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Space Research: Gravitoinertial Instruments

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Abstract—The paper discusses the results of joint developments carried out by the Institute of Physics, Russian Academy of Sciences (RAS); Space Research Institute, RAS; and ROSCOSMOS organizations (Central Research Institute of Mechanical Engineering, Lavochkin Scientific-Production Association, the branch affiliate of Khrunichev State Research and Production Space Center, VNIITransmash) for gravitoinertial measurements aboard spacecraft, Earth satellites, and planets of the solar system in solving problems of satellite accelerometry, gradiometry (precision accelerometric measurements aboard spacecraft and space stations, including Progress, Salyut, Mir, and the ISS), as well as measurements of the seismogravity fields of the planets of the solar system (the Fobos-Grunt, Solar Sail, MetNet, Luna-Resurs, and Exo-Mars projects).

Keywords: space research, gravitoinertial measurements, satellite accelerometer, seismogravity measurements

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INTRODUCTION

Improvement in hardware for performing gravitoinertial measurements aboard spacecraft and on the planets of the solar system facilitates the solution of a whole range of problems including refinement of the ephemerides of spacecraft and the Earth's gravitational field, measurements of the gravitoinertial fields of planets, detection of seismic activity, tidal effects, construction of models of internal structure of the planets, etc. (Dubovskoi et al., 2012b).

This paper briefly describes a whole series of accelerometers successfully used in measuring the gravitoinertial noise background on Progress spacecraft; the Salyut, MIR, ISS stations; and in the Phobos-Grunt, Solar Sail, MetNer, Luna-Resurs, and Exo-Mars projects. It is demonstrated that in the Phobos-Grunt and Solar Sail projects, the sensitivity reached a value of approximately 2×10^{-9} g and preliminary seismogravimeter tests of (Luna-Resurs, ExoMars) showed a sensor limiting sensitivity of 10^{-10} g.

IMU-128 THREE-COORDINATE MICROACCELERATION MEASUREMENT DEVICE

Since 1981, microacceleration measurement devices (Russian nomenclature: IMU) have been used to monitoring the gravitoinertial environment aboard Salyut-6, Salyut-7, and MIR manned spacecraft. Their performance characteristics were determined at the experimental base of the Institute of Physics of the Earth, RAS, under terrestrial gravity conditions and on a gravitational-acceleration stand (SSP-1) at the Central Research Institute of Mechanical Engineering under microgravity conditions. The IMU-128 devices (Fig. 1, Table 1) were mounted on the functional cargo block (FCB) and in the service module (SM) of the Russian segment of the International Space Station (RS ISS). In 2009, a digital microacceleration measurement device (IMU-Ts) that records information to an autonomous memory device was produced, verified, and certified; in the same year, it was mounted on the multipurpose research module (MIM-1), where it has operated faultlessly thus far.

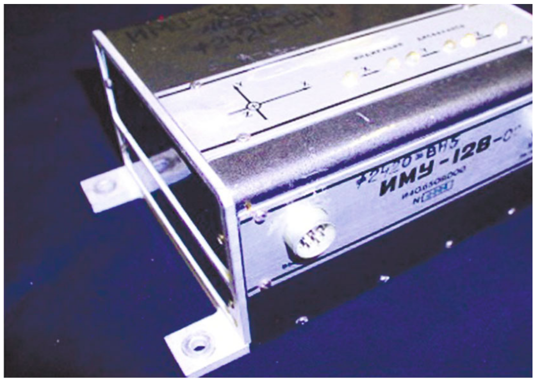

Fig. 1. IMU-128 device.

According to the operation results for the IMU-128 and IMU-Ts measurement devices, it was found that complete and reliable information on microaccelerations is sent from aboard the RS ISS.

MKA-ND MICROACCELEROMETERS

The MkA-ND microaccelerometer (Fig. 2, Table 2) is a joint development of the Schmidt Institute of Physics of the Earth and the Maksimov Space System Research and Development Institute of the affiliate branch of the Khrunichev State Research and Production Space Center (Dubovskoi et al., 2012a). In basic and applied space research, this device was used to solve the following major problems:

(1) to increase the accuracy in predicting the motion of the center of masses in low-orbit Earth remote sensing (ERS) spacecraft and, as a result, the quality in solving target problems;

(2) to increase the efficiency of control and optimization of the flow rate of the mass carrier in a microthrust propulsion system of geostationary spacecraft to increase its life time by ~10%;

(3) to make use of spacecraft atmospheric deceleration in the compensation systems at ultralow orbits to increase their life time by a factor of 5–6;

Table 1. Basic technical characteristics of IMU-128

Range, g	$\pm 10^{-2}$
Resolution, g	$\pm 10^{-7}$
Frequency range, Hz	0.01–50
Current consumption, mA	25
Power, V	27
Dimensions, mm	180 × 105 × 72
Weight, kg	1.0

Fig. 2. MkA-Nd device on earthquake-proof platform.

