PROSPECTS FOR THE DEVELOPMENT OF HELIOGEOPHYSICAL SATELLITE OBSERVATIONS ON SMALL SPACECRAFT

© 2025 A.A. Bragina*, V.T. Minligareev, S.D. Bogodyazh
Institute of Applied Geophysics named after Academician E.K. Fedorov, Moscow, Russia

**e-mail: anastasia .a.bragina@yandex.ru*

Received October 25, 2023
Revised February 21, 2024
Accepted February 22, 2024

The paper considers the prerequisites for the creation of satellite systems of small spacecraft of the cubesat type for heliogeophysical purposes. The history of the appearance and features of this type of platform are described, and examples of their implementation are given. The domestic satellite group of the small spacecraft, developed under the programs "Universat" and "Space-Pi", are also considered. Small spacecraft with magnetometric measuring equipment on board are described. Based on the results of the analysis, the main relevant directions for the development of on-board heliogeophysical and, in particular, magnetometric equipment have been identified. Problems have also been identified in the implementation system of the received data. As examples of modern developments in the field of satellite heliogeophysical observations, the activities of Institute of Applied Geophysics as a thematic customer, expert and manufacturer of equipment are described. The possibilities of analyzing data from already in use devices are described, and prospects for further development are also stated.

DOI: 10.31857/S00234206250109e9

INTRODUCTION

In 1999 , the California Polytechnic State University, together with the Stanford University Space Systems Development Laboratory, established a standard for CubeSat microsatellites. Such satellites represent various combinations of cubes (1 cube — 1U) with dimensions of 10×10×10 cm. Various service and scientific equipment is located inside the body. This standard has been adopted by many organizations around the world.

The purpose of creating small spacecraft (SSC) such as CubeSat was to facilitate access to space exploration for university students. Now, not only educational institutions can become developers, but also private companies and state enterprises. For example, one of the largest manufacturers of aviation, space and military equipment, "The Boeing Company." Its subsidiary, "Millennium Space Systems," conducted an experiment demonstrating technology that will quickly de-orbit satellites that have completed their mission. The experiment involved two 6U format CubeSat SSCs.

The history of microsatellite development in Russia began relatively recently. The first successful launch in 2012 of the Russian SSC — " *Chibis-M* " — became the prerequisite for the beginning of CubeSat creation. It was developed and built by the Space Research Institute of the Russian Academy of Sciences together with other domestic scientific and engineering-technological organizations (Sputnix, Engineering and Technology Center "Scanex", etc.). The project was successfully completed on 16.X.2014. The data obtained by "Chibis-M" made a significant contribution to the study of processes occurring in the atmosphere during electrical discharges [1, 2].

Since that time, an impressive number of scientific and technical experiments have been implemented. Among the quite successful ones, it is worth noting the work of SSC *SiriusSat* -1, -2 on the analysis of fast variability of electron fluxes in near-Earth space [3, 4] and experiments on real-time radiation monitoring in near-Earth space [5].

Microsatellites have a number of significant advantages compared to full-sized spacecraft. First of all, it is the high speed of preparation and simplicity of execution — the small size significantly simplifies the process of development, assembly, testing, and other stages of creating the device. Among the distinctive features is also the ability to work in low Earth orbits, at altitudes of 300-500 km. Among the disadvantages, there is a relatively short active lifetime and limitations on dimensions and mass.

Currently, a large number of domestic and foreign programs are being implemented to form satellite constellations of small spacecraft. A significant part of the target onboard equipment is aimed at solving Earth remote sensing (ERS) tasks, in particular, tasks of heliogeophysics and space weather monitoring. Among them: observation of near-Earth space, ionosphere, atmosphere, and magnetosphere. One of the most demanded areas among those listed is magnetometric satellite observations [6]. Currently, this is the main source of information about the Earth's magnetic field (EMF). Models of the anomalous and normal Earth's magnetic field (WDMAM, EMAG, IGRF) are calculated and constructed based on satellite survey data.

