

**Role and place of the technology described in the Orange Book CCSDS 551.1-O-2 “Correlated Data Generation” among CCSDS traditional technologies for improving interference resistance**

SpaceOps2025, ID # 73

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**Abstract**

The technology described in the Orange Book CCSDS 551.1-O-2 “Correlated Data Generation” is designed to improve reliability of radio channel data by making the most out of the diversity reception capabilities. It is the contribution of Roscosmos to CCSDS technologies.

This work aims to analyze the capabilities of complementarity of technologies that are based on the use of diversity reception of data (this technology is described in the Orange Book CCSDS 551.1-O-1 “Correlated Data Generation”) and use of CCSDS traditional technologies for improving interference resistance.

For brevity, the technology described in the Orange Book CCSDS 551.1-O-1 “Correlated Data Generation” is hereinafter referred to as the proposed technology, and CCSDS traditional technologies for improving interference resistance is hereinafter referred to as traditional technologies.

This work is a logical extension of the author’s work in the field of SpaceOps. Its results were presented in the conference proceedings of SpaceOps2018, SpaceOps2021, and SpaceOps2023. The work shows possible combination of elements of the technologies (the proposed technology and traditional technologies), their adaptation to conditions of integration in order to show promising directions of work in the CCSDS fields on development of technologies for improving interference resistance.

Besides the previously presented information on reasonability and features of integration of particular methods of the proposed technology and traditional technologies (in particular, of the proposed methods of diversity reception and CCSDS traditional methods of modulation and noiseless coding, see the Orange Book CCSDS 551.1-O-2 “Correlated Data Generation”) related to their sequential application, this work considers integration related to DTN technologies as well as VCM and ACM technologies of coding and modulation (see the CCSDS DVB-S2 standard) and shows a new method of integration with erasure coding/decoding that is supposed to promote in the field of CCSDS. (DTN - Delay/Disruption Tolerant Networking; VCM - Variable Coding and Modulation; ACM - Adaptive Coding and Modulation.)

**Keywords:** algorithm for generating correlated data, data, reliability, integration, interference situation, diversity reception.

**Acronyms/Abbreviations**

ACM – Adaptive Coding and Modulation  
AWGN – Additive White Gaussian Noise  
CCSDS – Consultative Committee for Space Data Systems  
DTN – Delay/Disruption Tolerant Networking  
SLS – Space Link Services  
VCM – Variable Coding and Modulation  
OBM = on-board memory  
OBITS = On-Board Information and Telemetry System  
OBRTS = On-Board Radio Telemetry System  
RM = Reproducing Mode  
DT = Direct Transmission  
RRS = Receiving and Recording Station  
SW&HW tools = Software and Hardware Tools  
TMI = Telemetry Information

## 1 Introduction

In 2012 at the CCSDS spring meeting in Darmstadt, a paper on a new technology for improving the reliability of data received from radio channels by making the most of the diversity reception capabilities was presented to the meeting participants for the first time.

That event can be considered as the starting point and beginning of the proposed technology promotion in the fields of CCSDS.

For now, the official result of its promotion is the Orange Book CCSDS 551.1-O-2 "Correlated Data Generation" [1], that is significantly improved, if compared with 2012.

So far, it has not been possible to develop this Orange Book into a Blue Book. However, it should not discourage.

Each technology and each method has its own history, its own path to practice. This path is often rather long. For example, LDPC codes were described in 1963. However, their full-fledged application began in the 1990s. The original theory of error-correcting codes based on the application of finite field theory was created in late 1940s, and Galois's work that laid the foundation for the general theory of finite fields was published in 1830. Therefore, it is necessary to continue working patiently on the development of the proposed technology itself [1-3] as well as on explanation of the technology features and capabilities that are relevant for both potential users of the technology and specialists aimed at participating in the technology development. This is an approach that is adopted to the work on promoting the proposed technology in the fields of CCSDS [4, 5] and SpaceOps [6-8]. It is a context in which the role and place of the proposed technology among traditional CCSDS technologies for improving interference resistance are shown in this Manuscript.

## 2 Overview of the correlated data generation process

The proposed technology is related to diversity reception of signals/data and to correlated data generation.

Figure 1 explains the substance of correlated data generation.

