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Ways to Improve the Efficiency of the Spacecraft Flight Control System

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Abstract. The article is devoted to the problem of increasing the efficiency of the spacecraft flight control system. Various options for the organization of the spacecraft flight control systems are con-sidered. Network solutions for the transmission of control information in a single stream with target information using the TCP/IP Protocol stack will automate the process of receiving and transmitting information as well as lead to the reduction in the number of onboard radio equipment. The use of the SCADA-system will serve to improve ergonomics. Combining relay satellites into a single network of inter-satellite communication lines will enable receiving information from the spacecraft even when it is in the Western Hemisphere without placing command and measurement and gateway stations there. The decision to employ a low-orbit constellation as relay satellites would reduce delays in the trans-mission of information and reduce the energy budget of the radio link between the spacecraft and re-lay satellite.

Keywords: communication, spacecraft, orbital constellation, flight control system, radio link, com-mand and measurement station, onboard equipment, antenna system

Introduction

One of the main spacecraft flight control system requirements is efficiency, which is defined by the time required for receiving information on the state (telemetry) of the object being controlled τ_c (system response time), decision time τ_d and by the time required to communicate the controlling actions to the object being controlled τ_r:

$$\tau_c=\tau_s+\tau_d+\tau_r. \quad (1)$$

The following (and no less important) requirement for a flight control system is reliability, which is defined by the guarantee of a timely and reliable reception of telemetry information (TMI) q_t from the object being controlled, by the quality of decision-making q_d and the guarantee of the timely and reliable communication of control actions to the object being controlled q_r:

$$\mathbf{q_c=q_s+q_d+q_r}. \quad (2)$$

The reliability of the flight control system q_c is also dependent on the flexibility of the communication and information processing system.

Consequently, the main aim of building a control system is to reduce the time of response (τ_c) and increase the reliability q_c.

Note that for commercial systems an important factor in boosting the profitability is the reduction of the cost of the control system.

Implementation of geostationary satellites for increasing the efficiency of a SC flight control system

The traditional approach to increasing the efficiency of a flight control system of a spacecraft (SC) is to organize a two-tier control and communication system with the implementation of three-four geostationary relay satellites (GRS) [1-4].

The use of two active phased antenna arrays (APAA) functioning as antenna systems (AS) of GRSs is proposed with the aim to increase the number of simultaneously established communication links with a SC as well as to decrease the transition time from one SC to another and to boost the reliability of antenna systems, which is conditioned by the absence of mechanical parts. These antennas are a receiving and transmitting one; and each consists of three-four modules positioned at an angle generating a multitude of pointed (pencil) beams.

It is possible to ensure a round-the-clock communication link between a single command and measurement station (CAMS) or gateway station (GS) simultaneously with all the spacecraft located at all parts of the trajectory if there is an intersatellite communication link (ICL) between GRSs.

The implementation of interconnected GRSs by intersatellite radio links as repeaters will make it possible to:

1) simultaneously receive information from all the SC at any point on the flight path, which will lead to an increase in control efficiency;

2) reduce the number of CAMS and decrease the cost of the control system.

This direction of development of SC flight control systems is present-day and promising, yet, it has such a disadvantage as large information transmission delays conditioned by high altitudes of GRS orbits (circa 36 000 km) and, consequently, by large distances between orbital slots.

A generalized scheme of the organization of communication with satellites via GRS is shown in Figure 1. Note: GLONASS SC are used to transmit ballistic navigation information and synchronization signals to other spacecraft.

Implementation of a satellite communication system on low Earth orbit relay satellites for boosting the efficiency of SC flight control systems

An orbital constellation (OC) of a satellite communication system (SCS) based on low orbit relay satellites (LRS) is a certain amount of spacecraft located in several orbital planes (OP). Neighboring (adjacent) spacecraft belonging to one constellation should be connected using ICLs in such a manner so that every spacecraft is connected to four adjacent satellites in a single or in adjacent OPs [5]. Such architecture is employed for the Iridium mobile personal satellite communication network (PSCN) [6]. It has also been proposed in research papers [7] and in patents for the creation of a low-orbit telecommunication system based on small spacecraft [7, 8].

The implementation of the TCP/IP protocol stack will help transmit control information in a single stream with the target information to a unified GS concurrently performing the function of a CAMS.

