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A NEW APPLICATION OF DATA REGISTERED BY MODIFIED WATER-TUBE TILTMETERS INSTALLED IN THE GEODYNAMIC LABORATORY IN KSIĄŻ (SW POLAND) IN TERMS OF RECENT GEODYNAMIC ACTIVITY

The Książ Geodynamic Laboratory is a unique research centre, both nationally and globally, conducting a comprehensive research program in the field of Earth sciences. It primarily focuses on studying tidal and non-tidal phenomena using water-tube tiltmeters. Over the past decade, the Laboratory has developed a research program aimed at predicting seismic events (strong seismic shocks with a magnitude of ≥3.6 of natural origin) by analyzing changes in stress conditions within the orogen. The modification of the water-tube tiltmeter recording system proposed in this article will significantly enhance the quality of ongoing research. First and foremost, modernis ation of the water-tube tiltmeter detector will increase the instrument's sensitivity by two orders of magnitude, enabling the measurement of water level changes at the picometer scale. Equally important, the upgrade will allow real-time data acquisition. This feature is critical for the practical application of observations, as real-time results can be used to forecast the risk of strong seismic shocks in two key Polish mining regions: the Upper Silesian Coal Basin and the Legnica-Głogów Copper District. Previous studies based on archival data (2013-2017) have confirmed the high effectiveness of this forecasting procedure (>95%). The insights gained will undoubtedly contribute significantly to mitigating seismic hazards in underground mines.

Keywords: Water-tube tiltmeters; geodynamics; seismic activity; tectonic activity; Geodynamic Laboratory in Książ; Świebodzice Depression

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1. Introduction

At the turn of the 20th and 21st centuries, the research centre in Książ was officially named the Geodynamic Laboratory of the Space Research Centre of the Polish Academy of Sciences (GL SRC PAS). In the previous 30 years, starting in 1974, SRC PAS conducted observations of tidal variations in vertical inclination. With the courtesy of the Institute of Geophysics of the Polish Academy of Sciences, SRC PAS utilised the underground facilities of the Geophysical Observatory belonging to the Institute. In 1974-1975, the first tidal instruments - quartz horizontal pendulums (HPs) with a sensitivity of approximately 1 milliarcsecond (MAS) were installed on concrete shelves cut into the corridor walls [1,2]. Tidal observations in the aspect of vertical inclination were conducted by Prof. T. Chojnicki, who used his proprietary analysis program to process data obtained from a horizontal pendulum. The collected observations enabled studies on tidal effects, interactions between Earth and ocean tides, resonance of diurnal tidal waves, and the determination of a local tidal ephemeris [2,3]. Additionally, pendulum measurements were used to study long-term variations in the aspect of vertical inclination in the Sudetes region and to analyse strong non-tidal vertical inclination signals caused by tectonic deformations of the Świebodzice Depression orogen.

For 30 years, the research conducted by SRC in Książ focused primarily on tidal phenomena. It was not until April 1997, with the initiation of modernisation efforts, that the installation of new instruments became possible, allowing for an expansion of the research scope to include non-tidal phenomena. A designated area within the underground facilities of the Geophysical Observatory was established and named the Geodynamic Laboratory (GL). Modernisation efforts were carried out to upgrade the Laboratory's research infrastructure. The power supply system was significantly enhanced, as the previous energy capacity was insufficient to support instruments requiring a stable power source. Additionally, the modernisation included the implementation of an internet connection linking the underground facilities of GL with the SRC Institute in Warsaw.

The valuable scientific results obtained from 30 years of continuous horizontal pendulum measurements, along with the favorable architectural conditions of the underground corridors – namely, horizontal, straight corridors approximately 100 meters long and perpendicular to each other (Fig. 1) as well as the geologically active tectonic surroundings and the modernized research infrastructure of GL, determined the decision to construct two water-tube tiltmeters (WTs). The installation and execution of WTs in 2003 opened new research directions at GL. These include the study of non-tidal phenomena, such as tectonic effects and medium- to high-frequency signals (~10^{-4} Hz), including Earth's free oscillations and infrasound signals [4-8]. This research was further enriched by geochemical studies on radon concentration variations in the laboratory's underground environment [9-11] and instrumental comparative studies between horizontal pendulums and water-tube tiltmeters [3]. Additionally, the geological conditions of the GL surrounding and the highly faulted orogen of Książ enabled the development of tectonic research based on kinematic measurements of the Książ rock mass, driven by the tectonic activity of the rock blocks associated with the installed instruments [4-7].

