Current use of Eötvös Torsion Balance, the tidal effect

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ABSTRACT: In the 20th century, many torsion balance measurements had been carried out around the world. The measurements still provide a good opportunity to detect the lateral underground mass inhomogeneities and the geological fault structures using the so called edge effects in gravity gradients. Usually, the horizontal gradients were used for geophysical prospecting, but the curvature gradients measured by torsion balance remained unused. However, curvature gradients are instrumental data in geodesy, using these gradients, precise deflections of the vertical can be calculated by interpolation and the fine structure of the potential surfaces of the Earth can be derived. Based on the horizontal and the curvature gradients of gravity, the full Eötvös tensor (including the vertical gradients) can be derived by the 3D inversion method. Application of torsion balance is also important in physics. Lorand Eötvös and his colleagues Dezső Pekár and Jenő Fekete executed a series of measurements (EPF experiment) from 1906 till 1908 to validate the equivalence of gravitational and inertial mass. Repeating this experiment by using a 90 years old, high precision torsion balance, but under better conditions with and applying the current modern technology for enhancing the precision, exposing and filtering out tiny environmental disturbances and barely perceptible flaws in instruments is a big challenge today..

Keywords: torsion balance, gravity gradients, Eötvös-experiment

1. Base principle of torsion balance

The *Eötvös torsion balance* (TB) was constructed and tested at the end of the 19th and the beginning of the 20th century by the Hungarian physicist Loránd Eötvös [1-3].

The torsion balance consists of a horizontal beam having the length 2l with masses m on each ends suspended from a torsion wire. One of the two masses is affixed to one end of the horizontal beam, while the other mass is suspended below the other end of the beam, on a wire of length h – as it can be seen on Fig. 1. The horizontal component of gravity acting on the two masses causes a torque, and the horizontal beam is rotated until an equilibrium position with the restoring torque of the suspending torsion wire (having the torsion constant τ) is reached. In the equilibrium condition of torques the scale reading is n, while the scale reading of the torsion-free zero position of the beam would be n_0 [4, 5].

The base equation of the Eötvös torsion balance is:

$$n - n_0 = \frac{DK}{\tau}\left(W_\Delta \sin 2\alpha + 2W_{xy}\cos 2\alpha\right) + \frac{2lDhm}{\tau}\left(W_{zy}\cos\alpha - W_{zx}\sin\alpha\right)$$,(1**Hiba! A könyvjelző**

where W_{zx} and W_{zy} are the horizontal gradients of gravity, W_Δ (W_Δ=W_{yy}–W_{xx}) and W_{xy} are the curvature gradients, K is the moment of inertia, α is the azimuth of the beam and D is the optical distance (see on Fig. 1). The earlier type of instrument is the *Cavendish* torsion balance, in which the two masses are on the same height on the two ends of the beam [4, 5]. This type of instrument is unable to measure the components of *horizontal gradient* W_{zx} and W_{zy}, because h = 0 in Eq. (1).

Based on Eq. (1) there are five unknowns (the scale reading of the torsion-free zero position n_0, the horizontal gradients W_{zx}, W_{zy} and the curvature gradients W_Δ, $2W_{xy}$) at each measuring site, so the readings should be made in five different α azimuths. Usually two beam systems are mounted in one instrument at antiparallel position to each other, so there is a new unknown torsion-free zero position n'_0 for the other beam system. Due to the additional unknown, minimum six measurements in three different azimuths (e.g. 0^o, 120^o, 240^o) are sufficient, but it is necessary to repeat the measurements in order to increase the accuracy.

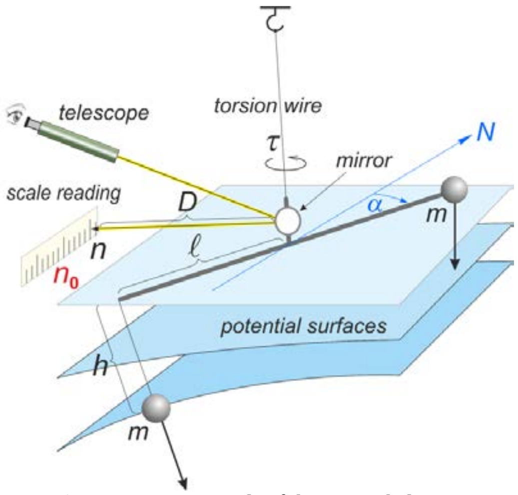

Figure 1. Base principle of the torsion balance.

2. Different types of torsion balances for geophysical field measurements

Different types of torsion balances were produced for field measurements [2, 3, 6]. On the left side of Fig. 2. the Auterbal (Automatic Eötvös-Rybar Balance) can be seen, which had a 40 min recording period until equilibration.