(4) to specify the parameters of the global model of Earth's gravitation field using methods of satellite gravi-gradiometry based on highly sensitive accelerometers;

(5) to create highly detailed and highly accurate planetary models of the Earth's gravity field;

(6) the construction of quasi-geoid models with an error at the level of the first few centimeters, i.e., with an accuracy comparable with an accuracy of modern satellite methods for determination of geodetic (ellipsoidal) heights;

(7) the creation of the main elevation datum and establishment of the common Earth's system of normal heights;

(8) to study Earth's internal structure, solve geodynamics problems, including study of the processes of earthquake preparation and prediction;

(9) to identify and predict the orbits for artificial earth satellites and refine the ephemerides for GLONASS satellites;

(10) to study Earth's oceanic circulation and climatology;

(11) to measure the relativistic precession of gyroscopes, which requires highly precise compensation of nongravitational acceleration;

(12) to detect gravity waves using satellites as proof masses in gravitational arrays, etc.

Figure 3 shows an example of determining the noise characteristics of microaccelerometers (MkA-ND) under terrestrial conditions using an earthquake-proof platform. The resultant signal of two microacceleration sensors (Mka-ND) mounted on the earthquake-proof platform in antiphase is an objective characteristic of the upper noise limit (Dubovskoi et al., 2011).

For the values of the measured accelerations in the range of ±5 × 10^{-8} g, the amplitude of the resultant signal of the two accelerometers was ±(1–2) × 10^{-9} g, which is the upper limit for determining the noise characteristics of devices tested under terrestrial conditions.

Table 2. Basic technical characteristics of the MkA-ND microaccelerometer

Range (two ranges), g	8×10^{-5} and 8×10^{-4}
Scale coefficient, g/V	2×10^{-5}
Resolution, g	2×10^{-9}
Nonlinearity, %	0.1
Frequency range, Hz	0.1–0.001
Output signal, V	±4
Temperature range,	−20…+50
Scale temperature coefficient, %/°C	0.03
Power consumption, W	<1
Dimensions, mm	115 × 55 × 65
Weight, g	350

SEISMOGRAVIMETER: THE LUNA-RESURS PROJECT

Figure 4 shows a diagram of this seismogravimeter, and its main characteristics are given in Table 3. The device is a vertical pendulum suspended from a vertical spring (the cylindrical shaped proof mass). Three independent capacitance sensors for displacement of the proof mass (one along the vertical axis and two along the horizontal axis) make it possible to measure oscillations of the base of the device in three mutually perpendicular directions. The gaps between the stationary plates of the capacitance sensors and the surface of the proof mass are 100–200 μm. The problem of placing the device with respect to the local gravity vertical with an error of ~3 arcmin is solved in an original way: the sensor is suspended by a gimbal with its bottom part fastened to a low-melting metal.

After landing on the rough surface of the Moon, a furnace is switched on, the metal melts, and the sensor is automatically set along the vertical. Then, the furnace is switched off, the metal passes to the solid phase, the sensor is fixed in the vertical position, and measurements commence.

SEISMIC ACCELEROMETER

The described seismic accelerometer was used in the Fobos-Grunt (Space Research Institute, RAS; Lavochkin Scientific-Production Association) and MetNet (Space Research Institute, RAS; Finnish

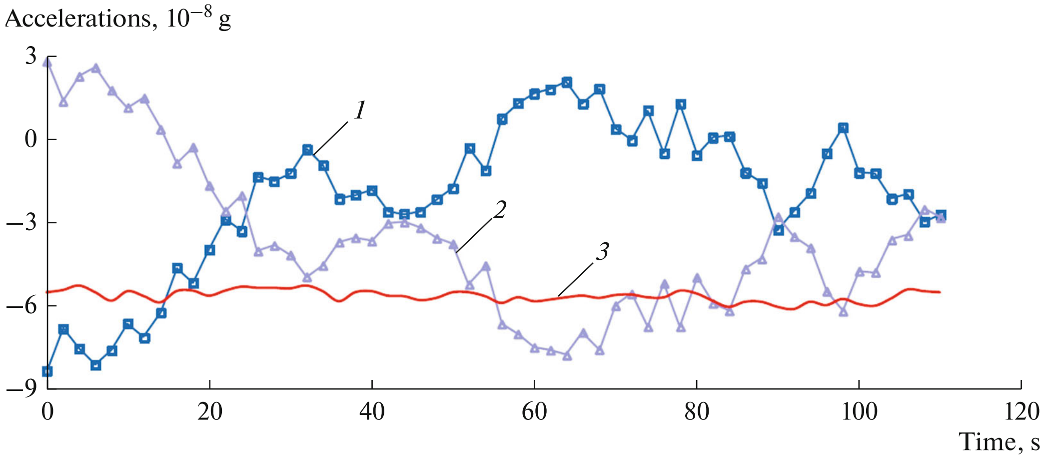

Fig. 3. Records of accelerations by two MkA-ND devices (*1*, *2*) mounted on earthquake-proof platform in antiphase and their resultant signal (*3*).