SATELLITE MAGNETIC OBSERVATIONS

The tasks of studying the Earth's magnetosphere have attracted the attention of scientists from various countries since the beginning of the space era. The first step in studying this Earth's shell was made by S.N. Vernov's team using the spacecraft " *Sputnik* -2". An increase in the level of radiation background in northern latitudes was detected, from which the existence of a radiation belt was subsequently concluded [7]. Satellite measurements of the EMF in the world began with the creation of the Soviet artificial Earth satellite " *Sputnik* -3", which was equipped with a fluxgate magnetometer [8]. The spacecraft was launched in the USSR in 1958 . The equipment for it was developed at IZMIRAN and at the Research Institute of Nuclear Physics of Moscow State University. The research continued in 1964 on the satellite *Cosmos* -26. In 1965 , the magnetic field was measured from the satellite *Cosmos* -49 over a large area in the latitude range of –50° to +50° [9].

Later, in 1979–1980 , the spacecraft *MAGSAT* was launched, developed in the USA, also carrying out measurements of the EMF. Then there was a 20-year break in the flights of satellite magnetometric systems, which ended with the launch of the Danish satellite *Ørsted* in 1999 (https://space.oscar.wmo.int/satelliteprogrammes/view/Orsted).

At the beginning of the 21st century, interest in planetary geomagnetic research has increased. The "International Decade of Geopotential Research" program was implemented. Within this program, two spacecraft were launched: *CHAMP* and *Ørsted2* [10]. Since 2010, satellite observations have become the main source of information about the geomagnetic field.

Currently, the following space systems (SS) for magnetic observations are functioning: foreign *SWARM* (circular inclined orbit) and *GOES* (geostationary orbit), domestic " *Arktika* M *M*

" (highly elliptical orbit) and " *Elektro* L *Л* " (geostationary orbit) and many others [11]. Based on open data, the main SS with magnetometric equipment on board were identified (Fig. 1).

Fig. 1. Development scheme of SS with magnetometric equipment on board

In recent years, the task of miniaturizing magnetometric equipment for their subsequent implementation on microsatellites such as CubeSat has become increasingly relevant. Instruments for small spacecraft must meet a greater number of requirements, comply with mass and dimensional constraints, and at the same time not be inferior in technical characteristics to full-sized counterparts. A group of small spacecraft with magnetometers on board will enable observation of the Earth's magnetic field in low circular orbits, up to altitudes of 500 km. This will allow monitoring the state of the magnetosphere in near-Earth space, analyzing and forecasting dangerous space weather phenomena. *These tasks are handled by one of the four global International Space Weather Centers for Safe Air Navigation, located at the Fedorov Institute of Applied Geophysics ((FSBI " IAG ") and is part of the Russian-Chinese Space Weather Consortium CRC.*

DOMESTIC SPACE CONSTELLATIONS OF SMALL SPACECRAFT

The development of small spacecraft constellations in Russia mostly occurs within the framework of separate interdepartmental programs. Currently, such programs are "Universat," organized by Roscosmos, Roshydromet, and the country's leading universities, and the "Space-Pi" project, organized by the Innovation Promotion Foundation. These projects allow for the implementation of promising initiatives from schoolchildren and students, providing them with the necessary resources. Microsatellites are sent into orbit as piggyback payloads [12].

Project " Universat "

"Universat" is a large-scale project to support and accompany the development and launches of cubesat-type small spacecraft. In collaboration with domestic educational institutions, the Roscosmos State Corporation provides assistance in developing the rocket and space industry. The project partner is the Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet), and participants include Lomonosov Moscow State University, Bauman Moscow State Technical University, Amur State University (AmSU), Novosibirsk State University (NSU), and other educational institutions, as well as FSBI M.V. Lomonosov, MSTU named after N.E. Bauman, Amur State University (AmSU), Novosibirsk State University (NSU) and other educational institutions, as well as FSBI "IPG" [13-15].

The universities are directly engaged in developing the microsatellite structure and creating specialized equipment. FSBI "IPG" provides expert assessment of instruments designed for heliogeophysical measurements. For an appropriate level of reliability and comparability of measurement results, the equipment on small spacecraft requires high-quality metrological support [16]. The final stage is the launch of small spacecraft as a piggyback payload, which is carried out by the Roscosmos State Corporation.

