

# Development of Engineering Models of Nanosatellites for Student Training

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## Abstract

The work purpose is the development of BSUIM-1 and BSUIM-2 complexes for training specialists in the aerospace industry with the used engineering test beds and experimental facilities.

Two sets of nanosatellite engineering models and ground stations had developed. They allow testing hardware and software of the onboard equipment and payload, simulating operation modes, and flight programs, and enable students to gain practical skills in working with ultra-small satellites. The complexes include ground stations, 2 ultra-small satellite simulators, BSUSAT-1 low-orbit nanosatellite, remote access laboratory, local and external servers for data storage. The complexes' website and database allow for full-time and remote training. The experience gained in conducting experiments, processing telemetry, and structuring information in the database is used for further development. All the developed equipment is made based on commercial off-the-shelf elements. It has reduced development costs, flexible equipment reconfiguration, and easier access to the simulator's internal architecture for demonstration purposes.

The developed complexes allow students to practically study the ultra-small satellite components design and ground stations, methods for receiving and processing telemetry and scientific information, attitude determination and control algorithms. The complexes allow to conduct of research in the development of individual onboard systems and special-purpose equipment of the nanosatellite and their testing in the loop.

The results obtained are introduced into the educational process and are used in lectures and laboratory classes for aerospace specialties students. The developed complexes make it possible to carry out term papers, theses, and master's works related to the design of hardware and software for nanosatellites and a ground station, the setting up of space experiments, the development of new algorithms and a flight program for ultra-small satellites.

**Keywords:** nanosatellite, Cubesat, ground station, education, onboard systems.

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# Разработка инженерных моделей наноспутников для обучения

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Целью работы являлась разработка комплексов для подготовки специалистов аэрокосмических специальностей на основе практических тренажёров и экспериментальных установок.

Разработаны два комплекса инженерных моделей-имитаторов наноспутников и наземные станции приёма, которые позволяют проводить отработку оборудования и программного обеспечения бортовой аппаратуры и полезной нагрузки, имитацию режимов работы, программы полёта, дают возможность студентам получать практические навыки работы со сверхмалыми космическими аппаратами. Комплексы включают в себя: наземные станции приёма, 2 имитатора сверхмалых космических аппаратов, низкоорбитальный спутник BSUSAT-1, лабораторию удалённого доступа, локальный и внешний серверы для сбора и хранения данных. Собственный веб-сайт комплексов и база данных позволяет обеспечить как очное, так и удалённое проведение лабораторных работ. Полученный опыт в проведении экспериментов, обработки телеметрии и структурированная в базе данных информация используется для дальнейших разработок. Всё разработанное оборудование выполнено на основе доступной элементной базы. Это позволило снизить стоимость разработки, гибко реконфигурировать оборудование и облегчить доступ к внутренней архитектуре тренажёров для демонстрации.

Разработанные комплексы позволяют студентам практически изучать устройство сверхмалых космических аппаратов и наземных станций приёма, методы приёма и обработки телеметрии и научной информации, алгоритмы определения положения и управления спутником. Комплексы позволили проводить исследования в области разработки отдельных бортовых систем и целевой аппаратуры наноспутника и последующего их тестирования.

Полученные результаты внедрены в учебный процесс и используются при чтении лекций и проведении лабораторных занятий для студентов аэрокосмических специальностей. Разработанные комплексы позволяют выполнять курсовые, дипломные и магистерские работы, связанные с проектированием программно-аппаратных средств наноспутников и наземной станции, постановкой космических экспериментов, разработкой новых алгоритмов и программы полёта сверхмалого космического аппарата.

**Ключевые слова:** наноспутник, Cubesat, наземный комплекс управления, обучение, бортовые системы.

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## Introduction

There are currently dozens of leading manufacturing companies that provide both off-the-shelf onboard systems for CubeSats [1, 2], CubeSat simulators [3, 4], and complete satellites. It is common practice for developers to create their modules based on commercial off-the-shelf elements. This method provides the most effective compliance with the technical and operational requirements of the CubeSats. To confirm the performance and specified technical characteristics of the developed equipment or onboard system, it is necessary to conduct preliminary testing [5–7]. Comprehensive tests are performed in the joint operation of onboard systems and the ground control complex.

