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Geodynamical observations using spatially distributed gravimeters, tiltmeters, and laser strainmeters

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Abstract

The advanced methodology of geodynamical observations, which is based on accounting of all possible components of elastic body movements, is being developed. This approach means the allowance for simultaneous measuring the Earth surface spatial displacements, tilts (inclinations), and strains (deformations). For experimental workout of this methodology we use the spatially distributed system of pendulum (spring) gravimeters, inclinometers (tiltmeters), and laser deformometers (strainmeters) including equal-arm and unequal-arm configurations. The distance between separate instruments varies from a few hundred meters within local site installations, and up to hundreds kilometers for a different remote sites and observatories, which have been placed within the Moscow region. The experience of the developed method application is discussed and some observational results such as effects of powerful atmosphere and global ionosphere disturbances are presented.

Keywords: Gravimeter, Tiltmeter, Laser strainmeter, Earth oscillations, Earthquake precursors, Hurricane

1. Introduction

Investigators when studying geophysical processes have to concern with a wide variety of natural and artificial phenomena and occurrences. Nevertheless, all processes in the Earth can be divided in two basic categories:
(i) The processes occurring in the Earth continuously and being excited by the external forces: the tidal deformations of the whole Earth due to tidal gravity forces of the Moon and the Sun, microseismic oscillations spreading along the Earth crust under influence of permanent dynamical processes in atmosphere and oceans.
(ii) The processes that occur after any events: earthquakes, volcanic eruptions, typhoons (hurricanes), etc. They are the seismic waves, the free oscillations of the Earth, the fault creeps, and slow earthquakes, tectonic shifts and other spontaneous occurrences in the solid Earth body. These processes are so-called the event-processes.

For an instrumental recording of tidal processes the extended class of devices with high sensitivity, stability, and wide dynamic range has been developed: tidal gravimeters (seismo-gravimeters), tiltmeters (seismo-tiltmeters), and extensometers (strain-seismometers). These instruments being good for measurements the diurnal (semidiurnal) and seasonal tidal deformations of the Earth with the high accuracy also can be used to record the ultra-small ground oscillations (i) occurring in a wide frequency range permanently, as well as to detect non-periodic event processes (ii) in the Earth crust. Comprehensive investigations of all these phenomena are important for understanding both origins of natural disasters (earthquakes, hurricanes), and mechanisms of coupling the processes observed at the solid Earth and in the adjacent geospheres.

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Selected experimental results, which were obtained during past decades, are presented and discussed in this paper. The results show a measure ability of the developed instrumental techniques and demonstrate their application for research of poorly studied phenomena.

2. Methodology and Instrumentations

Gravimeters, especially super-conducting (cryogenic) gravimeters, are the most precise devices for the tidal processes investigation now. But the gravity tides that are measured by these instruments contain only the vertical component of the tidal force. If we want to study completely Earth crust deformations, it is necessary to measure also the horizontal components. The contribution of the elastic deformation of the Earth to the direct gravimetric signal is close to 25% or 15% if we consider the atmospheric pressure or the tidal force variations respectively, while it reaches 30% for tidal tilt (Melchior, 1983). Strainmeters, especially laser strainmeters, are the only ground based instruments measuring directly the tidal Earth deformation with accuracy 10^{-10} and better (Takemoto et al., 2006; Kravtsov et al., 2011) that can be compared with the accuracy of the modern gravimeters. At last, the full representation of the Earth surface motions requires simultaneous observations with gravimeters, clinometers and strainmeters.

From the other hand the necessity of horizontal deformation measurements is caused by the constitution of upper layers of the solid Earth, which are fragmented and consist in a number of geo-blocks. The vertical dimensions of the lithosphere strata are less than 1% of the globe radius. The rest of the Earth body includes the solid or liquid strata: astenosphere, mantle and core, where transversal tensions are small. Therefore the effective scale estimations of horizontal inhomogeneities of the observed deformations of the Earth are very important, and they could be determined as a result of our measurements. These estimations may elucidate the nature and origins both the continuous (i) and event (ii) processes mentioned above owing to the characteristics of theirs spatial distribution. These features can be specified in every observed phenomenon just by spatially distributed instruments, which are fit to measure both the vertical deformation (through variations of gravity) and horizontal tilts and strains of the Earth surface. With application of such techniques the distinctions between local and global processes and similarly between endogenous and exogenous phenomena in the Earth will be available.

Three different kinds of precise geophysical instruments have been applied to deformation measurements of the Earth surface. Two of them use the inertial and gravitational properties of mass of the accurate pendulum: gravimeter (seismo-gravimeter) and tiltmeter (seismo-tiltmeter). The third one: precise laser interferometric strainmeter measures relative displacements of two points at the Earth surface to which the interferometer is anchored.

The improved and modernized ASKANIA gravimeter GS-11 and portable tiltmeter station have been used in presented experiments. The objective in improvement of pendulum registration systems was to extend the characteristics of instruments: sensitivity, stability, dynamical and frequency ranges. Research and developments have been fulfilled in the Institute of Physics of the Earth. The design of a capacitive displacement transducer of pendulum in an electric field (Volkov et al., 1985) allowed the next instrument characteristics to be obtained: pendulum displacement resolution of 10 nm, tidal gravimeter resolution of 0.2 μGal, vertical accelerometer resolution of 20 nGal with a bandwidth from 200 s to 5000 s. Additionally two long-period seismic channel with bandwidths 10-100 s and 10-1000 s have been realized. Selective results of processes (i) and (ii) registration by seismo-gravimeter are shown in Fig.1 (a, b) and Fig.4 (c).

2.1. Two-components tiltmeter NP-1M

The composition of tiltmetric station includes: sensor, control electronics, and recording equipment. Sensor operation is based on the principle of vertical pendulum. Sensor consists of 100 mm vertical pendulum which is mounted on the base with three adjustable screws. The main components are mounted in the case which is protected by the sealed cap. The control unit can be connected to the sensor by signal cable with lengths up to 1 km.

Tiltmetric station is designed for the measurement of the relative slopes of the Earth surface in two mutually perpendicular directions. The aims: studying the tidal deformation; studying the modern movements of the Earth crust; finding earthquake precursors in the form of abnormal tilts and strains; tests of bases and parts of large engineering structures. Tiltmeter resolution is estimated as 1 milliarcsecond (mas) in tidal channel and 0.1 mas in seismic-accelerometer channel. Tiltmeter with horizontal pendulum installation has been also used in our observations (Kalinina et al., 2004). The highest resolution of this instrument is estimated as 0.1 mas in tidal channel and 0.01 mas in seismic-accelerometer channel. Selective results of registration of processes (i) and (ii) are shown in Fig.2 (a, b).

