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REAL-TIME CARRIER ROCKET MISSION CONTROL USING SPACE RELAY SYSTEM

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One of the purposes of the multifunctional space relay system "Luch" is telemetry provision for the timely control of launches from the "Vostochniy" spaceport. Launch vehicles and upper stage units have special high-speed and low-speed relay user equipment for telemetry relaying using the relay system "Luch". This article is about special programs for processing such kind of telemetry at the Mission Control Centre (MCC) of the federal state unitary enterprise "Central Research Institute for Machine Building" (TsNIIMASH) for mission launch control. These programs are the part of telemetry processing software-hardware system of the MCC. Their purpose is real-time reception, processing and depicting results of processing telemetry data from high-speed and low-speed relay user equipment. This article contains description of the telemetry structure, transmission scheme and description of telemetry reception and processing approach based on the specific characteristics of such kind of telemetry. It contains information about tasks, solved by the MCC telemetry complex for giving timely, objective and correct information about a launch process as well. Created programs, processing algorithms and representation forms of the results of telemetry processing successfully provided missions control of the launches of the spacecraft "Kanopus-V-IK", "Meteor-M"№2-1 in 2017, "Kanopus-V" №3, 4 in 2018. We propose to use developed programs for telemetry provision of the timely control of orbital mean insertion during the next launches from the "Vostochniy" spaceport.

Keywords: relay user equipment, launch vehicles, upper stages, telemetry processing, launch control.

ТЕЛЕМЕТРИЧЕСКОЕ ОБЕСПЕЧЕНИЕ ОПЕРАТИВНОГО КОНТРОЛЯ ПОЛЁТА РАКЕТ И РАЗГОННЫХ БЛОКОВ С ИСПОЛЬЗОВАНИЕМ СПУТНИКОВОГО КОНТУРА УПРАВЛЕНИЯ

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Телеметрическое обеспечение оперативного контроля запусков с нового космодрома «Восточный» на участках выведения, расположенных вне зоны видимости наземных измерительных пунктов, осуществляется с помощью многофункциональной космической системы ретрансляции «Луч». Для передачи телеметрической информации (ТМИ) через систему ретрансляции «Луч» на ракете-носителе (РН) и разгонном блоке (РБ) установлены комплекты высокоскоростной и низкоскоростной абонентской аппаратуры ретрансляции. В статье описаны средства, разработанные в ЦУП ФГУП ЦНИИмаш для оперативного контроля полета РН и РБ по информации, полученной с абонентской аппаратуры ретрансляции. Разработанные средства в составе телеметрического информационно-вычислительного комплекса ЦУП ЦНИИМаш обеспечивают прием, обработку и отображение результатов обработки телеметрической информации РН и РБ в режиме реального времени. Приведена структура передаваемой информации, схема ее передачи и особенности, определяющие алгоритмы приема и обработки телеметрической информации. Указаны основные задачи, решаемые на средствах телеметрического информационного комплекса ЦУП для предоставления оперативных, объективных и качественных данных о процессе выведения. Созданные в ЦУП средства, разработанные алгоритмы обработки и формуляры отображения телеметрической информации высокоскоростной и низкоскоростной абонентской аппаратуры ретрансляции успешно применялись для оперативного контроля выведения космических аппаратов «Канопус-В-ИК» и «Метеор-М» № 2–1 в 2017 г. и «Канопус-В» № 3, 4 в 2018 г. Созданные средства *предполагается использовать для телеметрического обеспечения оперативного контроля процесса выведения орбитальных средств при последующих запусках с космодрома «Восточный».*

Ключевые слова: абонентская аппаратура ретрансляции, ракеты-носители, разгонный блок, обработка ТМИ, представление результатов обработки ТМИ.

Introduction. By 2018 three launches of "Soyuz-2" launch vehicles for the spacecraft of scientific and socio-economic purposes had been performed from the new spaceport called "Vostochniy" [1–3]. The main launch routes from the new spaceport are beyond the visibility of existing ground telemetry stations, and the construction of new ground telemetry stations or the use of mobile ground telemetry stations in the Far North and the Pacific Ocean is expensive and difficult. High-speed relay user equipment was created for transmitting the telemetry data of launch vehicles via the "Luch" satellite transponders [4] during launches from the "Vostochniy" spaceport, as well as low-speed relay user equipment [5–7] was developed for transmitting telemetry data of upper stages. The work considers the reception, processing and display of telemetry data of launch vehicles and upper stages received from the relay user equipment at the MCC of the federal state unitary enterprise TsNIIMASH.

The scheme of data transmission through the "Luch" multifunctional space relay system. To control the flight of the "Soyuz-2" launch vehicles by telemetry data of high-speed relay user equipment at the MCC using a telemetry processing software-hardware system, programs for receiving, processing and displaying incoming telemetry data have been developed. Fig. 1 shows a telemetry data reception scheme where created programs are highlighted in yellow. The high-speed relay user equipment starts transmitting telemetry data from the 400th second of the flight of a launch vehicle, when a rocket approaches the border of the visibility range of spaceport measuring tools. The real-time telemetry data is transmitted to the earth-based relay station "Klyon-R" № 304 ("Vostochniy" spaceport) via the "Luch-5A" relay satellite. The telemetry data is received by two sets of RT-428 receiver. From the first set, data is transmitted directly to the MCC to the hardware-software complex of relay user equipment [8] to the relay and communication control center [9]. From the second set, data is transmitted through the special control software of the earth-based relay station "Klyon-R" to the automated exchange system of relay and communication control center. The telemetry processing software-hardware system receives and processes information from both sources [10]. The results of processing telemetry data are displayed on individual and collective drawing tools in the relay and communication control center.

Telemetry data is transferred from the hardware and software complex of the relay user equipment to the telemetry processing software-hardware system in accordance with the protocol for the information exchange of the hardware-software complex of the relay user equipment, based on TCP protocol. Moreover, in addition to telemetry data, two types of data are transmitted to the telemetry processing software-hardware system: "RT-428 profile" messages and "RT-428 status vector" messages.

"RT-428 Profile" messages contain information about the configuration of a receiver, such as:

– the results of self-diagnosis of a receiver;
– set frequency range and frequency letter;
– set operating mode (transfer speed and frame size);
– use of Reed-Solomon codes and Viterbi codes.

"State vector RT-428" messages contain current information about the RT-428. This information includes signal-to-noise ratio, number of errors, presence of capture and frame synchronization.

