Juziyeva Shynar Aitkozhyevna and Yensebayeva Madina Rishatovna
Prerequisites for modeling nanosatellite elements in semi-natural mode.
SENIOR THESIS
Specialty 5B074600 – Space technique and technology

Almaty 2020

MINISTRY OF EDUCATION AND SCIENCE OF THE REPUBLIC OF KAZAKHSTAN

Satbayev Kazakh National Technical University

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**Technical Task for
Senior Thesis defense**

For deans: *Juziyeva Shynar Aitkozhyevna and Yensebayeva Madina Rishatovna*

Theme*: Prerequisites for modeling nanosatellite elements in semi-natural mode*
Approved *by the order of the University rector№1781-бom « 28 » 02 2019_y.*

Deadline for completion of completed work« 18» 05 2020_ y.

Initial data for the thesis:*experimental necessity of nanosatellite environmental testing through the modeling and simulation of the orientation and stabilization system*

A list of tasks to be developed or a summary of the thesis:

a) Current state of research on modeling of the natural environment during nanosatellite flight to assess the performance of orientation and stabilization systems

b) Analysis of the experimental stand systems to understand and improve the simulation process

c) Development of optimal algorithms for controlling the magnetic field of the stand for more efficient testing of satellite system

d) Assumption of the possible results of experimental testing of a nanosatellite to obtain information about the state of its systems

Listofgraphicmaterials:

1. Theblockdiagramofthealgorithms

2. Photographs of the testing stand and it's systems

3. And other presentation and graphic materials, no more than 15 slides

Recommended main literature: from 2 titles:

1. S. O. Karpenko, M. Yu. Ovchinnikov, Laboratory stand for semi-figures-development of orientation systems for micro-and nanosatellites, IPM Preprints M. V. Keldysh, 2008, 0382.

2. PhD A.N.Gormakov, Geomagnetic field simulator for the ground based testing of Nanosatellites orientation systems

Schedule
preparation of a thesis (project)

Name of sections, list of issues being developed	Deadlines for submission to the supervisor and consultants	Notes
Current state of research on modeling of the natural environment during nanosatellite flight to assess the performance of orientation and stabilization systems	15.03.2020	More work on satellites construction
Analysis of the experimental stand systems to understand and improve the simulation process	29.03.2020	Most of the work is done properly
Development of optimal algorithms for controlling the magnetic field of the stand for more efficient testing of satellite systems	25.04.2020	Pursue the greater formula for the testing
Assumption of the possible results of experimental testing of a nanosatellite to obtain information about the state of its systems	9.05.2020	Results on the satellites found online

Signatures
Of the consultants and standard controller for the completed thesis (project)
with an indication of the relevant sections of the work (project)

Thesectiontitles	Consultants, I. O. F. (academic degree, title)	Date of signing	Signature
Normcontrol	Smailov N.K.		

Scientific adviser   E. Tashtay

The task was accepted   by the students Juziyeva Shynar Aitkozhyevna

Yensebayeva Madina Rishatovna

Date   "21"052020 y.

АҢДАТПА

Магниттік бағдарлау жүйесі бар спутникті орбитаға шығару үшін оны жартылай табиғи жағдайда қалай басқаруға болатындығын пысықтау қажет, ол үшін жер бетіндегі тірек құру қажет. Мұндай жағдай жасау үшін геомагниттік өрісті спутниктің орбиталық қозғалысына ұқсас өзгеру үлгісімен модельдеу қажет. Мұндай стендтер бұрыннан бар және тестілеу үшін белсенді қолданылады.

Олардың функционалдығы наносаттық спутнигінің нақты ғарыш жағдайында жұмыс жасамас бұрын оның жұмысын тексеру үшін барлық қажетті манипуляцияларды жасауға мүмкіндік береді.

Жұмыста SX025 стендінің мүмкіндіктері, сонымен қатар үш негізгі басқару алгоритмін қолданып кезең-кезеңімен орындалатын наносателлиттерді толық масштабты режимде сынамалау қарастырылған.

АННОТАЦИЯ

Чтобы запустить на орбиту спутник с магнитной системой ориентации, необходимо отработать, как управлять им в полунатурных условиях, для этого требуется создание наземного стенда. Для создания таких условий необходимо смоделировать геомагнитное поле с закономерностью изменения, аналогичной движению спутника по орбите. Такие стенды уже существуют и активно используются для проведения испытаний. Их функциональность позволяет выполнять все необходимые манипуляции для проверки работы наноспутника перед его эксплуатацией в реальных космических условиях.

В работе анализируются возможности стенда SX025, а также моделирование испытаний наноспутников в полунатурном режиме, выполненных поэтапно с использованием трех основных алгоритмов управления

ANNOTAION

To launch a satellite with a magnetic orientation system into orbit, it is necessary to work out how to control it in semi-natural conditions, this requires the creation of a ground stand. To create such conditions, it is necessary to simulate a geomagnetic field with a pattern of change similar to the movement of the satellite in orbit. Such stands already exist and are actively used for testing. Their functionality allows you to perform all the necessary manipulations to test the operation of the nanosatellite before its operation in real space conditions.

This senior thesis analyzes the capabilities of the SX025 stand, as well as simulations of testing nanosatellites in semi-natural mode, carried out in stages using three main controlalgorithms.

CONTENT

INTRODUCTION

Almost any project to create a small satellite requires minimizing the cost of its design and operation. Significant savings in these costs occur when the correct design characteristics of the satellite are selected, as well as when optimizing its systems at the initial design stage. At the same time, it is very important to be able to correctly assess the composition and characteristics of the orientation and stabilization system, and this, in turn, is difficult to do without modeling. At the same time, mathematical and computer modeling plays an important role, but it is very important to check their operation, feasibility and effectiveness in practice for a specific hardware implementation at the first stages. This requires a ground-based test bench. It is advisable to use it, in particular, for functional testing of the onboard orientation control system at the early stages of design. It can also be useful as a training base for students dealing with the problems of orientation of the IPO. The need for ground-based testing of orientation control algorithms led to the creation of a stand for semi-natural modeling at the Department of Space engineering and technology at Satpayev University. It consists of a magnetic field simulator and a layout suspended from a string. String suspension actually provides an imitation of one degree of freedom (rotation of the layout in a horizontal plane) or, if the suspension point coincides with the center of mass, three rotational degrees of freedom. Previous research on the topic has determined that the use of two stands makes it possible to study the relative movement of two control objects, which is of interest in the task of joint flight of several satellites (formation flying configuration).

1. AVAILABLE ANALOGUES

1.1 Historical review

Stands for testing satellite orientation control systems appeared in the 60s of the last century. They were used both in industrial enterprises and in universities. As a rule, they solved the problems of working out systems for determining the orientation of a solid body that has three degrees of freedom, i.e., it is able to rotate around a fixed point. The body (layout) was equipped with orientation detection sensors, Executive elements, and a system responsible for the control logic. Turning around the point was provided in the vast majority of cases so called air, or aerodynamic, suspension (Fig. 1). An air suspension is a spherical bearing that uses a jet of gas that is pressurized by the feed system instead of lubrication. The peculiarity of such suspensions is the required accuracy of manufacturing the mating surfaces of bearings used in such systems; it is thousandths of a millimeter. The bearing consists of a Cup (steel, aluminum), into which compressed gas is supplied under pressure; a joint and a system of arresters that supports the layout when pressure is removed. According to [1], the diameter of the joint in the systems known by the end of the 60s varied in the range of 70-500 mm, the load - from 13 to 7,000 kg. The gas pressure in the supply system was from 0.4 to 20 bar, and the flow rate was from 0.15 to 6 m3 / min. The moment of friction in such systems was from 0.003 to 10 N*m. As for mobility, this suspension usually allowed one of the axes to rotate 360°, while the other two axes could have rotation angles from 30 to 120°.
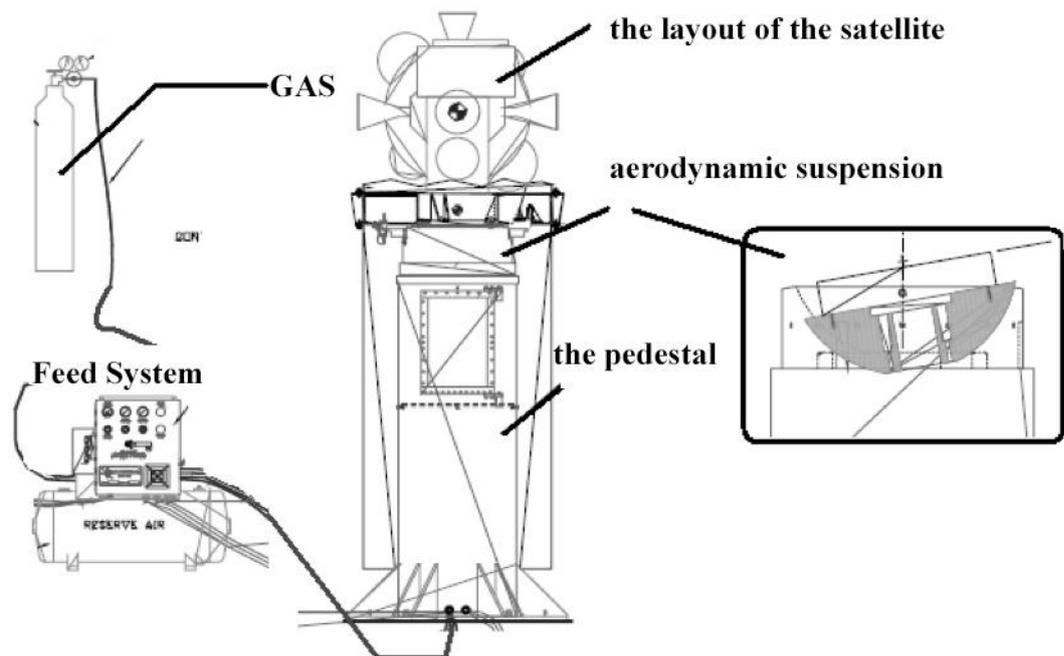
1.1 Fig.–The principle of operation of an aerodynamic suspension

The paper [2] describes one of the first systems of semi-natural modeling on an aerodynamic suspension used at the Langley Research Center, USA. The satellite layout (Fig. 2) had three flywheels, a magnetic system for unloading; the orientation detection system consisted of 12 phototransistors, as well as tachometers that measure the speed of rotation of the flywheels; the control laws were implemented as part of the so-called logic block. The task of the stand was to demonstrate the stable operation of the control system, and to work out the stabilization algorithms. An interesting feature is that the system was not completely Autonomous; power to the layout was supplied from an external source using very thin wires about 3 m long running from above. 150-watt spotlights were used as light sources. The weight of the model was 45 kg together with the magnetic flywheel unloading system. The magnetic system consisted of permanent magnets, and the flywheels were unloaded by turning the desired magnet in the desired direction using servomotors. The paper [2] describes one of the first systems of semi-natural modeling on an aerodynamic suspension used at the Langley Research Center, USA. The satellite layout (Fig. 2) had three flywheels, a magnetic system for unloading; the orientation detection system consisted of 12 phototransistors, as well as tachometers that measure the speed of rotation of the flywheels; the control laws were implemented as part of the so-called logic block. The task of the stand was to demonstrate the stable operation of the control system, and to work out the stabilization algorithms. An interesting feature is that the system was not completely Autonomous; power to the layout was supplied from an external source using very thin wires about 3 m long running from above. 150-watt spotlights were used as light sources. The weight of the model was 45 kg together with the magnetic flywheel unloading system. The magnetic system consisted of permanent magnets, and the flywheels were unloaded by turning the desired magnet in the desired direction using servomotors.
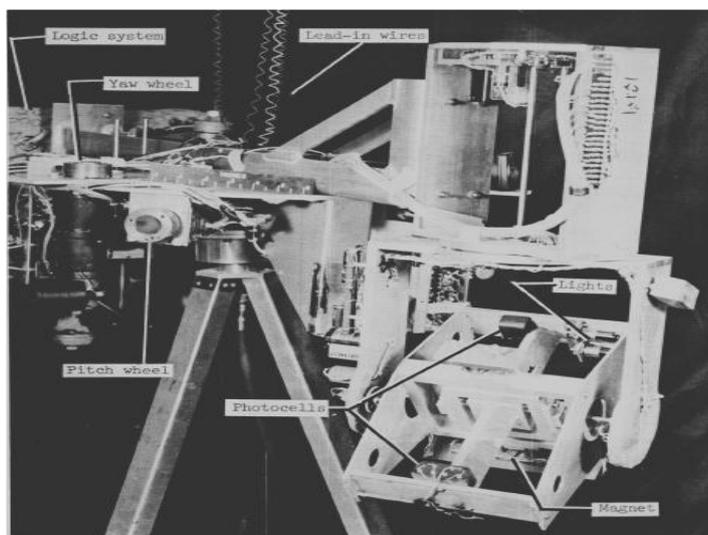

