УДК 621.391
Doi: 10.31772/2712-8970-2024-25-1-33-42

Для цитирования: Повышение срока активного использования бортовой электронной аппаратуры космических аппаратов / А. Л. Тимофеев, А. Х. Султанов, И. К. Мешков, А. Р. Гизатулин // Сибирский аэрокосмический журнал. 2024. Т. 25, № 1. С. 33–42. Doi: 10.31772/2712-8970-2024-25-1-33-42.

For citation: Timofeev A. L., Sultanov A. Kh., Meshkov I. K., Gizatulin A. R. [Increasing the period of active use of on-board electronic equipment of spacecraft]. *Siberian Aerospace Journal.* 2024, Vol. 25, No. 1, P. 33–42. Doi: 10.31772/2712-8970-2024-25-1-33-42.

Повышение срока активного использования бортовой электронной аппаратуры космических аппаратов

А. Л. Тимофеев, А. Х. Султанов, И. К. Мешков, А. Р. Гизатулин

Уфимский университет науки и технологий
Российская Федерация, 450076, г. Уфа, ул. З. Валиди, 32
E-mail: a_l_t@inbox.ru

Для электронной аппаратуры космических систем, и в первую очередь устройств памяти, актуальна задача защиты от воздействия ионизирующего космического излучения и других внешних факторов, искажающих хранимую и обрабатываемую информацию. В данной работе предложен голографический метод кодирования, позволяющий восстанавливать информацию при большом числе ошибок. Метод основан на записи в память вместо исходных данных цифровой голограммы виртуального цифрового объекта, соответствующего блоку данных. Использовано свойство делимости голограммы, позволяющее восстановить записанный блок данных по его фрагменту. Достигаемый уровень помехоустойчивости определяется размером голограммы. Для 8-разрядного блока данных запись 256-разрядной голограммы обеспечивает восстановление информации при потере 75 % записанной голограммы. Разработанный декодер корректирует пакет зависимых (группирующихся) ошибок, искажающих все биты голограммы. Количество случайных независимых ошибок, которые корректирует декодер, может составлять до 40 % записанной информации. Система хранения информации, устойчивая к ионизирующему излучению, представляет собой массив памяти увеличенной емкости с учетом выбранного коэффициента избыточности, и контроллер памяти, осуществляющий голографическое кодирование при записи информации и декодирование с автоматическим исправлением ошибок при чтении информации. Алгоритм работы самого контроллера может быть реализован в виде программируемой логической интегральной схемы, либо хранится в постоянном запоминающем устройстве, не подверженном влиянию ионизирующего излучения.

Ключевые слова: голографическое кодирование, корректирующий код, исправление случайных и группирующихся ошибок.

Increasing the period of active use of on-board electronic equipment of spacecraft

A. L. Timofeev, A. Kh. Sultanov, I. K. Meshkov, A. R. Gizatulin

Ufa State Aviation Technical University
32, Z. Validi St., Ufa, 450076, Russian Federation
E-mail: a_l_t@inbox.ru

For electronic equipment of space systems, and primarily memory devices, the task of protection from the effects of ionizing cosmic radiation and other external factors that distort stored and processed *information is relevant. This paper proposes a holographic coding method that allows to restore information in the event of a large number of errors. The method is based on recording into memory, instead of the original digital hologram data, a virtual digital object corresponding to a data block. The divisibility property of a hologram is used, which makes it possible to reconstruct a recorded data block from its fragment. The achieved level of noise immunity is determined by the size of the hologram. For an 8-bit data block, recording a 256-bit hologram provides information recovery if 75 % of the recorded hologram is lost. The developed decoder corrects a package of dependent (grouping) errors that distort all bits of the hologram. The number of random independent errors that the decoder corrects can be up to 40 % of the recorded information. The information storage system, resistant to ionizing radiation, is a memory array of increased capacity, taking into account the selected redundancy factor, and a memory controller that performs holographic encoding when recording information and decoding with automatic error correction when reading information. The operating algorithm of the controller itself can be implemented in the form of a programmable logic integrated circuit, or stored in a read-only memory device that is not affected by ionizing radiation.*

Keywords: holographic coding, correction code, correction of random and clustered errors.