The automatic rotation of this instrument to different azimuths was done by a clock mechanism and data reading was photographically recorded. The automation made the constant presence of the observer unnecessary, but the complex control structure needed constant attention [2, 3, 6].

The other type is the Eötvös-Pekár torsion balance which was designated as the Small Original Eötvös G-2, can be seen in the right side of the Fig. 2. This instrument had three variants; they differed from each other in the length of the torsion wires only. Our model on the Fig. 2., which was manufactured in 1930 has 30 cm long torsion wire. The developer of this instrument, D. Pekár, with long experiences in field measurements, strived to achieve high accuracy and simplicity of the instrument, and therefore preferred manual rotation and visual reading rather than automatic operation. The only disadvantage of the Pekár balance is the need for the constant presence of the observer [2, 3, 6].

The third type of TB available to our measurements can be seen on the Fig. 3. This instrument, designated E54, was designed for geophysical prospecting in the 1950s.

Figure 2. *Two types of historical torsion balances for field measurements, the Auterbal on the left side, and the Eötvös-Pekár torsion balance on the right side can be seen.*

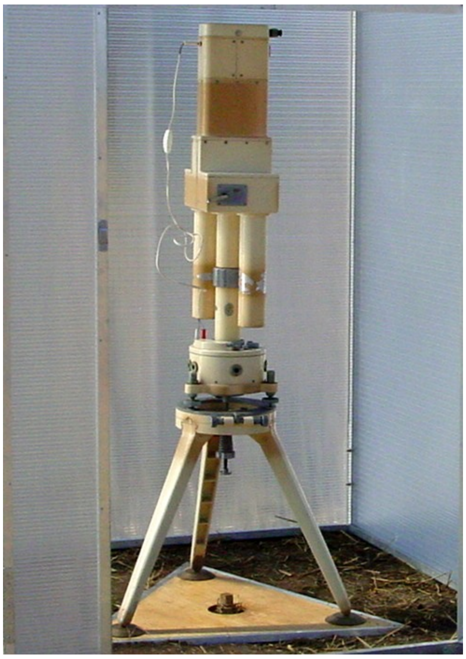

Figure 3. *The third type of torsion balances for field measurements purposes is the E54 balance.*

3. Modernization of the torsion balances

The biggest enemy of the high precision TB measurements with original methodology is the man himself [6]. The mass of the observer's body changes the damped position of the TB, and going toward the instrument the noise of the observer's steps cause ground vibrations, which also disturbs the damped position of the TB. Solutions for these problems can be achieved with two important enhancements: by applying computer-controlled scan on a CCD sensor instead of visual reading and by using remote-controlled rotation mechanics to rotate the TB into various azimuths.

By mounting a CCD sensor instead of visual reading (see Fig. 4.), we can determine the very precise position of the balance arm by evaluating the resulting digital image [6-8]. The original optical results in a readout of the equilibrium position with accuracy of 0.1 scale division, but now with CCD sensors and continuous reading (up to 10 readings/sec) with the accuracy of 0.002 scale division is possible. Scale division is exactly 1/3 mm, while the scale-mirror distance is 450 mm. From these numbers 0.002 scale division means 0.3″. To improve the reading accuracy, we have designed a new barcode scale with a computer evaluation process.

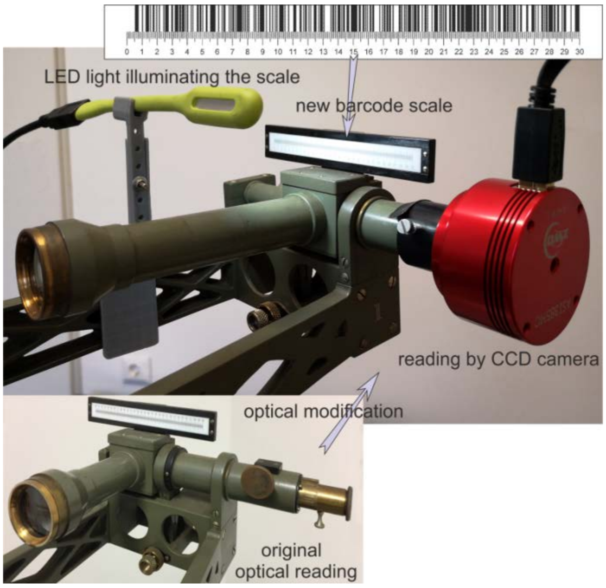

Figure 4. *Reading the scale of the torsion balance by CCD camera*

An essential requirement is the precise determination of the damped position of the balance arm [6, 8, 9]. Originally the equilibrium position was determined after a waiting time of 40 to 60 minutes by a single visual reading. Unlike the original experiment, the equilibrium position is determined now by fitting a theoretical damping curve to the real damping curves of the TB arms. Therefore the damped position can be determined with a higher accuracy on the basis of more data, and on the other hand, by continuously monitoring of the oscillation of balance bars, we can get important information about the behavior of the TB during measurements.

