SMALL SATELLITE FOR SPACE WEATHER MONITORING: MISSION RESULTS

Daria Stepanova[(1)], Diego Garcia[(1)], Ravneet Kaur[(1)]

[(1)] *German Orbital Systems GmbH, 10-11, eing S. Reuchlinstrase, Berlin, Germany, 13349, info@orbitalsystems.de*

Changes on the surface of the Sun and the intensity of the solar wind lead to changes in Earth's magnetosphere and ionosphere, which can affect the operation and reliability of terrestrial, air- and space-borne technical systems, as well as threaten the life and health of people, the safety of air and space flights. Solar and space physics is one of the scientific domains, which can benefit from CubeSats. Space weather monitoring is one of the dominant applications in this domain – several CubeSat missions in the past have already addressed related topics.

Space weather monitoring requires precise measurement and analysis of space radiation as well as monitoring of solar activity and understanding of its influence on the radiation environment in different Earth orbits. The use of CubeSats for space weather monitoring missions has several obvious economic advantages as compared to larger platforms. The significantly reduced mission costs due to standardized satellite format have been discussed in several other papers over the last decades. One less obvious scientific advantage of the concept results from the reduced costs: by using several CubeSats to monitor space weather, simultaneous multipoint measurements of the phenomena become affordable. In perspective, this capability will significantly improve our understanding of space weather effects.

The main goal of the current experiment was to analyze the space weather using CubeSat platforms. The mission objectives of the project were to develop, implement and test several satellite platforms and payloads, launch satellites, and conduct a set of experiments, including the collection and analysis of data from different payloads, as well as automation of work with satellite platforms to ensure daily data transfer to the ground station. During the yearlong mission, a set of data was collected from satellites and the model of radiation belts behavior was updated. This work shares the satellite architecture specifics as well as preliminary results while the mission continues.

1 INTRODUCTION

The study of the ionizing radiation fluxes from outer space is one of the most important tasks of space weather monitoring. The Earth's magnetosphere is a dynamic system that is influenced by solar wind and exchanges the mass and energy with the ionosphere. The understanding of the dependency of the magnetosphere on the solar wind variations is an open problem as it involves different mechanisms of energy release and multi-scale coupling phenomena. Currently, it is hard to predict its behavior due to immaturity in the understanding of the physical processes behind it.

This topic is both interesting from scientific and applied perspectives: formation of spatial and temporal variations of ionizing radiation fluxes can enable new models of radiation belts while the determination of their influence on the spacecraft performance and functionality can support the prediction of spacecraft lifetime and development of additional redundancy measures. According to the research, more than half of the failures and malfunctions in the operation of spacecraft onboard systems are due to the adverse impact on the materials and elements of spacecraft equipment of factors of the space environment, the main role among which is played by radiation effects. Electrons, move close to the speed of light and have energies on the order of one million electron volts (MeV). These particles can damage spacecraft components via surface charging or deep dielectric discharging. A second threat is energetic ions, with energies up to GeVs, that can disrupt electronics or cause single-event upsets (SEUs) in component memory. Very high-energy protons can have harmful and potentially lethal radiation effects on astronauts in space.

The main scientific objective of the project is to study the flows of energetic charged particles in the near-Earth space, capable of penetrating inside the spacecraft body and influencing their radio-electronic equipment. These are mainly streams of energetic electrons and protons of the Earth's radiation belts as well as short-term intense fluxes of energetic particles from solar flares.

A small satellite constellation for space weather monitoring can provide consecutive passes by the same area of closely located satellites, which will allow the most reliable separation of spatial and temporal effects; simultaneous measurements on different L-shells, which is necessary to restore the dynamic picture of the distribution of fluxes of trapped particles in a wide range of orbits, which will allow observing the displacement of the maximums of the radiation belts during geomagnetic disturbances; simultaneous measurements at the same altitude with instruments of the same type located on several satellites, shifted in longitude relative to each other, which will make it possible to assess the influence of the local time factor on the dynamics of particle fluxes.