Introduction

There is a significant assignment to protect electronic equipment of space systems, and primarily memory devices the effects of ionizing cosmic radiation and other external factors that distort stored and processed information [1]. Radiation effects and cosmic particles create a large number of accumulated errors in memory devices. Using the known methods of error-resistant information coding produces an effect for a limited time, until the number of errors becomes too large. The critical systems use ECC-memory; it is a type of computer memory that automatically recognizes and corrects spontaneous changes (errors) of memory bits: one error per one machine word. With a machine word length being 64 bits, the number of corrected errors is < 1.5%.

To increase the reliability of information storage, we could focus on a form of data recording that ensures the recovery of a block of information from its fragment - a holographic recording method using the divisibility property of a hologram (the ability to recover a complete image of an object from a fragment of a hologram) [2].

Holographic method of information recovery

The idea of using holographic coding principles was formulated in [3; 4], but full digital simulation of a hologram required large computational resources, therefore, pseudo-holographic coding was considered. In accordance with the proposed method, the elements of a digital two-dimensional array are uniformly mixed in a certain way, as a result of which a reduced copy of the original array can be reconstructed from any part of the reordered array. The research [5–8] continued studying pseudo-holographic methods. The described methods have a scope limited to the tasks of encoding information arrays with large internal redundancy, and they are an analogue to the interleaving method [9], used in communication systems to combat error bursts.

The research [10] has proposed using full holographic coding for error correction. The considered method is based on modeling a hologram as an interference pattern of a flat image formed by a matrix representation of the original digital data block. Encoding and decoding operations in this case require quite large computing resources. However, the complexity of calculations can be significantly reduced if we take into account that for a digital hologram the number of points, but not their relative position, is of decisive importance. The research [11] shows that coding efficiency is maintained when moving from a matrix hologram to a linear one with the same number of points. Therefore, it is rational to use one-dimensional data arrays and one-dimensional holograms.

The holographic method of error-correcting coding, which corrects multiple errors, consists of mathematical modeling of a digital hologram of a virtual object being a block of input data. During the encoding process, the k-bit binary code of the input data block is converted into a secondary block –

a unit positional code with the number of positions $n = 2^k$. In this case, information redundancy is established with the number of bits $r = n–k$. The secondary block has $(n–1)$ zeros and one one at the position specified by the original data. Therefore, the input data block is used as the address of the unit position in the null sequence of the unit position code of the secondary block. Holographic coding involves the formation of a linear hologram of a secondary block, considered as a virtual optical object. The research [11; 12] describes the procedure for forming a hologram and reconstructing the original object from the hologram. The research [13; 14] has proposed using a holographic method of converting information to increase the resistance to ionizing radiation of information processing and storage systems. We could consider the possibility and effectiveness of using the holographic method of noise-resistant coding in memory devices exposed to external factors leading to the appearance of random and deterministic (burst) errors.

Modelling results

The study of the corrective ability of the holographic code was carried out by modeling in the MATLAB environment the process of distortion of the H_O hologram by random and burst errors.

Fig. 1 demonstrates a linear hologram of an 8-bit input data block with a value of $X = 99$, with the size of the hologram recorded in the memory is 256 bits, the redundancy factor is 32.

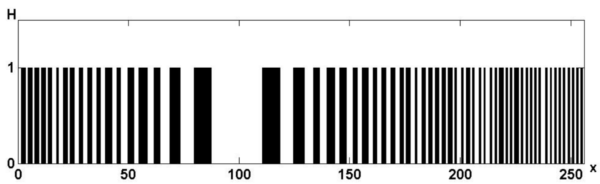

Рис. 1. Голограмма H_O для X=99

Fig. 1. Hologram H_O for X=99

Figure 2 shows the result of A_R decoding, where the maximum position $Y = 99$ obtains the information about the encoded value. The resulting array contains a small decoding noise, due to the finite number of discrete values of the hologram, and the noise does not interfere with the extraction of information value.

