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The Technology Described in the Orange Book CCSDS 551.1-O-2 «Correlated Data Generation» and Prospects for Its Further Development

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Valery Vorontsov
Moscow Aviation Institute (MAI),
Volokolamskoe shosse, 4, Moscow, 125993, Russian Federation,
e-mail: vorontsov762642@gmail.com

Abstract

The technology described in the CCSDS Orange Book titled Correlated Data Generation (CCSDS 551.1-O-1) [1] is designed to improve reliability of radio channel data via the fullest use of the diverse reception capabilities. It is the contribution of the State Space Corporation Roscosmos to CCSDS technologies (hereinafter referred to as the "proposed technology").

The following areas are related to the proposed technology:

a) ensuring the required reliability of data received from space radio links by using the elaborated methods and algorithms for data reliability improvement;

b) applying the elaborated criteria, models and techniques to select rational strategies for improving data reliability;

c) integrating the aforesaid methods and algorithms related to the proposed technology and other methods and algorithms for improving data reliability recommended by CCSDS.

The most important feature of the proposed technology lies in the fact that it focuses on arbitrary interference with characteristics associated with great uncertainty.

For a relatively long time (before the publication of Orange Book CCSDS 551.1-O-1 in 2015 and after the publication of its second version in 2020 [1]), the aforesaid technology has been improved, as evidenced by a number of published papers (in particular, see [2–8]). Therefore, it is advisable to determine the most relevant directions for further development of the proposed technology, based on a retrospective analysis of its development process.

The purpose of this paper is to analyze retrospectively the development process of the proposed technology designed to improve the reliability of radio channel data via the fullest use of the diverse reception capabilities and to determine the most relevant directions for its further development, based on the analysis results.

The paper considers various aspects of the proposed technology development (technical and organizational, related to practical implementation and research work).

Acronyms/Abbreviations

ACM = Adaptive Coding and Modulation
AWGN = Additive White Gaussian Noise
CCSDS = Consultative Committee for Space Data Systems
CEG = coding energy gain
MOIMS = Mission Operations and Information Management Services
MOIMS-SM&C = MOIMS – spacecraft Monitor and Control
SLS = Space Link Services
SLS-C&S = SLS – Coding and Synchronization
SLS-DC = SLS – Data Compression
SLS-RFM = SLS – RF Modulation
SLS-SLP = SLS – Space Link Protocols
VCM = Variable Coding and Modulation
WG - Working Group
SHT =Software and Hardware Tools
DM = Decision Maker

1. Introduction

In 2012 at the spring CCSDS meeting in Darmstadt, a paper on a new technology for improving the reliability of data received from radio channels via making the most of the diverse reception capabilities were presented to the meeting participants for the first time. The fundamentals of the proposed technology are described in the monograph [2]. At the meeting, the CCSDS management approved the promotion of the proposed technology on the CCSDS margins. This approval was the impetus for writing the White Book, on the basis of which the Orange Book CCSDS 551.1-O-1 "Correlated Data Generation" was published in July 2015.

The results of the proposed technology improvement (in particular, see [3, 4, 5]) are reflected in the second version of the Orange Book [1] published in August 2020. Being an addition to the previous version of the Book, these results in this new version [1] are indicated with vertical bold lines by the CCSDS technical editor. It provides visual clarity of the proposed technology development.

Basic provisions of the Orange Book [1] are formulated in accordance with the requirements of the CCSDS for Blue Books (i.e. in the form of Recommendations) to simplify the process of its transformation into a Blue Book in the future as much as possible. To clarify the provisions of the Orange Book [1], the usual CCSDS practice approach is applied, that is to clarify the Blue Book Recommendations in the relevant Green Books. In our case, annexes of the Orange Book [1] became an alternative to the aforesaid Green Books.

Initially, there were two opinions on what CCSDS area the proposed technology is related to: MOIMS or SLS. As a result, it was assigned to the MOIMS area (to the MOIMS-M&C WG) erroneously, in the author's opinion. At present, the new head of the MOIMS-M&C WG also believes that the proposed technology is not related to his WG. However, with the decision having been made, the author is not happy about this now because there is a great uncertainty in the prospects for the proposed technology development on the CCSDS margins.

This background would not be interesting if it did not concern important aspects of the CCSDS technical policy.

The point is that the working groups of the SLS area (SLS-RFM, SLS-C&S, SLS-DC, SLS-SLP) focus on signals/data generated by the data source, while in the opponents' opinion the main activities associated with the proposed technology are carried out by ground software and hardware tools (SHT). However, the data source SHT used to implement, for example, modulation methods [9] or noiseless coding methods [10] only refer to a part of the radio link (there must be its ground part as well). Therefore, to evaluate the interference resistance they provide, they simulate typical (generally accepted) procedures carried out by the corresponding ground SHT, moreover, in the form of additive white Gaussian noise (AWGN) when under interference conditions.

In addition, the CCSDS documents (in particular, see [9, 10]) contain links to other specific CCSDS documents, the provisions requirements of which must be taken into account.

Thus, it provides the necessary system approach to the construction of the CCSDS standards in general and the SLS area standards in particular.

It is shown [2,7,8] that this approach is ideal for AWGN interference conditions, but is not suitable for arbitrary interference. Note that the conclusion on the nature of interference in the analyzed radio channel makes a decision maker who decides whether they can be considered as additive white Gaussian noise or whether they are arbitrary interference.

With such a DM, as we can see, there are no contradictions between traditional CCSDS technologies related to the SLS area and the proposed technology. Technologies are complementary. Limitations of existing CCSDS Standards for the SLS area are eliminated by applying the proposed technology.

The proposed technology development is associated with the following areas:

a) assuring the required reliability of data received from space radio links by using the elaborated methods and algorithms for data reliability improvement;

b) applying the elaborated criteria, models and techniques to select rational strategies for improving data reliability;

c) integrating the aforesaid methods and algorithms related to the proposed technology and other methods and algorithms for improving data reliability recommended by CCSDS.

Besides, this paper concentrates on these areas. With that, we base on the fact that its reader has instant access at least to works [1,5,7], which are relevant in terms of understanding the essence of further development of the proposed technology, and in the context of the above areas.

2. Brief explanations of the essence of the correlated data generation process

Figure 1 explains the essence of correlated data generation.