Fig. 1.2. The layout of the satellite in the Research center Landli, USA

At the Goddard Space Flight Center, USA there was a system of full-scale simulation of the Earth's magnetic field (Fig. 1, [3]), used for calibration of

magnetometers. It consisted of three pairs of orthogonal Helmholtz coils (Fig. 3), with the characteristics given in table 1.1

1.1 Table - Parameters of the geomagnetic field simulator in the Goddard Center, USA

| Parameter	Value
Field amplitude for each of the axes,nT	±60000
Static speed,nT	±0.1
Max. heterogeneity of the field in the working area,%	0.001
Dynamic accuracy,nT	±120
Max. speed of rotation of the field,rad/sec	100
Coil diameter,m	12
Diameter of the working area,m	6
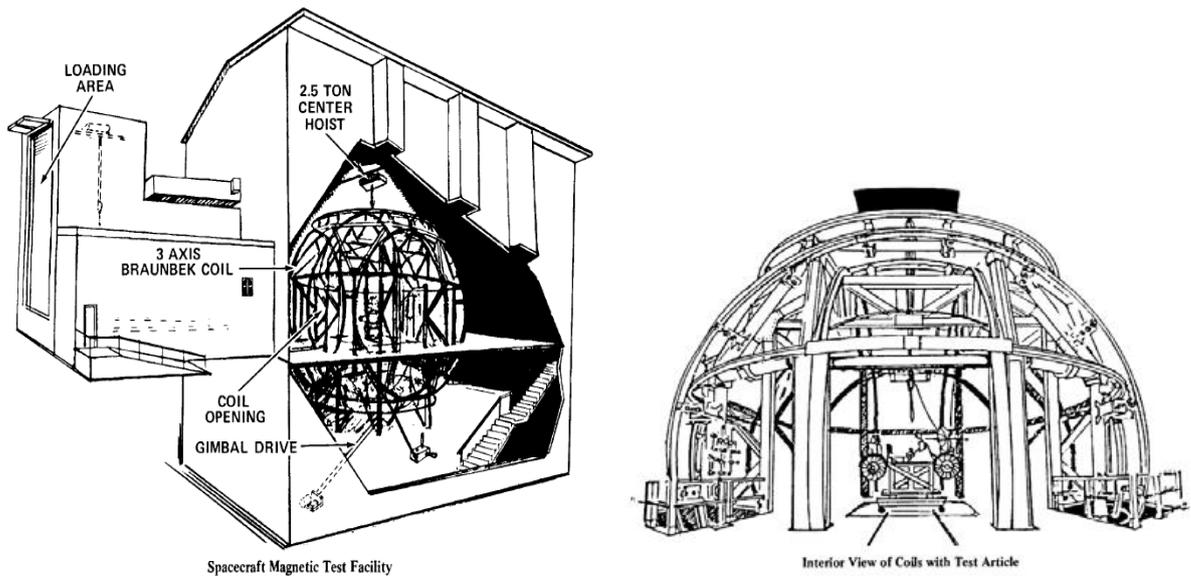
1.3 Fig. – General view of the geomagnetic field simulator in the Goddard Center, USA

Mention of one of the first installations of semi-natural modeling for educational purposes, created at Stanford University in 1975, is available in [4].

1.2 Current state of the problem

Such factors as the capabilities of modern computers and sensors, their miniaturization; the creation of powerful simulation software systems; and finally, the commercial availability of functional analogues of space systems gave a new impetus to the development of semi-natural modeling systems. These systems became known as" software simulators with hardware elements in the control loop " (hardware-in-the-loop simulation). There are also other approaches used at different stages of design: the so-called "model in the loop" (mil), "processor in the loop" (pil), "control algorithm in

the loop" (control software in the loop, SiL).The first example of one of these systems is a stand for initial testing of algorithms for mutual movement on the plane of two Autonomous SPHERES objects (Syncronized Position Hold, Engage and Reorient Experimental Satellites), created in 2003. students of the Massachusetts University of technology, USA. To ensure the translational and rotational movement of objects, they used an aerodynamic system [5], similar in principle to air hockey.Simulator of three-axis motion and satellite control [6], developed in 1995 at the research laboratory of the higher naval school of the United States (Naval Postgraduate School (USNA), laboratory of optical relay spacecraft), is an aerodynamic suspension platform that
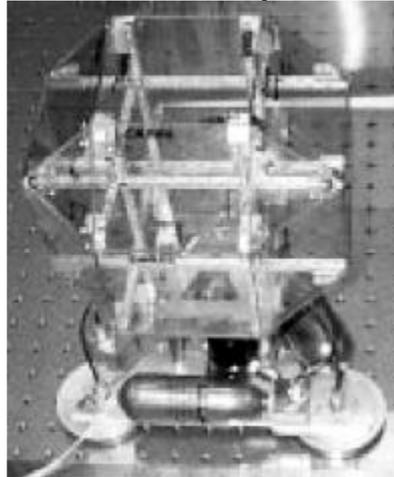

1.4 Fig. - One of these SPHERES during the test on the planeincludes three flywheels, compressed gas engines, a gyroscope, a magnetometer, and an optical orientation sensor.The weight of the platform is about 200 kg, the rotation in the horizontal plane can be 360°, at the other two angles ±45°. The purpose of the stand is to test data transmission systems between satellites using laser radiation.

1.5 Fig. - One of the developers of the three-axis motion simulator at USNA

In addition, USNA students also use semi-natural simulation models in their laboratory practice to learn the basics of designing microsatellite orientation control systems. Several special layouts (LABSat) have been created for the laboratory workshop, each of which is intended for experiments with one specific system [7]. For the study of orientation control systems, there are models with a magnetic stabilization system, a flywheel stabilization system, and a micro-jet engine control system.
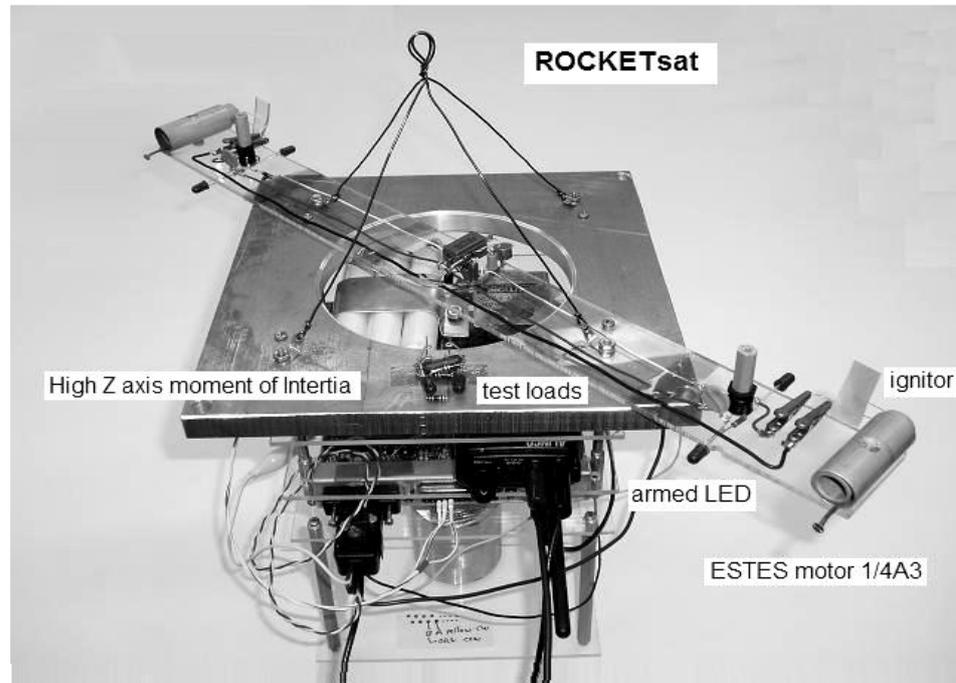
1.6 Fig.- Layout in USNA for testing micro-jet engines
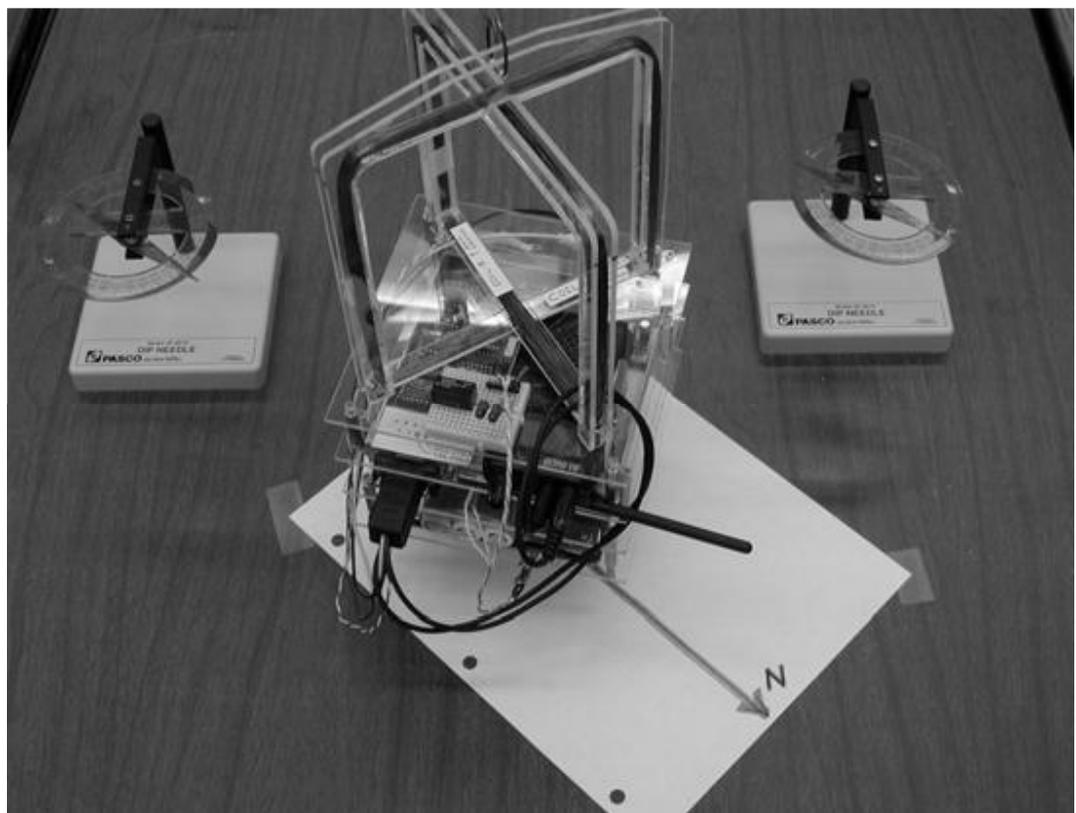
1.7 Fig. - Layout in USNA for testing the magnetic stabilization system

