MODELING AND OPTIMIZATION OF CRYOGENIC – OPTICAL GRAVIMETERS

Vitaliy Yatsenko, Nikolay Nalyvaychuk

Abstract: *This paper considers the problem of designing and developing optical-cryogenic devices using optimization techniques, modeling, and new materials. We have shown how to produce reliable YBCO thin films with controllable surfaces and physical properties and how to integrate them in a ring form into the optical-cryogenic gravimeter so as to reduce its size and render it convenient for future space applications. Its function is based on the magnetic levitation phenomenon of the probe and on the measurement of its displacement with subsequent data processing.*

Keywords: *gravimeter, modeling, optimization, HTSC, YBCO, thin films, superconducting ring*

ACM Classification Keywords: *1.6. Simulation and modeling, H.1 Models and principles. Optimization*

Introduction

Since their discovery, the high temperature superconducting (HTSC) materials have always been a very promising technology for integration in electronic multilayered assemblies, such as antennae, filters, SQUID-s etc. due to their exotic properties.

YBa2Cu3O7-x (YBCO) has attracted a lot of research interest since it is still superconducting at temperatures above that of liquid nitrogen (70 K) and exhibits the highest currents recorded in the literature, of the order of 10^8 A/cm^2 [Vassiloyannis, 1999], enabling the construction of experimental devices highly sensitive in magnetic field changes. In this paper we concentrate in an attempt to integrate YBCO thin films in a ring form into the gravimeter described in [Yatsenko, 2003] in order to reduce its size and make it convenient for future space applications.

Highly monocrystalline good quality YBCO thin films can be reliably deposited onto SrTiO3 substrates by Pulsed Laser Deposition (PLD) with Tc values ranging from 89 up to 91 K [Wellhofer, 1998]. Films grown on nominal [001] substrates exhibit, however, non-controllable surface morphologies [Vassiloyannis, 1997], with island growth and deep trenches in between which render the material unreliable for further integrations, since these features tend to create undesired holes and joins between adjacent deposit layers. It has been shown [1] that offcutting the STO substrate by 1.69^o off the (001) towards the (100) plane allows the growth of smoother YBCO films with a controllable surface morphology (with average surface roughness Ra ~ 1.05 nm, even less than the YBCO unit-cell height) and with improved physical properties, i.e. an average current density Jc measured up to 108 A/cm^2 for B = 0.2 T and T = 4.2 K. In this report we propose the integration of 130-230 nm thick YBCO films grown on 1.69^o miscut STO substrates with single offcut direction [5] for the construction of a gravimeter.

The concept of the cryogenic-optical sensor

The sensor is based on a new type of free suspension of the probe of the superconducting gravimeter. Its functioning is based on the magnetic levitation phenomenon of the probe and on the measurement of its displacement with subsequent data processing. A free suspension of a probe can be realized using the Braunbeck-Meisner phenomenon due to the ideal diamagnetism of a superconductor solid sphere. Our conception is based on the zero electrical resistance of a closed coil, for example, a ring which, due to levitation, may have a free equilibrium position. As a consequence of the superconducting phenomenon, the ring achieves zero electrical resistance. At the same time, modern methods of signal processing are used for estimation of a small perturbation (against a background of significant noise) which corresponds to parameters of the measured gravitational field.

The newly developed superconducting gravimeter is represented by a spring type suspension. An analogue of the mechanical spring of our device accomplishes the magnetic returning force acting on a superconducting probe in a non-uniform magnetic field of superconducting rings or in a permanent magnet (in another variant). Due to the high stability of the superconducting currents of the rings, a highly stable non-dissipative spring is created.

The gravimeter is based on the following principle. In balance a probe is levitated in the position where the gravitational force is compensated by the magnetic force which acts in the opposite direction. At a gravitation change of the probe, it is moving from its zero position and an optical sensor measures an error signal. Due to current change in a control ring, a self-tuning system creates an additional magnetic field that is proportional to the signal which keeps the probe in zero position. Since the returning force is a linear function of the current, its measurement in a control ring provides linear estimation of the gravitation force changes.

This suspension needs a high precision optical registration system for the probe displacement. It is proposed to estimate the position of the probe by a laser sensor that allows to exclude the electric and magnetic fields which affected the probe. For detection of supersmall displacements it is proposed to use a modern interferometry method and dynamical effects of a laser signal constrained that correlates with mechanical displacement of the probe. An interferometric method can provide a precision of coordinate measurement of the probe at most 0.1 nanomenter.