There are many engineering debugging models of nanosatellites [8–9]. For example, the Pumpkin CubeSat debug kit of the American company Pumpkin Ink [10] has a control system, data acquisition and processing, a communication system, and an expansion board with RS-232, USB PCI/ISA interfaces for the payload. But in the tested set, there are no attitude determination and control system (ADCS) and full-fledged power supply system. It does not allow comprehensive testing of all satellite systems in various operating modes. Also, this complex lacks additional interfaces, such as I2C, SPI, CAN, and RS-422/485, widely used in satellites. Another disadvantage of this kit is the lack of redundant systems. All this reduces the reliability of equipment testing.

The EyaSat nanosatellite engineering educational model [11] serves as a full-fledged demonstration model. It allows for conducting laboratory classes in the process of specialist training and retraining in the aerospace industry. This model can be used in the control algorithms of the development and educational programming of attitude determination and control systems [12]. However, it is impossible to test the engineering model's components and the onboard system in various operation modes. But the main EyaSat engineering model disadvantage is the onboard systems redundancy lack.

This paper describes the technical features and capabilities of 2 practical and affordable test bed nanosatellite simulators – BSUIM-1 and BSUIM-2. The development and implementation were realized at the Faculty of Radiophysics and Computer Technologies Belarusian State University supported

by the scientific research Republic of Belarus State programs “High-tech technologies and equipment” “Digital and space technologies, human, society and state security”. The nanosatellite simulator's structural and hardware components are also considered as the education courses part.

## BSUIM-1 on-board systems

First, the test bed BSUIM-1 is considered. This complex includes following software and hardware elements: remote control system (RCS); engineering nanosatellite model – nanosatellite simulator; software and information center for the development of onboard equipment; laboratory workshop “On-board systems and nano- and pico-satellites ground system”.

The engineering model schematic diagram shows in Figure 1. The nanosatellite engineering model has a non-hermetic design, a vertical layout and consists of modules that simulate the operation of the basic onboard systems: onboard computer; communication system; electric power system; ADCS; interfaces module; payload. The primary purpose of this engineering model is to provide full-loop nanosatellite designing, onboard systems and payload verification in operation mode, conducting experiments on testing the equipment of the ground control center. It suggests use for practical education aerospace specialists.

The main engineering model onboard systems – the control system (onboard computer) and the communication module have been duplicated to ensure reliability. The remote control feature of onboard systems provides: power on/off, software operating modes switching depending on the onboard systems state; independent subsystems controlled by user commands. The control channels of the nanosatellite technical model have been duplicated using the main onboard computer (based on the industrial computer CM-720) and the backup computer (based on the STM32F429 microcontroller). Channels for receiving commands and transmitting telemetry to the ground station had implemented using two identical transceiver models TE-CC430F51-433 and an additional GSM modem. The nanosatellite engineering model has a primary MNP-M7 GPS receiver and a backup uBlox neo6-M GPS module to improve the accuracy of time stamps during testing.

