Russian Technological Journal. 2025;13(5):75–86 ISSN 2500-316X (Online)

Modern radio engineering and telecommunication systems

Современные радиотехнические и телекоммуникационные системы

UDC 621.396.969
https://doi.org/10.32362/2500-316X-2025-13-5-75-86
EDN RTWBZR

RESEARCH ARTICLE

Optimization criterion for spacecraft observation planning algorithms

Alexander V. Ksendzuk [1, @],
Ivan A. Kuznetsov [2]

[1] *MIREA – Russian Technological University, Moscow, 119454 Russia*
[2] *MAK Vympel, Moscow, 125480 Russia*
[@] *Corresponding author, e-mail: ks_alex@mail.ru*

• **Submitted:** 25.02.2025 • **Revised:** 31.03.2025 • **Accepted:** 25.07.2025

Abstract

Objectives. One of the critical tasks of space monitoring is the planning of observations due to the quality and amount of information obtained depending on how well the observation plan is developed. However, the selection of a method for planning spacecraft observations is hampered by a lack of unified criteria for comparing different planning algorithms. Therefore, the work sets out to develop planning quality criteria on the basis of physical observation principles based on radar, radiotechnical, and optical monitoring approaches in order to analytically determine their main parameters and check these parameters numerically.

Methods. The proposed quality criteria are deterministic, limited in energy by signal strength and observation time. The limiting values of the quality criteria for fixed observation time are analytically determined. In order to obtain the values of the quality criteria for four scheduling algorithms, a computational experiment is carried out.

Results. The proposed "weight–observation time" quality criterion is used to compare different observation planning algorithms that take into account spacecraft priority and total observation time. In order to account for the structure of the total observation time, the "weight–observation structure" criterion is introduced. It is analytically confirmed that the limited criteria values differ for different scheduling methods. The conducted numerical experiment is used to confirm the nature of the change of criteria for different planning methods and parameters included in the criteria.

Conclusions. The proposed observation planning quality criteria, which are based on the physical observation principles by radiotechnical and optical means, are used to numerically compare the results of spacecraft observation planning to take into account the priority of observation, as well as observation time and structure (how many and how long are the intervals into which the total observation time is divided). The possibility of using the proposed "weight–observation time" and "weight–observation structure" criteria to compare different planning algorithms is confirmed by computational experiment. Therefore, it is reasonable to use the proposed criteria for optimization of scheduling algorithms or their numerical comparison for different satellite observation conditions.

Keywords: observation planning, quality criterion, spacecraft, spacecraft monitoring, conflict observation

For citation: Ksendzuk A.V., Kuznetsov I.A. Optimization criterion for spacecraft observation planning algorithms. *Russian Technological Journal.* 2025;13(5):75–86. https://doi.org/10.32362/2500-316X-2025-13-5-75-86, https://www.elibrary.ru/RTWBZR

Financial disclosure: The authors have no financial or proprietary interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

К вопросу выбора критериев качества алгоритмов планирования наблюдений за космическими аппаратами

А.В. Ксендзук [1, @],
И.А. Кузнецов [2]

[1] *МИРЭА – Российский технологический университет, Москва, 119454 Россия*
[2] *Межгосударственная акционерная корпорация «Вымпел», Москва, 125480 Россия*
[@] *Автор для переписки, e-mail: ks_alex@mail.ru*

• **Поступила:** 25.02.2025 • **Доработана:** 31.03.2025 • **Принята к опубликованию:** 25.07.2025

Резюме
Цели. Одна из важнейших задач мониторинга космического пространства – это планирование наблюдений за космическими аппаратами. От того, насколько хорошо составлен план наблюдений, зависят качество и объем получаемой информации. В настоящее время существует множество различных методов планирования наблюдений за космическими аппаратами, однако единые критерии, которые позволяют сравнить различные алгоритмы планирования, отсутствуют. Цель работы – на основе физических принципов наблюдения радиолокационными, радиотехническими и оптическими средствами мониторинга разработать критерии качества планирования, определить их основные параметры аналитически и проверить численно.
Методы. Предложенные критерии качества – детерминированные, ограниченные по энергии мощностью сигнала и временем наблюдения. Аналитически определены предельные значения критериев качества для фиксированного времени наблюдения. В вычислительном эксперименте для 4 алгоритмов планирования получены значения критериев качества.
Результаты. Для сравнения различных алгоритмов планирования наблюдений, учитывающих приоритет космического аппарата и общее времени его наблюдения, предложен критерий качества «вес – время наблюдения». Для учета структуры общего времени наблюдения введен критерий «вес – структура наблюдения». Аналитически показано, что значения критериев ограничены, а также различаются для разных методов планирования. Выполнен численный эксперимент, который подтвердил характер изменения критериев для различных методов планирования и параметров, входящих в критерии.
Выводы. Предложенные критерии качества планирования наблюдений основаны на физических принципах наблюдения радиотехническими и оптическими средствами и позволяют численно сравнить результаты планирования наблюдений за космическими аппаратами с учетом приоритетности наблюдения, времени наблюдения и его структуры. Вычислительный эксперимент подтвердил возможность применения предложенных критериев «вес – время наблюдения» и «вес – структура наблюдения» для сравнения различных алгоритмов планирования. Предложенные критерии целесообразно использовать для оптимизации алгоритмов планирования или их численного сравнения для различных условий наблюдения за космическими аппаратами.

Ключевые слова: планирование наблюдений, критерий качества, космический аппарат, мониторинг космических аппаратов, конфликтное наблюдение

Для цитирования: Ксендзук А.В., Кузнецов И.А. К вопросу выбора критериев качества алгоритмов планирования наблюдений за космическими аппаратами. *Russian Technological Journal*. 2025;13(5):75–86. https://doi.org/10.32362/2500-316X-2025-13-5-75-86, https://www.elibrary.ru/RTWBZR

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

At present, a significant increase in the number of spacecraft (SC) and quantity of space debris is accompanied by a relatively slow growth in the quantity and quality of optical, radar and radiotechnical systems of monitoring near-Earth space[1] [1]. Under these conditions, the task of planning observations by monitoring means acquires special importance. The relevance of this problem is confirmed by the works [2–8], in which the authors propose various algorithms for planning observations, including those of astronomical objects [9, 10].