The main implemented directions: space weather monitoring, radio occultation monitoring of the Earth's atmosphere and ionosphere (GNSS-monitoring), aircraft tracking. For Earth magnetic field observation tasks, miniaturized magnetometric equipment is installed on the spacecraft " *Yarilo* No.3" and *SamSat-ION* .

As part of the project, according to data as of July 2023 , 16 cubesat-type microsatellites have been launched. The first launch was conducted on 05. VII .2019 from the Vostochny Cosmodrome, the second — 28.IX.2020, from the Plesetsk Cosmodrome, and the third — 27.VI.2023 from the Vostochny Cosmodrome (Table 1).

Table 1. List of small satellites participating in the "Universat" program

Satellite Name	Launch	Organization	Description
" *Socrat* "	05.VII.2019 Vostochny Cosmodrome	SINP MSU	-monitoring of space weather in low Earth orbits; -testing of new technical solutions and instrument composition;
" *VDNKh* -80"		SINP MSU	-telemetry with data on radiation environment (charged particle concentration, MPF profile);
" *AmurSat* "		AmSU	-monitoring of space weather in low Earth orbits; -testing of new technical solutions and instrument composition;
" *DECART* "	28.IX.2020 Plesetsk Cosmodrome	SINP MSU	-obtaining radiation data; -testing systems for monitoring civilian aircraft;
" *Norby* "		NSU	-monitoring of heliogeophysical parameters of near-Earth space; -board testing;
" *Yarilo* " #1 and #2		Bauman MSTU	-flight tests of experimental power supply, radio communication, orientation and stabilization systems;
" *Yarilo* " #3 and #4	27.VI.2023 Vostochny Cosmodrome	Bauman MSTU	-measurement of energy reflected from Earth's surface; -MPF measurement;
" *Hors* " #1 and #2		Bauman MSTU FSBI "IPG"	-research of galactic cosmic rays (GAMVEKI instrument - developed by FSBI "IPG"); -testing of high-frequency plasma propulsion system;
" *Avion* "		SINP MSU	-monitoring of space radiation;
" *Norby* - 2"		NSU	-observations of the solar corona; -testing of electronic component base;
" *Impulse* -1"		MISIS	-experiments in solar activity monitoring; -testing elements of satellite quantum communications system and classical laser communication;

" *SamSat-ION* "		Samara University	-research of upper ionosphere parameters, plasma state and MPF;
" *Saturn* "		KubSU	-monitoring of space weather in near-Earth space

FGBI IPG was also directly involved in the development of scientific equipment for the “Horse” spacecraft No. 1 and No. 2. The GAMVEKI heliogeophysical equipment at the “Horse” cubesat No. 2 (consists of two units — GAMVEKI-GM and GAMVEKI-H) was developed at the institute and is an analog of a full-size device for measuring electron flux density and GALS-VE protons, installed on such spacecraft as “Arctic-M” No. 1 and No. 2, “Meteor-M” No. 2-2, No. 2-3, No. 2-4 and “Electro-L” No. 3, No. 4, as well as an analog of the GALS/1 spectrometer for the Ionosphere spacecraft the Ionozond space complex.

53 spacecraft were launched into orbit from the Vostochny cosmodrome from “Ionosphere-M” spacecraft No. 1, No. 2 by the Soyuz-2.1b launch vehicle and the “Fregat” upper stage on 5.XI.2024 (Fig. 2), including 6 under the UniverSat program (Fig. 3). “GAMVEKI-GM” devices manufactured by FSBI IPG are installed on the “Vladivostok-1” and “MTUCI-1” spacecraft. Horse spacecraft No. 3, No. 4, and “SamSat-Ionosphere” were launched into orbit with target heliogeophysical equipment for radio-exchange sensing of the atmosphere and ionosphere, as well as for space weather research and monitoring.