German Orbital Systems GmbH has developed the 6U CubeSat mission to demonstrate the feasibility of providing space environment measurements based on a CubeSat platform. This paper outlines an overview of mission design, spacecraft design, and mission results.

2 MISSION DESIGN

The mission goal is to provide a generic spacecraft for the in-orbit demonstration/validation of several experiments. It aims to collect data about space weather in Low Earth Orbit, mainly radiation and charged particles. The main scientific tasks are to study fast electron flux variations in the area between radiation belts; study the dynamics of particle flows and gamma-radiation in a low orbit depending on geomagnetic conditions. For the mission basis GROOVE-EVO 6U CubeSat platform was selected.

2.1 Payload

The selected payload can measure fluxes and spectra of charged particles and gamma radiation in the range of 0.1–2 MeV. This payload is a detector of cosmic radiation registering short-term changes in the fluxes of electrons and gamma rays. The selected instrument will provide the datasets to study the fast variations in electron fluxes in the areas of precipitation and the gap between the radiation belts, and the dynamics of particle fluxes and gamma radiation in low orbits depending on geomagnetic conditions.

Table 1: Payload specifications

Parameter	Value
Registered types of particles	Gamma, electrons
Energy release range	0.1–2 MeV
Dynamic Range: total flow monitoring spectral-temporal analysis	0–1000 cm-2 0–25 cm-2
Effective area	18 cm^2
Geometric factor	50 cm^2
Time resolution	20 μs
Weight	400 g
Dimensions	102 × 90 × 36 mm
Detector consumption	0.7 W

The generated data corresponds to particle count rates which are measured and recorded once every few seconds and detailed readings from the detector with a time resolution of 20 μs.

2.2 Concept of operations

The current mission consists of one satellite with a form factor of 6U. For the baseline orbit the Sun Synchronoss Orbit of height 550km and inclination of 97.8 deg. The small satellite shall carry 3 detectors with apertures located perpendicularly: on the x, y, and z sides of the satellite. This will enable the measurements of particles from 3 different directions.

Table 2: Mission concept of operations

Phase	Start	Event
N/A	L0 – 1mo	Spacecraft delivery and launcher integration
E1	L0	Launch
	L0 + 2hrs	LEOP
E2	L0 + ~2wk	Commissioning
E3	L0 + ~2mo	Nominal Operations
F	L0+ ~14mo	Decommissioning

The scientific experiment is based on regular data collection and the transition of data to the ground segment. The detailed recording mode on pre-defined orbits of the satellite trajectory can be turned on while the satellite is passing through the zones of possible variations in the fluxes of trapped and quasi-trapped particles.

2.3 Mission analysis

Two scenarios were analyzed: the possibility to use a proprietary ground station, or a commercial ground station network service. For the proprietary ground station, the GOS office which is equipped with a ground station located in Berlin, Germany is used. Access to the ground stations was calculated using AGI STK.

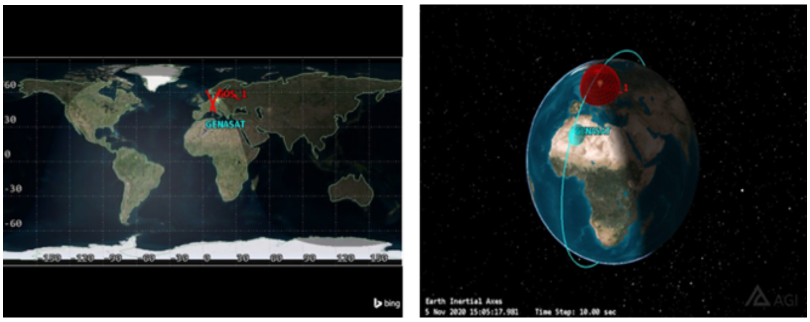

Figure 1: Orbit propagation simulation with GOS station

First, the GOS-based Ground Station is analyzed. From a single day propagation, we would get a total of 7 access to the ground station while some of them are too low to conduct the communication session resulting in a total of 3.68 access per day with passes long enough to conduct communication. Throughout the day the access intervals are separated with a considerable interval of no access.