Telemetry data is transmitted from the automated exchange system of the relay and communication control center to the telemetry processing software-hardware system using the protocol compatible with the structure of transmission packets over networks of the National Ground-Based Automated Control Centre using UDP packets. Herewith, decoding such information is fraught with a number of difficulties caused by the fact that the data format of the National Ground-Based Automated Control Centre is poorly adapted to transmit information using relay user equipment. Firstly, telemetry data in this format is transmitted in 12-bit words packed into 16-bit ones. With that, the RT-428 packet for the information of high-speed relay user equipment has the length of 3568 bytes or 28544 bits, which is not divided by 12 without a remainder, that is why it is necessary to supplement such a packet with zero bits. Secondly, such a packet size is too large for UDP transmission, that is why the automated exchange center of the relay and communication control center breaks it into smaller packets, and only the last one will contain additional zero bits. If the selected size is odd, an additional problem arises: it is impossible to put an integer number of 16-bit words into such a packet (one word can be divided into two packets). Thirdly, at present, the automated exchange system of the relay and communication control center does not transmit time information, which makes it impossible to accurately correlate telemetry data with time.

It should be noted that the direct transmission of telemetry data of the high-speed relay user equipment from RT-428 receiver installed at the "Vostochniy" spaceport to the hardware-software complex of the relay user equipment was unsatisfactory according to the test results. Due to the small size of the network buffer being used to transmit telemetry data from the receiver and the significant time it took to transmit telemetry data from the earth-based relay station "Klyon-R" of the "Vostochniy" spaceport to the MCC, the actual speed of telemetry data transmission was not more than 180 kbit / s instead of the nominal 256 kbit / s; that caused regular loss of telemetry data during transmission in real time. The developers of the receiver managed to solve this problem using an additional gateway for transmitting data from the earth-based relay station "Klyon-R", which was not used during the launch work (it is shown in grey in fig. 1).

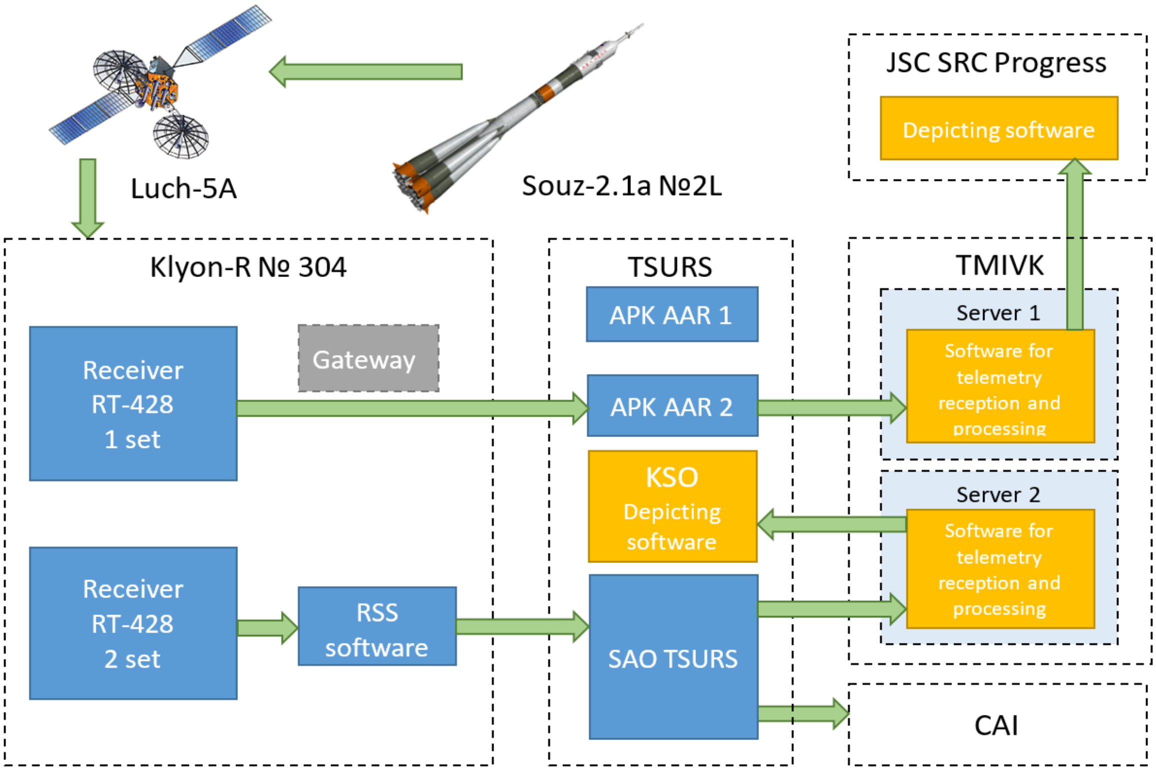


Fig. 1. Scheme of telemetry reception of high-speed relay user equipment at MCC

Рис. 1. Схема приёма телеметрической информации
высокоскоростной абонентской аппаратурой ретрансляции в ЦУП

The main tasks of telemetry processing software-hardware system for processing the telemetry data of the relay user equipment. The main tasks to be solved using the telemetry processing software-hardware system of the MCC to ensure high-quality relay of telemetry data from relay user equipment of a launch vehicle and an upper stage and operational control of the output process are the following:

– assessing the quality and reliability of telemetry data (percentage of failed and reliable frames, the number of errors recovered by Reed-Solomon codes), the level of the received signal;

– assessing the timeliness of the beginning and end of the reception of relayed telemetry data in accordance with the sequence diagram of the operation of the relay user equipment;

– switching the telemetry data streams received from the various "Luch-5" relay satellites and from ground-based aids (while ensuring transmission at the MCC);

– exact binding of TM-frames to time;

– assessing the current parameters of the orbit of a space rocket and an upper stage;

operational control of the onboard systems, including fix– ing the moments of separation of the parts of a launch vehicle, payload, control system commands, turning on and off the marching and corrective propulsion systems of the upper stage, the operating modes of the telemetry system and relay user equipment;

– processing telemetry data received from relay user equipment both during flight tests and during ground testing [11–14];

– providing data for the interdepartmental commission in the event of an emergency launch;

– real-time processing of data from the on-board video monitoring system transmitted through the "Luch" multifunctional space relay system (when implementing such an outcome).

Most of these tasks have already been implemented in the telemetry processing software-hardware system. Let us consider the above tasks in more detail.

The operational assessment of the quality and reliability of the received telemetry data is necessary when conducting ground and flight tests of launch vehicles and upper stages in order to:

– determine the correct operation of relay user equipment and the structure of generated telemetry data;

– make the comparative analysis of various "Luch-5" relay satellites and ground receiving stations;

– select the optimal configuration of the on-board relay equipment of the "Luch-5" relay satellite;

– measure the actual data content of the communication channels being used, the frequency of data loss and delay in data transmission;

– identify one-time and prolonged interference in the transmission of telemetry data;

– compare the quality of received telemetry data at different sessions, on different days, on different products.