2.2. Laser interferometers, extensometers, and strain-seismometers

Investigations and developments of laser interferometers for geophysical measurements are being carried out in the Institute of Radio-engineering and Electronics (IRE RAS) in cooperation with the Institute of Physics of the Earth (IPE RAS) since 1970th (Dubrov et al., 1989). The number of new prototypes of laser interferometers, deformometers, and strain-seismometers have been developed and tested during last decades. Laser deformometers (strainmeters) with horizontal and vertical arm orientations both equal-arm and unequal-arm configurations have been investigated. The original optical schemes of laser instruments provided with special procedures of recording and signal selection were used and the field observation experience was accumulated.

Two versions of laser strainmeters for geophysical and seismological application have been developed. They include jam-proof laser feedback interferometer prototypes (path length varies from 10 m up to 850 m), and unequal-arm Michelson interferometers with length of 1-10 m. The first one has resolution of 1 nm on the basis up to 300 m. The resolution of Michelson interferometer recorder is about 1 pm under 180-190 dB dynamic ranges in 1 Hz frequency band. The top relative strain resolution is $dL/L = 10^{-11}$ -10^{-12}, frequency range 10^{-6}-10^{2} Hz. The digital PC data acquisition systems extend the recording and analyzing range up to 0.1-1 kHz. The instruments allow the wide variety of the Earth surface displacements and strains to be measured with high accuracy without vacuum or evacuated facility. The number of spatial distributed laser instruments were installed and tested both in non-seismic area (Moscow Region) and in active seismic (Pamir and Tien Shan) regions. Selective results of registration of processes (i) and (ii) by different laser strainmeters are shown in Fig.3 (a, b) and Fig.4 (a, b).

The example of records of microseismic storms 4-6 s (0.17-0.25 Hz) presented in Fig. 4(a) have been made by simultaneously operated and spatially distributed laser strainmeters. The first of them (IRE RAS testing site, Fryazino) has measuring arms about 500 m, and the length of the second strainmeter (Observatory Protvino) is 16 m, distance between these instruments is 135 km (Dubrov et al., 1989). Both strainmeters have recorded the clear pulsing waves with the relative amplitudes $dL/L \sim 10^{-10}$ and about of 1 minute retardation; instrumental resolution is the order of 10^{-11} relative units.

High frequency microseisms or “micro-tremors” (1-100 Hz) have artificial origin on the whole. They are generated by human activity and sometimes occur as a result of sharp weather changes. These microseisms contain both surface and body waves which lay the information not only about of industrial machine operations but also on the Earth interior especially on upper layers of the solid Earth, where the earthquake precursors may develop (Dubrov et al., 1987). Fig. 4(b) shows the results of time-frequency analysis of microseism recordings made by two laser strainmeters: (1) within 2-3 m underground at IRE RAS testing site (Fryazino), and (2) about 30 m in depth (Obninsk Observatory) being 140 km apart. Two instruments near of the same lengths (100 m and 90 m respectively) record quite different tremors in 0.5-3.5 Hz frequency band (Kravtsov et al., 2011). The weak spectral components with amplitudes up to $dL/L \sim 10^{-12}$ can be resolved.

2.3. Records with gravimeters

The example of data processing in ultra-low frequency band is shown in Fig. 4(c). Free oscillations of the Earth, being excited after powerful Sumatra M=9.1 earthquake and recorded by seismo-gravimeter in Obninsk (Fig. 1 a, b) have been filtrated in frequency band of the fundamental mode ${}_0S_2$. The rotational overtones of the main mode ${}_0S_2$ (53.94 minutes) produced the pulsing signal of 27 days duration (Fig. 4 c). In result of spectral splitting four overtones: 52.33 minutes, 53.11 minutes, 54.79 minutes, and 55.48 minutes have been revealed. The regular discrepancy of the order of 0.3% - 0.7% with Bullen's model have been found. It demonstrates that improved and modernized vertical pendulum gravimeter with accurate recording system is available for high precision measurements when combining with sensitive tiltmeters and laser strainmeters. The suggested methodology and instrumentations, which are based on the multicomponent and spatially distributed measurements of the Earth motions, are the new approach to geophysical observations.

3. Results and Discussion

During long-term observations many authors detected the Earth background free oscillations excited on seismically quiet days, see e.g. review in (Petrova, 2000). The oscillations have a time-dependent intensity and intensity increases have been observed before strong earthquakes (Petrova and Volkov, 1996; Volkov et al., 1999).

There are two types of background signals in frequency band 0.05-0.5 mHz: (1) the oscillations existing in frequencies known as modes of free Earth oscillations after earthquakes, and (2) the oscillations which are not identified with those modes. The nature of these continuously excited background signals is under debate now. The amplitudes of free oscillation modes (1) are too high to be attributed to weak earthquakes and their origin has been related to atmospheric disturbances (Kobayashi and Nishida, 1998). The oscillations of type (2) may be connected with such powerful processes in the World Ocean as tropical cyclones: typhoons and hurricanes (Golovachev et al., 2011). Therefore the disturbances in atmosphere and hydrosphere of the Earth are much probable sources of continuous processes as well as event processes that force the Earth crust (Klügel and Wziontek, 2009).

The multiform interactions of lithosphere and atmosphere disturbances have been first investigated and analyzed in detail by the synchronous operating and spatial distributed seismo-gravimeter, tiltmeter, and laser strainmeter (Dubrov et al., 2000). The joint data analysis from sites being apart at 140 km one from another has been carried out. The dynamic disturbances in the atmosphere were found to have the wave microstructure and to be accompanied by complicated Earth surface strains, tilts, and gravity variations. These interactive "waves" propagate along the atmosphere-ground boundary with the velocities of 30 - 50 km/h. Owing to partial coherency they would hamper the precise geophysical data acquisition. However the correct knowledge of those ground motion mechanisms would provide new technique for the Earth material testing (Volkov et al., 1999).

The ultra-long period (3 minutes...6 hours) oscillations of the Earth together with the atmospheric pressure micro-variations in the same period range were investigated during last decades (Petrova and Volkov, 1996). This type of disturbances were for the first time identified in the result of data analysis of observations made by seismo-gravimeters of different design in 1987 (St. Petersburg and Obninsk) and 1992 (St. Petersburg, and Borovoe, Kazakhstan). The similar signal was found when analyzing synchronous observations made with a seismo-gravimeter installed in St. Petersburg and a quartz strainmeter in Apatity during May 3-10, 1993. The essential growth of 4-5 hour period disturbances during 2 days before the earthquake March 25, 1998, Mp,s=7.0-7.9 have been observed by a laser strainmeter and seismo-gravimeter in Moscow region (Volkov et al., 1999).