Long-term horizontal pendulum measurements have simultaneously confirmed the high stability of the concrete structures in the underground corridors (concrete lining). The installation of water-tube tiltmeters in the Laboratory has resulted in the ability to measure vertical inclination at GL using two different types of tiltmeters, each employing a distinct measurement method. This has created unique opportunities for conducting instrumental comparative studies between horizontal pendulum and water-tube tiltmeters [3].

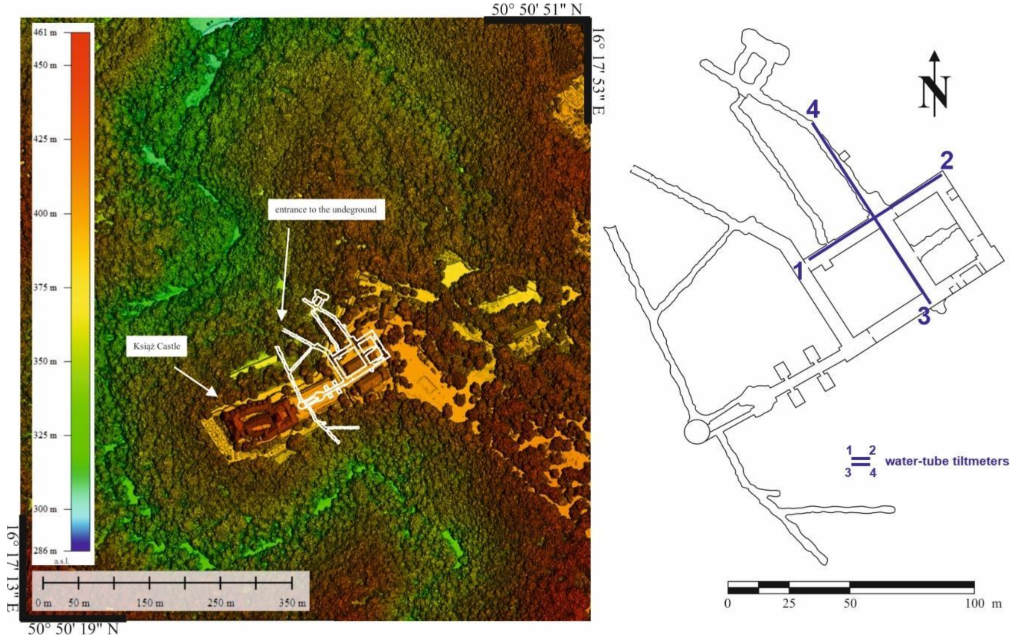

Fig. 1. The Geodynamic Laboratory in Książ: the plan of the underground complex and localisation of water-tube tiltmeters

In the close vicinity of the underground laboratory, two permanent GNSS stations were installed in 2006 and 2013. These stations are used to monitor the movement of the main tectonic structure (tectonic fault) surrounding the GL, known as the Southern Fault [4,7]. The development of the instrumental setup at GL in Książ has expanded the measurement capabilities related to phenomena associated with the tectonic activity of the region. This is particularly relevant to monitoring seismic activity, as strong shocks have been recorded in neighbouring geological-tectonic units across Poland, the Czech Republic, and Germany, reaching magnitudes of up to 4.8 [12-14]. The modernisation of the WTs measurement modules (the main topic of the article) will shorten the time required for data processing operations and automate the process. Additionally, the modernisation will enhance the sensitivity of the measuring instruments.

2. Natural conditions – geology of the Świebodzice Depression

The Świebodzice Depression is a distinct geological-tectonic unit within the Sudetes. Its area, compared to other units within the Sudetes, is relatively small, covering approximately 100 km^2 (Fig. 2).

The Świebodzice Basin has a rhomboidal shape, with its longer axis oriented in a NW-SE direction. The tectonic structures that define its boundaries include the Sudetic Marginal Fault (to the east), the Szczawienko Fault (to the south), the Struga Fault (to the west), and the group of tectonic structures of the Kaczawa Mountains (to the north). A dense network of surface discontinuities is also a characteristic feature of the internal structure of the unit itself [15-21].

