space source (SS) required to calculate the clock difference must be measured using correlation signal processing similar to that used in radio interferometry, which yields the highest measurement accuracy.

2. MAIN PART

Considering relatively simple design (in particular, for synchronization of radio signals), it seems appropriate to place the onboard RC of the spacecraft ULBI system on the geostationary orbit [2,3]. Geometric interpretation of the proposed trajectory tracking method is the double difference in the propagation time of radio signals from the SC, reference SC and reference SS (see **Fig. 1**). Then ULBI measurements can be represented as

$$\Delta T = \Delta T_{\mathrm{SC}} - \Delta T_{\mathrm{SC0}} = (t_1 - t_2) - (t_3 - t_4),$$

where $\Delta T_{\mathrm{SC}} = (t_1 - t_2)$ is time difference between t_1 (signal propagation time between ground RC and target SC) and t_2 (time between target SC and reference SC).

$$\Delta T_{\mathrm{SC}} = t_1 - t_2 = (B\cos\alpha)/\mathrm{c},$$

where α is an angle between the baseline and direction of the target SC; c is the speed of light, $c = 2.99792458 \cdot 10^8$ m/s; B is the measurement baseline; $\Delta T_{\mathrm{SC0}} = (t_3 - t_4)$ is the time difference of signal propagation between the ground-based RC and reference SS, and between reference SS and reference SC.

ΔT_{SC0} can be calculated using the following formula

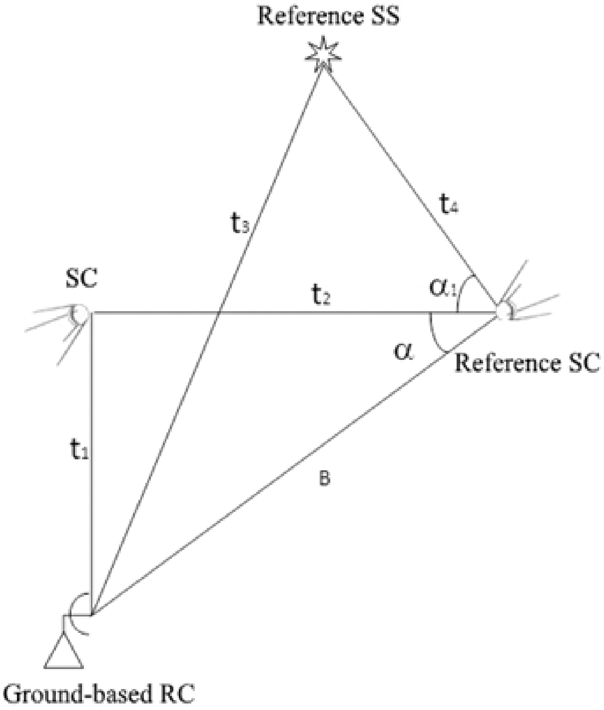

Fig. 1. *Geometrical interpretation of the trajectory interferometric system.*

$$\Delta T_{\mathrm{SC0}} = t_3 - t_4 = \mathrm{B}\cos(\alpha\text{-}\alpha\_1)/\mathrm{c},$$

where α_1 is an angle between direction of the reference SC to the target SC and direction of the reference SC to the reference SS.

With a sufficient degree of accuracy for measurement error ΔT, the following approximation will hold true

$$\Delta T = -\frac{\alpha_1 B}{c}\sin\alpha. \tag{1}$$

Therefore the ratio for calculating an angular inclination of the SC relative to the reference SC (as projected onto the baseline) according to the ΔT measurement will be as follows

$$\alpha_1 = \frac{c\Delta T}{B\sin\alpha}. \tag{2}$$

It can be seen from expression (2) that measurement error for angle α_1 is proportionally dependent on ΔT measurement error and for a given accuracy it will decrease as the value of $B\sin\alpha$ increases. To achieve the highest possible accuracy in spacecraft trajectory measurements, it is desirable that the baseline length B and angle α are as large as possible.

Given the fact that the reference SC is located on the geostationary orbit, the proposed trajectory measurement method helps achieve the measurement baseline that significantly exceeds the maximum possible baseline when only ground-based RCs are used in ULBI measurements.