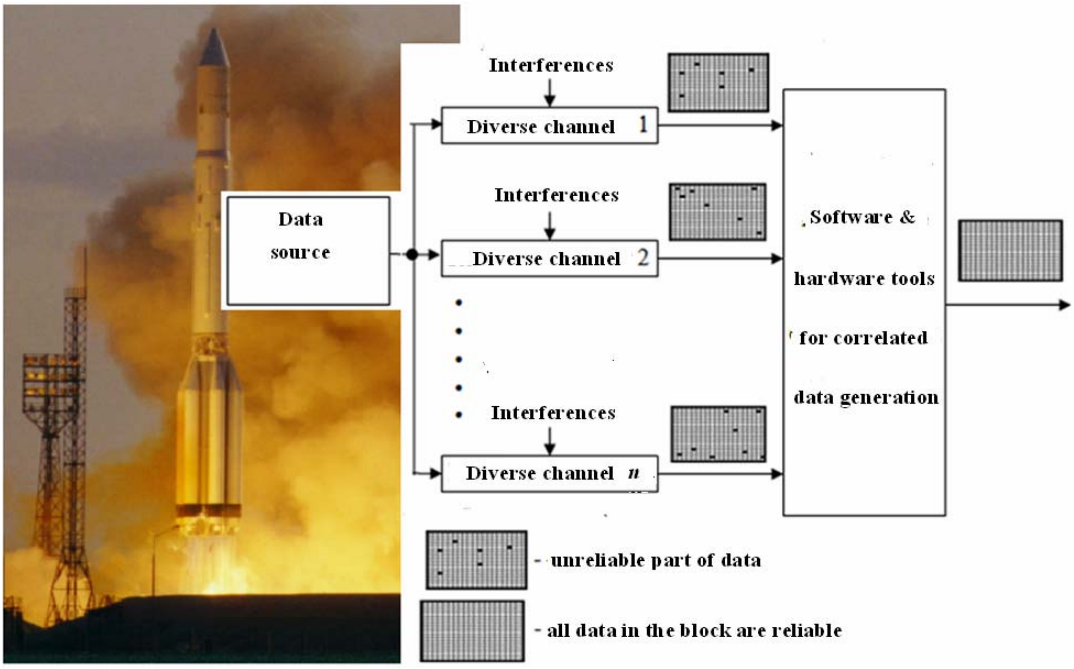

Fig. 1. Correlated data generation process

Data from a single source (according to figure 1, the onboard radio telemetry system is such a source) via *n* radio channels (via *n* diverse channels) enter the inputs of a software and hardware tool for generating correlated data. With that, data of different diverse channels are distorted by interference to varying degrees. The most reliable data are selected. They form correlated data [1].

Diversity of data/signals is achieved in the following ways:

a) by frequency (different carrier frequencies; for example, very high frequency and ultra-high frequency);

b) by polarization (e.g. vertical and horizontal polarization signals);

c) in space (to different antennas located at a distance from each other);

d) in time (using on-board memory).

It is shown [1-8] that being developed for arbitrary noise conditions, the algorithms A_4 and A_{42} for generating correlated data as well as their modifications significantly exceed the known auto-selection and majorization, in terms of the reliability to be provided.

3. Expected Cross Support of space agencies for the proposed technology

From the cross support point of view, the most important usage area for the proposed technology is the complementarity of the received data (Fig.2).

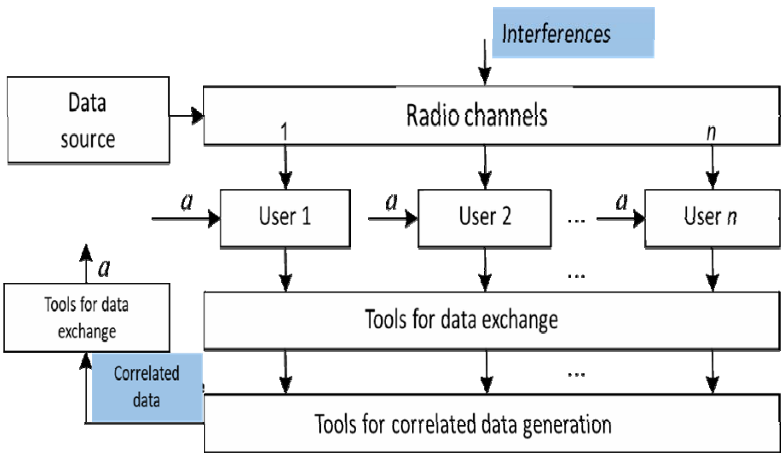

Fig.2. A simplified scheme for improving reliability of an individual user's data via data complementarity

The data consumer sends the received data for the subsequent generation of correlated data and receives correlated data with improved reliability. In this case, one of the consumers can take on additional functions of generating correlated data and sending them to other consumers. Consumers can be from different space agencies.

The proposed technology is invariant with respect to a number of factors (in particular, to the semantic component of the data arriving from the channels of data diversity, to the formed structures of the applied data blocks) that makes it relatively universal. That is why there is a very wide range of conditions, in which the proposed technology application is reasonable.

The data block can contain data of launch vehicle telemetered parameters, images of a planet panorama, sound data (speech, melody, etc.), text data, etc. Additionally, the structure of the words in the data block does not matter. From the received data blocks, the data extracted from the analog implementations of the digital signal (this is elementary data) are selected into the correlated data block. Their size can be 1 or 2 bits (for example, when using a two- or four-position telemetring signal, respectively). If in each initial m-bit word (m >> 1) some elementary data are unreliable, then there is a reason to expect that there will be no unreliable correlated elementary data in the word formed using the proposed technology.

Prospective relevant areas in which individual consumers (space agencies) can apply the proposed technology re as follows:

1) the received data complementarity that improves the reliability; moreover:

a) a training sample is required to be injected into the body of the source data block;

b) a standard structure for recording data by ground stations and correlated data is reasonable;

2) a unified technique for evaluating data reliability in the conditions of arbitrary interference, which is necessary in the implementation of joint projects;

3) integration of diverse reception and coding/decoding methods, and decoding algorithms are important for using in the conditions of arbitrary interference.

Complete mutual support for the proposed technology by space agencies is expected after the CCSDS Orange Book "Correlated Data Generation" [1] being transformed into the Blue Book.

4. Methodological aspects of systematization of knowledge related to the proposed technology

To ensure targeted selection of the most effective strategies for the use and improvement of the proposed technology, systematization of knowledge related to it has been implemented [5].