The growths of oscillation intensities discovered before the earthquakes in April 29, 1987 (Iran), December 12, 1992 (Indonesia), and May 11, 1993 (Philippines), were identified as traveling disturbances lasting 85 – 120 h and having slight excess about the mean amplitude, common spectral components, and stable shapes of the envelope along the propagation path. It is important that these observations were conducted during the periods of low seismic activity, and the disturbances were observed before strong earthquakes.

3.1. Co-seismic processes preceding the Sumatra M=9.1 earthquake

The analysis of the "bursts" of periodic oscillations and their synchronization before strong earthquakes have been recently reported (Sobolev, 2011). Three earthquakes with magnitudes M =7.8 -9.1 were considered: Kronotskoe earthquake (December 5, 1997), the Hokkaido earthquake (September 25, 2003), and the Sumatra earthquake (December 26, 2004). It is important that "bursts" before two of these earthquakes could be attributed to powerful atmospheric excitations in result of strong tropical cyclones in the North-West Pacific Ocean. They are: typhoon PAKA, November 27 - December 21, 1997 (Sobolev, 2011) and super-typhoon MAEMI, September 09-13, 2003, which was followed by two less intensive tropical cyclones in NW Pacific (Golovachev et al., 2011). The both powerful cyclones PAKA and MAEMI had the highest Category 5 SSHS with maximum wind velocities of 260 km/h and 280 km/h respectively. The third event of the "burst" oscillations before the strongest Sumatra M=9.1 earthquake on December 26, 2004 was assumed (Sobolev, 2011) to be attributed to another remote earthquake which occurred 3 days earlier (Macquarie earthquake, December 23, 2004, M = 8, 49.31 S–143.91 E, see Fig.1a) and any typhoons had not been taken into account. It was the cause what made this kind of earthquake precursors ambiguous (Sobolev, 2011).

Let us consider co-seismic processes preceding the Sumatra M=9.1 earthquake (Fig.1 a, b, Fig.2 b, and Fig.4 c) in more detail. Data from tiltmeters and strainmeters, which measure horizontal components of deformation, seem to be more appropriate for this goal than gravimeters, which measure vertical motions of the Earth surface (Section 2). Results of tilt measurements from Observatory Jezeri (Czech) obtained in November-December 2004 were taken for analysis. Two months of 10-minutes sampling data have been divided in two fragments of 30 days durations which are presented in Fig.5 (a, b). Peak-to-peak amplitudes of the semidiurnal tidal waves vary in the range of 0.2–0.4 msec and slightly irregular drifts of 0.1–0.2 msec per day are observed.

These fragments, each containing 4320 samples have been developed by computer spectral-temporal subroutine with 25% analyzed window. The results of Time-Frequency analysis of these data fragments are presented in Fig.5 (c, d). Diurnal and semidiurnal tidal waves are marked on both diagrams as two contrast horizontal bands at frequencies near 0.012 mHz and 0.022 mHz. Their maximum amplitudes vary between 0.03-0.04 relative units (see column to the right of each diagram). The November time-frequency diagram contains additionally the intense disturbance of spectral components at ultra-low frequencies beyond 0.003 mHz with amplitudes up to 0.1 relative units. This disturbance has probable strain-baric origin and may be related to occurrence of Intense Tropical Cyclone BENTO Category 5 (SSHS) in South-West Indian Ocean during November 19 – December 4, 2004. The peculiarity of December diagram consists in a special sort of disturbances with increasing frequencies from 0.002 mHz to 0.006 mHz during December 14-21, 2004. The amplitudes of spectral components have the order of tidal wave amplitude and they have appeared a few days just before the powerful earthquake into consideration. No more tropical cyclones with Category > 1 (SSHS) were observed in Pacific, Atlantic or Indian Ocean in the second half of December, 2004 while extra-tropical cyclonic activity was recorded by observatories in Europe and Asia in this period (http://www.eas.slu.edu/GGP/sumatra2004/). The spectral and temporal features of the considered eventual perturbations are similar to the other events of oscillation "bursts" mentioned in (Sobolev, 2011). Therefore, in the all three occurrences of powerful earthquakes (December 5, 1997; September 25, 2003; December 26, 2004) the hurricanes or typhoons were followed by the arising of the Earth oscillations. This result makes such kind of short-term earthquake precursor to be more attractive and sufficiently probable.

3.2. Global geophysical disturbances on March 15, 2013

The geophysical event-processes (ii) may have their origin in the Earth interior (earthquakes, volcanoes), in atmosphere and ocean (typhoons, hurricanes), as well as in ionosphere (geomagnetic storms, auroras), and in the space (sun flare and ejections, flight of comets or meteorites). All of them eventually may have sufficiently high power and bring considerable victims and destructions.

Let us consider the recent example of geophysical disturbances of extra-terrestrial origin, which have been recorded by spatially distributed instruments on March 15, 2013. Data from three measuring sites in the East Europe are presented: Geophysical Observatory Jezeri (Czech), IRE RAS Testing Site (Fryazino) and IZMIRAN Space Weather Prediction Center (Troizk, Moscow Region).

After the Last Quarter Moon on March 4, 2013 the Observatory Jezeri NS tiltmeter has recorded near a smooth sinusoidal semi-diurnal tidal wave with rising amplitude from 2 msec to 8 msec till the New Moon on March 11. The oscillating disturbances with 1-2 h periods appeared at smooth recording traces on March 14-15 (see Fig.6 a). The maximum 1-2 msec amplitude of these oscillations was observed between 12-14 h on March 15. The synchronous atmospheric pressure variations with opposite sign are clearly seen at the atmospheric pressure trace (Fig. 6 b) in Jezeri. Much more contrast irregular waves of atmospheric pressure with amplitudes up to 0.7-0.8 hPa were recorded in Troizk (http://forecast.izmiran.ru/) about two hours later and Fryazino about three hours later (between 14-16 h, Fig. 6 c, d).

