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NORBY CubeSat nanosatellite: design challenges and the first flight data

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Abstract. The paper presents the NORBY 6U CubeSat nanosatellite, launched on 28 September 2020 into a low-Earth orbit. The design of NORBY is briefly described, the main characteristics of its subsystems are given, and the results of the first flight tests are presented. The main features of the NORBY design are full hardware duplication of all subsystems and information interfaces, as well as the use of LoRa modulation in radio communications between the satellite and a ground station. The first results of the NORBY flight tests confirm the effectiveness of the key technical solutions applied in the NORBY design. For the first time, the operability of the LoRa modulation in satellite radio communications has been experimentally confirmed. The LoRa satellite-to-ground radio channel functioned sustainably at all tested parameters.

1. Introduction
Within the framework of the Federal Target Programme funded by the Ministry of Science and Higher Education of the Russian Federation, Novosibirsk State University has developed a nanosatellite platform compatible with the CubeSat standard. The basic set of platform subsystems includes:
- Structures in 1U, 3U and 6U formats;
- Electrical Power System (EPS);
- On-Board Radio Complex (BRC) with on-board computer functions;
- Attitude Determination and Control System (ADCS).

The platform is designed to create relatively inexpensive specialised nanosatellites with a targeted payload for scientific, technological or commercial applications.

The NORBY CubeSat is the first nanosatellite developed and manufactured on the basis of this platform. It was successfully launched on 28 September 2020 by a Soyuz-2.1b carrier rocket from the Plesetsk cosmodrome into a near-polar orbit with an inclination of 82.3°, apogee of 584 km and perigee of 547 km.

The main distinguishing feature of NORBY is full hardware duplication of all subsystems and information interfaces, which is incorporated into the nanosatellite design to increase its reliability.

Another important new technical solution implemented at NORBY is the use of LoRa modulation in the satellite radio channel. The LoRa modulation makes it possible to significantly increase the communication range or reduce the transmission power, thus reducing the power consumption of the transmitter. This is the first time that LoRa modulation has been used in satellite radio communications.

The main goals of the launch of the NORBY nanosatellite are flight tests of the developed platform, verification of its functional capabilities and technical solutions under real conditions in low-Earth orbit, as well as carrying out scientific and technological researches envisaged by the nanosatellite payload programme. It was also an important task to gain experience in carrying out of all stages of space mission.

The purpose of the paper is to briefly describe the design of the NORBY nanosatellite, to give the main characteristics of its subsystems and to present the first results of flight tests. A description of NORBY's payload and the results to be obtained using it will not be discussed here; they are the subject of a subsequent article.

2. NORBY design overview

It is no secret that nowadays multiple engineering teams worldwide have already accumulated significant experience in manufacturing and launching of small satellites. The CubeSat form factor has been developing since around 2000 and by now "spare parts" for such satellites are even available from online stores. This was one of the first challenges for the development team – to carry out its own research and development of subsystems on a competitive level.

The first step in designing the NORBY nanosatellite was to develop its breakdown structure. The list of subsystems used in NORBY is presented in table 1. Looking a little ahead, it should be noted that each of these subsystems was developed independently and each has a number of advantages over its known counterparts. A number of such advantages have already proven their effectiveness in flight tests, as will be described below.

Table 1. NORBY basic subsystems.

Subsystem	Description
Structure	6-Unit CubeSat structure
Electrical Power System (EPS)	Solar panels and battery packs
On-Board Radio Complex (BRC)	UHF transceiver Control functions
Attitude Determination and Control System (ADCS)	DSG sensor module: • Sun/Earth sensors • 3-axis magnetic sensor • 3-axis angular velocity sensor • 3-axis accelerometer • Temperature sensor A magnetic control system GLONASS receiver
Payload	Registration of gamma rays and charged particles Testing of SpaceFibre/SpaceWire technology

Based on our own many years of experience in developing on-board satellite equipment for huge satellites, we paid particular attention to reliability during NORBY development. Thus, the first design solution non-typical for small satellites was a full hardware duplication of all subsystems and information interfaces. Another feature of NORBY is the building of the spacecraft's information structure on the basis of a duplicate CAN bus, which made it possible to organize a uniform distributed register map from all NORBY subsystems. Thus, it has been implemented the possibility of low-level control and monitoring of all subsystems of the spacecraft through a set of unified commands via radio channel from the ground station.

