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DETECTION OF THE SIGNALS OF THE TERRESTRIAL RADAR STATIONS BY SPACECRAFT WITH A PASSIVE SYNTHESIS OF THE ANTENNA APERTURE

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ABSTRACT

Context is due to the need to analyze the electromagnetic accessibility of terrestrial radio radiation sources at long distances, which is typical for the operation of a spacecraft of radio technical intelligence with a passive synthesis of the antenna aperture.

Objective is to calculate the probability indicators of detecting the fact of signal emission of ground-based radar stations using radio-technical intelligence installed on a space carrier.

Method. Analytical calculation of the correct detection probability of the signal of the radio radiation sources by the spacecraft of radio technical intelligence based on the determination of the signal-to-noise ratio at the input of the detection device. The analysis of the technical characteristics of the group of ground radars made it possible to calculate the probability of correct detection only for the virtual radar, which generates the minimum number of pulses with the minimum energy during reconnaissance among all the analyzed radars.

Results. The fulfillment of the conditions of electromagnetic accessibility is checked and the correct detection probability of the signals of modern radar stations by the space radio-technical intelligence system with a passive synthesis of the antenna aperture was calculated.

Conclusion. Proposed use of the correct detection probability of the signal as the resulting indicator of electromagnetic accessibility of the radio radiation source. In the example radar stations of the air defense proved, that the proposed parameters of the space radio technical intelligence system with a passive synthesis of the antenna aperture provide the values of the correct detection probability of the signal, which are quite acceptable for modern monitoring systems.

KEYWORDS: spacecraft, synthesis of the antenna aperture, radio technical intelligence, a radar station, and electromagnetic accessibility.

ABBREVIATIONS

RRS is a radio radiation source;
RLS is a radar station;
RTI is a radio technical intelligence;
SC is a spacecraft;
EIRP is an equivalent isotropic radiated power.

NOMENCLATURE

T_{REC} is a receiver noise temperature;
T_A is an antenna noise temperature;
G_{RSS} is a gain RRS antenna;
G_{RTI} is a gain RTI antenna;
η_{RRS}, η_{RTI} is an antenna efficiency;
R_E is the Earth's radius;
S_A is a geometric antenna area;
K_A is an antenna surface using factor;
T_S is a space noise temperature;
T_{ATM} is an atmosphere noise temperature;
T_E is an Earth noise temperature;
L_{LOSS} is a total signal loss;
P_N is a noise power;
K_N is a receiver noise factor;
q is a signal-to-noise ratio;
ΔF is a signal search range by frequency;
λ is a wavelength;
H_0 is an orbit altitude;
V is a speed of the SC;
ΔF_K is a receiver bandwidth;
L_ε, L_β are antenna sizes by elevation angle and azimuth;
τ_i is an impulse duration;
P_i is an impulse power;
F_i is a pulse repetition frequency;
$\Delta\varepsilon$ is a viewing zone by elevation angle;
Ω_A is an angular velocity antenna rotation;
$R_{\max}$ is a maximum distance;
P_S is a power-useful signal;

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F, D is a false alarm and correct detection probabilities;

t_R is a reconnaissance time;

N_f is the number of receiver reconfigurations by frequency;

M is a number of pulses at the receiver input;

k is Boltzmann's constant.

INTRODUCTION

Detection of radiation from active radio-electronic devices located on the earth's surface is using passive monitoring systems in a certain frequency range. The use of the RTI spacecraft with a passive synthesis of the antenna aperture allows an increase in the accuracy of the azimuthal direction measurements at the RRS. At the same time, both the parameters of the synthesized aperture and the quality indicators of the signal detection of the terrestrial RLS depend on the parameters of the spacecraft orbit and the technical characteristics of both the RTI station and the terrestrial RLS. The signal-to-noise ratio generated by the radio-electronic means at the input of the RTI station analysis device must be sufficient to search the signal in the space and for frequency.

The object of research is the process of the radio radiation sources detected on the Earth's surface by the RTI spacecraft.

The subject of research is the electromagnetic accessibility of terrestrial radio radiation sources for the RTI spacecraft with a passive synthesis of the antenna aperture.

The purpose of the work is to determine the electromagnetic accessibility of the terrestrial radar stations for the RTI spacecraft with a passive synthesis of the antenna aperture.