An experimental scheme with a laser displacement sensor has been selected and realized. This sensor provides a conversion of a signal into the digital form for signal processing. Recently it has been shown that the optical sensor based on a laser diode with an external resonator as a source of monochromatic radiation, and a single mode optical fibers as a channel for light transportation to the probe preserving the coherence of an optical radiation) satisfiy all the necessary requirements.

Several stages are used for signal processing in a cryogenic-optical gravimeter. The first stage consists of noise compensation which influences the mechanical part of the device. The second stage is focused on the use of an inverse dynamical model of the sensor. An adaptive digital filter is used at the third stage of signal processing. A combination of a free probe suspension, the use of an optical registration system, and new tools of signal processing provide new dynamic properties to our device.

Modeling and Optimization

A fundamentally new optic-cryogenic sensor based on superconductive nanofilms has been grounded and mathematically modeled. Also the problem of optimal supersmall acceleration estimation has been investigated. The new principles of such sensor construction, has been proposed. We analyze the problem of the sensor resistance using modern theoretical and experimental approaches. Also a model of a quantum device for optimal information processing has been consodered. Solving of these problems requires further development of the bilinear dynamical systems theory and investigation of chaotic regimes of the “10^{-10} g” dynamics. Taking into account the sensor competitiveness and high sensitivity to gravitational perturbations, we plan to cover the device by a patent. Also mathematical modeling of separate sensor components (superconductive suspension, laser sensor and software) has been conducted. The modeling of the satellite sensor for micro-gravitational perturbation estimations has been grounded. Moreover, nanomaterials suitable for constructing such accelerometers have been determined. This will allow creation of adaptive micrometer-size gravimeter sensors for microsatellites. In this chapter, we describe a superconducting gravity meter, its mathematical state. We have also presented a mathematical model of the superconducting uspension which is based on a magnetic levitation. A nonlinear control algorithm has been implemented for the purpose of maintaining chaotic behavior in the sensor.

Nonlinear properties of a magnetic levitation system and an algorithm of a probe stability are studied. The phenomenon, in which a macroscopic superconducting ring chaotically and magnetically levitates, is considered. A nonlinear control scheme of a dynamic type is proposed for the control of a magnetic levitation system. The proposed controller guarantees the asymptotic regulation of the system states to their desired values. We found that if a non-linear feedback is used then the probe chaotically moves near an equilibrium state. An optimization approach for selection of optimum parameters is discussed

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In contrast to the conventional recursive schemes, the latter can be implemented by performing a sequence of Givens rotations in a highly efficient manner with numerical robustness. In addition, the inclusion of linear dynamic link connections has been shown to enhance convergence. Finally, simulation examples have been described to demonstrate the potential of the new RBF noise cancellation filter design. These results, coupled with the on-line monitoring capabilities of the model validity tests, suggest that the new RBF filter provides an appropriate structure for noise cancellation filter design. A comparison with earlier results given in Billings and El-Hitmy (1990), which employed various simpler linear and nonlinear polynomial models with the present design, indicates that the new design framework based on the recurrent RBF network structure coupled with the hybrid training algorithm exhibits excellent complexity can be avoided by employing a new approach that mitigates the problem of bias without introducing excessive computational complexity.

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Experiments

The superconducting gravimeter is a spring type gravimeter in which the mechanical spring is replaced by a magnetic levitation of a superconducting sphere in the field of superconducting, persistent current coils. The object is to utilize the perfect stability of supercurrents to create a perfectly stable spring. The magnetic levitation is designed to provide independent adjustment of the total levitating force and the force gradient so that it can support the full weight of the sphere and still yield a large displacement for a small change in gravity. The gravimeters provide unequaled long term stability so that instrumental noise can be either below geophysical and cultural noise or indistinguishable from it over periods ranging from years to minutes. This article reviews the construction and operating characteristics of the instruments, and the range of research problems to which it has been and can be applied. Support for operation of the instruments in the United States has been limited so that operation of multiple instruments for periods much longer than a year has not been possible. However, some of the most appropriate applications of the instrument will require records of several years from arrays of instruments. Commercial versions of the instruments have now been purchased in sufficient numbers elsewhere in the world so that a world-wide array has been organized to maintain instruments and share data over a period of six years.