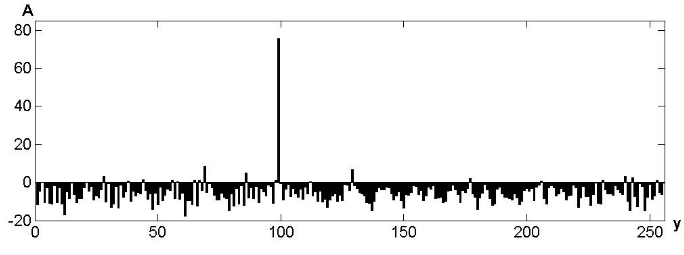

Рис. 2. Восстановленный массив A_R при n = 256, Y = 99

Fig. 2. Restored A_R array at n = 256, Y = 99

We consider the code robustness to erasures, random and burst errors.

The view of the hologram at the decoder input when erasing (losing) 75% of the hologram size $n = 256$ is shown in Fig. 3.

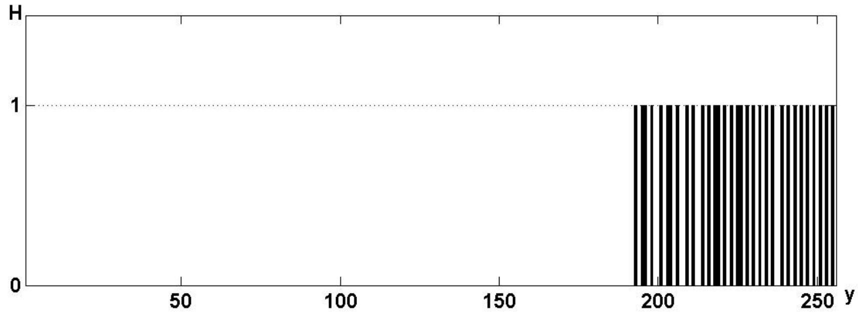

Рис. 3. Голограмма H_R для X=99. Потери 75 %

Fig. 3. Hologram H_R for X=99. Losses 75 %

Figure 4 shows the result of restoring a data block for the remaining 25%. The maximum point at position Y = 99 corresponds to the transmitted value X = 99 and uniquely determines the value of the encoded block.

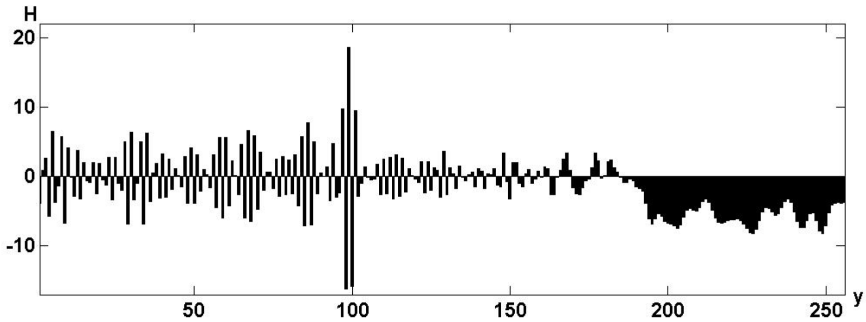

Рис. 4. Восстановленный массив A_R при потерях 75 %, n = 256, Y = 99 = X

Fig. 4. Restored A_R array with 75 % loss, n = 256, Y = 99 = X

Holographic coding provides resistance to both information loss and to random errors. The occurrence of errors is modeled by replacing a part of the hologram with a binary random sequence (noise). Fig. 5 presents the array reconstructed from a hologram of size n = 256, containing 75% noise.