For example, Reed-Solomon codes and CRC-16 checksum used in the telemetry data for high-speed relay user equipment allow you to accurately determine the reliability of the received telemetric frame and the number of distortions that occurred in it during the transmission over the radio link.

Software and hardware tools of a telemetry processing software-hardware system allow performing in-depth processing of a telemetry data in real time, providing the solution to most of the above tasks [10–14]. For a detailed manual analysis, the means for viewing the initial telemetric frames, transmitted over the network data packets and intermediate results of processing telemetry data are available.

Determining the exact time of the start and end for receiving the telemetry data of relay user equipment helps to evaluate the accuracy of the on-board flight sequence, the “Luch” relay satellite guidance, flight path, and orientation of a launch vehicle/upper stage.

Depending on the flight path, launch vehicles and upper stages can get simultaneously or sequentially into the visibility areas of two satellite transponders, as well as ground-based measuring points. At the same time, independent assessing of the telemetry data flows coming from each source should be provided, as well as automatic switching of all received flows into a single stream for the most high-quality and continuous processing. During the switching process, telemetry processing software-hardware system tools allow fully synchronize telemetry data flows regardless of the delays of data. In addition, the algorithms that allow you to restore a telemetry frame from several failed ones received from different sources have been developed.

Due to the fact that the telemetry frames of a launch vehicle and upper stage use their own different on-board time, counted from the moment the equipment was turned on or the NOV command was transmitted, while ground-based telemetry data processing, there is a problem of linking the received information to decreed Moscow time (DMT). This normally uses the time of registration of telemetry data at ground measuring stations, synchronized with the central timing system, however, when processing data received through the “Luch” multifunctional space relay system, this approach is not applicable for two reasons. Firstly, the transfer of the telemetry data from a launch vehicle/upper stage to the “Klyon-R” earth-based relay station via the “Luch-5” relay satellite takes a long time (during the launch from the "Vostochniy" spaceport using the “Luch-5A” relay satellite, the radio signal travels over 260 ms covering the distance of about 79000 km). Therefore, it is impossible to use directly the time of registering telemetry data at the station, but it is necessary to take into account the amendment depending on the current position of a product, the position of the relay satellite and the earth-based relay station being used. Secondly, at the present time the task of telemetry data registering by the central timing system time has not been solved at the “Klyon-R” earth-based relay station. Telemetry data is linked to the time at the hardware-software complex of the relay user equipment (relay and communication control center) or at the telemetry processing software-hardware system (in the case of reception from the automated exchange system of relay and communication control center), which is fraught with the large errors caused by the inconsistent time of transmission of the telemetry data from a remote earth-based relay station to the relay and communication control center and delays in all the software and hardware used in the transfer means. Prior to solving the problem of accurate linking telemetry data to time at the “Klyon-R” earth-based relay station, the registration of on-board events using the telemetry data of high-speed relay user equipment can be carried out only with fairly rough accuracy.

The operational assessment of the ballistic parameters of the launch vehicle and the upper stage based on the state vectors received from on-board satellite navigation system allows controlling the accuracy of the output, the deviation of the product from the computed path, the fact of performing the correcting pulse of an upper stage, and the accuracy of directing the “Luch-5” relay satellite to the target. Additionally, the ability to independently determine the separation parameters for spacecraft controlled from the MCC will increase the reliability of getting into communication with them at the first revolutions in the event of the significant deviation of the orbit parameters from the calculated ones until official data are received from the upper stage UMCC. Let us list the main ballistic parameters being calculated at the stage of the operational processing of state vectors:

$\vec{v}$ – speed;
H – height;
H_{min} – minimum height;
H_{max} – maximum height;
T – tact;
i – inclination;
e – eccentricity
a – major axis;
Ω – longitude of the ascending node;
ω – perigee argument;
u – latitude argument;
φ – latitude;
λ – longitude.

Monitoring the system health of onboard systems according to the telemetry data of the relay user equipment allows you to quickly evaluate the accuracy of the flight program, including the flights out of sight of ground-based tracking stations. Among the main controlled indicators of a launch vehicle and upper stage:

– deviation of pitching motion and yawing from the program values, product orientation;
– voltage on the bus of onboard power system;
– operability of onboard control system elements;
– operability and the mode of operation of a telemetry system and relay user equipment, calibration levels;
– performance indicators of propulsion sysrems;
– residues of propellant components;
– contacts of separation of detachable parts and payload;
– indications of emergency situations;
– commands and events recorded by the onboard control system;
– temperature indicators of main components of the product.

Separately it is worth noting the importance of processing the telemetry data of relay user equipment not only during start-up, but also during ground preparation of the product at the launch complex, as well as using the telemetry data records obtained during factory tests. During such processing, it is possible to verify the correct operation of transmitting and receiving equipment, the processing algorithms of telemetry data in the structure of the relay user equipment and the entire transmission path of the telemetry data of relay user equipment. At this stage, it is possible to identify such inconsistencies in the work as: inconsistencies in the operation of the standard telemetry system and relay user equipment, inconsistencies in the structure of the generated data, delays and distortions in the transmission of data along the entire path, errors in measuring individual parameters, etc.

In the event of the emergency completion of a launch, the results of processing of telemetry data of the relay user equipment at telemetry processing software-hardware system at the MCC of TsNIIMASH are supposed to be used during the work of the interagency commission as an additional data source, and tools for analyzing the initial (unprocessed) telemetry frames and faulty information as a source of additional information, that is not available in the results of automatic processing of telemetry data.

After installing the equipment for relaying video data on the launch vehicle/upper stage, from the onboard video monitoring system it will be possible to carry out processing of received information in real time with the help of telemetry processing software-hardware system with its display on the individual and collective drawing tools for additional control of flight.

Data structure of the high-speed relay user equipment of a launch vehicle. As part of the telemetry frame of the high-speed relay user equipment, a subset of the telemetry frame of the modernized digital radio-telemetering system RTSTsM-1 (the main telemetry system of the "Soyuz-2" launch vehicle) is transmitted. The frame structure of the high-speed relay user equipment was built in accordance with the recommendations of the CCSDS international committee [15; 16] and it contains a header, checksum, Reed-Solomon codes. In concluding pseudo-randomization and convolutional coding algorithms are applied to the signal (fig. 2).