From the point of view of a nanosatellite in low Earth orbit, the maximum power of a NORBY on-board radio transmitter of 4 W may seem excessively high. However, this powerful transmitter can be considered as a payload installed on NORBY for flight tests. Successful testing of the transmitter will make it possible to experimentally determine its capabilities for use in higher orbits. On the other hand, the increased power of the on-board transmitter proved to be extremely useful during the initial phase of NORBY's operations in orbit. The powerful transmitter and the use of LoRa modulation made it possible to establish stable radio communication with NORBY immediately after separation from the launch vehicle even prior to the full deployment of antenna system.

The composition of NORBY's payloads deserves special attention, which is also shown in table 1. One of the applications of the developed platform is to carry out rapid scientific and technological experiments. This is exactly what has been demonstrated in this project. Only two years have passed between the first discussion of payload composition and the launch of NORBY into orbit!

The registration of charged particles and gamma-quanta with the DeCoR instrument (Moscow State University, Skobeltsyn Institute of Nuclear Physics) is a scientific mission to study space weather. As for the SpaceFibre/SpaceWire technology test equipment, it is interesting from two points of view. Firstly, it was manufactured by an international cooperation of major companies, including Information Satellite Systems – Reshetnev Company (Russia) and Thales Alenia Space España (Spain), and the experiment itself serves to increase the level of technological maturity for future applications of these equipment in more global missions. Secondly, NORBY is the first spacecraft with SpaceFibre interface on board.

3. NORBY structure and configuration

The NORBY 6-Unit structure is a load-bearing frame made of aluminium alloy designed with the CubeSat standard in mind. The basic NORBY subsystems and the payload module are installed inside the structure (figure 1). In contrast to the basic NORBY subsystems, which are mainly printed circuit boards, the payload module is structurally separate and can be manufactured independently. The basic NORBY subsystems are located near the small faces of the structure, while the payload module is in the central part.

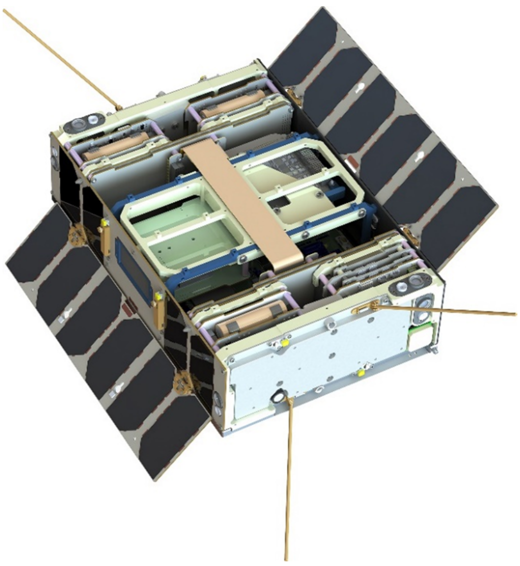

Figure 1. NORBY nanosatellite design: 6U CubeSat structure, fully duplicated subsystems, integrated payload.

On the small faces of the NORBY structure there are antenna modules of the on-board radio complex with folding antennas as well as sensor sets of the attitude determination and control system. The set of subsystems and navigation sensors located on one side of the spacecraft are fully duplicated by subsystems of the opposite side.