At the same time, if trajectory measurements are made from one baseline, then SC localization area on the celestial sphere is represented by a strip, width of which is determined by the error α_1 (along the baseline projection). When two intersecting baselines are used (with the second baseline represented by the distance between the ground-based RC and the reference SS or reference SC) the spacecraft localization area is determined by the intersection of the strips described above. Moreover, if we introduce the following notations: α_1' are the errors of measuring the angular position of the SC along the first baseline, α_2 are the errors of measuring the angular position of the SC along the second baseline, and α_3 is the angle of baseline direction intersection, then the maximum distances between the boundaries of the localization area, measured by two orthogonal directions (arbitrarily considering the direction α_1 as the first one) will be determined by the following values:

— α_1 in the first direction;

— $[\alpha_1 + \alpha_1 \cos\alpha_3]/\sin\alpha_3$ in the second direction.

The minimum uncertainty of the SC localization area in both directions will be when the baseline directions are orthogonal, i.e.

$\alpha_3 = \pi/2$.

ULBI measurements from two intersecting baselines yielding the angular position of the object on the celestial sphere are supplemented by the measurement of the third coordinate, i.e. distance to the SC. In this case, a complete spatial definition of the SC is achieved, which is very valuable for the operation of space systems. In the limiting case, use of even two such triples of measurements makes it possible to solve the navigational problem of SC control.

Creation of a trajectory radio interferometer is largely dependent on proper selection of the RCs used for measurements and, in particular, their antenna systems. This is due to the fact that not only the coordinate-spatial characteristics of the SC are measured, but also the spatiotemporal characteristics of the reference SS.

Signal-to-noise ratio in ULBI measurements is determined by the expression

$$h = \sqrt{\frac{2\Delta f T}{k T_n}} \pi o_1 o_2 S_s, \tag{3}$$

where o_1, o_2 are the diameters of the antennas used, with surface area utilization factors equal to 0.5; S_s is spectral flux density of a point source (radio emission from a SS or SC); Δf is registration band; T is signal accumulation time; T_N is noise temperature of the ground-based RC; k is the Boltzmann constant.

It is clear from expression (3) that RCs with large diameter antennas are required in order to increase the signal-to-noise ratio. However, in the proposed trajectory radio interferometric system, one of the monitoring stations is located on board the reference SC. Therefore, increasing the size of the antenna of this RC is a complex and expensive task. In this regard, it seems appropriate to increase the diameter of the antenna of ground-based RCs. Of particular interest in this case are the RCs, which are already involved in SC control operations.

The analysis performed gives us grounds to assert that it is appropriate to use a RT-70 antenna for a trajectory radio interferometric system.

RT-70 antenna [4] is located at the point with coordinates 45°11'N and 33°11'E and it is of full-revolving Gregory type with a quasi-parabolic main mirror of 70 m and a field of view of 0° to 360° in azimuth plane and 6° to 90° in elevation plane. Main specifications of the monitoring station equipped with the RT-70 antenna are given in [4,5].

Before we start reviewing astrophysical aspects affecting selection of the SS, we will briefly analyze parameters and specifics of the RT-70 antenna application for receiving SS signals, while taking into account the data in **Table 1**.

For estimates in the spectral measurement mode, we will set the radial velocity resolution ΔV = 1 km/s, from which the spectral resolution and corresponding analysis bandwidth depending on the frequency will be calculated by the following formula

$$\Delta v = \Delta v_L = v\frac{\Delta V}{c}.$$

In this measurement mode, typical integration time is approximately 1 hour. For continuum estimates, it would be appropriate to set an integration constant of 1 s. We will use two analysis bandwidth options: B1 = 5 MHz (available at the moment, for example, at a frequency of 6 GHz) and prospective B2, the provision of which is quite realistic. Time required for a point source to pass through the radiation pattern was estimated from the expression

$$t_{\min} = \frac{\Delta\Theta}{15},$$

where $\Delta\Theta$ is beamwidth, measured in arcminutes. Calculation results for the limiting parameters of radio astronomical values are given in Table 1.

As expected for this antenna, the limiting parameters of the radio astronomical values are adequate. We will also find out how well the ground-based RC is matched in terms of spatial resolution and sensitivity resolution. For the purpose of estimation, we will use a 5-cm wave because the best parameters of the system are achieved at this wavelength [4].