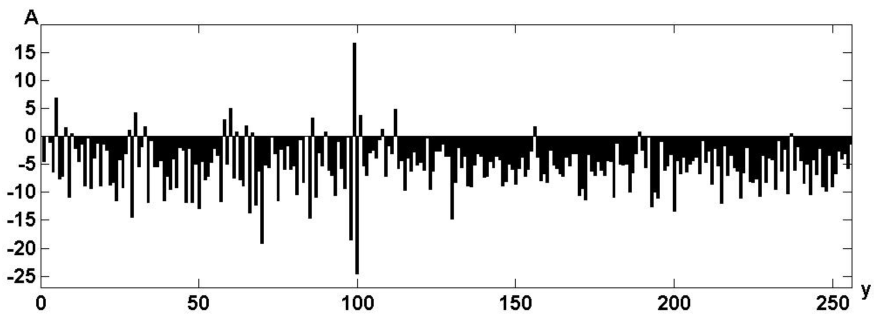

Рис. 5. Восстановленный массив A_R при длине шумовой последовательности 75 %, n = 256, Y = 99 = X

Fig. 5. Restored A_R array with noise sequence length 75 %, n = 256, Y = 99 = X

An increase in the size of the hologram leads to an increase in noise immunity. If $n = 2^{14} = 16394$, successful information recovery occurs when the length of the noise sequence is up to 95 % of the hologram size.

When replacing part of the hologram with binary noise, the number of errors that arise is less than the number of noise positions, since about half of the noise positions will coincide with information bits and will not create errors. Therefore, the maximum possible number of independent random errors in a sufficiently large hologram is 50 % of the number of bits in the hologram. If the number of errors is more than 50%, the errors are dependent, and 100 % of errors corresponds to the completely deterministic case - bit-wise inversion of the hologram.

The most difficult situation for decoding is the number of random errors approaching 50%. The correcting ability of a holographic code depends on the size of the hologram *n*. Statistics of the simulation results shows that with $n = 256$, the probability of a decoding error is 10^{-3} with the number of errors at the decoder input being 30 %. With an error rate of 25 % and a number of trials of 10,000, no decoding errors were recorded. If $n = 1024$, a decoding error probability of 10^{-3} is achieved with 41% errors are in the hologram.

The studied examples of information recovery are typical for cases with independent random errors. Simultaneously, most binary information systems are characterized by a correlation between errors and their combination into packages [15]. Burst errors occur under intense exposure to ionizing radiation, when recording information is in data storage, as well as in communication channels [16].

To correct errors occurring during information storage, noise-resistant codes are widely used. One of the most effective is the Reed-Solomon code (RS code), widely used in data recovery systems from CDs, when creating archives with information for recovery in case of damage, and in noise-resistant coding [17]. The limit of the correcting ability of a RS code is determined by the Singleton limit [18], due to which, in order to correct errors, the code must have at least two check symbols per error. With a high degree of redundancy, the number of corrected errors approaches 50% of the length of the code word. The specific feature of the RS code is that it demonstrates such a high correcting ability only for burst errors [15], inferior, for example, to the Reed-Muller code (RM code) in correcting independent random errors. The RM code with a codeword length $n = 2^m$ corrects $2^{m-2}-1$ errors of any kind [18], occupying almost 25% of the code combination.

The basic holographic code decoder, like the RS code, eliminates errors occupying no more than 50% of the code word. However, due to the specific feature of the holographic method of presenting information, it is possible to build a universal decoder that corrects any number of grouped burst errors up to 100% of the hologram size, that is, when all symbols are distorted.

The task of correcting 100% of errors is trivial: to perform this, it is enough to invert each bit of the codeword. However, here for all codes except holographic, the problem arises of choosing one of two equally probable decoding results - direct or inverted. A holographic code gives a matching decoding result, both for an undistorted codeword and for a codeword containing 100% errors. Fig. 6 exhibits the result of decoding an inverted block containing 100% errors. This shows that burst errors lead to inversion of the maximum in the restored array, but its position is preserved, so information is restored correctly.