The Świebodzice Depression is primarily filled with folded sedimentary formations, which are dated to the Upper Devonian to Lower Carboniferous period. In some areas, their thickness reaches up to 4,000 meters [22]. It is also important to note that the Upper Devonian deposits

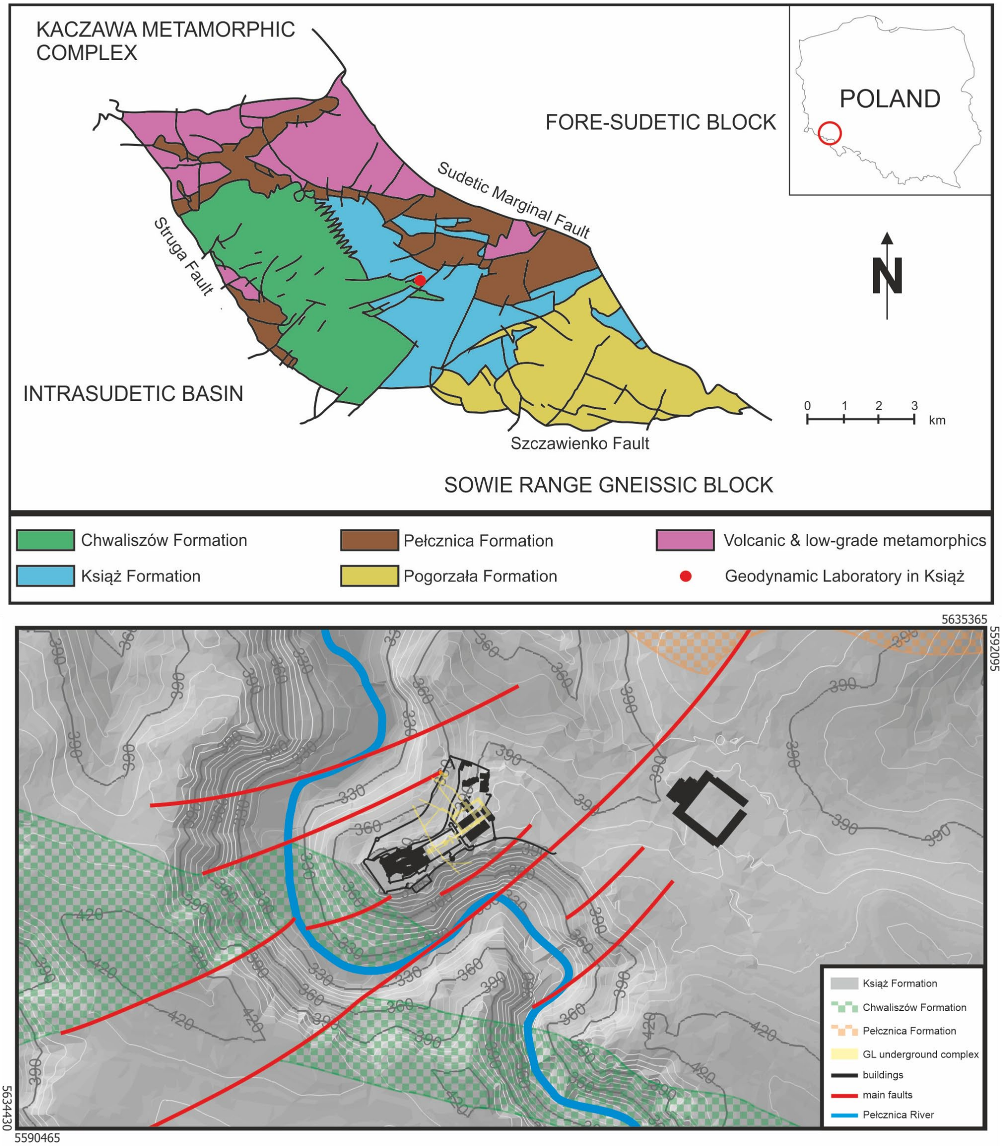

Fig. 2: Geological setting of the Geodynamic Laboratory in Książ: (top) general geological sketch of the Świebodzice Basin; (bottom) geological map of the surroundings of the Książ Geodynamic Laboratory (after [28])

are considered synorogenic formations [23], which were uplifted during the Variscan orogeny, although they were not directly subjected to the main folding events of this orogeny in the Sudetes region. Among the sediments filling the Świebodzice Basin, four main groups (lithostratigraphic units) have been identified: the Pogorzała Formation, the Książ Formation, the Chwaliszów Formation, and the Pełcznica Formation [24].