Table 1

Calculation results of limiting parameters of radio astronomical values for RT-70

Operating frequency, MHz	B2, MHz	$S_{\min}$, Jy		$T_{\min}$, K		t, s	Δv_L, kHz	$TL_{\min}$, K
		B1	B2	B1	B2			
740	20	0.10	0.05	0.10	0.05	165	2.5	0.07
930	50	0.05	0.02	0.05	0.02	130	3.1	0.04
1668	100	0.03	0.006	0.04	0.01	75	5.6	0.02
5008	100	0.02	0.005	0.04	0.01	25	16.7	0.01
5885	100	0.02	0.005	0.04	0.01	20	19.6	0.01

Number of sources that are identifiable by a ground-based RC along a hemisphere is approximately estimated by the formula

$$N(\mathrm{r}) = 0.1\frac{2\pi}{\Delta\Theta^2} = 10^6.$$

Based on the analysis of the available statistical data for the sources, as well as their spectra, and models of the Universe, it is known that the number of sources with flux densities of 5 to 20 mJy does not exceed $N(d) = 10^7 \ldots 10^6$ which is close to the value of $N(r)$, which indicates almost optimal matching of the instrument in terms of sensitivity and resolution. Some excess of sensitivity is not harmful, because for studies of, for example, lines or pulsars, the "entanglement" effect is not so dangerous due to availability of such additional criteria for distinguishing such as frequency and time.

Thus, the use of the RT-70 antenna for the ground-based RC of the trajectory radio interferometric system makes it possible to use galactic and extragalactic SSs as reference objects and, moreover, will ensure reception and processing of uncontrolled radiation signals from onboard equipment to obtain trajectory and identification information about the SC [6].

The main difference between the proposed method for gathering information about the current navigation parameters of SCs and existing systems is the use of a satellite channel for reception and transmission of information between the ground-based RC and the reference SC, as well as between the ground-based RC and target SC, and between the reference SC and target SC. Moreover, data from the reference SSs and from the reference SC also come via satellite communication channels. Given that these channels, in addition to information about the space-time position of the SS, the reference and target SC of the ULBI system, also transmit program-command and telemetry information used for controlling the SCs involved, tense energy relation arise both along the Earth to SC path and SC to the Earth path. This circumstance necessitates the analysis of the specifics associated with collection of information about current navigation parameters (ICNP) in the ULBI system including selection of the main parameters, as well as energy calculation of the entire trajectory radio interferometric system, and optimization of areas serviced by the reference SC.

To obtain information about the current navigation parameters of the SC, it is appropriate to use uncontrolled radiation signals (URS) (leaking through the waveguide radiation paths of permanently functioning blocks of onboard equipment: master oscillators, local oscillators, etc.) from these SCs. Then the reference SC must ensure transmission of the following 6 channels to the ground-based RC: a command radio link to the target (controlled) SC, a trajectory radio link from the target SC, a special (according to functional layout) radio link from the target SC, a command radio link to the reference SC, a trajectory radio link from the reference SC, as well as radio links for receiving signals from the reference SS.

To serve as a reference SC we find it suitable to use a geostationary satellite with a 11/14 GHz repeater transponder (**Fig. 2**)[7].

Radio signals received by the onboard antenna pass through a preliminary low-noise amplifier (LNA) and a band-pass channel filter used to separate the transponders and to decouple the receiving path from the transmitting path of the SC. Additional amplification and clipping is performed to bring the signals in each transponder to the proper level. Gain control is carried out via a command radio link from a ground-based RC. The signals are then transported down the frequency and amplified by the traveling-wave tube (TWT) amplifier. If there are several signals at the TWT input, non-linear distortions in the frequency band may occur. To avoid this, the input power level is reduced to the required level by means of an adjustable amplifier (AA). An amplitude limiter (AL) can be installed at the input of the TWT amplifier (TWTA) to prevent the amplifier from being overloaded by the peak value of the signal.