In order to evaluate the effectiveness of the scheduling algorithm, the influence of each factor (weather conditions, particle dispersion level, etc.) on the final result is distributed in a percentage based on the influence of each factor on the quality of the problem solution [2]. In this work, each parameter is evaluated in the range from 1 to 10 points, then the value of the parameter is multiplied by its corresponding importance percentage, and all weighted scores are summarized.

In [3], maps of SC detection efficiency are constructed for observation planning purposes using the resulting efficiency factor, which is calculated as the product of criteria (extinction coefficient, angular velocity, etc.) together with its weighting factor.

The use of a covariance matrix trace for describing the average change in the contribution to the measurements when selecting the SC to be monitored is set out in [4]. Such a trace can be related to the informativity parameters, for example, the change of differential entropy.

In [5], the effectiveness of "greedy" optimization methods that do not require significant computational and mathematical resources is analyzed. As a criterion, a cost function is used based on potential observations and how well the observations fit the objective, while numerical and analytical formulas for calculating "fit" are not given.

In [6], optimization is performed on the object observation time, taking into account the observation switching time from the previous object. Although the described global optimization approach can be used to maximize the total SC observation time, the authors do not take priority of SC observation into account.

The authors of [7] describe the use of average satellite observation time minus the deviation of the observation time of each satellite with respect to the mean value multiplied by the Lagrange factor to obtain an observation criterion. This criterion takes the maximum value when all satellites are observed for the same time.

Thus, despite the availability of a large number of methods, algorithms, and scheduling software, there are no generally accepted quality criteria that allow us to compare these methods. Consequently, the development of physically based criteria becomes an urgent task.

1. PLANNING TASK STATEMENT

When planning SC observations, one of the main problems concerns how to resolve conflicts when the number (bandwidth) of observation channels is less than the number of simultaneously visible SC, i.e., the need to choose which SC should be observed [11]. SC visibility is understood as the possibility of its observation in space (geometric visibility), in energy parameters (radar and radiotechnical visibility) and in the frequency domain (for radiotechnical systems, the frequency of the SC signal must be within the range of operating frequencies).

If there were no conflicts, the task of forming an observation plan would be reduced to sequential tracking of visible SCs and, if necessary to save the resource of observation facilities, stopping observations when the required amount of information has been obtained.

In realistic observing conditions involving a lack of observational means, conflicts frequently arise in terms of the simultaneous visibility of multiple satellites, for each of which a decision must be made as to which of the SCs to observe. Different conflict resolution methods lead to the formation of different observation plans.

The initial data for planning are: the matrix of SC visibility, SC priority and time sufficient for obtaining information of the required quality. For the convenience of planning, the time is assumed to be discrete.

In the **visibility matrix** $\mathbf{V}(i, t)$, the row i corresponds to the SC number, while column t corresponds to the time, and each cell $V_{i,\,t}$ shows the visibility of the SC

[1] https://www.space-track.org/. Accessed January 20, 2025.

by the monitoring tool. In the simplest case, the values in the matrix take the values 0 and 1 (visibility based on geometric relations). In a more complex variant, the cells contain a value related to the quality of observation, for example, the signal-to-noise ratio by power or the probability of SC observation. The sum of the rows within a column indicates how many SCs are visible (can be observed) at the same time.

The vector of priority (weights) of the SC for each SC defines a weight w_i representing a positive integer that indicates the importance of the SC observation (the larger the value, the higher the priority and value of the observation of this SC).

The vector of sufficient (continuous) observation time for each ith SC determines the (continuous) time interval $T_{\text{suf}\,i}$, sufficient to obtain the required amount of information/quality of parameter estimates. The requirement of interval continuity is based on the principles for estimating parameters constantly over the observation interval. If this requirement is optional, $T_{\text{suf}\,i}$ can be the full observation time. In cases when the signal-to-noise power ratio is used in the observation matrix, $T_{\text{suf}\,i}$ defines the power signal-to-noise ratio on which the quality of estimates depends [12].

The result of planning is the **observation matrix O** (i, t), the dimensionality of which coincides with the dimensionality of the visibility matrix. For each ith row (SC number) at time t in the cell $O_{i,\,t}$ can be the value 1 (ith SC at this time will be observed by the monitoring instrument) or 0 (SC will not be observed). At one moment of time t (column of the matrix), the number of SC being monitored shall be equal to the number of channels of the monitoring instrument.

An example showing the type of input data for planning and the result of planning is shown in Fig. 1.

2. NUMERICAL OBSERVATION RATES

Numerical parameters used to calculate the quality criterion and analyze the observation and visibility matrices are described as follows:

$t = 1 \ldots T_{\text{plan}}$, T_{plan} is the planning interval (time interval for which the observation plan is prepared, usually a day).

$i = 1 \ldots I_{\max}$ is the number of visible SCs in the planning interval T_{plan}.

$T_{\text{vis}\,i}$ is the visibility time of the ith SC is the sum of its free (conflict-free) $T_{\text{vis.free}\,i}$ and conflict $T_{\text{vis.conf}\,i}$ visibility time $T_{\text{vis}\,i} = T_{\text{vis.free}\,i} + T_{\text{vis.conf}\,i} = \Sigma_{t=1\ldots T}V_{i,\,t}$. The visibility time shows the potential observation capability of the SC.

$I_{\text{obs}} \leq I_{\max}$ is the number of observed SCs in the planning interval T_{plan}.

$T_{\text{obs}\,i}$ is the observation time for the ith SC is the sum of the conflict-free $T_{\text{obs.free}\,i}$ and conflict $T_{\text{obs.conf}\,i}$ observation time. These values show the realization of a particular observation plan, with $T_{\text{obs}\,i} \leq T_{\text{vis}\,i}$.

w_i is the priority (weight) of the SC, which indicates the value (contribution) of its observation. The priority is set by an integer number lying in a given range $\{w \in \mathbb{N} \mid 1 \leq w_i \leq w_{\max}\}$; the larger it is, the higher the priority of the SC (in most real-world tasks, it is sufficient to set w_i values from 1 to 5; this range is used in numerical calculations in this study).