A $YBa_2Cu_3O_{7-x}$ thin film of 130-230 nm in thickness was grown onto a $SrTiO_3$ substrates vicinally offcut at 1.69^o off the (001) towards the (100) plane. The substrate was firstly pre-annealed at 900^{o}C for two (2) hours and then studied using a Digital Instruments Nanoscope II AFM in air with the cantilever force at 8 nN in order to evaluate its surface stepped structure. The YBCO film was subsequently deposited onto the substrate by Pulsed Laser Ablation (PLD) with the specimen being heated during the whole process at a temperature of 820^o C in an oxygen atmosphere at a dynamical pressure of 0.4 Torr [3]. The film orientation with respect to the substrate c-axis was examined by conventional θ-2θ scans using a Siemens D5000HR high resolution, four circle, six axis diffractometer, with a CuKa source. Rocking curve experiments enabled measurement of the film full width at half maximum (FWHM), whilst -scans through the (018) YBCO peaks were conducted to evaluate the film in plane alignment. The film surface was characterized using a Digital Instruments Nanoscope II STM (scanning tunneling microscope) operating in constant current mode at a bias of 800 mV and a tunneling current of 50 pA. Average magnetization measurements have been performed at temperatures of 4.2, 25, 50 and 77 K using an Oxford Instruments Vibrating Sample Magnetometer (VSM).

The specimens firstly reached the required temperatures in zero field cooling mode and data were collected with the field being increased up to 12 T at a sweep rate of 10 mTs^{-1} and then decreased down to 0 T. M-O images were received of the specimen using a typical ferromagnetic iron garnet ($Bi_x Lu_{3-x}Ga_yFe_{5-y}O_{12}$) grown on a GGG garnet ($Gd_3Ga_3O_{12}$) ([1] and references therein) in combination with a mercury arc light source and filter. The polarizer/analyzer system maintained stable at all processing times at an extinction angle of 6o off their crossed position. A CCD camera with various shutter speeds (from 1/120 up to 1/40000 s^{-1} of a Nikon Optiphot 100S optical microscope with a x5 objective lens and a 60 W white light was used to capture the M-O images.

Results

X-ray Characterisation: A sharp superconducting transition at ~ 90 K has verified the good superconducting character of the specimen under study [Vassiloyannis, 1999]. A full width at half maximum (FWHM) value of 0.3212^o for the (005)YBCO reflection confirmed the onocrystalline nature of the film. θ-2θ diffractograms with only (001) peaks of the film and the substrate verified only one crystalline phase of the film with its c-axis aligned along the substrate c-axis[Vassiloyannis, 1999]. The -scan diagrams captured evidenced the absence of impurity phases or of grains of different orientation on the film [Vassiloyannis, 1999].

AFM-STM Evaluation: The data received during the AFM study on the STO substrate after the preanneling treatment revealed a uniformly shaped substrate surface. An image received of a representative area 1×1 m^2 of the substrate surface is shown in Fig. 1 as a “top view” plot with the color scale representing the height above the lowest point of the AFM scan: steps uniformly shaped with a width of 114 nm and a height of 2.93 nm were visible along the (100) direction demonstrating the sample offcut direction, while some rare steps smaller in width were also seen along the (010) and (110) directions. The steps consist of several STO unit cells in height (STO unit cell height ~ 0.389 nm ([Vassiloyannis, 1999], and references therein)), while they are also larger in width than the STO unit cell as expected by the specimen offcut angle. The stepped structure of the substrate influenced the structure of the film deposited, the surface structure of which also followed a well consistent stepped morphology. In that case, as can be seen in the 0.5×0.5 μm^2 image shown in Fig. 2., the YBCO film surface also consists of almost single oriented steps, with an average surface roughness R_a=1.05 nm (even smaller that the YBCO unit cell height, 1.12 nm [Vassiloyannis, 1999], , while some smaller steps are also distinguished along the (110) direction.