The model of clastic material transport and accumulation was thoroughly described by [25-27]. According to this model, sedimentary layers can generally be characterised as sequences formed in a marine sedimentary basin in the submarine segments of deltaic fan systems. The main source of material for these layers was the alluvial fans located at the foreland of the forming tectonic depression.

3. The construction and operating principles of the water-tube tiltmeters installed at the Geodynamic Laboratory in Książ

Water-tube tiltmeters are tidal instruments, meaning they measure angular changes in the vertical reference line relative to the rock mass to which they are rigidly attached. The two tiltmeter arms, designed and constructed by M. Kaczorowski [29,30] and currently operating at the Geodynamic Laboratory in Książ, utilise the fundamental property of liquids – specifically, water – that they naturally assume a position where their free surface aligns with the local, instantaneous equipotential surface. Any inclination of the equipotential surface relative to the liquid causes the vertical reference line (the direction of gravitational field forces) to deviate from being perpendicular to the water's surface. At this point, tangential forces act upon the liquid surface, attempting to reposition the water to a new equilibrium state where its surface once again conforms to the modified equipotential surface. This adaptation process, in which the water surface continuously responds to changes in the vertical reference line, is ongoing and continuous [31].

3.1. Main elements of the construction of the measurement system of the water-tube tiltmeters

The water-tube tiltmeters installed in Książ consist of two main components. The first component comprises two tubes measuring 65.24 m and 93.51 m in length, arranged at a 90° angle to each other, with azimuths of –121.4° and –31.4°, respectively (Fig. 3). The low-pass damping systems used in the tiltmeters allow for the recording of long-period signals in the frequency range of 10^{-3} to 10^{-4} [Hz], even tens of minutes after the occurrence of high-frequency seismic signals [8].

The second main component of the measuring instrument consists of classic Newtonian interferometric gauges equipped with frequency-stable He-Ne lasers, positioned at both ends of each tube. Measurements are conducted relative to the surface of reflective lenses submerged in water. The type of glass used in the lenses prevents deep light penetration while simultaneously protecting against secondary reflections (Fig. 4). The phase analysis of interferometric images applied in the study ensures measurement accuracy of water level changes within the range of single nanometers, i.e., 10^{-9} m.