Atmospheric conditions in two close sites Troizk and Fryazino were strongly correlated owing to powerful snowfall in Moscow region on March 15, 2013. The correlation of geophysical processes recorded at the remote sites (Czech - Moscow region) is indirectly confirmed by the comparison of geomagnetic data from Troizk (Fig. 7 a) and tiltmeter data in Jezeri (Fig. 7 b). The mentioned above low period disturbances on tiltmeter track being started at ~5h30m in Jezeri coincides with the beginning of magnetic field variations in Troizk (they are indicated by arrows in Fig. 7 a, b). Distance between these sites is near 1600 km; therefore geophysical processes in consideration may not to be attributed to any local phenomena. Similarly the spreading of irregular tilt-baric waves from Czech to Moscow region cannot be related to atmosphere motion: the value of signal retardation is too small to substantiate this way of its propagation. Existence of magnetospheric disturbances in the observed processes means that ionospheric layers have to be also involved (Dubrov and Smirnov, 2013) and extra-terrestrial phenomena origin would be quite probable. Indeed, it is the comet C/2011 L4 (PanSTARRS) transited between the Earth and the Sun on March 2013 that may ground the occurred situation. Comet PanSTARRS was closest to the Earth on March 5, 2013 (approach about $1.6 \cdot 10^8$ km) and it was closest to the Sun on March 10; since then it has been receding from the Sun and Earth, heading back to the outer solar system. During its transit in March 10-18, 2013 the geostationary satellite GOES15 of Space Weather Prediction Center (NOAA, USA, http://www.swpc.noaa.gov/index.html) recorded every day events of an arising X-ray flux. The maximum of those events occurred on March 15 and had outstanding intensity above $1 \cdot 10^{-5}$ $W \cdot m^{-2}$ this day (see Fig.7 c). The beginning of this X-ray event was happened in ~5h30m on March 15 and coincided with the start of geomagnetic variations and low-period disturbances in tiltmeter data (see arrows in Fig.7 a, b, c). Satellite GOES13 being 14° to the East on the geostationary orbit began to record the essential growth of proton flux after 19 h this day (see Fig.7 d). The synchronization of X-ray (c) variations detected at high space orbit together with ground-based magnetometer (a) and tiltmeter (b) is observed with small retardation, which is used to be a few orders greater for common solar occurrences. This moment has been critical for Troizk instruments - pressure and geomagnetic recordings were stopped this time (Fig.6c and Fig.7a) for 2 days. The growth of proton flux was being continued for 2 days, reaching above two order of magnitude with maximum level over 10 particles$\cdot cm^{-2} \cdot s^{-1} \cdot sr^{-1}$ and was finished by strong geomagnetic storm with Kp=6 on March 17. Furthermore, Friday March 15, 2013 was an unusual day also due to other events: besides the Troizk instrument irregularities, the operations of laser strainmeter (Fryazino), tiltmeter (Pribram, Czech), and X-ray receiver at GOES15 were partially broken too; heavy snow precipitations provoked many destructions and edifice fractures in Moscow Region this day.

4. Conclusion

The extended abilities of the wide-band tidal recording instruments for non-traditional geodynamic observations have been shown. Two specific examples of global high power processes in atmosphere and space are presented and their probable influence upon the Earth surface deformations has been manifested. The results have been obtained by using the system of simultaneously operating and spatially distributed wide-band tidal recording instruments: pendulum gravimeters, tiltmeters, and laser strainmeters. Such complementary information seems to be very important when poorly studied phenomena are investigated. The main feature of our approach is the simultaneous application of various spatial components of earth ground motion (vertical displacements, horizontal strains and tilts.)

Two types of background signals have been observed in ultra-low frequency band 0.002-0.5 mHz: (1) frequency modes of free Earth oscillations, and (2) the oscillations which are not identified with those modes. These signals being partially coherent could hamper the precise geophysical data acquisition. However the correct knowledge of those ground motions would bring the new technique for the Earth material testing. There is an opportunity to use atmospheric variations as sounding signal to study the elastic properties of the crust.

Comparison of spatially distributed ground-based data with accompanying processes in atmosphere, ocean and ionosphere seems to be presented at first time. We suppose that deployment of the detailed mechanism of the atmosphere and adjacent geospheres connections with processes in the solid crust would give a chance to understand the physical mechanisms of interaction of powerful processes at the Earth and in the Solar system, as well as to find the regularity and origins of such natural disasters as earthquakes and hurricanes.

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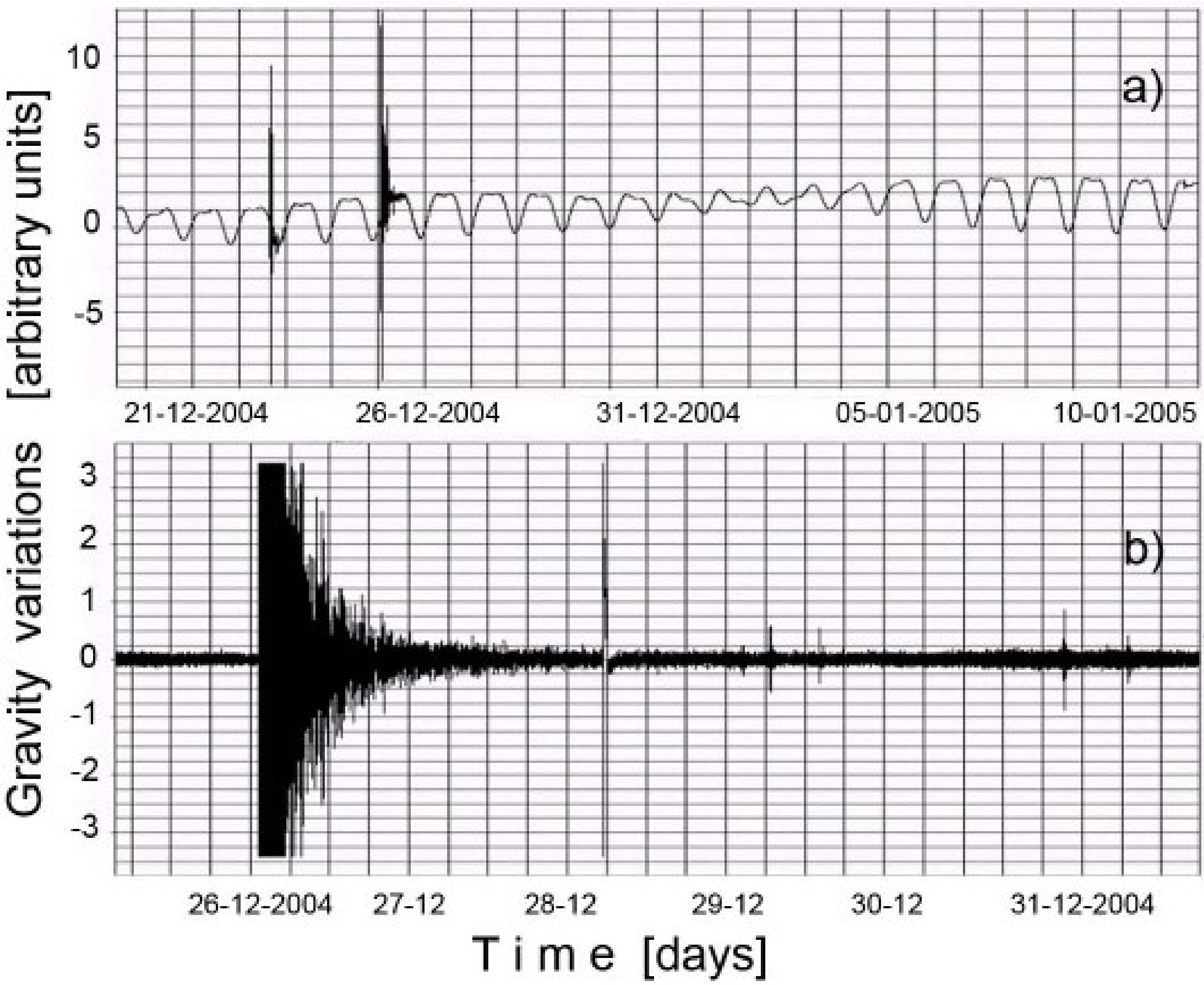

