Instrumentation system for registration of ultra low frequency gravitational field disturbances*

S.A. Shopin,
M. Sc., IEEE Student Member, main specialist on informational technologies and geoinformation systems
Tul'skya geologorazvedochnaya partiya Ltd., Tula
sshopin@mail.ru

Keywords: gravitational field, torsion pendulum, position-sensitive detectors

Annotation

Wideband gradiometer instrumentation system based on the usage of "Cavendish balance" type torsion system allowing real-time registration of ultra low frequency (<10^{-2} Гц) disturbances of the terrestrial gravitational field has been considered. The principle of torsion system rotation angle measurement using position-sensitive detector as well as electronic circuits of the instrumentation system have been described. Examples of the instrument readings have been presented.

1. Introduction

In the result of the long-term research, which main results are presented in [1], it has been determined that such natural accidents as earthquakes, typhoons, storms are the different realizations of the same energy process in the planet system. Process of such events preparation is long-term and is accompanied by the radiation of the waves within different frequency ranges but the primary process, determining localization and the energy properties of the future event, is associated with the ultra low frequency radiation (ULF, $10^{-12}-10^{-2}$ Гц). Due to ultra low frequencies such radiation is practically unscreenable and doesn't decay passing through different anisotropic mediums so it can be registered at the great distance (thousands of kilometers) from its source. ULF radiaton results in the gravitational field disturbances which can be registered by the special instrumentation system described in this paper. For the interpretation of system data ideas of Lobachevsky's function and principles of the interconnected polarized media are used.

2. Asymmetrical torsion balance

In physics, it is known the weak force measurement principle utilizing high sensitivity instrument being the torsion balance also known as Coulomb balance. Torsion balance was used in the experiments of Coulomb, Cavendish, Eötvös and others, with its usage there were determined various physical constants [2].

Torsion balance is a balanced beam suspened by the fiber. At the ends of the beam sensitive elements are placed. Force field acting on the sensitive elements produce twisting torque which twists the fiber until it is balanced by the torque of the fiber elastic forces. Value of the fiber angle of twist (which is equal to the rotation angle of the beam) is the measure of the field (fig.1).

For the measurement of the nonhomogeneous gravitational field parameters various geometry weights are used.

Construction of the torsion balance, used in the system being described is this article, is presented on the fig.2a. Torsion system of such type is asymmetrical under the finite dimensions of the weights and the beam. Its motion is complex: rotation of the beam is accompanied by the pendular oscillations of the weights and the whole "beam-weights" system.

---

* This work was performed in cooperation with A.V. Surkov, V.A. Shopin, S.P. Kurotchenko, A.V. Legkov, R.V. Parshutin under the guidance of Dr.Sc., Prof. O.V. Martynov, Tula State University, Tula.

The simplest model of the torsion system, in which the "beam-weights" system is replaced by the asymmetrical rigid body having the same mass and intertial characteristics as the torsion system, is the mechanical system having 5 degrees of freedom. The model complexity and the number of degrees of freedom depends on the specific construction of the weights and their suspensions. On the figure 2b the main types of motion in the simplest torsion system model are presented: one rotational motion θ_3 which is the rotation of the beam and the main type of motion in the system, and four pendular motions – θ_4 and θ_5, being the deviations of the suspension fiber from the vertical, and θ_1 and θ_2, being the pendular oscillations of the beam relative to the two axes. Angles θ_1, θ_2, θ_3 are the Euler's angles characterizing beam orientation relative to the main axes of inertia of the "beam-weights" system.

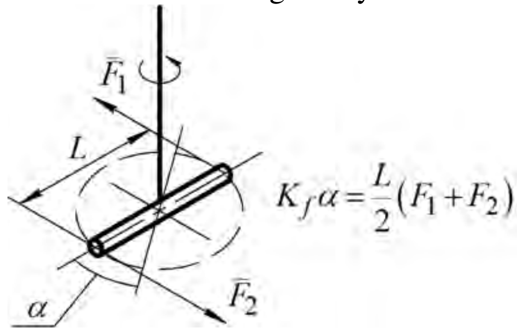
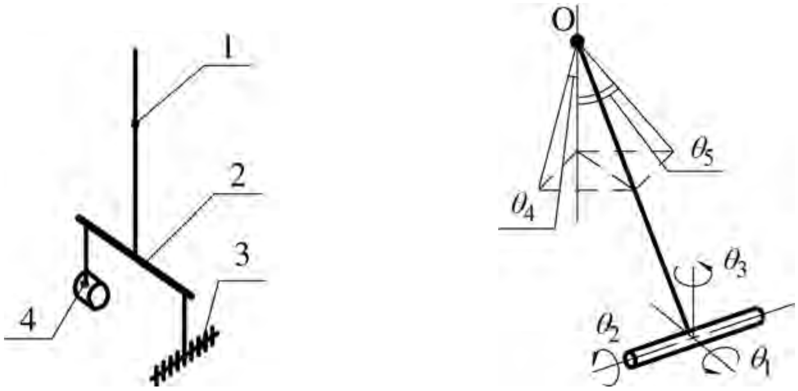


Fig. 1. Torsion balance principle of operation

α – beam rotational angle, K_f – torsional rigidity of the fiber, F_1 и F_2 – forces acting on the sensitive elements

Asymmetrical torsion balance is the complex oscillating system having frequency selectivity [3]. Frequency properties of the torsion system depend on the length and the material of the suspension fiber, and on the mass-inertial characteristics of the weights and the beam.



a) б)

Fig. 2. a) Torsion system of the instrument: 1 – suspension fiber; 2 – beam; 3 – weight-antenna; 4 – weight-counterbalance; б) main types of motion of the torsion system: O – torsion system point of suspension

In the considered system for registration of the components of the nonhomogeneous gravitational field gradient vector, it was used asymmetrical weight system consisting of weight-antenna with complex geometrical shape and weight-counterbalance. Geometrical shape of weight-antenna is chosen on the basis of spectral parameters of the disturbances, for which registration the system is designed.