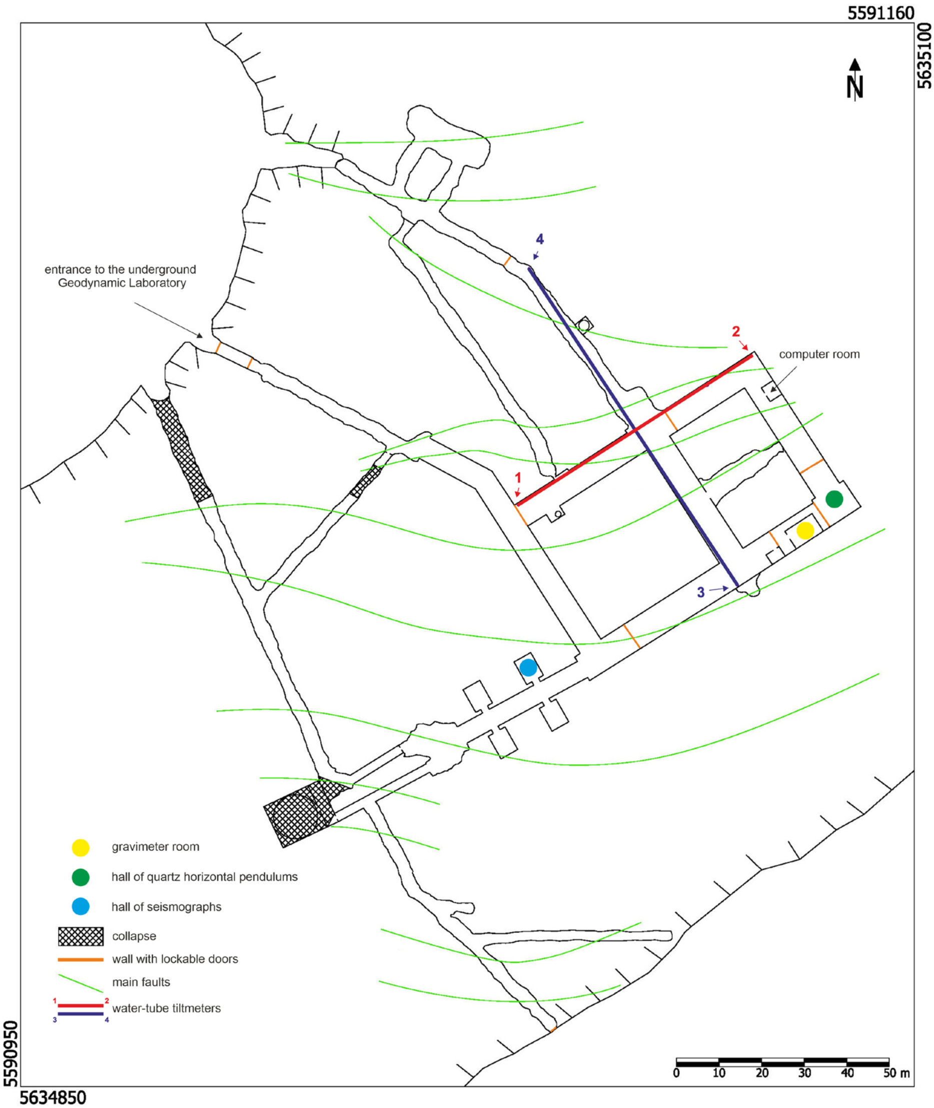

Fig. 3. Detailed plan of the underground corridors of the GL in Książ with marked location of water-tube tiltmeters

3.2. Metrological properties of the interferometric measurement system currently used in water-tube tiltmeters

The properties of the developed hydrodynamic system of the water-tube tiltmeter enable the registration of geodynamic signals in the frequency range from 5×10^{-3} Hz to infinity without significant phase delays. This means that the instrument responds to and records the effects of geodynamic phenomena (tilts and vertical ground movements) in real time. The tiltmeter tubes

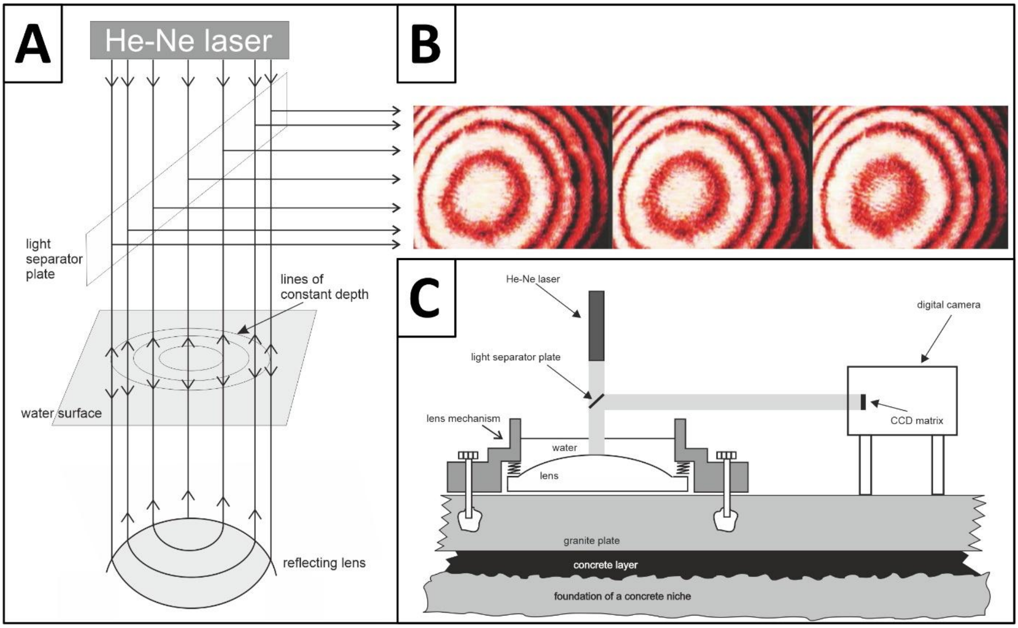

Fig. 4. (A) Main optic elements of interferometer applied in WT; (B) series of image of Newtonian rings of red color laser He-Ne of 632.8×10^{-9} [m] length of light – situation depicts a decrease in the water level above the reference lens; (C) the reflected lens fastening to the rocky foundation and some elements of the water-tube tiltmeter on the measurement platform

are half-filled with water, ensuring a free liquid surface along the entire length of the tubes, while also minimising the effect of thermal expansion [3,31].