Fig. 2. Launch on November 05, 2024, Vostochny Cosmodrome

Fig. 3. Small spacecraft of the UniverSat program launched into orbit on November 05, 2024

Space-Pi Project

The "Space-Pi" project, like "UniverSat," is aimed at supporting educational organizations in the field of space research. Partner organizations such as the Innovation Promotion Foundation, the "Talent and Success Foundation ", Skolkovo Institute of Science and Technology, and State Corporation "Roscosmos" are combining their efforts to create an accessible educational environment in the field of space exploration and small spacecraft design and development tasks with the involvement of young scientists, students, and schoolchildren. Currently, there are 35 microsatellites in orbit that have been launched as part of the project (Table 2).

Table 2 . List of small spacecraft participating in the "Space-Pi" program

Spacecraft Name	Launch	Organization	Description

CubeSX Sirius-HSE *Sirius-HSE CubeSX-HSE*	March 22, 2021 "Baikonur" Cosmodrome	HSE University, "Sirius" Educational Center	- monitoring of Earth's ecological condition;
OrbiCraft Zorkiy		SPUTNIX	- testing of a new high-precision solar sensor;
Polytech Universe -1 and 2	August 9, 2022 "Baikonur" Cosmodrome	Peter the Great St. Petersburg Polytechnic University	- studying the level of EM radiation on Earth's surface in various frequency ranges;
ReshUCube -1		Reshetnev Siberian State University Reshetneva	- monitoring of the radiation environment in orbit; - study of the Earth's atmosphere and magnetosphere;
Monitor -1		SINP MSU	- registration of radiation-hazardous proton fluxes from solar flares in outer space;
Kuzbass -300		KuzSTU	- remote sensing tasks;
KAI -1		"NILAKT DOSAAF" KNRTU-KAI	- remote sensing tasks;
Skoltech B *Б* 1 and *B* 2		Skoltech	- testing technology for inter-satellite communication at long distances; - monitoring of cosmic radiation and gamma-ray bursts;
StratoSat TK -1	27.VI.2023 Vostochny cosmodrome	"Stratonavtika"	- delivery of 6 pico-class spacecraft to Earth orbit;
UmKA -1		Center for Scientific Creativity of School 29 in Podolsk	- imaging of deep space objects;
Vizard-meteo		LLC "NIS"	- monitoring the formation of dangerous meteorological phenomena in the atmosphere;
Nanozond -1		OSU named after I.S. Turgenev	- study of the influence of the space environment on the satellite body;
Sirius-SINP -3U		"BG-Optics" "Neuro-Master"	- research of electrons, protons and gamma radiation;
Polytech Universe -3		SPbPU named after Peter the Great	- creation of a three-dimensional non-stationary model of electromagnetic radiation level distribution near Earth;
Monitor -2, -3 and -4		SINP MSU	- observation of cosmic flares in X-ray and gamma radiation;
ReshUCube -2		SibSU named after M.F. Reshetnev	- flight experiments with promising network protocols

Part of the scientific equipment installed on the "Space-Pi" microsatellites is aimed at solving remote sensing and heliogeophysical tasks. Observations of the Earth's magnetic field within the project are carried out by the microsatellite *ReshUCube* -1, manufactured at SibSU named after M.F. Reshetnev.

In addition to various cameras, spectrometers, telescopes, and sensors monitoring space weather, there is also service equipment on board. The applied tasks performed by small spacecraft in near-Earth orbit include: monitoring the movement of marine vessels and aircraft, testing new communication technologies, monitoring dangerous natural phenomena, testing new propulsion systems and platforms, etc. The "Space-Pi" program provides an opportunity to test new technological solutions in various areas of space activities.

TASKS OF MAGNETOMETRIC EQUIPMENT MINIMIZATION

The target equipment intended for installation on small spacecraft has additional requirements for mass, dimensions, and power consumption. The physical foundations and operating principle are similar to full-sized instruments, but the magnetometer for a microsatellite must be compact. There is experience in minimizing magnetometric equipment in both domestic and foreign developments.