For the reconstruction of components of vector fields complex acting on the torsion systems on the base of the registered data their registration using multiple torsion systems having different natural frequencies and consequently different kernels of the integral transform "external force action – instrument signal" , is necessary. This can be achieved by the usage of different suspension fiber lengths and the special constructions of weights-antennas.

3. Instrumentation system structure and principle of operation

Utilizing torsion systems described in the section 2 it was developed multichannel system of the wideband gradiomenters (WBG) having 2-, 3- and 4- channel devices. This system is deployed in the laboratory of the Tula State University.

WBG is instrumentation system intended to the measurement of nonhomogeneous gravitational field gradient by the registration of the angular position of the torsion system beam. WBG consists of system case-shield, inside which the torsion systems are placed, electronic registration subsystem and personal computer having special software installed. Special software performs preprocessing of the incoming data and its archiving in the database.

Structural chart of WBG is presented on the fig.3

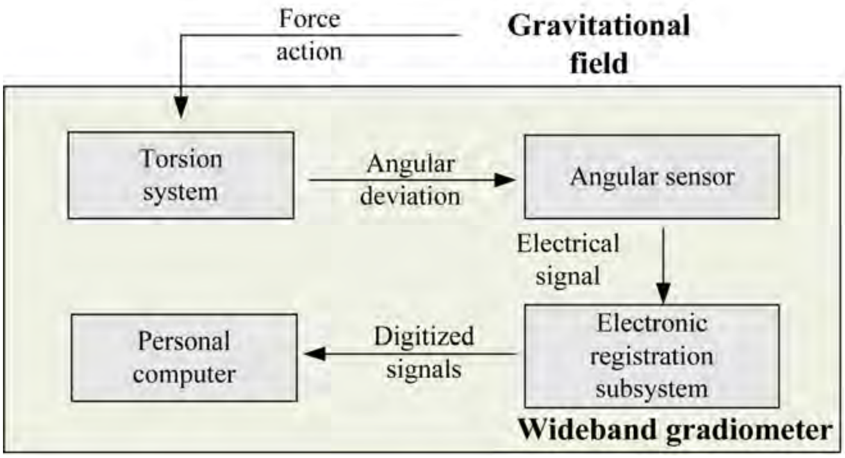


Fig. 3. Structural chart of WBG instrumentation system

Elements of the WBG's torsion system such as fiber, beam and weights are made of nonmagnetic and optically non-transparent materials. For the elimination of external electromagnetic fields influences (including low frequency ones) the torsion system itself is placed inside the closed metallic vessel (system case-screen) made of thick steel (thickness is about 20mm). System case-screen is grounded.

Construction of the case-screen of 2-channel device having 2 torsion systems in it, is presented on fig. 4.

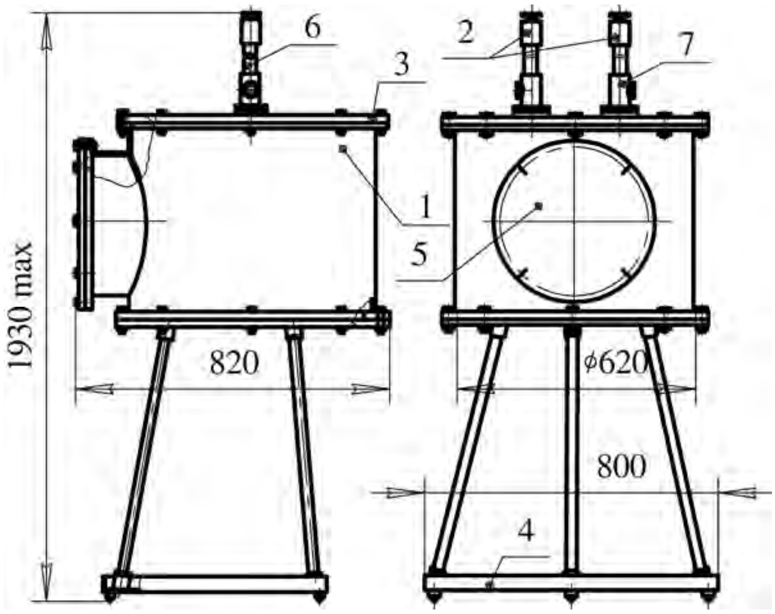


Fig 4. System case-screen: 1 – working volume of the case; 2 – fastening and regulation device of the torsion system; 3 – case cover; 4 – instrument basement; 5 – cover of the working window; 6 – duct;7 – duct stand

Torsion systems of the instrument are placed inside the working volume of case 1. Suspension fibers are located in the ducts 6. Setup of the zero angular position of the torsion systems and fastening of the suspension fibers is performed using block 2. Working window covered by the cover 5 is used for the access inside of the working volume 1 during instrument assembly and adjustment. Construction of the basement 4 is chosen to minimize the influence of mechanical type interference (eg, seismic) on the torsion systems of the instrument.

For the elimination of the air convection influence on the torsion systems all joinings of the case-screen are sealed and case-screen itself is placed in temperature-controlled room.

For the measurement of the beam rotation angle, angular sensor is used, its elements are placed in duct stands 7.

Angular sensor principle of operation presented on the fig.5 consists in the position measurement of the light beam reflected by the mirror fastened on the suspension fiber.

