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Advanced Technique of Spacecraft Flight Control of One Orbital Constellation Using Intersatellite Radio Links

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Abstract. The paper is devoted to the problem of boosting the effectiveness of the flight control system for spacecraft in an orbital constellation. The paper offers to apply modern transferring methods using the TCP/IP protocol stack and to employ up-to-date methods of remote control. The concept of creating orbital constellations with spacecraft interrelated by intersatellite radio links will allow one to control the entire orbital constellation in quasi-real time. Thus, the orbital constellation will be a digital network of data transfer, where each spacecraft will function as a relay satellite to transfer control data to any spacecraft, as well as serve as an object to be controlled. The article gives a justification to use the above-mentioned technologies, and graph and network schemes for linkage to control spacecraft flight.

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

Introduction

One of the main requirements for spacecraft flight control systems is efficiency. Our country's traditional spacecraft flight control systems permit to pass control data to and from the satellite only when the spacecraft is in the radio coverage zone of one of the ground-based command and measurement complexes (CAMC). Thus, for most of the flight time there is no connection to the spacecraft. One of the solutions to this problem is creating a two-tier configuration of control and communication with the use of three–four geostationary relay satellites (GRS) [1, 2, 3, 4, 5]. With the help of an intersatellite radio link, it is possible to provide one CAMC with a 24-hour link to any satellite (to one, several or all at once). This direction of development of spacecraft (SC) flight control is present-day and advanced, yet it does not lack such limitations as latency. The altitude of geostationary relay satellite orbits (circa 36,000 km) conditions latency. This results in large distances between two orbital slots.

Figure 1 depicts the link configuration (orbital segment) for connecting to a satellite via four GRS.

Figure 2 shows the generalized scheme of the link configuration for connecting to a satellite via three GRS.

1. Topological model of a communication and flight control system for an orbital constellation using intersatellite radio links

1.1 Communication link configuration and network architecture

The orbital arrangement of a single satellite constellation is a certain amount of spacecraft located in several orbital planes (OP) — e.g., satellite constellations for Earth remote sensing (ERS), satellite communication systems in medium-Earth orbit (MEO SCS) or low-Earth orbit relay satellites (LEO RS), satellite navigation systems.

Neighboring spacecraft belonging to one constellation should be connected using intersatellite radio links in such a manner so that every spacecraft is connected to four neighbor satellites in a single or in adjacent OPs. Therefore, the orbital constellation will form a fully connected satellite network for data transmission, where every spacecraft is a satellite router with its own information input/output ports:

– 1 global network port – connection to a command and measurement station (CAMS) – radio data downlink

– 4 global network ports – for retransmitting data to neighbor satellites using intersatellite radio links

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

Such architecture is employed on the Iridium satellite system and has the following advantages:

1) it allows to create a flexible network, where adaptive routing protocols can be implemented to build any data transfer route:

a) with a minimum length path for real-time traffic;

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

c) 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) shows 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 communication link configuration (consisting of six OPs with twelve SC on each OP) for flight control of a space communication system (SCS) orbital constellation (OC) is given in Figure 3. The system uses LEO relay satellites.

Figure 4 shows the orbital constellation flight control network architecture.

1.2 Intersatellite radio link (IRL)

For communication via an IRL, it is sensible to use bands K, Ka, V and Q, and, eventually, switch to transmitting data using frequencies of the optical spectrum.

The use of bands K, Ka, V or Q will permit to do the following [10]:

– reduce the dimensions of antenna-feeder devices (AFD) and UHF-equipment;

– reduce the energy consumption of AFD and UHF-equipment pointing systems;

– broaden bandwidth and increase data rates (from 300 Mbit/s to 1 Gbit/s);

– surmount the limitations of radio link energetics that exist for lower frequency ranges due to high load levels.

Therefore, for communication via IRL using bands K, Ka, V or Q, it is reasonable to employ four pencil beam