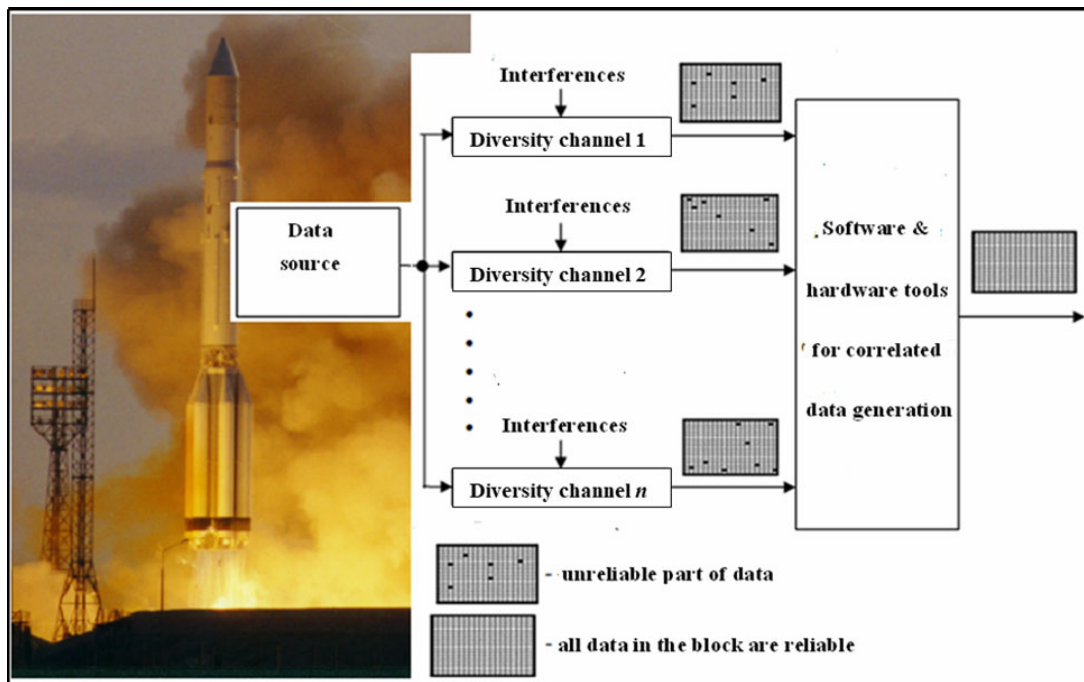


Fig. 1. Correlated data generation process

Data from a single source (based upon figure 1, an on-board radio telemetry system is such a source) arrive at the inputs of software and hardware tools for correlated data generation via  $n$  radio channels (via diversity channels). And data of different diversity channels are distorted by interferences to varying degrees. The most reliable data are selected for generating correlated data [1].

Diversity of data (signals) is achieved by the following ways:

- frequency diversity (different carrier frequencies; e.g. very-high frequency and ultra-high frequency bands);
- polarization diversity (e.g. vertical and horizontal polarization signals);
- space diversity (to different antennas located at a distance from each other);
- time diversity (using on-board memory devices).

It has been shown [1-8] that the algorithms  $A_4$  and  $A_{42}$  and their modifications for correlated data generation developed for arbitrary interference situations are considerably superior to the well-known algorithms of auto-selection and majorization in terms of reliability provided.

### 3 Main directions of the proposed technology development

Use of the proposed technology is connected with the following areas of activity:

- a) assuring the required reliability of data received from space radio links by using the elaborated methods and algorithms for data reliability improvement based on diversity reception technology;
- b) applying the elaborated criteria, models and techniques to select rational strategies for improving data reliability;
- c) integrated use of the aforesaid methods and algorithms related to the proposed technology as well as other methods and algorithms for improving data reliability recommended by CCSDS.

To ensure goal-oriented selection of the most effective strategies for both the use and improvement of the proposed technology, a systematization of the knowledge related to the proposed technology has been carried out [6], based on a set-theoretical approach and morphological analysis. When providing rationale for the choice of development strategies for the proposed technology using systematized knowledge, it is necessary to take into account [8] both fundamental and real possibilities for development determined by the state of affairs. The choice often highly depends on the circumstances at the certain moment.

A special value of the proposed technology for the CCSDS community has been recognized [8], that is in wide capabilities of integration of the proposed technology elements and traditional elements of CCSDS technologies, primarily technologies related to radio links [9-11] that are in responsibility of the CCSDS SLS area. Such integration is a source of additional capabilities of CCSDS.

### 4 Features of the proposed technology

The main features of the proposed technology are as follows:

- a) this technology focuses on counteracting arbitrary interference acting in radio channels;
- b) it provides complementarity of data received by different users and can be the only alternative to traditional CCSDS technologies;
- c) it is invariant to the structures of the data received and to their semantic load;
- d) it allows for implementing the great capabilities of integration of the proposed technology and traditional CCSDS technologies related to radio links, that ensure considerable reduction in information loss.

Let us explain the above-listed features of the proposed technology that ensure its relevance among traditional CCSDS technologies and in combination with them.

Features of arbitrary interferences are as follows:

- a) their probability density is unknown a priori;
- b) it can be instable interferences;
- c) it can be strongly dependent interferences; they cause error packet generation;
- d) they can be additive and/or multiplicative.

The developed algorithms for generating correlated data [1] are automatically rebuilt (adapted), based on posteriori information on the states of interference situation [7] that ensuring the highest reliability. At the same time, in terms of application of the above-mentioned algorithms, interferences in the form of AWGN are special cases of interference situations (i.e. special cases of arbitrary interference manifestation).

Data complementarity give advantages of diversity reception over other methods of improving interference resistance (including methods traditional for CCSDS). It is shown (see fig. 2 and explanations to fig. 2 [8]) how the above-mentioned data complementarity is performed. Practical situations are described [1, 8] when diversity reception is the only way to obtain reliable data (in particular, in the case of complete loss of information due to interference influence in particular diversity channels).