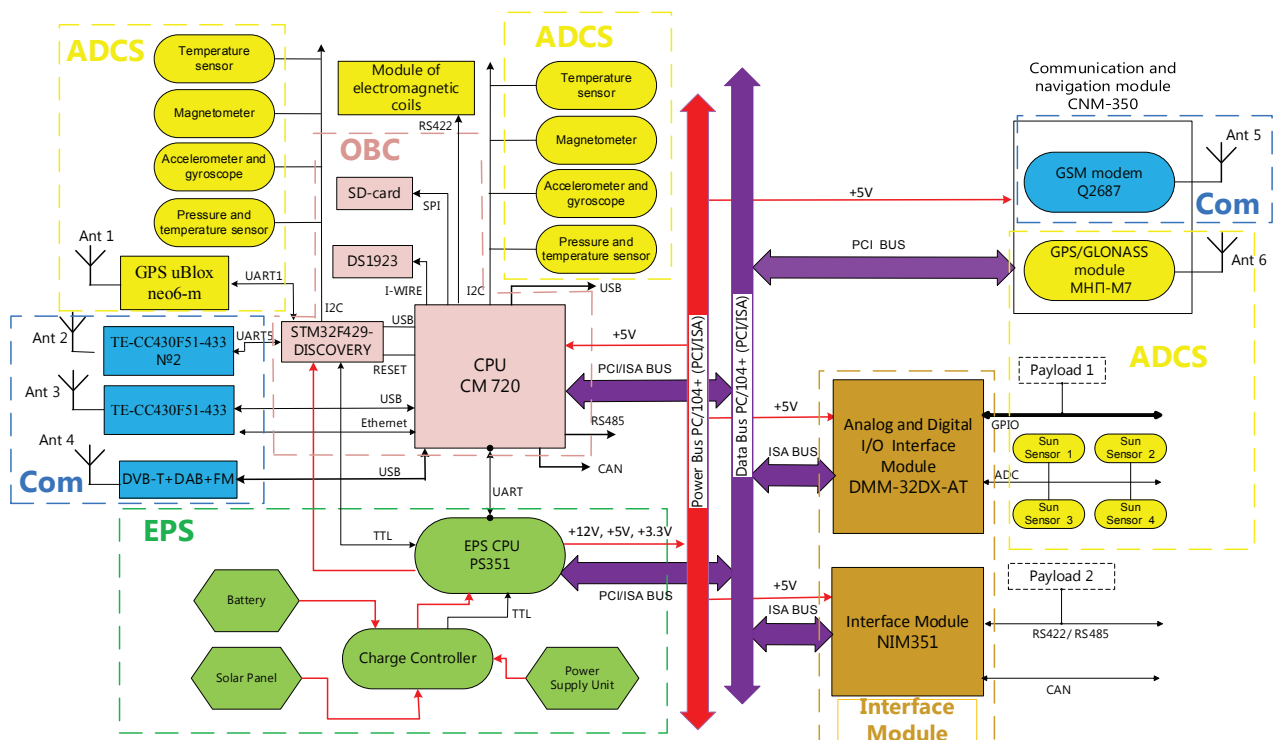


Figure 1 – The BSUIM-1 systems flowchart

## Ground station of BSUIM-1

The remote control system (RCS) is a ground station for control and reception. It can receive telemetry and special-purpose information from the orbited ultra-small satellite. It also makes it possible to simulate the operation of the ground satellite control in co-verification with the BSUIM-1 nanosatellite simulator. The remote control system allows to generate and transmit control commands to the BSUIM-1 nanosatellite simulator, receive, process, and display response data packets on the control commands execution, telemetry, and payload information. It also makes it possible to config of an operating model of the satellite onboard equipment or the tested equipment on the simulator as a part of modeling routine work with the satellite.

The RCS includes software and hardware for working with orbited ultra-small satellites: transceiver IC-9100; antenna-feeder devices of the command-telemetry radio link; power amplifiers; modems; control computer with software; uninterrupted power supply; and a mobile module of the remote control system for testing on-board systems and payloads with the BSUIM-1 nanosatellite simulator in the loop.

The equipment of the RCS mobile module is duplicated to ensure reliability. The channels of the BSUIM-1 nanosatellite simulator for receiving telemetry and control duplicates by the main and backup mobile modules of the RCS. Also, in each of the RCS mobile modules, two transceivers based on the CC430 radio module (main and backup) are used. The remote control system features a user-friendly graphical interface for displaying command and telemetry information, voicing the main parameters of the simulator, transferring and storing data on the local and remote servers of the BSUIM-1 nanosatellite simulator [13] [www.satellite.by](http://www.satellite.by).

For convenient operation, the special graphical user interface of the remote control system was developed [14]. It consists of two main panels – the Control Panel and the Telemetric Information Display Panel. The control panel allows flexible control of the onboard systems and payload of the BSUIM-1 nanosatellite simulator both using a large set of ready-made commands and commands developed by users. The telemetry panel displays raw telemetry packets in JSON format and structured (decoded) telemetry for onboard systems and the payload of the BSUIM-1 nanosatellite simulator. Each system has separate tabs with decoded information.