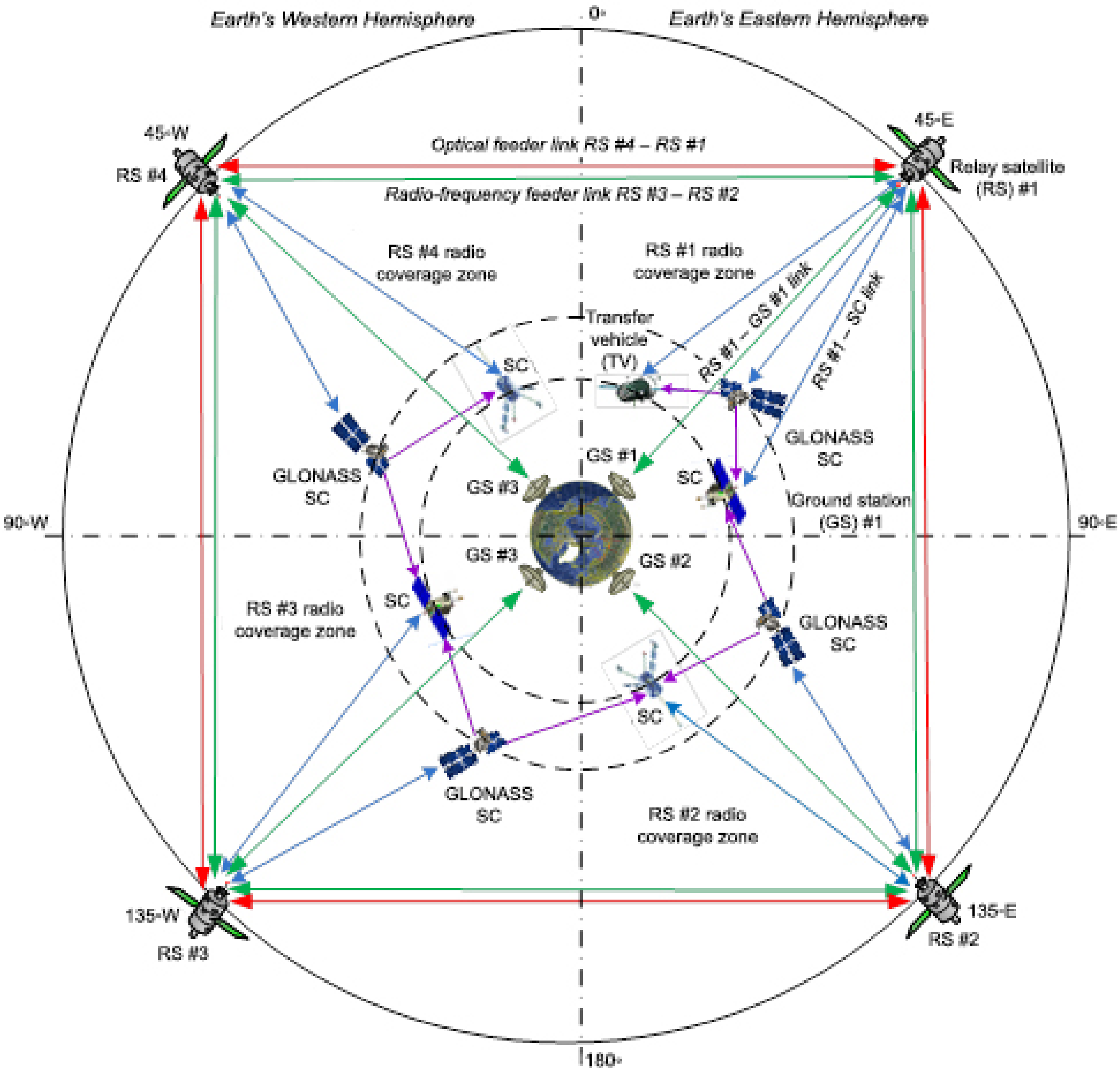

Fig. 1. Link configuration (orbital segment) for connecting to a satellite via four GRS

reflector antenna arrays (AA) with a small diameter (up to 0.3–1 m) [10] located along spacecraft X and Z axes of symmetry.

The use of the optical spectrum will allow us to:

– reduce future AA and UHF-equipment dimensions by four-fold;

– cut down energy consumption of AA and UHF-equipment pointing systems;

– substantially broaden bandwidth and increase data transfer rates (up to 10 GGbit/s);

– lift the existing restrictions of radio link energetics for radio frequency bands.

At first, optical communication systems for IRLs can be used in parallel with radio band communication systems.

Laser receiving-transmitting antenna arrays should be located along axes X and Y of the spacecraft.

