APPLICATION OF PHASED ANTENNA ARRAY WITH DIGITAL BEAMFORMING TO ESTABLISH THE INTERNAL RADIO NETWORK OF THE DISTRIBUTED SATELLITE

[1]Mikhail ILCHENKO, [1]Teodor NARYTNYK, [2]Vladimir PRISYAZHNY, [2]Sergii KAPSHTYK, [1]Maxym DENISENKO, [1]Alexandra NARUSHKEVICH

[1]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine.
[2]National Space Facility Control and Test Center, Kyiv, Ukraine.

E-mail: ilch@kpi.ua;
director@mitris.com;
maxdeniss56@gmail.com;
sashanarushkevych@gmail.com;
ncuvkz@spacecenter.gov.ua;
sergii.kapshtyk@gmail.com

Abstract

The possibility of application of the Phased Antenna Array with Digital Beamforming (PAA-DB) to establish the Internal Radio Network (IRN) of the Distributed Satellite (DS) is shown, which allows increasing the efficiency of the IRN by using the spatial separation of information flows between Core and Edge Satellites. The issues considered are related to choosing the Reference Coordinate System in which it is proposed to measure the relative motion of the satellite of the DS. An Orbital Coordinate System of the Core Satellite is proposed as the Reference Coordinate System. It is shown how the information about the coordinates of the Edge Satellites in the Orbital Coordinate System of the Core Satellite enables to obtain information about the coordinates of the Edge Satellites in the Orbital Coordinate System by the method of recalculation.

Introduction

The 20s of the XXI century have become rich for active implementation of several projects on the creation of the Low-Earth-Orbit (LEO) Satellite Telecommunication Systems. Today, at least two LEO Internet Broadband Access Satellite Systems, like Starlink and OneWeb, are in the stage of active satellite constellations formation. 1,842 Starlink satellites have already been launched into an LEO with an altitude of 547 km. 358 OneWeb satellites have been launched into LEO at 1200 km altitude. Thus, at least two groups of telecommunication satellites, unprecedented in their numbers, are being formed on LEO. According to their plans, only these two satellite systems announce that more than 20 thousand satellites to be launched in total during the next ten years. The main goal of the Starlink and OneWeb orbital constellations being formed is to provide Internet Broadband Access Services for various groups of customers.

In parallel with the services and infrastructure development for Internet Access, services based on the protocols and infrastructure of Internet Networks are being developed. These services include the Internet of Things (IoT) and its industrial implementation, the Industrial Internet of Things (IIoT). The prospects for the IoT and IIoT services implementation stimulate the growth of demand for bandwidth regardless of the telecommunications infrastructure development level at the service provider location. Terrestrial 4G and 5G Generation Mobile Networks do not provide total and continuous coverage, as from the economic point of view these networks' deployment corresponds with the population density in the service area. Areas with low population density do not provide acceptable cost-effectiveness for 4G and 5G Networks.

1 Tasking

The term "Distributed satellite" (DS) defines a Micro-Constellation of Microsat and CubeSats that perform a functionality simultaneously and perform a group flight near one another [3,4]. The DS technology implementation enables the utilization of small spacecraft to perform functionality that, for various reasons, cannot be performed through one large spacecraft utilization. The DS peculiarities include the distribution of the payload over several spacecraft, which, in aggregate and during the interaction, makes it possible to ensure the efficient performance of a functional task. In this case, the spacecraft payloads inside the DS can be duplicated, or it can be unique for this DS.

There are two approaches in the DS Architecture: Centralized or Hierarchical, and Decentralized [2]. In the Centralized Architecture, the DS includes one central or Core, satellite, and several Edge Satellites. As a rule, the Core Satellite is a Microsatellite, and the Edge ones are nanosatellites or CubeSats. The DS Core Satellite provides flight control of all satellites involved in the DS, control of the Edge Satellites interaction to perform DS functional tasks, and interaction with other DS from the Satellite System. Edge Satellites perform limited functional tasks.

To ensure information interaction between satellites inside the DS, an Internal Radio Network (IRN) is established. The IRN goals are:

- providing information exchange between the Core and Edge Satellites as part of the DS for the satellite's payloads to carry out tasks for the functional purpose of the System;
- ensuring the transmission of command and telemetry information between the Core and Edge Satellites from the DS and the Ground Control Complex (GCC) of the System;
- Edge Satellites positioning and movement measurements about the Core Satellite to ensure the flight safety of the DS subordinates.

IRN is built based on the mobile broadband standard proposed by the 3GPP research group, subject to its adaptation to the application peculiarities as part of the space system [2]. Among the advantages of these standards, there are built-in mechanisms occurrence for measuring the mutual range between subscribers of the radio network and ensuring the subscriber's operation synchronization. Paper [4] considers the possibility of the WiMAX protocol utilization for the IRN construction and suggests ways for modifying this protocol to adapt to the providing peculiarities of information exchange between DS subordinates.