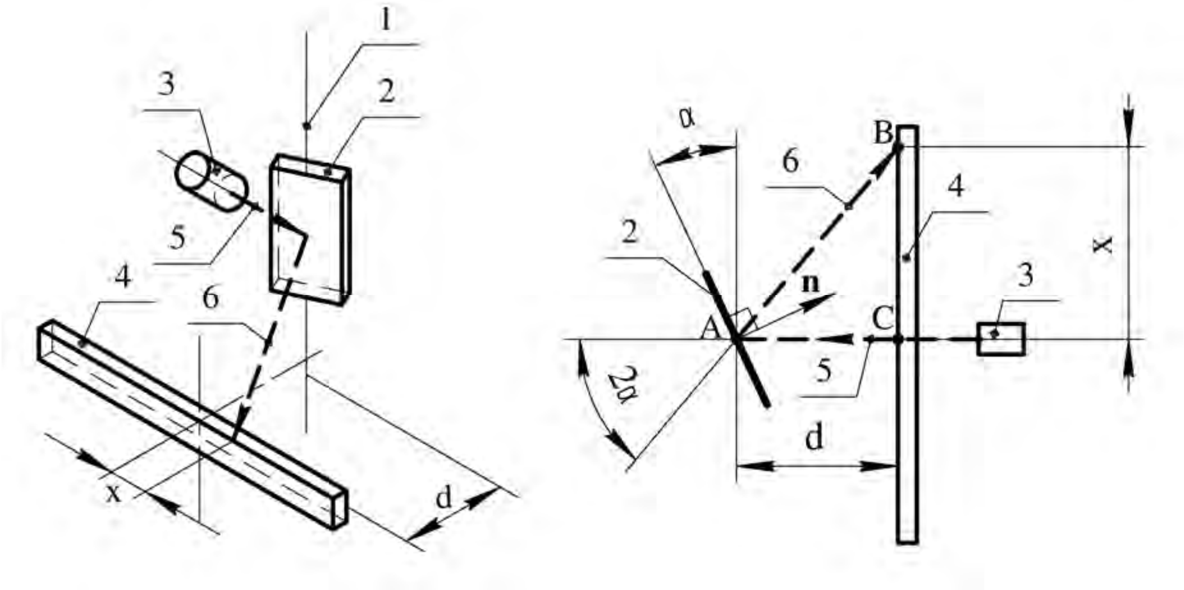


Fig. 5. Angular sensor principle of operation: 1 — suspension fiber, 2 — mirror, 3 — light-emitting diode (LED) and the optical system, 4 — photodetector, 5 — LED light ray, 6 — ray reflected by the mirror, d — distance from the photodetector to the mirror, x — distance from the photodetector centre to the light beam centre, α — beam rotational angle, **n** — horizontal component of the vector perpendicular to the surface of the mirror

Using the photodetector the value of x is measured and then the rotation angle α is calculated. Equation for calculation can be derived from geometrical considerations for the triangle ABC utilizing light reflection law (angle of incidence is equal to the angle of reflection):

$$\alpha = arctg\left(\frac{x}{d}\right) \tag{1}$$

Fragment of the duct stand model with mounted angular sensor elements is shown on the fig.6.

4. System hardware

Angular sensor uses as the photodetector a one-dimensional position-sensitive detector (PSD) S3270 by the Hamamatsu Photonics. Some characteristics of the PSD are presented in the table 1 [4]. PSD photo is shown on the fig. 7.

Table 1 – Characteristics of the PSD

Photosensitive are size, mm	Spectral response range, nm	Peak sensitivity wavelength, nm	Photosensitivity, A/W
37x1,0	700…1100	960	0,55