Fig. 3 shows the structure of the data part of a user package. One user package contains the telemetry data of two complete reading frames of MAS1, TSM2, MAS3 and TSM 6 of the second stage of commutation of telemetry.

The distribution of telemetry data over transmission channels is determined by the telemetry data collection program for a particular product.

To control and correct possible transmission errors in the telemetric frame, Reed-Solomon coding is used, where the entire frame is encoded except for the attached synchronization marker (framing pulse), with the following parameters:

– block length – 255 bytes, where the data portion is 223 bytes, the remainder is 32 bytes;

– multiplicity of the errors being corrected: E = 16;

– polynomial generating the field: $F(x) = x8 + x4 + x3 + x2 + 1$;

– generating polynomial: $g(x) = \prod_{i=0}^{15}(x-\alpha^{h(GSi+1)})$, where $h = 1$, GS = 1

The encoded part of the frame is conventionally divided into blocks with the length of 223 bytes; two complete blocks and one shortened block of 88 bytes are obtained. The shortened block during encoding / decoding is supplemented by non-transferable characters (zeros) to the full length of the block (Virtual Fill). The multiplicity of the errors being corrected $E = 16$ means that when decoding it is possible to correct transmission errors of characters up to 16 bytes in each block. The remnants of the polynomials of all three blocks are transmitted at the end of the frame, prior to the framing pulse. Remnants are transmitted in the same sequence as the original information blocks.

It is worth noting that using another method of splitting a telemetric frame for Reed-Solomon coding could slightly increase the restoration ability of the algorithm. That is, if instead of dividing the frame into blocks of 223 + 223 + 88 bytes (supplementing the latter with zeros), we can break the frame into blocks of equal length of 178 + 178 + 178 bytes (supplementing each one with zeros). It will be possible to restore for the first block not 16/223 = 7.1 % of errors but 16/178 = 9.0 % of errors. Thus, the potential resistance to accidental failures on average will be higher.

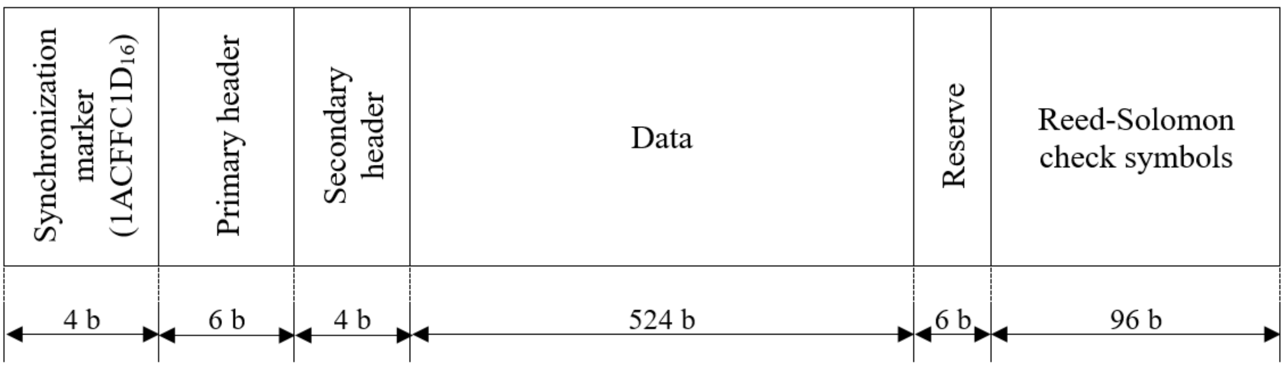


Fig. 2. The structure of the telemetric frame of high-speed relay user equipment

Рис. 2. Структура телеметрического кадра ВААР

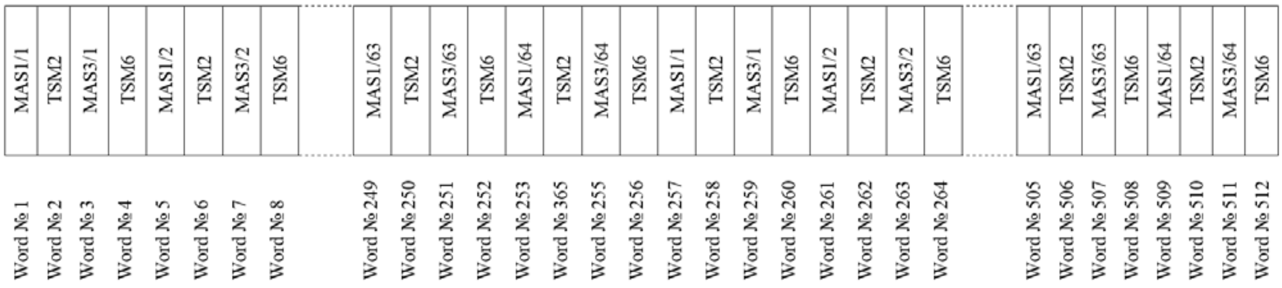


Fig. 3. The structure of transfer frame data part

Рис. 3. Структура информационной части пользовательского пакета

The accuracy of the received user data packet is additionally checked using the checksum transmitted in the data field. The checksum is calculated using the CRC-16 algorithm with the polynomial 0x1021 ($x16 + x12 + x5 + 1$).

To reduce the power spectral density of the transmitted signal, the main frames are pseudo-randomized based on the 0xA9 sequence (except for framing pulse).

When processing the received telemetry data of the high-speed relay user equipment, the checksum and Reed-Solomon codes can reliably evaluate the accuracy of the received telemetry data and correct up to 48 distorted bytes in each frame.

Let us consider some of the features of receiving telemetry data of the high-speed relay user equipment. The first task that arises during reception is to search for telemetric frames in the bitstream. A frame is a sequence of 8-bit words (bytes) of 640 bytes in length, starting with a framing pulse. However, data from a receiver comes in the form of packets with the length of 3568 bytes, and these bytes contain the densely packed bits of the bitstream received by the RT-428. Most often they do not correspond to the bytes of the frames, but contain them with some bit shift. To search for the correct bit shift, a framing pulse, the Reed-Solomon codes or the checksum are used, since it is necessary to take into account the possibility of false framing pulses inside the frame. If for 640 bytes, starting from the found framing pulse, the checksum converges, then the correct frame is found and the bit shift is correctly determined, i.e. the next framing pulse should be sought immediately after the end of the found frame. If the checksum does not converge, this can indicate that there are failures in the frame, and that the framing pulse is false, so the next initialization vector will be searched sequentially, taking into account all possible bit shifts.

Data structure of the low-speed relay user equipment of an upper stage. Let us consider the structure of the information generated by the upper stage “Fregat-M” low-speed relay user equipment of the and the features of its processing.