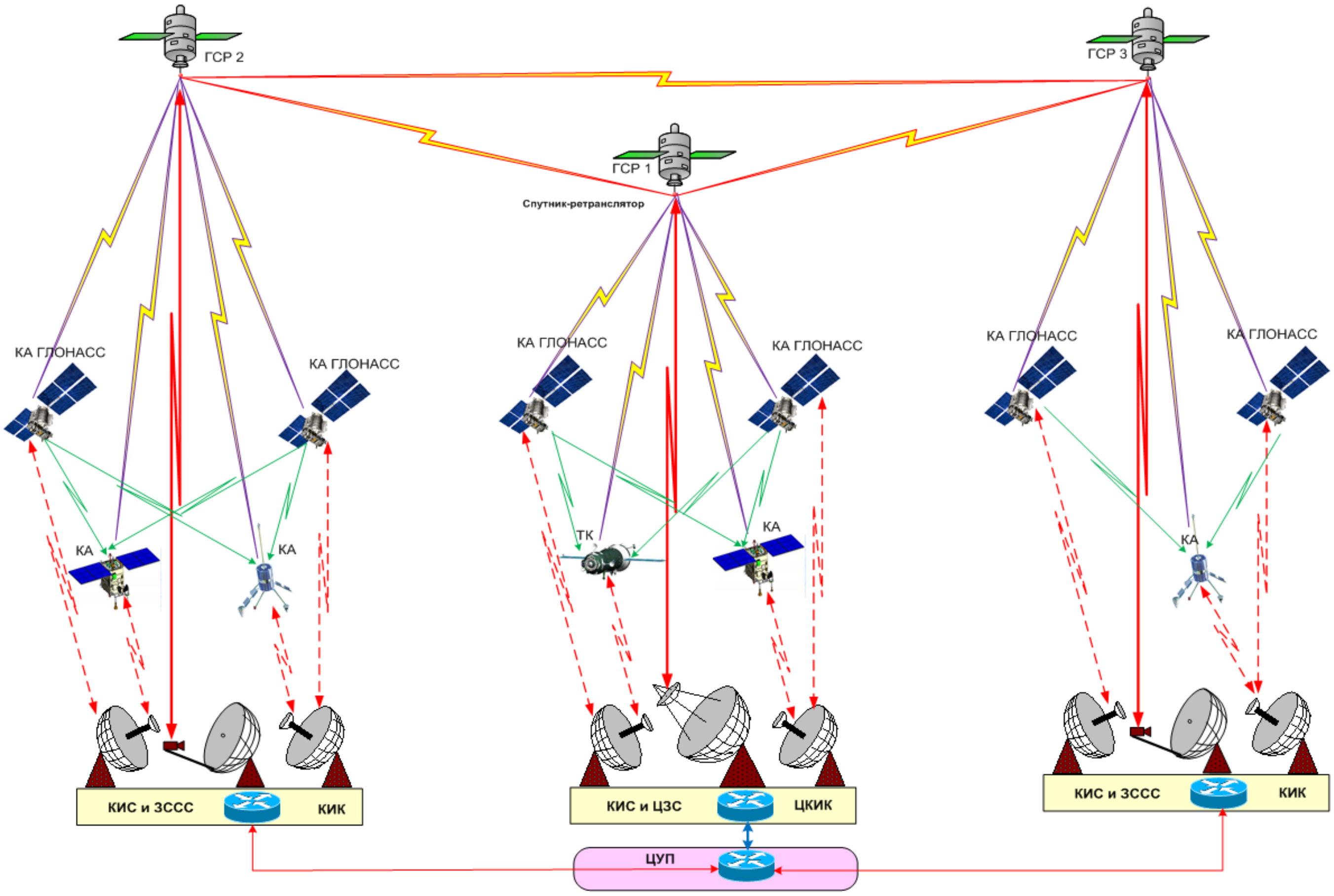

Fig. 1. Generalized scheme of link configuration for satellite communication via GRS.

Thus, an OC forms a fully connected satellite network for data transmission with the use of TCP/IP protocol stacks, where every spacecraft is a satellite router with its own information input/output ports:

– 1 global network port – connection to a CAMS – radio uplink (radio link, RL) Earth – SC in S-band;

– 1 global network port – connection to a GS, Earth – SC radio link in V-band or in the optical band;

– 4 global network ports – for retransmitting data to neighbor satellites using ICL;

– 1 local network port – for transmitting control data to spacecraft's own onboard equipment (OE).