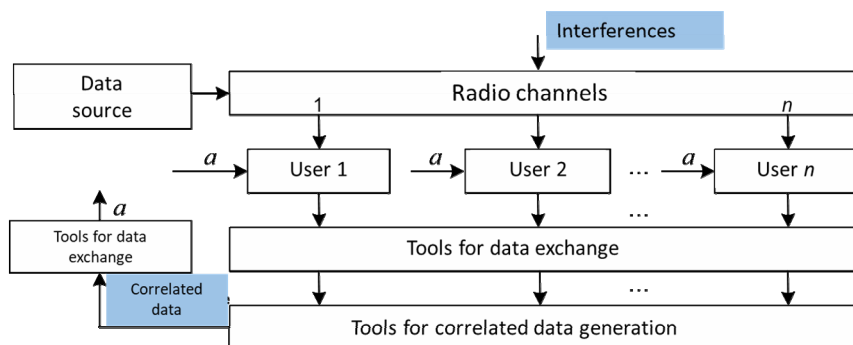


Fig.2. A simplified scheme of improving reliability of an individual user's data via data complementarity

The proposed technology is invariant to data structures and their semantic load. It is only necessary that data blocks should be of the same size and the same structure for all users (for example, CCSDS Transfer Frames [1]). A data block may contain data on the telemetered parameters of a launch vehicle, planet panoramic image data, audio data (speech, melody, etc.), text data, etc. The structure of words placed in a data block also does not matter. Data extracted from analog implementations of a digital signal (these are elementary data) are selected from the received data blocks into a correlated data block. Their size may be one bit or two bits [1] (for example, when using a two- or four-position telemetry signal respectively).

According to the results of the proposed technology development by integration [1-8], certain traditional CCSDS methods related to radio links have become a very important part of the proposed mature technology. Integration is implemented both in the form of simple complementarity of diversity reception methods and methods related to traditional CCSDS technologies that provide improvement of interference resistance, and in the form of a combination of the proposed technology elements and elements of traditional technologies. At the same time, there are great possibilities for development of new methods of integration, which are hidden reserves for a considerable reduction in information loss due to influence of interference acting in radio channels. In current conditions, in terms of scientific and technical aspects of the proposed technology development, integration is the most promising direction.

Please note that soviet scientists saw the existence of the above-mentioned reserves associated with integration more than 50 years ago: "... it is not permitted to oppose repetition code systems with correcting code systems, as some authors do" [12].

Below the capabilities of integration are considered in more detail, and a new method of integration [13] is described, that is supposed to supplement a new version of the Orange Book CCSDS 551.1-O-2 "Correlated Data Generation".

## **5 Integration by simple complementarity of diversity reception methods and methods related to traditional CCSDS technologies**

The methods of noiseless coding and modulation methods are considered as methods related to traditional CCSDS technologies [1-3].

The reasons are given [2] that when integrating methods of diversity reception and methods of noiseless coding /decoding, it is advisable to apply first diversity reception and then decoding to ensure better interference resistance.

In this connection, the capabilities of integration when applying decoding focused on a soft decision in demodulation (in particular, decoding with the Viterbi algorithm) that provides additional improvement in data reliability by making better use of the information on the interference situation have been investigated [3-5]. Modifications of the algorithms  $A_4$  and  $A_{42}$  [1] for generating correlated data focused on a soft decision in demodulation have been developed [3-5] (the algorithms  $A_4$  and  $A_{42}$  of the initial modification [1, 2] are focused on a hard decision for a demodulator).

The capabilities of diversity reception in the conditions of equally spaced signals and asymmetric communication channels provided by modulation methods are shown [1-3].

It follows from the above that the "simple" complementarity of methods means the sequential application of methods of the diversity reception, modulation and coding/decoding. At the same time, there are a number of features [1-3, etc.] that should be taken into account in order to improve interference resistance (in particular, it is advisable first to implement diversity reception; for this purpose, modifications of the algorithms  $A_4$  and  $A_{42}$  have been developed [1-3]. "Simple" complementarity of methods implies that there are more complex methods of integration (in terms of combining and modifying) associated with using elements of traditional CCSDS technologies and the proposed technology elements (see below).

## **6 Integration by complementarity of the proposed technology elements and elements of traditional CCSDS technologies**

Below is a brief description of integration capabilities related to the technologies of ACM (Adaptive Coding and Modulation), VCM (Variable Coding and Modulation) and DTN (Delay/Disruption Tolerant Networking).

### *6.1 Complement of the technologies of ACM and VCM*

In the CCSDS practice there are technologies that, when implemented, involve prompt integration of methods for improving interference resistance (for ensuring the required interference resistance). In particular, technologies for integrating VCM and ACM methods of modulation and noiseless coding presented in the DVB-S2 standard [11] are known.

The essence of the adaptive coding and modulation technology (ACM) is the ability of prompt changing of the modulation type and error-control code rate depending on the interference situation state assessed by the signal-to-noise ratio on the receiver's side. In this case, combinations of modulation and noiseless coding parameters, structure and semantic load of commands generated on the receiver's side for the correct adjustment of the modulator and encoder are determined a priori. The data generated on the information source side for sending them to the receiver contain reference information on the modulator and encoder settings. This allows for automatic adjustment of the demodulator and decoder

settings on the receiver's side. Adjustment of the modulator and encoder settings [11] (and the demodulator and decoder settings, respectively) is performed without information loss.

In the case of Variable Coding and Modulation (VCM), the prompt change of the modulation type and error-control code rate is performed programmatically.

The capabilities of the ACM technology integration associated with using the  $A_4$  algorithm for generating correlated data are considered [8]. It is shown [8] that if it is implemented, the useful properties of the ACM technology will be supplemented by the useful properties of the  $A_4$  algorithm, and the prerequisites for improving the reliability of the data received will be created.