$T_{\text{suf}\,i}$ is the sufficient (continuous) time of SC observation. It is determined for each satellite depending on the observation task (signal detection, estimation of signal parameters, estimation of parameters of the transmitted information flow, etc.), known, predicted or calculated statistical characteristics of the observation (signal-to-noise ratio, probability of satellite observation). Observation of the SC during the (continuous) time

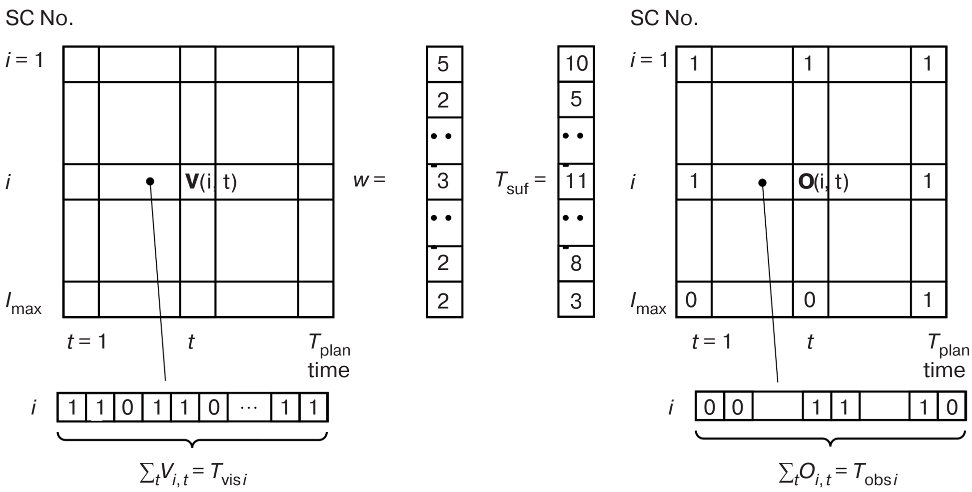

Fig. 1. Type of basic matrices and vectors when planning observations

interval $T_{\text{suf }i}$ provides with the required probability the necessary quality of its parameter estimation. Observation for a shorter time interval does not provide the required quality. Observation for a longer interval is excessive.

$T_{\text{vis.s}}$ is the total (sum) time of visibility (at least one of $i = 1 \ldots I_{\max}$ SCs can be observed), determined by the visibility matrix $\mathbf{V}(i, t)$:

$$T_{\text{vis.s}} = \sum_{t=1\ldots T} T_{\text{vis.s }t} = \sum_{t=1\ldots T} \text{sign}\left[\sum_{i=1\ldots I_{\max}} V_{i,t}\right]. \quad (1)$$

N_t is the number of simultaneously visible SCs at the moment of time t:

$$N_t = \left[\sum_{i=1\ldots I_{\max}} V_{i,t}\right]. \quad (2)$$

$T_{\text{obs.s}}$ is the total observation time (at least one of $i = 1 \ldots I_{\max}$ SCs), is determined by the observation matrix $\mathbf{O}(i, t)$:

$$T_{\text{obs.s}} = \sum_{t=1\ldots T} T_{\text{obs.s }t} = \sum_{t=1\ldots T} \text{sign}\left[\sum_{i} O_{i,t}\right]. \quad (3)$$

While the free and conflict observation time can be integrally determined by analyzing the visibility matrix $\mathbf{V}(i, t)$, the calculation of the redistribution of this time between the satellites is based on an analysis of the corresponding observation matrix $\mathbf{O}(i, t)$ for this planning method. As an example, Fig. 2 shows the result of scheduling observations by a single-channel SC constellation tool in the presence of free and conflict observations.

The observation matrix depicted in Fig. 2 confirms the conservation of free observation time for all SC. **The free observation time** is preserved unless **the resource limitation of the observation time** $T_{\text{obs.s}} \le T_{\text{res}}$, $t = 1 \ldots T_{\text{plan}}$ is used to extend the lifetime of the monitoring instruments or to use part of the time for other purposes, e.g., to analyze the environment (interference emissions are evaluated using radiotechnical and radar instruments, while astroclimatic factors are examined by means of optical monitoring instruments). In the absence of such restrictions, one of the methods for checking the correctness of the planning algorithm $T_{\text{vis.free }i} = T_{\text{obs.free }i}$ is preserving the time of free (conflict-free) observation.

Conflict observation time is distributed among the SCs according to the planning method used (including the simplest method involving termination of observations in case of conflict). In the example considered in Fig. 2, the priority is given to the SCs at the beginning