A fully connected architecture of a satellite communication network, which is made up of SC connected via intersatellite communication links, has the following advantages [5, 8, 9]:

1) it supports the creation of a flexible network, where adaptive routing protocols can be implemented to build any data transfer route:

– with a minimum length path, which is especially critical for delays;

– with optimal throughput with account for onboard relay system (ORS) loading – for broadband traffic;

– with routes bypassing faulty SC or SC that are located in special areas (e.g., on the dark side of the orbit, in disaster areas and war zones);

2) demonstrates high survivability and adaptivity;

3) allows a single command and measurement station (CAMS) to have real-time access to any of the constellation SC.

The application technology of SCS based on LRS for SC flight control was implemented for the first time and perfected when controlling the flight of the TNS-0 No. 1 nanosatellite, developed and built at JSC "Russian Space Systems" [10]. This system used the SC of the Globalstar orbital constellation as relay satellites. Currently, the TNS-0 No. 2 flight program is being executed.

Unlike the existing SCS based on Globalstar LRS, the relay satellites of the proposed SCS are additionally equipped with four or six sets of receiving and transmitting wide-beam antenna (WBA) systems, located along two or three axes, for example: 1st variant: -Y and +Y, -Z and +Z;

2nd variant: -Y and +Y, -Z and +Z, -X and +X. For the needs of intersatellite communication, the Radio Regulations distributed a bandwidth in the S band the following way: 2025-2110 MHz – for the direct communication link and 2200–2290 MHz – for the feedback channel. In this frequency range, it seems most optimal to use a horn or spiral antenna system or a system of spiral antenna systems with a gain of 6-8 dB as wide-beam antennas.

Connected via intersatellite communication links, orbital constellation spacecraft form a global satellite network for data communication. A GS or CAMS, by establishing communication with a single SC from the OC within its radio coverage zone, gains access to any of the SC in the orbital constellation. By switching from one SC to another, 24-hour access to any spacecraft can be achieved with the use of one or several gateway stations.

In relation to another SC, a SC is a subscriber of the mobile satellite communications network (MSCN). Unlike the MSCN user terminal, each SC is assigned a basic and backup frequency on a regular basis as well as primary and backup code sequences, which are required for code-controlled access to the ICL between the LRS and SC. The spacecraft constantly receives pilot signals from various LRS via the service channel using wide-beam antennas. The decision-making device of the SC chooses the antenna that receives signals with the maximum amplitude. The pilot signals with a signal-to-noise ratio exceeding allowable threshold values are chosen. Then, using the Doppler frequency shift, the LRS, which is approaching the SC rather than moving away from it, is determined [10]. Having identified the optimal LRS for registration, the SC sends a registration request. After receiving the registration request, it transfers data via the LSR. If the value of the signal-to- noise ratio of the pilot signal worsens, the SC selects a different LRS using the abovementioned criteria and sends a registration request. After receiving a registration request, it transmits data via the newly chosen LRS, having completed the communication session with the previous LRS.

The repeaters of the SCS on the LRS with spacecraft, which are the objects being controlled, operate in multiple access mode in the LRS-SC radio link (forward channel) using MCPC technology (many stations on a single carrier) and in the SC-LRS link (reverse channel) – the SCSC is used (one station on one carrier)

Each SC is provided with two (2) fixed frequencies in the Ka-band and two spread-spectrum code combinations for reception and transmission. When the SC passes relative the LRS, a token-passing procedure (handover) between beams of one LRS and between LRSs is performed. During connection to LRS: authentication, registration and establishment of VPN-tunnels are carried out for information protection.

Every SC monitors the LRS-SC radio link, reads the headers of IP packets. If they identify their IP address, then they send the IP packets addressed to them into processing. The LRS receives and monitors every reverse frequency communication channel and then relays the IP packets via IRL and FRL (in the presence of a GS) to the MCC.

The architecture of SC flight control with the implementation of a SCS based on LRS is shown in Figure 2.

A functional diagram of a LRS satellite communication system is given in Figure 3 [2].

Link and control organization using one LRS is demonstrated in Figure 4.

An organizational chart of communication and control with the implementation of two LRSs is shown in Figure 5.