On the four large outer faces of the NORBY structure there are smart panels made on the base of printed circuit boards that combine the functionality of magnetic coils and solar panels. Along the two long ribs of the structure, additional foldable solar panels are attached on the opposite sides. The printed circuit boards installed on the external sides of the NORBY structure have a special copper coating to intensify the heat exchange between the external surface of the boards and the nanosatellite frame.

Sufficiently severe mechanical strength requirements are imposed on the design of the spacecraft, as the spacecraft undergoes significant vibration and impact loads when being launched into orbit. However, once in orbit, mechanical requirements become secondary and the thermal properties of the spacecraft come to the forefront.

For CubeSat nanosatellites, providing a thermal regime is more critical than for large satellites. Due to mass and energy restrictions, the range of active means of supplying the thermal regime of CubeSat on-board equipment is significantly narrower. The use of a non-special electronic base requires thermal conditions that are close to normal ground conditions, otherwise the failure-free operation of electronic components will be reduced. Unlike large satellites, nanosatellites have a smaller mass to area ratio, which means a more intensive specific radiation heat exchange with the surrounding space. Nanosatellite temperature variations therefore have a larger amplitude, especially in low Earth orbits, which also contributes to the shorter life span of on-board equipment.

The spacecraft is under conditions of radiation heat exchange with the surrounding space. The heating of the spacecraft by external sources and the release of heat into the surrounding space are performed by radiation and are determined by the properties of the spacecraft surface materials – the absorption coefficient of solar radiation and the radiation coefficient of infrared radiation [1-4].

NORBY's surface consists of a structure made of an anodised aluminium alloy, printed circuit boards covered with a solder mask and photovoltaic converters. Of the materials listed, optical absorption/radiation coefficients with good accuracy are known only for photovoltaic converters. The optical surface properties of an aluminium alloy are generally unknown and depend on the surface roughness and thickness of the oxide layer grown during anodization. The optical properties of the different types of solder masks are also unknown, but they are more repeatable due to their high seriality.

A special feature of the NORBY thermal mode assignment is the choice of type of solder mask of printed circuit boards forming the outer surface of the nanosatellite. For this purpose, the absorption factor of sunlight and radiation coefficient in the infrared range have been measured [4]. Calculations using the measured coefficients have shown that the solder mask, which occupies about one-third of the surface of the device, can have a sufficiently strong influence on the average temperature of the nanosatellite. Thus, a white solder mask provides an average temperature of 17°C lower than a black and a green solder masks and 10°C lower than a red mask when the nanosatellite is oriented with its maximum projection to the Sun. As a result, a white soldering mask was chosen to avoid overheating the equipment. The batteries are individually heated in case of overcooling.

An example of temperature measurements on board the NORBY nanosatellite is shown in figure 2. As can be seen from figure 2, the temperature of the nanosatellite subsystems was within the optimal temperature range during the first month of NORBY operation in the orbit. In the initial testing phase (0-400 h), work was carried out with NORBY subsystems that have relatively low heat dissipation. Then, at a time interval of 400-950 h, payloads were tested, which produced from 3 to 10 W of additional heat. We can see that in this case the average temperature of the various NORBY subsystems increased by 10-15°C, which is quite consistent with our model calculations [1-4].