We can see illustration of useful properties associated with the integration of ACM and diversity reception technologies on fig. 2. To implement integration, the input of the ACM software and hardware tools (SW&HW tools) must be connected to the output of tools for correlated data generation (see fig. 2). Then, the ACM SW&HW tools will assess the interference situation based on the generated correlated data. Therefore, the modulation and noiseless coding parameters will adjust. Users (see fig. 2) will receive a useful effect in the form of improved reliability of the received data by controlling the modulation and noiseless coding parameters and the parameters of diversity reception in time-varying conditions of interference situation.

In the case of VCM technology, the VCM software and hardware tools and tools for correlated data generation (see fig. 1) operate autonomously. In this case, a useful effect in the form of improved reliability of the received data (see fig. 2) is ensured by software setting of the required parameters of modulation and noiseless coding determined on the basis of a priori knowledge of the interference situation conditions and, as in the case of using ACM, by controlling parameters of diversity reception (in particular, by selecting weight characteristics of reliability for the  $A_4$  algorithm for generating correlated data [1]).

To ensure effective integration of ACM and VCM technologies and diversity reception technology, it is necessary to meet the requirements (restrictions) determined by the essence of the integration itself.

It is necessary to take into account the conditions (environment) in which the integration is supposed to implement.

Thus, in the case of using the ACM technology, it is necessary that the rate of change of the interference situation be small relative to the signal delay time in communication channels (in diversity channels), for example, delays due to a large distance from a data source (see fig. 1) to ground receiving and recording stations. This is a natural requirement (limitation) for the ACM technology both in the case of its autonomous operation and in the case of integration with the diversity reception technology. Then, when giving reasons for the rate of generating correlated data in the case of integration of the ACM technology and the diversity reception technology, it is necessary to make correction for the rate of change of the interference situation conditions and, respectively, for the rate of adjustment of the modulation and noiseless coding parameters by the ACM software and hardware tools.

It should be noted that it is useless to apply the ACM technology in the case of a relatively high rate of change of the interference situation conditions and a relatively large signal delay time in communication channels (in diversity channels). In such a situation, an alternative way to improve the reliability of data received may be autonomous use of the VCM technology and/or the diversity reception technology.

## 6.2 Complement of the DTN technology

The essence of DTN (Delay/Disruption Tolerant Networking) of CCSDS [14] is as follows.

In the practice of using space radio links, situations arise when communication with an object and ground receiving and recording stations (RRS) is impossible for a relatively long time. There is a need to build RRS for retransmitting data from these objects to Earth, and in conditions of the absence of the possibility of retransmitting at the rate of data receipt from the object. For example [15], it is impossible to transmit data from an object on the surface of Mars to Earth via a relay satellite located in Mars orbit at the rate of their receipt from the object. DTN (the DTN technology) ensure the delivery of data blocks to users from the object via DTN nodes, in which accumulation and storage of data is carried out, when pending favorable conditions for retransmission of the data, and the retransmission is carried out automatically.

In conditions of constant or frequent interference in radio channels of DTN, there are opportunities to improve the data reliability by integrating the DTN technology and the diversity reception technology.

In this case, three methods of integration can be seen.

The first of the possible methods of integration is to duplicate DTN nodes that provide space diversity of data. The data received from the diversity channels (from these duplicated DTN nodes) must be sent to the inputs of the tools for correlated data generation (see fig. 1 and 2). When generating correlated data, it is necessary to make an adjustment for the time delays of the data received from different diversity channels. Generation may be performed in a delayed mode, not at the rate of data receipt (with adjustment for time delays).

The second method of integration involve time diversity (repeated transmission of data accumulated on the object or in the DTN node). In this case, control of repeated data transmission can be implemented in different ways: from establishing a constant (fixed) number of repetitions to implementing methods of controlled diversity reception [3, 16] which ensure improved data reliability, compared to conventional diversity reception methods, by making better use of the possibilities of adaptation to changing interference situation conditions. It is assumed that creation of favorable conditions for

implementation of diversity reception (for implementation of algorithms for generating correlated data; for example, the A<sub>4</sub> algorithm [1]) with control of repeated data transmission can be ensured by appropriate modification of the DTN data exchange protocol.

The third method of integration can be implemented by combining the first and second methods. The detailed description of this combination should begin with an analysis of the capabilities of controlled diversity reception [3, 16] with a considerable increase in time intervals between repeated data transmissions, and consequently, of the possibilities of improving the DTN data exchange protocols.

It should be noted that the above descriptions of possible methods for integrating DTN and diversity reception technologies are very general. To begin work on integration, it is necessary to have initial information, primarily concerning the interference situation conditions, the radio coverage zones of the involved SW&HW tools where problems must be solved with the integrated DTN and diversity reception technologies.

## 7 Method for improving interference resistance by integrating coding/decoding and diversity reception of telemetry data

### 7.1 Explanations

A method for improving interference resistance of telemetry data has been developed [13]. It consists in forming blocks with information data of telemetry and the corresponding data blocks of check bits of the set code on a telemetered object. Moreover, information data are transmitted in the direct transmission (DT) mode, and check bit data are transmitted via an on-board memory operating in the "delay line" mode. The coding/decoding technology is applied, that allows for restoring information data when decoding telemetry data received by ground-based SW&HW tools in cases of relatively long time intervals with losses of telemetry information (TMI) in downlink channels (due to data distortion by interference).