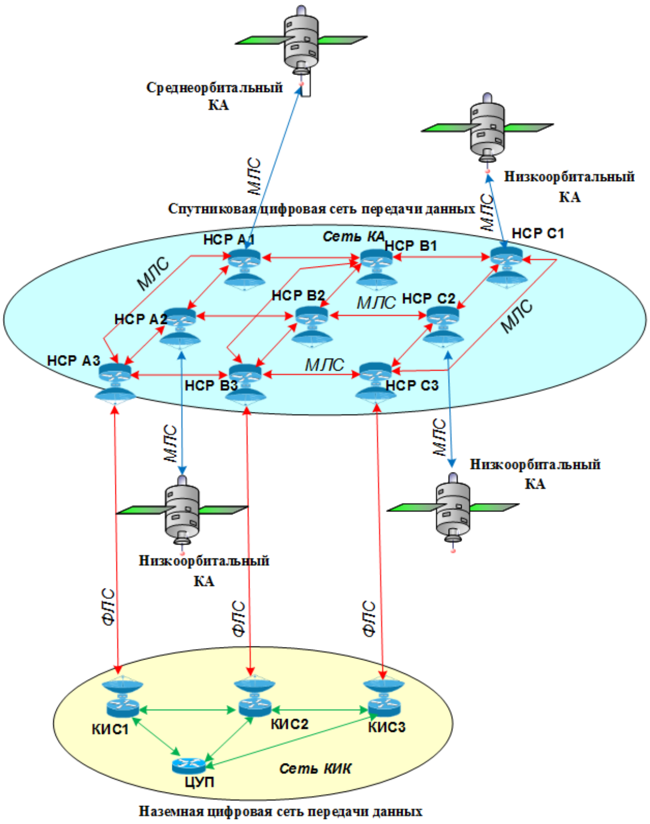

Fig. 2. Architecture of SC flight control with the implementation of a SCS based on LRS.