The measurement modules, which are interferometric sensors are installed at the ends of both WTs on specially designed shelves. Each module consists of a base, a plano-convex reference lens that reflects light, a laser, a beam-splitting plate, and a recording system with a CCD camera (cf. Fig. 4C).

A He-Ne laser beam with a wavelength of 632.8 nm is directed perpendicularly onto the water surface and the submerged reference lens. The laser light reflects off the lens and interferes with the light reflected from the water's surface. The reflected beams, after interference and reflection from the beam-splitting plate (cf. Fig. 4A), form an interferometric pattern of Newton's rings on the CCD camera sensor (cf. Fig. 4B). The interferometric images of Newton's rings are transmitted to a computer and recorded on a disk [32].

Newton's rings correspond to isolines of the water layer depth above the reference lens. The change in the thickness of the water layer that results in the formation of a new Newton's ring is determined by the ratio $\lambda/2n$.

For a He-Ne laser wavelength of $\lambda = 632.8 \times 10^{-9}$ m and a water refractive index of $n = 1.33$, the water level change corresponding to one Newton's ring is 2.38×10^{-7} m.

The developed WT design allows for the measurement of the distance between consecutive rings with a relative accuracy of 1% (equivalent to a few degrees of phase accuracy in the interferometric image).

Applying formula (1), it follows that the accuracy of water level change measurements is no worse than 2,38×10^{-9} m and equals:

$$\Delta = 0{,}01(\lambda/2n) \tag{1}$$

where:

λ – wavelength of laser light,
n – value of the refractive index for water [29,31].

4. Project for the modernisation of the water-tube tiltmeters measurement module – the possibility of processing geodynamic signals in real-time

The proposed modernisation of the WT measurement module does not require a complete overhaul of the existing hydrodynamic system of the instrument. This system is made of highly durable plastic materials. In the current solution, each WT measurement module is equipped with a He-Ne laser. The main disadvantage of this setup is the thermal interference in the measurement chamber area caused by the heat generated by the laser itself. The use of optical fibers will distance the laser from the measurement chambers, effectively resolving the thermal interference issue with the tiltmeter. The laser light will be delivered from a single central laser, transmitted through optical fibers to the four WT measurement modules.

The laser measurement system used in the modernised WT will be designed in a digital version, utiliing the latest advancements in interferometric measurement techniques. The measurement system will feature a dual-frequency laser interferometer operating in a heterodyne configuration within the 1 GHz range. This approach will allow for noise reduction proportional to the inverse of the frequency (1/f), enhancing the measurement resolution to 50 picometers (50×10^{-12} meters).

The device will be featured with a dual-frequency He-Ne laser with frequency stabilisation using a liquid crystal ferroelectric cell that is surface-stabilised (Patent PL 175589). This solution will ensure laser frequency stability at the level of 1×10^{-9}. Potential influences of water temperature changes on the optical path length will be automatically compensated for through humidity, temperature, and pressure sensors, as well as the implemented software procedures. The reference system of the interferometer (the so-called reflector) will be designed to minimise the impact of ambient temperature changes on the positioning of optical elements, thereby reducing thermal errors in the determination of water level changes.

The measurement results of water level changes will be transmitted directly to the computer's memory and saved in text files containing, among other things, the values of water level changes expressed in nanometers and the measurement time (each record will correspond to one entry in the measurement database). The software of the new instrument will allow programming of the measurement interval up to a frequency of 100 Hz, as well as management of data acquisition. The recording program will enable the adjustment of the sampling frequency in case of rapid geodynamic phenomena, such as seismic events.

In the new measurement system, registering any graphic files is not expected, which will significantly reduce memory usage for observational data. The measurement results, i.e., the instantaneous water level, will be provided digitally in real-time. It is expected that the data will be automatically stored during the continuous operation of the system for up to one year.

5. Scientific and practical aspects of using water-tube tiltmeters resulting from the modernisation of the WT for geodynamic signal interpretation

The new measurement capabilities obtained through the modernisation of the WT system, such as:

- real-time measurement of water level changes,
- sampling frequency of up to 100 Hz,
- a two-order-of-magnitude improvement in measurement accuracy,

have a significant impact on both the research and application potential of this measuring instrument. As a result of the WT modernisation, there will undoubtedly be a development of research directions in the Geodynamic Laboratory in Książ [8].