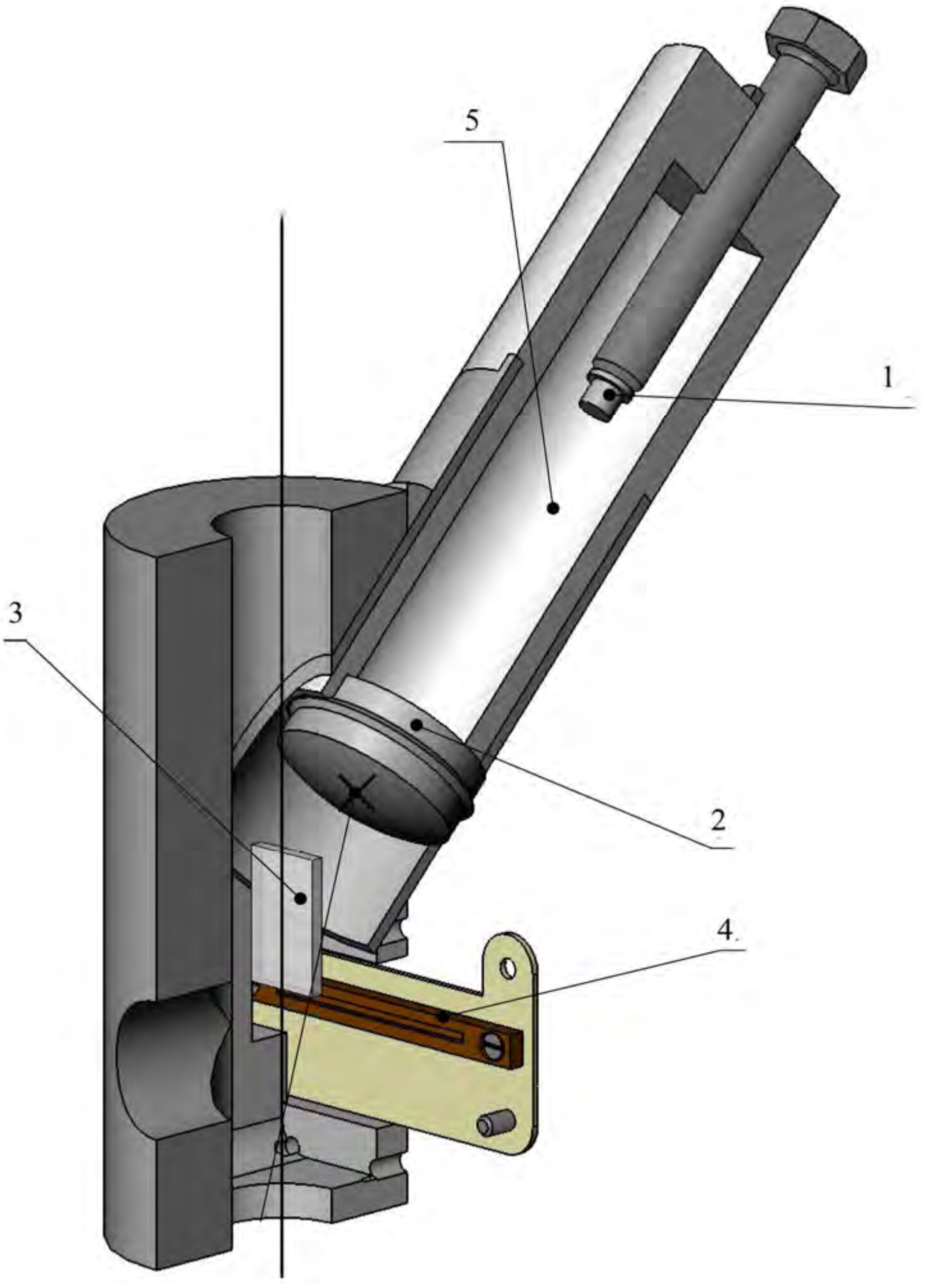


Fig.6. Fragment of the duct stand model: 1 – LED, 2 – lens, 3 – mirror, 4 – photodetector, 5 – surface covered with black light absorbing material

Fig. 7. S3270 photo

PSD is designed as a layer of conductive p-type material deposited on the semiconductor n-type substrate with a large resistivity. Between p- and n-layers the low doped n-type layer is located. On the both ends of the conductive layer and in the centre of the substrate the electrodes are formed (fig. 8) [5,6].

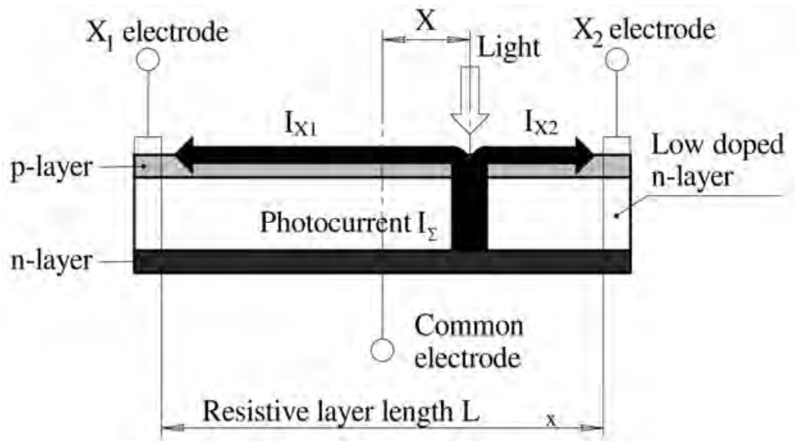


Fig. 8. PSD construction and the principle of operation:
I_{X1} and I_{X2} — photocurrents of X_1 and X_2 electrodes respectively, I_Σ —total photocurrent, X – distance from the photodetector centre to the light beam centre position on the photosensitive surface of the PSD

PSD construction is similar to the construction of the PIN photodiode with addition of resistive photocurrent divider (fig. 9)

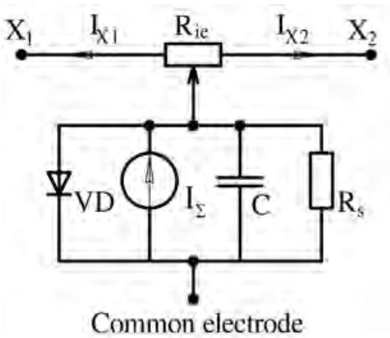


Fig.9. Equivalent circuit of the PSD: VD — ideal diode, , C — PSD capacitance, R_s — resistance of p-n junction, R_{ie} — interelectrode resistance (resistance of phtosensitive area)

When the light strikes the photosensitive surface of the PSD, photocurrent proportional to light intensity is generated because of the photovoltaic effect. Total photocurrent is divided between the pair of electrodes depending on the distance from them to the place of light incidence according to the following equations:

$$\begin{cases} I_{X1} = I_\Sigma \dfrac{L_X/2 + x}{Lx} R_{ie}, \\ I_{X2} = I_\Sigma \dfrac{L_X/2 - x}{Lx} R_{ie}. \end{cases} \qquad (2)$$

From the equations (2) follows the advantage of this measurement method: as inevitably LED brightness will decay because of semiconductor degradation, the total photocurrent will also decay but the portions of the I_{X2} and I_{X1} currents will be determined by the measurable distance X.

From the equations (2) it can showed that distance from the PSD centre to the light beam centre position on the photosensitive surface can be expressed as

$$X = \frac{L_x}{2} \cdot \frac{I_{X2} - I_{X1}}{I_{X2} + I_{X1}}. \qquad (3)$$

Electronic registration subsystem of the WBG device performs instrumentation of photodetector currents, their prefiltering, sampling, and transfer to the personal computer (PC) for the calculation of the rotation angle and following archiving in the database.

Structure chart of the registration subsystem is shown on the fig.10.