At the Polytechnic University of Virginia (USA) developed on the basis of commercially available elements of the aerodynamic suspension of Space Electronics Inc. (Germany) a simulation system consisting of two layouts [8]. The first, smaller

layout (Whorl-I) is a platform with a mass of 135 kg, which has three degrees of freedom: rotation in the horizontal plane is not limited, deviations in the slope are limited to angles of ±5°. The layout is equipped with three flywheels, a three-axis accelerometer and a two-axis tilt sensor; there is a center-of-mass balancing system; power is provided from batteries. A large layout (Whorl-II), developed a little later [9.10] than Whorl-I, carries a platform weighing 169 kg (Fig. 9, 10, 11). Rotation in the horizontal plane is not limited, the maximum possible deviation is ±30°. The hardware composition of the platform is almost identical to Whorl-I
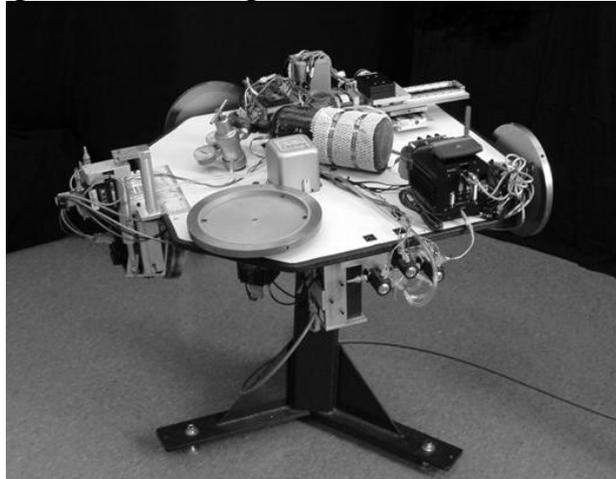

1.8 Fig. - Whorl-I Layout
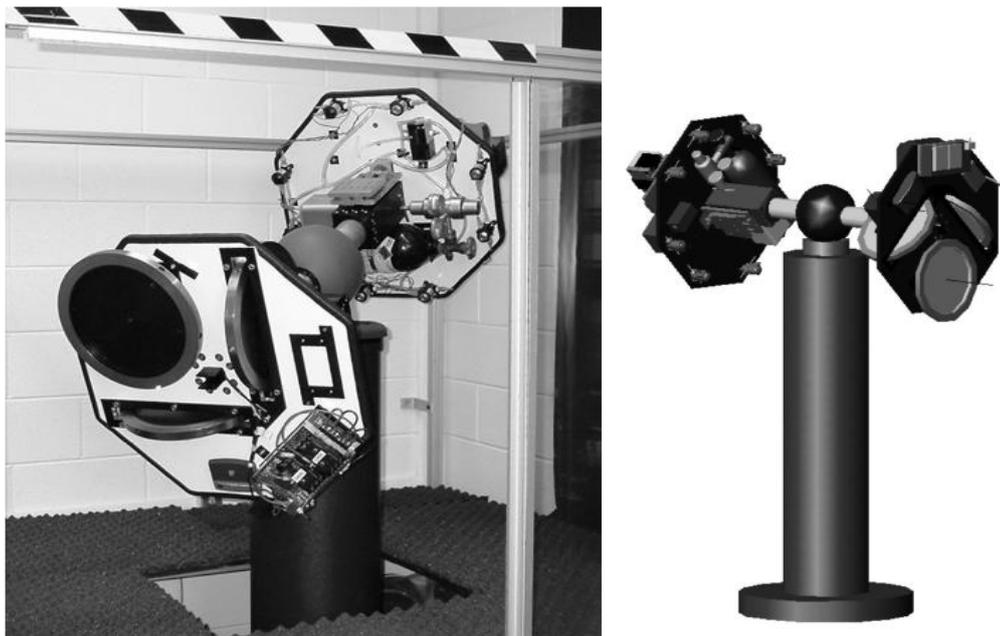
1.9 Fig. - the layout of the Whorl-II

A system for testing orientation control systems was also created in the Laboratory of remote sensing and technology of the Institute of geography, Mexico [12]. It is a platform (Fig. 12) mounted on an aerodynamic suspension, with a diameter of 76 mm, weight of 35 kg, with three degrees of freedom (full rotation around the

vertical, slopes up to ±50°).The instrument structure of the platform includes gyroscopes for measuring angular velocity; accelerometers; a three-axis magnetometer; a sun sensor; 4 Earth sensors; flywheels with tachometers; magnetic coils; wireless communication with the layout is used; special attention is paid to its balancing system. A system similar to Whorl-II is also available at the University of Michigan, USA [11], (Fig. 11).

1.10 Fig. -System of two layouts Whorl-I and Whorl-II
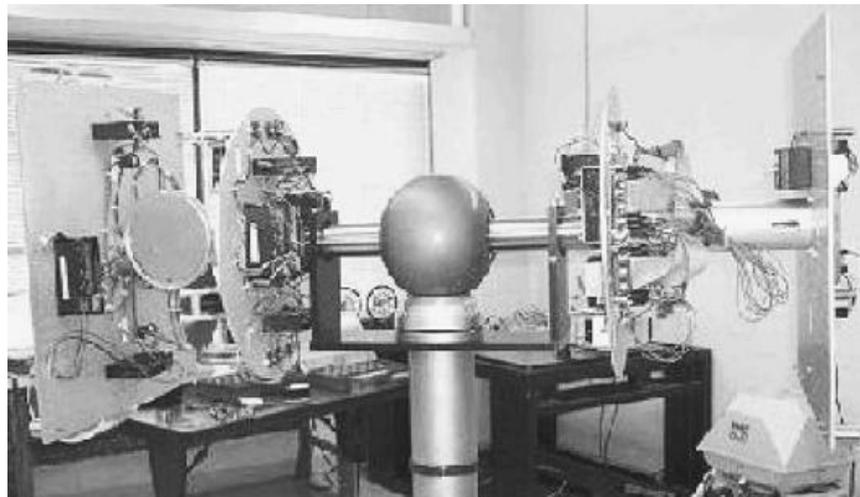
1.11 Fig.- the Layout at the University of Michigan is almost completely similar to Whorl-II
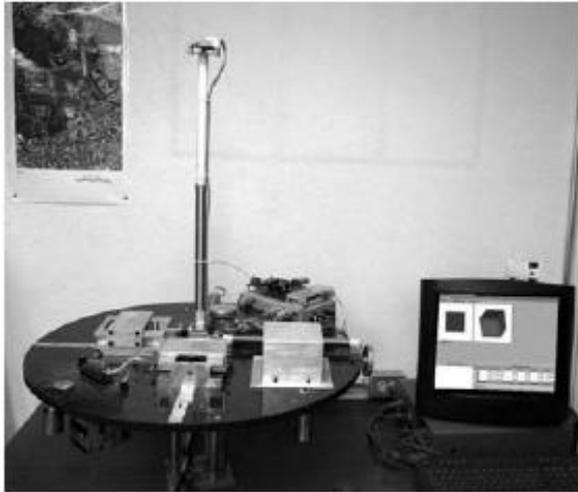
1.12 Fig.- Layout in the laboratory of remote sensing and technology of the Institute of geography, Mexico

A stand at the University of Federico II in Naples, Italy (SMAFIS-Space Magnetic Field Simulator) was created specifically for testing the magnetic orientation system of the SMART microsatellite [13]. It is intended for calibration of magnetic coils and magnetometer, functional testing of the magnetic stabilization system, studying the interaction of the device with the magnetic field. Movement around the center of mass was provided by the air suspension system MADS (Microsatellite Attitude Dynamics Simulator).
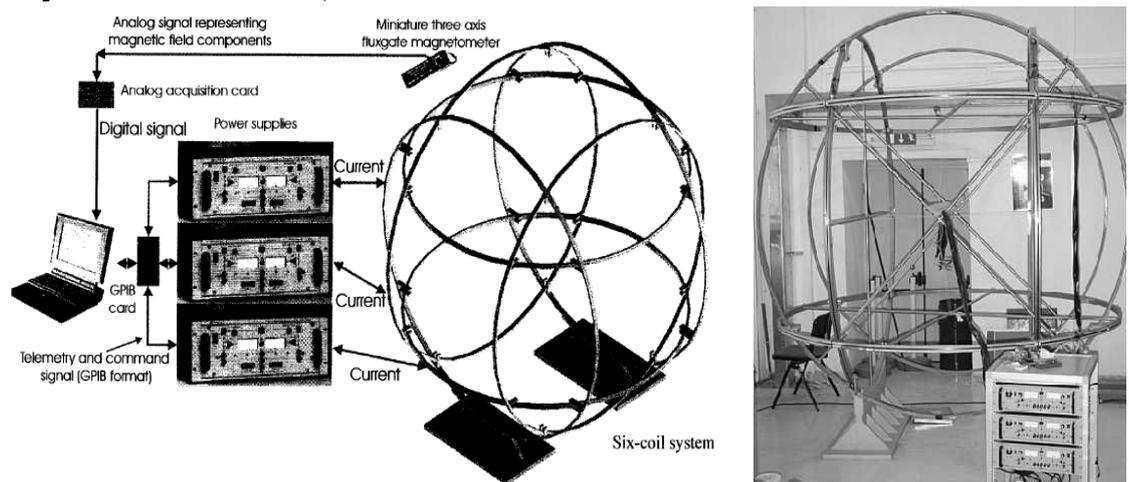
1.13 Fig. Geomagnetic field Simulator at the University of Federico II of Naples

| Characteristics of the coils		X	Y	Z
Electrical characteristics	Resistance, Ohms	0.94	0.96	0.99
	Inductance, H	$1.51*10-4$	$1.55*10-4$	$1.59*10-4$
	Maximum current, A	20	20	20
	Maximum power, W	400	400	400
Dynamic parameter	Max. amplitude of the generated field,nT	840000	820000	800000
	Maximum frequency of the field,kHz	6.66	6.66	6.66
Accuracy characteristics	COO of the generated field value relative to the specified value, in % of the maximum	0.01	0.01	0.01
Geometric characteristic	Diameter of the coilm,mm	2523	2587	2651
	Weight, together with wire,kg	72.9	74.8	76.6
	The size of the uniformity zone, with a field uniformity of less than 1% mm	881	903	926

Table 2. Main characteristics OF the smafis geomagnetic field simulator

2 Main structures

2.1 Computer simulation

In parallel with the creation of semi-natural stands, there is a purely computer approach to the study of satellite movement, which simulates the conditions of outer space, the dynamics of rotation of the device, the operating conditions of sensors, onboard systems and satellite actuators in varying detail. There are a large number of software systems, packages, and simulators that are specially designed for certain tasks, adapted after use in several projects, or created from scratch. If we talk about microsatellites, these software tools are usually specially developed applications written in high-level languages, or packages developed in the Simulink/Matlab environment. There are even open source system projects that anyone can continue developing [14].

As an example of implementation in the MATLAB environment, we present the ConSat system [15], built on the basis of Simulink and used in the project for creating the PoSAT-1 microsatellite.
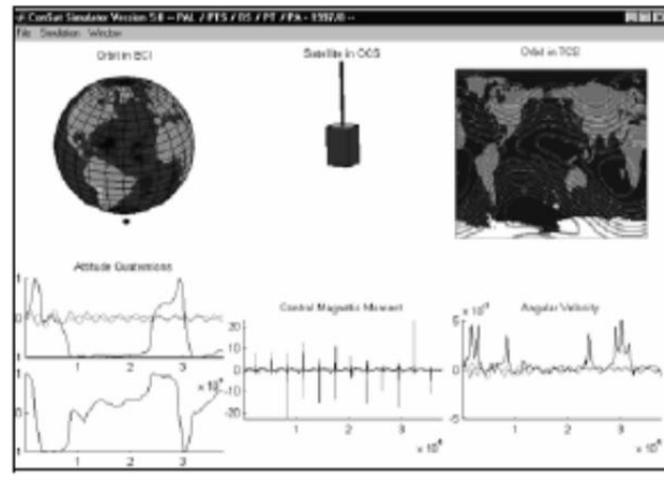
2.1 Fig. – The app's user interface ConSat

he package simulates, first, the dynamics of translational and rotational motion of the satellite; second, all the main environmental conditions that affect the satellite in orbit; simulates the operation of sensors for determining the orientation of the system: a magnetometer, a solar sensor, an Earth sensor. As the control elements of the modeled magnetic coils and flywheels. The package allows the user to embed their own algorithms and has a developed user interface (Fig. 14).

We also give examples of systems such as "control Algorithm in the simulation loop" (SiL). Their peculiarity is that the control loop can include an onboard computer and some subsystems, but the actual operating controls and orientation sensors have been replaced with software models that simulate their real behavior.