1.3 Radio uplink

For communicating via a radio uplink, it is reasonable to use bands Ka, V or Q and, with time, pass on to creating an optical data transmission backup link. Due to the fact that each SC has a sizeable radio coverage

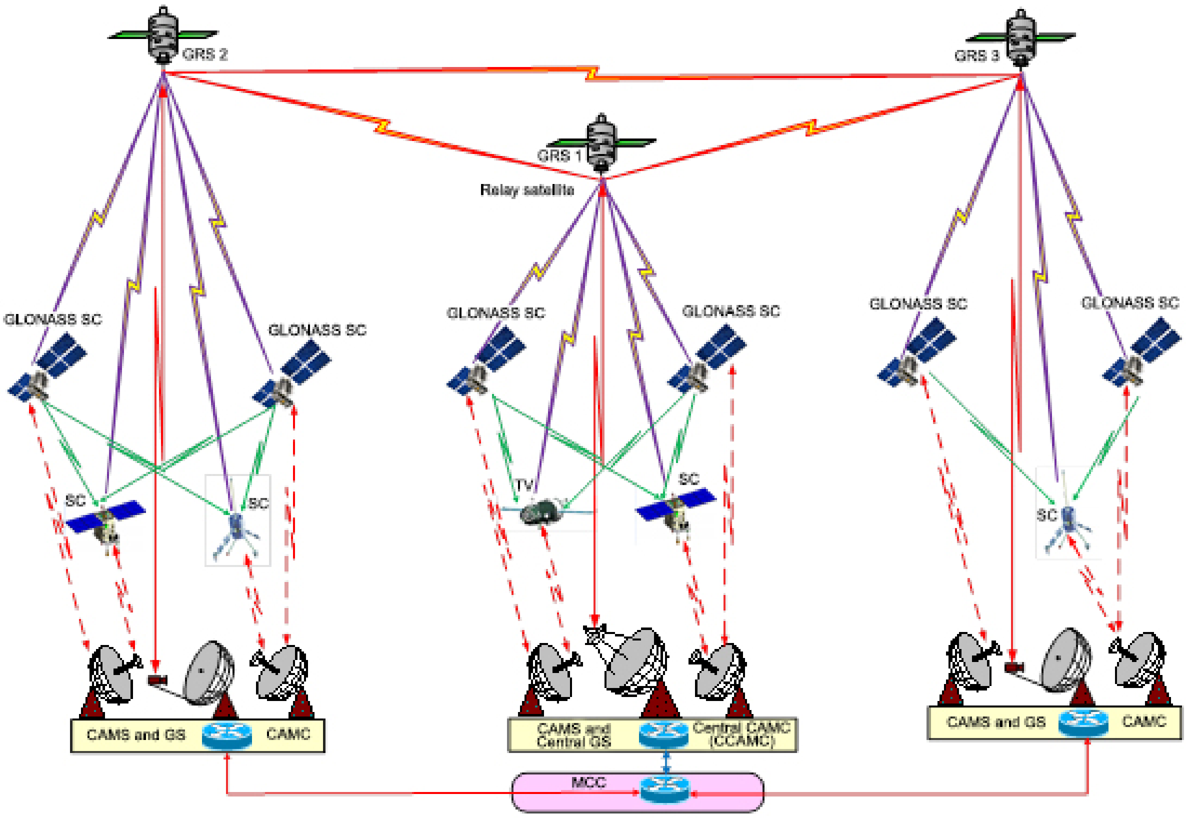

Fig. 2. Generalized scheme of link configuration for satellite connection via GRS

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 CAMSs located in other RCZs via IRL.

Thus, for a radio uplink in the Ka, V or Q bands it is, once again, more sensible to use one pencil beam reflector antenna array of a small diameter (up to 0.3–1 m). Reflector antenna arrays, laser receiving-transmitting antenna arrays should also be Earth-oriented and located along the minus-Y axis of the SC.

1.4 Link organization topological diagram

For a more detailed look at the configuration of CAMS–SC communication, a topological model of the scheme is given below in the form of a graph. The configuration scheme of intersatellite links is depicted in Figure 5. In Figure 4, we see that in the presence of intersatellite links in the SC–SC communication channel the graph becomes fully connected. Full-connectedness indicates that there are several routes from the CAMS-1 initial vertex to the SC-N terminal vertex. This improves communication system flexibility and fault-tolerance. Dynamic routing protocol implementation will be instrumental in fulfilling the tasks of routing and connection set-up in automatic mode [7, 8, 9].

The logical topology of the SC–SC connection scheme is “every satellite with every adjacent satellite”, while the logical topology of the SC–CAMS communication is “point-to-point”. This statement is the result of the SC connection logic given below.

The topological diagram of MCC–SCS OC SC on LEO via IRL communication configuration is presented in the form of a graph in Figure 5.