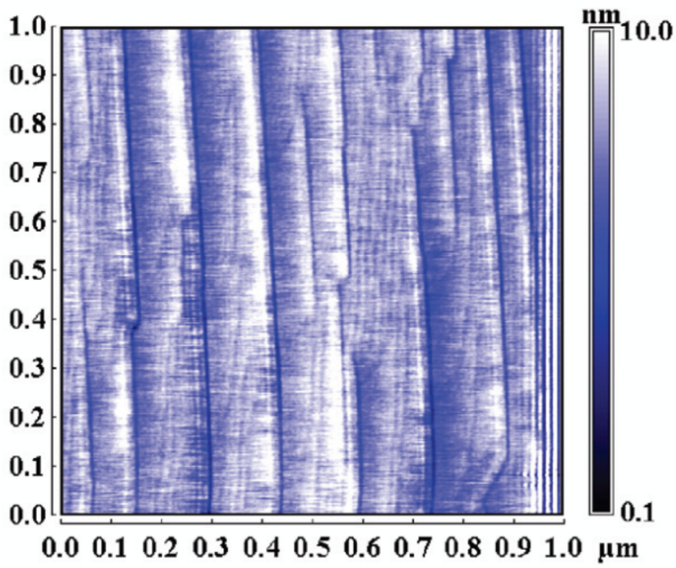


Figure 1 – AFM-image of the 1.69° off cut STO substrate

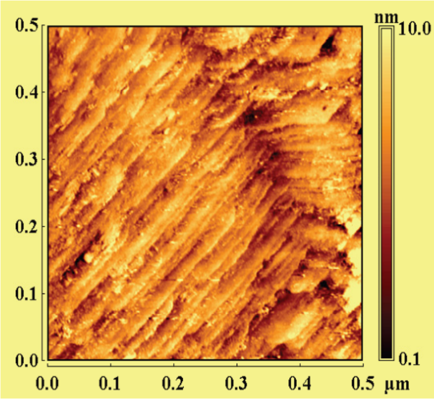


Figure 2 – Corresponding STM-image of the YBCO film grown

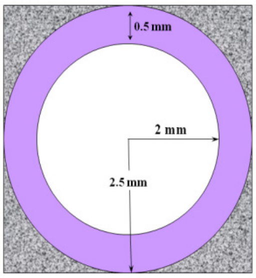


Figure 3 – Schematic representation of a superconducting ring 0.5 mm in diameter (purple area) on a 5.5 mm² YBCO thin film platelet with outer radius 2.5 mm and inner radius 2mm

***VSM Measurements**:* The magnetic hysteresis half-loops received by the VSM measurements are symmetrical for fields above 0.2 T for all temperatures [Wellhofer, 1998]. Therefore, the average current density flowing within the film can be extracted according to the Bean model and references therein) using the following formula:

$$J_c = 240(\nabla M/t) \tag{1}$$

where ∇ M is in emu, t in cm and J_c in A/cm^2. The average current density dependence over field increase for the four (4) different temperatures studied for the 1.69^0 sample are illustrated in figure 4. A top value of 6x10^{11} Am^{-2} is captured for B=0.2 T and T=4.2 K.