The MDVE (Model-based Development and Verification Enviroment) software package created by Astrium is designed for complex testing of onboard algorithms in real time, interaction with the satellite's ground control station, and verification of the telemetry collection system. To solve each specific task, it must be specially adapted. For example, MDVE was adapted to solve the problem of testing the control system of the Flying Laptop microsatellite (Fig. 15) [16].
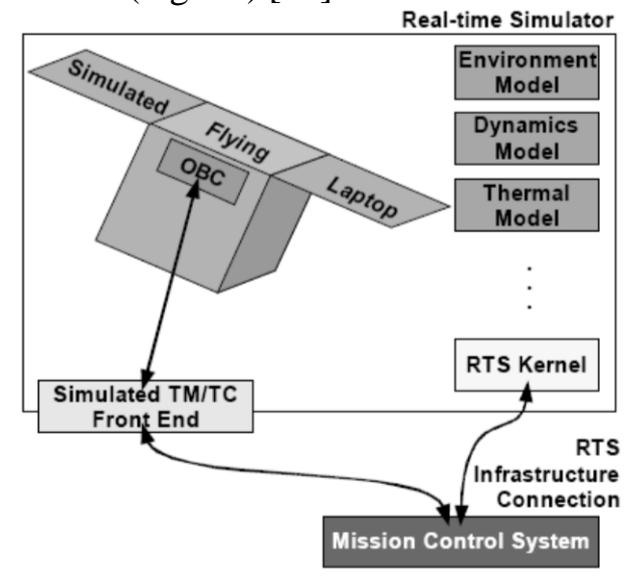

2.2 Fig. - The scheme of simulation of a control system of the Flying Laptop

The AttSim software simulator is created in a high-level C language and is designed specifically for purely software debugging of microsatellite orientation control algorithms [17]. It was created so that the source codes created by the user within the project could easily be adapted to a specific processor of the satellite's onboard computer. The package implements IGRF magnetic field models, MSIS86 atmospheric model, and simulates stabilization algorithms using flywheels, low-thrust engines, sun sensors, and a star camera.

2.2 Outline

A review of the literature shows that semi-natural simulation stands are widely used both in industry and in educational institutions, and play an important role in the design and simulation of real satellite systems, teaching students to create and test systems in conditions close to real operating conditions.

Computer simulation systems also play an important role in testing satellite systems. They are widely used at various stages of development: when evaluating the design parameters of the device as a whole, its systems, algorithms, etc.
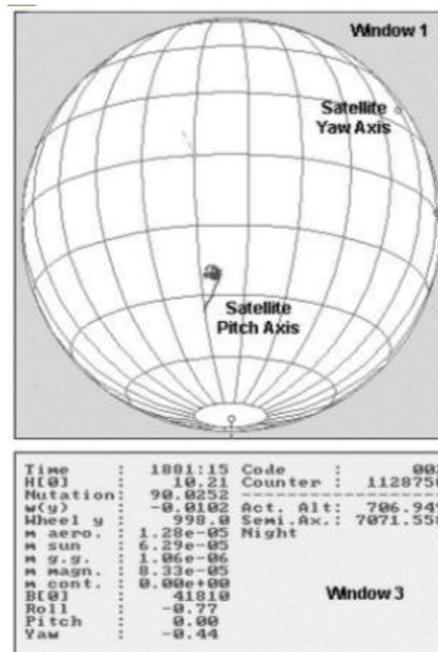
2.3 Fig.- AttSimapplicationInterface

Obviously, there is no clear boundary between these two classes of systems: purely computer models are the basis for building software used in semi-natural modeling stands. Therefore, it is necessary to consider in a separate paper the mathematical foundations of software used for modeling systems for controlling the orientation of microsatellites.

2.3 Profile of our stand.

The General view of the stand is shown in Fig. 1. the stand includes: a layout of the orientation system, a magnetic field simulator, a Sun simulator, an aerodynamic suspension, a stationary control computer. The layout of the orientation system consists of the orientation and stabilization system itself, a single-Board computer with a wireless communication channel for transmitting data to a stationary computer,batteries,a software-controlled current source(SCCS), and a platform balancing system on which all the system elements are installed.

The flywheel engines are based on a contactless DC motor with a controlled torque (Fig. 3) and are intended for use as an Executive body in the orientation and stabilization systems of small spacecraft.The electric motor provides rotation of the rotor-flywheel with a given frequency. The value of the torque (control) moment created by it can change smoothly in a certain range in accordance with the control signal supplied to the input of the flywheel motor. The mechanical moment from the flywheel control motors is created when the speed of their rotation changes and changes in the range of ± 0.4 mn· m in laboratory conditions. The speed of rotation of the flywheels varies in the range of ± 20000 rpm in laboratory conditions.

The orientation and stabilization system control unit is the link between sensors and controls, as well as between the orientation and stabilization system and external control devices. The main functions of the unit are collecting and processing system sensor readings using orientation detection algorithms, generating commands for stabilization system elements using control algorithms, receiving commands from an external onboard control controller, and transmitting data to satellite telemetry channels.

The orientation and stabilization system consists of orientation detection sensors, Executive bodies, and an orientation system control unit. [16]. As Executive elements of the orientation control system on the layout, electromagnetic current coils and control motor-flywheels are used. Current coils induce a controlled magnetic moment, which, when interacting with an external magnetic field, creates a controlling mechanical moment. The orientation and stabilization system control unit is the link between sensors and controls.

To simulate the geomagnetic field, the stand uses a system of three pairs of mutually perpendicular square coils (Helmholtz rings) The sun simulator creates a constant parallel luminous flux at a distance of up to 1.5 m with a power of at least 80,000 Lux. The par-64 searchlight with a Philips 1000W230V lamp was chosen as a Sun simulator. Thanks to the aerodynamic suspension, the movement of the layout has three degrees of freedom, namely rotation around three axes with minimal friction. The vertical axis can be rotated 360°, and the two horizontal axes can be rotated ±30°.The aerodynamic suspension consists of a pedestal and a bearing in the form of a hemisphere (Fig. 4). the Layout of the orientation system is attached to the bearing.
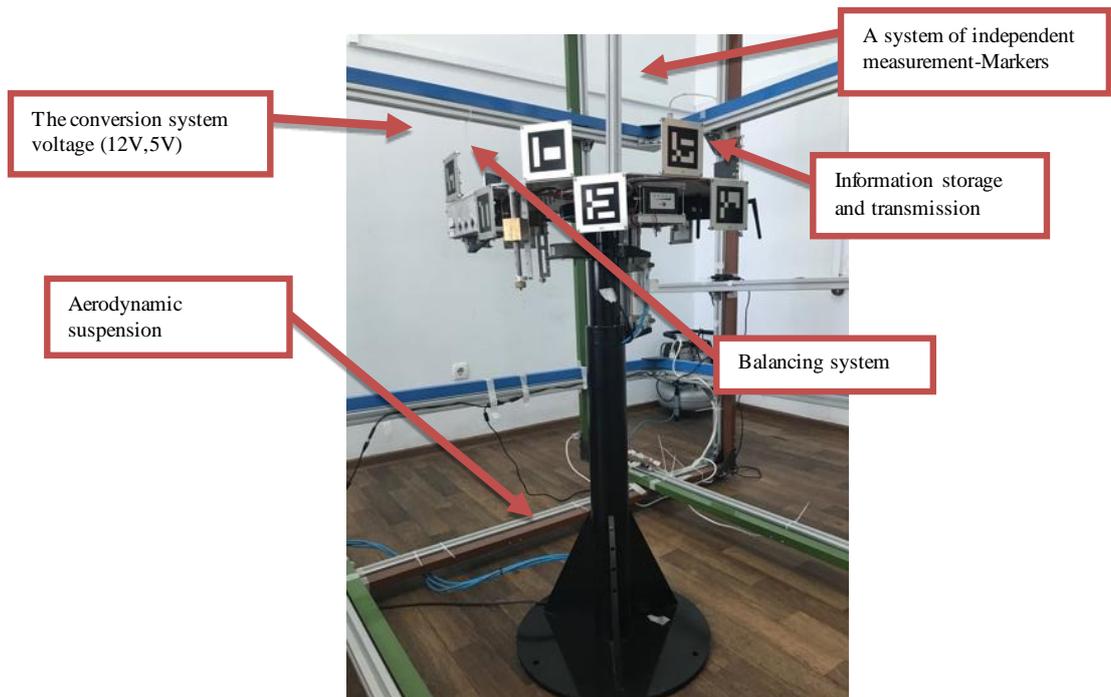
2.4 - Fig.Defining individual parts of the stand.

One of the problems when implementing a successful test is the presence of air flows. That is, if there is no air flow in the laboratory and the layout equipment is working (which does not create large magnetic moments), the only disturbance is the unbalance of the layout. In turn, an unbalance can be caused by heating the layout elements (which causes the layout's center of mass to shift).

The total maximum error in determining the layout position using orientation sensors is up to 5°. The total maximum error in determining the layout position using orientation sensors is up to 5°. However, when all the devices on the layout work continuously (it is when they are turned on and off that they can create magnetic field disturbances), there are no magnetic storms, then the magnetic field vector is determined with an accuracy of 0.1–0.2°.And when the layout is stabilized, when the solar sensor practically does not move along the cone of the sun simulator beam, the detection accuracy reaches 0.1°. thus, in the stabilization mode, for example, the orientation accuracy can be reached up to 0.1–0.2°.

2.4 Geomagnetic field simulator.

Helmholtz coils, named after the German physicist Hermann von Helmholtz, consist of two identical parallel electromagnetic coils whose centers are mirror-like, as shown in Figure 1, located on the same axis. Passing through both high-frequency Helmholtz coils in the same direction, an electric current creates a magnetic field between them.Such coils are often used to neutralize the background magnetic field (the Earth's field), for measurements and calibration, and for testing electronic equipment for susceptibility to magnetic fields.

Scheme and design of Helmholtz coils. High-frequency Helmholtz coils consist of two coils. Since two magnetic coils are designed to be identical, when the radius of the coils is equal to the distance between them, a uniform magnetic field is formed. The two coils are connected in series so that they are fed by the same current, which would create two identical magnetic fields. When added together, the two fields create a uniform magnetic field in a cylindrical volume in the center of the space between two parallel coils.

This uniform field occupies a volume of cylindrical space with a radius approximately equal to 25% of the radius of the coil (R), and a length of 50% of the distance between the coils. High-frequency Helmholtz coils can be one-, two - and three-coordinate. Multi-coordinate magnetic coils generate magnetic fields in all directions of the three-dimensional space inside the Helmholtz pair. Most often, high-frequency Helmholtz coils have a round shape. Square Helmholtz coils are also common.

Management of high-frequency Helmholtz coils. There are three ways to obtain a high-frequency magnetic field. The first of them is the direct control method. This is

the simplest way to get a magnetic field for experiments. It makes it very easy to change the frequency and magnetic field during experiments. The second method is consistently resonant. This method is effective for obtaining a powerful magnetic field and a very high frequency-about hundreds of kHz, or even MHz. The third way is based on the use of a new method of resonant current amplification. This method allows you to generate a magnetic field with the highest density. Each technology will be described in the following sections.

The method of direct control.
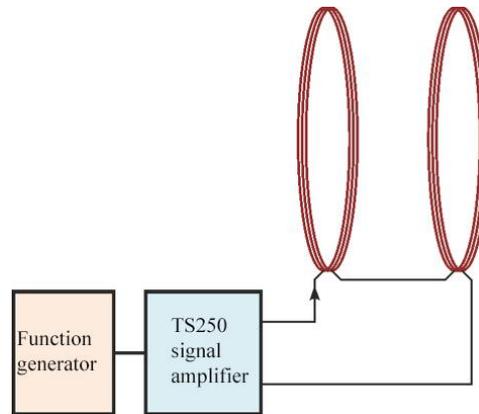
2.4 Figure – The TS250 generator signal amplifier controls a pair of Helmholtz coils.