1.5 SC and CAMS IP-addressing

Protocol IP v.6 is applied for addressing in an OC network.

The first 48 bits of the IP-address (numbers in the first, second and third octets) are the address of the OC network and are assigned by the international committee to the entire network.

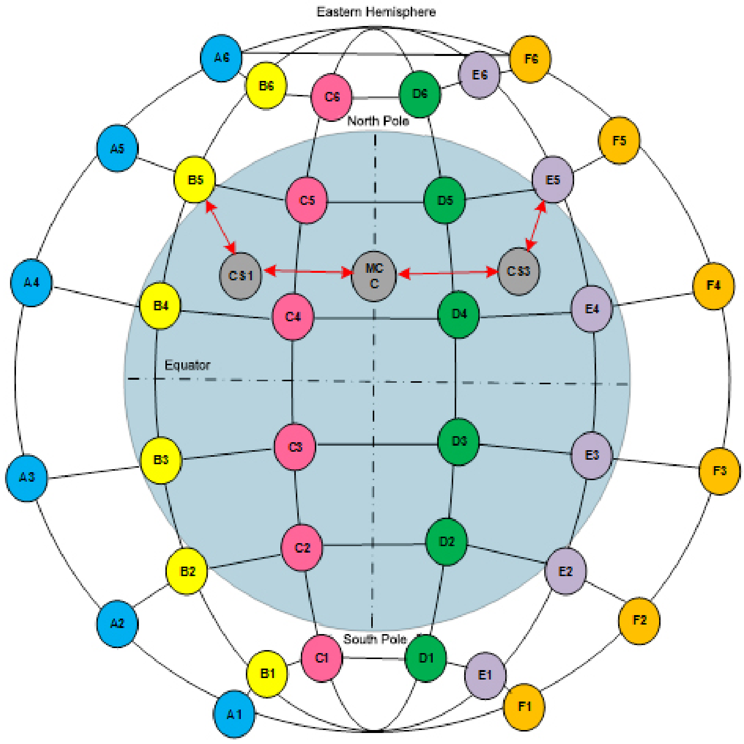

Fig. 3. Communication link configuration for flight control of SCS OC using LEO RS

Notation keys:

MCC – Mission Control Center (MCC)

CS 1 – CS 2 – CAMS #1 – CAMS #3

A1 – A6 – low-Earth orbit SC of OC #1, lettered A

B1 – B6 – low-Earth orbit SC of OC #2, lettered B

C1 – C6 – low-Earth orbit SC of OC #1, lettered C

D1 – D6 – low-Earth orbit SC of OC #1, lettered D

E1 – E6 – low-Earth orbit SC of OC #1, lettered E

F1 – F6 – low-Earth orbit SC of OC #1, lettered F.

The last 48 bits of the IP-address (fourth quartet) are the node address.

The middle 32 bits of the IP-address are the subnet address and are reserved for specific tasks.

For illustrative purposes, the SC and CAMP IP-address structure is given in the form of a table (Table 1).

The first number in the fifth octet represents SC priority; the second number in the fifth octet stands for traffic priority.

The third and fourth numbers of the fifth quartet denote the number of the SC, where the first number defines the orbital plane and the second number denotes the SC number on the orbital plane, e.g., A2.

For specifying the CAMS, the number of the CAMS should be indicated.

Radio link identifiers should be given in the sixth and seventh octets.

The first number in the sixth quartet represents the RL type and takes on the following values:

– 1 – for radio uplink;

– 2 – for intersatellite radio link (IRL);

The second number of the sixth quartet stands for the band, which can either be radio or optical-spectrum frequency:

– number 1 denotes optical spectrum frequency,

– number 2 stands for radio band.

The third number of the sixth quartet represents the number of the AA, the fourth number in the sixth quartet shows the type of tranceiving equipment:

Table 1. SC IP-address structure

<table>
<tr><td colspan="4">1</td><td colspan="4">2</td><td colspan="4">3</td><td colspan="4">4</td><td colspan="4">5</td><td colspan="4">6</td><td colspan="4">7</td><td colspan="4">8</td></tr>
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<tr><td colspan="12" rowspan="2">OC network</td><td colspan="4" rowspan="2">Reserved</td><td colspan="2">Priority</td><td colspan="2" rowspan="2">SC #</td><td colspan="8">Radio link</td><td colspan="2" rowspan="2">Reserved</td><td colspan="2" rowspan="2">SC equipment #</td></tr>
<tr><td>SC</td><td>Traffic</td><td>RL type</td><td>Radio/optical</td><td>AA #</td><td>RCV/XMIT</td><td>Equipment unit #</td><td>Band</td><td colspan="2">Subband</td></tr>
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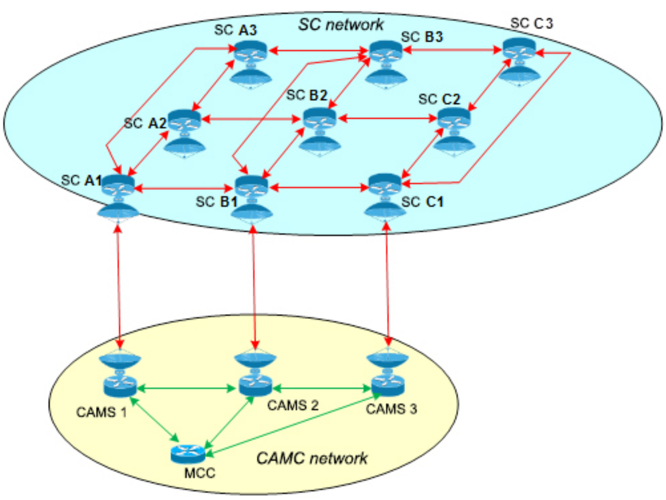

Fig. 4. Orbital constellation flight control network architecture

– number 1 – receiver,

– number 2 – transmitter.

The first number in the seventh quartet stands for the tranceiving equipment unit number; the third and fourth numbers represent the bandwidth and subband, respectively.

The first and second numbers of the eighth octet denote the spacecraft equipment type:

– number 1 – service,

– number 2 – special.

The third and fourth numbers of the eighth octet are the SC equipment number.

2. OC SC flight control system operation algorithms

2.1 The use of IRL for real-time SC flight control

Connected via IRL, orbital constellation SC form a global satellite data communication network. A CAMS, by establishing communication with a single SC in its radio coverage zone, gains access to all of the spacecraft in the constellation. Full-time communication with any SC using one or several CAMS is achievable by switching from one SC to another.

To give an understanding – the implementation of the TCP/IP protocol stack (widely used in present-day local area and distributed communication networks [1, 2]) is considered to be an advanced approach to data processing and transmission (carried out by the onboard equipment (OE) of the spacecraft as well as by ground-based wired and satellite communication networks).

The basic flight control mode is remote access to the central controlling machine (CCM) of the SC OE by means of setting up VPN tunnels connecting the MCC local computer network (LCN) and the spacecraft LCN via wired and intersatellite links [7, 8, 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