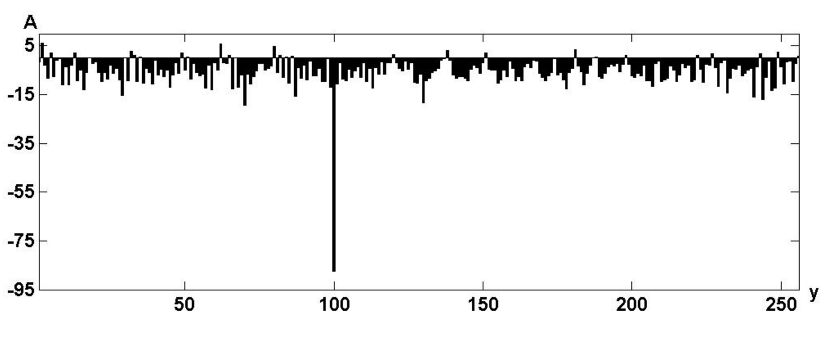

Рис. 6. Восстановленный массив A_R ($Y = 100$), число ошибок – 256 (100 %)

Fig. 6. Restored A_R array ($Y = 100$), number of errors – 256 (100 %)

Recovery is more difficult when the number of burst errors is about 50 %. To solve this problem, the decoded data block is divided into two equal parts and each part is decoded in direct and inverted form. Each of the four decoding options produces a complete output array, with all implementations having different noise levels (Fig. 7). Joint analysis of these arrays allows to determine the value of the decoded data block.

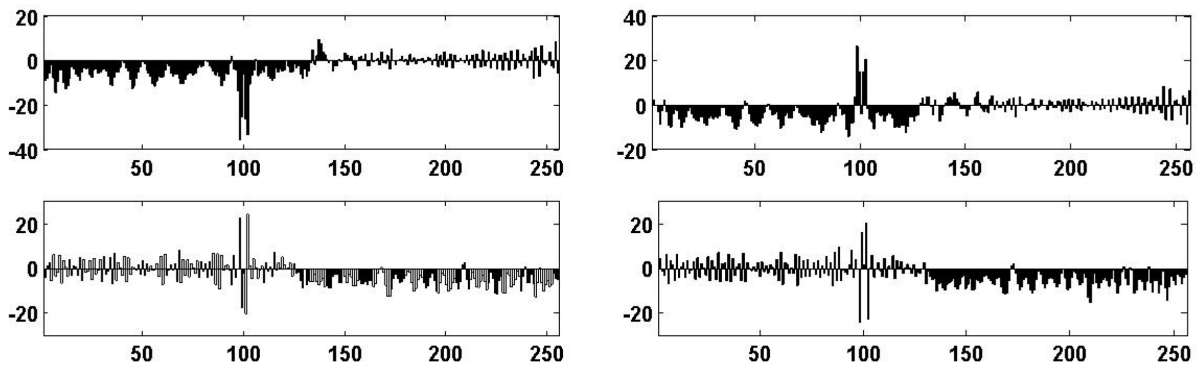

Рис. 7. Результаты работы четырех декодеров

Fig. 7. Results of four decoders

Fig. 8 presents a fragment of one of four arrays when decoding a hologram containing 128 errors with $n = 256$ (50 % errors), coded value $Y = 100$. It shows that, despite the absence of an extremum at point $Y = 100$, the value of the input block can be recovered from a characteristic combination of symmetrically located four side maxima.

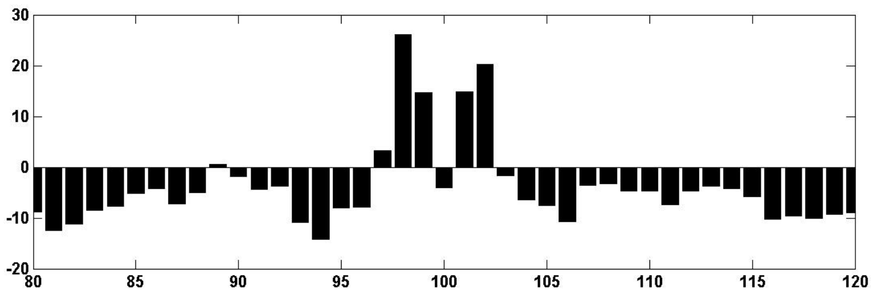

Рис. 8. Фрагмент гистограммы восстановленного массива A_R ($Y = 100$)

Fig. 8. Fragment of the histogram of the reconstructed A_R array ($Y = 100$)

Modelling has shown that a universal decoder containing 4 decoders and a maximum extraction block corrects any number of burst errors - from 0 to 100% of the recorded data block. This decoder is effective in eliminating random and burst errors. When the number of errors is less than 50%, they are random and the decoder provides information recovery with 41% of errors in the codeword. When the number of errors is more than 50%, they are dependent and form the right side of the graph (Fig. 9).