Telemetric data for transmission through the low-speed relay user equipment to the “Luch” relay satellite is formed by the onboard telemetry system BR-9TsK-1 from a full telemetry frame. Telemetry data can be transmitted in the form of small frames (64 words) or full frames (512 words). Three modes of information rates and data transmission rates of the low-speed relay user equipment are possible:

1) Transmission of small frames (64 words) at the speed of 62.5 bit / s (when the “Luch-5” relay satellite is operating in the multi-station access mode). In this mode, the transmission of one frame takes 10.24 s, the transmission rate is 0.097 frames / s.

2) Transmission of small frames (64 words) at the speed of 8000 bit / s (when the “Luch-5” relay satellite is in individual access mode). In this mode, the transmission of one frame takes 0.080 s, the transmission rate is 12.5 frames / s.

3) Transmission of full frames (512 words) at the speed of 8000 bit / s (when the “Luch-5” relay satellite is operating in the mode of individual access). In this mode, the transmission of one frame takes 0.640 s, the transmission rate is 1.56 frames / s.

The main transmission mode is the delivery of small frames.

A frame word consists of 10 bits. 8 bits (from the 2nd to the 9th) are informational. The first bit in the word is the least significant, and the tenth is a high-order digit. The 1st and the 10th bits are service ones. During the transmission of the 10th bit, an impulse is transmitted, supplementing the number of units in the current word to an even number. The presence of a parity bit allows processing the received telemetry data to check the correctness of each word of the received frame.

64 consecutive 10-bit words make up the small frame of the system. The structure of the small frame is shown in fig. 4.

The first word of the frame contains command and service data on data transmission rate, frame length, type and channel of satellite navigation equipment - command word. The command word contains information about the frame size, output speed, type and channel of satellite-navigational equipment. The structure of the command word is shown in fig. 5.

Time stamps from the second-fourth words of the frame contain the time of formation of a small frame. Telemetry data of satellite-navigational equipment (SNE) transmitted within the frame is transmitted with its time as well.

The last word of the small frame – the frame synchronization label – contains units in all 10 bits; it can be used to check the accuracy of frame searching process.

The small frame includes the telemetric parameters of the on-board systems of the "Fregat" upper stage:

– control system;

– propulsion system;

– satellite navigation equipment;

– telemetry system BR-9TsK-1;

– state of the separation contacts of the payload.

The full composition of the small frame is presented in the telemetry program for a specific product.

Let us consider the features of receiving telemetry data of the low-speed relay user equipment. The first task that arises during the reception is frame search. A frame is a sequence of 64 or 512 10 bit words ending by ten units, and data comes from the RT-428 in packets of 8 to 223 bytes in length. RT-428 packs the incoming bits in bytes, starting with the high-order bit, and BR-9TsK-1 system outputs the bits, starting with the least significant, so before searching for a frame in the stream coming from RT-428, one must "flip" the bits in each byte, and then connect right to left bytes in FIFO order. In order to find a frame in the resulting sequence of bits, it is necessary to determine the correct bit shift, that is, find the beginning of 10-bit words in an unstructured stream. For this purpose, one cannot use end-of-frame marker, since the combination of 10 units can occur randomly inside a frame if, for example, one word ends in 5 units, and the next starts with 5 units. Therefore, the main criterion in determining the correct bit shift is the service parity bit. A correct bit shift should be considered such a shift at which the maximum number of resulting 10-bit words will have the correct parity. Next, the frame search problem is solved by finding the end-of-frame marker.

Of particular note is the solution to this problem at a transmission rate of telemetry data of 62.5 bits/s. At this rate, a frame is formed in 10.24 seconds. This imposes certain restrictions on data buffering: if at the rate of 8000 bits/s it is possible to accumulate some amount of data in order to analyze possible bit shifts and parity, at the rate of 62.5 bits/s it is not possible to accumulate too much, since delays of the telemetry data processing can reach dozens of seconds in the course of this approach. Such buffering is permissible only for post-session processing.

Presenting the results of processing telemetry data of relay user equipment. The traditional way of presenting the results of telemetry data processing is tabular forms, where the values of telemetric parameters in physical units or in the form of text editions are displayed in the screen together with the units of measurement and the time of the last change in value. To display dynamically changing parameters graphs are used.

To perform operational control, the results of processing telemetry data of relay user equipment in telemetry processing software-hardware system are presented to users in real time in the form of mnemonic diagrams, tables, graphs and text protocols; in the post-session mode – in the form of graphs, tables, text protocols and various printouts. Operational display tools are created at the MCC (based on the ability to perform the simplest and most comprehensive flight control). Let us give examples of some of them.

Fig. 6 shows the example of a mnemonic diagram used to control the flight of the "Soyuz-2.1a" launch vehicle according to the telemetry data of the high-speed relay user equipment during the launch of the "Kanopus-V" spacecraft No. 3, on February 4, 2018.

The mnemonic diagram contains the following elements:

– general state of telemetry data receiving (at the top);

– phase trajectory (on the left);

– current elements of the orbit (in the center);

– space rocket orientation (on the right);

– state of signal parameters (left-bottom);

– state of calibration levels (at the bottom);

– control system status (at the bottom);

– operation of the high-speed relay user equipment transmitter and RT-428 receiver (right-bottom).

Word number	1	2	3	4	5 … 63	64
Content	Command word	Time stamp			Data	Sync label

Fig. 4. Small frame structure

Рис. 4. Структура малого кадра

Bit number	1	2	3	4	5	6	7	8	9	10
Value	Not used	Codeblock length: 0 – 64 words 1 – 512 words	Main codeblock transfer rate: 0 – 8000 bit/s 1 – 32000 bit/s	Small codeblock transfer rate: 0 – 62.5 bit/s 1 – 8000 bit/s	Type of navigation equipment: 0 – SNE-F 1 – SNE	SNE channel number: 0 – 1st 1 – 2nd	0	0	1	Parity check