In 2023 specialists from FSBI "IPG" calibrated the magnetometer intended for installation on board the small spacecraft "Yarilo No. 3" (Fig. 4). The magnetometric sensor installed in the device is Honeywell HMC100x (Table 3). The sensor's operating principle is not fluxgate, as on most spacecraft, but magnetoresistive. Such elements have a wide range of operating temperatures, have a long service life, and can measure very weak magnetic fields (about 0.1 nT). The magnetometric system is located on a 2-meter-long carbon fiber boom (the optimal length was calculated theoretically) to eliminate the influence of the housing's magnetic noise. The design and deployment system of the boom is developed by students and staff of Bauman Moscow State Technical University N.E. Bauman [17].

Fig. 4 . Bauman Moscow State Technical University magnetometer with Honeywell HMC100x sensor during calibration Bauman with Honeywell HMC100x sensor during calibration

Table 3. Technical Specifications of Honeywell HMC100x Magnetic Sensor

Parameter	Value
Measurement range, nT	± 200,000
Measurement frequency, Hz	1
Resolution, nT	2.7
Supply voltage, V	5–12
Dimensions, mm	12.7 × 7.3 × 2.5

The microsatellite *SamSat-ION* , developed by students of Samara University named after S.P. Korolev uses the MMC5883MA magnetic sensor (USA). There are two magnetometers on board the small spacecraft — one inside the housing, the other on an extension boom. The technical specifications of the magnetic sensor are presented in Table 4.

Table 4. Technical Specifications of the MMC5883MA Magnetic Sensor.

Parameter	Value
Measurement range, nT	± 800,000
Noise, nT	40
Sensitivity, %	± 5
Supply voltage, V	1.62–3.6

MAG3110 magnetic field sensors manufactured by Olimex (Bulgaria) are used in the *ReshUCube* -1 project of the Siberian State University of Science and Technology named after academician M.F. Reshetnev (SibSU). The technical specifications of the magnetic sensor are presented in Table 5.

Table 5. Technical Specifications of the MAG3110 Magnetic Sensor.

Parameter	Value
Measurement range, nT	± 1,000,000
Sensitivity, nT	100
Noise, nT	250
Supply voltage, V	1.95–3.6
Dimensions, mm	29×18
Weight, g	25

Magnetic sensors that form the basis of the instrument are mainly of foreign production. Therefore, the development of a domestic analog, similar in design, technical characteristics, and price accessibility, is an important and promising direction. By analyzing the existing experience in creating satellite magnetometric equipment, we can determine further prospects for its development. This includes improving accuracy, instrument resolution, recording frequency, digitization quality, and ensuring high-quality data transmission between the spacecraft and the ground segment. Also important is work on the reliability of the instrument — its service life, resistance to temperature, shock, and vibration effects.

Currently, the FSBI "IPG" is working on creating a magnetometric instrument complex for low-orbit spacecraft and small spacecraft of the CubeSat type. As a result, technical requirements have been developed for a miniaturized magnetometer for small spacecraft, taking into account limitations on weight, dimensions, and power consumption. A magnetometer model for small spacecraft (measuring unit with sensor, electronics unit, housing) is in the assembly process. The prospects for creating a cluster of small spacecraft with magnetometers on board have been analyzed, and the tasks to be solved have been determined. Requirements for the number of small spacecraft, orbits, and altitudes have been developed. The possibility of integrated work with ground-based magnetic variation stations (MVS) is being considered.

The instrument is planned to be used as a payload on the satellite magnetometric grouping being developed to solve the tasks of magnetosphere monitoring.

CONCLUSION

Thus, heliogeophysical satellite observations are currently a promising and rapidly developing direction. The implementation of such research using small spacecraft of the CubeSat type significantly facilitates the solution of both applied and scientific tasks. Projects such as

"Universat" and "Space-Pi" provide the opportunity to timely and efficiently test new technologies, hardware solutions, and methods for satellite research.

Building a communication line between educational organizations — manufacturers of small spacecraft platforms and equipment for them, and enterprises — thematic customers, main consumers, will allow structuring the system of data exchange and use. Currently, FSBI "IPG" is developing a unified database of satellite magnetometric observations [18]. The acquisition of information and coordination of actions on magnetometric equipment on active small spacecraft is being considered.