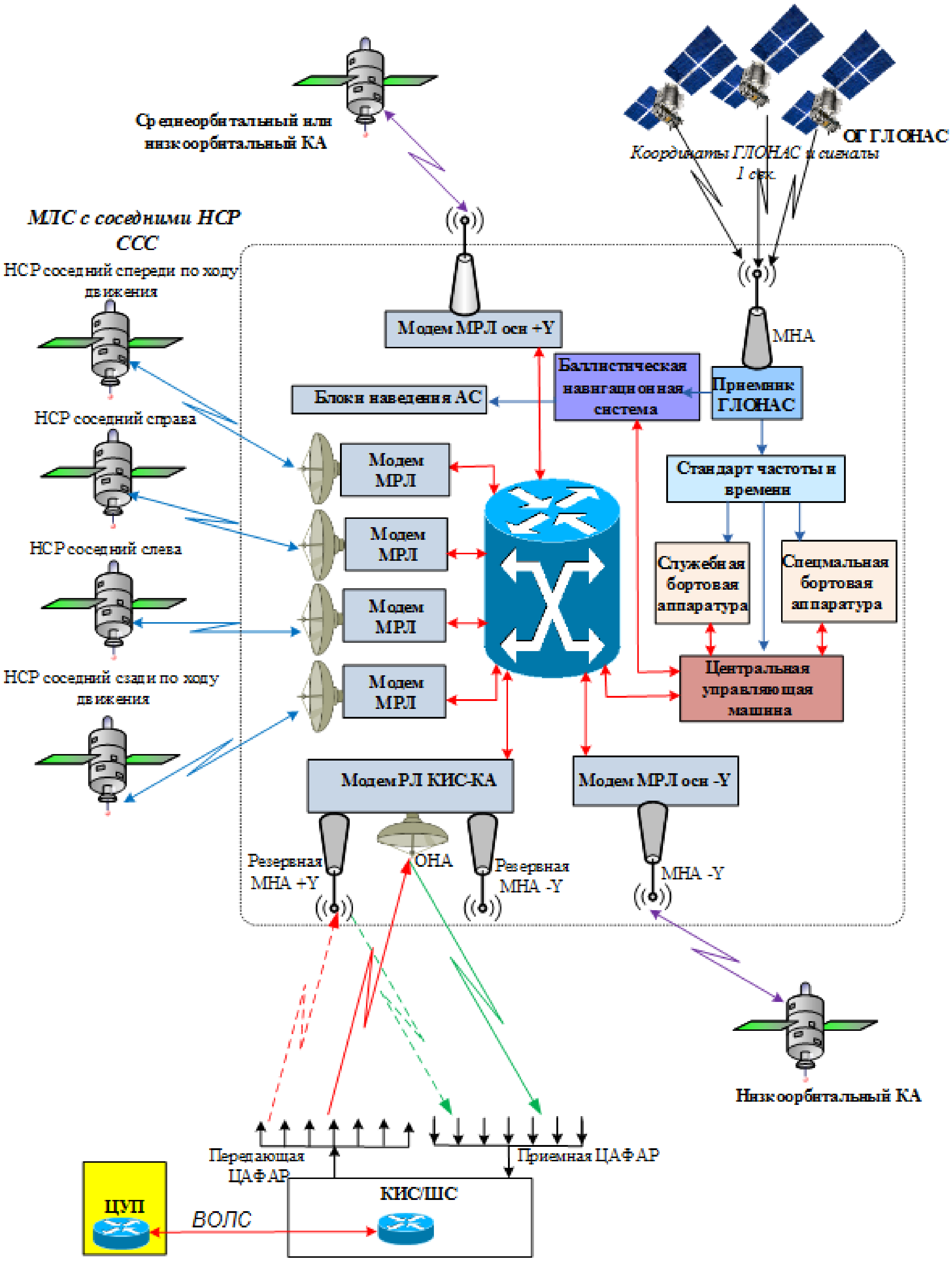

Fig. 3. Functional diagram of a SCS using LRS.