When implementing the proposed method of integration, the erasure coding/decoding technology is used [17].

Let us explain this.

Suppose that a volume of each data block with TMI (information data block) contains  $N_{bit}$  bits and a group of such  $N_{DB}$  data blocks is selected. For this group, check bits of the set code is generated. They are inserted in  $m$  blocks, and a volume of each of these  $m$  blocks is also  $N_{bit}$  bits (fig. 3).

The structure of the above-mentioned data blocks is presented in the form of a matrix  $M$  (see fig. 3). A separate row of the matrix  $M$  contains  $N_{bit}$  elements, and a separate column of the matrix  $M$  contains  $(N_{DB} + m)$  elements. Therefore, the matrix  $M$  contains  $(N_{DB} + m)$  rows and  $N_{bit}$  columns, and the volume of the corresponding data is equal to  $V_M$  bits, where

$$V_M = (N_{DB} + m) \times N_{bit}. \quad (1)$$

For information data related to a separate  $j$ -th column of the matrix  $M$ , check bits of the set systematic code related to this column are generated. Consequently, the volume of information data of the  $j$ -th column is equal to  $V_{column\_inf\_j}$  bits, and the volume of test data related to them is  $V_{column\_test\_j}$ , and in total is

$$V_{column\_j} = V_{column\_inf\_j} + V_{column\_test\_j}, \quad 1 \leq j \leq N_{bit}. \quad (2)$$

The elements (bits) of each data block are transmitted sequentially (see fig. 3) via a radio channel and the data blocks are also transmitted sequentially (i.e. from the first data block to  $(N_{DB} + m)$ -th data block).

If there is a complete loss of information of any transmitted data block due to interference in this radio channel, then there will be no more than one erroneously bit received among the received  $V_{column\_j}$  (2) data corresponding to the  $j$ -th column of the matrix  $M$ . Therefore, if  $N_{DB\_err}$  transmitted data blocks are corrupted with interferences, then the data related to the  $j$ -th column of the matrix  $M$  contain  $N_{column\_j\_err}$  unreliable (erroneous) bits, where

$$N_{column\_j\_err} \leq N_{DB\_err}, \quad 1 \leq j \leq N_{bit} \quad (3)$$

Information data	Bit 1	Bit 2	.....	Bit ( $N_{bit} - 1$ )	Bit $N_{bit}$	Data block 1	→	
			.....			Data block 2	→	
	.....						.....	
			.....			Data block ( $N_{DB} - 1$ )	→	
			.....			Data block $N_{DB}$	→	
Test data			.....			Data block 1	→	
			.....			Data block 2	→	
	.....						.....	
			.....			Data block ( $m - 1$ )	→	
			.....			Data block $m$	→	

Fig. 3. Data block structure and transmission queue

If the maximum tolerable number of erroneous bits in the data of  $V_{column\_j}$  (2) is equal to  $N_{column\_err\_tol}$  (this is correction capabilities of the set code), then this is equivalent to the tolerability of complete loss of information in  $N_{DB\_err\_tol}$  transmitted data blocks among all  $(N_{DB} + m)$  data blocks related to the matrix  $M$ :

$$N_{DB\_err\_tol} \leq N_{column\_er\_tol} \quad (4)$$

The proposed method of integration uses the erasure coding/decoding technology [17]. Information data blocks are transmitted in the direct transmission mode (DT) and test data blocks are transmitted in the reproducing mode (RM) via an on-board memory (OBM) operating in the “delay line” mode. This order of transmitting TMI is similar to the order implemented, for example, in the on-board radio-telemetry systems (OBRTS) called Quartz and Skut-40 [18]. In these OBRTS the full TMI flow is parallelized (TMI of all channels of the central switching system) into two flows for the following direct transmission ( $TMI_{DT}$ ) of one of them and for transmission with a set constant time delay via an OBM ( $TMI_{RM}$ ) of the other flow [18]. In this case, the data transfer rates of  $TMI_{DT}$  and  $TMI_{RM}$  are the same. However, in the case of the OBRTS of Quartz and Skut-40, the content (semantic load) of  $TMI_{DT}$  and  $TMI_{RM}$  is the same, and in the case of the proposed method of integration,  $TMI_{RM}$  is test data formed with an allowance for the  $TMI_{DT}$  values. In terms of the proposed method of integration, the equality of the  $TMI_{DT}$  and  $TMI_{RM}$  data transfer rates means that

$$N_{DB} = m. \quad (5)$$

When condition (5) is met, the code rate  $R_{code}$  is

$$R_{code} = N_{DB} / (N_{DB} + m) = N_{DB} / 2N_{DB} = 1/2. \quad (6)$$

### 7.2 Description of integration method

Steps for implementing the proposed method of integration on a *telemetered object* are as follows.

1. Sequential transmission of information data blocks ( $TMI_{DT}$ , see fig. 3), and at the same time accumulation of  $N_{DB}$  blocks.
2. Generation of  $m$  (5) test data blocks for the data accumulated as defined in step 1.
3. Storage of  $m$  blocks of test data generated as defined in step 2 (this step is optional).
4. Sequential transmission of  $m$  blocks of test data generated as defined in step 2 (if the data were not stored) after their generation or after their storage as defined in step 3 (if the data were stored).

The cyclogram (fig. 4) shows the chronological order of the steps described above.