REFERENCES

1. *Zelyony L.M., Klimov S.I., Angarov V.N. et al.* The "Chibis-M" microsatellite project. Experience of creation and implementation // Study of solar-terrestrial relations on micro-, nano- and picosatellites: Proceedings of the scientific session of the Solar-Terrestrial Relations Section of the Space Council of the Russian Academy of Sciences. Ser. "Mechanics, Control and Informatics" Moscow: IKI RAS, 2015. P. 91–118.
2. *Zeleny L.M., Gurevich A.V., Klimov S.I. et al* . Academic microsatellite Chibis-M // Space Research. 2014. Vol. 52. No. 2. P. 93–105.
3. *Bogomolov V.V., Bogomolov A.V., Dementyev Yu.N. et al.* Scientific and educational space experiment on satellites "SiriusSat-1,-2" // Moscow University Bulletin. Ser. 3. Physics. Astronomy. 2020. No. 6.
4. *Prokhorov M.I., Bogomolov V.V., Bogomolov A.V. et al.* Analysis of rapid variations of electron fluxes in the gap region by the method of normalized range based on measurement data from the SiriusSat-1 satellite // Space Research. 2022. Vol. 60. No. 4. P. 271–284.
5. *Bogomolov A.V., Bogomolov V.V., Iyudin A.F et al.* Space Weather Effects from Observations by Moscow University Cubesat Constellation // Universe. 2022. V. 8. Iss. 282.
6. *Kopytenko Yu.A., Petrova A.A., Guryev I.S. et al* . Analysis of the informative content of the Earth's magnetic field in near-Earth space // Space Research. 2021. Vol. 59. No. 3. P. 177–190.
7. *Vernov S.N., Grigorov N.L., Logachev Yu.I. et al.* Measurement of cosmic radiation on an artificial Earth satellite // Artificial Earth Satellites. 1958. Issue 1: Results of scientific research conducted under the IGY program using the first and second artificial Earth satellites. P. 5–8.
8. *Solovyev A.A.* Some Problems of Geomagnetism Solved Using Ground-Based and Satellite Observations // Geology and Geophysics. 2023. Vol. 64. No. 9. P. 1330–1356.
9. *Dolginov Sh.Sh., Zhuzgov L.N., Pushkov N.V.* Preliminary reports on geomagnetic measurements on the third artificial Earth satellite // Artificial Earth Satellites. 1958. Issue 2. P. 50–52.
10. *Olsen N., Holme R., Luehr H.* A magnetic field model derived from Ørsted, CHAMP and Ørsted-2/SACC observations // Proc. AGU Spring Meeting. Washington, D.C., USA. 2002
11. *Bragina A.A., Arutyunyan D.A., Minligareev V.T.* Review of space systems for heliogeophysical purposes with magnetometric equipment // Heliogeophysical Research. 2022. No. 34. P. 40–48.
12. *Simonov V.L.* Application of CubeSat nanosatellite development in the educational process // Modern Information Technologies in Education, Science and Industry: Proceedings of the XXI International Conference. XIX International Competition of Scientific and Scientific-Methodological Works. Moscow, Russia. 2022. P. 81–84.

13. *Fomin D.V.* "AmGU-1" ("AmurSat") — the first satellite of AmGU // Cosmonautics: Science and Education: Proceedings of the All-Russian Scientific Conference. Blagoveshchensk, Russia. 2019. P. 15–18.
14. *Sadovnichiy V.A., Panasyuk M.I., Lipunov V.M. et al.* Monitoring of natural and man-made space threats: results of the Lomonosov mission and the Universat-SOCRAT project // Space Research. 2019. Vol. 57. No. 1. P. 46–56.
15. *Rachkin D.A., Tenenbaum S.M., Melnikova V.G. et al.* Development of CubeSat small spacecraft — experience of Bauman Moscow State Technical University named after N.E. Bauman // K.E. Tsiolkovsky and the progress of science and technology in the XXI century: materials of the 56th scientific readings dedicated to the development of scientific heritage and the development of ideas of K.E. Tsiolkovsky. Kaluga, Russia. 2021. P. 24–27.
16. *Minligareev V.T., Zabolotnov V.N., Denisova V.I. et al.* Ensuring the uniformity of magnetic measurements on the state observational network // Heliogeophysical Research. 2013. No. 6. P. 8–19.
17. *Bogachev S.A., Golovin A.A., Dyatkov S.Yu. et al.* Small-scale space magnetometer for Yarilo nanosatellite No. 3. // Cosmonautics and Rocket Engineering. 2023. No. 1(130). P. 123-134.
18. Certificate 2023622956. Minute measurements of INTERMAGNET network magnetic variation observatories for the period from 1991 to 2018 after processing. Database / Vishnyakov D.D., Bragina A.A., Arutyunyan D.A., Shklyaruk A.D. (RU); publ. 28.08.2023.