Fig. 5. Structure of small frame command word

Рис. 5. Структура КСС малого кадра

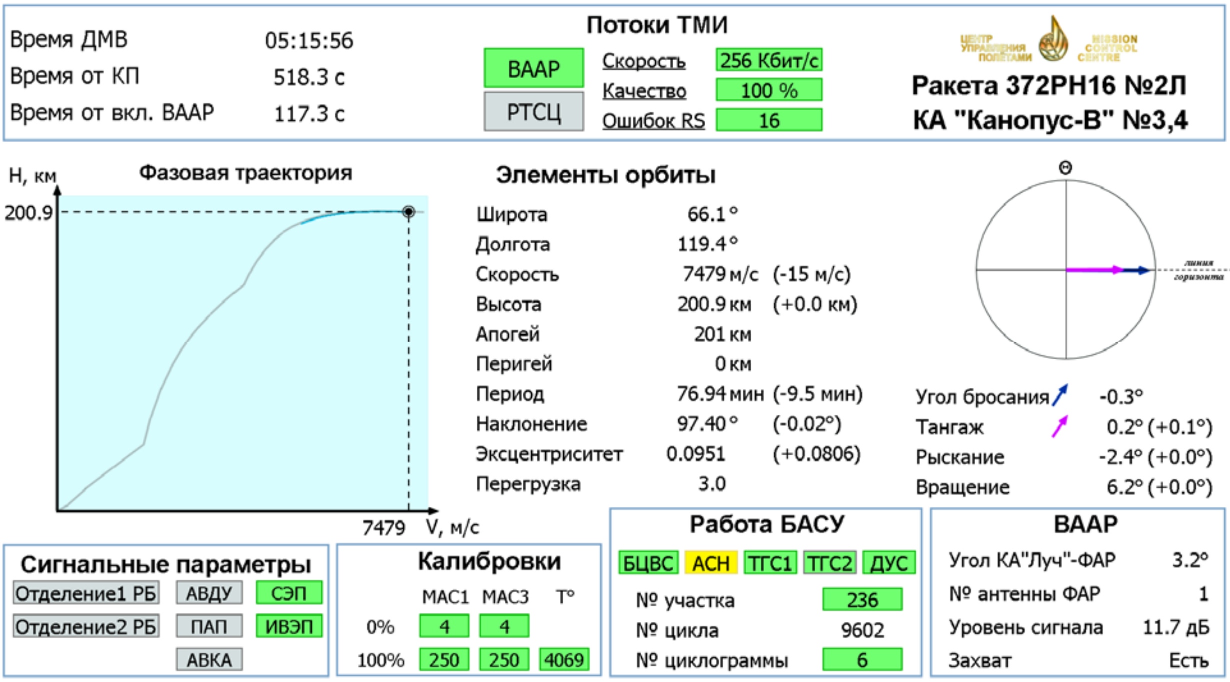


Fig. 6. The mnemonic diagram of the status display of the Launch vehicle “Soyuz-2.1a”

Рис. 6. Мнемосхема отображения состояния РН «Союз-2.1а»

Operational monitoring of the propulsion system of a launch vehicle is carried out on a separate mnemonic diagram.

On the given mnemonic diagram three times are displayed: the current Decreed Moscow Time, the time before the initial motion switch – before the start or after the initial motion switch – after the start, the time before turning on the high-speed relay user equipment or from the moment of turning on the high-speed relay user equipment. The high-speed relay user equipment and RTSTs blocks signal about receiving the telemetry data flows from the high-speed relay user equipment and RTSTsM-1 transmitters, respectively. Next, the current selfdescriptiveness of receiving telemetry data is calculated. 256 kb/s is a nominal value. In the case of loss of telemetry data in terrestrial data transmission channels at the indicated launch, data rate sometimes decreased to 180 kb/s, which was immediately highlighted in yellow or red. The quality of the telemetry data contains the percentage of reliable telemetry data frames to the total number of frames received in the last 2 seconds. Reliability is determined by the Reed-Solomon codes and checksum. The “RS errors” field displays the number of failed channels recovered using Reed-Solomon codes in the last 2 seconds.

On a large diagram we can see calculated and actual space rocket phase trajectory, calculated on the basis of state vectors received from the navigation user equipment; the horizontal axis presents the product rate module, and the vertical axis – the current height above the common ellipsoid. The phase trajectory allows us to visually assess (easily and efficiently) the deviation of launch vehicle movement from the calculated trajectory.

The current elements of the orbit are given along with their deviation from the calculated ones. In terms of altitude and speed, the comparison is performed for the current moment of flight, and the deviation from the target parameters of the orbit is displayed for the remaining elements. Axial overload is calculated based on the navigation user equipment measurements as well.

The information on the orientation of a launch vehicle in space along the pitching, yawing and rotation angles is displayed in the right area of the screen. Moreover, for the convenience of estimation, the pitch angle is recalculated to the current tangent to the Earth's surface in such a way that at the final seconds of the flight it becomes close to zero. Based on the navigation user equipment measurements, the so-called departure angle is calculated – the angle between the space rocket velocity vector and the tangent to the Earth's surface. The throw angle and the recalculated pitch are displayed in a pie chart for a visual assessment.

Among all the signal parameters of a launch vehicle for operational control, those that can operate after 400 seconds of flight (turn-on time of high-speed relay user equipment) are selected: these are two contacts of separating an upper stage from a launch vehicle, the voltage presence on the onboard power buses along with the voltage levels of the secondary power sources and various signs of emergency completion of flight.

The calibration levels of 0 and 100 % on two working single blocks of data gathering equipment and the temperature switch of RTSTsM-1 are displayed in decimal with the results of the assessment: the values in the tolerance are highlighted in green, out of the tolerance – yellow or red.

Operational control of the onboard automated control system is carried out according to the following systems:

– digital airborne computation system;

– satellite-navigational equipment (system, subsystem);

– three-axis gyrostabilizer;
– angular rate sensors.

The control of each system is performed by a set of telemetric parameters. If there are some insignificant problems in the system, the system turns yellow. If there are some significant ones, the system turns red.

The operation of transmitting and receiving equipment of satellite relay is controlled by the following parameters:

– the angle between the current direction of radiation of the antenna (implemented phased array) and the selected “Luch-5” relay satellite;
– the number of the selected direction of radiation of the implemented phased array;
– the level of the registered signal in the RT-428 receiver;
– the presence of signal capture in the RT-428 receiver.

The described mnemonic diagram allows us to control about 100 telemetric parameters. When using the tabular forms to control all these parameters, 2–4 separate forms would be required, which would not provide such visibility as a mnemonic diagram.