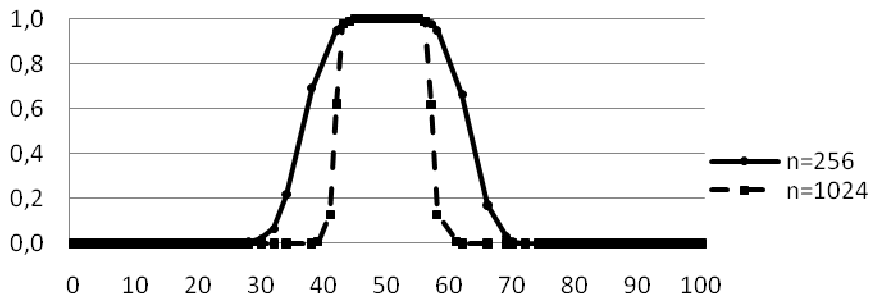

Рис. 9. Вероятность ошибки на выходе декодера в зависимости от числа ошибок на входе декодера для голограмм размером n = 256 и n = 1024

Fig. 9. Probability of error at the decoder output depending on the number of errors at the decoder input for holograms of size n = 256 and n = 1024

Therefore, holographic coding corrects errors if their number is less than 40 or more than 60 percent of the codeword length for n = 1024 (Fig. 9). This makes it possible to increase the reliability of data recovery in information storage systems exposed to ionizing radiation, temperature and other factors that cause degradation of the parameters of the element base.

Conclusion

The information storage system, resistant to ionizing radiation, is a memory array of increased capacity, taking into account the selected redundancy factor, and a memory controller that performs holographic encoding when recording information and decoding with automatic error correction when reading information. The operating algorithm of the controller itself can be implemented in the form of a programmable logic integrated circuit, or stored in a read-only memory device that is not affected by ionizing radiation.

The equipment can be used on any computer architecture. To perform this, it is necessary to modify the memory controller by installing an encoding/decoding module in it.

Благодарности. Работа выполнена при поддержке гранта Российского научного фонда, проект № 24-29-0008, https://rscf.ru/project/24-29-00080/.

Acknowledgements. The study was supported by the grant of Russian Science Foundation № 24-29-00080, https://rscf.ru/project/24-29-00080/.

Библиографические ссылки

1. Максимов И. А., Кочура С. Г., Авдюшкин С. А. Основные положения методологии обеспечения стойкости бортовой аппаратуры космических аппаратов к воздействию радиационных эффектов космического пространства // Сибирский аэрокосмический журнал. 2023. Т. 24, № 1. С. 116–125. Doi: 10.31772/2712-8970-2023-24-1-116-125.

2. Collier R. J., Burckhardt C. B., Lin L. H. Optical Holography. Murray Hill, New Jersey. 1971.

3. Bruckstein A.M., Holt R.J., Netravali A.N. Holographic image representations: the subsampling method // IEEE Int. Conference on Image Processing. Santa Barbara. California, USA. 1997. Vol. 1. P. 177–180.

4. Bruckstein A. M., Holt R. J. Netravali A. N. Holographic representation of images // IEEE Transactions on Image Processing. 1998. No. 7. P. 1583–1587.

5. Bruckstein A. M., Holt R. J., Netravali A. N. On Holographic Transform Compression of Images // Proceedings 15th International Conference on Pattern Recognition ICPR-2000. John Wiley & Sons Inc. 2001. P. 244–252. Doi: 10.1109/ICPR.2000.903528.