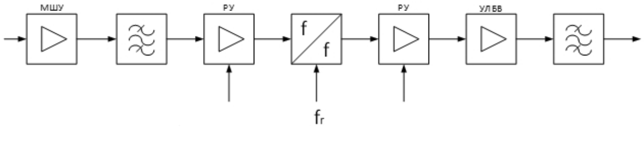

Fig. 2. *Block diagram of a repeater transponder on the reference SC.*

Thus, the onboard RC of a reference SC is a complex radio device, which can be modelled by an inertial nonlinear system with distributed parameters [7]. Such systems are extremely time consuming to analyze, so we will use a simplified model featuring localized linear inertial part (band-pass filter), nonlinear inertia-free part (limiter) and the nonlinear inertial part (source of amplitude-phase conversion). Each of these parts and all of them together cause a number of effects that lead to a decrease in the noise immunity and throughput of the RC.

We are to calculate the frequency parameters of the six-channel signal of the RC onboard the reference SC. According to the well-known technique [7], we will first calculate the minimum frequency band needed to transmit single-channel information at a rate of $\nu = 4.5$ Mbps by using the double phase-shift modulation (PSM). This band is equal to

$$\Delta f_{\min} = 1.5\frac{\nu}{2} = 3.375\cdot 10^6.$$

We will assume that the allowable energy loss of the model in relation to the signal energy to the noise power spectral density Δh is equal to 0.7. This loss corresponds to Δa equivalent value, by which the signal amplitude must be reduced to account for additional losses. Values $\Delta a/a$ and Δh are related by the following formula [8]

$$\frac{\Delta\alpha}{\alpha} = \frac{1}{10^{-\frac{\Delta h}{20}}}. \tag{4}$$

Now it is possible to formulate requirements that a filter must adhere to in order to achieve the calculated value of $\Delta a/a$. Attenuation $\delta_k(\Omega)$ of a kth-order filter at the normalized frequency Ω depending on $\Delta a/a$ is calculated by the following formula [7]

$$\delta_k(\Omega) = -20\lg\frac{\Delta\alpha}{0.84\alpha}. \tag{5}$$

At $\Delta h = 0.7$, formulas (4) and (5) will give us the following results

$$\frac{\Delta\alpha}{\alpha} = 1 \div 10^{\frac{-0.7}{20}} = 0.077,$$

$$\delta_k(\Omega) = -20\lg\frac{0.077}{0.84} = 20.8\ dB.$$

Attenuation of 20.8 dB is achievable by using a 4th-order Butterworth filter at a relative frequency Ω of 1.7 [9].

After having selected characteristics of the filters that provide proper filtering of the channels, it is possible to lay out channeling arrangement in the frequency spectrum of the transponder and size of the guard bands. We will denote frequency band of each channel as Δf, filtering band as Δf_p, and the value equal to ($\Delta f_p + \Delta f/2$) as δf. In [8], the following formulas are given to calculate these values

$$\Delta f = A\Delta F - C\delta f, \tag{6}$$

where $A = 2/(n + 1)$, $C = 2(n - 1)/(n + 1)$; n is number of channels; ΔF is frequency band of the transponder being part of RC onboard the reference SC.

To account for frequency response unevenness at the ends of the transponder spectrum, we will take ΔF as 32 MHz. At the ends of the transponder spectrum, narrow-band channels for transmitting service information can be placed, for which the unevenness of the magnitude response and phase response in the channel band will be less significant.

Parameter δf can be calculated as follows [7]

$$\delta f = -\frac{1}{2(1-C\Omega)}\times\Big(2f_0 + C\Omega f_0 - A\Omega\Delta F + \sqrt{\left(2f_0 + C\Omega f_0 - A\Omega\Delta F\right)^2 + 4A\Omega\Delta f f_0\left(1+C\Omega\right)}\Big), \tag{7}$$

where f_0 is central frequency of the modem that is equal to 20 MHz.

Inserting $\Omega = 1.7$ into (6) and (7) gives us $\delta f = 3.4$ MHz , $\Delta f = 4$ MHz, $\Delta f_p = 1.6$ MHz. It is known [7] that the standard intermediate frequency in the satellite channel is 70 MHz, and $f_0 = 20$ MHz is the intermediate frequency of the modem at which the signals are filtered. The modems are fitted with frequency converters, in which the signal spectrum translation is carried out.