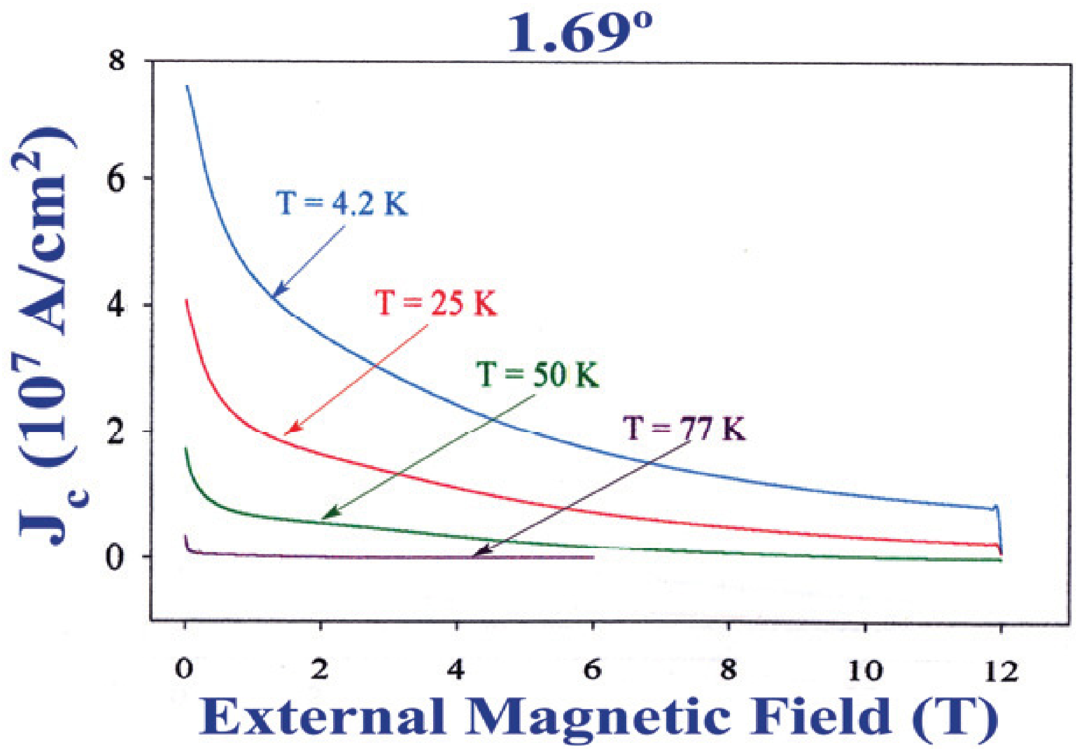


Figure 4 – Average current density Jc for the 1.69° specimen extracted by VSM hysteresis loop measurements

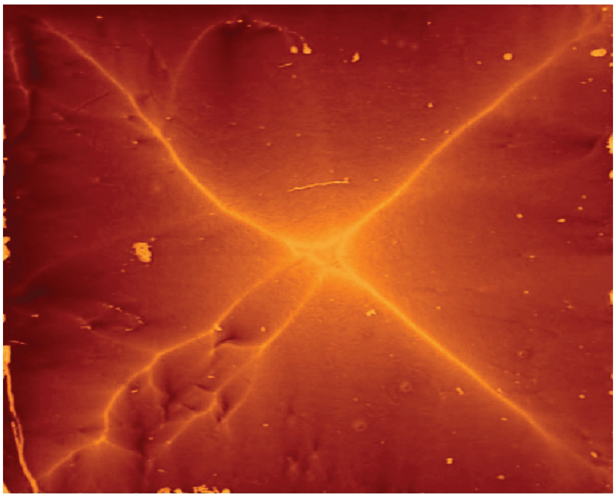
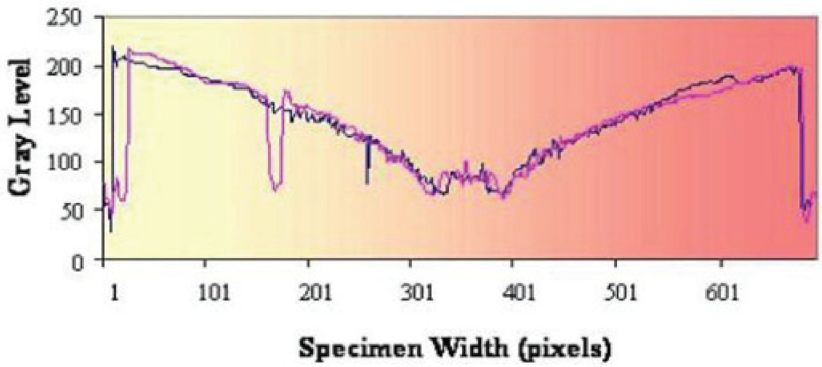


Figure 5 – Top-view M-O image of the 1.69° film for full penetration of the external field at T=25 K and B=103.8 mT



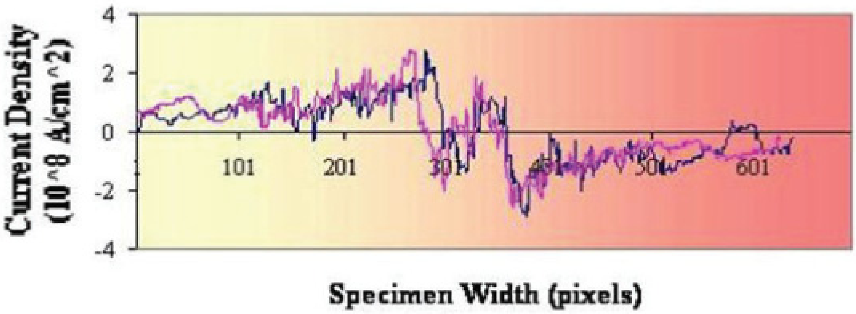


Figure 6 –J_c current densities in the parallel (blue) and perpendicular (pink) direction of the specimen [100] direction. J_c current densities in the parallel (blue) and perpendicular (pink) direction of the specimen [100] direction