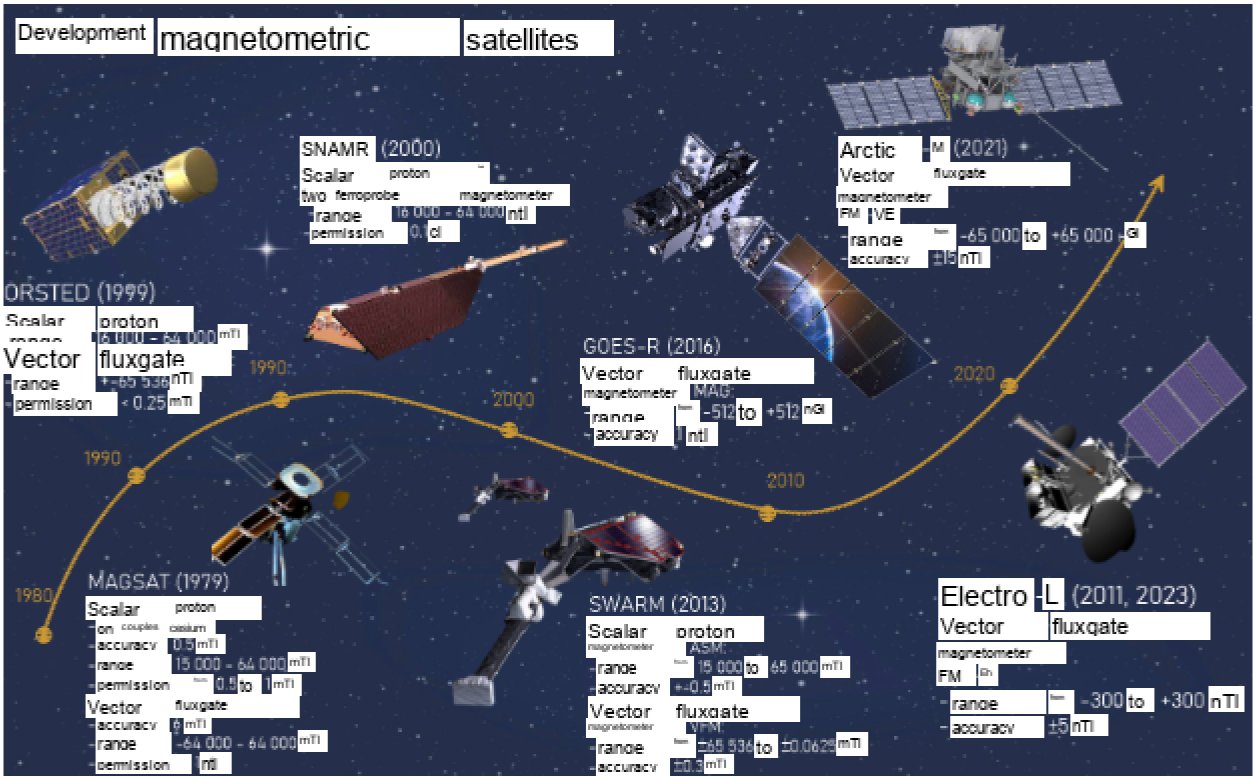


Fig. 1. Development scheme of spacecraft with magnetometric equipment on board.