The results of the power generation analysis for the GROOVE-EVO satellite are shown in Table 3: Power budget summaryTable 3. Orbit average power considers the eclipse duration, while the peak power corresponds to the maximum power generated on the solar panels.

Table 3: Power budget summary

Non-deployable	LVLH Aligned	Sun Pointing	Tumbling
Peak [W]	43.23	50.41	48.60
Orbit Average [W]	23.04	31.89	26.27

The analysis shows that the deployable solar panel configurations almost double the amount of available power that could be achieved in comparison to standard 6U platforms that do not have deployable solar panels.

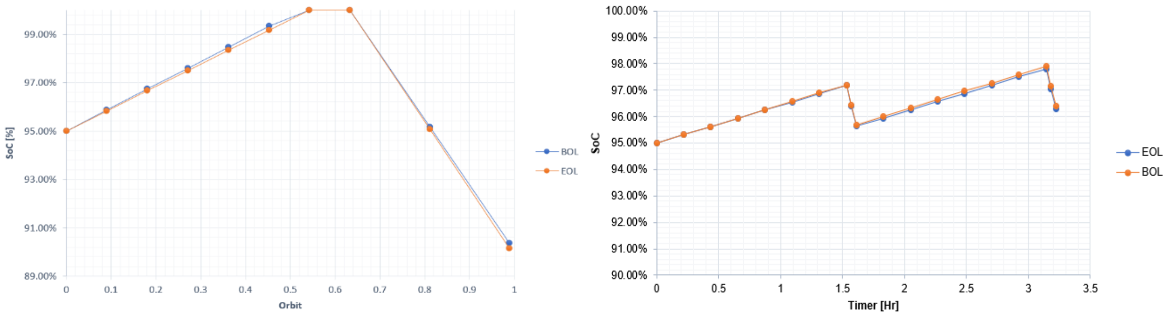

Figure 2: the State of Charge While Performing Nadir Pointing Operations for an Orbit (Sunlight and Eclipse)

The spacecraft can be equipped with up to two transceivers a UHF/VHF and one S-Band transmitter. The UHF/VHF transceiver is intended to be used for basic telemetry and telecommand to operate the bus. The S-Band transceiver will be primarily used for payload data and platform historical telemetry downlink and software update uplink.

A UHF/VHF ground station at GOS headquarters and a commercial ground station network service will be used for GROOVE-EVO. The primary communication module of the platform is a UHF/VHF (UHF downlink / VHF uplink). It will be used for basic telemetry and telecommands to operate the spacecraft's main bus. The UHF/VHF module in combination with a basic monopole antenna was used as a basis for the calculation of the following link budget.

The link budget assumed worst-case scenarios for propagation losses and transceiver losses. Figure 3 shows a summary of the downlink capabilities of the spacecraft and depicts the link margin at different elevations. It can clearly be seen that even at low elevations the link margin is still significantly above the threshold.

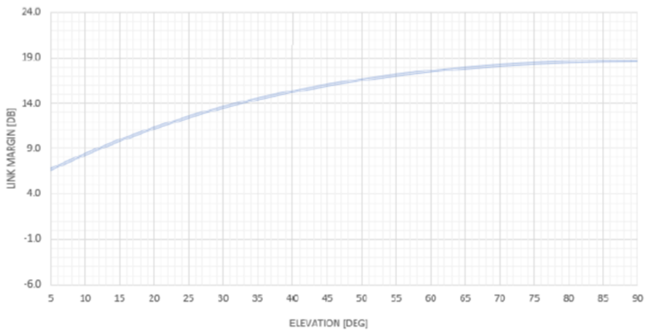

Figure 3: S-band link margin analysis vs elevation

3 SATELLITE DESIGN

The current section describes the proposed configuration of a satellite based on the GROOVE-EVO platform. The GROOVE-EVO platform is a 6U platform based on the CubeSat form factor. Of the 6 CubeSat units, 4 will be occupied by the multiple payloads and the remaining 2 will be used by the bus systems.