The systematization of knowledge [5] consists in establishing the attributes *At* that characterize the proposed technology (Fig.3). There are four of them. Each of the attributes of the *At* set corresponds to certain levels relating to established aspects of the proposed technology; $At_i\ (j)$ is a subset of the *At* set with the *j*-n level of the *i*-n attribute ($At_i\ (j) \subset At$, $i = 1, \ldots, g$; $j = 1, \ldots, h$). The *At* set consists of non-intersecting subsets of the type of $At_{k1\ k2\ldots\ kg}$ ($At_{k1\ k2\ldots\ kg} = At_1(k_1) \cup At_2(k_2) \cup \cdots \cup At_g(k_g)$). The number of such subsets is finite and equal to 60.

The following attributes and levels of $At_i\ (j)$ related to the proposed technology are considered [5]:

1) area (At_1):

a) developed methods and algorithms to improve the reliability of data received from communication channels ($At_1(j=1)$);

b) developed models, criteria and techniques to choose rational strategies for improving data reliability ($At_1(j=2)$);

c) integration of the aforesaid methods and algorithms related to the proposed technology, and other methods and algorithms for improving data reliability, in particular those recommended by CCSDS ($At_1(j=3)$);

2) theory/practice (At_2):

a) new rules for the development (construction) and rationale of the choice of methods, techniques, algorithms, models and criteria ($At_2(j=1)$);

b) the order of the implementation and/or use of the developed (selected) methods, techniques, algorithms, models and criteria ($At_2(j=2)$);

Note: a sign of theory is the generation of new knowledge regarding the proposed technology, and a sign of practice is the applicability of methods, techniques, algorithms, models and criteria described in the CCSDS Orange Book "Correlated Data Generation" [1].

3) stage (At_3):

a) implemented (($At_3(j=1)$);

b) perspective (i.e. expected or proposed to be implemented) ($At_3(j=2)$);

4) work (work on use and improvement of the proposed technology) (At_4):

a) Research, Development and Engineering (RDE) (regulated by relevant guideline documents) ($At_4(j=1)$);

b) writing and publishing research papers ($At_4(j=2)$);

c) participation in scientific and technical conferences and workshops (including international ones) ($At_4(j=3)$);

d) standardization (representation of the proposed technology in the form of provisions of standards) ($At_4(j=4)$);

f) implementation of individual projects ($At_4(j=5)$).

As a result, information on the proposed technology is presented as a four-dimensional space divided into 60 areas (see Fig. 3). That allows efficient using of the tools of the set-theoretical approach and morphological analysis to work with them, and thereby providing favorable conditions for the targeted selection of the most effective strategies (from a DM's point of view) for the using and improving the proposed technology [5].

Fig.3 shows one of such areas as an example (At_{1224}, hatched), and table 1 presents the description of its essence. Table 2 presents a full set of subsets $At_{k1\,k2 \dots\, kg}$ [5] related to the proposed technology (60 subsets, or areas). Areas marked in green are areas that, at the time of drawing up table table 2 [5], were seen as the correspondent most effective strategies for using and improving the proposed technology.

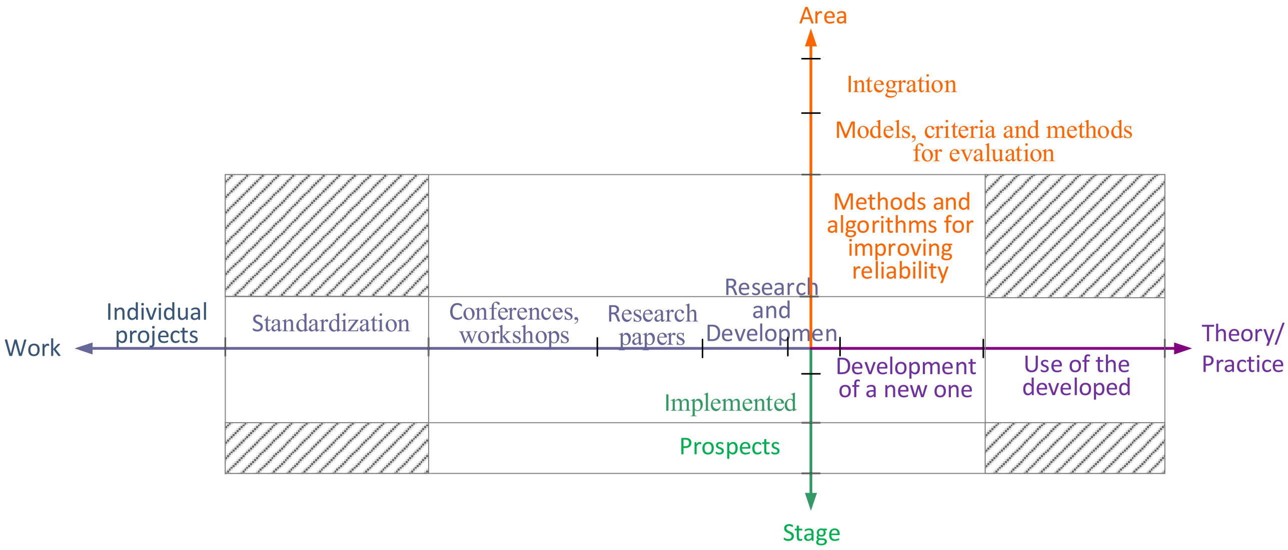

Fig.3. The proposed technology is presented in the form of a four-dimensional space. The At_{1224} space area is shown.

Table1– Entities of the option related to the subset At_{1224}.
An option corresponding to the subset At_{1224}.

At_{1224} →	Use when solving problems of standardization ($At_4(j=4)$)
→	Use in prospect ($At_3(j=2)$)
→	Procedure for using the developed methods and algorithms (($At_2(j=2)$)
→	Methods and algorithms for improving data reliability ($At_1(j=1)$)

Table 2 – Subsets $At_{k1\ k2 \dots\ kg}$ that constitute the set At and are related to the proposed technology

At_{1111}	At_{2111}	At_{3111}	At_{1211}	At_{2211}	At_{3211}	At_{1121}	At_{2121}	At_{3121}	At_{1221}	At_{2221}	At_{3221}
At_{1112}	At_{2112}	At_{3112}	At_{1212}	At_{2212}	At_{3212}	At_{1122}	At_{2122}	At_{3122}	At_{1222}	At_{2222}	At_{3222}
At_{1113}	At_{2113}	At_{3113}	At_{1213}	At_{2213}	At_{3212}	At_{1123}	At_{2123}	At_{3123}	At_{1223}	At_{2223}	At_{3223}
At_{1114}	At_{2114}	At_{3114}	At_{1214}	At_{2214}	At_{3214}	At_{1124}	At_{2124}	At_{3124}	At_{1224}	At_{2224}	At_{3224}
At_{1115}	At_{2115}	At_{3115}	At_{1215}	At_{2215}	At_{3215}	At_{1125}	At_{2125}	At_{3125}	At_{1225}	At_{2225}	At_{3225}

Let's consider how the strategies for the development of the proposed technology were implemented; what are the obtained results and how do they correspond to the "green" areas of table 2. We will also determine relevant directions for the proposed technology development in the future (i.e. we will correct table 2, if necessary).