The most critical element of mechatronic solutions is the construction of a unit for remote rotation of the instrument [6, 8]. For rotation of the TB into various measuring azimuths, the structure shown in Fig. 5 was made, applying a special motor, which is connecting to the upper part of the free rotating TB via a ribbed belt drive.

The rotating mechanism has low weight and low metallic content. We used 3D printing technology (using PLA filament) to produce most of the parts. A low power DC motor rotates the TB through a timing belt with a 1:10 gear ratio hence its magnetic field has negligible influence. A cascade position control loop is realized on the microcontroller with a 100Hz sampling frequency which meets the desired closed-loop requirements. A scripting language has been also designed allowing the definition measurement protocols for several days during which the pendulum is subsequentially and/or repeatedly rotated to different azimuths.

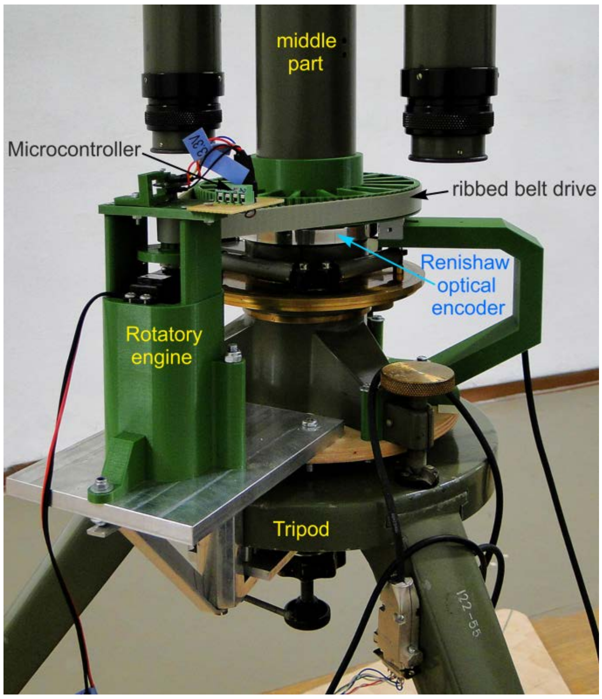

Figure 5. *The rotation mechanism of the torsion balance*

Since the precise reading of the azimuth value is an important requirement for the overall measurement accuracy, a high resolution absolute optical encoder is used with an accuracy under 3" (arcsec) [6]. The rotating mechanism includes a timing belt transmission therefore the azimuth measurements happen directly on the vertical rotating axis of the instrument, in order to avoid the influence of the belt flexibility on accuracy. Let us note that the precision requirement for the closed-loop angular positioning is far less stringent compared to the azimuth measurement precision since the specified repetition accuracy is ±0.1° (deg).

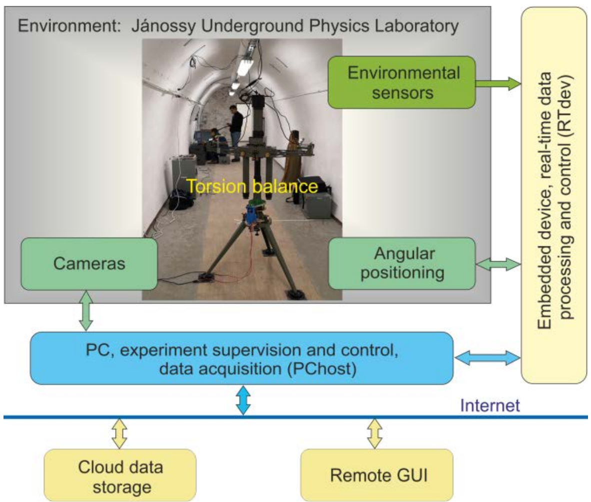

Figure 6. *The DAC system built around the torsion balance*

The architecture of the data acquisition and control system (DACS) is depicted in Fig. 6. [6]

The task of DACS is to log the information gathered by the sensors (including the cameras) and to periodically update the duty cycle of the PWM signal sent to the motor allowing the automatic azimuth change of the TB. The real-time data acquisition of the sensors (excluding the cameras) and the calculation of the feedback law are realized by a microcontroller based embedded device. The cameras feed the images directly to a PC where they are saved and then processed. The image processing is executed real-time. All data logged during the experiments are stored on a dedicated server for possible later analysis [6].