The application of the multiple access method based on Orthogonal Frequency Division Multiplexing (OFDM) and MIMO (Multiple Input Multiple Outputs) technologies is a peculiarity of the 3GPP group protocols. The MIMO technology allows for increasing the efficiency of the network operation via spatial selectivity, which allows for reducing energy costs, reusing the allocated frequency band, and improving the quality and, consequently, the speed of information transmission in the network.

All satellites subordinates from the DS perform a group flight at a distance of no more than 1 km from one another. This distance is significantly less than the currently accepted flight safety standards for space objects. Therefore, when developing the DS technology, a particular concern is being given to providing the measurement of the relative motion parameters of satellite subordinates in the DS. The report [5] presents the results of two CubeSats' mutual motion modeling on LEO and predicts their relative position changes based on the information utilization from the GPS. However, such a solution requires permanent GCC support for spacecraft functioning.

In paper [6], the method based on slant range measurement was proposed for the DS Edge Satellites' relative motion parameters, which are supported by the built-in mechanisms of the IEEE 802.16 protocol family, subject to their adaptation to the satellite system's peculiarities. However, the proposed method also requires periodic support from the GCC.

2 Parameters of the Edge Satellite's relative motion inside the Orbital Coordinate System of the Core Satellite

To ensure the DS spacecraft-subordinates' flight safety an important issue is the choice of a Reference Coordinate System in which the relative motion of the satellite will be measured. As the DS Reference Coordinate System, the Body Reference Coordinate System (BRCS) of the Core Satellite $OX_0Y_0Z_0$ can be chosen, since the Core Satellite provides the movement control of the DS Edge Satellite. Figure 1 shows the Coordinates Determination Scheme for the Edge Satellites in the Core Satellite's BRCS. The BRCS Center is located at the Center of Mass of the Core Satellite (point O in Fig. 1). The OX_0 axis is directed along with the satellite movement, the OY_0 axis is located in the orbital plane and is in the opposite direction from the Earth's Center, and the OZ_0 axis complements the Coordinate System to the right [7]. The Core Satellite Orbital Coordinate System (OCS) $OX_gY_gZ_g$, which is used in Flight Dynamic Calculations, is uniquely associated with the Core Satellite's BRCS. The OCS center coincides with the BRCS Center and is located in the Center of Mass of the Core Satellite. The BRCS and OCS axes deviation is determined by the Onboard Attitude Control System Sensors' parameters of the Core Satellite. Information about the Edge Satellites' coordinates within the Core Satellite's $OX_0Y_0Z_0$ BRCS enables obtaining information about the Edge Satellites' coordinates inside the $OX_gY_gZ_g$ OCS via the recalculation method.

The Edge Satellites' location in the Core Satellite's $OX_0Y_0Z_0$ BRCS is determined by three parameters (see Fig.1): ranger *r*, the angle θ between the direction to the Edge Satellite and the OX_0 axis, and the angle φ between the direction to the Edge Satellite and the OZ_0 axis. The given parameters determine the $\vec{R}$ vector length and orientation of the Edge Satellite location in the Core Satellite BRCS.

The slant range measuring technique, which assumes the 3GPP Group protocols adaptation to operating terms inside the DS was given in the paper [6].

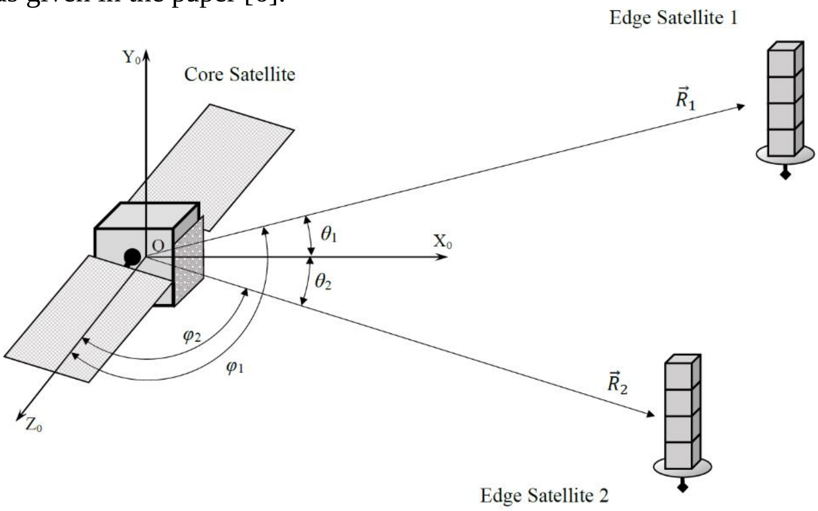

Fig.1. The Edge Satellites coordinate determination in the Body Reference Coordinate System of the Core Satellite

For the IRN Establish, the Core Satellite is equipped with a Phased Antenna Array with Digital Beamforming (PAA-DB). Radio-technical measurements, which are performed with the PAA-DB application, are being executed in $OX_pY_pZ_p$ PAA-DB Coordinate System (Fig.2). The PAA-DB CS Reference Point (see point O, Fig.2) is located in the center of the PAA-DB Aperture Plane. The X_p and Y_p axes are located in the PAA-DB plane. The Z_p axis is located perpendicularly to the PAA-DB aperture plane.