5. Obtained results of the proposed technology development

It should be noted that after the publication of the first version of the Orange Book "Correlated Data Generation" in 2015, it was originally planned to work on transforming it into the Blue Book. According to the CCSDS rules, the necessary condition for such a transformation is the production of at least two samples of the implementation of the technology described in the Orange Book, with production by different space agencies. However, due to organizational reasons, it did not happen with samples related to the proposed technology.

By 2020, a situation has arisen when, on the one hand, the deadlines for mandatory revision of the aforesaid Orange Book were rapidly approaching, and, on the other hand, by this time new results of the proposed technology development have been obtained. In the circumstances, it was decided to reissue the Orange Book.

The above explanations of the reasons for the reissue of the Orange Book "Correlated Data Generation" in 2020 will allow the reader of this paper to understand why areas of the proposed technology selected as promising do not fully correspond to the entities of the proposed technology described in the Orange Book CCSDS 551.1-O-2 "Correlated Data Generation" [1]. For example, it was originally intended for several space agencies to implement the developed methods and algorithms for improving the reliability of data described in the first version of the Orange Book "Correlated Data Generation" (see At_{1223}, At_{1224}, At_{1225} in green in Table 2), then to write the corresponding Blue Book, and only then to supplement this Blue Book with new results of the proposed technology development.

Thus, to analyze the results of the proposed technology development, there are comprehensive background information presented in two versions of the Orange Book "Correlated Data Generation". They fully reflect the 5-year development period, from the first version publication in 2015 to the second version publication [1] in 2020.

The aforsaid analysis was carried out using information (knowledge) on the proposed technology structured according to the subsets (areas) presented in table 2. At the same time, information (knowledge) related to each individual level of the area At_1 is considered, and then information (knowledge) related to the levels of other areas in accordance with the proposed technology is considered.

5.1 Ensuring the required reliability of data received from space radio links using the developed methods and algorithms for improving data reliability

When developing the proposed technology, the developed methods and algorithms for improving data reliability, in particular, algorithms for obtaining correlated data A_4 and A_{42} focused on a hard decision demodulator, were supplemented [1] by their modifications focused on a soft decision for demodulation [1,3,4]. Entities of this modification process correspond to subsets (areas) At_{1121}, At_{1122}, At_{1123}, At_{1124} (see Table.2), reflecting entities of the proposed technology development strategies. For example, entities of the action option corresponding to the subset (area) of At_{1124} are as follows:

a) methods and algorithms for improving data reliability ($At_1(j=1)$); **clarification:** algorithms A_4 and A_{42} for generating correlated data;

b) development of a new one ($At_2(j=1)$); **clarification:** development of new modifications of algorithms A_4 and A_{42}, focused on the soft decision of the demodulator;

c) perspective use ($At_3(j=2)$); **clarification:** it is accordingly planned to improve the technology described in the Orange Book CCSDS 551.1-O-1 "Correlated Data Generation";

d) use when solving standardization problems ($At_4(j=4)$); **clarification:** reissue of the Orange Book CCSDS 551.1-O-1 "Correlated Data Generation".

Modified algorithms A_4 and A_{42} for correlated data generation are designed to improve the data reliability via the fuller use of information on the interference environment, and for cases when decoding focused on a soft decision during demodulation is carried out, after receiving correlated data (in particular, decoding using the Viterbi algorithm). The relevance of such a modification is related to reasonability of integrating methods of diverse reception and coding/decoding (see explanation of entities of modernization of algorithms for correlated data generation in the Appendix D [1]).

5.2 Using the developed criteria, models and methodologies to select rational strategies for improving data reliability

Features of criteria, models and techniques related to the proposed technology and used in evaluating methods and algorithms for data reliability improvement, which are important attributes of strategies [8] for improving data reliability, are related to their applicability for the conditions of arbitrary interference acting in radio channels [1-8]. These conditions are described (see Attachment E [1]).

As a consequence, the development of the proposed technology as applicable to the aforesaid criteria, models and methods is shown [1], depending on the development of new methods and algorithms and modifications of existing ones for data reliability improvement (see Attachment D [1]) focused on arbitrary interference.

Previously (see above), it was stated that tools for evaluation of data reliability improvement methods and algorithms focused on interference being traditional for CCSDS in the form of AWGN and being focused on arbitrary interference complement each other. The DM decides which one to use. To understand the choice of the DM, below is a brief retrospective analysis of approaches to modeling interference acting in radio channels, as well as an analysis of approaches to assessing the impact of other harmful factors that cause distortion of signals/data transmitted over radio channels.

In the 60s - 70s of the 20th century, Soviet scientists paid considerable attention to studying the influence of various types of interference acting in radio channels (see [11,12,13 etc.]).

Various conditions of interference situation and corresponding descriptions (models) of their entities are known. In particular, the following types of interference are known [13]:

a) additive fluctuation interference (including those that are with changing signal phase);

b) slow general fading (when single and diverse receptions);

c) fast fading;

d) impulse interference;

e) narrowband interference.

The entities of the models of the interferences listed above are explained [13].

Interference that is linearly added to a signal is called additive [13]. Normal fluctuation interference that has a uniform spectrum over such a wide frequency band that it can be considered infinite is called "normal additive white noise" (see also AWGN – additive whit Gaussian noise [14]).

Normal fluctuation interference can also have a non-uniform spectrum [13].

It has been shown [14] that in the process of filtering the received signal with AWGN the noise probability density can be expressed as a normal law.

Models of normal fluctuation interference are often used in solving various problems related to the interference resistance of a radio link. The interest in them is explained by the following conditions [13]:

a) normal fluctuation interference is more thoroughly studied;

b) they have the highest entropy for a given average power and therefore reduce the communication channel capacity the most (which is important on the theoretical side);

c) they are inevitably present in all real channels in the form of thermal noise arising in the equipment;

d) they approximate well enough the sum of any interference from different sources that is always present in real channels, especially in radio channels.

Impulse interference is characterized by [13] short duration compared to the duration of the signal element, and a wide spectrum. Narrowband interference has a narrow spectrum [13].