M-O Analysis: A M-O image captured of the 1.69o sample at T=25 K and B=103.8 mT (full field penetration into the sample) is illustrated in Fig.5. as top-view image, with the color gradient representing the field gradient within the platelet [Vassiloyannis, 2006]. The color gradient corresponds to field numerical values and, thus, the current density within the sample can be extracted inverting the Maxwell equation: $\nabla B = \mu_0 J$ (for E = 0). To achieve the inversion a Pascal program is used [Vassiloyannis, 1997], based on the formula:

$$H_Z(\vec{\rho},d)=\frac{1}{4\pi}\int_s g(\vec{\sigma})\int_0^t \frac{2(d+\xi)^2-|\vec{\rho}-\vec{\sigma}|}{[|\vec{\rho}-\vec{\sigma}|^2+(d+\xi)^2]^{5/2}}d\xi d^2\sigma \quad (2)$$

The grey profile of the image in Fig. 6 corresponds to the 3-D field distribution within the film. Two crossed lines have therefore been selected, which passed from the specimen center, shown in Fig.6. top plot. After the inversion process the corresponding crossed lines which passed from the current distribution profile center (the "inverted" surface) were depicted and are illustrated in Fig. 6 bottom plot. The currents along the crossed lines ("blue" [100] and "pink" [010] specimen directions) are equal, thus no discernible anisotropy is detected rendering the 1.69o specimen reliable for the gravimeter rings.

HTSC Ring Construction: The YBCO film grown can be used for integration into the gravimeter proposed in [Yatsenko, 2003]. The main measurement device is based in 2 rings of a conventional low temperature superconductor (niobium-titanic) of a 2.38 cm inner diameter and 2.5 cm outer radius. The top plane of the probe is polished in order to be used as a reflecting plane for the laser registration system. The gap for levitation, depending on the weight of the probe, is selected from 7 mm up to 15 mm. Such working models have been investigated theoretically and experimentally in the frame of the system suspension registration sensor. In particular, the presence of an additional ferromagnetic mass on the probe has been analyzed. The influence of the passive filter on the accuracy of the measurements has also been studied.

We propose the replacement of the conventional superconductor rings by rings patterned on HTSC platelets of the type of the 1.69^o specimen developed. The proposed HTSC ring is schematically illustrated in Fig. 6: the surface of the film platelet is 5 ×5 mm^2, while its thickness is ~200 nm (dark rectangular "marble area"). A HTSC ring of 2.5 mm outer radius and 2 mm inner radius ("purple" area), with a thickness of ~ 200 nm can be patterned by either optical (UV) or electron beam patterning. For the rings replacement it is also necessary to reduce the dimensions of the gravimeter of [2] to 1/10 of the current device.

Conclusions

We describe a new gravimeter, which is suitable for long-term continuous observations. It uses laser interferometry to measure the acceleration of a falling corner cube with reference to atomic standards. Between drops, the corner cube is lifted to the top by rotating the vacuum pipe around a horizontal axis with an angular velocity high enough to keep the cube fixed by centrifugal force. This method has an enormous advantage for making a large number of measurements since there is no complicated mechanism inside the vacuum pipe. This absolute gravimeter seems to have no source of systematic error which will exceed one part in 109 if we can reduce the amplitude of the mechanical vibration to less than about 1.5 nm. We describe here the principle and the results of the experiments that we have made to date.

In this paper, we have shown how to integrate YBCO thin film rings into the optical-cryogenic gravimeter in order to reduce its size and make it convenient for future space applications. Its function is based on the magnetic levitation phenomenon of the probe and on the measurement of its displacement with subsequent data processing. A free suspension of the probe is realized using the magnetic potential well effect. Preliminary experimental investigations have shown that the developed sensor can provide a displacement measurement precision for the probe of ~ 0.1 nanometer, which corresponds to a measurement precision for the Earth's gravity field acceleration at a level of ~ 10^{-10} g.

We report in this paper the results of a measurement of the gravitational constant *G* obtained in a laboratory at distances of about 1 m, using a superconducting gravimeter. The instrument measured the gravitational effect due to an annular mass of about 330 kg moving up and down around the gravimeter. The experiment yielded for the gravitational constant the value *G* _=_(6:679 - 0:008) 10^{-11} Nm^2 /kg^2 which agrees, within its uncertainty, with the last CODATA valu anometer, which corresponds to a measurement precision for the Earth's gravity field acceleration at a level of ~ 10^{-10} g.

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Area of research: remote sensing, space instrumentation