Table 4: Satellite architecture summary

Spacecraft Overview		
Dimensions	Stowed	[243-mm x 106-mm x 340-mm]
	Deployed	[512-mm x 415-mm x 373-mm]
Mission	Reference Orbit	LEO: 500 – 650 km, SSO
	Lifetime	2 years
Mass	Satellite and payload	6.7kg
Structure	GOS 6U Structure	

Comms.	Band	S-Band
	Frequency	DL: 2100 MHz MHz
	Antenna	S-band patch
	Data rate	1.05Mbps
CDH	OBC	180 MHz, 3 GB redundant NAND Flash, 512 Kb of external SRAM
	PDH	1GB RAM, 1.2GHz processor speed, memory 32 GB
TMTC	Band	UHF
	Antenna	Deployable UHF Antennas
	Data Rate	9.6 kbps
AOCS	3-Axis Stabilized	
	Sensors	Sun Sensors, Magnetometers, Star tracker, Gyro, GPS
	Actuators	Magnetorquers, Fluid Dynamic Actuators
	Determination accuracy	Up to 0.03 deg
	Slew rate	10 deg/sec
	Pointing accuracy	Up to 0.1 deg
	Regimes	Nadir, Sun, Zenith, Target
Thermal	Active	Temperature telemetry, heaters & radiators
Power system	Solar Panels	Deployable panels 72 W
	Batteries	142 Wh

The satellite consists of two main blocks: bus module and payload module. Bus module incorporates all the required instrumentation for autonomous functionality in orbit, including the Electrical Power System (EPS), Command and Data Handling Unit (CDH), Attitude and Orbit Control System (AOCS), and elements of a Thermal Control System. These subsystems oversee providing the necessary resources to the Payload Module. The Payload Module consists of several radiations and ultraviolet detectors and a payload control unit, which is responsible for payload communication, control, and monitoring. A system functional diagram is depicted in Figure 4 outlining the different subsystems and the respective interface between them.