A channel in which the amplitudes of components of signal $z'(t)$ arriving at the receiver are affected by fluctuations is called a fading channel [13]:

$$z'(t) = \sum_{k=1}^{K} \mu_k z(t - \tau_k) + n(t). \qquad (1)$$

The meaning of expression (1) (formula (1.16) in [13]) lies in the fact that the signal *z(t)* arrives at the receiver in *K* different paths, and the attenuation on each of these paths is characterized by the transmission factor μ_k and the delay time τ_k. The sum of signals arrived in different paths and additive interference *n(t)* is observed at the input of the receiving device (figure 4; figure 4 is similar to figure 5.1 in [13]).

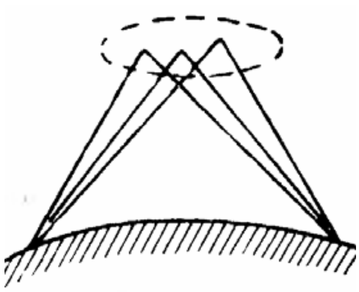

Fig.4. Multipath signal propagation

With fading, the phase of the incoming signal is also uncertain to some extent [13]. It is considered [13] that fading is typical for most of radio channels. Slow and fast fading, as well as their varieties, namely general fading, selective fading, etc., are possible [13].

A relationship between *h* and μ is established, in particular (see formula (5.7) in § 5.2 in [13]):

$$h^2 = \frac{\mu^2}{\mu_0^2} h_0^2, \qquad (2)$$

where h^2 is the ratio of signal element energy to interference spectral density,

h_0^2 is expectation of h^2 during fading,

μ_0 is root-mean-square value of transmission factor μ;

and then the dependence of the error probability *p* in the channel, in particular (see formula (5.8) in § 5.2 in [13]) for a channel with slow general fading, is:

$$p = p(h_0) = \int_0^{\infty} w(\mu) f\left(\frac{\mu h_0}{\mu_0}\right) d\mu, \qquad (3)$$

where *f(h)* is the error probability function in the channel without fading,

w(μ) is the probability density of transmission factor, that characterizes the fading.

From a brief analysis (presented above) of the effects of interference in the form of fading, it follows that h is functionally dependent on the transmission factor μ and the error probability p in the channel is functionally dependent on h. As a result, p is functionally dependent on μ (3).

It has been shown [7] that the signal-to-noise ratio h_0^2 is widely used to evaluate the interference resistance in solving a wide range of problems related to radio links, including radio links that comply with CCSDS recommendations:

$$h_0^2 = \frac{E_b}{N_0}\ , \qquad (4)$$

where E_b is the energy per one bit;

N_0 is the noise power spectral density expressed as the noise power divided by the bandwidth W.

It is believed [14] that it is a natural criterion for the quality of radio links in which digital signals are used. It has been shown [14] that since E_b is measured in Joules, and N_0 is measured in Watt/Hertz, then the measurement unit for the E_b/N_0 ratio is dimensionless. Therefore, it can be considered as a metric that allows comparing the quality of different systems (the less the required E_b/N_0 ratio, the more efficient the detection process for a given error probability).

The functional dependence $Q(z)$ between h_0 (4) and the error probability p in the channel has been established [15], in particular, in the case of coherent reception of a two-position signal of phase modulation:

$$p = Q\left(\sqrt{2R_{code}}h_0\right), \qquad (5)$$

where R_{code} is the code rate.

When determining the error probability in a channel without coding ($R_{code} = 1$), formula (5) takes the following form:

$$p = Q\left(\sqrt{2}h_0\right). \qquad (6)$$

The decision on the choice of the required noiseless coding method is usually made on the basis of the energy gain obtained during coding. Coding energy gain (CEG) g_{code} is defined as the difference between the signal-to-noise ratios at the receiver input with uncoded transmission $h_0^2{}_{uncod}$, dB, and coded transmission $h_0^2{}_{cod}$, dB, that provide the same value of the error probability P_{err} per information symbol [15] (fig.5):

$$g_{code} = h_0^2{}_{uncod} - h_0^2{}_{cod},\ \text{dB} \qquad (7)$$

From fig.5 that illustrates the essence of CEG, it follows that to ensure the error probability P_0, it is possible to soften requirements for the energy characteristics of the radio link by applying noiseless coding (CEG g_{code} (7) characterizes such softening). From fig. 5, it also follows that to reduce the error probability from P_1 to P_0, it is necessary either to improve the energy characteristics of the radio link or to apply noiseless coding.

The influence of interference of different types is usually assessed by the error probability (for example, of an erroneously received bit or symbol) or by energy characteristics of the radio link (such as the signal-to-noise ratio h_0^2 (4) or CEG g_{code} (7)) that can be used to calculate the above error probabilities (see graphs in fig. 5). At the same time, to describe the essence of interference, certain parameters (such as μ in (3)) can be used, and a functional dependence between these parameters and assessments of the interference impact (such as the dependence between μ and p in (3)) can be established.

This approach (as we will see below) is used not only to assess the impact of interference in radio channels but also to assess the impact of other harmful factors that cause distortion of signals/data transmitted over radio channels.

Thus, in the CCSDS practice, the E_b/N_0 ratio (4) is used (see annexes and recommendations to section 4.1.3 in [9]) to evaluate jitter loss (loss due to phase noise in the received RF carrier), demodulator/detector loss, wave form distortion loss (loss due to wave form distortion when filtering and non-linearity in the transmission channel data), etc.