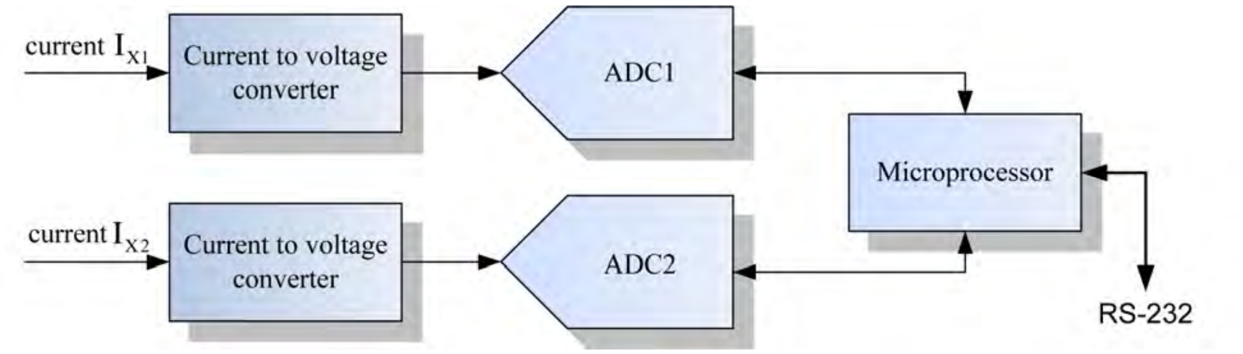


Fig.10. Registration subsystem components

Photocurrents measurement is performed by the current to voltage converter, which circuit is show on fig.11. For the both photodetector currents the identical instrumentation circuits are used. Converters contains transimpedance amplifier, consisting of operational amplifier DA1 (OPA277), resistor R1, capacitor C1, and the summing amplifier consisting of instrumentation amplifier DA2 (INA114) shifting zero to the level of reference voltage REF.

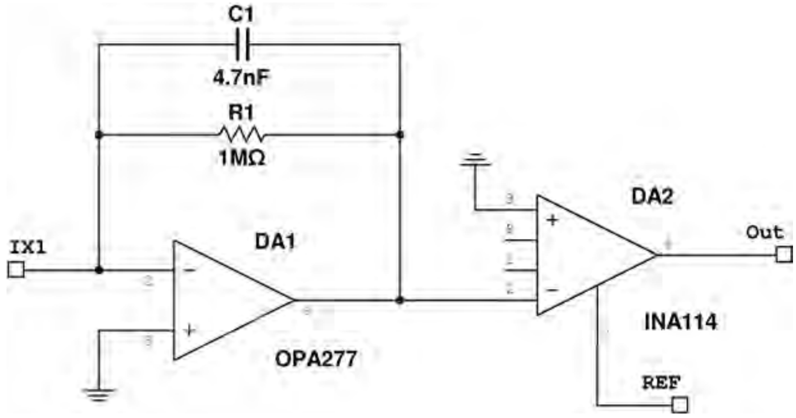


Fig. 11. Current to voltage converter

Sampling of the current to voltage converters output voltages is performed by the 24-bit precision low speed delta-sigma analog to digital converters (ADC) AD7719 by Analog Devices. To ensure the simultaneous sampling two identical ADCs with a common clock frequency are used. Reference voltage for both ADCs is generated by the precision voltage reference ADR421 by Analog Devices.

For signals sampling of the different torsion systems angular sensors, channels of the ADCs are used in pairs.

To ensure precision and long-term stability (which is very important for ULF measurements) it is used precision, high-stable resistors with tolerance 0,1% of C2-29V type, polypropylene capacitors with low dielectric absorption by Epcos, and also precision operational and instrumentation amplifiers by Texas Instruments.

Measured currents are very small (about 1μA) so the special construction techniques are used for elimination of the unwanted errors: all connectors in the low signal circuits have gold-plated contacts, printed circuit boards are coated with the Urethane lacquer, all interconnection signal cables and case are shielded.

Registration subsystem is controlled by the microprocessor which generates the necessary commands to control the ADCs and provides the transfer of the data to a PC through a standard interface RS-232.

5. System software[†]

WBG software consists of data manager, data acquisition module "DAQ2" and user interface software "DAQ Appo" which is used for visualization, processing and analysis of acquired data (fig. 12).

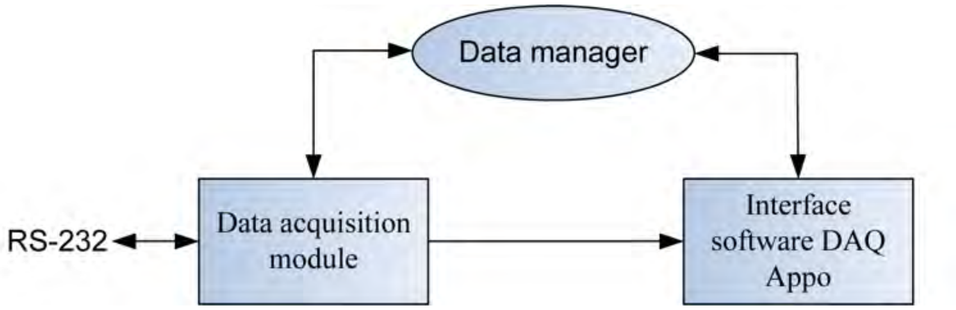


Fig. 12. Software modules and their interaction

As the data manager the Microsoft® SQL Server® 2005 Express is used.

DAQ2 module is developed as the operational system service, functioning in the background. Module sends commands to and received data from electronic registration subsystem using RS-232 interface, calculates beam rotational angle from the measured currents, sends queries to the data manager for inserting acquired samples to the database and also performs registration of the system failures and errors in the system log.

Interface software "DAQ Appo" requires Microsoft® Windows® 2000 or higher to run and has following features:

– database query according to the selected unrestricted time interval and channel group, query visualization;

– pointwise tracking of every displayed graph with current location displaying;

– plotting of the linear, cubic and polynomial trend for the query;

– plotting of the simple, linear, exponential, triangular and sine-weighted moving average of the query;

– import and export of the whole database contents or the part of it to the XML, compressed XML or text files;

– real-time monitoring of the acquired data with the channel group selection.

Overview of the "DAQ Appo" interface is presented on the fig.13

6. Examples of registered data

Different generations of the WBG systems are used over 20 years. Modification of the WBG system described in this paper has been operating for over 3 years in the twenty-four-hour service. During this time, it is accumulated extensive material for statistical studies of the instrument readings.

Examples of the registered system data are shown on the fig. 14. The vertical axis represents the rotational angle of the torsion system beam in the arbitrary units being referred to as A, the horizontal axis is the time axis.