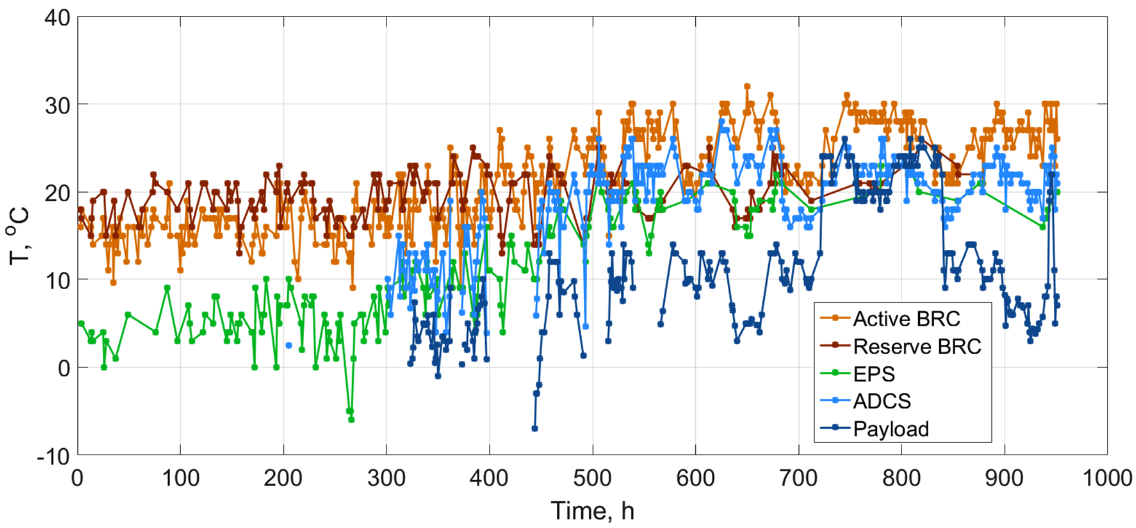

Figure 2. Temperature dynamics of NORBY subsystems during flight tests.

4. Electrical power system

The NORBY electrical power system is designed to supply power to satellite subsystems. The functionality of the EPS includes the distribution of incoming and stored energy between NORBY subsystems according to a given algorithm, as well as monitoring the current status of system parameters. The EPS comprises four function blocks (figure 3):

- the power generation block;
- the power storage block;
- the electricity conversion block;
- the monitoring and control block.

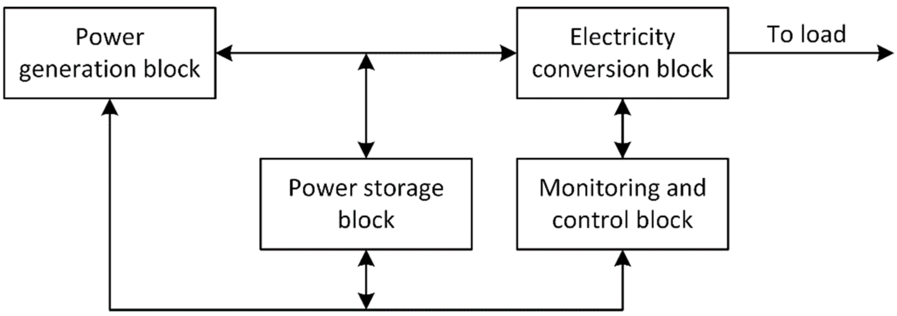

Figure 3. Functional diagram of the NORBY electrical power system.

The power generation block is a functional unit that converts solar energy into electrical energy and then transfers it to the other EPS blocks.

NORBY has six solar panels. Four of them are rigidly fixed to the outer sides of the satellite structure. Two of the panels are fold-out. Between 6 and 12 photovoltaic (PV) cells are located on each solar panel. Solar panels on the sunny side of the orbit generate electricity proportional to the power of incident light, with cell efficiency reaching 28% and a maximum output power of 1.25 W per PV cell. Each PV cell is connected to its own DC/DC converter, which ensures that maximum power is withdrawn from the cell. Each converter is daisy-chained to another of the same converters to produce a total output voltage in the range of 5 V to 8.3 V. At the output of each such pair is a diode to protect the entire solar panel in case one of the panel elements fails. The maximum power of the power generation block is 25 W. Maximum generated power registered on NORBY during the first month in orbit is 21 W.

The power storage block ensures the storage of electricity generated by the power generation block and the return of the accumulated energy to other NORBY subsystems.

The NORBY energy storage block consists of three battery modules. All modules are included in parallel to store more energy and ensure greater system reliability. The block diagram of the battery module is shown in figure 4.