Location of subchannels in the frequency transponder of the onboard RC on the reference SC relative to the intermediate frequency (or "frequency plan") is shown in Fig. 3.

Distance between the carriers is 5.6 MHz, and the bandwidth allocated to each of the six data transmission subchannels is 4 MHz. Guard bands are placed at the ends of the transponder spectrum, in one of which a relatively narrow-band service communication channel is located at a frequency of 87.6 MHz.

Thus, using one transponder of the reference SC, it is possible to create an information system for ULBI (ground-based RC — onboard RC) with a total speed of about 30 Mbps. Noise immunity of such system depends, on the one hand, on the coding algorithms, modulation, and signal processing, and, on the other hand, on the parameters and statistical characteristics of the signal and noises in the radio channel.

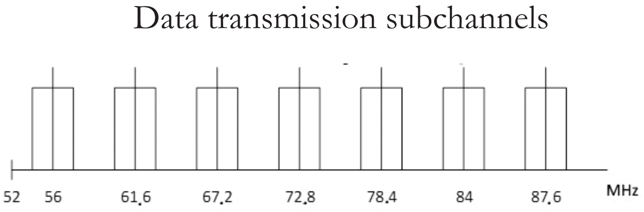

Fig. 3. *Frequency plan of the six-channel complex.*

Accuracy of synchronization of the remote clocks via a satellite radio communication signal also depends on the signal used, its processing methods and signal-to-noise ratio at the ends of the satellite link. This physically understandable commonness made it possible to develop a unified method for analyzing noise immunity and potential synchronization accuracy of ULBI.

Fig. 4 shows a diagram describing how current navigation parameters of the SC are collected and processed.

Onboard RC is placed on the geostationary orbit within visibility area of the ground RC. The reference SS is located in the same area. Flight control center (FCC) receives all information flows from the ground RC with subsequent processing of these information flows. At the same time, FCC generates command and program information for controlling the target and reference SCs, as well as navigation information for the ground and onboard RCs to ensure this control.

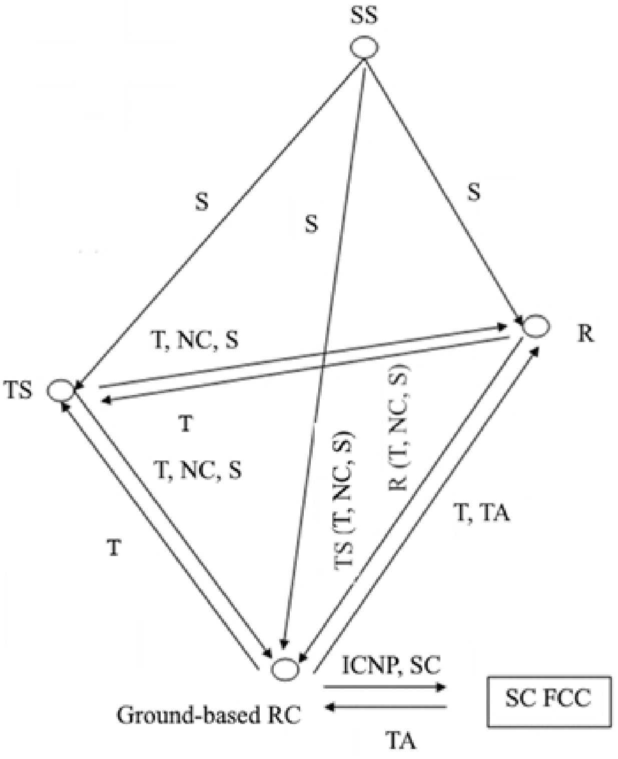

Fig. 4. *Collection and processing of ICNP of SC.*

Given the existing requirements for such systems [13,14], the reliability of information reception is:

— radio astronomy of 10^{-3};

— command-trajectory and telemetry of 10^{-6};

— service communication - 10^{-6}.

where *SS* is space source; *R* is reference spacecraft; *TS* is target spacecraft; *T* is trajectory signal of the onboard *RC; NC* is non-controlled radiation signal from the onboard *RC; S* is space source signal; *TA* is target assignment for *RC* antennas.

Specified reliability is to be ensured when working in sessions throughout 95% of the year.