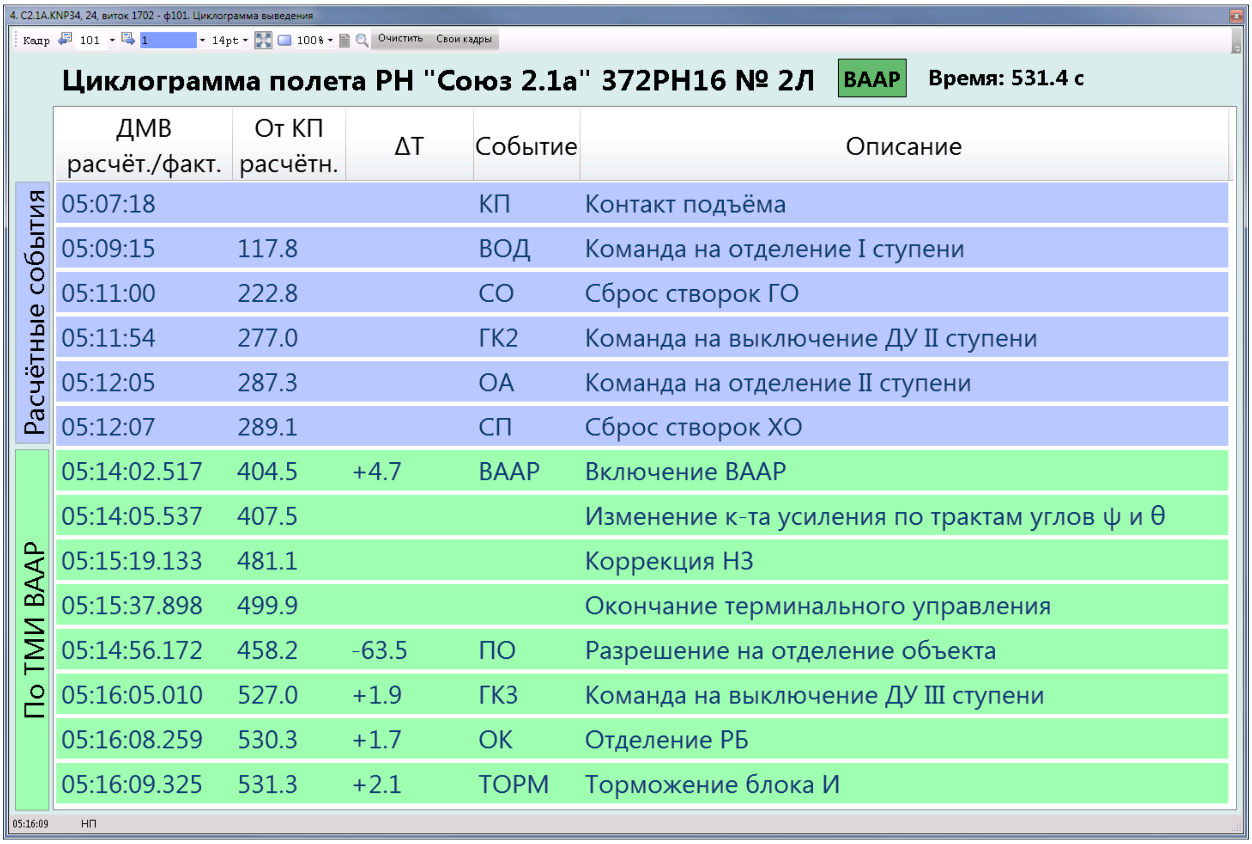
Fig. 7 presents the mnemonic diagram showing the main events of the flight profile of the “Soyuz-2.1a” launch vehicle.

Initially, the entire mnemonic diagram is displayed against a white background. The events that occur on the launch vehicle up to the 400th second of flight (before turning on the high-speed relay user equipment) are shown in blue according to the estimated time. Events recorded by the signal parameters of slowly changing parameters and by digital telemetry are highlighted in green as they are recorded.

Note: due to the peculiarities of the time linking of the telemetry data of the high-speed relay user equipment described above, the time indicated on the operational control mnemonic are approximate. The exact time reference of telemetry data of the high-speed relay user equipment is carried out after matching the timeline with central timing system.

Fig. 8 shows the example of the flight control profile of the “Fregat” upper stage during the launch of the “Kanopus-V-IK” satellite with the hosted payload on July, 14th, 2017 using small frames of the telemetry data of high-speed relay user equipment. The mnemonic displays the current time (DMT and time before and after the initial motion switch), the time boundaries of the “Luch” relay satellite zones, the speed of the telemetry data output, its quality, as well as the orbit elements, the state of the propulsion system, the presence of the compartment contacts and the main parameters of the central computing complex.

As an example of the graphs analysis of telemetry data, fig. 9 shows the graph of axial overload with the marked events tkst, tgk3 *, tka, SC1, ttorm.


Циклограмма полета РН "Союз 2.1а" 372РН16 № 2Л ВААР Время: 531.4 с

	ДМВ расчёт./факт.	От КП расчётн.	ΔT	Событие	Описание
Расчётные события	05:07:18			КП	Контакт подъёма
	05:09:15	117.8		ВОД	Команда на отделение I ступени
	05:11:00	222.8		СО	Сброс створок ГО
	05:11:54	277.0		ГК2	Команда на выключение ДУ II ступени
	05:12:05	287.3		ОА	Команда на отделение II ступени
	05:12:07	289.1		СП	Сброс створок ХО
По ТМИ ВААР	05:14:02.517	404.5	+4.7	ВААР	Включение ВААР
	05:14:05.537	407.5			Изменение к-та усиления по трактам углов ψ и θ
	05:15:19.133	481.1			Коррекция НЗ
	05:15:37.898	499.9			Окончание терминального управления
	05:14:56.172	458.2	-63.5	ПО	Разрешение на отделение объекта
	05:16:05.010	527.0	+1.9	ГК3	Команда на выключение ДУ III ступени
	05:16:08.259	530.3	+1.7	ОК	Отделение РБ
	05:16:09.325	531.3	+2.1	ТОРМ	Торможение блока И

Fig. 7. The flight profile of the launch vehicle “Soyuz-2.1a”

Рис. 7. Циклограмма полёта РН «Союз-2.1а»