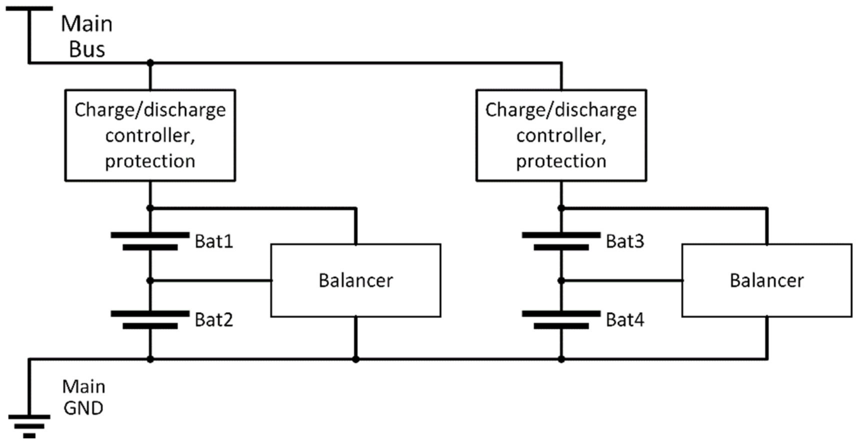

Figure 4. Block diagram of the NORBY battery module.

Each battery module includes two independent branches of 2s-1p lithium-ion batteries. In addition, the module includes charge/discharge control, protection, heaters and balancers to equalise the charge on the batteries. Thus, NORBY has 6 independent battery branches with a common bus voltage of 5 V to 8.3 V, a maximum discharge current of 18 A and a maximum accumulated power of 120 Wh.

At the beginning of NORBY's operation in orbit, all the batteries were severely discharged and an imbalance between the battery branches emerged during the charging process. As a result, some battery branches had to be recharged separately. Separate charging has corrected this situation and now all the batteries have the same level of charge and the NORBY electrical power system is operating in normal mode, fully compliant with design parameters.

5. On-board radio complex with on-board computer functions

The main functions of the NORBY on-board radio complex with the functions of the on-board control system are:

- organisation of radio communications with the Ground Control Complex (GCC);
- control of NORBY subsystems according to autonomous algorithms or by commands received from GCC via radio channel;
- monitoring the status of NORBY subsystems and transmitting information on their state to the GCC via radio channel;
- acquisition of data via the internal information bus from NORBY subsystems, external measurement modules and payloads, their packaging and transmission via radio channel to GCC;
- maintenance of the event archive and transmission of the archive data on request from GCC.

The NORBY BRC uses an SX1278 transceiver [5]. In addition to the traditional FSK, GFSK, MSK and GMSK modulation methods, the SX1278 transceiver also supports LoRa modulation technique. The LoRa modulation is based on the chirp spread spectrum (CSS) technique where the data is encoded by a wideband chirp signal in which the frequency linearly increases or decreases with time. LoRa can improve receiver sensitivity by more than 20 dB compared to conventional FSK modulation. This enables long communication ranges or the reduction of transmission power, thus lowering transmitter energy consumption [5].

Although LoRa modulation is considered one of the most promising technologies for use in satellite Internet of Things projects based on satellite constellations in low Earth orbit, it has never been used in satellite radio communications until now. This is due in particular to the fact that the LoRa modulation specification does not provide clear criteria for applicability in the conditions of a large Doppler shift caused by a very high satellite speed in orbit, especially when the Doppler shift changes rapidly with time.

During the development of the on-board radio complex, we carried out laboratory and outdoor experimental studies to determine the possibility of applying LoRa modulation in CubeSat radio communication systems [6, 7]. The experiments showed that the LoRa modulation has very high immunity to the Doppler effect. This immunity allows for the use of LoRa modulation in satellite radio communications in orbits above 550 km without any restrictions associated with the Doppler effect. In lower orbits, under certain conditions, a dynamic Doppler effect can destroy the satellite-to-Earth radio channel [7].