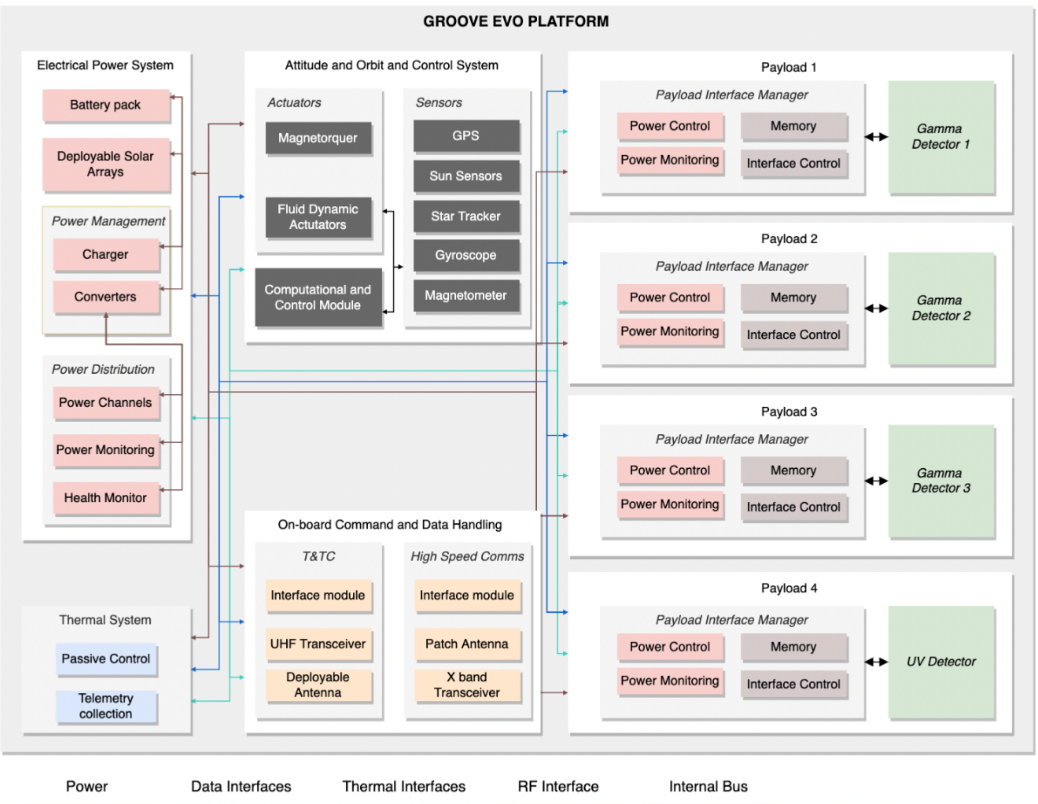

Figure 4: Satellite architecture

Figure 5 shows the external appearance of the proposed 6U platform baseline that will be used for the mission, derived from the first de-risk activity.

3.1 Satellite configuration

The satellite is built based on a standard GOS 6U GROOVE-EVO platform. It has a modular and highly integrated design. Patch antennas are located on the 3U sides. GNSS antenna is pointing upwards in the -Z direction while the X-band antenna is located on the bottom 3U +Z panel. Deployable mechanisms including a magnetometer and UHF/VHF antennas in a stowed configuration are connected to release mechanisms on the solar panels. Star tracker is located in the tuna can and can be installed and uninstalled without modifying internal satellite components – this allows to reduce costs if payloads do not require precise pointing. In stowed configuration deployable solar panels are lying on the 6U panels. After deployment, one 6U side is still arranged with solar cells, while another 6U side is occupied by payload apertures.

The internal layout of the spacecraft is shown in Figure 6. Most of the satellite subsystems are accommodated within a 2U volume while sensors, antennas, and AOCS components are distributed on the inner side of the side panels. This frees up a volume of up to 4U for the payloads placement while keeping the satellite highly functional in terms of attitude control and power system characteristics. A highly dense boards stack based on the backplane approach includes main computational and control modules such as OBC board, EPS control module, UHF / VHF transceiver, GNSS, and Radiation sensors.