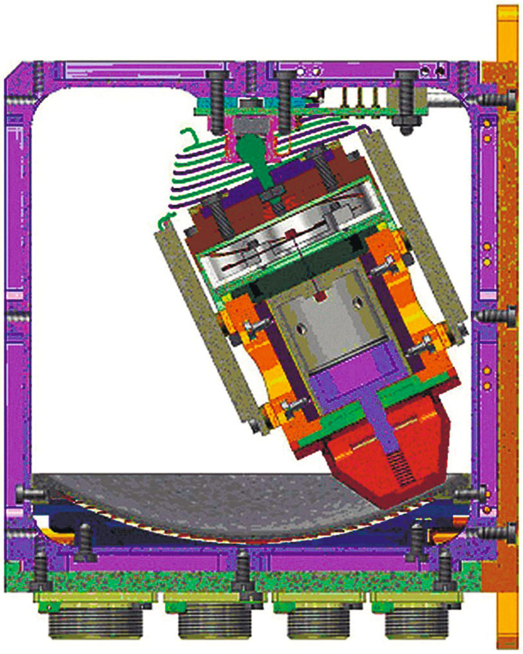

Fig. 4. Diagram of lunar seismogravimeter.

Table 3. Basic characteristics of seismogravimeter

Gravimeter	
Range, m/s^2	$\pm 10^{-2}$
Resolution, m/s^2	10^{-8}
Seismometer	
Frequency range, Hz	0.1–10
Resolution of base displacements at frequency of ~0.1 Hz	2.5×10^{-7} m
At frequencies over 5 Hz for all axes	10^{-10} m
Tiltmeter	
Range, rad	$\pm 2.5 \times 10^{-3}$
Resolution, rad	5 × 10–8 (0.01 arcs)
Seismogravimeter mass, g	≤750
Dimensions, mm	90 × 90 × 60
Limiting sensitivity is determined by thermal noise of mechanical oscillator, m/s^2	$\sim 10^{-9}$

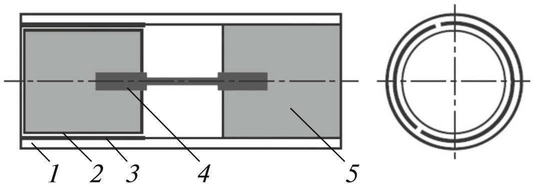

Fig. 5. Diagram of seismic accelerometer: (*1*) molybdenum glass tube; (*2*) molybdenum proof mass; (*3*) evaporated electrodes; (*4*) elastic element; (*5*) molybdenum stationary cylinder.

Meteorological Institute) projects for equipping a special platform at ISS-Nauka-APP-F (a customer of VNIITransmash) (Manukin et al., 2010).

Table 4 presents the basic characteristics of the seismic accelerometer, and Fig. 5 shows a diagram of the sensitive element in the device: cylindrical proof mass *2* on elastic element *4* with bending stiffness depending on rod diameter (0.8 mm for the sensitive element of large accelerations and 0.2 mm for the sensitive element of small accelerations).

CONCLUSIONS

The above examples convincingly indicate that the Russian developments can aid in solving the problems of studying gravitoinertial fields aboard a spacecraft and the planets of the solar system with the required sensitivity level.

Analysis of the technical characteristics of the developed accelerometers showed that their sensitivity level and dynamic range corresponds to advanced international developments, which can solve a broad range of problems in space engineering and research (Manukin et al., 2015). In particular, they can be suc-

Table 4. Characteristics of seismic accelerometer

Large acceleration measurement range, m/s^2	$200–5 \times 10^{-4}$
Small acceleration measurement range, m/s^2	$10^{-3}–10^{-8}$
Gap in sensor measurement capacitance, μm	~50
Capacitance in sensor system, pF	~8
Thermal expansion coefficient of glass, 1/deg	57×10^{-7}
Thermal expansion coefficient of molybdenum, 1/deg	60×10^{-7}

cessfully used on Russian low-orbiting ERS spacecraft to increase the accuracy in predicting orbital parameters and quality in solving target problems in space geodetic systems of the GEO-IK series, to refine the parameters of Earth's gravitational field, etc.

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