The signals on the fig.14 have regular, not noise-type character. Area I is corresponded to the relatively quiet, undisturbed state of the torsion system. In the area II WBG system registered disturbance as a long time and a significant value deviation of the torsion system from the equilibrium state, the deviation is synchronous at all three channels. In the area II shorter time and higher-frequency signals III and IV are embedded. At the same time, when considering a larger time interval, an anomaly II itself will be embedded in the wave with a significantly greater duration, for which the specified arguments is also true.

Frequency selectivity of the torsion systems results in the different but at the same time similar shapes of the graphs clearly visible in Figure 14.

[†] System software was developed by the A.V. Surkov together with this paper author.

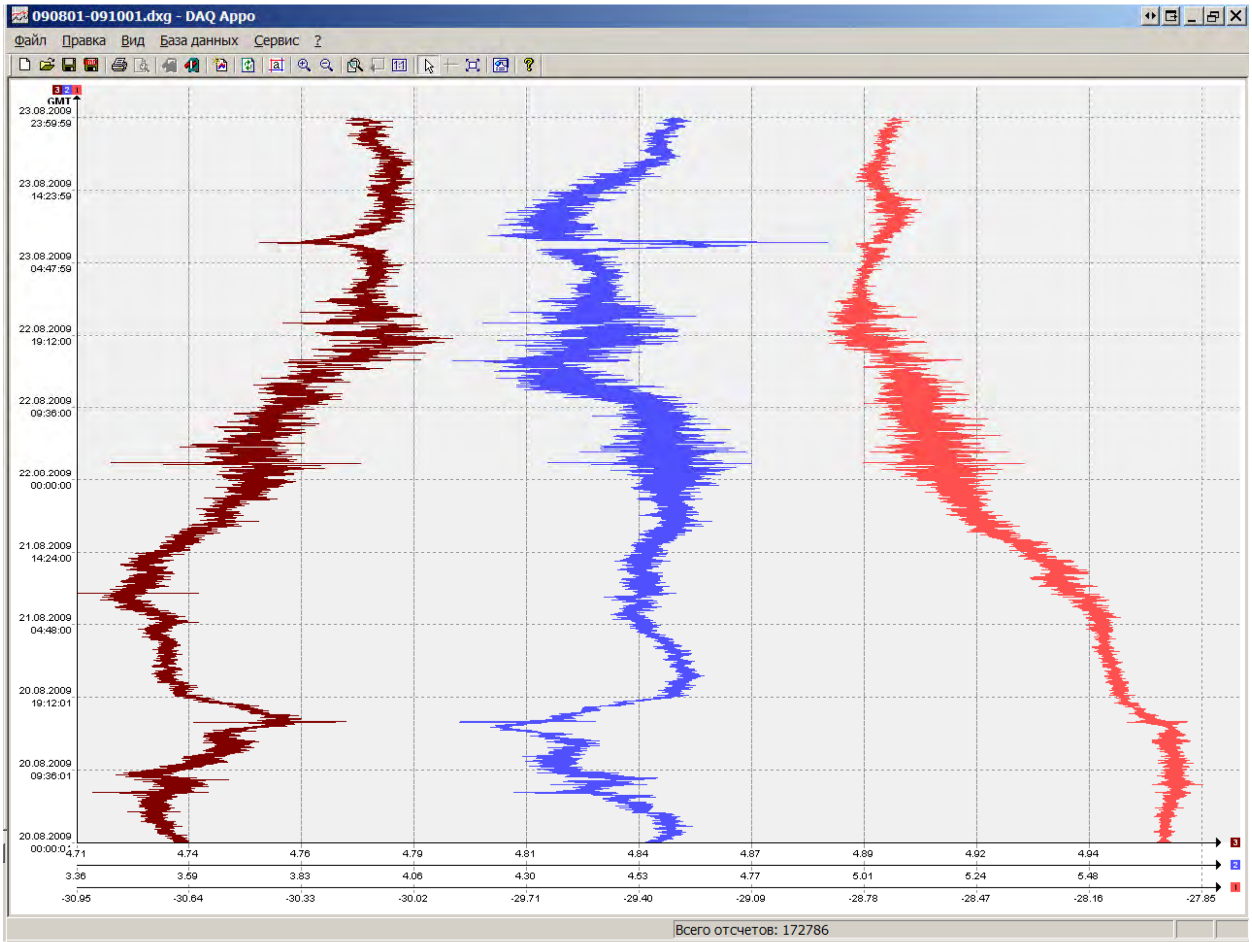


Fig.13. "DAQ Appo" software interface

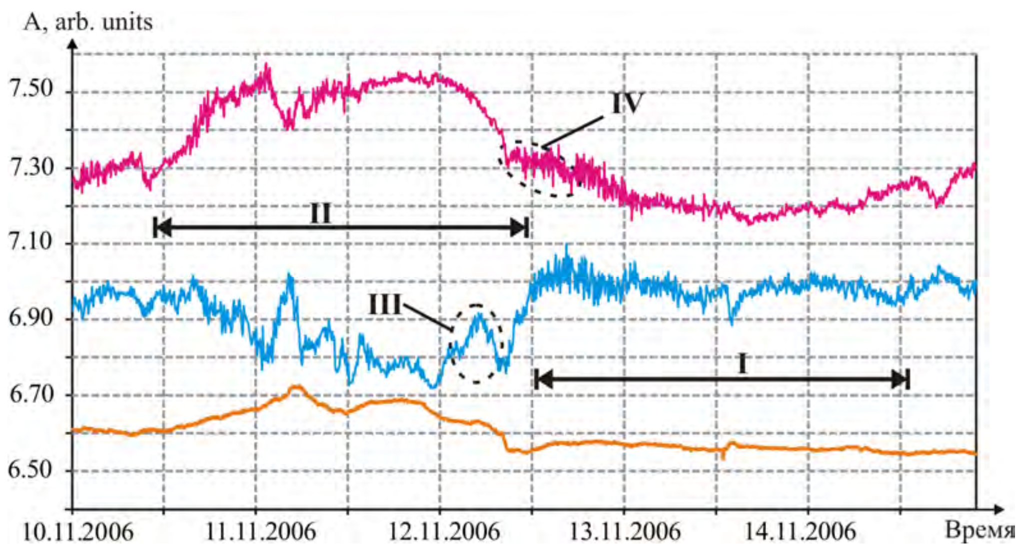


Fig. 14. WBG's signals examples

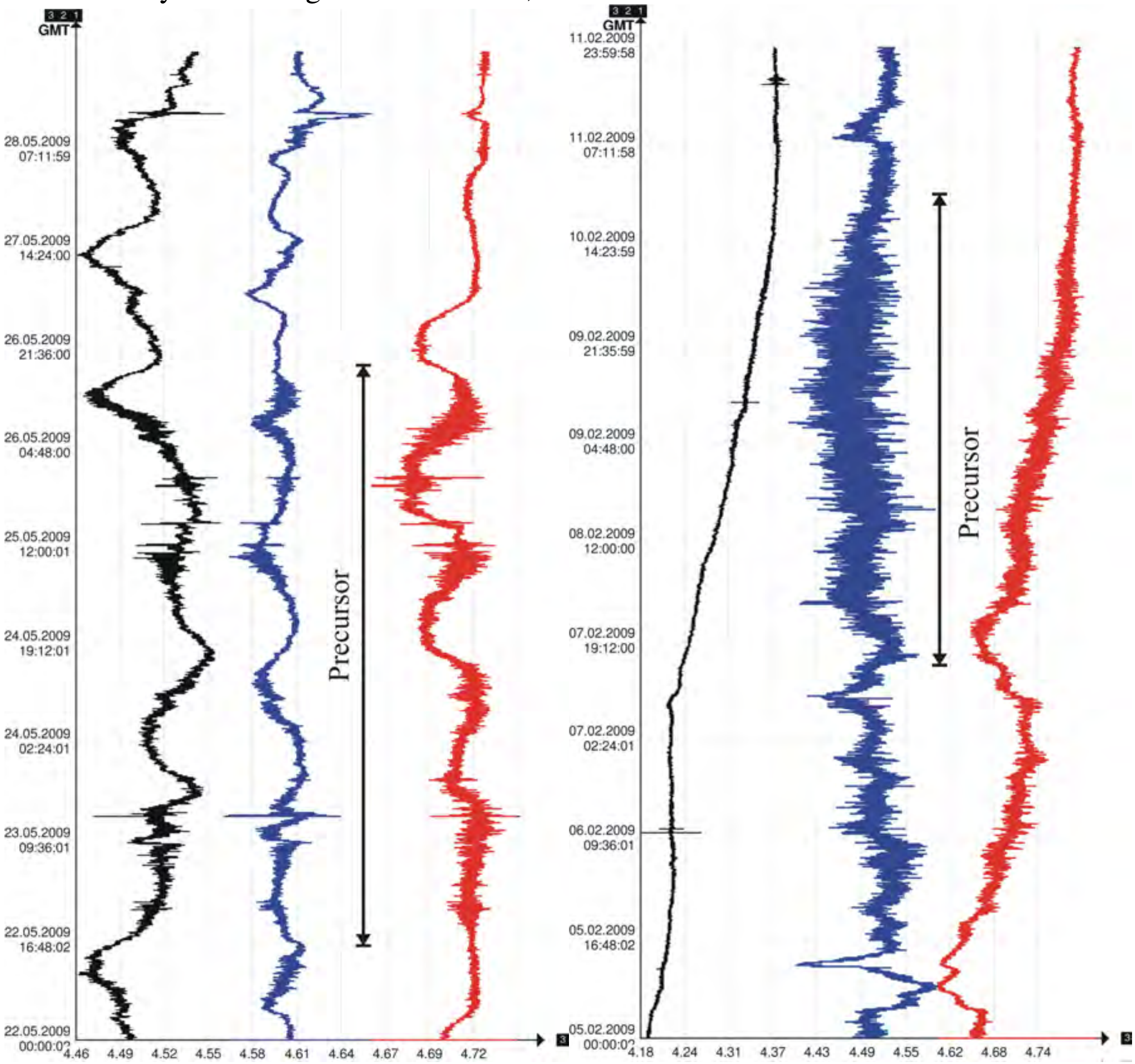
On the fig.15–16 high frequency (but also inside of the ULF frequency range) disturbances of the gravitational field are shown. These signals are the precursors of the seismic events registered by the WBG system about 3–5 days prior to the great earthquakes of the 2009 year:

– 11.02.2009 Mw 7.1 3,93°N, 126,54°E, Indonesia (fig. 15a);
– 28.05.2009 Mw 7.1 16,69°N, 86,26°W, Honduras (fig. 15b);
– 29.09.2009 Mw 8.1 15,42°S, 172,13°E, Samoa (fig. 16a, precursor 1);
– 30.09.2009 Mw 7.6 0,76°S, 99,84°E, Indonesia (fig 16a, precursor 2);

– cycle of the 3 events in south hemisphere 07.10.2009: Mw 7.4 12,98°S, 166,33°E; Mw 7.8 12,57°S, 166,35°E; Mw 7.4 13,04°S, 166,33°E (fig. 16b).