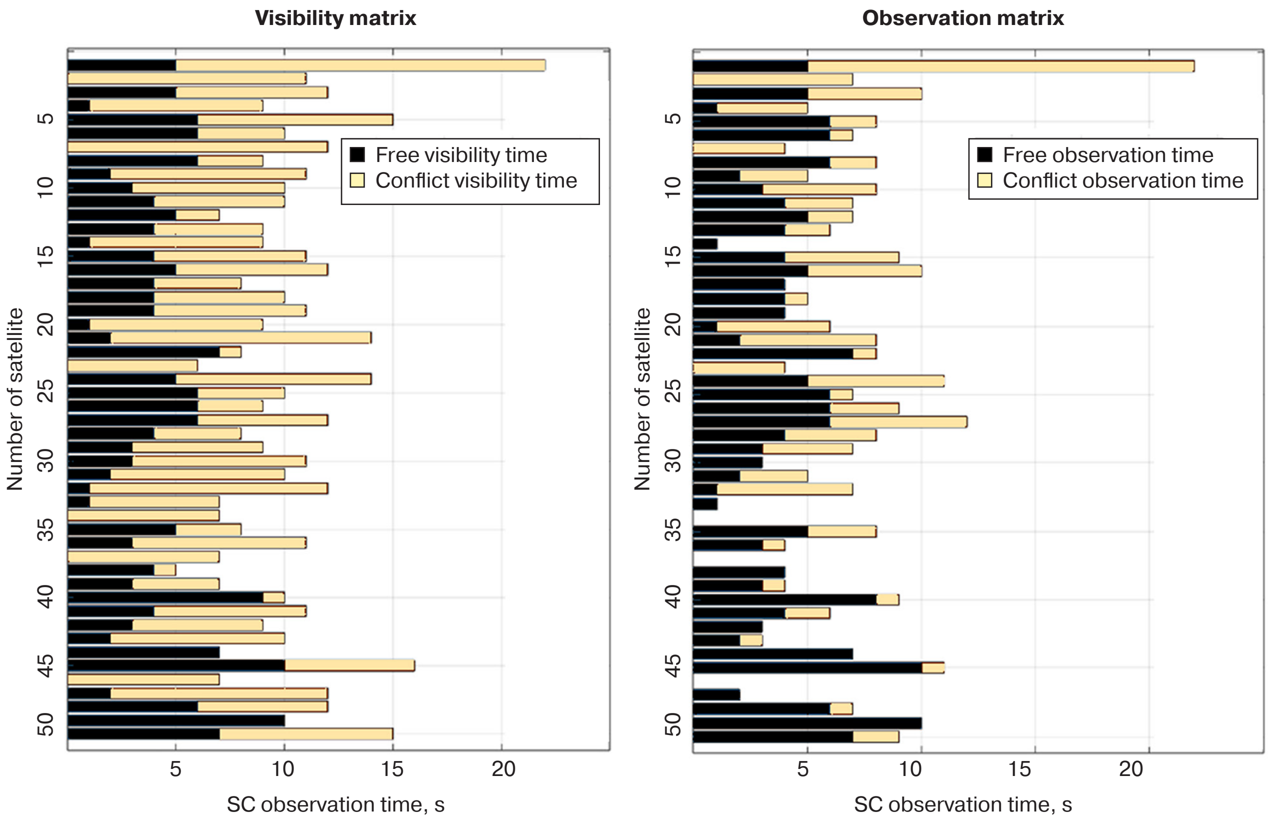

Fig. 2. Example of the visibility matrix (left) and observation plan (right)

of the list (all possible conflict observation time is used), while for the rest the time is redistributed.

Total observation time in the absence of resource constraint should coincide with the total visibility time $T_{vis.s} = T_{obs.s}$, which should be used to verify the correctness of the scheduling algorithm.

3. QUALITY CRITERIA FOR OBSERVATIONS

To compare different planning methods, it is necessary to introduce a numerical indicator based on numerical, measurable parameters of the observation plan [13]. Since in the considered case visibility and planning result are deterministic functions, we will determine the quality of planning without using probabilistic indicators. However, it is not difficult to take probabilistic parameters into account within the framework of the proposed approach—it is enough to put the probabilities of SC observation pre-calculated or determined on the basis of statistical data as the values of elements in the cells [14].

3.1. “Weight–observation time” criterion

The first planning quality criterion proposed in this paper is introduced using the priority of the SC and the total time of its observation (without taking into account how many intervals it is divided into). This variant can be used for the case when one discrete time interval is sufficient to estimate the parameters of the SC with the required quality. The criterion “weight–observation time” is defined by the sum of **the contributions from the observation of the individual SCs** Q_{wt_i}:

$$Q_{wt} = \frac{1}{I_{\max}} \sum_{i=1}^{I_{\max}} Q_{wt_i} = \frac{1}{I_{\max}} \sum_{i=1}^{I_{\max}} (a_i)^n \ln\left(\frac{T_{\text{obs } i}}{T_{\text{suf } i}} + 1\right), \quad (4)$$

where:

- $a_i = w_i/w_{\max}$ is the relative priority of the ith SC, taking values in the interval (0; 1];
- w_i is the priority of the ith SC;
- $w_{\max}$ is the maximum observation priority from the set of visible SCs;
- n is the relative priority degree indicator, making it possible to vary the contribution of w_i: $n = 1$ is the linear dependence on the priority of the SC, $n = 0$ is the priority of the SC is not taken into account;
- $I_{\max}$ is the amount of the visible SCs;
- $T_{\text{obs } i}$ is the observation time of the ith SC obtained as a result of planning;
- $T_{\text{suf } i}$ is the time sufficient to obtain information / estimates of parameters of the required quality for the ith SC.

The proposed criterion “weight–observation time” has the following properties:

1. If the ith SC is not observed (i.e., $T_{\text{obs } i} = 0$) in the planning interval T_{plan}, but is included in the set of visible satellites $I_{\max}$, the contribution from this SC is equal to zero:

$$Q_{wt_i}\,|_{T_{\text{obs}\,i=0}} = \left(\frac{w_i}{w_{\max}}\right)^n \ln(1) = 0. \quad (5)$$

2. If the observation time of the ith SC is equal to sufficient time ($T_{\text{obs } i} = T_{\text{suf } i}$), the contribution from its observation will depend on the SC priority:

$$Q_{wt_i} \approx 0.69\left(\frac{w_i}{w_{\max}}\right)^n, \quad (6)$$

while for the SC with the maximum priority, the contribution will be equal to 0.69. The same value of Q_{wt_i} will be for a satellite with any priority at $n = 0$ and observation for sufficient time ($T_{\text{obs } i} = T_{\text{suf } i}$).

3. The contribution from the observation of the ith SC has a maximum (bounded from above) value when the time of SC observation tends to the time of its visibility $T_{\text{obs } i} \to T_{\text{vis } i}$. The limit for continuously visible SCs is equal to the planning time $T_{\text{obs } i} \to T_{\text{plan}}$:

$$\max(Q_{wt_i}) = \left(\frac{w_i}{w_{\max}}\right)^n \ln\left(\frac{T_{\text{vis } i}}{T_{\text{suf } i}} + 1\right). \quad (7)$$

For the SC with the maximum priority (or for any SC if the observation priority is not taken into account), $n = 0$) $\max(Q_{wt_i}) = \ln\left(\frac{T_{\text{vis } i}}{T_{\text{suf } i}} + 1\right)$.

A diagram of the SC observation contribution Q_{wt_i} as a function of the observation time $T_{\text{obs } i}$ versus the sufficient observation time $T_{\text{suf } i}$ at different priority ($w_i = 1 \ldots 5$) and its degree of consideration $n = 0, 0.5, 1, 2$ is shown in Fig. 3.

