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RESEARCH ARTICLE

Analysis of the effectiveness of methods for ensuring the reliability of a communication satellite transponder

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Abstract
Objectives. Since the launch of satellite communication systems in practical use, approaches towards enhancing their operational quality and durability have been developing in the direction of increased reliability of airborne transponders. This is mainly achieved by increasing redundancy and using components with a lower failure rate. In this regard, the creation of new technologies and new materials is a particularly promising direction. However, since durability testing of complex systems can take several years, the problem of ensuring an effective combination of redundancy methods and elements having a reduced failure rate remains challenging. The purpose of the work is to analyze the effectiveness of methods for ensuring the reliability of a communication satellite transponder based on a proposed methodology for determining the durability index using a mathematical model of the probability of failure-free operation.
Methods. In order to describe the complex structure of a satellite communication system transponder, a logical-probabilistic method is used, in which the dependence of the system reliability indicators on the reliability indicators of the transponder elements is formulated as a logical function of operability. Mathematical models of system reliability are created on this basis including for redundant systems. Graphs and analytical methods are used to compare different systems.
Results. The influence of various methods for ensuring the redundancy of transponder devices and the use of more reliable components on the reliability and durability indicators is considered. A gamma-percentage resource-based technique for determining the durability indicator based on the constructed mathematical models of the probability of failure-free operation is presented along with a comparative analysis of measures to increase the gamma-percentage resource of the transponder.
Conclusions. The presented method for determining the durability index using a mathematical model of the probability of no-failure operation can be used to determine the time interval within which redundancy increases the probability of no-failure operation as compared with a decrease in the failure rate of elements. On this basis, the most effective combination of redundancy methods and approaches for reducing the failure rate of elements can be identified.

Keywords: reliability, satellite communication, airborne transponder, redundancy, gamma-percentage resource

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НАУЧНАЯ СТАТЬЯ

Анализ эффективности методов обеспечения надежности ретранслятора спутника связи

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Резюме

Цели. Повышение качества и долговечности работы спутниковых систем связи с момента начала их практического использования развивается в направлении увеличения надежности бортовых ретрансляторов. Это достигается применением методов резервирования и использованием элементной базы с меньшей интенсивностью отказов. Наряду с резервированием большие перспективы в этом плане открывает создание новых технологий и материалов. Весьма актуальной является проблема эффективного сочетания методов резервирования и способов уменьшения интенсивности отказов элементов. Испытания на долговечность сложных систем могут продолжаться несколько лет. Цель работы – анализ эффективности методов обеспечения надежности ретранслятора спутниковой связи на основании предложенной методики определения показателя долговечности по математической модели вероятности безотказной работы.

Методы. Для описания структуры сложной системы, в данном случае бортового ретранслятора системы спутниковой связи, используется логико-вероятностный метод, в котором зависимость показателей надежности системы от показателей надежности элементов формулируется в виде логической функции работоспособности. Эта функция дает возможность создавать различные математические модели надежности систем и построить их логические схемы надежности, в т.ч. для резервированных систем. Для сравнения различных систем применяются графоаналитические методы.

Результаты. Рассмотрено влияние различных методов резервирования устройств ретранслятора и применения более надежной элементной базы на показатели безотказности и долговечности. Представлена методика определения показателя долговечности – гамма-процентного ресурса – по построенным математическим моделям вероятности безотказной работы. Проведен сравнительный анализ мероприятий по увеличению гамма-процентного ресурса ретранслятора.

Выводы. Рассмотренная методика определения показателя долговечности по математической модели вероятности безотказной работы позволяет определить интервал времени, в пределах которого резервирование дает выигрыш по вероятности безотказной работы по сравнению с уменьшением интенсивности отказов элементов. Таким образом возможно обеспечить эффективное сочетание методов резервирования и способов уменьшения интенсивности отказов элементов.