Information is exchanged via an onboard RC combined with a system of the Luch type of a geostationary SC in the 11/14 GHz band.

Main technical specifications of the Luch system are given in [7,14].

Further calculations were made for an onboard RC equipped with the Luch system.

We decided to use Luch-type SC as a reference SC where onboard RC is placed, with SC being located on the geostationary orbit with location points of 80°E, 90°E, 95°E, which is suitable for the previously selected region where ground-based RC will be located. [7,16]

In this case, the ground-based RC is in the service area with field level of –2 to –3 dB, which makes it possible to thoroughly study these three options for placement of the reference SC.

The next step of the study is to calculate the radiation power flux density of the earlier selected reference SCs at the location of the ground-based ULBI RC, while considering instability of the position of the SC and its antennas. This step is applicable not only to the target SCs, but also to geostationary reference SCs, which not only shift relative to the calculated location point, but also experience oscillatory movements, thus altering the exposure level onto the Earth's surface. This effect is especially strong at the border of the

Table 2

Input data

Parameter	Value
Roll angle, deg.	0.42
Pitch angle, deg.	0.33
Yaw angle, deg.	1.16
Longitude shift angle, deg.	0.3
Latitude shift angle, deg.	1.55
Angle of initial rotation of the antenna, deg.	0
Antenna gain	1000
Antenna pattern opening angle at –3 dB level, deg.	5
Antenna beam shape	sinx/x
Onboard transmitter power, W	15
Losses in antenna and waveguide transmission line during transmission, dB	2

service areas. Input data for the calculation are given in **Table 2.**

To account for this specific effect, calculations were made according to the technique described in [15].

For each given point, the values of the SC power flux density near the Earth's surface were calculated at its normal position in the orbit (W_{nom}), as well as the lowest (W_{min}) and largest (W_{max}) values arising from fluctuations in the position of the SC and onboard antenna within the specified parameters.

Calculations were performed for the "clear sky" conditions (without intense rains), which, as shown by special studies of attenuation statistics on ULBI satellite lines, corresponds to 95% of the time of the year.

Table 3 shows calculation results for the ground-based RC with coordinates 43°11'20" and 33°11'13" (Evpatoria).

To ensure fairness of further research it seems reasonable to choose a reference ULBI SC with average values of the power flux density near the Earth's surface, i.e. with coordinates 90°E (western beam) at standardized aiming point positions of the onboard antennas.

Table 3

Calculation results

Location	Signal levels, dB W/m^2		
	W_{min}	W_{nom}	W_{max}
80°	–126.9	–125.8	–125.1
90°	–129.1	–121.6	–126.6
95°	–131.6	–129.7	–128.1

Energy calculation of the radio link of the ULBI trajectory measurement system was carried out for the single-signal operating mode of the onboard RC.

Analysis of the discrepancy between the results of preliminary and final calculations showed that $W_{nom} \approx (1 \pm 2)$ dB, i.e. the calculation accuracy satisfies the existing requirements for similar systems [7]. In this case, the last calculation should be considered more reliable (see Table 2), however, it is necessary to take into account from Table 3 the magnitude of the decrease in W_{nom} down to W_{min} (resulting from antenna holding and aiming errors at the center of the service area) and adjust the final results accordingly in order to perform the worst-case calculations in the future.

Optimization of the service areas of the reference SC is of particular importance for the ULBI trajectory system. The calculations performed showed that at the currently accepted aiming points of the antennas of the onboard RC Luch, the requirements for service areas of the ULBI trajectory system are fulfilled only by the western beam of the reference SC located at 90°E.

However, even this aiming point is not optimal for passing target SCs, therefore, in the proposed system we find it suitable to provide for the possibility of using another reference SC.

3. CONCLUSIONS

Analysis of the obtained results leads to two important conclusions:

1. Selection of any of the above aiming points for all SCs makes it possible to have only one reference SC suitable for the ULBI trajectory system.

2. It is impossible to find such a single aiming point, at which at least two reference SCs could

be used simultaneously for the needs of the system.

Thus, to make it possible for the ULBI trajectory system to use 2 or 3 SCs for operation, it is necessary to make arrangements to ensure that position of the onboard RC antennas can be adjusted by a command from the ground-based RC. At the same time, optimization of the aiming points of reference SCs makes it possible to double the number of target SCs suitable for use in the ULBI trajectory system.