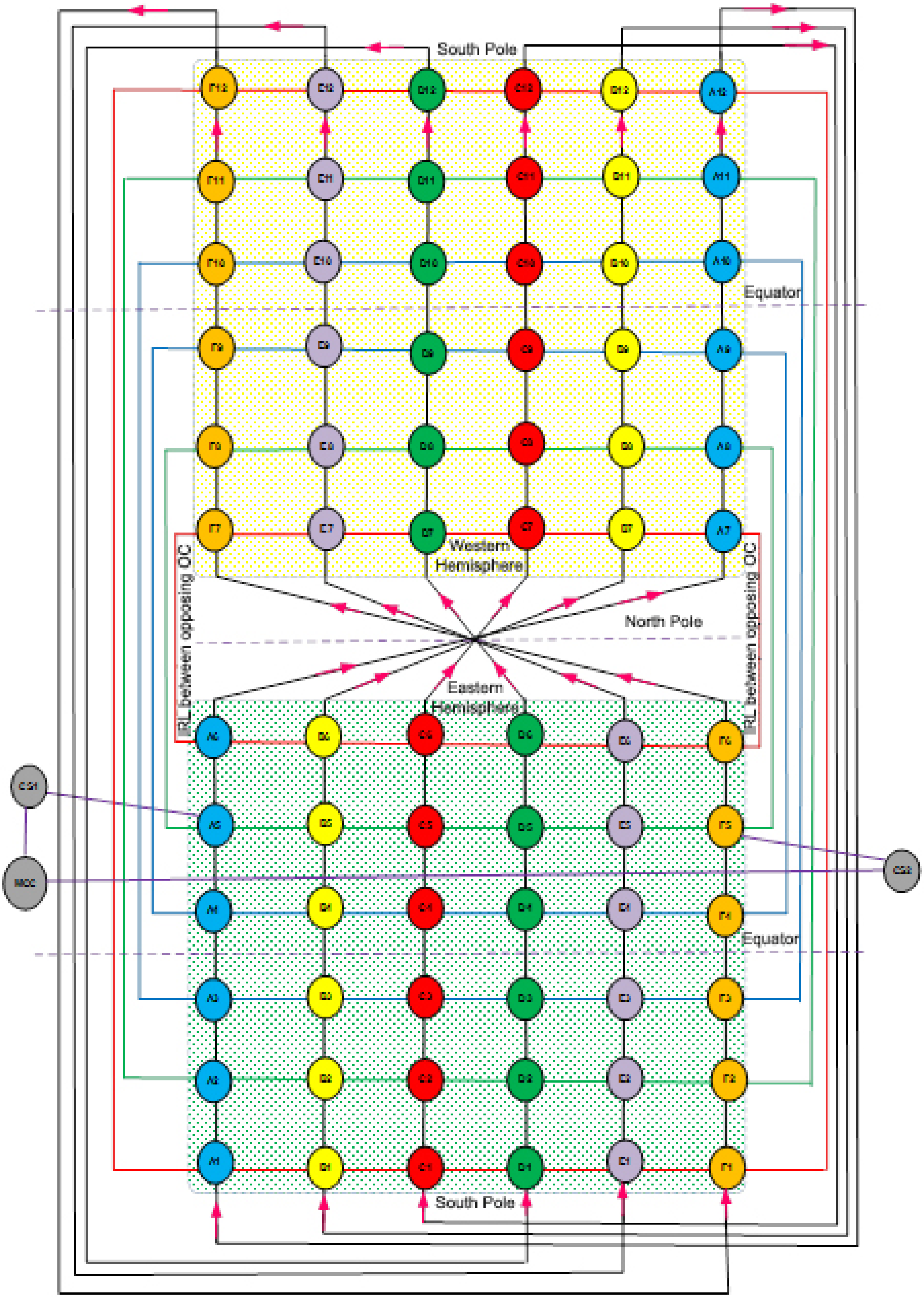

Fig. 5. MCC–SCS OC SC on LEO via IRL communication configuration scheme in the form of a graph

Table 2. Requirements for control data transmission rates through a link

Mode	Access Protocol	
Text	remote control – Telnet protocol implementation	from 9.6 kbit/s
Graphics	WEB-interface access	from 64 kbit/s
	Telemetry data reception, imaging and command – SNMP protocol implementation	from 64 kbit/s
	Desktop access – VNC system and RDP protocol implementation	from 128 – 256 kbit/s
	Telemetry data reception, imaging and command – SCADA system implementation	from 9.6 kbit/s