Ключевые слова: надежность, спутниковая связь, бортовой ретранслятор, резервирование, гамма-процентный ресурс

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INTRODUCTION

The reliability of satellite communication systems is determined by their characteristics: efficiency, durability, readiness, and risk [1]. To ensure high reliability indicators, it is necessary that the satellite system meets the requirements for a variety of criteria, such as the probability of failure-free operation, mean time to failure, gamma-percentage resource, and operational availability factor [2]. Enhancement in the reliability of satellite communication systems since the beginning of their practical use has been evolving in the direction of increasing the probability of failure-free operation of airborne transponders [3–7]. The lifetime of modern satellite transponders reaches 15 years [4, 8], which is ensured by the use of redundancy methods and the use of components with a lower failure rate. To achieve the required values of reliability indicators, different redundancy methods are used [1, 9–11]. For example, it was shown in [1] that with separate redundancy by replacement with an unloaded reserve, a greater gain in mean time to failure and gamma-percentage resource is provided, and with constant redundancy, a greater gain in the probability of failure-free operation is attained. In addition, the implementation of permanent redundancy is less expensive. The use of redundancy leads to the complication of transponders and, consequently, to an increase in energy consumption, weight, size, and cost indicators of systems. Therefore, it is often necessary to look for the optimal solution that allows one to obtain a given reliability indicator at minimal cost, or maximum reliability for given quality indicators [8, 12–14]. For example, in [15], the effectiveness of optimal redundancy by replacement was evaluated and it was shown that an unloaded redundancy, compared to a loaded one, provides a greater gain in the probability of failure-free operation for any operating time and in average time to failure. In addition, the cost of a transponder with a loaded redundancy is higher, because of increased weight, size, and energy indicators.

Methods for reducing the failure rate of elements are based on new technologies and design principles [3, 8], as well as load redundancy associated with facilitating electrical, thermal, mechanical, and other operating modes of elements [1, 9]. Increased reliability of the elements is characterized by patterns that have pronounced "saturation" areas, determined by the fact that, following an initial period of a sufficiently effective impact on reliability, no further actions or material investments in the development and manufacturing of elements have a significant impact on the increase in reliability. This is due to the achievement of the physical limitations inherent in each class of the components. However, with new generations of component technologies, it is possible to sharply increase reliability levels.

Obviously, the choice of methods for ensuring the reliability of satellite transponders significantly affects their weight, size, energy, and cost indicators.

The aim of the present work is to analyze the effectiveness of combining the methods of redundancy and reducing the failure rate of components based on the determination of the durability indicator in terms of gamma-percentage resource, using a mathematical model of the probability of failure-free operation.

MATHEMATICAL MODELS OF THE PROBABILITY OF NO-FAULT OPERATION

Let the reliability logic diagram of the transponder have the form shown in Fig. 1. The transponder consists of three sections.

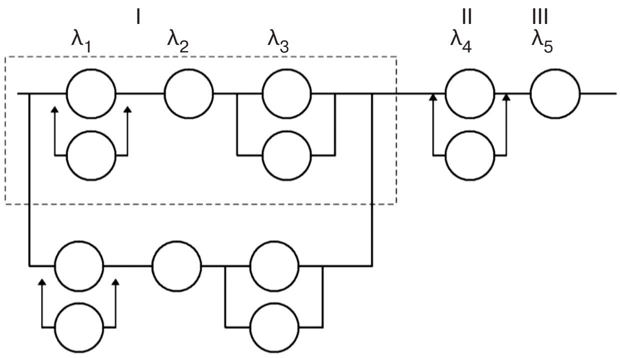

Fig. 1. Logic diagram of the reliability of the transponder

The probability of failure-free operation of the entire transponder P_{trp} is equal to the product of the probabilities of failure-free operation of each section of the device:

$$P_{\text{trp}} = P_{\text{I}}P_{\text{II}}P_{\text{III}}. \quad (1)$$

Section I (highlighted in Fig. 1 by a dashed line), comprising the main receiver, consists of three elements connected in series, the first having a failure rate λ_1 is redundant by substitution (unloaded reserve), while the second element with a failure rate λ_2 is not redundant and the third element with a failure rate λ_3 has permanent redundancy.