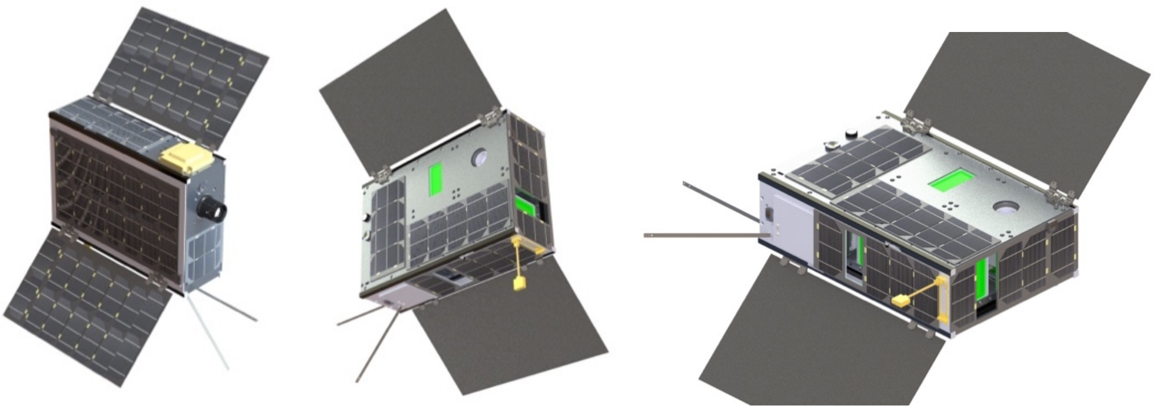

Figure 5: GROOVE-EVO platform overview

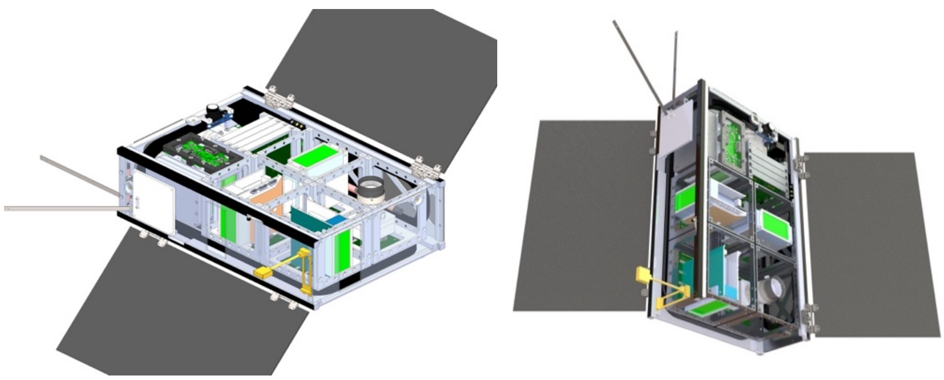

Figure 6: Internal GROOVE-EVO layout

Due to the high-density design of the platform avionics, a new interconnection concept has been chosen. It makes use of edge connectors and a high-density avionics backplane, which connects the subsystems among each other as well as features several protection circuits, switches, and isolators. Some of the existing TRL9 systems, such as PDH, OBC, AOCS controller, and EPS must be adapted to the new interface by rerouting the signals on one side of the PCB and exchanging the PC104 connector with the new connector type. This has no influence on the used component base as well as on the routing of the signals in the sensitive areas of the PCBs. Only a mechanical requalification is required for these components. It will be performed on the sub-assembly level for all TRL8 systems at once.

3.2 Structure and payloads allocation
The GROOVE-EVO satellite structure design approach is inspired by previous GOS missions. 6U GOS structure has successfully undergone the required tests and handled the launch loads in several missions. The changes in the primary structure will be considered. The baseline of the structure will be revised and will include the distribution of the bus components, payloads apertures, and mechanical simulations. The foreseen distribution of the bus components is confined practically to 2Us, leaving nearly a 4U volume of space for the payload.

In the 2U volume, the main stack, the battery pack, the star tracker, solar sensors, and dosimeter will be located. The ring long flat shape of the Fluid Dynamic Actuators (FDAs) allows them to be installed on the internal faces of the structural panels, without taking essential internal volume from the bus components or the payload volume. The rest of the small components, such as solar sensors or patch antennas, will be mounted on the external faces of the panels.

3.3 Electrical Power System
Different configurations of GOS EPS have proven their reliability and achieved great performance onboard ten CubeSat missions. The EPS modules for the GROOVE-EVO platform will be based on this heritage.

EPS control module consists of two parts: Bus Power Processing Unit (BPPU) and Bus Power Distribution Unit (BPDU). The BPPU is dedicated to power processing functions and reliable power conversion while BPDU allows adjustable power parameters selection for internal systems. BPPUs charger unit is implemented to automatically charge the battery providing undercharging and overcharging protection, gauge control, and capacity monitoring. The bus energy processing guarantees the selection of power interfaces required for the main satellite subsystems' functionality. The BPPU implements the MPPT to improve solar power performance as well as hardware-based over-voltage and over-current protection. Bus Power Distribution Unit includes a set of switches to control the power channels for the main bus, ADC modules, and current sense assembly of amplifiers to track the consumption of systems. The system provides an adjustable set of regulated buses, as well as unregulated buses.

3.4 Attitude and Orbit Determination System
An active AOCS shall ensure the required pointing modes for payloads and platform components as well as required orbit knowledge. Most of the AOCS components are flight-proven. The unique advantage of the selected AOCS design approach is in the actuator's configuration and optimization of their placement in the satellite.