Fig. 2 . Launch 5 . XI.2024, Vostochny Cosmodrome

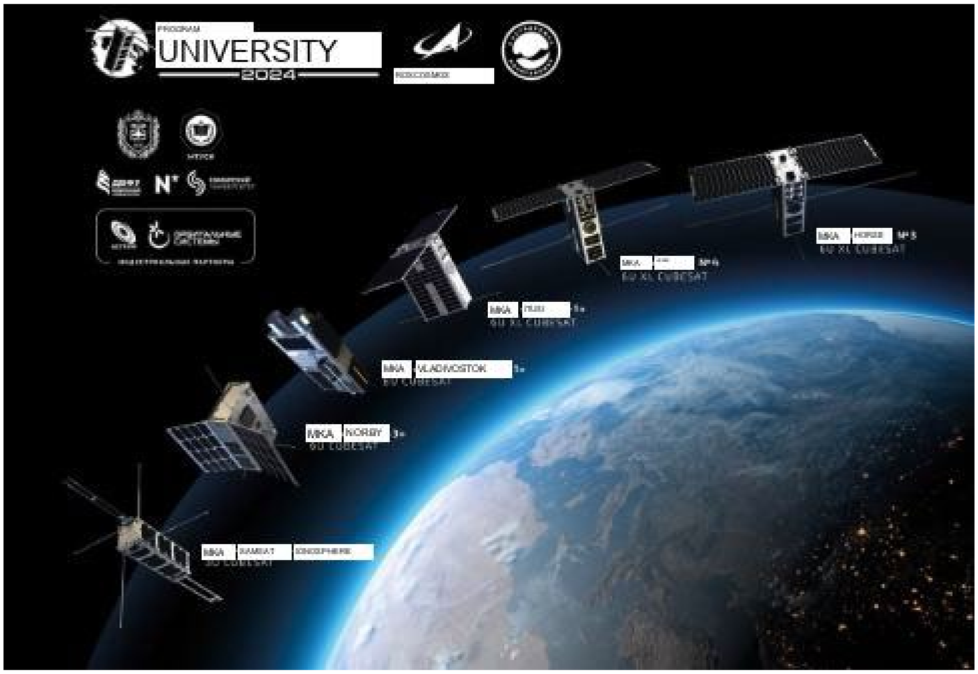
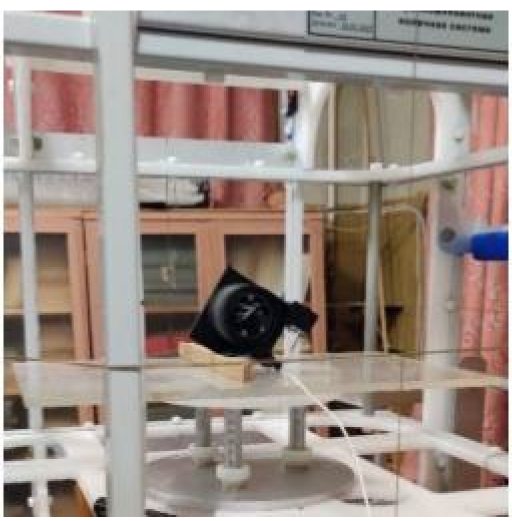


Fig. 3 . Small spacecraft of UniverSat program launched into orbit on 5.XI.2024



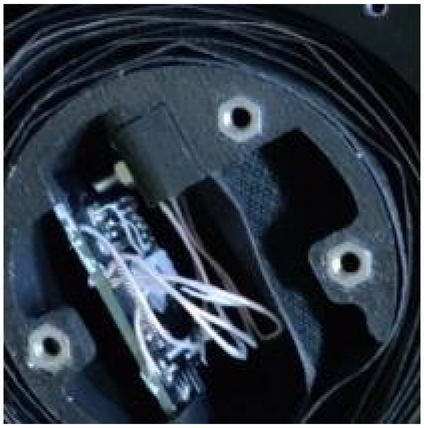


Fig. 4 . Magnetometer of Bauman MSTU with Honeywell HMC100x sensor during calibration