If the experiment is conducted at low frequencies, or the coils have a low inductance, or both factors are present, the Helmholtz coils can be controlled directly using a generator signal amplifier, such as the TS250 instrument manufactured by Accel Instruments. Due to the low frequency or low inductance, the impedance of the coil is small enough that it can be excited directly by the amplifier, as shown in Figures 5 and 6

$$V = I\sqrt{[\omega(L_1 + L_2)]1^2 + (R_1 + R_2)1^2} \quad (1)$$

where

I – peak current,
w – angular frequency, w = 2pf,
$L_1 + L_2$ – total inductance,
$R_1 + R_2$ – total resistance.
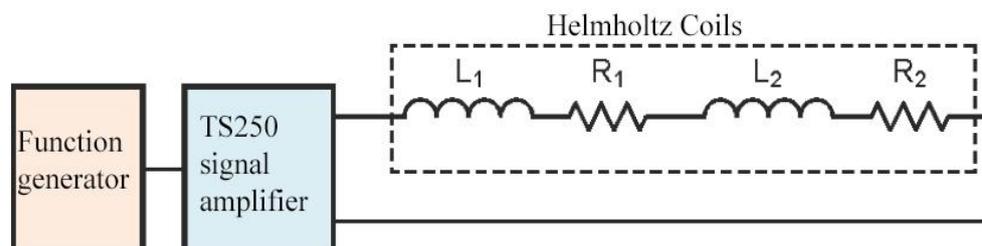
2.5 Fig. - representation of a circuit in which a generator signal amplifier directly controls a pair of series-connected Helmholtz coils.

To calculate the coil current required to generate a given magnetic field, use the expression (1). Then use the expression (2) to calculate the maximum required voltage. Note that a small parasitic resistance is ignored. The voltage is maximum when both the current and frequency are maximum. Finally, you need to connect a high-current high-frequency signal source to the Helmholtz coils, which can be formed, for example, using a TS250 amplifier.

The method of sequential resonance. If the frequency of the generated magnetic field is high, the impedance of the Helmholtz coils increases with frequency ($Z = jwL$). At high frequency, the coil impedance becomes very high, so a very high voltage is required to produce a large coil current. For example, at a frequency of 200 kHz, the impedance of a coil with an inductance of 2 mH will be 2512 Ohms. For example, if you supply a 40 V coil, you can get about 16 mA (40 V/2512 Ohms = 16 mA).To get the necessary magnetic field, this current will not be enough for most applications. For applications with a strong magnetic field, a stronger current must be passed through the coil. However, in order for a current of 2 A to go through the coil, a voltage of 5024 V must be applied to it! Generate 5 kV at a frequency of 200 kHz is not so easy.

If you need to obtain a large current and a high-frequency magnetic field, you can recommend a sequential resonant method.

To operate high-frequency Helmholtz coils in resonant mode, a series capacitor is added to the circuit, as shown in Figure 7.The impedance sign of this capacitor is opposite to the coil. Thus, the capacitor acts as an impedance compensation device. At the resonant frequency, the reactance of the capacitor (the imaginary part of the impedance) fully compensates for the reactance of the coil. That is, the reactance of the coil and the capacitor have the same value and opposite signs.
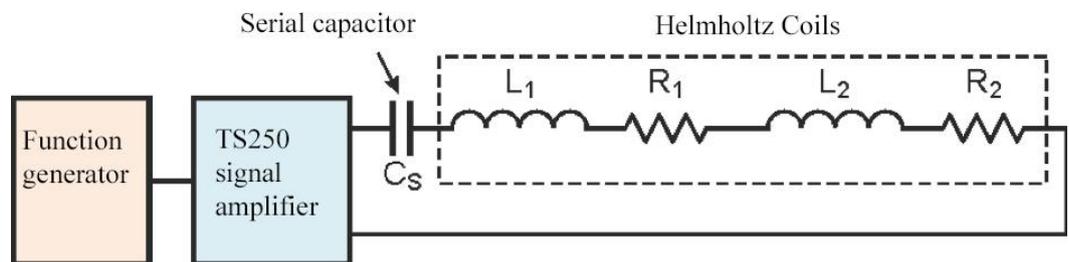
2.6 Fig. - at the resonance frequency, the generator signal amplifier gives a large current to the Helmholtz coils.

Only the parasitic resistance of the inductor remains. Now that only the resistive component of the impedance prevents current flow, the generator signal amplifier (TS250) can pump a large current through the Helmholtz coils (LCR circuit) even at high frequency. This method allows the signal amplifier to give higher current to high-frequency coils, but it is only applicable in a very narrow range near the resonant

frequency.The disadvantage of the resonant method is the need to recalculate the capacitance of the capacitor with each change in frequency.

$$f_s = \frac{1}{2\pi\sqrt{(L_1+L_2)C_s}} \qquad (2)$$

$$C_s = \frac{1}{(2\pi f)^2(L_1+L_2)} \qquad (3)$$

The calculation of the frequency of sequential resonance of Helmholtz coils is given in the expression (3). The serial capacitance CS is calculated based on the expression (4).the Voltage on the serial capacitor can be calculated using the expression (2). At high frequency and high current, this voltage can reach thousands of volts. For example, if a current of 1 A with a frequency of 200 kHz is passed through a high-frequency Helmholtz coil with an inductance of 2 mH, the voltage on the capacitor will be 2512 V! The capacitor must be designed for at least this voltage.

Caution: risk of electric shock. The high-current (electromagnetic) Helmholtz coils discussed above can accumulate enough energy to create a threat of electric shock. Make sure that all electrical connections are insulated using high-voltage materials. The connecting wires must also withstand the corresponding voltages. Always disconnect the signal amplifier output of the generator before connecting or disconnecting the coil and capacitor.

The method of resonant current amplification. Another resonant method, even more powerful than serial, is called resonant current amplification. This newly discovered method can increase the current of Helmholtz coils by half. It allows you to get a coil current equal to twice the current of the generator signal amplifier. Therefore, the resonance amplifies the current and magnetic field. More detailed information about this newly discovered method can be found in the instructions for using a high-frequency magnetic field generator.

Figure 8 shows the inclusion of Helmholtz coils when using resonant current amplification. This requires two capacitors of the same capacity. One capacitor is connected in series with the coils, just as in the above scheme of sequential resonance, and the second – in parallel with the two coils. The effect of a parallel capacitor is similar to the parasitic capacitors discussed above in the description of the equivalent Helmholtz coilscheme.
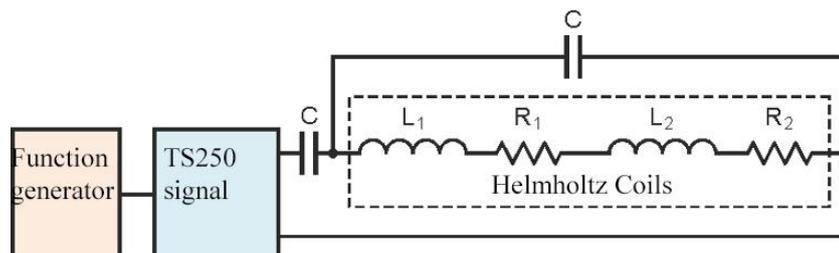
2.8 Fig. - formation of a high-frequency Helmholtz field using resonant current amplification to double the magnetic field.

The resonant frequency is calculated using the formulas (5) or (6). the Capacitances of the two capacitors are found from the expression (7). At the resonance frequency, the impedance of the Helmholtz coils is purely resistive and four times higher than the parasitic resistance. Coils that should be used in the resonant current amplification scheme should preferably be designed so that their resistance is as low as possible. It should also be borne in mind that due to the skin effect, the resistance of the coils to alternating current is greater than to direct current.

$$\omega_0 = \frac{1}{\sqrt{2(L_1+L_2)C}} = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{(L_1+L_2)C}}(4)$$

$$f_0 = \frac{1}{\sqrt{2}}\left(\frac{1}{2\pi\sqrt{(L_1+L_2)C}}\right)(5)$$

$$C = \frac{1}{2(L_1+L_2)(2\pi f_0)^2}(6)$$

Findings.

Three methods of controlling high-frequency Helmholtz coils were considered. The simplest method is direct control, but in General it is only applicable for low frequencies or small inductors. The method of sequential resonance makes it possible to pass a large current through the Helmholtz coils and obtain a high-frequency magnetic field. A new method of resonant current amplification allows you to create even stronger magnetic fields, even at high frequencies.

Characteristics of the coils(one in a pair)		X	Y	Z
Electrical characteristics	Number of wire turns	128	144	150
	Wire diameter (copper), mm	0.75	0.75	0.75
	Max. amplifier voltage, V	70	70	70
	Resistance, Ohms	23	26	26.5
	Inductance, H	$5.8*10-4$	$6.6*10-4$	$6.9*10-4$
	Maximum current, A	2	2	2
	Maximum power, W	100	100	100
Dynamic parameter	Max. non-linearity of characteristic B(I) in the operating range,% of the calculated value	less than 0.0001	less than 0.0001	less than 0.0001
	Max. amplitude of the generated field,nT	350000	350000	350000
Accuracy characteristics	COO generated value of the field relative to the specified value,nT	300	300	300
Geometric characteristic	Diameter of the coilm,mm	1200	1200	1200
	Weight, together with wire,kg	2.2	2.2	2.2
	The size of the homogeneity zone r, with a field inhomogeneity of less than 1%, the degree of inhomogeneity in the direction of less than 0.5°	180	180	180

Table 3. Main characteristics of Helmholtz coils

According to [22], the degree of inhomogeneity of the field, which is discussed in the table, is performed in the volume bounded by a sphere of radius r=0.15 ac   (2.8 Fig.). Recall that the degree of inhomogeneity of the field strength module is the ratio of the deviation of the strength module from the nominal value to the nominal value.

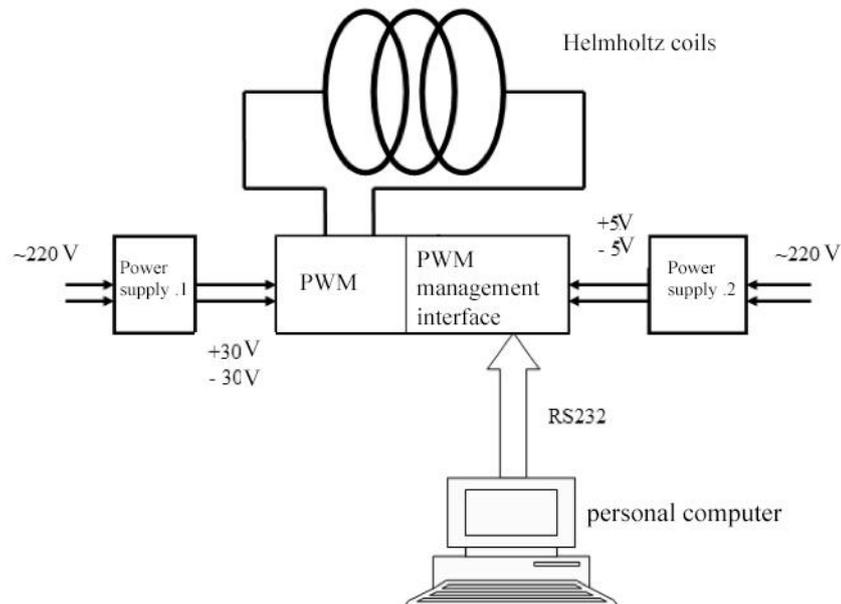$$\delta_m = \frac{B - B_0}{B_0}.$$
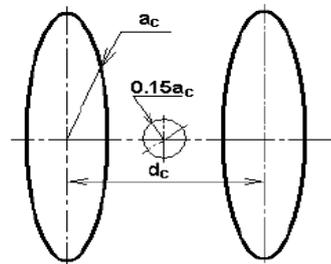
2.8 Fig. - determination of the homogeneity zone of the modeled field