3.5 Command and Data Handling System
The CDH unit was a core system for all GOS missions in the past. Reliable configuration of hardware solutions and redundant arrangement of critical components together with developed in-house software packages allowed 10 CubeSats to successfully perform their mission. Most of the GOS CDH component's heritage will be preserved in the GROOVE-EVO platform.

The CDH subsystem has two core functions: to gather and format satellite housekeeping data for down-link and to receive and distribute commands from the ground. The hardware consists of an OBC computer with distributed memory unit to store the payloads and house-keeping data before downlinking it and a UHF/VHF module for low data rate communication with ground stations. The software component includes a telemetry collecting (housekeeper) module and protocols.

The CubeSat OBC is a key element for controlling and maintaining the health status of the satellite. The OBC includes failure management functionalities to ensure that the spacecraft can autonomously recover from anomalies and enter a safe state without interaction from the ground operators, in case of emergency.

3.6 Payload Data Handling System

The Payload Data Handling system is a modular system distributed between a powerful controller, several payload compartments with local power management MCUs and individual payload Interface Controllers. This system allows smooth and easy payload control as well as payload and main bus data exchange. Since different payloads might require vastly different approaches to data handling a flexible data handling solution is proposed. Each payload can use its personal Interface Controller with a broad set of interfaces to access and control the payload over the satellite network.

PDH unit oversees commands and data processing from and to payloads, Compartment MCUs perform power management tasks while Interface Controllers are responsible for interfacing the payloads, establishing required communication protocols as well as payload specific data handling. The pre-processing of payloads data will occur in the PDH unit.

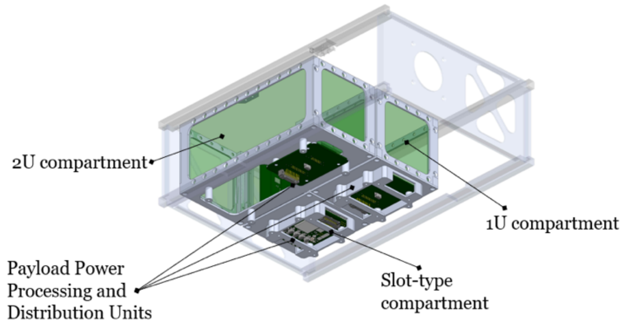

Figure 7: PDU modules distribution in the satellite

3.7 High-speed communication

A high-speed communication link is required for payloads data downlink, satellite telemetry access as well as payload scripts upload. The downlink requirements drive the selection of the communication module. To meet mission requirements S-band communication channel was selected. S-band transceiver from IQWireless is selected for the mission. Hispico is an advanced system for S-band communication. It provides the radio interfaces and protocols compliant with CCSDS. Supported modulation schemes include BPSK, QPSK, and higher-order types of modulation with appropriate FEC encoding schemes. Adaptive modulation and coding schemes are applicable to maximize data throughput.

The selected patch antenna for S-band is a high-gain, small shape antenna for uplink and downlink frequencies (RHCP and LHCP). Downlink data rates with net payload rates of up to several Mbps are possible depending on the link quality, however, the estimated data rate depends on the ground station setup and is foreseen to be around 1.05 Mbps.

4 MISSION RESULTS

With the baseline design described above, the hardware components were manufactured, and satellite and payloads were assembled and launched. The satellite's internal and external parts are shown in Figure 8.

Figure 8: Satellite assembly and integration

Some of the sample data from the mission are shown in Figure 9 and Figure 10 - the monitoring channels count rates are recorded with a time resolution of 1 s in relation to time. These are channels that are corresponding to the count rate of gamma quanta with energies above 100 keV and electrons with energies above 300 keV recorded in the detector crystal. The moments when the satellite is in the outer radiation belt of the Earth (L ≈ 3.5−7) can be observed, due to the registration of both direct electrons and gamma quanta generated by them due to bremsstrahlung during the interaction of electrons in the substance of the satellite and the device itself.