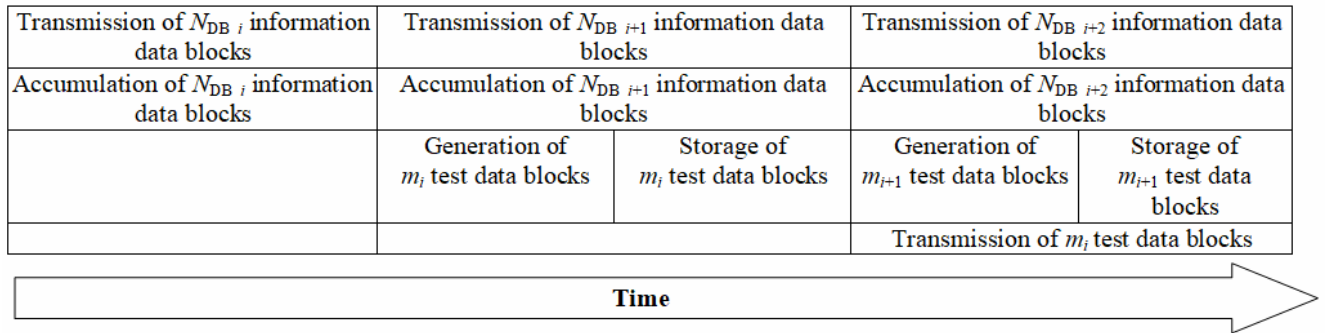


Fig. 4. Cyclogram of steps to implement the proposed method of integration on a *telemetered object*

The subscripts  $i$ ,  $i + 1$  and  $i + 2$  indicate the current numbers of data block groups (the sequence of matrices  $M_i$ ,  $M_{i+1}$ ,  $M_{i+2}$ ). For example, (see the first row in fig. 4) in the case of  $N_{DB\_i}$ , the subscript  $i$  means that the  $i$ -th group of information data blocks in the amount of  $N_{DB}$  blocks is transmitted; in the case of  $N_{DB\_i+1}$ , the  $(i+1)$ -th group in the amount of  $N_{DB}$  blocks is transmitted, and so on.

According to the cyclogram (see fig. 4), the time of generation of  $m$  test data blocks is less than the time of transmission of  $N_{DB}$  information data blocks (see (5)). Storage (see fig. 4) of the  $m$  generated test data blocks can be applied for adjusting the data transmission time delay value when it is set. The cyclogram (see fig. 4) shows that the timepoint of the beginning of transmitting the  $(i + 2)$ -th group of information data blocks and the timepoint of the beginning of transmitting the  $i$ -th group of test data blocks coincide.

The steps for implementing the proposed method of integration in the case of data received by ground-based SW&HW tools are as follows.

1. Extraction of information data from the TMI received by the receiving and recording stations and transmission of them to their destination (if necessary, for example, to solve the problems of express processing of TMI and the following express analysis [3]; this step is optional).
2. Transmission of the TMI received by the RRS to the inputs of the SW&HW tools for generating a correlated telemetry data array (collection of TMI in interests of correlated telemetry data array generation [3], see fig. 1).
3. In SW&HW tools for generating a correlated telemetry data array (see fig. 1), correlated data are generated from the data received from diversity channels (from downlink channels) [1, 3], and:
  - a) possible methods of signal/data diversity are as follows: by frequency, by polarization, in space (see above);
  - b) the methods of diversity listed in clause 3a are applied to  $N_{DB}$  information data blocks and to  $m$  (5) test data blocks separately ( $N_{DB\_corr}$  and  $m_{corr}$  blocks of correlated data are received, respectively).

4. In SW&HW tools for generating a correlated telemetry data array, arrival of  $N_{DB\_corr\_i}$  and  $m_{corr\_i}$  blocks of correlated data are synchronized (adjusted in time) (see above the information on subscripts  $i, i+1$  and  $i+2$ ; “corr” denotes blocks of correlated data). An illustration of adjusting  $N_{DB\_corr\_i}$  and  $m_{corr\_i}$  of the  $i$ -th group of blocks is shown in the cyclogram (fig. 5) and corresponds to the cyclogram of steps performed on a *telemetered object* (see fig. 4).

5. In SW&HW tools for generating a correlated telemetry data array, decoding (data processing of  $N_{DB\_corr\_i}$  and  $m_{corr\_i}$  blocks) is performed and  $N_{DB\_corr\_correct\_i}$  data blocks are generated (i.e.  $N_{DB\_i}$  blocks with corrected data are generated; see fig. 5).

6. Delivery of  $N_{DB\_corr\_correct\_i}$  generated blocks of correlated information data to the output of the SW&HW tools for generating a correlated telemetry data array (see fig. 1).