Let's call the degree of inhomogeneity of the field direction the angle between the intensity vector of the nominal field and the real field at a point:

$$\delta_a = \cos^{-1}\left(\frac{\mathbf{BB_0}}{\mathrm{BB_0}}\right)(7)$$
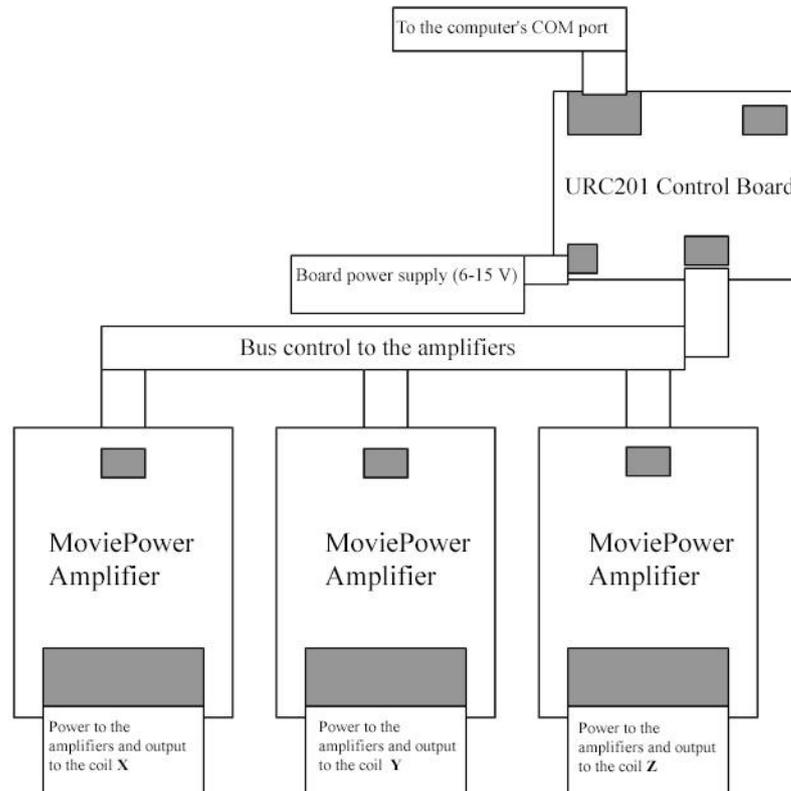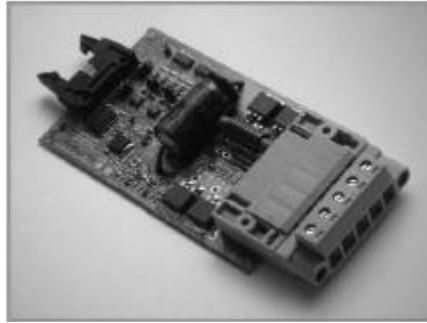
2.4 Control system simulator of the geomagnetic field.

The General control scheme of the simulator coils is shown in 2.9 Fig.

2.9 Fig. - The control circuit coils of the geomagnetic field simulator

The system includes three MoviPower pulse width modulators (PWM), the URC201control interface, two power supplies, and a personal computer. Special software installed on a personal computer calculates the required amount of magnetic induction that the simulator should generate, and using the known characteristic $B(I)$ (the dependence of the induction value on the current strength), issues commands to the PWM control interface to set the specified amount of current in the coils.In accordance with this command, the interface gives the PWM amplifier a code word that sets the frequency of modulation of current pulses fed to the windings of the corresponding coil. The amount of induction generated by the coil is inversely proportional to the frequency of current pulses applied to its winding.

To the computer's COM port

URC201 Control Board

Board power supply (6-15 V)

Bus control to the amplifiers

MoviePower Amplifier

MoviePower Amplifier

MoviePower Amplifier

Power to the amplifiers and output to the coil **X**

Power to the amplifiers and output to the coil **Y**

Power to the amplifiers and output to the coil **Z**

2.10 Fig. -the control Board (left) and connection diagram of PWM amplifiers and control Board URC201

One of the power supply units (power) ensures the operation of MoviPower amplifiers. The second (laboratory) is used to power the control boards. Each coil is controlled independently of the others. The coil control interface from the RS232 computer. Special software will be discussed later. The connection of MoviPower amplifiers and the URC201 Board is shown in figure 21.To start the simulation process, the operator turns on the stand control computer and the coil control system unit (Fig. 22), launches the MicrosatelliteModeler application, and configures it to work with the stand.
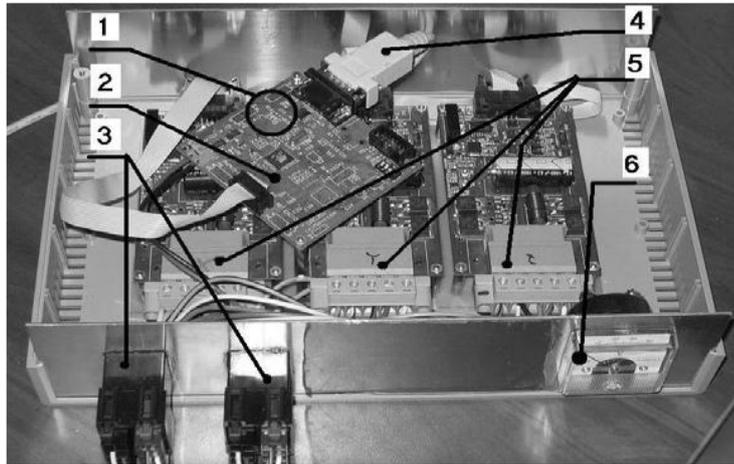
2.11 Fig.- the control unit of the coils of the stand. (1) - LED indicators of the control board; (2) - control board; (3) - power cable; (4) - PC control cable; (5) - power amplifiers; (6) voltage indicator.

Then, using the graphical interface, it selects the required law of change in the magnetic induction vector of the simulated field (for example, the change in the field in the orbital coordinate system) and the required scale factor of the simulation (acceleration or deceleration of the field change compared to reality). After that, it starts the simulation process by pressing the Start button in the application and then controls the change of the field components according to the magnetometer readings and ammeters of the current measurement system in the coils.

 String suspension
The main characteristics of the string are shown in table 4.

| Parameter	Value
The length of the string,mm	1600
The maximum angle of twist, turnover	10
String material	steel
String diameter, mm	0.1
Maximum weight of the layout, kg	7

Table 4. Features string suspension.

2.5 Entire system.

2.5.1 Executive elements of the stabilization system
Magnetic coils and a flywheel motor are used as Executive elements of the orientation control system on the layout. In addition, the layout can be equipped with passive elements of the stabilization system - a permanent magnet and hysteresis rods.
2.5.2 Electromagnetic coils
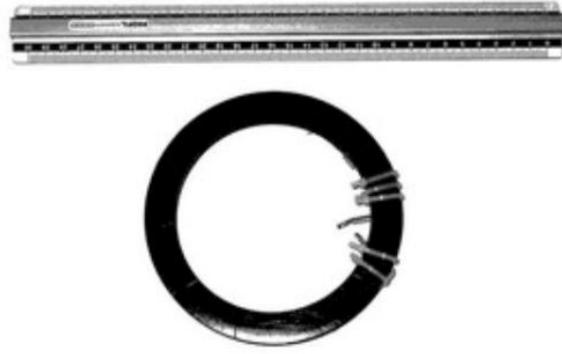
2.12 Fig.- electromagnetic coil of the layout

The main characteristics of the coils are shown in table.

Characteristics of the coils		X	Y	Z
Electrical characteristics	Number of wire turns	800	800	800
	Wire diameter (copper), mm	0.01	0.01	0.01
	Max. amplifier voltage, V	12	12	12
	Resistance, Ohms	0.806	0.750	0.752
	Inductance, H	5.6	5.6	5.6
	Maximum current, A	0.02	0.02	0.02
	Maximum power, W	0.3	0.3	0.3
Dynamic parameter	Max. non-linearity of characteristic B(I) in the operating range,% of the calculated value	less than 0.0001	less than 0.0001	less than 0.0001
	Max. amplitude of the generated field,nT	0.21	0.21	0.21
	Maximum frequency of the field,kHz	???	???	???
Accuracy characteristics	COO generated value of the field relative to the specified value,nT	0.2*10-4	0.2*10-4	0.2*10-4
Geometric characteristic	Weight, together with wire,kg	125	125	125
	Diameter of the coilm,mm	25	25	25

Table 6. Characteristics of the layout's electromagnetic coils

On the layout there are three orthogonal coils (Fig.26). The principle of operation and connection scheme of the coil control system is similar to the control of the coils of a geomagnetic field simulator. The only difference is that less powerful PWM amplifiers are used. The coils are controlled by the onboard computer via the RS232 interface.

2.5.3 Power supply system

All systems and sensors in the layout require voltage ratings of either 5V, or in the range of 6..15V (table 8). The maximum current consumption of all systems (table 7) is about an ampere. This leads to requirements for the power supply system of the layout – the voltage distribution unit (Fig. 27) and batteries. The main characteristics of the BOT are shown in table 8.ВУМ

Voltage distribution unit	
Manufacturer	TracoPower
Voltage rating/ Max. current, A	5B/8A, 12B/2.5A
Rechargeable battery	
Type	NiMH
Capacity, A h	3
Output voltage, V	7
Number of batteries	2

Table 7. Characteristics of the power supply system

Component	Power consumption, W	Voltage, V	Management interface
«Onboard» computer	5	5	Bluetooth, Wi-Fi
Coil controls	0.5	12	RS232
The AMR magnetometer	0.1	5..16	RS232
The flywheel(prototype)	1.7	3.6	RS232

Table 8. Characteristics of the system layout
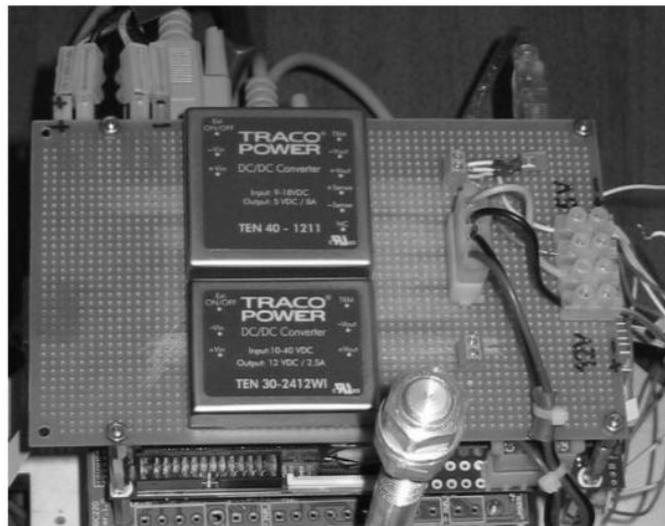
2.13 Fig. - the power management system layout

2.5.4 A wireless communication system

Commercially available Wi-Fi devices are used to provide wireless communication between the stand control PC and the layout. The main characteristics of such a device are shown in table .

Signal frequency, KHz	2412..2483.5
Maximum transfer speed, Mbit / s	up to 54
Range, m	up to 40

Table 9. Characteristics of the wireless communication system between the layout and the personal computer

4. MicrosatelliteModeler software.

The stand's software combines all its hardware resources into a single system. The main requirements for it, formulated at the design stage:
- must be created in a high-level language, preferably using object-oriented programming technologies;
- should be easy to develop, debug, with an accessible development environment;
- it should be modular with the ability to simply allocate code that implements the functionality of certain models or algorithms, for its transfer to a specific implementation on a real computer;
Functional requirements for the SOFTWARE include:
- ease of organizing links such as "control softwate in the loop", " hardware in the loop " between functional blocks of modeling objects;
- the possibility of a purely computer simulation of rotational and translational motion of the satellite in orbit under the control of different algorithms; a wide range of models of external environment, control algorithms and data processing measurement sensors; numerical methods for solving systems of equations of motion; models for prediction of satellite motion along the orbit.
- flexibility in configuration, convenient graphical interface.
Based on these requirements, the MicrosatelliteModeler software package was developed (Fig. 31), designed for both controlling the magnetic field simulator and the layout service systems. It is a distributed application that works both on the layout side (server side) and on the management PC side (client side), combining all the hardware resources of the stand into a single system of semi-natural modeling. MicrosatelliteModeler implements the following numerical modeling capabilities:
- calculation of satellite movement in earth orbit and space parameters along the flight path;
- integration of equations of rotation of the device around the center of mass;

- implementation of various algorithms for stabilization and determining the orientation of the device;

- calculation of the energy balance on Board;

- analysis of satellite operating modes and transitions between them;

- simulation of the sensor operation, processing of measurement results;

layout management:

- controls the layout stabilization system (coils and flywheels) according to the specified algorithms;

- provides collection and processing of sensor measurements using various algorithms;

- provides recording of telemetry to disk and transmitting parameters of the client part to the stand management computer;

how to control a geomagnetic field simulator:

- implements the required law of change of the components of the magnetic induction vector;

- measures the parameters of the generated field using a magnetometer.