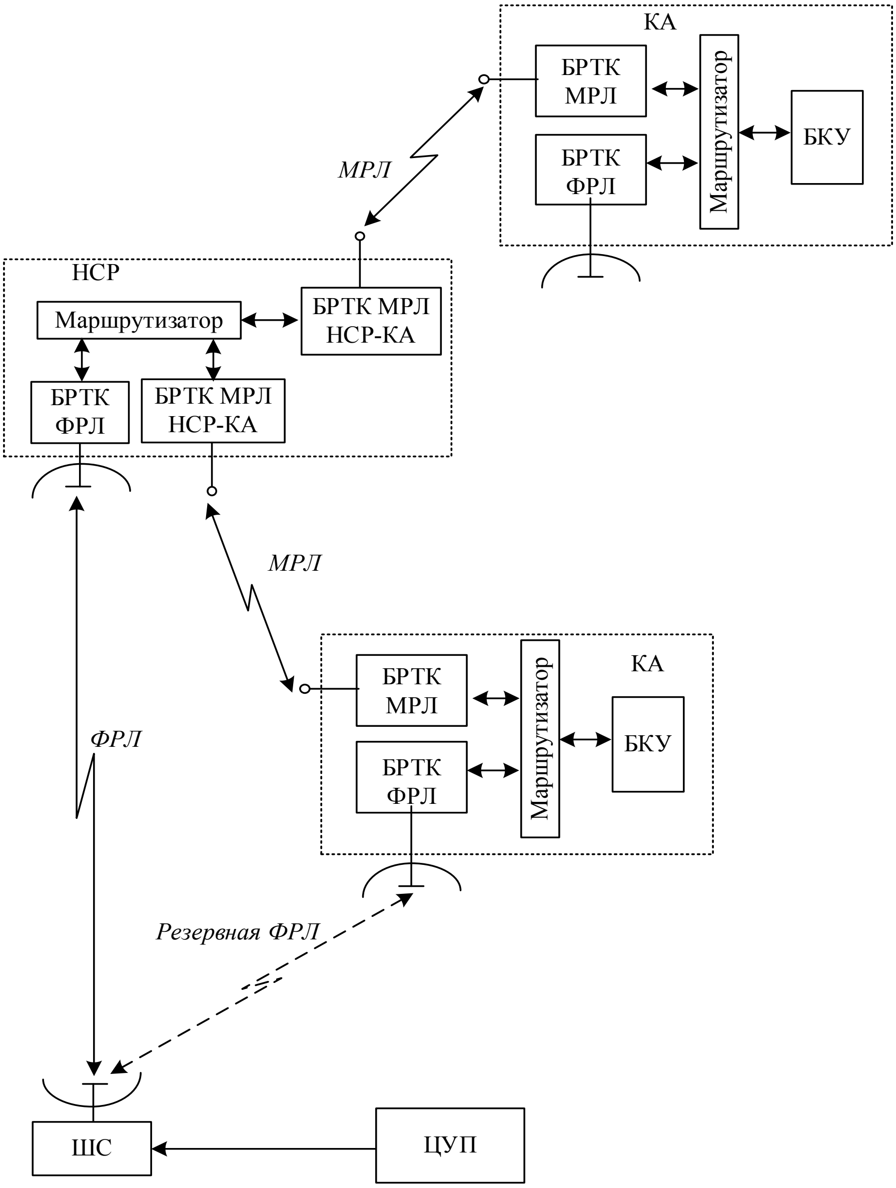

Fig. 4. Organizational chart of linkage and control using one LRS. Notation key: FRL – feeder radio link; IRL – intersatellite radio link; CRL – command radio link; GS – gateway station; ORU – onboard radio unit; OCU – onboard control unit

The highlighted advantages boost the efficiency of spacecraft flight control τ_c and the reliability of the control system q_c.

Thus, an LRS-based SCS is a satellite-based digital transport network for data transfer intended for relaying information of the information channel from the Mission Control Center (MCC) via GS and LRS to the SC and vice versa. The use of an LRS-based satellite communication system with a single GS will allow having simultaneous access to every SC of different OC, which will ensure high reliability and efficiency of the control system.

For communication between LRSs of the SCS through the ICL, it is most sensible to use the V-radio band and, in the future, switch to transmitting data in the optical band of radio waves.

The application of the V-band [5, 9] will allow us to:

– reduce the dimensions of antenna-feeder devices (AFD) and of the waveguide path of the microwave equipment;

– reduce the energy expenditures required to power the guidance systems of the AFDs and microwave equipment;