Analyzing the results of numerical calculation of the proposed “weight–observation time” criterion confirms the above properties:

- Q_{wt_i} monotonically increases with increasing observation time;
- at small observation time relatively sufficient $T_{\text{obs } i}/T_{\text{suf } i} \to 0$ the criterion “weight–observation time” $Q_{wt_i} \to 0$;
- for the SC with the maximum priority $w_i = 5$ the contribution, depending on the relative observation time $T_{\text{obs } i}/T_{\text{suf } i}$ grows logarithmically, taking at

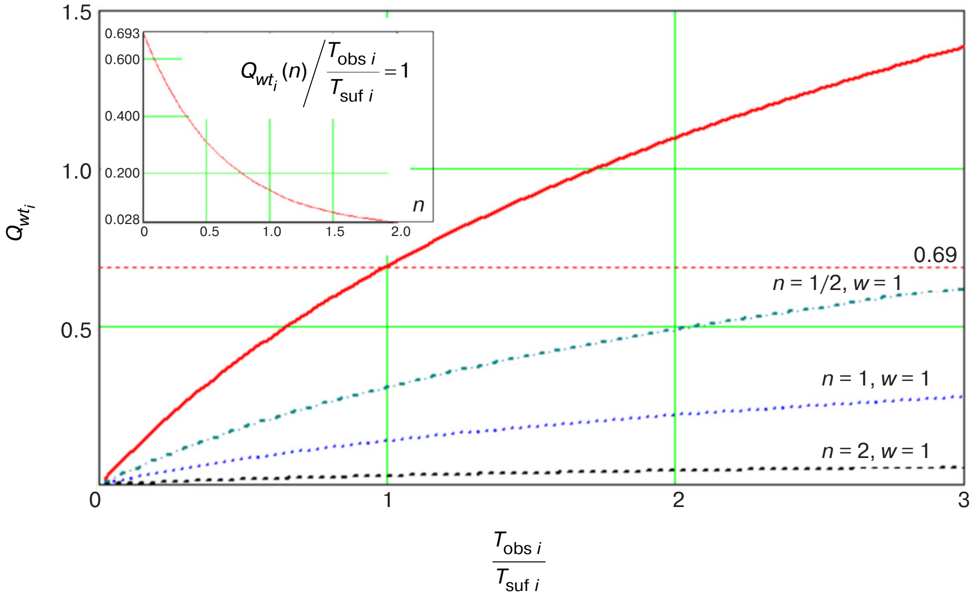

Fig. 3. The value of the quality index Q_{wt_i} at satellite observation depending on the parameters (n, w) and the value of Q_{wt_i} (n; w = 1) at $T_{\text{obs }i}/T_{\text{suf }i} = 1$

the point where the observation time of the ith SC is equal to a sufficient $T_{\text{obs }i} = T_{\text{suf }i}$, value of 0.69. The value of n does not affect the position of this graph, since $(a_i)^n = \left(\frac{w_{\max}}{w_{\max}}\right)^n = 1$;

- for the SC with minimum priority ($w_i = 1$, $w_{\max} = 5$), the contribution for the same relative observation time $T_{\text{obs }i}/T_{\text{suf }i}$ is less and is determined by the degree n, which takes into account the weight of the SC priority: the larger is n, the less is the contribution from the observation of SC with low priority. In the considered example, at the point $T_{\text{obs }i} = T_{\text{suf }i}$ for $n = [0 \ldots 2]$ $Q_{wt_i} = [0.69 \ldots 0.028]$, the diagram is shown in the inset of Fig. 3.

3.2. "Weight–observation structure" criterion

For SCs whose signal parameters may change over time, continuous long observation intervals are of great value (e.g., it is more accurate to determine a linearly time-varying frequency from a single long-time interval rather than from a set of short ones).

In order to take the structure of the observation time into account, i.e., how many intervals of what duration into which the total observation time of the SC $T_{\text{obs }I}$ is divided, it is proposed to introduce the equivalent observation time $T_{\text{obs.eq }i}$, which is calculated by the formula:

$$T_{\text{obs.eq }i} = \frac{\sum_{k=1}^{K_i}\left(T_{\text{obs }i_k}\right)^2}{T_{\text{obs }i}}, \qquad (8)$$

where K_i is the number of noncontiguous observation intervals of the ith SC during the period T_{plan}; k is the number of the observation site of the ith SC; $T_{\text{obs }i_k}$ is the observation time at the kth site.

Figure 4 shows the dependence of the equivalent observation time $T_{\text{obs.eq}}$ of a SC on the continuous interval $T_{\text{obs }k}$ of its observation reduced to the total observation time T_{obs} of the SC.

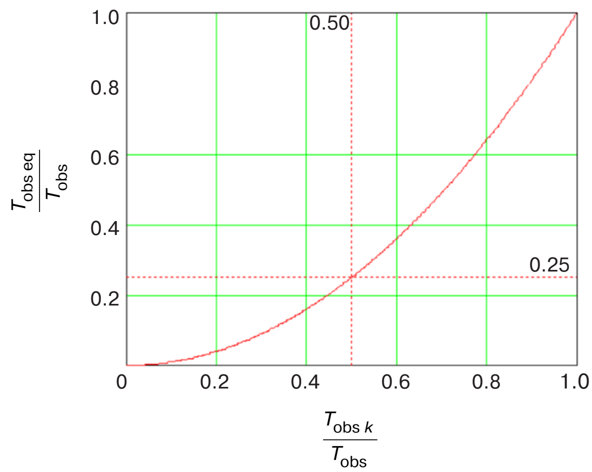

Fig. 4. Dependence of $T_{\text{obs eq}}$ values on the observation interval $T_{\text{obs }k}$ when normalized by the total satellite observation time T_{obs}

The properties of the equivalent observation time following from expression (8) and confirmed by the diagram in Fig. 5:

1. For one SC observation interval (K = 1), the equivalent observation time is equal to the observation time $T_{\text{obs }i}$ itself:

$$T_{\text{obs.eq } i} = \frac{\left(T_{\text{obs } i_k}\right)^2}{T_{\text{obs } i}} = T_{\text{obs } i}, \tag{9}$$

2. At a large number of observation time intervals ($K_i \gg 1$) and one "long" interval $T_{\text{obs } i_k} \gg T_{\text{obs } i_j}$ the equivalent observation time of the SC is determined by the maximum duration of the site $\max(T_{\text{obs} i_k})$.
3. When the number of sites $K_i \to \infty$ with the same small observation time $T_{\text{obs } i_k}$ is large, the equivalent observation time tends to zero:

$$T_{\text{obs.eq } i} = \frac{\sum_{k=1}^{K_i \to \infty} \left(T_{\text{obs } i_k}\right)^2}{T_{\text{obs } i}} \to 0. \tag{10}$$

The second "weight–observation structure" planning quality criterion proposed in this article uses in (4), instead of the total observation time of the ith SC $T_{\text{obs } i}$ its equivalent observation time $T_{\text{obs.eq } i}$:

$$Q_{ws} = \frac{1}{I_{\max}} \sum_{i=1}^{I_{\max}} Q_{ws_i} = \frac{1}{I_{\max}} \sum_{i=1}^{I_{\max}} (a_i)^n \ln\left(\frac{T_{\text{obs eq} i}}{T_{\text{suf} i}} + 1\right) =$$

$$= \frac{1}{I_{\max}} \sum_{i=1}^{I_{\max}} \left(\frac{w_i}{w_{\max}}\right)^n \ln\left(\frac{\sum_{k=1}^{K}\left(T_{\text{obs } i_k}\right)^2}{T_{\text{obs } i} T_{\text{suf } i}} + 1\right), \tag{11}$$

where the relative priority of the ith SC $a_i^n = (w_i / w_{\max})^n$ and the ratio of the equivalent observation time of the ith spacecraft $T_{\text{obs.eq } i}$ to the continuous interval $T_{\text{suf } i}$ sufficient for obtaining estimates of the required quality are taken into account.