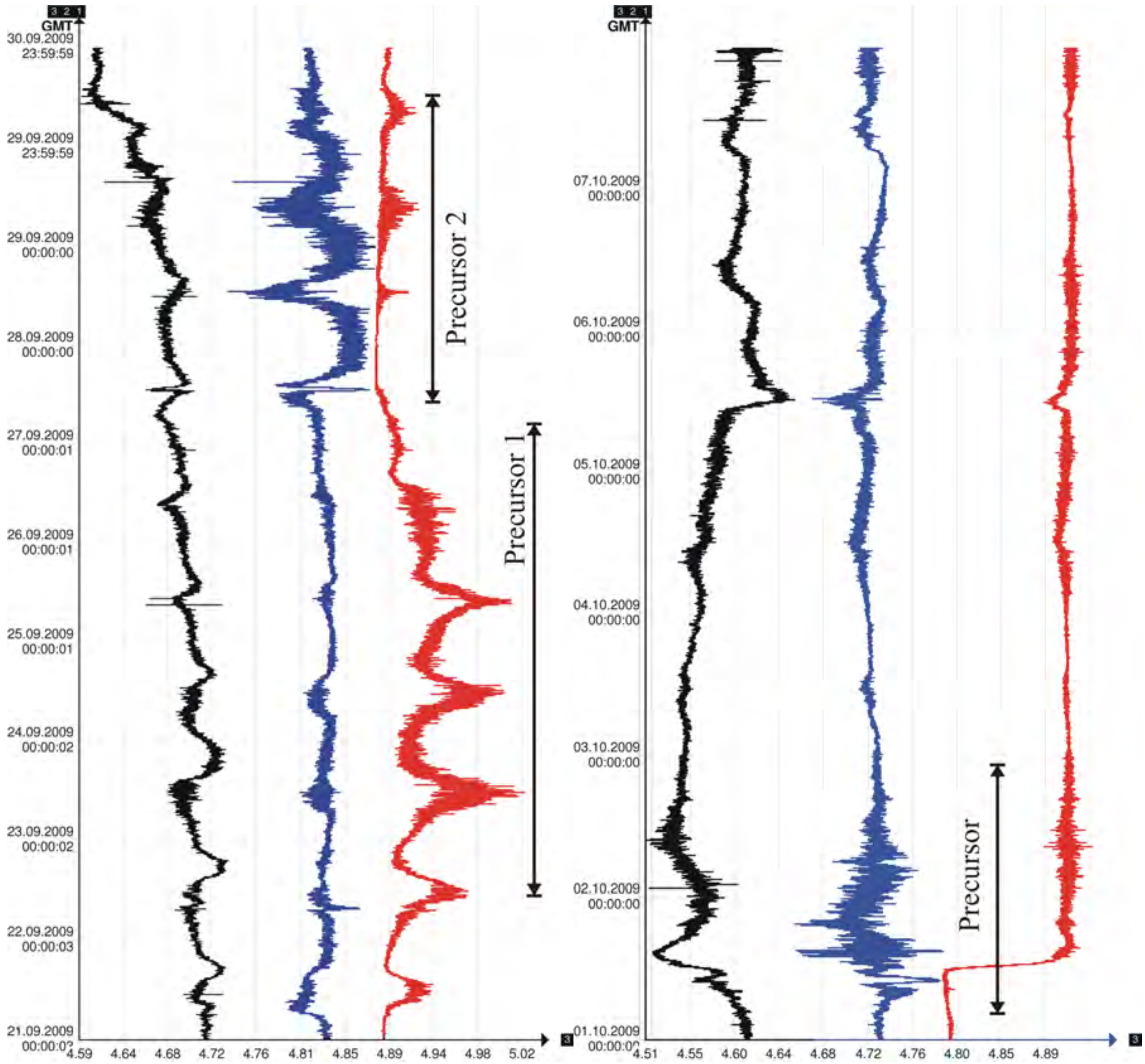
Information about seismic events parameters is obtained from the open sources that are available in the Internet: databases of the United States Geological Survey Earthquake Hazard Program [7] and the European-Mediterranean Seismological Centre [8].

On the fig. 15–16 the horizontal axis represents the rotational angle of the torsion system beam in the arbitrary units being referred to as A, the vertical axis is the time axis.



a) b)

Fig. 15. HF signals prior the earthquakes: a) in the Indonesia in February and b) in the Honduras in May 2009.



a) b)

Fig. 16. HF signals prior the earthquakes: a) in the Indonesia and Samoan in September and b) in the Southern hemisphere in Octiber 2009.

7. Conclusions

Described instrumentation system allows registration of the ultra low frequency disturbances of the terrestrial gravitational field, appearing in the different ULF frequency ranges.

System data can be used for real-time monitoring of the natural accidents preparation processes and also for the development of the equipment allowing geodynamical processes energy usage to produce clean energy, which is not associated with environmental pollution.

8. References

1. **Martynov O.V. The Natural Accidents Forecasting System Concept and the Practical Results, Obtained from Nonlinear Physics, Mathematics and System Data** / O.V. Martynov // Nonlinear world.— 2008.— №10.— C.579 — 615.

2. Naker G.L., Blackburn J.A. The Pendulum. A Case Study in Physics.— Oxford University Press, 2005.— ISBN 0-19-856754-5.

3. **Kalinnikov I.I.** Gorizontal'nye krutil'nye vesy — sejsmopriemnik s mnogolepestkovoj diagrammoj napravlennosti / I.I. Kalinnikov // DAN.— 1991.— Volume 317, №4.6.

4. One-dimensional PSD S3979, S3931, S3932, S1352, S3270: Datasheet. KPSD0001E01.— USA: Hamamatsu Photonics K.K., 2004.— http://usa.hamamatsu.com/assets/pdf/parts_S/S3979_etc.pdf.

5. Position-Sensitive Detectors. USA: Hamamatsu Photonics K.K., 2003. — http://usa.hamamatsu.com/assets/pdf/catsandguides/Psd.pdf.
6. Position Sensing Detectors: Theory Of Operation.— USA: On-Trak Photonics Inc., 2004 — http://www.on-trak.com/pdfs/PSDTO.pdf.
7. USGS National Earthquake Information Center.— USA: USGA.— http://www.neic.cr.usgs.gov/neis/epic-global.html.
8. European-Mediterranean Seismological Centre.— Europe: EMSC.— http://www.emsc-csem.org.