1 PROBLEM STATEMENT

Today, one of the priority directions of the aerospace industry of Ukraine is the creation of effective aerospace intelligence [1]. The concept of the National targeted scientific and technical space program of Ukraine for 2021–2025 provides for the use of space information, in particular, to ensure the realization of the state's interests in the region of national security and defense [2]. Surveying the earth's surface with spacecraft in different frequency ranges allows for solving various tasks [3]. Recent military conflicts have shown the importance of obtaining timely and reliable information about the enemy's active RLS. Detection of radiation from active radio-electronic devices located on the earth's surface is using passive monitoring systems in a certain frequency range. The use of the RTI spacecraft with a synthesized aperture of the antenna allows an increase in the accuracy of the azimuthal direction measurements to the RRS [4]. Quite a lot of attention is paid in the literature to the issue of optimizing the orbital grouping of satellites with a synthesis of the antenna aperture, based on ensuring a survey of a given area of the earth's surface [5, 6]. At the same time, attention is not enough to the fact that the signal-to-noise ratio created by the radio-electronic means at the input of the RTI station analysis device must be sufficient to correctly detect the signal. Therefore, determining the electromagnetic availability of terrestrial RRS and calculating the probability indicators of signal detection by the RTI spacecraft, when synthesizing the antenna aperture on based pulse radar signals, is an actual scientific task.

2 REVIEW OF THE LITERATURE

Today, RTI systems are widely used as part of onboard complexes placed on aircraft and SC and allow to ensure security due to the timely detection of enemy RRS over a large area [7]. Synthesizing the antenna aperture of the RTI spacecraft carried out by external RRS signals. The literature is given the results of checking the possibility of passive synthesizing the antenna aperture, in particular, based on signals from navigation satellite systems or sources of radio astronomical radiation [8].

Peculiarities of passive synthesis of the antenna aperture on based pulse radar signals [4]:

– the parameters of the received radio signals are unknown in advance;

– the parameters of the synthesized antenna aperture depend on the wavelength and radar pulse repetition rate;

– the unambiguity of determining the azimuth direction on the RRS depends on the parameters of the RLS signal and the orbit altitude of the spacecraft.

The required orbit altitude of the RTI spacecraft with the passive synthesis of the antenna aperture using the terrestrial radar signals is determined in [4]. However, the sufficiency of the signal-to-noise ratio value at the input of the RTI space station analysis device for detecting the terrestrial radar signal did not check.

3 MATERIALS AND METHODS

Active radio devices detect using the radio technical intelligence system. The location of such systems on the SC gives the possibility of conducting reconnaissance of theoretically any part of the earth's surface, regardless of weather conditions and time of day [1].

The analysis of methods for detecting signals of radio-electronic systems showed, that to obtain the specified indicators of the quality of RRS detection necessary perform the following conditions:

– to obtain a high probability of meeting the antennas pattern of the RRS and the RTI station it is necessary, that the RTI station has a wide antenna pattern;

– the value of the signal-to-noise ratio created by the radio-electronic means at the input of the RTI station's analysis device must be sufficient to detect a signal with the required quality indicators;

– at the time of receiving the signal the RTI station must be tuned to the frequency of the signal emitted by the RRS;

– the duration of the received signal must be sufficient for its processing.

Suppose that the analysis of electromagnetic accessibility is subject to a group of ground radars, that emit

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pulse signals of a certain power P_i and a certain duration τ_i. The wavelength of the signal λ is given, but the pulse repetition frequency F_i can variable within certain limits. The RLS has the dimensions of the antenna L_ε, L_β and carries out a circular survey of the space with the angular speed of rotation of the antenna Ω_A. The RTI station is placed on a SC which moving in a circular orbit with an altitude of H_0 (see Fig. 1) and has a non-directional antenna. The analysis receiver has a fixed bandwidth ΔF_K and performs a sequential search the radar signal by the frequency range ΔF. The noise coefficient of the receiver K_N is constant in throughout the search range by frequency.

For a group of ground radars, it is necessary to calculate:

– the signal-to-noise ratio, that created by the RLS at the input of the RTI station's analysis device;

– the number of pulses that will enter the input of one frequency channel of the analysis receiver when it is tuned to a certain frequency;

– probability of correct detection of the signal of the radars by the analysis device of the RTI station.

The conditions of electromagnetic accessibility can be calculated using the following methodology.