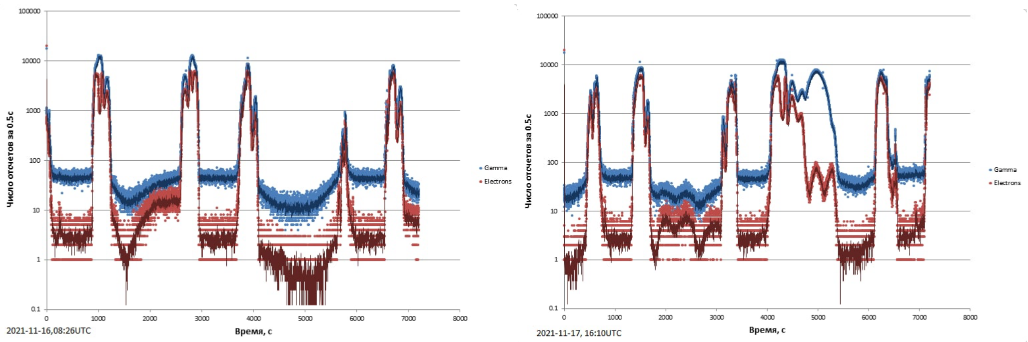

Figure 9: Particles count from November experiments 2021 (1)

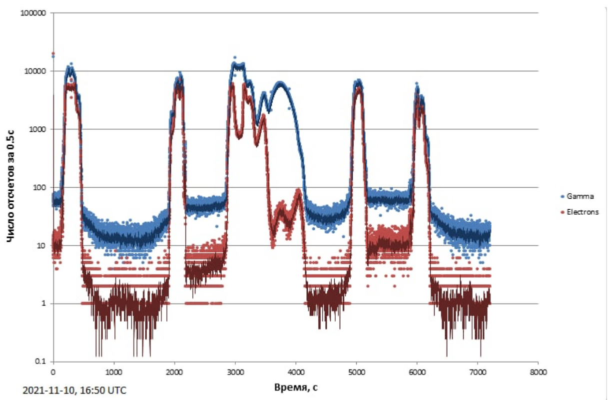

Figure 10: Particles count from November experiments 2021 (2)

The parallel activation of identical devices on different spacecraft enables instant successive measurements in the same regions of the near-Earth space. This makes it possible to separate temporal and spatial effects in the registered count rate variations. Such an example is data on the distribution of electron fluxes of sub relativistic energies in the outer radiation belt. A comparison of the readings showed the similarity of the main characteristic features: counting rate maxima corresponding to the passage of the outer belt; narrow maxima observed symmetrically near the inner boundary of the belt corresponding to precipitation zones.

The fluxes of electrons of sub relativistic energies near the geomagnetic equator are relatively smaller than in the zones of trapped radiation and the outer radiation belt observed ones. For providing special attention to their registration, devices with sufficiently large geometric factors are required. This helps to measure register weak fluxes along with their time variations. Conclusively, the anisotropic nature of electron fluxes was indicated near the geomagnetic equator, which may imply their characterization by a rather narrow pitch-angle distribution. Hence, further studies of such electrons are of great interest.

5 CONCLUSION

The proposed demonstration mission can verify the approach for the radiation measurements collection. The mission upgrade to a constellation can significantly increase the amount of scientific data. The presence of two spacecrafts flying in the vicinity of each other with the same payload can make it possible to compare the instrument readings on two satellites to separate temporal and spatial effects. The challenging task, in this case, is to enable mutual attitude control so the detectors of both the spacecrafts are aligned. Simultaneous Multi-point space weather measurements are needed especially to describe the ionosphere behavior where the changes occur in short time scales.

An important factor that makes it possible to carry out scientific research more efficiently is the installation of the instrument on two satellites flying sequentially through the same region of near-Earth space. Due to this, it is possible in principle to separate the temporal and spatial effects in the registered variations in the count rates of the detectors, which is fundamental for understanding the nature of the acceleration and precipitation of magnetospheric electrons. An important advantage of multi-satellite experiments is the possibility of simultaneous measurements at different points of the near-Earth space and measurements in the same areas during the successive passage of vehicles through them.

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