Increasing the sampling frequency to 100 Hz will enable the registration of seismic phenomena and improve the determination of the Earth's free oscillation signals [31]. The two-order-of-magnitude increase in the sampling frequency will allow for the development and interpretation of non-tidal harmonic signals and high-frequency signals (10^{-3} Hz), which are generated by the Earth's free oscillations, as well as very low-frequency atmospheric signals – infrasounds recorded by WT using the so-called reverse barometer effect method [5].

The modernisation of WT (increase in sensitivity and sampling frequency) will also contribute to the development of research on tidal phenomena (10^{-4} Hz), including the determination of geodetic coefficients from time series: gravimetric and clinometric [29,30,33]. Tidal research encompasses studies on the effects of annual and semi-annual modulation of oceanic tidal waves, as well as investigations into intermediate oceanic loading and gravimetric effects. The modernisation of WT enables the study of Earth's core nutation and the resonance of diurnal waves.

One of the tidal phenomena with significant practical importance is the determination of Love numbers h and k based on gravimetric and clinometric geodetic coefficients. In the few observatories where both gravimetric and clinometric observations are conducted simultaneously, the determination of Love numbers h and k is carried out [34-36].

Love numbers h and k, which describe the Earth's deformational properties, have applications in various fields, including space technologies (such as satellite navigation), the design of artificial satellite orbits, and studies of the Earth's interior and its motion.

Increasing the accuracy of water level change measurements from ~3.5 nm to 5×10^{-2} nm corresponds to an improvement in the measurement accuracy of vertical inclination changes to 2×10^{-2} [MAS] for pipes with lengths of 65.24 m and 93.51 m in a measurement system based on dual-frequency heterodyne interferometers.

In the old measurement system, additional errors were generated by algorithms used to determine the phase of Newton's rings. The new solution allows for:

1. Eliminating the time-consuming process of analysing interferometric images, i.e., reading brightness cross-sections and determining the phase of Newton's rings before calculating water level changes in nanometers.
2. Obtaining observation results directly in numerical form in real-time.
3. Ensuring the continuity of phase changes and maintaining continuous recordings of rapid geodynamic phenomena, such as seismic effects and Earth's free oscillations, by increasing the sampling frequency to 100 Hz.
4. Minimising disk space usage, with results saved in text files.

What is particularly important from the perspective of one of the most rapidly developing research directions, the modernisation of the WT measurement system enables the empirical verification of the hypotheses presented in Kaczorowski's [14] publication.

Among these hypotheses, the most significant is the concept of a large-scale tectonic stress field encompassing both the Czech region and southwestern Poland (while the actual extent of this field is likely much larger, based on the hypotheses proposed in the previously mentioned, the conducted experiments, and the obtained and interpreted results, the authors of this study prefer not to extend beyond the current state of knowledge).

This hypothesis explains the existence of detected coincidences between the phases of low deformation rates of the Świebodzice Depression orogen and the temporal distribution of seismic events in the Fore-Sudetic Monocline, particularly in the area of underground mining operations carried out by KGHM Polska Miedź SA.

6. Example of the applicability of geodynamic signal research conducted in the Książ Geodynamic Laboratory

A comparative analysis of the tectonic activity of the Świebodzice Depression orogen and seismic events recorded between 2016 and 2019 in the neighbouring geological-tectonic units revealed that over 95% of high-energy seismic shocks (Mag $\geq$ 3.6) occurred during epochs of low values of the derivative of the so-called Tectonic Activity Function (TAF) proposed by Kaczorowski et al. [14]. These correspond to epochs of low deformation rates of the Świebodzice Depression orogen. It was observed that the fulfilment of the low TAF derivative condition improves as the energy of the seismic shock increases. Conversely, during epochs of high deformation rates (i.e., high values of the TAF derivative), no high-energy seismic events were recorded in the studied period. Examples of these coincidences are illustrated in graphs of the TAF derivative and the temporal distribution of seismic events in the fourth quarter of 2016 (Fig. 5).

The TAF function method will achieve practical applicability after the modernisation of the WT recording process, enabling real-time determination of the TAF function and the current phase of the compression-extension process. The extension phases (characterised by low derivative values of TAF) are associated with periods of increased susceptibility of the rock mass to failure (Fig. 5). This is the time when an earthquake is more likely to occur, making it a highly suitable period for effective stress relief measures in the rock mass.