1. The maximum distance between SC and RRS is determined [9]:

$$R_{\max} = \sqrt{(R_E + H_0)^2 - R_E^2}\,. \tag{1}$$

2. The power-useful signal the RRS creates at the input of the RTI station receiver can be calculated according to the expression [10]:

$$P_S = \frac{P_i \cdot G_{RRS} \cdot G_{RTI} \cdot \lambda^2 \cdot \eta_{RRS} \cdot \eta_{RTI}}{(4\pi)^2 \cdot R_{\max}^2 \cdot L_{LOSS}}. \tag{2}$$

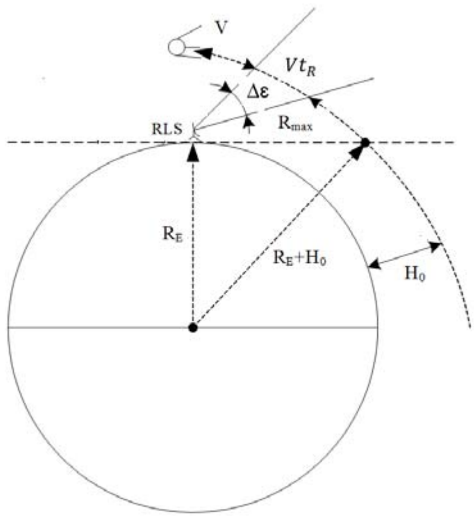

Figure 1 – The conditions of the conducting research

The gain RRS antenna can be calculated as follows:

$$G_{RRS} = \frac{4 \cdot \pi \cdot S_A \cdot K_A}{\lambda^2}. \tag{3}$$

The geometric antenna area is determined according to the expression:

$$S_A = L_\varepsilon \cdot L_\beta. \tag{4}$$

3. In the case when the source of interference is the antenna noise and the inherent receiver noise, the total noise power at the input of the receiver can be determined according to the expression [12]:

$$P_N = k \cdot (T_A + T_{REC}) \cdot \Delta F_k\,. \tag{5}$$

The receiver noise temperature can be determined according to the expression $(T_0 = 300K)$:

$$T_{REC} = T_0 \cdot (K_N - 1). \tag{6}$$

The influence of external noise is taken into account by entering the antenna noise temperature:

$$T_A = \eta_{RTI}(T_S + T_{ATM} + T_E) + (1 - \eta_{RTI})T_0. \tag{7}$$

4. The signal-to-noise ratio can be calculated as follows:

$$q = \sqrt{\frac{2P_S}{P_N}}. \tag{8}$$

5. Having set the false alarm probability F, can find the correct detection probability of the signal with a random amplitude and an initial phase [12]:

$$D = F^{\frac{1}{1+q^2/2}}. \tag{9}$$

6. To check the fulfillment of the last two conditions of the electromagnetic availability of the RRS, it is enough to calculate the number of pulses of the terrestrial RLS, which will arrive at the input of the RTI receiver channel.

The number of receiver reconfigurations by frequency of the RTI station during the sequential search can be calculated according to the expression:

$$N_f = \frac{\Delta F}{\Delta F_K}. \tag{10}$$

The reconnaissance time is determined:

$$t_R \approx \frac{\Delta\varepsilon \cdot R_{\max}}{V}. \tag{11}$$

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The number of pulses at the IRT receiver input, when it is tuned to a certain frequency can be calculated as follows:

$$M = \frac{F_i \cdot t_R}{2N_f} \quad (12)$$

4 EXPERIMENTS

For further research, we will consider ground-based air defense RLS as RRS [13]. The analysis of tactical and technical characteristics of RLS showed that they can be combined into groups according to the working wavelength, at each of which a change of the pulse repetition frequency F_i is possible. Most devices work with a wavelength of 23 cm (F_i from 180 Hz to 680 Hz) and ten cm (F_i from 200 Hz to 1000 Hz).

The parameters of typical RLS, for which the probability indicators of signal detection by the RTI spacecraft will be calculated, are given in Table 1. RLS perform a circular viewing of space with a different angular velocity of antenna rotation and have a different operating range, which provided by the size of the antenna system and the energy of the emitted signal.

The analysis carried out in [4] for typical RLS showed that the fulfillment of the conditions for the unambiguity of measurements in azimuth is ensured when the RTI station is placed on the SC with an orbit altitude of 14200 km (SC speed V=4.4 km/sec). At the same time, the maximum range to the RRS, according to (1), will not exceed 20,000 km.

Instead of calculating the signal-to-noise ratio for each RLS given in Tab.1, this value can be calculated for a virtual RLS with minimum signal energy. From Tab.1 can be seen that the minimum EIRP value is 101 dB and the minimum impulse duration is two µs.

Therefore, the signal-to-noise ratio can be calculated for a virtual radar that uses the signal with an impulse duration of two µs at a frequency of three GHz and has EIRP = 101 dB.

5 RESULTS

The calculation of the signal-to-noise ratio for the virtual RLS can begin with the determination of the noise power at the input of the analysis unit of the RTI station.