The probability of failure-free operation of the main receiver is equal to the product of the probabilities of failure-free operation of each of these three elements, taking into account their redundancy.

$$P_{\text{rec}} = P_1P_2P_3 \quad (2)$$

For the first element redundant by the substitution,

$$P_1 = e^{-\lambda_1 t}\left(1+\lambda_1 t\right). \quad (3)$$

The second element is not redundant,

$$P_2 = e^{-\lambda_2 t}. \quad (4)$$

For the third element with permanent redundancy,

$$P_3 = 1-\left(1-e^{-\lambda_3 t}\right)^2. \quad (5)$$

Substituting (3)–(5) into (2), we obtain:

$$P_{\text{rec}} = e^{-\lambda_1 t}\left(1+\lambda_1 t\right)e^{-\lambda_2 t}\left(1-\left(1-e^{-\lambda_3 t}\right)^2\right).$$

When the receiver is duplicated, the probability of failure-free operation of the first section of the transponder in Fig. 1 is defined by the expression:

$$P_{\text{I}} = 1 - (1 - P_{\text{rec}})^2. \quad (6)$$

Section II consists of one transmitter with a failure rate λ_4, redundant by substitution (unloaded reserve). The probability of failure-free operation of this section is determined by the expression:

$$P_{\text{II}} = e^{-\lambda_4 t}\left(1+\lambda_4 t\right). \quad (7)$$

Section III consists of one non-redundant element—the antenna-feeder device of the transponder. The probability of failure-free operation of this section:

$$P_{\text{III}} = e^{-\lambda_5 t}, \quad (8)$$

where λ_5 is the failure rate of the antenna-feeder device.

Substituting (6)–(8) into (1), we obtain the expression for the probability of failure-free operation of the transponder of the communication satellite for the case of the duplicated receiver and the redundant-by-replacing transmitter, as well as when the first element is redundant by replacing, and when the third element of the receiver has permanent redundancy:

$$P_{\text{trp}} = \left(1-\left(1-P_{\text{rec}}\right)^2\right)e^{-\lambda_4 t}\left(1+\lambda_4 t\right)e^{-\lambda_5 t}.$$

Without duplication of the receiver, as well as without redundancy of the first and third elements of the receiver, the probability of failure-free operation of the transponder is described by the formula:

$$P_{\text{trp}} = e^{-\lambda_1 t}e^{-\lambda_2 t}e^{-\lambda_3 t}e^{-\lambda_4 t}\left(1+\lambda_4 t\right)e^{-\lambda_5 t}.$$

For the case of redundancy by replacing the first element and permanent redundancy of the third element of the receiver, but without duplication of the receiver, the probability of failure-free operation of the transponder is described by the formula:

$$P_{\text{trp}} = \\ = e^{-\lambda_1 t}\left(1+\lambda_1 t\right)e^{-\lambda_2 t}\left(1-\left(1-e^{-\lambda_3 t}\right)^2\right)e^{-\lambda_4 t}\left(1+\lambda_4 t\right)e^{-\lambda_5 t}.$$

EFFECT OF REDUNDANCY ON PROBABILITY OF FAILURE-FREE OPERATION

Let us consider the effect of redundancy methods on the probability of failure-free operation and the durability of a transponder when there is a change in the failure rate of the receiver, transmitter, and antenna-feeder device. As an indicator of durability, we use the gamma-percentage resource, which is determined from the graphs of the dependence of the probability of failure-free operation of the transponder on time at $P_{\text{trp}} = 0.9$.

Graphs of the dependence of the probability of failure-free operation of the transponder on time for three redundancy methods are shown in Fig. 2–4 for different failure rates of elements (cascades).

Method 1. Duplication of the receiver and redundancy by replacing the transmitter, as well as redundancy by replacing the first element and permanent redundancy of the third element of the receiver. Graphs of the dependence of the probability of failure-free operation on time are presented in Fig. 2. The parameters of the graphs and the results of calculating the gamma-percentage resource are shown in Table 1.

As expected, the gamma-percentage resource increases with a decrease in the element failure rate. So,

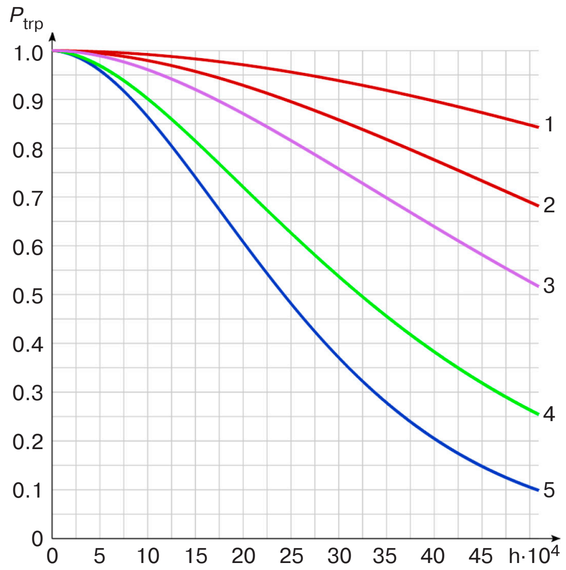

Fig. 2. Dependencies of the probability of failure-free operation on time for the first redundancy method