However as noted earlier, to ensure operation of such system it is necessary to achieve the required accuracy of synchronization of time scales in the ground-space radio interferometer.

REFERENCES

1. Polyakov AL, Rachinsky AP, Lomonosov SE, Morgun AA. Analysis of possibilities of increasing the efficiency of space situation monitoring and analysis system for navigational support of spacecraft control. *Navigation, Control and Communication Systems,* 2007, 1:7-11. Kyiv, Central Research Institute for Navigation and Control.
2. Kozelkov SV. Application of planetary radar for spacecraft navigation tasks. *Information Processing Systems: Collection of Scientific Works,* 1999, 1(5):139-142. Kharkov, National Academy of Sciences, PANM, Kharkov University of Science and Technology.
3. Kozelkov SV, Bogdanovsky AN, Pashkov DP, Polyakov AL. Method of planning the observation of space objects by optical-electronic means. *Navigation, Control and Communication Systems*, 2007, 2:3-6. Kyiv, CNDI of Navigation and Control.
4. Gusev LI, Molotov EP. Ground-based network for tracking deep-space satellites and high-apogee artificial satellites. *Cosmic Bulletin*, 1995, 2(1):11-13.
5. Vinitsky AS (ed.). *Radio systems of interplanetary spacecraft*. Moscow, Radio i Svyaz' Publ., 1993, 328 p.
6. Polyakov AL, Afonin IL, Tyshchuk YN, Polyakov DA. Method of identification of spacecraft. *Journal of Radioelectronics* [*electronic journal*]. 2020, №5. Access mode: http://jre.cplire.ru/jre/may20/10/text.pdf. DOI: 10.30898/1684-1719.2020.5.10 (access date 10.12.2022).
7. Kaidanovskii NM. Construction of satellite data transmission systems for radio interferometers with ultra-long bases: *Thesis Doctor of Engineering Sciences,* Saint Petersburg, Institute of Applied Astronomy RAS Publ.,1998, 281 p.
8. Koyama Y. Automated Remote Operation System for the Key Stone Project VLBJ Network. *Tactical Warning and Attack Assessment'96*. Kashima, Japan, 1996, pp. 139-143.
9. Abolitz AK. Energy relations in frequency division transmission through a nonlinear repeater. *Elektrosvyaz'*, 1967. 3:19-23 (in Russ.).
10. Okunev YB. *Theory of Phase-Difference Modulation*. Moscow, Svyaz' Publ., 1979, 216 p.
11. Kazarinov YuM (ed.). *Radiotekhnicheskie sistemy* [Radio technical systems]. Moscow, Vysshaya shkola Publ., 1990, 496 p.
12. Kantor LYa (ed.). *Spravochnik po sputnikovoy svyazi i veshchaniyu* [Handbook on Satellite Communications and Broadcasting]. Moscow, Radio i svyaz' Publ., 1986, 287 p.
13. Silvestrov SD, Lazarev VM, Kornienko AI, Panshin MI. T*ochnost' izmereniya parametrov dvizheniya kosmicheskikh apparatov radiotekhnicheskimi metodami* [Accuracy of Spacecraft Motion Parameters Measurements by Radio Engineering Methods]. Moscow, Sovetskoe Radio Publ., 1990, 320 p.
14. Livshits II, Rozhkov VM, Ryabov BA. Ispol'zovanie ISZ dlya svyazi v diapazone

millimetrovykh voln [Using ISZ for Communications in the Millimeter Wave Range]. *Zarubezhnaya radioelektronika*, 1987, 5:41-49 (in Russ.).

15. Mashbitz LM. *Zony obsluzhivaniya sistem sputnikovoy svyazi* [Zones of Satellite Communications Systems]. Moscow: Radio i svyaz' Publ., 1982. 152 p.
16. Makshanov AV, Musaev AA, Stepanyuk OM. Metody statisticheskoy regulyarizatsii v zadachakh navigatsionnogo opredeleniya orbit KA [Methods of statistical regularization in tasks of navigational determination of SC orbits]. *Kosmicheskie issledovaniya*, 1984, 22(3):468-471 (in Russ.).