6. Dovgard R. Holographic image representation with reduced aliasing and noise effects // Image Processing. IEEE Transactions. 2004. No. 13(7). P. 867–872.

7. Колесов В. В., Залогин Н. Н., Воронцов Г. М. Метод псевдоголографического кодирования // Радиотехника и электроника. 2002. Т. 2, № 5. С. 583–588.

8. Баринова Д. А. Разработка и исследование алгоритмов обработки цифровых изображений, представленных в псевдоголографических кодах // Компьютерная оптика. 2005. Т. 27. С. 149–154.

9. Clark G. C. Jr., Cain J. B. Error-Correction Coding for Digital Communications // Plenum Press. New York. Second printing, 1982.

10. Тимофеев А. Л. Использование голографического кодирования для повышения помехоустойчивости каналов связи // ИТпортал. 2018. Т. 18, № 2 [Электронный ресурс]. URL: http://itportal.ru/science/tech/ispolzovanie-golograficheskogo-kodi (дата обращения: 02.01.2024).

11. Timofeev A. L., Sultanov A. Kh. Holographic method of error-correcting coding // Optical Technologies for Telecommunications. 2018. Proceedings Vol. 11146, 111461A. 2019. Doi: 10.1117/12.2526922.

12. Тимофеев А. Л., Султанов А. Х. Построение помехоустойчивого кода на базе голографического представления произвольной цифровой информации // Компьютерная оптика. 2020. Т. 44, № 6. С. 978–984. Doi: 10.18287/2412-6179-CO-739.

13. Тимофеев А. Л., Султанов А. Х. Применение помехоустойчивых позиционных делимых кодов // Проблемы техники и технологий телекоммуникаций-2020 : сб. тр. XXII Междунар. науч.техн. конф. Самара: ПГУТИ, 2020. С. 12–15.

14. Timofeev A. L., Sultanov A. Kh., Filatov P. E. Holographic method for storage of digital information // Proc. SPIE 11516, Optical Technologies for Telecommunications. 2019. Vol. 1151604. N. Y.: SPIE, 2020. Doi: 10.1117/12.2566329.

15. Gallagher R. Information Theory and Reliable Communication. New York: Wiley, 1968.

16. Anderson J. B., Mohan S. Source And Channel Coding An Algorithmic Approach // Springer Science+Business Media. New York. 1991.

17. Sklar B. Digital Communications: Fundamentals and Applications. Second Edition // Prentice Hall P T R Upper Saddle River. New Jersey. 2001.

18. Mac Williams F. J., Sloane N. J. A. The Theory of Error-Correction Codes // Bell Laboratories. Murray Hill. NJ 07974. U.S.A. 1977.

References

1. Maximov I. A., Kochura S. G., Avdyushkin S. A. [The main provisions of the methodology for ensuring the resistance of the onboard equipment of spacecraft to the effects of the radiation effects of outer space]. *Siberian Aerospace Journal*. 2023, Vol. 24, No. 1, P. 116–125. Doi: 10.31772/2712-8970-2023-24-1-116-125 (In Russ.).

2. Collier R. J., Burckhardt C. B., Lin L. H. Optical Holography. Murray Hill, New Jersey, 1971.

3. Bruckstein A. M., Holt R. J., Netravali A. N. Holographic image representations: the subsampling method. *IEEE Int. Conference on Image Processing*. Santa Barbara. California, USA. 1997, Vol. 1, P. 177–180.

4. Bruckstein A. M., Holt R. J., Netravali A. N. Holographic representation of images. *IEEE Transactions on Image Processing*. 1998, No. 7, P. 1583–1587.

5. Bruckstein A. M., Holt R. J., Netravali A. N. On Holographic Transform Compression of Images // Proceedings 15th International Conference on Pattern Recognition ICPR-2000. *John Wiley & Sons Inc*. 2001, P. 244–252. Doi: 10.1109/ICPR.2000.903528.