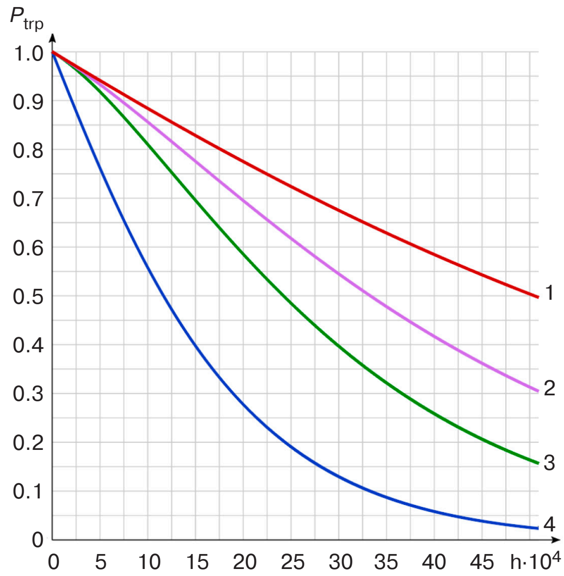

Fig. 3. Dependencies of the transponder failure-free operation probability on time for the second redundancy method

Table 1. Graphs parameters and calculation results (Fig. 2)

Curve No.	Failure rate of elements of the transponder, 10^{-8}/h					Gamma percentage resource, h·10^4
	λ_1	λ_2	λ_3	λ_4	λ_5	
1	20	50	50	100	1	38.8
2	20	50	50	200	1	24.0
3	20	50	50	300	1	16.9
4	20	50	50	500	1	9.8
5	100	200	200	500	1	8.2

Table 2. Graphs parameters and calculation results (Fig. 3)

Curve No.	Failure rate of elements of the transponder, 10^{-8}/h					Gamma percentage resource, h·10^4
	λ_1	λ_2	λ_3	λ_4	λ_5	
1	20	50	50	100	1	8.4
2	20	50	50	300	1	7.1
3	20	50	50	500	1	5.7
4	100	20	20	500	1	2.1

for example, with a decrease in the transmitter failure rate by 2, 3, and 5 times, the gamma-percentage resource increases by 1.6, 2.3, and 4 times, respectively.

Method 2. Redundancy by replacing the transmitter, without redundancy of the receiver and its elements. Graphs of dependence of the probability of failure-free operation on time are presented in Fig. 3. Table 2 shows the parameters of the graphs and the results of calculating the gamma-percentage resource.

Analysis of the graphs in Figs. 2 and 3 along with the data of Tables 1 and 2 shows that, without redundancy of the receiver and with the same failure rates of the elements, the gamma-percentage resource decreases by more than 4 times. However, with more reliable components without redundancy of the receiver, a less significant decrease in the gamma-percentage resource is observed, which does not exceed 1.7 times in the cases under consideration.

Method 3. There is no general duplication of the receiver; redundancy of the transmitter, as well as the first and third elements of the receiver is implemented. Graphs of the dependence of the probability of failure-free operation on time are shown in Fig. 4. The results of the calculation of the gamma-percentage resource and the parameters of the graphs are presented in Table 3.

As follows from the graphs in Fig. 4 and data of Table 3, the antenna-feeder device having the highest reliability has practically no effect on the gamma-percentage resource: in the case under consideration, with an increase in the failure rate λ_5 by 10 times, the gamma-percentage resource decreases by less than 5%.