The "weight–observation structure" criterion Q_{ws} has the same properties as the "weight–observation time" criterion Q_{wt} with the precision that the observation time should be replaced by an equivalent one.

4. ASSESSMENT OF THE APPLICABILITY OF THE PLANNING QUALITY CRITERIA

In order to evaluate the feasibility of the proposed quality criteria, we use several different scheduling algorithms for which the behavior of the proposed criteria Q_{wt} (4) and Q_{ws} (11) can be logically predicted. For these scheduling algorithms, we use the same visibility matrix for which we compute the observation matrix and the proposed quality criteria. The results of the behavior of the criteria, including their compliance with the logical assumptions and sufficient numerical spread for different planning algorithms, will confirm the possibility of applying the proposed quality criteria.

Algorithm 1 ("first on the list")

In case of a conflict observation, an unconditional transition to the observation of the SC that is first in the list is performed. Obviously, such an algorithm will give low time (continuous) observation of the SC at the end of the list. If the SCs with high priority are located there, the quality of planning by the Q_{wt} criterion will be low. The value of the criterion will significantly depend on which SC with what priority are located first in the list.

In order for such a simple and computationally undemanding scheduling algorithms to be practically useful, it is necessary to compile a list of the SCs, placing the highest-priority ones with the minimum total observation time at the top of the list.

Algorithm 2 ("inertia-free transition to priority satellite")

In case of a conflicting observation (collision), an unconditional switch to the observation of the SC that has a higher priority regardless of the time of its observation. In fact, this is a "greedy" algorithm that maximizes the quality criterion at each step [15]. Obviously, such an algorithm will give a higher (compared to Algorithm 1) quality of observation for criterion (4) Q_{wt} "weight–observation time"; for the criterion Q_{ws}, the contribution of lower-priority SCs will be low, since high-priority SCs will be observed in conflict observation. If the priority of all SCs is equal, the criterion Q_{ws} (11) "weight–continuous observation time" will be the same as for Algorithm 1.

Algorithm 3 ("inertial transition to a satellite with higher weight")

A modification of Algorithm 2 takes into account the observation time of the ith SC by calculating a coefficient equal to the ratio of the priority of the SC to the time it has already been observed ($w_i/T_{\text{obs } i}$). In contrast to Algorithm 2, the transition to the observation of a new, higher priority jth SC may not occur if the time $T_{\text{obs } j} \gg T_{\text{obs } i}$. That is, the formed "inertia" of the SC observation decreases when its observation time increases. Such a criterion should lead to a decrease in short observation intervals due to inertia and to an increase in the quality criterion (6) compared to Algorithms 1 and 2.

Algorithm 4 ("observation time equalization")

In this case, tracking of a SC is stopped if its observation time exceeds the same parameter of another satellite. The algorithm tries to "equalize" the observation time of all SCs.

To determine the maximum achievable indicators on the visibility matrix, it is reasonable to use the method of complete enumeration over all possible variants of the planning problem solution. However, for real conditions (plan for a day, more than 10000 SC overflights) such a solution can be theoretically obtained only with the use of quantum computing [16]. However, such a solution can also be obtained by restricting the list of satellites to those observed by radiotechnical systems of RTU MIREA [17].

An illustration of the working principle of Algorithms 1–4, for which the planning quality criterion is calculated, is shown in Fig. 5.

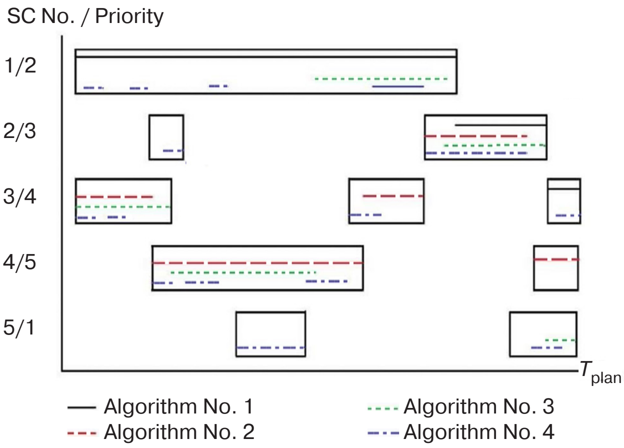

Fig. 5. Example of operation of Algorithms 1–4 on planning interval T_{plan} for 5 SCs with given visibility time and different observability priority a_i

Table summarizes the results of the calculation according to the proposed quality criteria. As input data, a SC visibility matrix consisting of 50 SC for the discrete planning interval T_{plan} = 500 was generated. For the table columns, the minimum values of the quality criteria are italicized, while the maximum values are given in bold.

Table. Results of numerical modeling

Algorithm designation	Q_{wt}		Q_{ws}	
	$n = 0$	$n = 1$	$n = 0$	$n = 1$
Algorithm 1	*0.382*	*0.255*	*0.219*	*0.148*
Algorithm 2	0.576	0.404	0.321	0.210
Algorithm 3	**0.618**	**0.530**	**0.370**	**0.295**
Algorithm 4	0.480	0.309	0.258	0.189

The numerical modeling results confirm the analytical conclusions and logical assumptions as follows:

- criteria Q_{wt} and Q_{ws} take maximum values for Algorithm 3 both when taking into account $n = 1$ and without taking into account $n = 0$ priority of the SC, because by its principle it has inertia, leading to the formation of longer observation sites, which is confirmed by Fig. 5;
- criteria Q_{wt} and Q_{ws} take minimum values for Algorithm 1 both when taking into account $n = 1$ and without taking into account $n = 0$ priority of the SC by enabling the observation of satellites at the beginning of the list without taking into account their priority (in the considered case, it is low) as confirmed by Fig. 5;
- the ratio of the minimum and maximum values of the criteria Q_{wt} is 2.078 when taking into account the priority of SC $n = 1$ and 1.617 without taking into account the priority $n = 0$, respectively. Consequently, the difference between the maximum and minimum values of the criterion "weight–observation time" is increased by taking into account the priority;
- the ratio of the minimum and maximum values of the criteria Q_{ws} is 1.993 when taking into account the priority of the SC and 1.689 without taking into account the priority. Similarly to the Q_{wt} criterion, taking into account the priority increases the difference between the maximum and minimum values of the criterion "weight–structure of observation".