We have now begun testing the LoRa NORBY to Earth radio channel at various LoRa modulation parameters. To date, we have tested radio communications with LoRa spreading factor $SF = 7$, 10 and 12 and the spread spectrum modulation bandwidth $BW = 250$ kHz and 125 kHz. The test results fully confirmed the results of ground experiments. The LoRa satellite radio channel functioned sustainably at all tested parameters. No disruptions of downlink radio communication were observed.

The main parameters of NORBY BRC are given in table 2. Based on the results of testing carried out so far, the main mode of operation of the BRC has been selected: LoRa modulation with $SF = 7$ and $BW = 250$ kHz, transmitter power 0.2 W. This mode provides reliable radio communication with NORBY at a data rate of 10.9 kbps at all angles of satellite visibility. The second duplicate mode is GFSK modulation with a data transfer rate of 9.6 kbps.

Table 2. The main parameters of the NORBY on-board radio complex.

Parameter	Value
Operating frequency	436.7 MHz
Modulation type	FSK, GFSK, MSK, GMSK, LoRa
Transmit power	From 0.1 to 4.0 W
Receiver sensitivity at various types of modulation	From -97 to -148 dBm
Data rate at different types of modulation:	From 0.18 to 250 kbps
Power consumption in the receiving (standby) mode	0.175 W
Power consumption in the transmission mode	From 1.5 to 8.5 W
Interfaces	CAN (duplicated), I^2C, GPIO

6. Attitude determination and control system

A feature of the NORBY attitude determination and control system is the integration of all orientation sensors in one small DSG sensor module, which includes Sun, Earth and temperature sensors, magnetometer, angular velocity sensor and accelerometer. A magnetic control system is used for satellite attitude stabilization. This quite simple magnetic control system makes it possible to solve the tasks of the CubeSat detumbling after separation from the launch vehicle and its orientation relative to the Sun and the Earth. The structural block diagram of the NORBY ADCS is shown in figure 5. Six DSG modules located on the six sides of the satellite body provide visibility of the Sun and the Earth in all spacecraft orientations if the fields of view of the Sun and Earth sensors are more than 90°.