Let us consider the redundancy options of various methods, in which the values of the gamma-percentage resource vary slightly. We will evaluate the efficiency of the transponder redundancy methods for the above cases in terms of the probability of failure-free operation by determining the efficiency factor of the redundancy method K_{eff} defined as the ratio of the probabilities of failure-free operation for the variants with the same values of the gamma-percentage resource. Figure 5 shows the time dependence of the redundancy efficiency factor of the compared options. Table 4 shows the parameters of

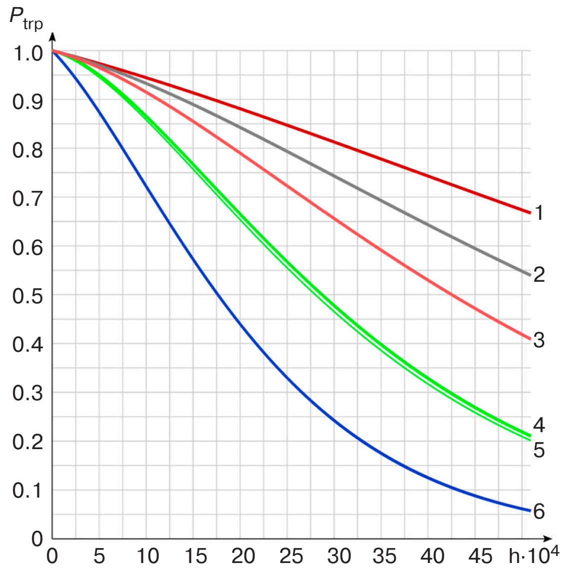

Fig. 4. Dependencies of the transponder failure-free operation probability on time for the third redundancy method

Table 3. Graph parameters and calculation results (Fig. 4)

Curve No.	Failure rate of elements of the transponder, 10^{-8}/h					Gamma percentage resource, h·10^4
	λ_1	λ_2	λ_3	λ_4	λ_5	
1	20	50	50	100	1	16.9
2	20	50	50	200	1	13.6
3	20	50	50	300	1	11.1
4	20	50	50	500	1	8.0
5	20	50	50	500	10	7.6
6	100	200	200	500	1	4.0

the graphs together with the results of determining the effectiveness of redundancy methods.

From the graphs in Fig. 5, an important conclusion can be drawn: there is a threshold value of time up to which redundancy gives a gain in the probability of failure-free operation of the transponder as compared to a decrease in the failure rate of elements. For example, the first redundancy method provides a gain compared to the third method in the time interval from 0 to 1.69 · 10^5 h even with a 3-fold increase in the transmitter failure rate, as well as an advantage over the second method in the time interval from 0 to 8.7 · 10^4 h; this applies even in the case of an increase in the failure rates of the first and fourth elements by 5 times, or the second and third elements—by 4 times.

The third redundancy method provides a gain in comparison with the second method in the time interval from 0 to 7.1 · 10^4 h even with a 5-fold increase in the transmitter failure rate.

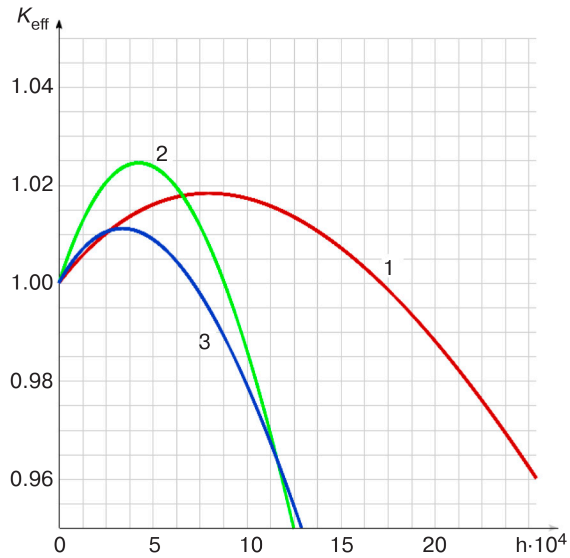

Fig. 5. Redundancy efficiency ratio

Table 4. Graph parameters (Fig. 5) and obtained effectiveness of redundancy methods

Curve No.	Compared redundancy methods	Failure rate of elements of the transponder, 10^{-8}/h					Threshold time h·10^4	Maximum value of K_{eff}
		λ_1	λ_2	λ_3	λ_4	λ_5		
1	1	20	50	50	300	1	16.9	1.018
	3	20	50	50	100	1		
2	1	100	200	200	500	1	8.7	1.025
	2	20	50	50	100	1		
3	3	20	50	50	500	1	7.1	1.011
	2	20	50	50	100	1		

When the threshold value of time is exceeded, there is no gain from redundancy; in this case, the factor that determines the probability of failure-free operation is the reliability of the transponder elements.