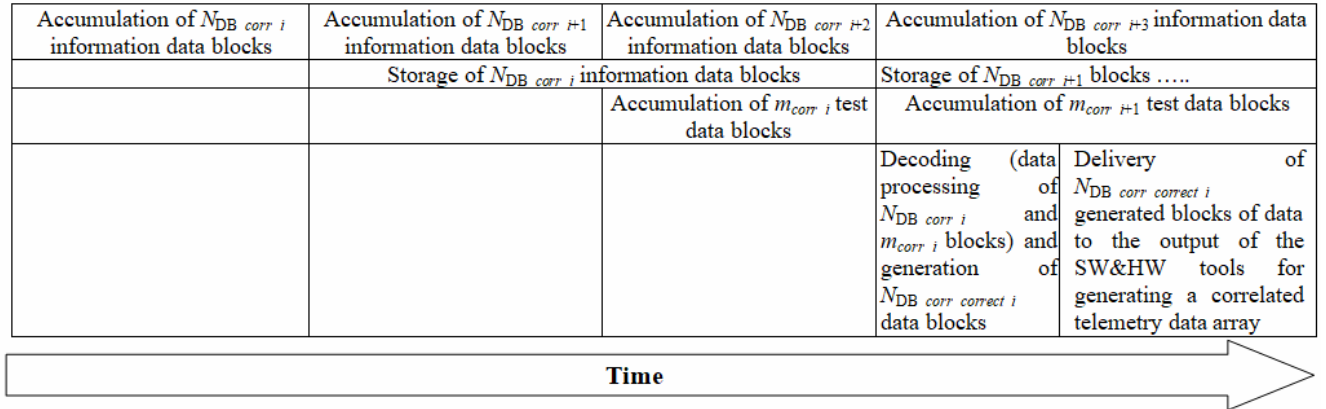


Fig. 5. Cyclogram of steps to implement the proposed method of integration in the case of data received by ground-based SW&HW tools

It should be noted that each separate block of the  $N_{DB}$  blocks and of  $m$  blocks (see fig. 3) can additionally contain test data of the code set for them. In this case, the introduction of additional artificial data redundancy improves interference resistance.

The features of application conditions of the proposed integration method that contain advantages of the method, that consist in reduction of TMI losses, are associated with the correcting capabilities of the set code (4).

Fulfilment of condition (4) means that the complete loss of information (complete distortion) of a certain number ( $N_{DB\_err\_tol}$ ) of transmitted data blocks is allowable, regardless whether these blocks contain information data or test data. In this case, it is possible to stop TMI losses including the cases under conditions of periodically repeating interference in diversity channels (in downlink channels). In other words, under certain conditions (4) the proposed method of integration can become a full-fledged alternative to the controlled diversity reception of TMI [3, 16].

If condition (4) is not fulfilled (i.e. there is relatively long-term interference), and a significant portion of distortions occurs in information data blocks, then TMI losses are inevitable.

If the maximum total duration  $T_{interf\_max}$  of the time interval with data distorted by interference (unreliable data) received from downlink channels during the time  $T_M$  of transmission of data corresponding to the matrix  $M$  is known a priori, then

$$N_{DB\_interf\_max} = T_{interf\_max} / T_{DB}, \quad T_{interf\_max} < T_M, \quad (7)$$

where  $T_{DB}$  is the transmission time of one data block;

$N_{DB\_interf\_max}$  is the maximum tolerable number of distorted (lost) blocks of data corresponding to the matrix  $M$ .

Then taking into account (4) to exclude information loss, the following condition must be fulfilled:

$$N_{DB\_interf\_max} \leq N_{column\_err\_tol}, \quad (8)$$

$$T_{interf\_max} / T_{DB} \leq N_{column\_err\_tol}, \quad T_{interf\_max} < T_M \quad (9)$$

The complexity (complexity of practical implementation) of encoding/decoding when implementing the proposed method of integration depends on the number of elements ( $N_{DB} + m$ ) (1) in the matrix  $M$  (on the number of bits  $V_{column\_j}$  (2)). In terms of the above-mentioned complexity, it is desirable that the data volume  $V_{column\_j}$  (2) be relatively small; and correspondingly,  $m$  (1) and  $N_{column\_err\_tol}$  (8) (9) should be small.

It follows from (8) and (9) that in order to simplify coding/decoding under conditions of intense interferences (with a relatively long time  $T_{interf\_max}$  (9)) it is necessary to increase the time  $T_{DB}$  (7) of transmission of one data block, with an unchanged number  $V_M$  (1) of elements of the matrix  $M$  ( $V_M = const$ ). In the case under consideration, an increase in the time  $T_{DB}$  (7) means an increase in the number of elements  $N_{bit}$  (1) in a row of the matrix  $M$ . In this case, the following features must be taken into account:

- the number of elements  $N_{bit}$  (1) in a row of the matrix  $M$  may not be limited by the volume of one data block  $N_{DB\_OBITS}$  formed in the *on-board information and telemetry system* (OBITS); i.e. the following is possible:

$$N_{DB\_OBITS} \ll N_{bit}; \quad (10)$$

- with an increase in the volume of the data block  $N_{DB\_OBITS}$ , the volume of lost information increases in the event of synchronization failures of these blocks (in case of synchronization failures, the use of algorithms for generating correlated data and decoding becomes senseless [1, 3]);

- in the case of an unchanged data volume  $V_M(1)$  ( $V_M = const$ , see above) and with a decrease in the data volume  $V_{column\_j}(2)$  corresponding to a column of the matrix  $M$ , the number of these columns ( $N_{bit}(1)$ ) increases proportionally; this complicates the practical implementation of the proposed method of integration (the rationale for choosing the ratio of the number of rows and columns of the matrix  $M$  with  $V_M = const$  in order to simplify the practical implementation is beyond the scope of this work).