Fig. 1. Seismo-gravimeter records from Obninsk Geophysical Observatory: a) unfiltered tides together with Macquarie (December 23, 2004, M = 8) and Sumatra (December 26, 2004, M=9.1) earthquakes; b) acceleration channel, Sumatra, December 26, 2004, M=9.1 earthquake.

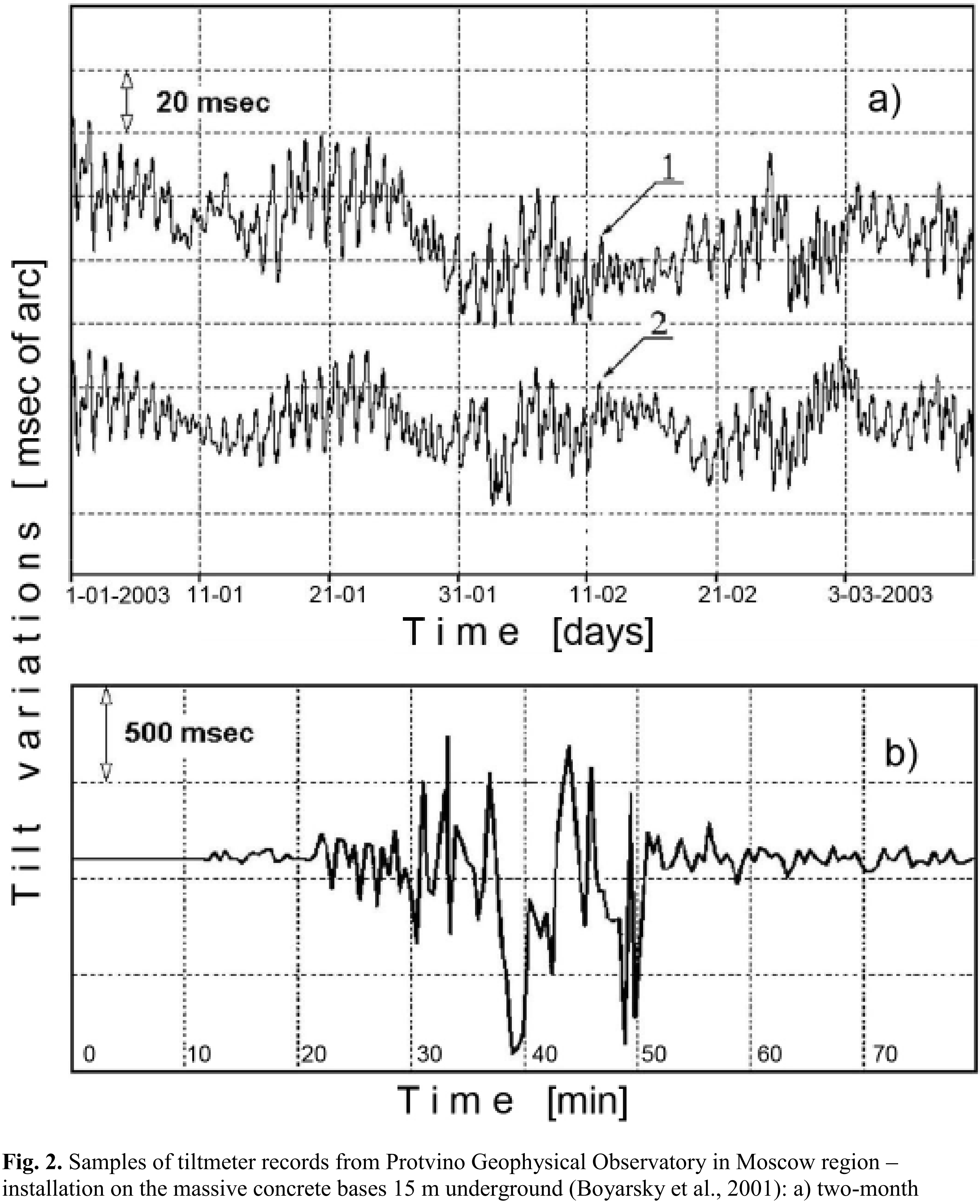

Fig. 2. Samples of tiltmeter records from Protvino Geophysical Observatory in Moscow region – installation on the massive concrete bases 15 m underground (Boyarsky et al., 2001): a) two-month unfiltered signal in tidal band (sensors 1 and 2 are located about of D=15 m apart); b) seismic channel, Sumatra, December 26, 2004, M=9.1 earthquake.