CONCLUSIONS

The gamma-percentage transponder resource increases with a decrease in the element failure rate. Although this durability indicator decreases in the absence of redundancy of the receiver and its elements, this decrease is not so significant with more reliable elements. By using the proposed method for calculating the gamma-percentage resource using mathematical models of the probability of failure-free operation, it becomes possible to determine the time interval within which redundancy provides a gain in the probability of failure-free operation in comparison with an increase in the reliability of elements. Thus, it is possible to provide an effective combination of redundancy methods and approaches to reducing the failure rate of elements.

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Authors' contributions

T.E. Gelfman—the research idea, scientific editing.

A.P. Pirkhavka—conducting research, writing and editing the text of the article.

V.O. Skripachev—analysis of literature, preparation of graphic materials, editing of the text of the article.

REFERENCES

1. Polovko A.M., Gurov S.V. *Osnovy teorii nadezhnosti* (*Fundamentals of Reliability Theory*). St. Petersburg: BKHV-Petersburg; 2008. 704 p. (in Russ.). ISBN 978-5-94157-541-1
2. Gelfman T.E., Pirkhavka A.P. The operational readiness factor of satellite communication networks. *Russ. Technol. J.* 2022;10(1):35–40 (in Russ.). https://doi.org/10.32362/2500-316X-2022-10-1-35-40
3. Sevastyanov N.N., Andreev A.I. *Osnovy upravleniya nadezhnost'yu kosmicheskikh apparatov s dlitel'nymi srokami ehkspluatatsii* (*Fundamentals of Reliability Management of Spacecraft with Long Service Life*). Tomsk: TGU; 2015. 266 p. (in Russ.). ISBN 978-5-94621-460-5
4. Maral G., Bousquet M., Sun Zh. *Satellite Communications Systems: Systems, Techniques and Technology.* 6th ed. Wiley & Sons Ltd; 2020. 792 p. ISBN 978-1-119-38208-9
5. Verma A.S., Jaiswal A.K., Kumar M., Nigam G., Srivastava S.K. Measurement of reliability and availability of satellite communication links: Progress and challenges. In: *2013 International Conference on Intelligent Systems and Signal Processing* (*ISSP*). 2013:268–271. https://doi.org/10.1109/ISSP.2013.6526916
6. Elbert B.R. *Introduction to Satellite Communication*. 3rd ed. Artech House Publishers; 2008. 447 p. ISBN 978-1-59693-210-4
7. Jung S., Choi J.P. End-to-end reliability of satellite communication network systems. *IEEE Systems Journal*. 2021;15(1):791–801. https://doi.org/10.1109/jsyst.2020.2980760
8. Mehmet N., Selman D., Hasan H.E., Cenk S. Reliability and cost focused optimization approach for a communication satellite payload redundancy allocation problem. *International Journal of Electrical, Electronic and Communication Sciences*. 2018;11.0(5). https://doi.org/10.5281/zenodo.1316576
9. Antonov A.V., Nikulin M.S. *Statisticheskie modeli v teorii nadezhnosti* (*Statistical Models in Reliability Theory*). Moscow: Abris; 2012. 390 p. (in Russ.). ISBN 978-5-4372-0009-4
10. Gelfman T.E., Gnuchev O.E., Lobyntsev R.Yu. Reservation methods satellite communication systems. In: *Actual Problems and Prospects of Development of Radioengineering and Infocommunication Systems. Proceedings of the III International Scientific and Practical Conference*. Moscow: Technological University (MIREA); 2017. P. 366–374 (in Russ.).