For the search of the RRS signal by frequency, it is necessary to set the parameters of the analysis unit of the RTI station. Suppose, that the signal search range by frequency $\Delta F = 0.5-18$ GHz and $\eta_{RRS} = \eta_{RTI} = 0.7$.

The receiver with a bandwidth $\Delta F_K = 1$ MHz carries out a sequential search by frequency and has $K_N \approx 3$.

Then, according to (6), the receiver noise temperature is $T_{REC} = 600K$. For a signal frequency greater than 1 GHz, the space noise temperature T_S is almost zero, the atmosphere noise temperature is $T_{ATM} \approx 110K$ and the average Earth noise temperature is $T_E \approx 250K$ [11]. The maximum of the RTI station antenna pattern is toward the Earth, therefore the component T_E is completely included in the noise temperature (7) and $T_A \approx 340K$. Then, according to (5), the noise power at the IRT receiver input $P_N \approx 1.3 \cdot 10^{-14} W$.

The power-useful signal at the input of the RTI station receiver with a non-directional antenna, that creates by the virtual RLS with $K_A = 0.7$ will be calculated according to the expression (2). At the same time, the total signal loss for the 3 GHz frequency does not exceed six dB [10]. Then, the power useful signal $P_S = 2.7 \cdot 10^{-10} W$ and the signal-to-noise ratio, according to (8), will be 23 dB. The correct detection probability of a signal with a random amplitude and an initial phase, according to (9), will be 0.99 at $F = 10^{-4}$.

A necessary and sufficient condition for detecting a signal is the arrival of at least one pulse at the input of the RTI receiver tuned to a certain frequency during the reconnaissance time. Verify the fulfillment of this condition can also by using a virtual radar, which generates the minimum number of pulses during reconnaissance. According to expressions (11) and (12), the minimum number of pulses at the input of the RTI station receiver will be at the minimum values of $\Delta\varepsilon = 20^0$ and $F_i = 180$ Hz.

The number of the receiver reconfigurations by frequency of the RTI station during the sequential search, according to (10), will be $N_f = 18000$ at $t_R \approx 1586$ sec.

During this time, at least seven pulses will arrive at the input of the RTI station receiver, according to (14), but even with one pulse, the virtual RLS signal is detected with sufficiently high-quality indicators.

Table 1 – RLS parameters

RLS	Range, km	λ, cm	τ_i, µs	P_i, kW	$L_\varepsilon \times L_\beta$, m	EIRP, dB	$\theta_\varepsilon(\theta_\beta)$ degree	Ω_a, rpm / $\Delta\varepsilon$ degree
AR5	400	23	2–5	2000	14.4x5.4	104	40 (1.2)	8/40
S625	340	23	5	4600	7.4x2.4	101	45 (2.3)	6/45
S690	400	23	10	3300	14.5x4.5	106	30 (1.25)	6/30
S640	600	10	10	6000	12.2x4.7	115	30 (0.62)	5/30
AN/TPS-32	550	10	30	2200	3.1x8.2	107	0.9 (2.2)	6/20

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6 DISCUSSION

The radar with an active synthesis of the antenna aperture uses the motion of the antenna over a surface Earth to provide finer spatial resolution than conventional beam-scanning radars. The altitude of the spacecraft orbit, size of the board antenna and the parameters of the RLS signal emitted is provide of the uniqueness main antenna pattern both in range and in azimuth. At the same time, the information about the parameters of the emitted signal is always known.

Recent military conflicts have shown the importance of obtaining timely and reliable information about the enemy's active RLS. Detection of radiation from RLS located on the earth's surface is using passive monitoring systems in a certain frequency range. The literature is given the results of checking the possibility of passive synthesizing the antenna aperture, in particular, based on signals from navigation satellite systems or sources of radio astronomical radiation. In contrast from this studies, in work estimated the electromagnetic accessibility of typical ground-based air defense radars. The use of the RTI spacecraft with a synthesized aperture of the antenna allows also an increase in the accuracy of the azimuthal direction measurements to the RLS. Therefore determining the electromagnetic availability of terrestrial RLS using the RTI station with a passive synthesis of the antenna aperture located on the SC is an actual scientific task.

At the same time, the parameters of the passive synthesis of the antenna aperture depend on the parameters of the SC orbit and the technical characteristics of both the RTI station and the terrestrial RLS. The air defense radars perform a circular viewing of space with a different angular velocity of antenna rotation and have a different operating range, which provided by the size of the antenna system and the energy of the emitted signal. The signal-to-noise ratio generated by the RLS at the input of the RTI station analysis device must be sufficient to search the signal in the space and for frequency. The analysis of the technical characteristics of the group of ground radars made it possible to calculate the signal-to-noise ratio only for the virtual radar, which generates the minimum number of pulses with the minimum energy during reconnaissance among all the analyzed radars.