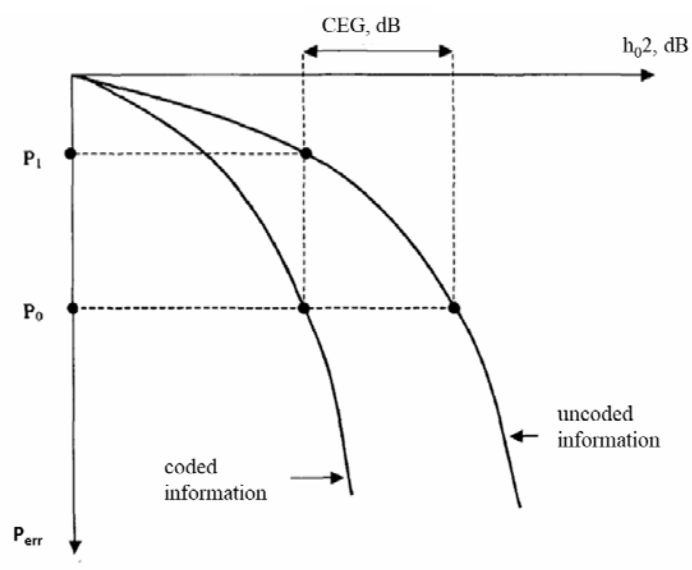

Fig.5. Illustration of the GER calculation

From the CCSDS recommendation (see Rec. 2.4.16 [9]), it follows that the total power contained in any single side emission should not exceed -60dBc (dBc is measured relative to the total power of the unmodulated carrier layer). One of the ways to meet this requirement is to eliminate the asymmetry of digital signal symbols at the modulator input. The essence of the CCSDS recommendation (see Rec. 2.4.8 [9]) is as follows: the symbol asymmetry should not exceed 0.2% (the recommendation provides a description of the "Symbol Asymmetry" parameter entities that means it provides a method for estimating the asymmetry). Another way is connected with the elimination of phase and amplitude instability. In the CCSDS recommendation (see Rec. 2.4.12A [9]; BPSK/(O)QPSK/GMSK modulators, suppressed carrier, space-to-Earth channels, Category A) are based in particular on the following: for quadrature modulation, in which the data rate and power of the in-phase (I) channels and quadrature (Q) channels are the same, phase jitter and amplitude jitter cause channel interference either due to the inability to maintain interchannel orthogonality or due to imperfect carrier tracking, that has an adverse impact on system performance effectiveness. Its essence is as follows: the instability of the modulator phase should not exceed 5 degrees and the instability of the amplitude should not exceed 0.5 dB between constellation points.

It was noted (70s of the 20th century, see [16]) that in practice there are very often strongly dependent interference (including intense ones) operating in radio channels, due to the influence of which errors are grouped into error packets. Error packets (grouped errors) have a significant effect, in particular, on results of decoding [17] and results of diverse reception [1, 7, 8]. These results depend heavily on the chosen methods of decoding [17] and diverse reception [1, 7, 8]. Consequently, estimates of data reliability provided by various methods for improving interference resistance are relevant, moreover, under the arbitrary interference influence (i.e. interference that is largely undefined) [1, 7, 8].

There are two radical approaches to assessing the influence of interference acting in radio channels as well as the influence of other harmful factors that cause distortion of signals/data transmitted over radio channels, namely:

a) an individual approach to assessment and, consequently, the development of a problem-oriented scientific and methodological apparatus for assessing the impact of each type of interference (each harmful factor);

b) ignoring differences between properties (characteristics) of any interference or harmful factors and developing a uniform scientific and methodological apparatus for their evaluation.

As for the first approach (a), under the current conditions of a steady increase in the number of methods and algorithms for improving the interference resistance of radio links, the consequence of its hypothetical expansion will be a proportional increase in the number of criteria, models and methods used in the evaluation, and a corresponding increase in effort and tools associated with the development and application of these criteria, models and methodologies. Such expected costs constrain the aforesaid expansion.

The consequence of the dominance of the second approach (b) is the costs associated with significant differences between real and simulated conditions of the interference situation due to which there is a high risk that interference resistance provided by the evaluated methods and algorithms will be significantly worse than expected (calculated).

The degree of differences between simulated interference situation conditions can be judged by the composition and number of parameters used to describe interference. For example, for a complete (comprehensive) description of interference in the form of AWGN only one parameter is sufficient, which is the interference dispersion. In the case of fading (see above), parameters μ_k (k = 1, 2, …, K) are used (1), and so on. It has been shown [2, 8] that both an insufficient and an excessive number of these parameters, as well as an incorrectly chosen composition of them can lead to a significant deterioration in the quality of estimates of interference influence.

The correct choice of tools (selection of the required scientific and methodological apparatus) for assessing the interference influence on the results of applying methods and algorithms for improving interference resistance depends on the correspondence of the simulated interference situation conditions to real conditions. A necessary criterion for the correct choice is the availability of a priori information on the entities of the real conditions of interference situation. In this case, the selected models of interference situation conditions can be both successful and relatively simple. So, if it is known a priori that in real conditions there are interferences in the form of AWGN, then only one parameter is sufficient to describe such a reality (see above).

However, it is unlikely that in real radio channels interference in the form of ideal AWGN or interference that perfectly matches some other kind of simulated interference is possible. Therefore, for example, when developing methods and algorithms for improving interference resistance, one has to make assumptions (reasoned to some extent), ignore some factors (for example, the dependence of interference, grouping of error packets) that are insignificant, according to the developer (according to the DM).

Moreover, arbitrary interference is possible in real radio channels [1, 2, 7, 8]. Their probability density may be a priori unknown. It may be non-stationary interference. These can be highly dependent interference, due to the influence of which error packets are formed. They can be additive and/or multiplicative. A characteristic feature of arbitrary interference is the significant uncertainty of their entities.

In the case of arbitrary interference, the traditional approaches considered earlier (approaches *a* and *b*, see above) turn out to be incorrect. In this regard, two new approaches have been applied to the development of a scientific and methodological apparatus for evaluating the reliability provided by diverse reception under arbitrary interference conditions, namely:

a) an approach based on the use of a diverse channel error source model and associated criteria and techniques used in the estimation [1, 2, 7, 8];

b) an approach based on the use of mathematical models that reflect the "reaction" of the tested algorithms for generating correlated data on various states of the interference situation [2, 7, 8].

In the case of the first approach (a) associated with arbitrary interference the developed [1, 2, 7, 8] model of the error source in the diverse channels allows simulating a variety of states in a wide range of interference situation conditions and with clear signs of arbitrary interference. Moreover, the applied combination of data blocks distorted by interference to varying degrees makes it sufficient to simulate a relatively small number of states of the interference situation (251 states).

The results obtained with this model are used in a comparative analysis of the developed (tested) algorithm for correlated data generation and basic algorithms (in particular, autoselection and majorization [1, 2]). The results of the comparative analysis are rated estimates of reliability, the essence of which is as follows:

a) the reliability provided by the tested algorithm is substantially better than that provided by basic algorithms;

b) the reliability is about the same;

c) the reliability is significantly worse.

The advantage of the developed model is the following [2, 8]:

a) the possibility of its implementation with a computer program that allows simulating various states of the interference situation quickly, and accelerate the receipt of simulation results;

b) taking into account unique features of practical diverse channels (in particular, of down-link channels used to transmit telemetry information during vehicle launchs);

c) obtaining estimates of the performance of the tested algorithms in a wide range of interference situation states;

d) clarity of test results.