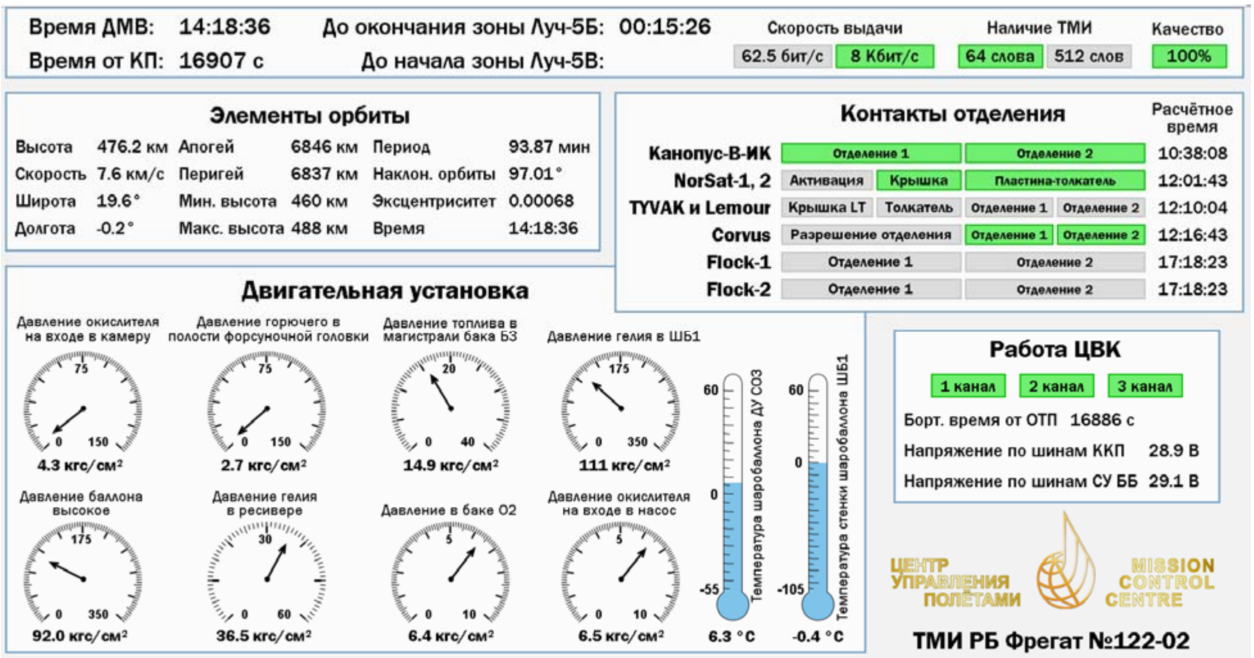


Fig. 8. The mnemonic diagram of the flight control of the upper stage “Fregat”
(based on the telemetry data of low-speed relay user equipment)

Рис. 8. Мнемосхема контроля полёта РБ «Фрегат» по ТМИ НААР

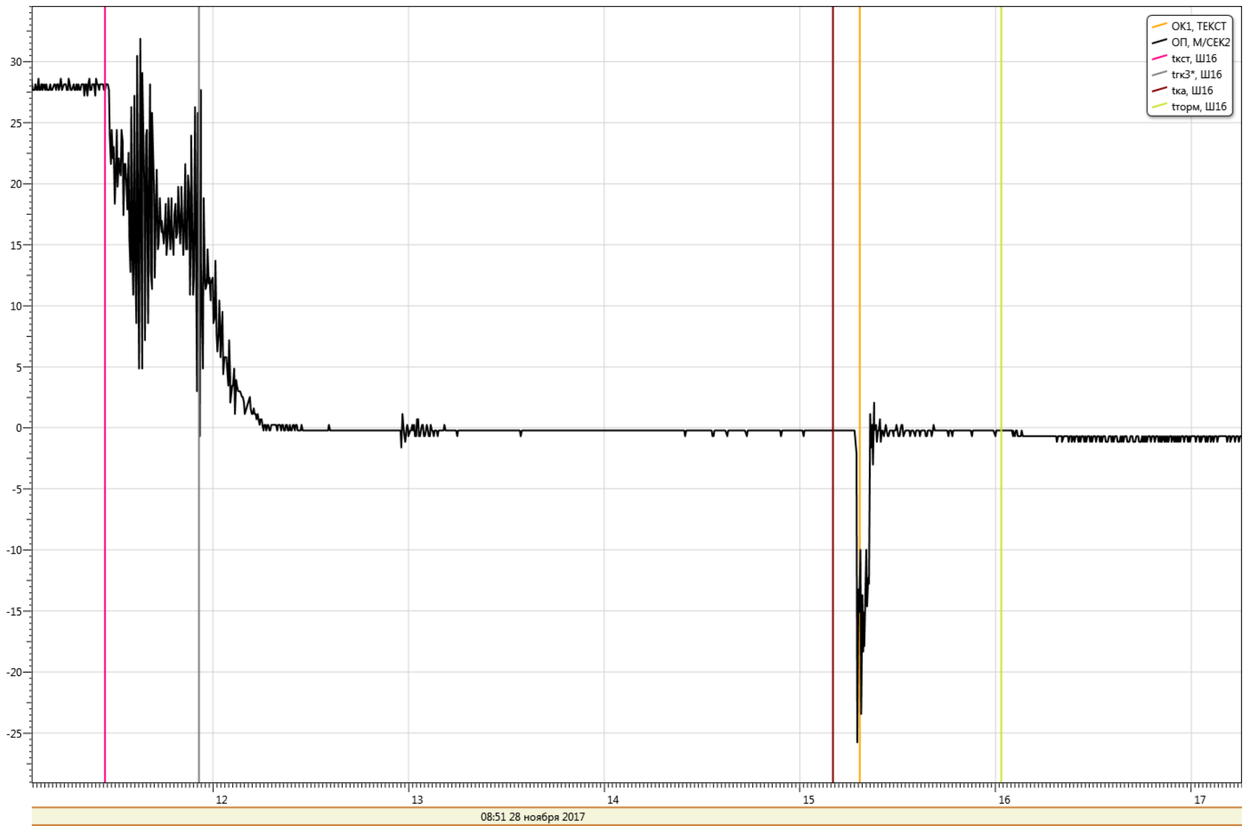


Fig. 9. Axial overload of the launch vehicle “Soyuz-2.1b” at the time of the “Fregat” upper stage separation 28.11.2017

Рис. 9. Осевая перегрузка РН «Союз-2.1б» при отделении РБ «Фрегат» 28.11.2017

Here tkst is the command to switch to the final thrust stage mode, tgk3* is the beginning of the airborne digital computation system command to turn off the remote control of the 3rd stage, tka is the command to separate the "Fregat" upper stage, SC1 (separation contact) is the operation of separation contact of an upper stage from a launch vehicle, ttorm is the braking command for block of the 3rd stage.

Conclusion. The means developed at the MCC, created processing algorithms and display forms of the telemetric data of low-speed and high-speed relay user equipment were successfully used for the telemetric support of operational control of the launching the "Kanopus-V-IK" and "Meteor-M" spacecraft No. 2-1 in 2017 and the "Kanopus-V" No. 3, 4 in 2018. The results of processing of telemetry data of low-speed relay user equipment at the start of 2018 from the "Vostochny" spaceport were transmitted in real time and displayed into the sector of the chief designer of the JSC SRC Progress. All of these means will be updated according to the results of these launches and will be used for the telemetric support of the operational control of upcoming launches from the "Vostochniy" spaceport.being used for the detailed

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