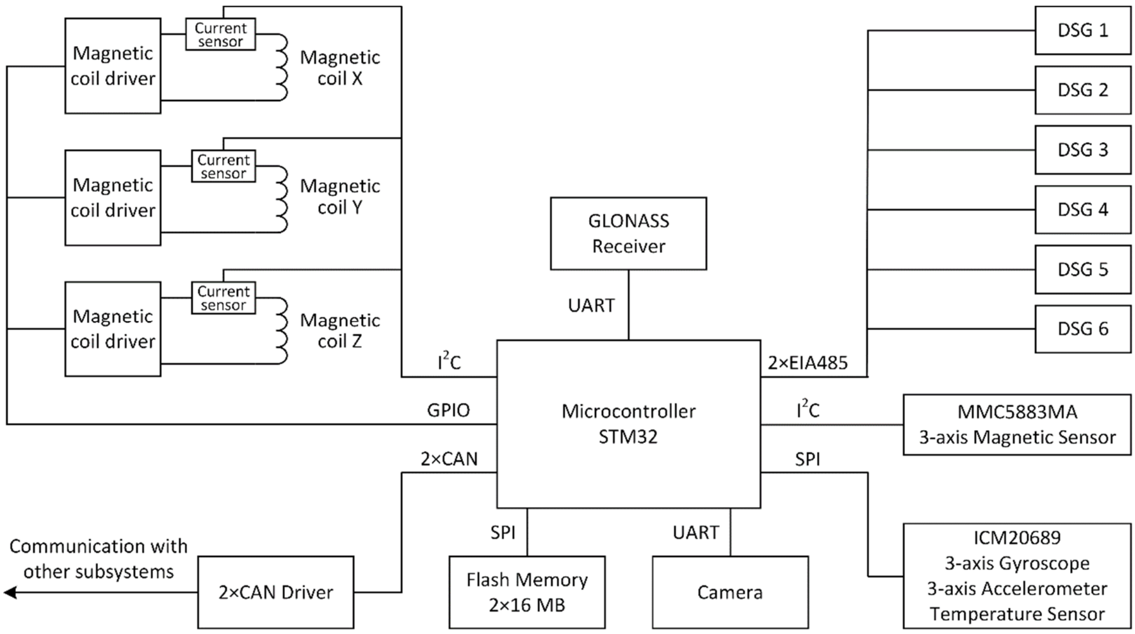

Figure 5. Structural block diagram of the NORBY attitude determination and control system.

6.1. DSG sensor module

A two-axis sun sensor [8] built into the DSG module is based on the registration of the sunspot formed on the matrix CMOS image sensor when the sun's rays pass through a round hole in the front mask. The sun sensor's field of view is 120° and the accuracy of the determination of direction to the sun over the entire range of viewing angles is better than 0.46°. The Melexis MLX90640 32×24 array of IR thermometers with field of view of 110□×75□ [9] is used as the Earth horizon sensor. The horizon of the Earth is determined on a thermal image obtained by the IR matrix sensor as the boundary between the warm Earth (about 300 K) and the cold space (about 2.7 K). Each DSG module also contains 3-axis magnetic sensor MMC5883MA and 6-axis MEMS for motion tracking ICM-20689. In addition, the MMC5883MA and MMC5883MA sensors are also located on the ADCS control board.

Figure 6 shows (a) a 3D model of the DSG module and (b) a photograph of the module without a body [8]. The module consists of a printed circuit board and a sensor body. The board contains a CMOS matrix of the sun sensor, an infrared matrix of the sensor of the Earth's horizon, magnetic and motion sensors, and electronics with a connector.

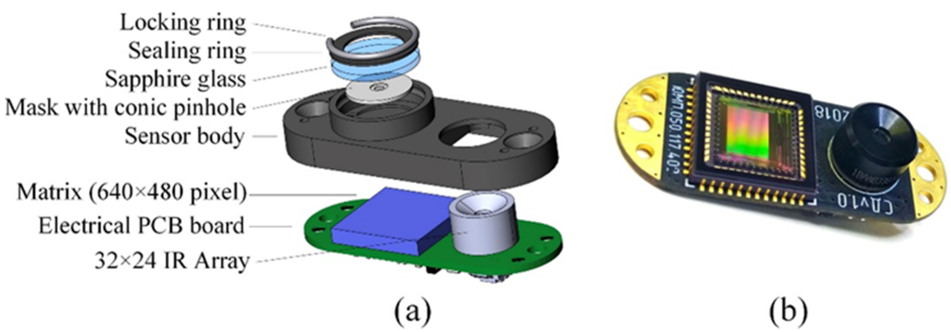

Figure 6. DSG sensor module design: (a) a 3D model and (b) a photograph of the module without a body [8].

The optical system of the sun sensor is located inside the sensor body. The main element of the optical system is a round aluminium mask with a calibrated conical pinhole 80 μm in diameter. To protect the hole from external influences, a protective sapphire glass is provided in the design of the sensor. The mask and the sapphire glass are fixed in the sensor body with the help of a locking ring through fluoroplastic sealing rings. The dimensions of the module are 42.5×17.5×11 mm, and the mass is about 10 g.

Placing all the sensors of the ADCS system in one housing, in DSG module, significantly simplifies the placement of sensors on a satellite, reduces the load on the main ADCS processor, provides sensor redundancy, which increases the reliability of the ADCS, and simplifies the calibration of the ADCS as a whole.