СПИСОК ЛИТЕРАТУРЫ

1. Половко А.М., Гуров С.В. *Основы теории надежности*. СПб.: БХВ-Петербург; 2008. 704 с. ISBN 978-5-94157-541-1
2. Гельфман Т.Э., Пирхавка А.П. Коэффициент оперативной готовности спутниковых сетей связи. *Russ. Technol. J.* 2022;10(1):35–40. https://doi.org/10.32362/2500-316X-2022-10-1-35-40
3. Севастьянов Н.Н., Андреев А.И. *Основы управления надежностью космических аппаратов с длительными сроками эксплуатации*. Томск: ТГУ; 2015. 266 с. ISBN 978-5-94621-460-5
4. Maral G., Bousquet M., Sun Zh. *Satellite Communications Systems: Systems, Techniques and Technology.* 6th ed. Wiley & Sons Ltd; 2020. 792 p. ISBN 978-1-119-38208-9
5. Verma A.S., Jaiswal A.K., Kumar M., Nigam G., Srivastava S.K. Measurement of reliability and availability of satellite communication links: Progress and challenges. In: *2013 International Conference on Intelligent Systems and Signal Processing* (*ISSP*). 2013:268–271. https://doi.org/10.1109/ISSP.2013.6526916
6. Elbert B.R. *Introduction to Satellite Communication*. 3rd ed. Artech House Publishers; 2008. 447 p. ISBN 978-1-59693-210-4
7. Jung S., Choi J.P. End-to-end reliability of satellite communication network systems. *IEEE Systems Journal*. 2021;15(1):791–801. https://doi.org/10.1109/jsyst.2020.2980760
8. Mehmet N., Selman D., Hasan H.E., Cenk S. Reliability and cost focused optimization approach for a communication satellite payload redundancy allocation problem. *International Journal of Electrical, Electronic and Communication Sciences*. 2018;11.0(5). https://doi.org/10.5281/zenodo.1316576
9. Антонов А.В., Никулин М.С. *Статистические модели в теории надежности*. М.: Абрис; 2012. 390 с. ISBN 978-5-4372-0009-4
10. Гельфман Т.Э., Гнучев О.Е., Лобынцев Р.Ю. Методы резервирования спутниковых систем связи. В сб.: *Актуальные проблемы и перспективы развития радиотехнических и инфокоммуникационных систем «Радиоинфоком – 2017». Сб. научных трудов III Международной научно-практической конференции*. Московский технологический университет (МИРЭА). 2017. С. 366–374.
11. Ямпурин Н.П., Баранова А.В. *Основы надежности электронных средств*. М.: Академия; 2010. 240 с. ISBN 978-5-7695-5908-2

11. Yampurin N.P., Baranova A.V. *Osnovy nadezhnosti elektronnykh sredstv* (*Fundamentals of Reliability of Electronic Means*). Moscow: Akademiya; 2010. 240 p. (in Russ.). ISBN 978-5-7695-5908-2
12. Bouwmeester J., Menicucci A., Gill E.K.A. Improving CubeSat reliability: Subsystem redundancy or improved testing? *Reliab. Eng. Syst. Saf.* 2022;220:108288. https://doi.org/10.1016/j.ress.2021.108288
13. Castet J.F., Saleh J.H. Satellite and satellite subsystems reliability: Statistical data analysis and modeling. *Reliab. Eng. Syst. Saf*. 2009;94(11):1718–1728. https://doi.org/10.1016/j.ress.2009.05.004
14. Kislaev A.G., Khropov A.N. Optimal redundancy as a method for improving the reliability of space communication systems. In: *Fundamental Problems of Radioengineering and Device Construction*. *Proceedings of the International Scientific and Technical Conference “INTERMATIC 2010.”* 2010;10(3):109–112 (in Russ.).
15. Gelfman T.E., Pirhavka A.P. Optimal redundancy of a communications satellite transponder. In: *Proceedings of the International conference “Radio Electronic Devices and Systems for Infocommunication Technologies,” REDS 2015*. Moscow: 2015. Issue LXX. P. 217–220 (in Russ.).

12. Bouwmeester J., Menicucci A., Gill E.K.A. Improving CubeSat reliability: Subsystem redundancy or improved testing? *Reliab. Eng. Syst. Saf.* 2022;220:108288. https://doi.org/10.1016/j.ress.2021.108288
13. Castet J.F., Saleh J.H. Satellite and satellite subsystems reliability: Statistical data analysis and modeling. *Reliab. Eng. Syst. Saf*. 2009;94(11):1718–1728. https://doi.org/10.1016/j.ress.2009.05.004
14. Кислаев А.Г., Хропов А.Н. Оптимальное резервирование, как метод повышения надежности систем космической связи. В сб.: *Фундаментальные проблемы радиоэлектронного приборостроения*. *Материалы Международной научно-технической конференции «INTERMATIC – 2010»*. 2010;10(1–3):109–112.
15. Гельфман Т.Э., Пирхавка А.П. Оптимальное резервирование ретранслятора спутника связи. В сб.: *Труды международной конференции «Радиоэлектронные устройства и системы для инфокоммуникационных технологий», РЭУС-2015*. М.: 2015. Вып. LXX. С. 217–220.

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