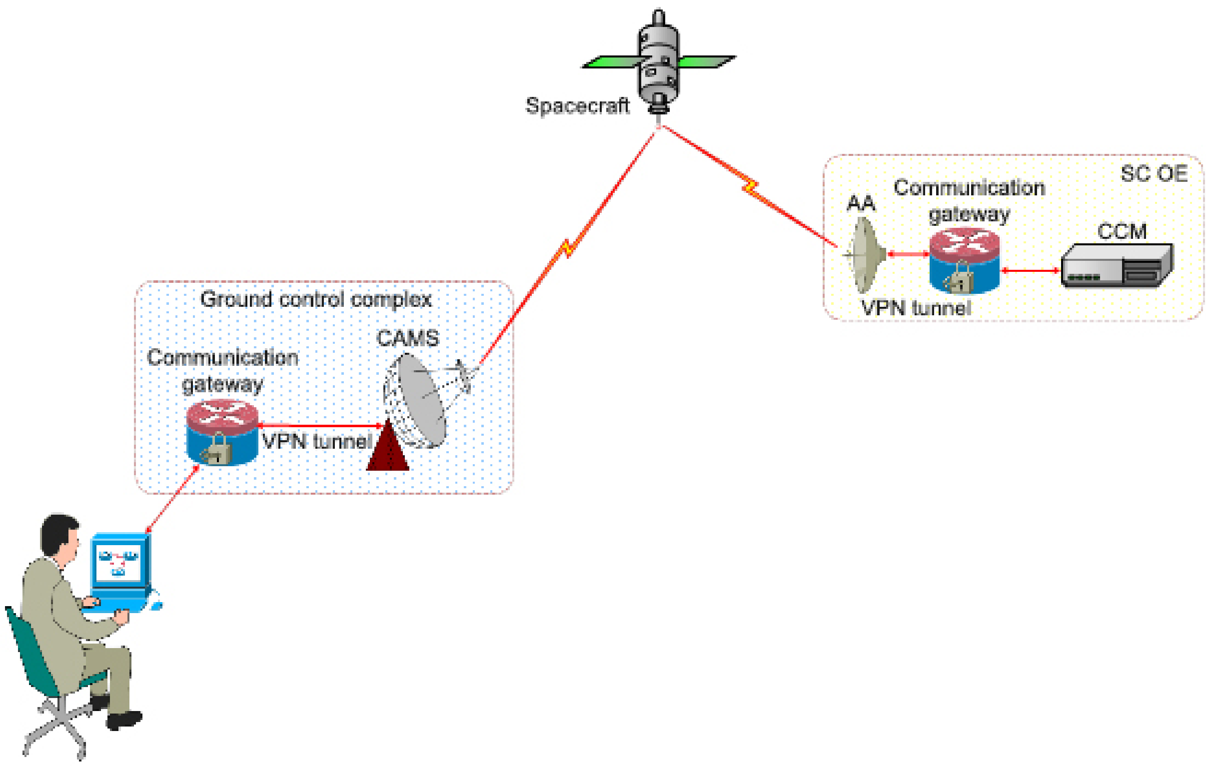

Fig. 6. Logical scheme of MCC operator access to the OE control system.

control system, improve its clearness, ergonomics and controllability along with reducing the decision-making time [1, 2]. The implementation of the TCP/IP protocol stack allows the transmission of flight control channel traffic and SC special purpose equipment data channel traffic through one radio link. For this purpose, the LCN is divided into two VLANs (Virtual Local Area Network): SC service-equipment-VLAN and SC special-purpose-equipment VLAN. With this in mind, the SC special-equipment VLAN is assigned the highest priority [7, 8, 9]. Transmitting overall SC traffic through a single radio link allows us to unify ground receiving stations (gateway stations) and CAMS.

The implementation of the TCP/IP protocol stack permits the usage of the following popular remote access protocols for SC onboard equipment control:

1) for text mode – tenet, SSH;
2) for graphics mode:

a) for WEB-interface access – HTTP protocols;