CONCLUSIONS

Under objective conditions of satellite orbital launch dynamics in relation to the increase in the number and capabilities of their monitoring means, the task of observation planning is of particular importance. Two quality criteria are proposed for comparing different methods of SC observation planning: "weight–observation time" and "weight–observation structure". The criteria are based on the formation of a value associated with the energy signal-to-noise ratio, which determines the quality of parameter estimates, as well as taking into account the priority of satellites and the structure of the total observation time (number of intervals).

Four scheduling algorithms used for verification give predictable results for the relative scheduling quality according to the introduced criteria. Numerical calculations of the quality criteria confirmed the theoretical assumptions on which they are based. For the same SC observation conditions, the quality criteria of the plan obtained by four different scheduling algorithms differ more than 1.5 times.

Further development of criteria is envisaged in terms of their specification, for example, for radiotechnical systems of monitoring available in "Cosmocenter" at the RTU MIREA synthesis of optimal methods of planning observations and their experimental confirmation.

Authors' contributions

A.V. Ksendzuk—formulating the problem; developing the criteria, key relationships, and conclusions.

I.A. Kuznetsov—developing the software for verification of calculations; analysis of simulation results.

REFERENCES

1. Liu J., Yang X., Cheng H., et al. Progress of China's Space Debris Research. *Chinese J. Space Sci.* 2022;42(4):824–829. https://doi.org/10.11728/cjss2022.04.yg26
2. Cowles K. Site selection criteria for the optical atmospheric visibility monitoring telescopes. *The Telecommunications and Data Acquisition Report* (*TDA Progress Rep.*). 1989;42–99:235–239.
3. Elenin L.V., Molotov I.E., Borovin G.K. Effective planning of observations of space objects on different types of orbits. *Preprinty Instituta prikladnoi matematiki im. M.V. Keldysha RAN = Preprints of the Keldysh Institute of Applied Mathematics.* 2018;72. 18 p. (in Russ.). https://doi.org/10.20948/prepr-2018-72
4. Fedeler S.J., Holzinger M.J., Whitacre W. Optimality and Application of Tree Search Methods for POMDP-based Sensor Tasking. In: *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference* (*AMOS*). Maui, Hawaii, USA. 2020. 24 p. Available from URL: https://amostech.com/TechnicalPapers/2020/Poster/Fedeler.pdf
5. Schubert M., Kebschull C., Gelhaus J., et al. Evaluating sensor tasking strategies for object cataloging in GEO. *Acta Astronautica.* 2024;228:7–16. https://doi.org/10.1016/j.actaastro.2024.11.026
6. Dhingra N.K., DeJac C., Herz A., et al. Space domain awareness sensor scheduling with optimality certificates. In: *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*. 2023. 15 p. Available from URL: https://amostech.com/TechnicalPapers/2023/SDA/Dhingra.pdf
7. Ksendzuk A., Grigorev V. Satellite Radio Monitoring Stations Observation Planning: Time Alignment Observation Algorithm. In: *2021 International Conference Engineering and Telecommunication* (*En&T*). IEEE; 2021. P. 2–6. https://doi.org/10.1109/EnT50460.2021.9681763
8. Tian M., Ma G., Huang P., et al. Optimizing satellite ground station facilities scheduling for RSGS: a novel model and algorithm. *Int. J. Digital Earth.* 2023;16(1):3949–3972. https://doi.org/10.1080/17538947.2023.2259870
9. Garcia-Piquer A., Morales J.C., Ribas I., et al. Efficient scheduling of astronomical observations –Application to the CARMENES radial-velocity survey. *Astronomy & Astrophysics.* 2017;604:A87. https://doi.org/10.1051/0004-6361/201628577
10. Johnston M.D. Scheduling tools for astronomical observations. In: Boroson T.A., Davies J.K., Robson I. (Eds.). *New Observing Modes for the Next Century. Astronomical Society of the Pacific Conference Series* (*ASP*). 1996;87:62–71. Available from URL: https://ui.adsabs.harvard.edu/link_gateway/1996ASPC...87...62J/ADS_PDF
11. Grigorev V.S., Ksendzuk A.V. Optimization methods for scheduling observations of spacecraft by ground-based radio measuring instrument. *Zhurnal Radioelektroniki = J. Radio Electronics.* 2023;7 (in Russ.). https://doi.org/10.30898/1684-1719.2023.7.1
12. Dulevich V.E. (Ed.). *Teoreticheskie osnovy radiolokatsii* (*Theoretical Foundations of Radar*). Moscow: Sovetskoe Radio; 1978. 607 p. (in Russ.).
13. Fal'kovich S.E., Khomyakov E.N. *Statisticheskaya teoriya izmeritel'nykh radiosistem* (*Statistical Theory of Measurement Radio Systems*). Moscow: Radio i svyaz'; 1981. 965 p. (in Russ.).
14. Fürbacher A., Fruth T., Weibigke A., et al. Concept for generic agile, reactive optical link planning. *CEAS Space J.* 2025. 10 p. https://doi.org/10.1007/s12567-025-00592-0
15. García A. Greedy algorithms: a review and open problems. *ArXiv Prepr.* arXiv:2408.08935 (2024). https://doi.org/10.48550/arXiv.2408.08935
16. Sigov A.S., Andrianova E.G., Zhukov D.O., Zykov S.V., Tarasov I.E. Quantum informatics: Overview of the main achievements. *Russian Technological Journal*. 2019;7(1):5–37 (in Russ.). https://doi.org/10.32362/2500-316X-2019-7-1-5-37
17. Ksendzuk A.V., Zamuruev S.N. Prospects for the creation of a radio engineering complex for monitoring outer space on the basis of the MIREA Space Center. In: *Actual Problems and Prospects of Development of Radio Engineering and Information Communication Systems* (*RADIOINFOCOM-2022*): *Proceedings of the 6th Scientific and Technical Committee*. Moscow: RTU MIREA; 2022. P. 72–75 (in Russ.). https://www.elibrary.ru/knywzk

СПИСОК ЛИТЕРАТУРЫ

1. Liu J., Yang X., Cheng H., et al. Progress of China's Space Debris Research. *Chinese J. Space Sci.* 2022;42(4):824–829. https://doi.org/10.11728/cjss2022.04.yg26
2. Cowles K. Site selection criteria for the optical atmospheric visibility monitoring telescopes. *The Telecommunications and Data Acquisition Report* (*TDA Progress Rep.*). 1989;42–99:235–239.