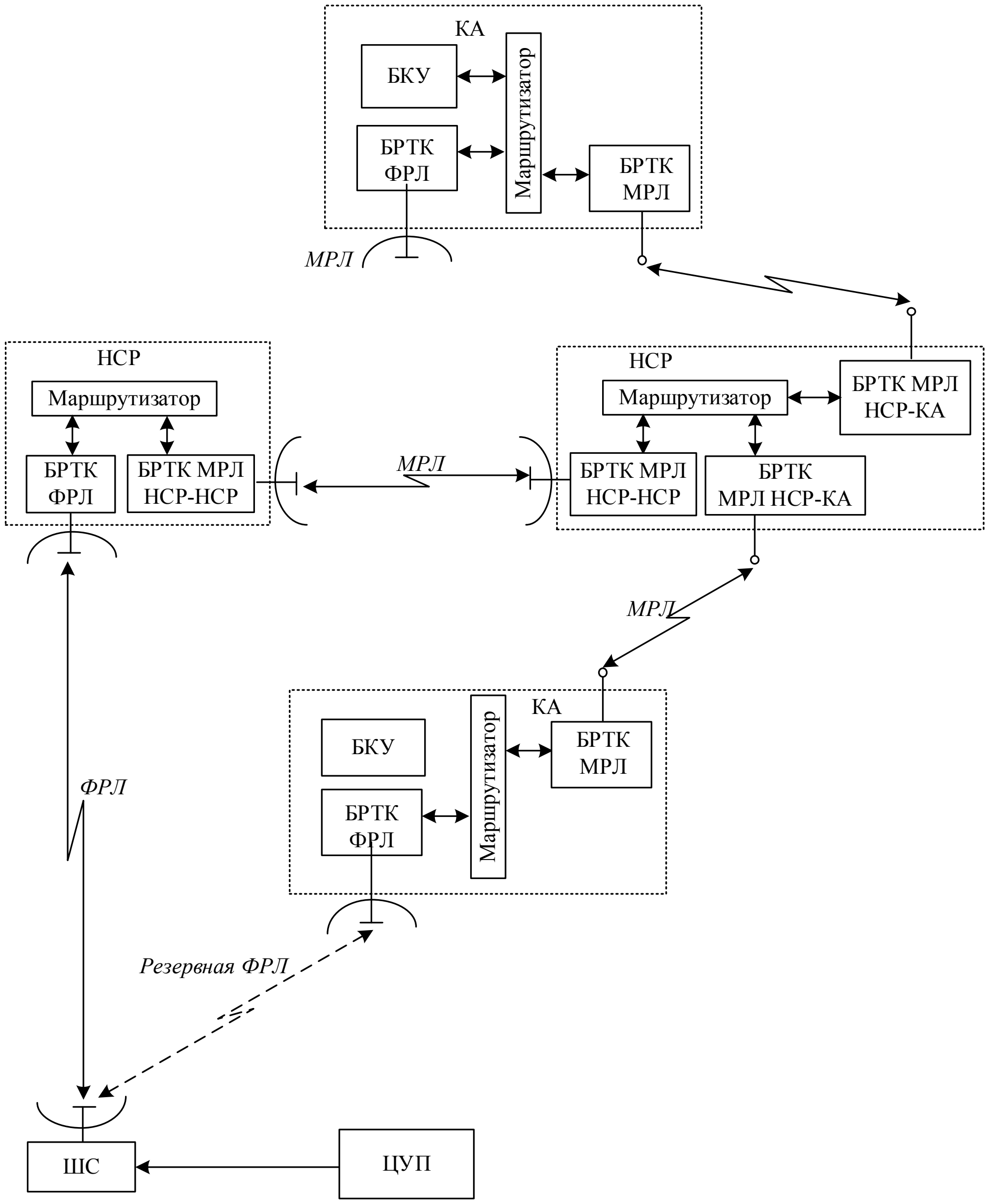

Fig. 5. An organizational chart of communication and control with the implementation of two LRSs.

– increase the bandwidth and the speed of information transmission (equal to and exceeding 10 GGbps).

Thus, for communication through an intersatellite radio link in V-band is most reasonable to use four pencil beam mirror antenna systems with a small diameter (up to 0.3 – 0.6 m) [7, 11], located along the X and Y axes of symmetry of the SC.

The implementation of the optical band in the ICL between LRS of the SCS [5, 6] will allow us to:

– reduce the dimensions by two to four times and the energy consumption of the onboard equipment of the intersatellite communication link in the future;

– significantly increase the bandwidth and information transmission rates (up to 10 GGbps).

Optical communication systems in the ICL, at the first stage of system operation, can be used alongside communication systems implementing the V-band radio ranges.

Optical receiving and transmitting antenna systems must be located along axes X and Z of the SC.

For communication via the Earth – SC RL (feeder communication link, FCL) it is most reasonable to resort to using the C, X, Ku or Ka-band, and it will be possible in the future to duplicate the radio channel by transmitting

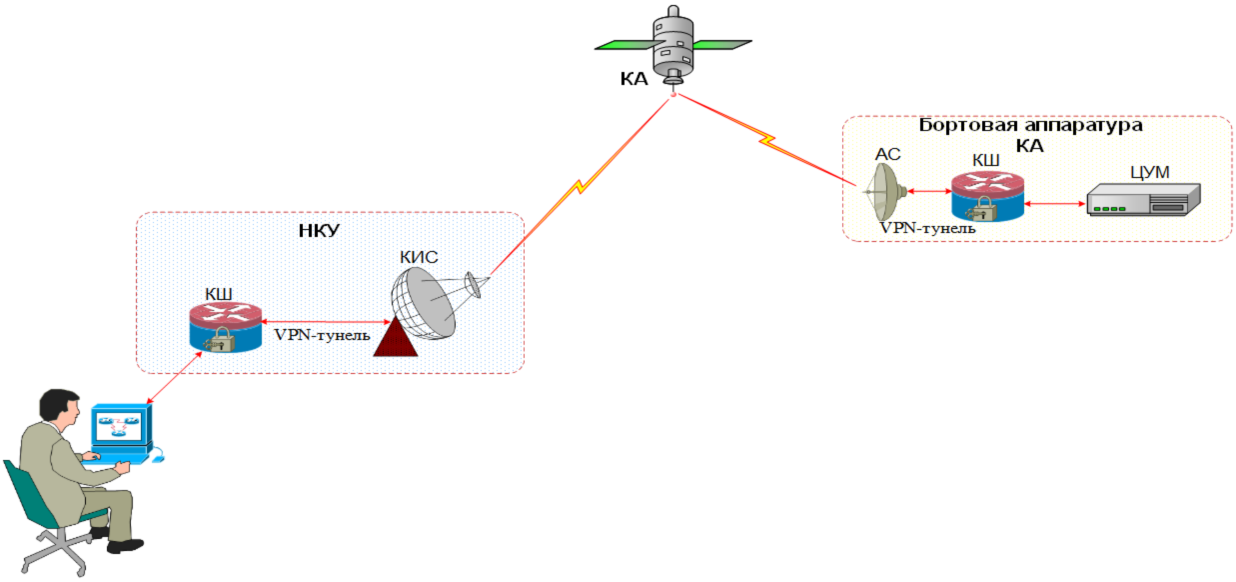

Fig. 6. Logical scheme of MCC operator access to the OE of the SC.