To increase ADCS reliability, the system has a duplicate channel of communication between the system's main microprocessor and DSG modules. Communication with other NORBY subsystems is also carried out via a duplicated CAN interface. The placement of all sensors in a separate physical and functional module with a duplicated communication channel enables fault-tolerant systems to be built on its basis. DSG module performs a specific final function of determining satellite orientation and has a duplicated communication channel. A total of ten DSG modules are available in NORBY, which operate in two duplicate ADCS systems. However, the orientation of the satellite will be determined if at least one DSG module with at least one communication channel is functioning.

Since the orientation calculation is performed in the DSG module itself, the ADCS central calculator is relieved of most of the computing load and the ADCS control board itself is significantly simplified.

DSG modules, using a duplicated communication channel and being in the same communication network, can communicate with each other, exchange information about optical orientations and other data to improve orientation accuracy. For example, the Sun is in the field of view of only one module. This module determines the rotational speed of the satellite by the movement of the Sun, and communicates this information to other modules, which use this data to correct the zero-offset of their angular velocity sensors.

An important point when placing orientation sensors on a satellite body is their mutual calibration. When sensors are placed separately, this calibration must be done after the entire spacecraft has been assembled, with all systems, which makes calibration difficult and increases the requirements for the readiness of all systems. On the other hand, the DSG module is ready for calibration immediately after assembly. In doing so, the calibration tables are stored in the memory of the module itself. Since the sensors are placed on the same board of the DSG module, their mechanical connection is much more rigid than if they were placed on different spacecraft boards connected by a chain of different structural elements. The structural rigidity of the DSG module also increases the reliability of the attitude determination and control system as a whole.

6.2. Magnetic control system

The executive organs of the NORBY attitude determination and control system are magnetic coils, implemented as printed circuit boards. In this, X and Y magnetic coils are integrated with the corresponding solar panels. Each magnetic coil consists of two parts located on opposite sides of the satellite body and is powered by a stabilised current, the value of which is calculated by the main ADCS microprocessor using the data from DSG sensors.

The nominal magnetic moment of each coil is 0.25 $A \cdot m^2$ with a power consumption of 0.5 W per coil. The NORBY ADCS uses a widely used algorithm for damping angular velocities B-dot. The power supply system of the magnetic coils ensures not only the accuracy and stability of their magnetic moment, but also the ADCS performance sufficient to stop the satellite from rotating at speeds of up to about three revolutions per second. A similar abnormally fast rotation of the spacecraft was observed, for example, after the launching of the CubeSat 1U nanosatellite into orbit [10]. NORBY's rotation speed after separation from the launch vehicle was about 4.5 degrees per second according to data from DSG modules. It is planned to stop NORBY rotation completely only after all components of the attitude determination and control system have been tested individually.

7. Conclusions

In this paper, we presented the NORBY CubeSat nanosatellite. The design of NORBY is briefly described, the main characteristics of its subsystems are given, and the results of the first flight tests are presented.

The main distinguishing features of the NORBY design are full hardware duplication of all satellite subsystems and information interfaces, as well as the use of LoRa modulation in radio communications between the satellite and the ground control complex.

All the NORBY subsystems have been switched on and are now operating in normal or test mode. Their functional and accuracy characteristics are being checked. The electrical power system has been fully tested and is operating in normal mode. The on-board radio system provides radio communication with the ground control complex, transmission of telemetric information and data from payloads, as well as NORBY control. At the same time, testing of various BRC modes of operation continues. DSG sensor modules of the attitude determination and control system are being tested. Solar and magnetic sensors have so far been verified. It is planned to start full-scale testing of ADCS after all its components have been individually tested.

For the first time, the operability of the LoRa modulation in satellite radio communications has been experimentally confirmed. To date, we have tested radio communications with LoRa spreading factor $SF = 7$, 10 and 12 and the spread spectrum modulation bandwidth $BW = 250$ kHz and 125 kHz. The LoRa satellite-to-ground radio channel functioned sustainably at all the tested parameters.

Overall, the first results of the NORBY flight tests confirm the effectiveness of the key technical solutions applied in the NORBY design.

Acknowledgments

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