The MicrosatelliteModeler package is implemented in Visual C++ and is designed to run Windows XP/Windows XP Embedded.

3.1 The principle of operation of the stand.

The principle of controlling the geomagnetic field simulator and the layout were discussed above.
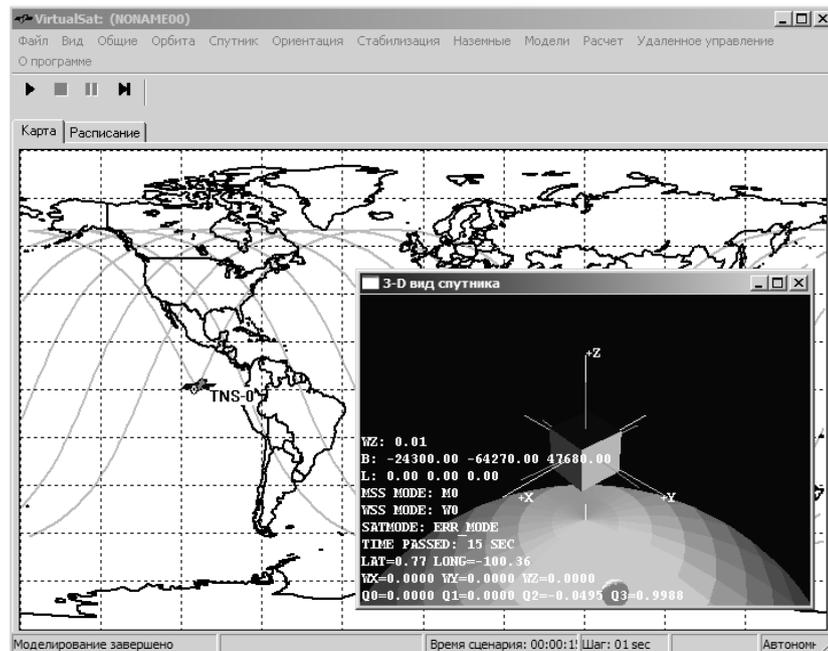

Fig. 31. The main window of MicrosatelliteModeler

Here are the main steps required to conduct an experiment to test the orientation control system:

- charge the layout's batteries;
- assemble the control system on the layout (connect sensors and actuators);
- place the layout on the string in the working area of the geomagnetic field simulator;
- start the geomagnetic field simulator control system, select the required law of change B(t);
- enable the layout, set up a wireless connection between it and the personal computer that controls the stand;
- sync MicrosatelliteModeler applications running on the layout and on the stand;
- select the required orientation control algorithms in the graphical interface of the MicrosatelliteModeler application running on the layout. The algorithms should be implemented by this time as part of the application and, if possible, be debugged in pure computer simulation mode;
- spin or push the layout on the string (depending on the control algorithms being studied);
-click Start in the MicrosatelliteModeler app on the layout and on the control PC.

After clicking Start, the application on the PC manages the simulator, as well as collecting and displaying telemetry parameters received from the layout via a wireless connection. The application on the layout implements the required control laws, collects, records and analyzes telemetry, displays the main traffic parameters on the screen, and so on. The General scheme of operation is shown in Fig.32.
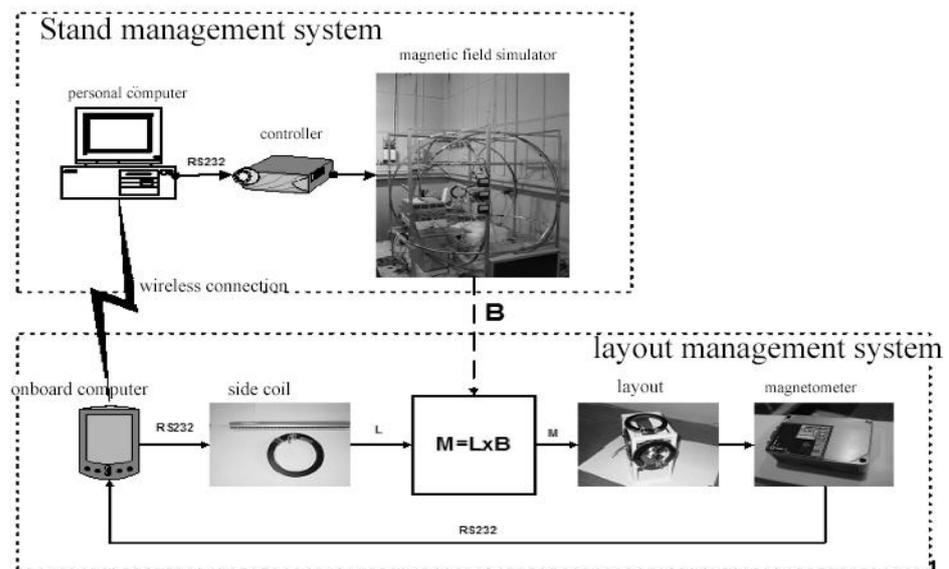
3.1 Fig.- scheme of functioning of the semi-natural modeling stand

3.2 An algorithm for controlling the layout orientation using flywheels.

This section provides a study of the controlled movement of the layout of the orientation system using flywheels. The following coordinate systems are used to describe the dynamics of an object.

OXYZ-laboratory coordinate system. The ox axis lies in the horizontal plane and is directed along the vector of the magnetic field, which during experiments is set constant in the direction, OY-vertically down, and OZ completes this system to the right orthogonal coordinate system.

Oxyz-related coordinate system. Its axes are the main Central axes of inertia of the layout of the microsatellite orientation system.

The transition between coordinate systems is performed using a matrix of guide cosines

A: $\mathbf{R}_{Oxyz} = \mathbf{A}\mathbf{R}_{OXYZ}$, where $\mathbf{R}_{Oxyz}$– a vector written in the associated coordinate system, and $\mathbf{R}_{OXYZ}$– in laboratory. To describe the movement near the equilibrium position, the plane angles α, β, γ (the sequence of turns 2-3-1 is shown in Fig. 5). the Relationship between the matrix **A** and the angles is as follows:

$$A = \begin{pmatrix} \cos\alpha\cos\beta & \sin\beta & -\sin\alpha\cos\beta \\ -\cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & \cos\beta\cos\gamma & -\sin\alpha\sin\beta\cos\gamma + \cos\alpha\sin\ \ \gamma \\ \cos\alpha\sin\beta\sin\gamma + \sin\alpha\cos\gamma & -\cos\beta\sin\gamma & -\sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma \end{pmatrix} (8)$$

The dynamics of an object is described by the equation

$$J\omega + \omega \times J\omega = M_{\text{внеш}} - H - \omega \times H \quad (9)$$

Here **J**– is the inertia tensor, ω – is the angular velocity vector, **H**– s a vector whose components are projections of the kinetic moments of the flywheels on the connected axes, the moment of gravity $\mathbf{M}_{\text{внеш}}$ associated with the non-ideal balancing of the layout acts as the moment of external forces (the center of mass does not coincide with the center of suspension).

The law of change of the kinetic moment vector of flywheels, which provides asymptotic stability of such a layout equilibrium position when $\omega = 0$ and the matrix **A**– is a unit, looks as follows [17]:
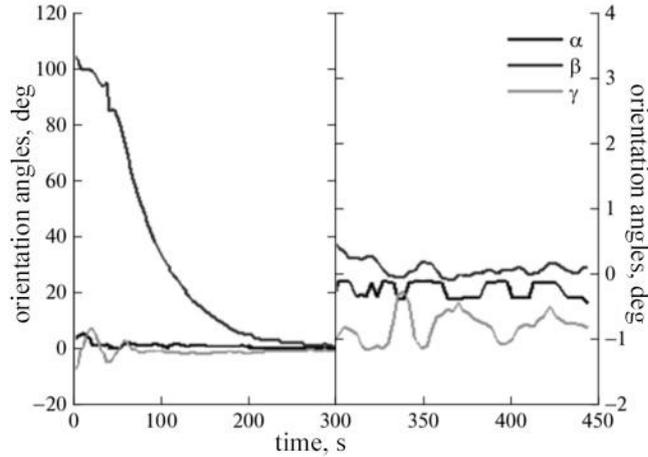
$$\dot{H} + \omega \times H = k_a S + k_\omega \omega - \omega \times J\omega \quad (10)$$

Here S – is diagonal elements of the matrix of guide cosines that are equal to zero in the equilibrium position, $k_\omega > 0$, $k_a > 0$– control parameter. In this case, the system of equations describing the movement of the layout will take the form

$$J\dot{\omega} + k_\omega\omega + k_a S = M$$
$$\dot{H} + \omega \times H = k_a S + k_\omega\omega - \omega \times J\omega$$
$$A = \dot{W}A,$$

Where

$$W = \begin{pmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & -\omega_x & 0 \end{pmatrix} (12)$$

3.3 Fig. -chart of layout orientation changes during the turn

– skew-symmetric matrix, $\omega_x, \omega_y, \omega_z$– components of the angular velocity vector. The moment of gravity is equal to

$$M = m_g \times Ag,$$

Where **g**– the acceleration vector of free fall, **r**– the radius vector of the center of mass. In other words, in this case, we assume that the axes of theOxyzcoordinate system are not Central, but simply main. Given that the OYaxis is directed vertically down, we get the moment in projections on the axis of the associated coordinate system

$$M = mg \begin{pmatrix} -r_y \cos\beta\sin\gamma - r_z \cos\beta\cos\gamma \\ r_z \sin\beta + r_x \cos\beta\sin\gamma \\ r_x \cos\beta\cos\gamma - r_y \sin\beta \end{pmatrix} (13)$$

The deviation of the equilibrium position is defined by the expressions

$$\alpha = 0 (14)$$
$$\beta = \frac{mgr_x}{2k_a + mgr_y}$$

$$\gamma = -\frac{mgr_z}{2k_a + mgr_y}$$

The moment of gravity force is excluded from the control law, since it is unknown in advance (or rather, the displacement of the center of mass relative to the suspension point is unknown) and is considered as a perturbation. Thus, the presence of such a moment will affect the deviation of the Oyaxis from the vertical (axisOY). The lower ther_y($r_y > 0$), the greater the deviation.

Figure 6-8 shows the results of experiments on layout reversal. Figure 6 shows graphs of the evolution of angles that define the layout orientation. Figure 7 illustrates the evolution of angular velocity components. Figure 8 shows the change in the speed of rotation of the flywheels.