## BSUIM-2 on-board systems

The second BSUIM-2 test bed complex includes:

- laboratory test bed simulating the onboard systems operation of an ultra-small satellite (onboard computer, attitude determination and control system, communication system, electric power system and payload) and ground control station;

- telemetry database of orbited ultra-small satellites and software for primary and secondary telemetry processing;

- hardware of remote access laboratory for simulator control, data transmission and data

processing based on packet and web servers, transceivers and antenna-feeder systems;

- remote access laboratory website;

- a set of educational and methodological materials for training specialists in the areas of “Ground stations” and “Spacecrafts”.

The second test bed allows to include in the architecture of the remote access laboratory, shown in Figure 2, a nanosatellite simulator made in the Cubesat 2U standard, the first test bed BSUIM-1 with a nanosatellite simulator and BSU’s low-orbit nanosatellite “CubeBel-1” for training [15].

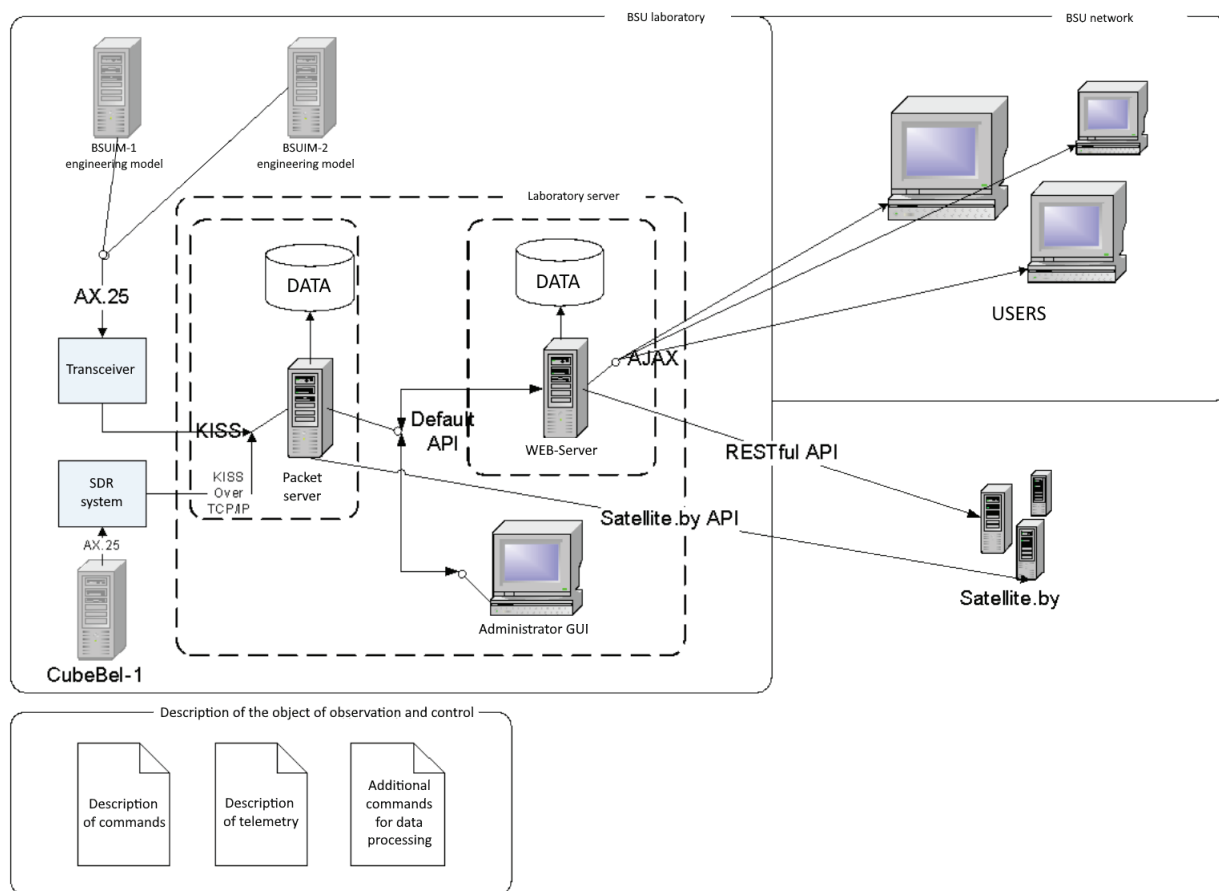


Figure 2 – Remote access laboratory architecture

The hardware part of the BSUIM-2 nanosatellite simulator systems is shown in Figure 3. It is made on a non-radioresistant element base and includes all the main onboard systems of an operated ultra-small satellite:

- two onboard computers based on STM32 ARM microcontrollers (main and backup);

- two onboard communication modules (main and backup) based on Si4463 transceivers and antennas;

- attitude determination and control system [16] based on: navigation module Lacosys MC1620; accelerometers and gyroscopes [17] (MPU-9250 and MPU-6050), pressure and temperature sensors (BMP280); magnetometers [18–20] (MAG3110 and MPU-9250); component parts of the stabilization system (electromagnetic coils);

- electric power system based on: rechargeable batteries; power regulators; solar cells.

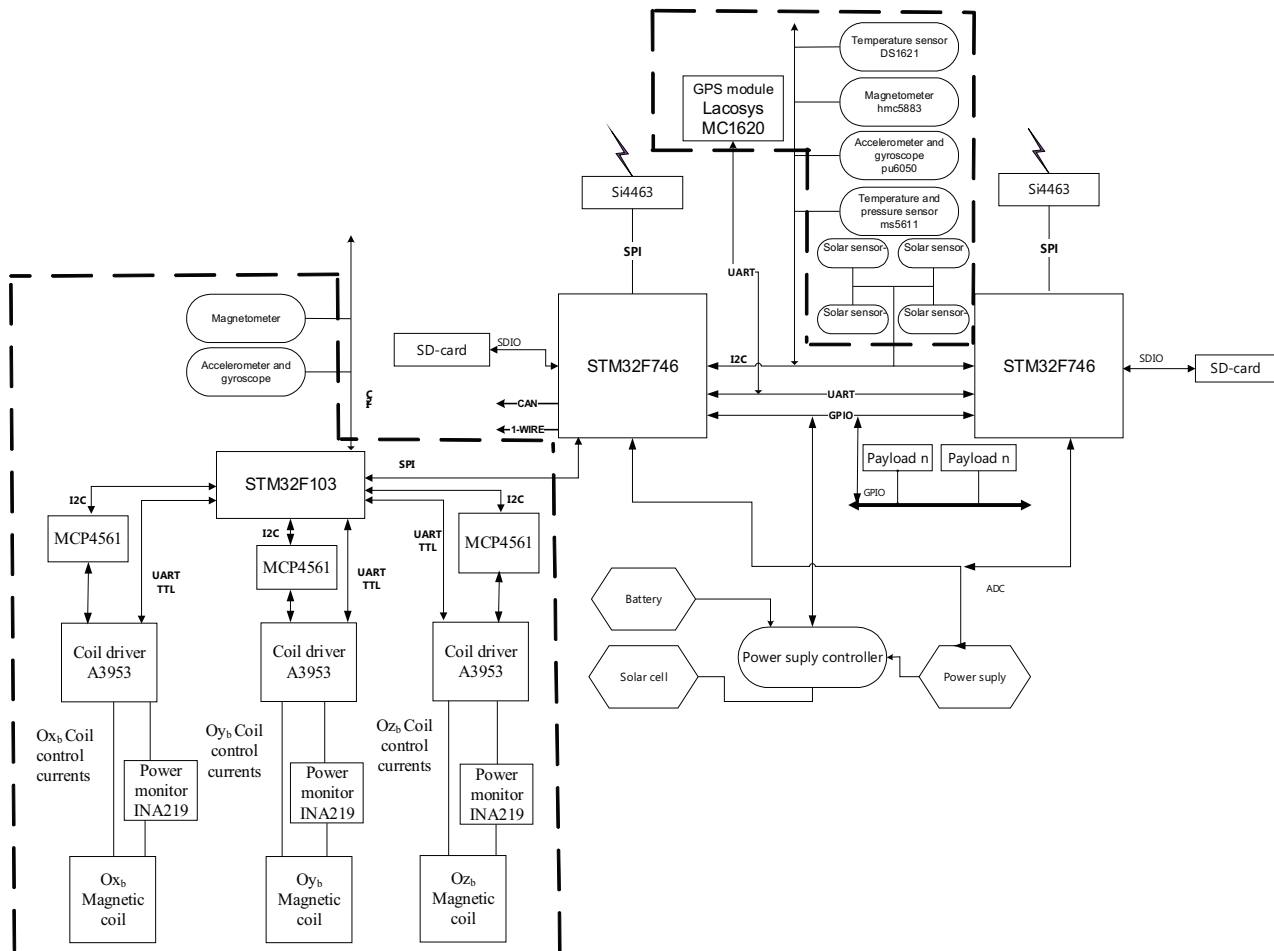


Figure 3 – The BSUIM-2 systems flowchart

Systems that simulate the operation of the ultra-small satellite onboard systems perform the following functions: power supply of onboard systems in all modes of operation; formation of regulated voltages 3.3 V, 5 V, 12 V; control of systems performance; systems configuration; packets formation for transmitting information over a radio channel; time binding of commands and parameters to onboard time; exchange of information with onboard systems via I2C, SPI, USB, CAN interfaces, through analog and digital input/output ports.

### Ground station of BSUIM-2

Nanosatellite simulators have a core communication system for receiving commands and transmitting telemetry. Moreover, the provided backup system can replace the main one in a crash case. The communication system sends the telemetry data to the ground station in the form of nested association lists in MsgPack format using the AX.25 protocol [21]. The communication systems for each

nanosatellite simulator have the same call sign but different SSIDs. Ground station transceivers are based on MSP430 microcontrollers [22] with KISS protocol control [23]. Commands for nanosatellite simulators are also association lists. The stack method uses to send them. Reception of telemetry from the orbited satellite CubeBel-1 provides by the SDR system [24]. It uses the existing UZ7HO sound modem software. It supports receiving packets using the KISS protocol over TCP/IP.

To support many different protocols for interaction with various orbited satellites (including those with one-way communication), the concept of a stack is introduced. The stack includes a set of protocols at different levels of interaction, similar to the OSI model [25]. For each stack variant specified by the configuration, a separated software component is launched that provides interaction with the satellites through the specified stack on the one hand with the package server core in a standard format on the other. Every protocol implementation on the stack can be reused. This allows multiple satellites to be supported at minimal cost.