In the case of the second approach (b) concerning arbitrary interference, each of the developed mathematical models [2, 7, 8] focuses on a certain algorithm for correlated data generation. The mathematical model is presented as sums of weight characteristics of reliability and the corresponding conditional probabilities that determine the algorithm “response” to various interference situation states which is characterized by the reliability provided by this algorithm (as the number of combinations of weight characteristics of reliability is limited, then the amount of computation is relatively small).

Unique feature of mathematical models that lies in the fact that each analyzed interference situation state is identified by an invariable “response” of the tested algorithm to different interference situation states allows minimizing the number of analyzed states without compromising the quality of reliability level estimates, and, therefore, to reduce the amount of calculations [2, 8].

The considered models related to arbitrary interference are complementary (when applying approaches *(a)* and *(b)*, see above). Their use allows getting new (more advanced) opportunities for constructing and choosing rational algorithms for correlated data generation among the tested ones for their further application or among algorithm modifications when managing the algorithm improvement process [2, 8].

Thus, the considered approaches to the development or rationale of the choice of criteria, models and techniques (i.e. scientific and methodological apparatus) for evaluating the reliability provided, in particular, by diverse reception, are the prerogative of DM. The relevance of each of these approaches is determines by DM depending on the essence of the tasks it solves and interference situation conditions corresponding to these tasks.

5.3 Integration of methods and algorithms related to the proposed technology and other methods and algorithms for improving data reliability recommended by CCSDS

Integration of methods and algorithms for improving reliability of radio channel data related to the proposed technology concerns primarily the diverse reception, modulation and coding/decoding [1, 2, 8]. Moreover, methods and algorithms of diverse reception refer to the proposed technology, and modulation [9] and noiseless coding [10] refer to traditional CCSDS methods and algorithms for improving interference resistance.

Development of the proposed technology in terms of the aforesaid integration is [1] in modifying algorithms A_4 and A_{42} for correlated data generation that focus on a hard decision modulator and in building their new modifications that focus on a soft decision modulator (see section 5.1). The new modified algorithms A_4 and A_{42} make it possible to carry out decoding that focuses on a soft decision during demodulation after diverse reception and correlated data generation (in particular, decoding with the Viterbi algorithm), that expands integration possibilities.

Please note that at present methods and algorithms for improving interference resistance related to the ground part of radio links are out of the SLS CCSDS area activities. Therefore, in particular, it is reasonable to consider decoding algorithms focusing on arbitrary interference as reserved CCSDS capabilities. Therefore, the integration of algorithms A_4 and A_{42} for correlated data generation and these decoding algorithms is a promising direction for CCSDS.

6 Relevant directions of the proposed technology development in the future

Below is a brief analysis of principal possibilities for further development of the proposed technology and a rationale for choosing the most promising directions of its development on the CCSDS margins, based on the current conditions.

6.1 Principal opportunities for further development of the proposed technology

It is appropriate to associate principal opportunities for further development of the proposed technology with activities in two fields, figuratively speaking.

The first field is the CCSDS field. Results of the proposed technology development are reflected in the Orange Book CCSDS 551.1-O-1 published in 2015 and in its second version published in 2020 [1].

Activities in the second field is working to improve information and telemetry support for the development of Russian launch vehicles that primarily include launch vehicles and boosters for space-mission vehicles. The results of this work are reflected in the monographs [2, 8] published in 2009 and 2021. Let's call this field “ITS”.

Conventionally, these two fields can be represented as intersecting sets with elements common for each of them. These elements are, for example, algorithms A_4 and A_{42} for correlated data generation, the model of a source of errors in diverse channels, etc.

In the course of work in the “ITS” field results were obtained, that, in principle, could be transferred to the CCSDS field (i.e. to supplement the proposed technology with new elements). In particular, methods of controlled diverse reception of telemetry data could become such new elements [6, 8].

In comparison with conventional methods of diverse reception [1, 2], the developed methods [6, 8] provide the data reliability improvement via the fuller use of the possibilities of adaptation to changing interference situation conditions. Their essence lies in automatic changing the delay time of the onboard storage device, depending on the need for retransmission of telemetry data to generate correlated data. Modifications of methods differ in dependance on the ground software and hardware tools that initiate commands to change the delay time of on-board memory. The implementation of methods creates conditions for decrease the number of mutually duplicated receiving and recording stations. As in the case of conventional diverse reception methods, there are great opportunities for their integration with other methods for improving interference resistance of radio channels.

It should be noted that in the process of the SLS CCSDS area technology development there are obvious and relevant opportunities for complementarity (integration).

For example, integration of methods of modulation and noiseless coding (variable coding and modulation and adaptive coding and modulation – VCM and ACM) described in the CCSDS DVB-S2 standard [18] is not exclusive of their integration with diverse reception methods.

In the case of ACM based on the estimates of data reliability received by the ground station, a decision on the required combination of modulation and coding methods is made (see combinations in Annex D [18]). The corresponding command that ensures the selection of the above combination comes to the data source via a return radio channel (for example, via a communication channel). Thus, the radio link is adapted to the time-varying conditions of the interference situation.

In the case of hypothetical integration of ACM [18] and, for example, algorithm A_4 for generating correlated data [1] from the data received by several mutually duplicated ground stations, correlated data (see fig. 2 and explanations for it) are generated. Based on their reliability estimates, the required combination of modulation and coding methods is selected. Moreover, the required combination is selected by using a return radio channel as it is done in the case of the described ACM technology [18].

Without going into the nuances of a detailed analysis of the value of the aforesaid hypothetical integration of ACM and algorithm A_4, there is reason to say that, if implemented, useful properties of the ACM technology will be supplemented by useful properties of algorithm A_4 and conditions for improving reliability of the received data will be created.

These are some aspects of a technical point of view.

From an organizational point of view, it is possible both incorporating the CCSDS DVB-S2 technology [18] into the proposed technology (i.e. supplement to the Orange Book [1] or new CCSDS documents developed on its basis) and vice versa: the use of the proposed technology elements in CCSDS documents related to the DVB-S2 standard.

From the above brief analysis, it follows that there are wide truly possibilities for the proposed technology development relating to both technical and organizational aspects. Therefore, it is possible to construct numerous variants of strategies [8] for its further development. In addition, the information provided in table 2 makes it possible to systematize knowledge about the proposed technology, helps to regulate its development process, but does not limit the number of the aforesaid strategies. Under these conditions, it is necessary to make a purposeful choice of promising directions of the proposed technology development on the CCSDS margins.