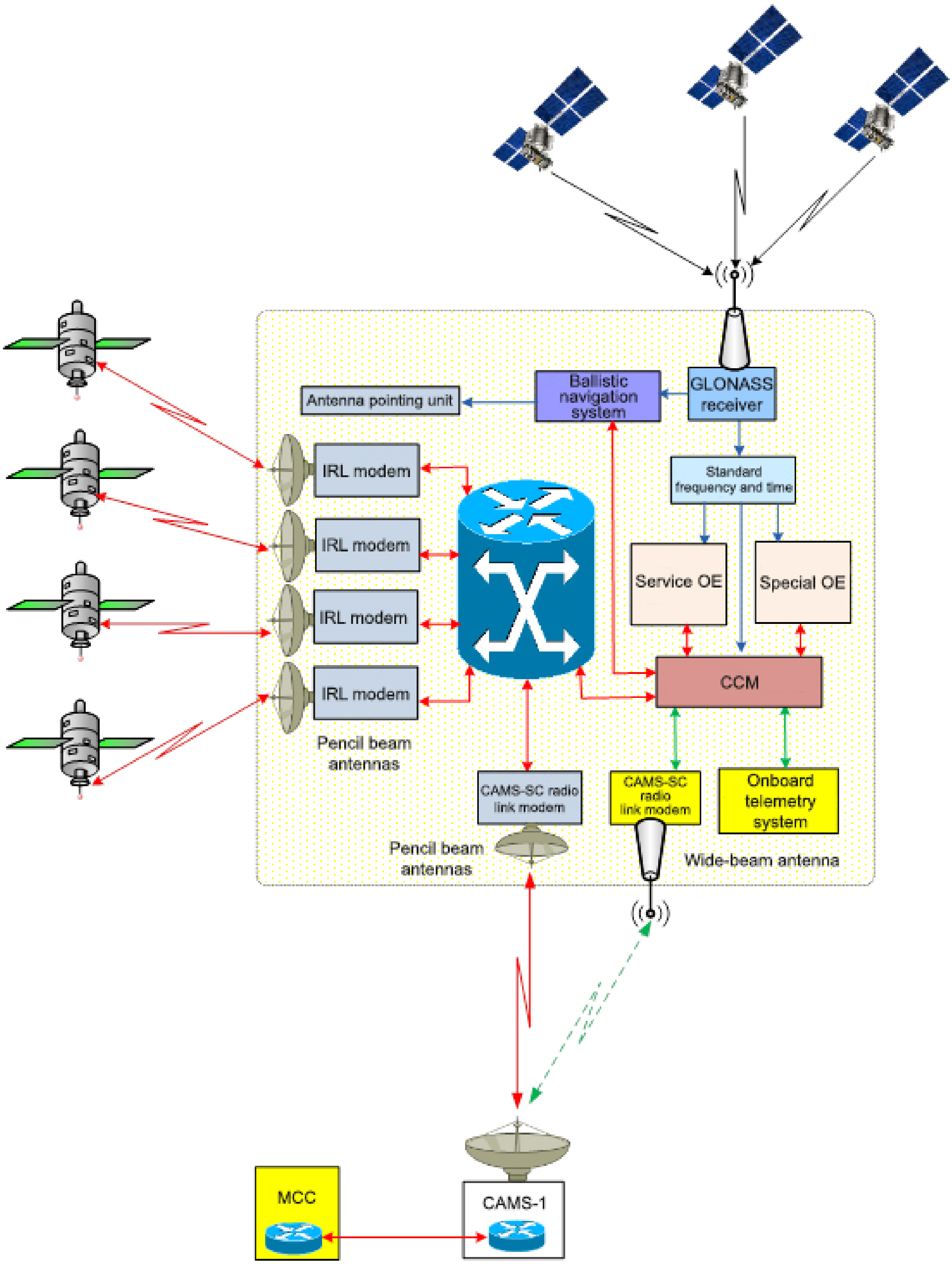

Fig.7. SC OE network architecture.

b) for desktop access – VNC (Virtual Network Computing) system (using the RFB (Remote Frame Buffer)protocol), RDP (Remote Desktop Protocol) – for example, Remmina Remote Desktop Client software;

c) for remote control – such computer network management protocols as SNMP (Simple Network Manager Protocol);

d) for remote control – SCADA (Supervisory Control And Data Acquisition) protocols, implemented for managing ground-based infrastructure elements of critical importance.

When remote access protocols are implemented, the MCC staff computer functions as a client, while the MCC or other SC onboard equipment that has controllers or management servers operates as a server.

The requirements for control data transmission rates through a link are set forth in Table 2.

Based on the information in Table 2, with an actual data transfer rate via ground-satellite uplink or IRL to pencil beam AA ranging from 300 Mbit/s, it is possible to control the entire OC using one or several CAMS.

The logical scheme of MCC operator access to the OE control system is given in Figure 6.

The network architecture of the spacecraft onboard equipment is shown in Figure 7.

2.2. Exploitation of traditional SC flight control technologies in the event of a contingency

The main problem of flight control through IRL is SC orientation accuracy during flight and pencil beam antenna array (AA) pointing accuracy. In the event of a single or multiple SC failure in the orbital constellation a way around them may be found by implementing dynamic routing protocols [7, 8, 9]. Yet, in this case, the issue of gaining access to the SC that lost its orientation arises. Consequently, there are at least two wide-beam AAs located along the spacecraft plus-Y and minus-Y axes of symmetry. They ensure a low-speed emergency radio link with a CAMS.

In the case of contingencies (for example, SC orientation loss), as well as during orbital insertion and disorbit, the CAMS is able to establish a connection with the SC via wide-beam AAs on the SC through the IRL or a ground-satellite uplink. However, the data link transfer rate will be low, ranging from 4.8 to 12 kbit/s. This is why it is necessary to switch to conventional SC flight control system mode – i.e., issuing control commands to the OE and receiving acknowledgement and telemetry data from the OE. Essentially, conventional SC flight control system mode will be a back-up mode for non-standard operating situations and it will help to ensure flight control system fault-tolerance.

Conclusion

The proposed control algorithm possesses the following advantages:

– control flexibility and agility

– flight control system high reliability

– provides a highly ergonomic and modern approach to solving the problems of SC flight control.

The implementation of TCP/IP protocols for computer networking will allow the usage of standard network equipment (custom-made) and standard software for building spacecraft OE along with setting up ground control complexes. This, in its turn, will significantly simplify the flight control system and 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 comprehensive and reliable, dynamic and effective communication and flight control system for SC in a single orbital constellation.

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