The modernisation of WT will enable the practical application of the detected observations in the current seismic hazard forecast for mining areas, including the Legnica-Głogów Copper District (LGOM; Poland), Upper Silesia (Poland), and the northeastern part of the Czech Republic. This will significantly enhance the ability to predict seismic risks and improve safety measures in these regions.

Due to the social and economic implications of tectonic activity in the Earth's crust and the associated geohazards in mining, the proposed method could have practical applications in the existing monitoring system for such phenomena. It is crucial to highlight that predicting earthquakes is a key objective of global geodynamics research. This makes the method particularly valuable for improving seismic risk management and safety protocols in mining regions.

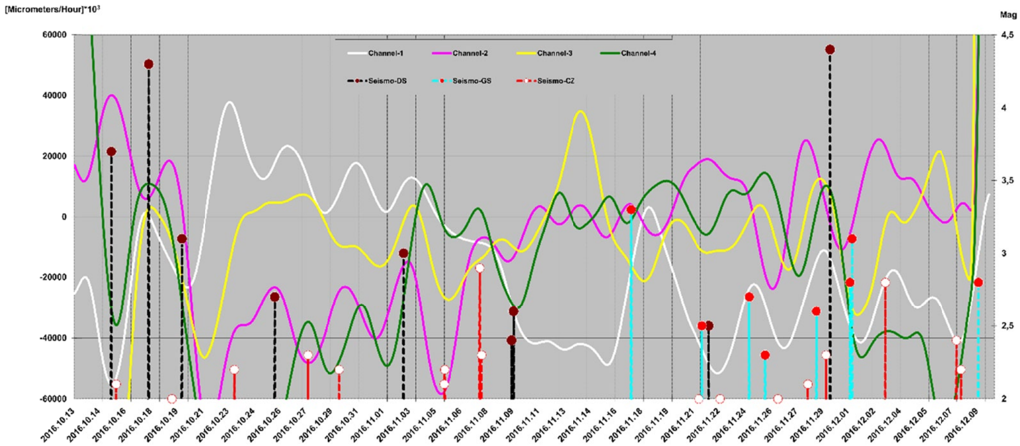

Fig. 5. The derivatives of the Tectonic Activity Function and seismic activity in 2016 highlight significant seismic events in different geological units. The analysis marks seismic shocks in the areas of the Fore-Sudetic Monocline (Seismo-DS), the Upper Silesian Basin (Seismo-GS), and the Bohemian Massif (Seismo-CZ). Special attention should be given to three tragic seismic events in mines: "Rudna" Mine – 4.3 Mag (October 17, 2016), "Lubin" Mine – 3.1 Mag (November 3, 2016), "Rudna" Mine – 4.4 Mag (November 29, 2016)

7. Conclusions

The Geodynamic Laboratory in Książ is currently one of the few centres in the world boasting a unique set of measuring instruments. The dominant research program at the Laboratory is tidal effects, utilising two classes of instruments, with a comparative measurement series spanning over 20 years (for horizontal pendulums and water-tube tiltmeters, with the horizontal pendulums alone having a near 50-year measurement series). This long history of measurements provides invaluable data for understanding geodynamic phenomena.

One of the latest research directions is the study of forecasting strong seismic shocks of natural origin, for which the epicentre locations are closely associated with underground mining areas in southwestern Poland and northeastern Czech Republic (specifically in the Legnica-Głogów Copper District and the Upper Silesian Coal Basin).

This research program uses complementary observations of two types of phenomena, monitored by two types of instruments. The first type involves changes in radon-222 concentration, detected by SRDN-3 probes. The second type focuses on interpreting changes in the stress state of the rock mass based on data from water-tube tiltmeters. This approach provides valuable insights into the relationship between mining activity and seismic events, improving the ability to predict potential hazards.

The proposed modernisation of the water-tube tiltmeter registration system (modifying the detector setup, data processing, and archiving) will not only enhance the instrument's sensitivity but also enable the real-time acquisition of observation results. This second element is particularly critical due to the urgency and significance of the phenomena being observed.

The research conducted thus far, as published by Kaczorowski et al. [14], has achieved an impressive success rate of over 95% in predicting significant seismic shocks in the LGOM area.

With the proposed modification, a warning system can be designed and implemented (e.g., procedures for the safety of underground mine workers) in the event of a predicted seismic shock, ensuring maximum safety conditions. This advancement represents a crucial step in improving the predictive capabilities and safety measures in mining regions affected by seismic hazards.

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