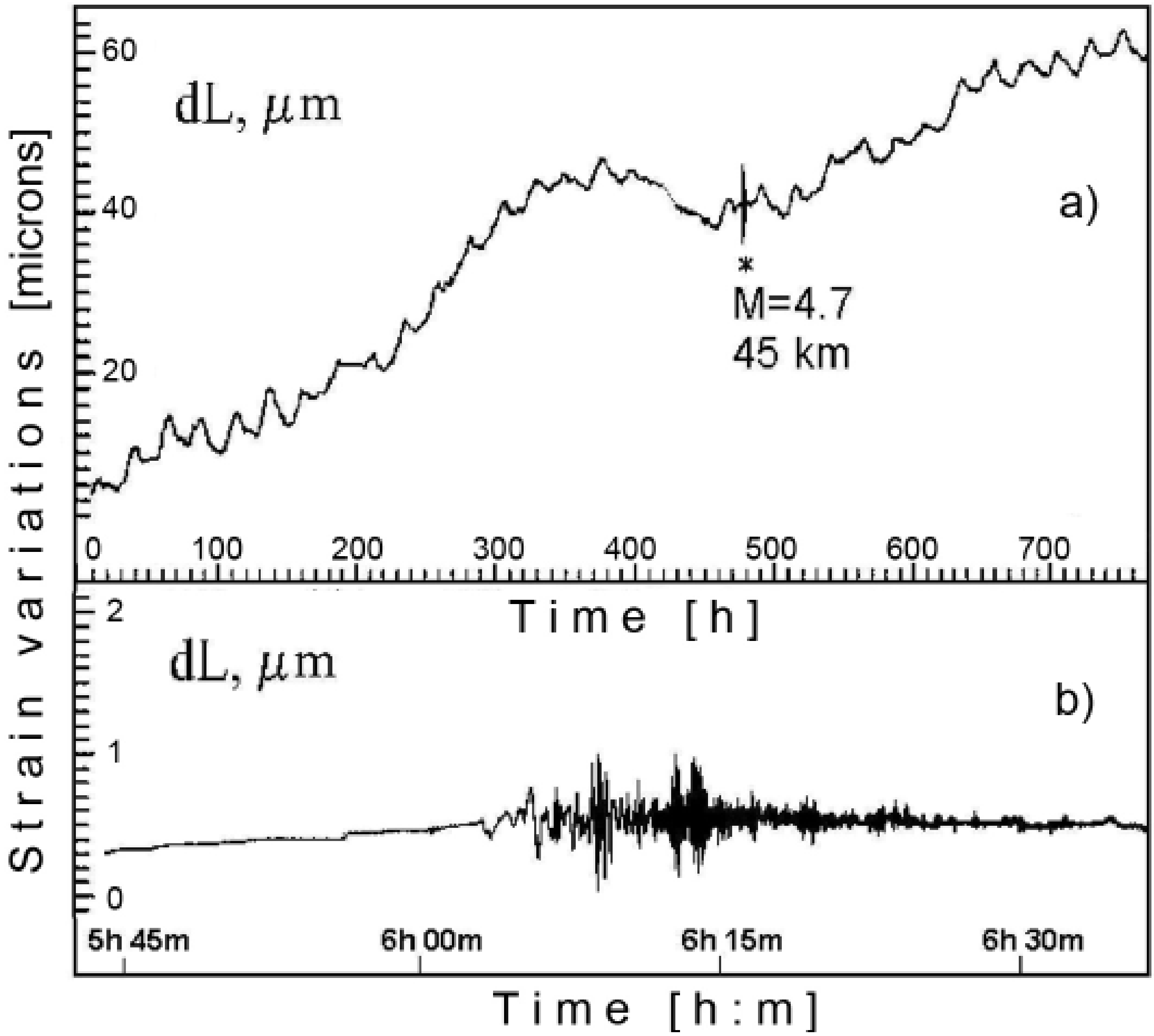

Fig. 3. Recordings made by two different laser strainmeters with 100 m measuring arms:
a) tidal-band deformations of the Earth surface (anomalous variation of a mean diurnal velocity of rock tension) before regional earthquake M=4.7 in Pamir (Dubrov, 2010); b) Laser extensometer (equal-arm interferometer at IRE RAS underground beam wave-guide, Moscow region) records the earthquake in Atlantics (Dubrov and Karmaleeva, 1976).

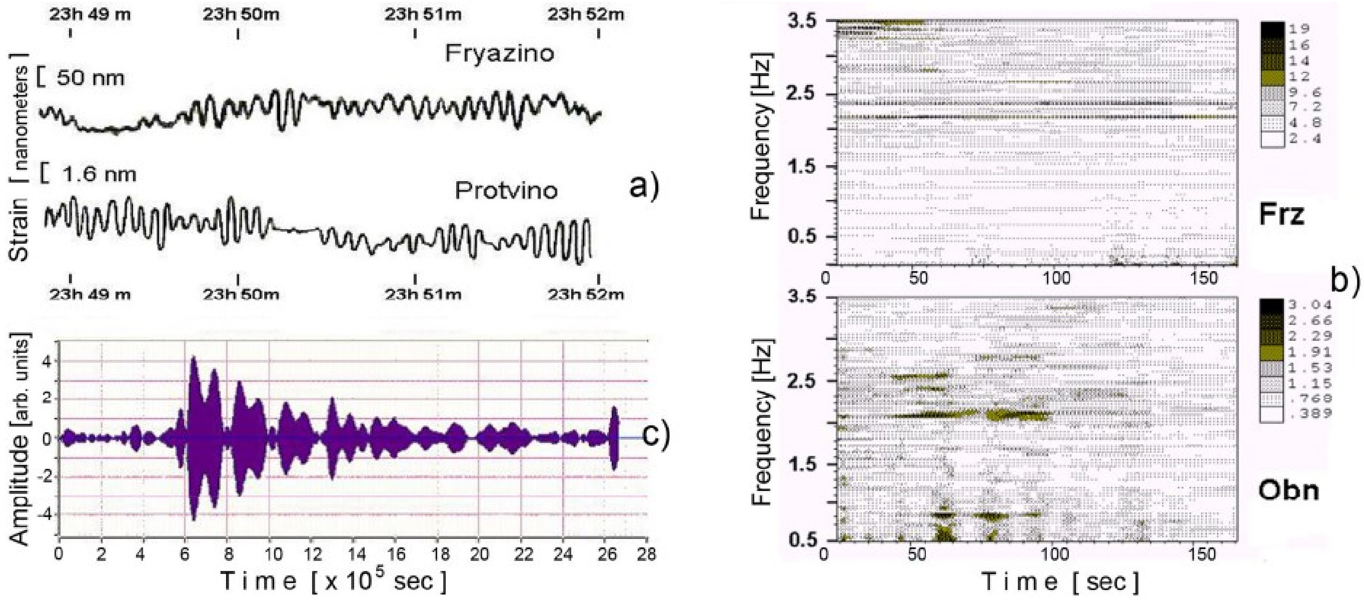

Fig. 4. Results of continuous (i) and event (ii) processes registration:
a) long-path laser strainmeter in Fryazino (500 m) and Protvino (16 m) synchronous records of storm microseisms from Atlantics; b) time-frequency diagrams of high frequency microseisms detected by laser strainmeters in Fryazino (Frz) and Obninsk (Obn); c) free oscillations of the Earth in frequency band of the fundamental mode $_0S_2$ recorded by seismo-gravimeter in Obninsk during December 20, 2004 – January 22, 2005