A necessary and sufficient condition for detecting a signal is the arrival of at least one pulse at the input of the RTI receiver tuned to a certain frequency during the reconnaissance time. Verify the fulfillment of this condition proposed to calculate also by using a virtual radar, which generates the minimum number of pulses during reconnaissance.

The distance for which the calculation of indicators of the electromagnetic accessibility of RLS is provide of the uniqueness of the main maximum of the pattern at passive synthesis of the antenna aperture both in range and in azimuth. Proposed use of the correct detection probability of the signal as the resulting indicator of electromagnetic accessibility of the RLS. Analytical calculation of the correct detection probability of the signal of the air defense radars by the SC of RTI based on the determination of the signal-to-noise ratio at the input of the detection device were carried out. The methodology for calculating electromagnetic accessibility indicators is based on generally accepted theoretical principles, so the obtained results can be considered reliable.

CONCLUSIONS

The scientific problem by the need to analyze the electromagnetic accessibility of terrestrial radio radiation sources at long distances, which is typical for the operation of a spacecraft of radio technical intelligence with a passive synthesis of the antenna aperture.

In contrast to similar studies using monitoring systems with the passive synthesis of the antenna aperture, an assessment of the electromagnetic accessibility of typical ground-based air defense radars.

The mathematical aspects of calculating the probability of correct detection of signals for a group of ground radars were further developed by introducing a virtual radar that generates the minimum number of pulses with the minimum energy during reconnaissance among all radars, which analyzes.

Practical significance. In the example radar stations of the air defense proved, that the proposed parameters of the space radio technical intelligence system with a passive synthesis of the antenna aperture provide quite acceptable values of the correct probability detection of the signal. The correct detection probability of a signal with a random amplitude and an initial phase is $D = 0.99$ at $F = 10^{-4}$.

When sequential searching for the virtual radar signal by frequency in the range of 0.5–18 GHz with a step of one MHz, during the reconnaissance time, at least seven pulses will arrive at the input of the RTI station receiver. The frequency of the search channel will be hopping by one MHz every 38 msec, which is quite acceptable for modern monitoring systems.

Directions for further research there is estimate the possible accuracy of the different methods determining the radar located on the Earth's surface when using the RTI spacecraft with the passive synthesis of the antenna aperture.

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ВИЯВЛЕННЯ СИГНАЛІВ НАЗЕМНИХ РЛС КОСМІЧНИМ АПАРАТОМ ІЗ ПАСИВНИМ СИНТЕЗОМ АПЕРТУРИ АНТЕНИ

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АНОТАЦІЯ

Актуальність зумовлена необхідністю проведення аналізу електромагнітної доступності та розрахунку ймовірнісних показників виявлення сигналів наземних джерел радіовипромінення на досить великих відстанях, що характерно для роботи космічного апарату радіотехнічної розвідки із синтезованою апертурою антени.

Метою роботи є визначення електромагнітної доступності наземних радіолокаційних станцій для космічних засобів радіотехнічної розвідки з пасивним синтезом апертури антени та розрахунок ймовірнісних показників виявлення факту випромінення сигналів.

Метод. Аналітичний розрахунок ймовірності правильного виявлення сигналу джерел радіовипромінення космічною системою радіотехнічної розвідки з пасивним синтезом апертури антени на основі визначення відношення сигнал/шум на вході пристрою виявлення, при заданих параметрах космічної системи розвідки. Аналіз технічних характеристик групи наземних РЛС дозволив розрахувати ймовірність правильного виявлення лише для віртуальної РЛС, яка генерує мінімальну кількість імпульсів з мінімальною енергією за час розвідки серед усіх РЛС, що підлягали аналізу.

Результати. Перевірено виконання умов електромагнітної доступності та розрахована ймовірність виявлення сигналів сучасних радіолокаційних станцій космічною системою радіотехнічної розвідки з пасивним синтезом апертури антени.

Висновки. Як результуючий показник електромагнітної доступності запропоновано використовувати ймовірність правильного виявлення сигналу джерела радіовипромінення. Доведено, що обрані параметри космічної системи радіотехнічної розвідки забезпечують цілком прийнятні значення ймовірності правильного виявлення сигналів наземних радіолокаційних станцій протиповітряної оборони.

КЛЮЧОВІ СЛОВА: космічна система, антена із синтезованою апертурою, радіотехнічна розвідка, радіолокаційна станція, електромагнітна доступність.

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