On the other hand, the batch server interacts with a number of different clients using different APIs. Some of them are defined as a single client (separate web server of a laboratory or collaborating university, local admin GUI). For some, only data transfer is used (for example, for Satellite.by). To support such a variety of clients, special modules are used that extend the Packet Server API and provide telemetry distribution tools (both for a specific client and for all clients at once).

## The discussion of the results

Engineering model test beds (simulators of nanosatellites) for teaching students the basics of working with ultra-small satellites are considered. The possibility of checking the operating modes, flight program, hardware, and software of the onboard equipment and payload is described. The advantage of the developed complexes is the principle of modularity. It allows for the addition or changes onboard modules and payloads of simulators for debugging and testing the simulator/satellite firmware without creating a new expensive engineering model. The second advantage is the ability to study various algorithms and programs for the simulator operation (onboard systems and the payload) in various modes typical for a real flight [26]. Moreover, the flexible software of the simulator and the ground station provides the possibility of modifying.

The core function of the complexes is to train new specialists for further work with operated satellites and ground stations. Thanks to the complex, it is possible to train specialists in several areas: satellite design; design of special-purpose and scientific equipment; satellite onboard systems design; development of ground stations; design and conduct of scientific experiments [27]; receiving and processing telemetry; dynamics, ballistics, satellite motion control; navigation and orientation devices [28].

In addition to studying nanosatellites, the complex allows students to gain practical skills in working with ground stations: study their structure, software and hardware and remote control methods [29]. It also allows students to learn the basics of receiving, transmitting, modulating, encoding and encrypting data. The developed complexes make it possible to study various configurations of ground stations. So, for example, with the help of an amateur radio RTL-SDR, you can assemble additional radio receiving stations for working with simulators [30].

## Conclusion

The developed complexes make it possible to carry out term papers, graduate works and master's thesis related to the design of hardware and software for nanosatellites and a ground station, the setting up of space experiments, the development of new algorithms and the flight program of an ultra-small satellite.

The results obtained are introduced into the educational process and are used in lectures and laboratory classes for students of aerospace specialties of BSU.

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