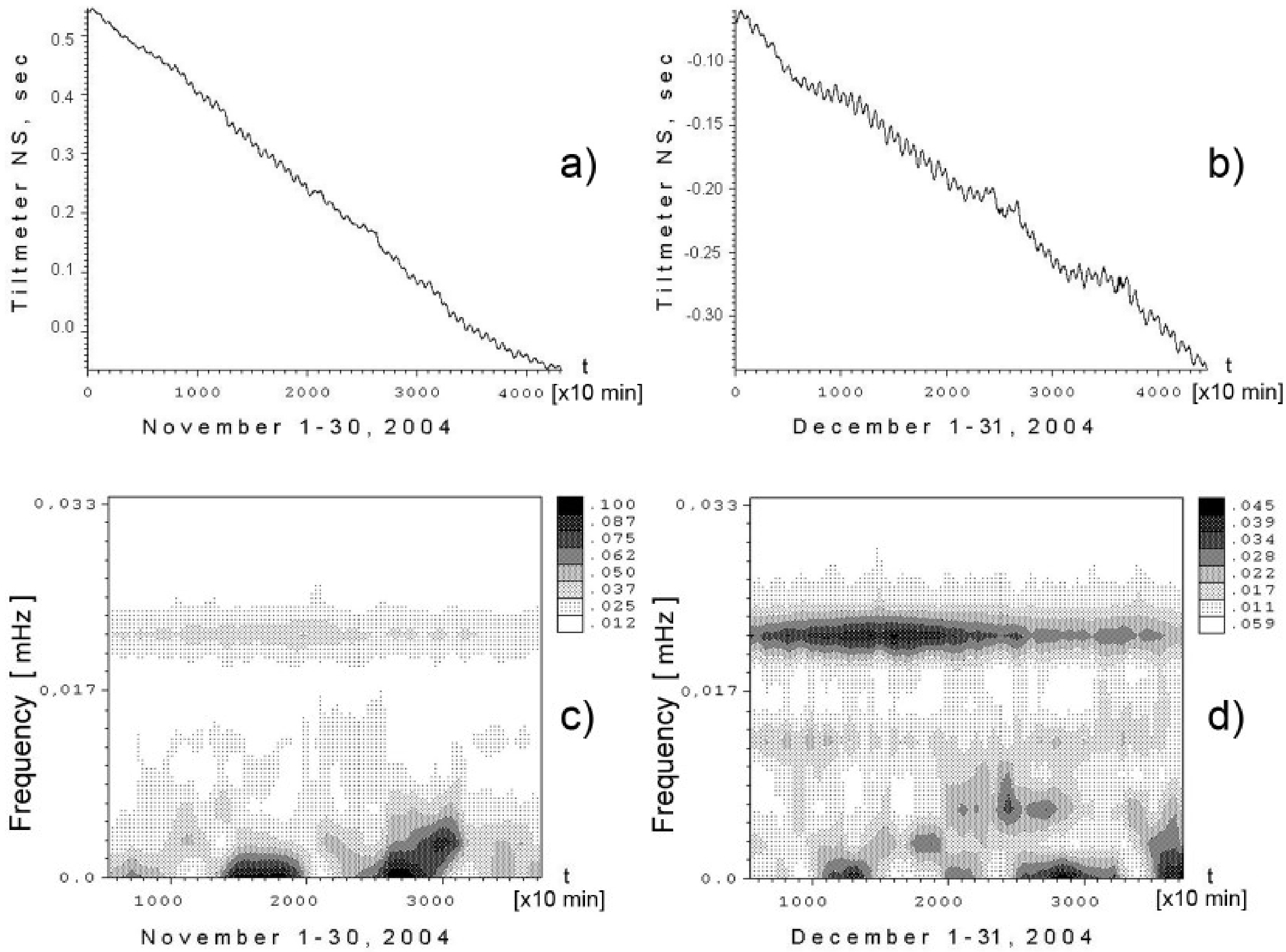

Fig. 5. Tiltmeter records from Observatory Jezeri-2 (NS component) during November 01 – December 31, 2004 (a, b) and time-frequency diagrams for corresponding periods (c, d); growth of spectral component intensities near 0.002-0.006 Hz in the second half of December is clearly seen.