The graphs show that the device stabilizes in a position close to$\alpha = \beta = \gamma = 0$. The deviation from the required position is due to external disturbances, namely, the moment of gravity. This deviation is defined by the expressions (2.2). The presence of a residual kinetic moment of the flywheels is associated with a non-zero initial angular velocity of the layout and imperfect balancing of the layout.
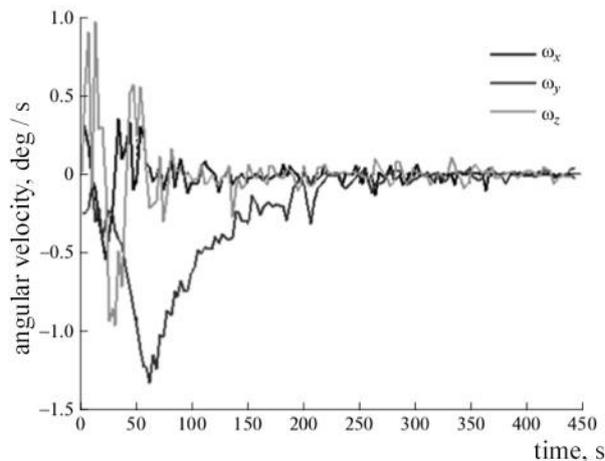
3.4 Fig. -the layout orientation during unloading
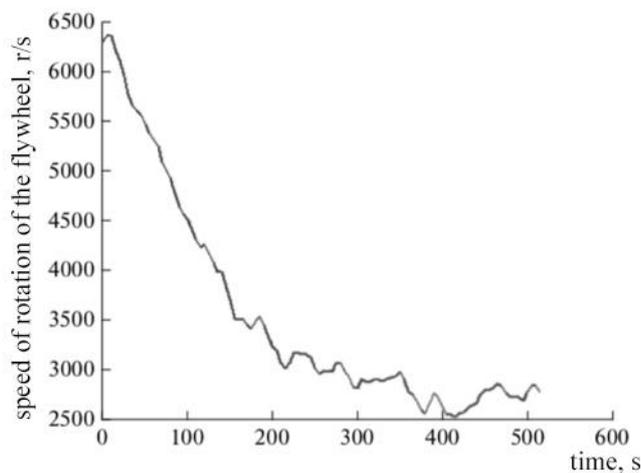
3.5 Fig. - evolution of the speed of rotation of the flywheels during the operation of the unloading algorithm

40

3.3 Algorithm for damping the initial spin using current coils.

One of the most frequently used Executive elements is magnetic coils. They create the satellite's own dipole moment **m**, which, when interacting with a geomagnetic field with induction **B**, forms a mechanical moment

$$M = m \times B \quad (15)$$

The use of current coils has a number of advantages: no consumption of the working fluid, low cost compared to other common Executive elements (flywheels, jet engines), low energy consumption. Thanks to these qualities, magnetic coils are especially often used on small satellites, which also allowed them to be installed on the "Chibis-M" microsatellite. The use of magnetic coils is complicated by the inability to create any mechanical moment specified in the direction. As can be seen from (4.1), the mechanical moment at any time lies in a plane perpendicular to the geomagnetic induction vector. Choosing the satellite's own dipole moment by changing the current in the coils allows you to determine the direction and magnitude of the mechanical moment vector in this plane. In addition, the accuracy of magnetic orientation systems is noticeably lower than the accuracy of, say, flywheels. This leads to the fact that the magnetic coils are installed either together with other Executive elements, or at the stage of quenching the initial angular velocity after separation of the satellite from the launch vehicle. On the "Chibis-M" microsatellite, the magnetic system will be used to dampen the initial angular velocity and unload the flywheels. The "-Bdot" algorithm is considered for damping the satellite's angular velocity [19]. In this case, the satellite's dipole magnetic moment has the form

$$m = -k\dot{B} \quad (16)$$

where the derivative is calculated in the associated coordinate system. Let's consider the logic of forming the control law (4.2). Write down the equations of motion as

$$\omega + \omega \times J\omega = M \quad (17)$$

If the satellite is affected by the gravitational moment, then the equations of motion admit the Jacobi integral

$$J = \frac{1}{2}\left[(\omega, J\omega) + 3\omega_0^2(e_3, Je_3) - \omega_0 - \omega_0(e_2, J\omega)\right] \quad (18)$$

Where e_3, e_2– are the orts of the satellite's radius vector and the normals to it in the orbit plane that make up two orts of the orbital coordinate system the third ORT is

completed so that the coordinate system is right orthogonal) and written in the associated coordinate system, ω_0 – is the orbital velocity of the satellite's center of mass (it is assumed that the orbit is circular).

If the satellite is also affected by the magnetic moment $M = m \times B$, this expression will no longer be the first integral. Consider $V = J - \omega^2_0 (3C - B)/2$ as a Lyapunov function, where B, C – are the main moments of inertia of the satellite $J = diag(A,B,C)$. Its derivative due to the equations of motion

$$V = \sum_{l=1}^{3} (\dot{\Omega}_l - \omega_0 e_{2l}) M_l = M(\dot{\Omega} - \omega_0 e_2)(19)$$

The last expression can be written as

$$\dot{V} = m(B \times \dot{\Omega})(20)$$

Where $\Omega = \omega - \omega_0 e_2$ – relative speed of the satellite. Expression (20) allows you to immediately select the dipole magnetic moment

$$m = k\Omega \times B, \quad (21)$$

providing asymptotic stability of the orbital orientation, in which the axes of the associated and orbital systems coincide. Here k– is a positive coefficient.

If the satellite has a large angular velocity $(\omega_0 \ll |\omega|)$, we can assume that $\Omega \approx \omega$. This ratio occurs when the satellite rotates rapidly after separation from the launch vehicle, which is damped using the "-Bdot"algorithm. In this case, the dipole moment control law takes the form

$$m = k\omega \times B(22)$$

The last expression can be converted as it is obtained based on the ratio

$$\dot{B} = \dot{B} + \omega \times B(24)$$

where the dash indicates the derivative in the inertial coordinate system. In the case of a large angular velocity of the satellite, the left part of this expression can be ignored and (23) immediately follows from (24).

Thus, the control law (22) provides damping of the relative angular velocity, the control law (23) – damping of the absolute angular velocity, and the control law (24) – damping of the absolute angular velocity to a value having the order ω_0 (the order of the rotation speed of the geomagnetic induction vector in inertial space).

Tests of the operation of the control law (24) were carried out at the stand. The magnetic field was kept constant during the experiment. This means that the control laws (23) and (24) are identical, since the derivative of vector **B** in the inertial coordinate system is almost zero. In fact, the field is stationary in a laboratory

coordinate system that rotates with the Earth. Therefore, if you choose an inertial system associated with the direction of the Spring equinox, the characteristic rotation speed of the magnetic induction vector in the inertial system will be equal to the speed of rotation of the Earth, which can be ignored in comparison with the angular speed of the layout.

The induction of the field created by the stand is about 10^5 nT, which is about 10 times the value of the geomagnetic field induction. This means that the damping of the initial angular spin in laboratory conditions will be approximately 10 times higher than the damping speed in a circular orbit with an altitude of 400 km, which is planned to launch the "Chibis-M" microsatellite.

In addition to the geomagnetic field, the accuracy of the simulator's magnetic field formation is also affected by other disturbances, in particular, currents in the equipment and wires of the stand. The results of the tests showed that the error in the formation of the magnetic field was no more than 1%.

Figure 12 shows the result of one of the tests. At the initial moment of time, the angular velocity is 15 deg / s, and the angular velocity vector is directed almost vertically (the layout is twisted around the direction of the local vertical). Damping occurs in about 700 s when using current coils with a dipole magnetic moment of 3.2 A·m^2. However, the angular velocity reaches a non-zero value of about 0.6 deg/s. Figure 13 shows the total dipole magnetic moment of all three coils. Sessions measurement of the magnetic field is turned off current coils with a duration 2 s alternated with control sessions with a duration of 3 s. Dark gray color corresponds to the coil located initially almost vertically, black and light gray – coils located in a horizontal plane. As can be seen from Fig. 13, until the angular velocity reached a roughly constant value, mostly horizontal coils worked. They were used to create a moment directed vertically (since the magnetic field is directed horizontally, like the coils). This allowed the initial spin to be damped around the local vertical. Also from Fig. 13 it can be seen that as the angular
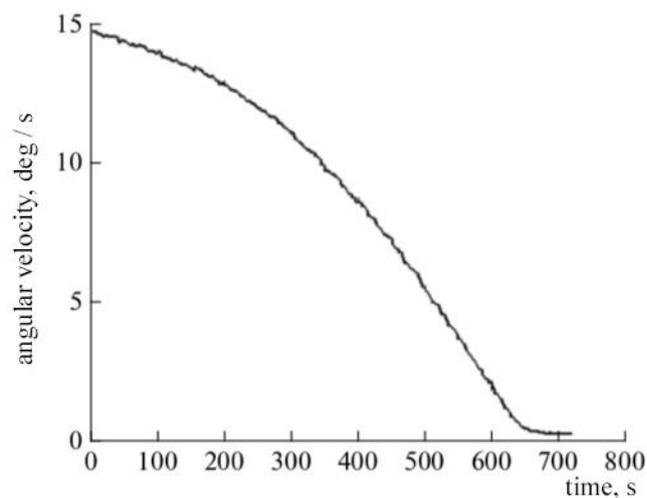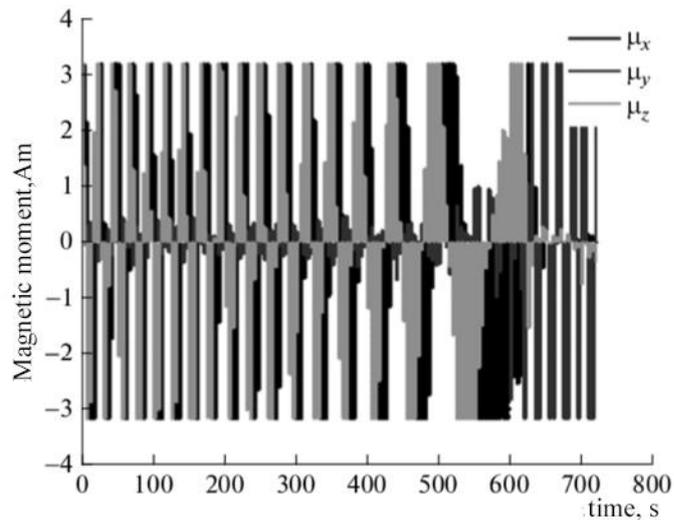

3.6 Fig. - angularvelocitydamping

Fig. 13. Currentsofsolenoidcoils

Velocity of the satellite decreases, the frequency of changes in the coil current also decreases .The inclusion of a vertical coil indicates that the damping of vibrations outside the horizontal plane has begun. Their occurrence is caused by the fact that the center of rotation of the layout does not coincide with its center of mass. As a result, the layout is affected by a disturbing gravitational moment. The resulting speed (in fact, the speed at which the layout "falls" on its side) and tries to dampen the coil located vertically. In addition to the disturbing moment, the work of magnetic coils is hindered by currents excited in the layout, which makes the magnetometer readings inaccurate.All these factors lead to the fact that the speed cannot be damped to zero. However, the achieved accuracy and speed can be considered sufficient for the stage of extinguishing the initial angular velocity of the device. If in laboratory conditions, where the magnetic field exceeds about 10 times The earth's magnetic field in a circular orbit 500 km high, the initial angular velocity of 15 deg / s is damped in 10 minutes, then in orbit, taking into account that the moments of inertia of the layout and the satellite differ by about 4 times, the device will dampen the same angular velocity of about 400 minutes (about four turns), which fully meets the requirements.

CONCLUSION

Creating the project on a small satellite requires setting the minimal cost of design and operation stages. Essential savings in these expenses occur when the necessary design characteristics of the satellite are implemented, as well as when optimizing its systems at the first design stage. It is very important to be able to correctly assess the composition and characteristics of the orientation and stabilization system, and this is complicatedprocess without the modeling. Nevertheless, mathematical and computer modeling plays a significant role, but it is very important to check their functionality, accessibility and effectiveness in practice for a specific hardware implementation at the initial stages. This requires a ground-based test bench. It is advisable to use it, in particular, for functional testing of the onboard orientation control system at the early stages of design. It is obtainable through correct implementation of the software on to the hardware system. To reach desirable results it's also significant to create the algorithms for the simulation program. The ground-based testing of orientation control algorithms led to the creation of a stand for semi-natural modeling, consisting of a magnetic field simulator and a layout suspended from a string. String suspension actually provides an imitation of one degree of freedom (rotation of the layout in a horizontal plane) or, if the suspension point coincides with the center of mass, three rotational degrees of freedom. Through the fix of all three elements of working stand (hardware, software and algorithms), the experimental results will play out the best for the final version of the satellite.

The SU satellites stand is very helpful as a training base for students dealing with the problems of orientation. Due to the fact that the new versions of satellites are announced every year, it's also essential to implement new software and update the hardware, to gain better results in shorter periods of time. Therefore, there is a great potential for the development of the existing stand. Previous research on the topic has determined that the use of two stands makes it possible to study the relative movement of two control objects, which is of interest in the task of joint flight of several satellites (formation flying configuration). It proves that SU stand is up to date, modern technology efficient in satellites testing and effective in improving the satellites' work in natural space environment. The importance for ground-based testing of orientation control algorithms led to existing stand for semi-natural modeling at the Department of Space engineering and technology at Satpayev University.

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