data in the optical range of radio waves [5, 6]. Due to the fact that every SC has a substantial radio coverage zone (RCZ), it is rare to have zone-wide poor weather conditions influencing atmospheric light transmission. Optical data traffic will be transmitted to a CAMS situated in favorable atmospheric light transmission conditions. Even if optical communication proves to be impossible in the given RCZ, it is possible to connect to a CAMS located in other RCZs via an ICL.

Therefore, for communication through the radio uplink (Earth-SC), it is most reasonable to install 1–2 pencil beam mirror antenna systems of a small diameter (up to 0.6 – 1 m) or a receiving and transmitting active phased array antenna (APAA) [5, 9]. Mirror antenna systems, APAA as well as optical receiving and transmitting antenna systems are to be located along the –Y axis of the SC and should be Earth-oriented.

The main flight control mode is remote access to the central controlling machine (CCM) of the SC onboard equipment (OE) achieved by setting up VPN-tunnels between the local area network (LAN) of the CCM and the LAN of the SC via wired and intersatellite communication links [1, 2, 5, 9]. Thus, MCC personnel are provided with remote access from their computers to the SC system control servers (controllers) and are able to promptly manage the OE of the SC by using specific software. A convenient windowed interface displaying images, graphs and tables will simplify the control system; improve its clearness, ergonomics and controllability along with reducing the decision-making time [5, 9].

Since the maximum information transmission rate in the flight control channel does not exceed 64 –128 kbit/s, it is possible to ensure the control of a large number of SC of a low-orbit OC via one or several CAMS at an objectively possible information transmission rate in the Earth-to-SC communication links and ICL.

The logical scheme of MCC operator access to the OE control system is given in Figure 6. [1, 2, 5, 9].

The main problem of flight control with the implementation of SCS on LEO RS, which are connected via ICL, is maintaining SC orientation accuracy during flight and pencil beam antenna array (AA) pointing accuracy. In the event that one or several SC in the OC fail, a way around them can be found with the use of dynamic routing protocols [5, 9], yet, in this case, arises the problem of gaining access to the SC, which had lost its orientation. For these purposes, at least two-four-six wide-beam AAs are available onboard, which ensure a low-speed emergency radio link with a CAMS of the ground-based control unit.

In the case of emergencies, for example loss of SC orientation, as well as during orbital insertion and disorbit, the CAMS of the ground-based control unit is capable of establishing a connection with the SC via wide-beam AAs on the SC through the ICL or a ground-satellite uplink.

The implementation of SCS based on low-orbit relay satellites, interconnected by ICLs, has all of the advantages as the methods described in part 1 but, unlike SCS based on geostationary relay satellites, it demonstrates additional advantages:

1) a smaller distance from the CAMS and GS to the SC and, as a result, data transmission delays are shortened and, thus, control efficiency is boosted;

2) apart from this, for this precise reason, the energy budget of the SC-SC radio link is reduced, which allows the use of wide-beam antenna systems based on LRS and SC. Thus, opens up the possibility of relaying control commands to a large quantity of SC without having to track them by pencil beam antenna systems.

3) has a high level of redundancy and, as a result, is highly reliable because the failure of several LRS, which can be easily be bypassed via ICL, cannot in any manner affect the timely delivery of the control channel information.

Conclusion

The comprehensive use of all of the abovementioned methods for solving the problem of boosting the efficiency of the SC flight control system provides the following advantages:

- control flexibility and agility;
- flight control system high reliability;
- provides a highly ergonomic and modern approach to solving the problem of control.

The implementation of data transmission protocols, which are standard for computer networks, (TCP/IP) will allow the implementation of standard network equipment (custom-made) and standard software for both building spacecraft onboard equipment and building onboard and ground-based control units. This will significantly simplify the flight control system and the architecture, and lower the production costs.

The flight control algorithms and architectural solutions for ground control and onboard control systems described in the paper make it possible to create a universal and reliable, dynamic and efficient communication and flight control system for any SC.

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