6. Dovgard R. Holographic image representation with reduced aliasing and noise effects. *Image Processing. IEEE Transactions*. 2004, No. 13(7), P. 867–872.

7. Kolesov V. V., Zalogin N. N., Vorontsov G. M. [Pseudo-holographic coding of digital information]. *Radiotekhnika i elektronika.* 2002, Vol. 2, No. 5, P. 583–588 (In Russ).

8. Barinova D. A. [Development and algorithm for studying the processing of digital images presented in pseudo-holographic codes]. *Komp'yuternaya optika.* 2005, No. 27, P. 149–154 (In Russ.).

9. Clark G. C. Jr., Cain J. B. Error-Correction Coding for Digital Communications. *Plenum Press*. New York. Second printing, 1982.

10. Timofeev A. L. [The use of holographic coding to increase noise immunity of communication channels]. *ITportal.* 2018, No. 2 (18). (In Russ). Available at: http://itportal.ru/science/tech/ ispolzovanie-golograficheskogo-kodi (accessed 02.01.2024).

11. Timofeev A. L., Sultanov A. Kh. Holographic method of error-correcting coding. *Optical Technologies for Telecommunications*. 2018, Proceedings Vol. 11146, 111461A, 2019. Doi: 10.1117/12.2526922.

12. Timofeev A. L., Sultanov A. Kh. [Building a noise-tolerant code based on a holographic representation of arbitrary digital information]. *Komp'yuternaya optika.* 2020, Vol. 44(6), P. 978–984 (In Russ). Doi: 10.18287/2412-6179-CO-739.

13. Timofeev A. L., Sultanov A, Kh. [Application of noise-resistant positional divisible codes]. *Problemy tekhniki i tekhnologiy telekommunikatsiy-2020 : sb. tr. XXII Mezhdunar. nauch.tekhn. konf.* [Proceedings of the XXII International Scientific and Technical Conference Problems of Engineering and Technologies of Telecommunications-2020]. Samara, 2020, P. 12–15 (In Russ.).

14. Timofeev A. L., Sultanov A. Kh., Filatov P. E. Holographic method for storage of digital information. *Proc. SPIE 11516, Optical Technologies for Telecommunications*. 2019, Vol. 1151604. N.Y.: SPIE, 2020. Doi: 10.1117/12.2566329.

15. Gallagher R. Information Theory and Reliable Communication. New York: Wiley. 1968.

16. Anderson J. B., Mohan S. Source And Channel Coding An Algorithmic Approach. Springer Science+Business Media. New York. 1991.

17. Sklar B. Digital Communications: Fundamentals and Applications. Second Edition. Prentice Hall P T R Upper Saddle River. New Jersey. 2001.

18. Mac Williams F. J., Sloane N. J. A. The Theory of Error-Correction Codes. Bell Laboratories. Murray Hill. NJ 07974. U.S.A. 1977.

Тимофеев Александр Леонидович – кандидат технических наук, доцент, Уфимский университет науки и технологий. E-mail: a_l_t@inbox.ru .

Султанов Альберт Ханович – доктор технических наук, профессор, Уфимский университет науки и технологий. E-mail: tks@ugatu.ac.ru.

Мешков Иван Константинович – кандидат технических наук, доцент, Уфимский университет науки и технологий. E-mail: mik.ivan@bk.ru.

Гизатулин Азат Ринатович – кандидат технических наук, младший научный сотрудник, Уфимский университет науки и технологий. E-mail: azat_poincare@mail.ru.

Timofeev Aleksandr Leonidovich – Cand. Sc., Docent, Ufa University of Science and Technology. E-mail: a_l_t@inbox.ru .

Sultanov Albert Khanovich – Dr. Sc., Professor, Ufa University of Science and Technology. E-mail: tks@ugatu.ac.ru.

Meshkov Ivan Konstantinovich – Cand. Sc., Docent, Ufa University of Science and Technology. E-mail: mik.ivan@bk.ru.

Gizatulin Azat Rinatovich – Cand. Sc., Junior researcher, Ufa University of Science and Technology. E-mail: azat_poincare@mail.ru.