3. Еленин Л.В., Молотов И.Е., Боровин Г.К. Эффективное планирование наблюдений космических объектов на орбитах различных типов. *Препринты Института прикладной математики им. М.В. Келдыша РАН.* 2018;72. 18 с. https://doi.org/10.20948/prepr-2018-72
4. Fedeler S.J., Holzinger M.J., Whitacre W. Optimality and Application of Tree Search Methods for POMDP-based Sensor Tasking. In: *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference* (*AMOS*). Maui, Hawaii, USA. 2020. 24 p. URL: https://amostech.com/TechnicalPapers/2020/Poster/Fedeler.pdf
5. Schubert M., Kebschull C., Gelhaus J., et al. Evaluating sensor tasking strategies for object cataloging in GEO. *Acta Astronautica.* 2024;228:7–16. https://doi.org/10.1016/j.actaastro.2024.11.026
6. Dhingra N.K., DeJac C., Herz A., et al. Space domain awareness sensor scheduling with optimality certificates. In: *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*. 2023. 15 p. URL: https://amostech.com/TechnicalPapers/2023/SDA/Dhingra.pdf
7. Ksendzuk A., Grigorev V. Satellite Radio Monitoring Stations Observation Planning: Time Alignment Observation Algorithm. In: *2021 International Conference Engineering and Telecommunication* (*En&T*). IEEE; 2021. P. 2–6. https://doi.org/10.1109/EnT50460.2021.9681763
8. Tian M., Ma G., Huang P., et al. Optimizing satellite ground station facilities scheduling for RSGS: a novel model and algorithm. *Int. J. Digital Earth.* 2023;16(1):3949–3972. https://doi.org/10.1080/17538947.2023.2259870
9. Garcia-Piquer A., Morales J.C., Ribas I., et al. Efficient scheduling of astronomical observations –Application to the CARMENES radial-velocity survey. *Astronomy & Astrophysics.* 2017;604:A87. https://doi.org/10.1051/0004-6361/201628577
10. Johnston M.D. Scheduling tools for astronomical observations. In: Boroson T.A., Davies J.K., Robson I. (Eds.). *New Observing Modes for the Next Century. Astronomical Society of the Pacific Conference Series* (*ASP*), 1996;87:62–71. URL: https://ui.adsabs.harvard.edu/link_gateway/1996ASPC...87...62J/ADS_PDF
11. Григорьев В.С., Ксендзук А.В. Оптимизационные методы составления расписания наблюдений за космическими аппаратами в околоземном пространстве наземными радиотехническими измерительными средствами. *Журнал радиоэлектроники.* 2023;7. https://doi.org/10.30898/1684-1719.2023.7.1
12. *Теоретические основы радиолокации*; под ред. В.Е. Дулевича. М.: Сов. радио; 1978. 607 с.
13. Фалькович С.Е., Хомяков Э.Н. *Статистическая теория измерительных радиосистем.* М.: Радио и связь; 1981. 965 с.
14. Fürbacher A., Fruth T., Weibigke A., et al. Concept for generic agile, reactive optical link planning. *CEAS Space J.* 2025. 10 p. https://doi.org/10.1007/s12567-025-00592-0
15. García A. Greedy algorithms: a review and open problems. *ArXiv Prepr.* arXiv:2408.08935 (2024). https://doi.org/10.48550/arXiv.2408.08935
16. Сигов А.С., Андрианова Е.Г., Жуков Д.О., Зыков С.В., Тарасов И.Е. Квантовая информатика: обзор основных достижений. *Russian Technological Journal*. 2019;7(1):5–37. https://doi.org/10.32362/2500-316X-2019-7-1-5-37
17. Ксендзук А.В., Замуруев С.Н. Перспективы создания радиотехнического комплекса мониторинга космического пространства на базе космоцентра МИРЭА. В сб.: *Актуальные проблемы и перспективы развития радиотехнических и инфокоммуникационных систем* («*РАДИОИНФОКОМ-2022*»): *Сб. научных статей по материалам VI Международной научно-практической конференции*. М.: РТУ МИРЭА; 2022. С. 72–75. https://www.elibrary.ru/knywzk

About the Authors

Alexander V. Ksendzuk, Dr. Sci. (Eng.), Head of the Department of Radioelectronic Systems, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: ks_alex@mail.ru. Scopus Author ID 56628472300, RSCI SPIN-code 2389-6036, https://orcid.org/0009-0001-7084-1433, https://www.researchgate.net/profile/Alexander-Ksendzuk-2

Ivan A. Kuznetsov, Postgraduate Student, Public Joint Stock Company VYMPEL Interstate Corporation (10-1, Geroyev Panfilovtsev ul., Moscow, 125480 Russia). E-mail: 0601ivankuznetsov@gmail.com. https://orcid.org/0009-0009-0045-6626

Об авторах

Ксендзук Александр Владимирович, д.т.н., заведующий кафедрой № 346 – радиоэлектронных систем, Институт радиоэлектроники и информатики, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: ks_alex@mail.ru. Scopus Author ID 56628472300, SPIN-код РИНЦ 2389-6036, https://orcid.org/0009-0001-7084-1433, https://www.researchgate.net/profile/Alexander-Ksendzuk-2

Кузнецов Иван Алексеевич, аспирант, ПАО «МАК «Вымпел» (125480, Россия, Москва, ул. Героев Панфиловцев, д. 10, к. 1). E-mail: 0601ivankuznetsov@gmail.com. https://orcid.org/0009-0009-0045-6626

Translated from Russian into English by L. Bychkova
Edited for English language and spelling by Thomas A. Beavitt