6.2 Prospective directions of the proposed technology development on the CCSDS margins

From the variety of truly possible strategies for the proposed technology development, priority strategies have been chosen. Their essence is related to the following directions:

a) decoding under arbitrary interference conditions;

b) formation of standard data logging structures.

Let's explain these directions.

The CCSDS recommendations pay considerable attention to coding [10]. Decoding, in principle, can be carried out with different algorithms. Their corrective abilities are different [17]. It is currently important to ensure efficient decoding under arbitrary interference conditions, when erroneously received data are grouped. Solving the problem of efficient decoding under arbitrary interference conditions is important both in terms of increasing the possibilities for improving reliability associated with coding/decoding, and in terms of increasing the capabilities for integrating [1, 8] methods of noiseless coding and diverse reception.

The CCSDS recommendations relating to the SLS area present data structures generated by the data source (fig. 6). In terms of the relevance of the exchange of data accepted by each user for more reliable correlated data (see fig. 2 and explanations for it), are relevant and standard (generally accepted) structures for data recording by ground stations. It should be noted that the data recording structure formed by a ground station (fig. 7), is not a mirror image of the data structure formed by the data source (see fig. 6). The Orange Book [1] shows a simplified structure similar to a structure shown in fig. 7. Some important information is missing in it. For example, station time scale data.

If to consider the chosen directions (decoding under arbitrary interference conditions (a) and the formation of standard data recording structures (b)) in accordance with the proposed systematization of knowledge (see sec. 4), then they should be assigned to the subset $At_1(j=1)$ (area: methods and algorithms for improving data reliability). At the same time, subsets $At_4(j)$ of subsets "Work" of At_4 are as follows: $At_4(j=1)$, $At_4(j=2)$, …., $At_4(j=5)$. This means that any kind of work on the proposed technology relating to its use and improvement, namely: R&D (At_4 (j=1)), writing and publishing scientific articles ($At4(j$=2) etc. are relevant (see sec. 4).

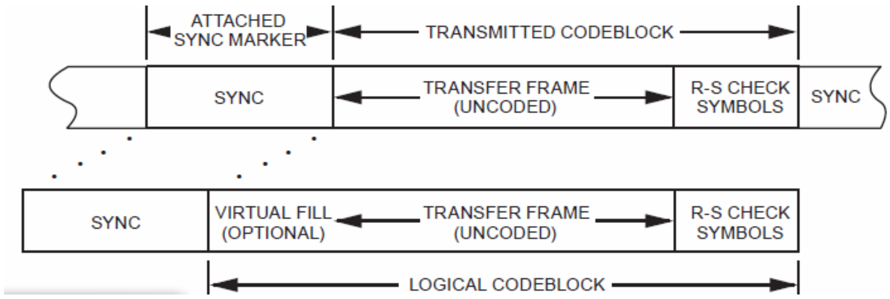

Fig.6. CCSDS data structure generated by a data source

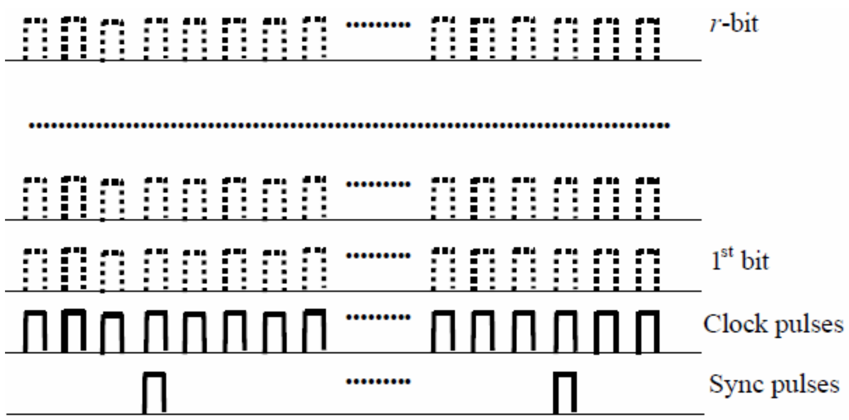

Fig.7. Simplified data structure generated by a ground station for its further registration

As expected, reasonability of choosing the considered areas (decoding under conditions of arbitrary interference (a) and generation of standard structures of data recording (b)) is due to the relative simplicity of solving organizational issues related to work in these areas in the CCSDS field. It is also due to the possibility of doing this work only in the "ITS" field in case of enforced departure from the CCSDS field.

It should be also noted that full-fledged work in these areas in the CCSDS field is associated with the transformation of the CCSDS Orange Book "Correlated Data Generation" [1] to the Blue Book.

7 Conclusions

1. The unique feature of the proposed technology based on diverse reception methods described in the Orange Book CCSDS 551.1-O-2 "Correlated Data Generation" is its focus on arbitrary interference rather than interference in the form of additive white Gaussian noise.
2. The proposed technology provides a significant improvement in data reliability via the fuller use of the diverse reception capabilities. Its implementation does not require the repeal of any existing CCSDS recommendations.
3. The special value of the proposed technology for the CCSDS community is in the wide possibilities of integrating its elements and traditional elements of CCSDS technologies. It harmoniously fits into the technologies related to the radio links that are in the area of SLS CCSDS responsibility, and it is a source of additional possibilities for CCSDS.
4. There are good prospects of the proposed technology development concerning its technical aspects, as evidenced by the results of the analysis presented in this paper. At the same time, the organizational side of the matter is in the fact that from the considered possible areas for its development on the CCSDS margins only decoding under conditions of arbitrary interference and the formation of standard data recording structures are selected as primary.
5. Ongoing diversification of work on the proposed technology development that consists in working both in the field of CCSDS and in the field of improvement of information and telemetry support for the development of Russian launch

vehicles remains relevant in the future. It allows performing tasks relatively autonomously in each of these fields, and under favorable conditions updating the proposed technology with new elements (at present, such elements, in particular, can be technologies for controlled diverse reception of telemetry data). This approach makes the process of the proposed technology development stable, which is important in the current conditions.

6. Full development of the proposed technology is connected with the transformation of the CCSDS Orange Book "Correlated Data Generation" into the Blue Book. Value of the proposed technology is expected to rise for the CCSDS community if it is described in the Blue Book. The door is open for space agencies willing to collaborate on the challenge of transforming the aforesaid Orange Book into the Blue Book.

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As this paper contains a retrospective analysis of the proposed technology development and the results of its development are shown, correspondently, it is appropriate and pleasant for the author to express his gratitude to those who stood at the origins of work on the CCSDS margins and whose merits have not lost their significance from today's perspective.

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