In the the $OX_pY_pZ_p$ PAA-DB CS, the $\vec{R}_1$и $\vec{R}_2$ vectors' directions, which characterize the Edge Satellites 1 and 2 (see Fig.1) relative position, are determined by the pare following angular parameters: the angles of deviation of the $\vec{R}_1$ or $\vec{R}_2$ vectors from the OZ_p axis, which correspond to angles θ_1 and θ_2 respectively (see Fig.2) and by azimuth angles, i.e. deviations of the $\vec{R}_1$ and $\vec{R}_2$ vectors' projections onto the PAA-DB OX_pY_p aperture plane from the direction of the OX_p axis - which correspond to angles α_1 and α_2 respectively. An alternative option is to describe the $\vec{R}_1$ and $\vec{R}_2$vectors orientations in the PAA-DB CS via two pairs of angles: the α_1 azimuth angle which is the angle between the $\vec{R}_1$vector's projection onto the PAA-DB aperture plane and the OX_p axis, and the β_1 elevation angle which is the angle between the $\vec{R}_1$vector and its projection onto the PAA-DB OX_pY_p aperture plane. In case of $\vec{R}_2$ vector, a pair of angles α_2 and β_2.

As can be seen from Fig.1, the PAA-DB Center Point of origin location differs from the location of the center of mass of the root satellite. This difference is determined by the PAA-DB location within the Constructive Coordinate System (CCS) of the Core Satellite, which coincides with the BRCS, but differs in the direction of the axes and the point of origin of coordinates [8]. The PAA-DB Center Point of origin displacement and the deviation of the DAA $OX_pY_pZ_p$ axes' orientation from the $OX_0Y_0Z_0$ ASC are being determined during the design and manufacturing process of the satellite – Core Satellite at the stage of the Testing in the facilities of the Assembly Plant. These parameters are included in the Design Data Package of the Core Satellite's PAA-DB and are registered in the form of constants into its test tag and into the database to consider when making measurements inside the DS and performing further flight dynamic calculations.

Thus, the 3GPP Group protocols utilization for IRN implementation in combination with PAA-DB installed in the Core Satellite makes it possible to measure the relative location of the DS Edge Satellites within the Core Satellite's BRSC. As a result of measurements for each Edge Satellite a parameters cluster is formed that uniquely locates the Edge Satellite coordinates in a Rectangular Coordinate System: the *r* slant range and two angles θ and φ.

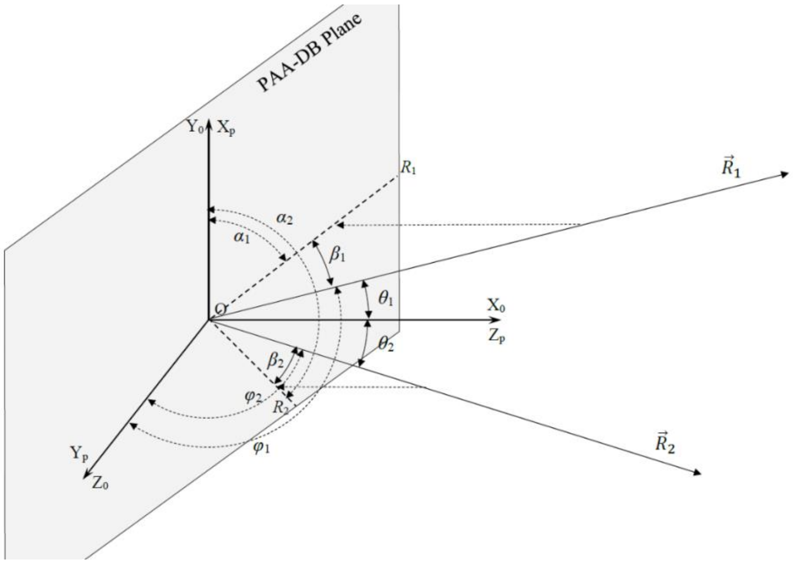

Fig. 2. Interaction between the BRCS of the Core Satellite and the PAA-DB coordinate system

Conclusion

An important aspect of ensuring satellite flight safety in the framework of the Distributed Satellite is the relative satellite position and movement measurements, one relative to the other. Such measurements can be fulfilled inside the Body Reference Coordinate System of the Core Satellite. The recalculation of the obtained values into the Orbital Coordinate System of the Core Satellite can be carried out subject to the Attitude Control System of the Core Satellite. Obtaining information about the current coordinates of all the DS satellite subordinates makes it possible to solve tasks on predicting the orbit of each satellite and take measures to prevent collisions and dangerous flyby rendevouz.

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