Based on condition (10) and related explanations, in order to expand the capabilities of the proposed method of integration, it is advisable to establish the correspondence of the  $K_{DB}$  data blocks generated by the OBITS to one row of the matrix  $M$ :

$$N_{bit} = K_{DB} N_{DB\_OBITS}, K_{DB} \gg 1. \quad (11)$$

In this case, the transmission of data blocks generated by the OBITS is carried out sequentially (similar to that shown in fig. 4), starting with the first block and ending with the  $K_{DB}$ -th block.

### 7.3 Results of integration method application

A practical example of implementing the proposed method of integration with  $T_{interf\_max} = 2.4$  s is considered [13].

Let the data blocks formed by the OBITS be subframes of the Russian radio telemetry system of the BRS-4 type; the transmission time of one subframe is  $T_{DB\_OBITS} = 80$  ms; one subframe (if the transmission of TMI via downlink channels is carried out with a four-position code) contains 51200 bits.

Let the extended Golay code (24, 12) with the code distance of  $d_{min} = 8$  be selected for implementing the proposed method of integration. Then  $R_{code} = 1/2$ ,  $N_{DB} = m = 12$ .

The correction capabilities of the selected code are  $N_{column\_err\_tol} = 3$ . This means that the loss of TMI contained in three data blocks ( $N_{DB\_interf\_max} = 3$  (8)) is allowable. Then, with tolerable TMI losses of  $T_{interf\_max} = 2.4$  s per three data blocks, 0.8 s ( $2.4$  s :  $3 = 0.8$  s) is per one data block. In other words,  $T_{DB} = 0.8$  s (7).

If  $T_{DB} = 0.8$  s and  $T_{DB\_OBITS} = 80$  ms, then  $K_{DB} = 10$  (11) ( $0.8$  s :  $0.08$  s = 10 blocks).

If one row of the matrix  $M$  corresponds to 10 data blocks formed by OBITS, then 12 rows correspond to 120 blocks ( $10 \times 12 = 120$ ). This means that the information data related to the matrix  $M$  are contained in 120 data blocks formed by OBITS. Besides, 120 data blocks formed by OBITS contain test data related to the matrix  $M$ .

The transmission time of 120 data blocks generated by OBITS is 9.6 s ( $80$  ms  $\times$  120 blocks = 9600 ms = 9.6 s). If this transmission time is related to the cyclogram shown in fig. 4, then the blocks with the test data will be delivered to the OBITS output with a delay of 19.2 s ( $9.6$  s  $\times$  2 = 19.2 s).

It should be noted that the transmission of information data and test data is carried out simultaneously (the  $TMI_{DT}$  and  $TMI_{RM}$  flows are parallelized, see above), the time  $T_{TMI\_DT}$  of  $TMI_{DT}$  transmission and the time  $T_{TMI\_RM}$  of  $TMI_{RM}$  transmission are the same, namely:  $T_{TMI\_DT} = T_{TMI\_RM} = T_M = 9.6$  s (7). The tolerable TMI losses on the time interval of 9.6 s are 2.4 s, or 25% ( $2.4$  s :  $9.6$  s = 0.25).

Since, according to the condition (see above), one block of data generated by OBITS (a subframe) contains 51200 bits, then 120 subframes contain 6144000 bits ( $51200$  bits  $\times$  120 = 6144000 bits  $\approx$   $6.1 \cdot 10^6$  bits). If to follow the given example, the actions on TMI shown in the cyclograms (see fig. 4 and 5) are connected with the data volume of  $\sim 6.1 \cdot 10^6$  bits.

The considered example is given just to illustrate the essence of the proposed method of integration (recommendations on the determination of the rational number of rows and columns of the matrix  $M$  are not formulated, the extended Golay code is chosen at random, without rationale of its choice, etc.).

Various modifications of the proposed method of integration are possible. For example, it is possible to improve interference resistance by interleaving [10] test data related to the columns of the matrix  $M$ . However, this work does not consider such modifications. It shows the essence and main capabilities of the proposed method of integration.

## 8 Conclusions

1. The proposed technology provides a considerable improvement in data reliability by making better using the capabilities of diversity reception. Its features (for example, it focuses on counteracting arbitrary interference acting in radio channels) allow it to be harmoniously combined with traditional CCSDS methods of improving the reliability of radio link data. Its full-fledged application does not require the cancellation of any existing CCSDS Recommendations.

2. The development strategies for the proposed technology are implemented with systematized knowledge related to this technology. There are both fundamental and real possibilities for its development that are often conditioned by the circumstances that have arisen, both in terms of its application in solving current problems related to improving the radio link data reliability and in terms of its improvement.

3. A very promising direction for the proposed technology development is integration, both in the form of simple complementarity of diversity reception methods and methods related to traditional CCSDS technologies for improving interference resistance, and in the form of a goad-oriented combination of elements of technologies (the proposed technology and traditional technologies).

4. As a result of the proposed technology development by integration, one can observe a tendency which consists in the fact that certain traditional methods of CCSDS for improving interference resistance of radio links have become (or may become in the future) part of the proposed mature technology. In this case, a synergy property related to the provided interference resistance can be observed.

5. The effective development of the proposed technology (including the above-mentioned integration) can be implemented both in the CCSDS fields and in solving problems of improving Russian systems of information and telemetry support for the development of various objects of rocket and space technology (in particular, the development of space transportation capabilities; primarily launch vehicles). These are platforms where complementarity is relevant. As for the CCSDS fields, the full-fledged development of the proposed technology is associated with the transformation of the Orange Book "Correlated Data Generation" into the Blue Book of CCSDS.

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