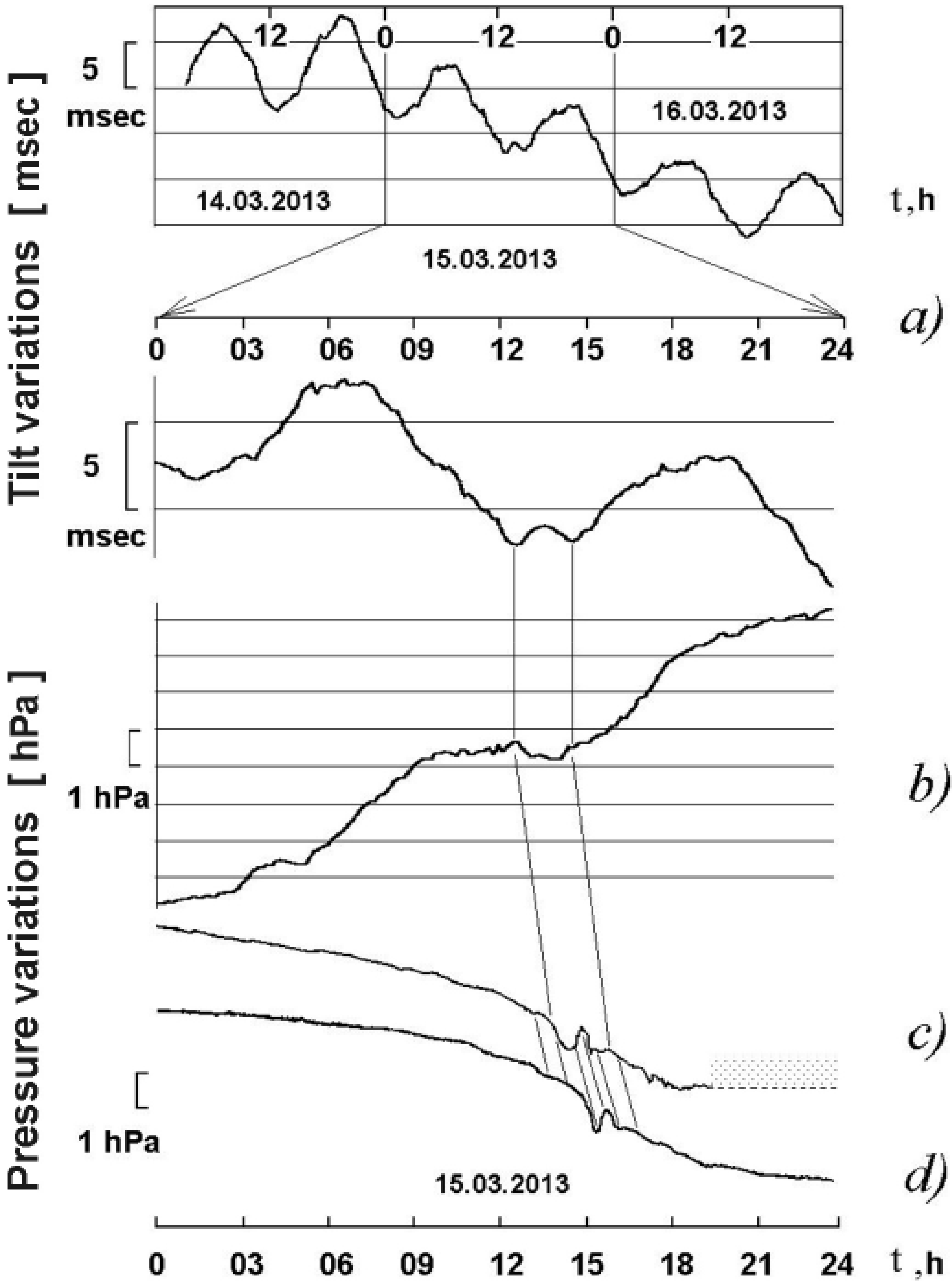

Fig. 6. Global disturbances recorded on March 14-16, 2013: tiltmeter (a) and atmospheric pressure (b) in Observatory Jezeri; atmospheric pressure in Troizk (c) and Fryazino (d).

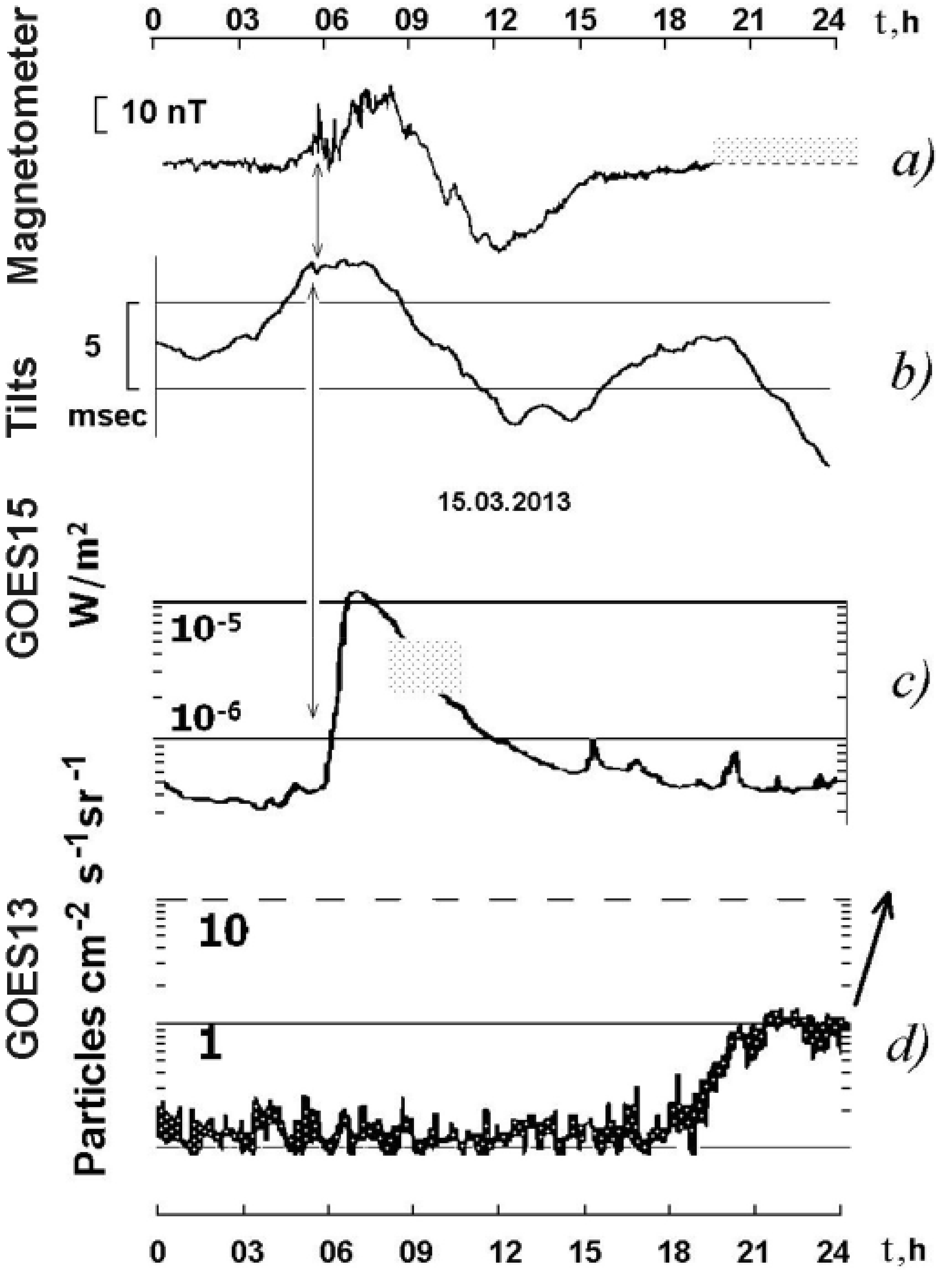

Fig. 7. Geomagnetic and ionosphere disturbances recorded on March 15, 2013: a) magnetometer in Troizk; b) tiltmeter in Observatory Jezeri; c) X-ray flux, satellite GOES15; d) proton flux, satellite GOES13.