4. The use of torsion balances today

From the beginning of the 20th century until the year 1967 almost 60000 torsion balance measurements were made in Hungary mainly for geophysical purposes. Unfortunately some data of the former measurements are lost, but many of them are available as on original field books or maps. From the year 1995 the experts of the Lorand Eötvös Geophysical Institute made lots of efforts to save those data to computer database by the financial support of the Department of Geodesy and Surveying of the Budapest University of Technology and Economics. At present 44852 valuable gradient data are waiting in this database for the further processing – mainly for geodesy [5].

The possible applications of torsion balance measurements in geodesy are summarized in Fig. 7. On the left-hand side of the figure the elements of Eötvös-tensor are arranged to three groups. Horizontal gradients of gravity are marked by blue shading area (these can be measured directly by torsion balance) while the curvature data are indicated with light-yellow shading. The crossed element (the vertical gradient) on the right lower side of the Eötvös tensor, is not measurable directly by torsion balance. On the right-hand side of Fig. 7 the possible applications of torsion balance measurements are shortly summarized [5].

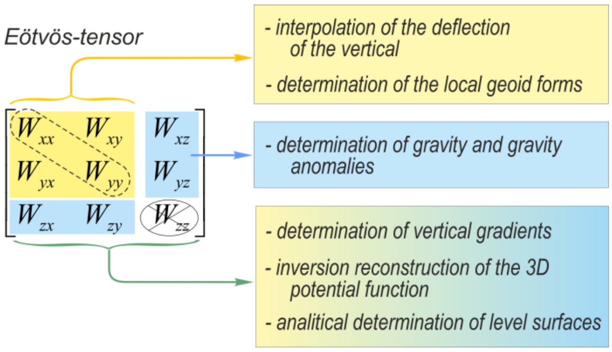

Figure 7. *Applications of the torsion balance measurements in geodesy*

If we know the observed values of the astrogeodetic deflection of the vertical at least in two points of an area, then values of the deflection of the vertical can be interpolated in each torsion balance points using the curvature gradients W_Δ and W_{xy} [10]. From the interpolated deflection of the vertical values it is possible to determine the geoid forms applying the astrogeodetic method [11].

Improvements of the new computational methods give new possibilities for the application of all elements of the Eötvös tensor. Besides the geodetic application of the curvature data the horizontal gradients of gravity measured by torsion balance can be used for geophysical and geodetic purposes too. Because the knowledge of the real gravity field of the Earth has a great importance in geophysics and physical geodesy, the possibility and the need for the usage of these horizontal gradients are important [12].

Torsion balance measurements give new possibility to determine vertical gradients by an interpolation method. This method, similar to the astronomical leveling, generates differences of vertical gradients between at least three points measured by torsion balance. For this interpolation it is necessary to know the real (observed) value of vertical gradients in some points of the area [13, 14].

Another new important application of torsion balance measurements is the 3D inversion reconstruction of gravity potential based on gravity gradients. This new inversion method gives opportunity to determine the function of gravity potential and their all first and all second derivates (the components of gravity vector and the elements of the full Eötvös tensor – including the vertical gradient) [15].

The most important application of the torsion balance measurements in physical geodesy is the determination of fine structure of the geoid. In 1997 a quasigeoid solution HGTUB2007 was computed for Hungary using least-squares collocation technique by combining different gravity data sets, some astrogeodetic deflections, topographic information, and the GPS/leveling network data. As the evaluation of the solution has showed, the obtained accuracy was about 3-4 cm in terms of standard deviation of geoid height residuals [16]. Now a new solution is planed to compute by joint inversion appending all Hungarian torsion balance measurements to the previous input data

The average distances between torsion balance stations vary between 500 m and 4 km, depending on the topography. Linear changing of the gravity gradients between the adjoining network points is an important demand for different interpolation methods (e.g. interpolation of the deflection of the vertical, geoid computations, and interpolation of the gravity values or the vertical gradients of gravity) [17]. So an important question is the nonlinearity of the gravity gradients between the former neighboring torsion balance stations. The question is, whether the point density of these measurements is enough or not satisfy the linear changing requirements of gravity gradients? To study the linearity of gravity gradients, new torsion balance measurements were made both at the field and in a laboratory: one is at the Csepel Island [18], and the other in the Geodynamical Laboratory of the formal Loránd Eötvös Geophysical Institute in the Mátyás cave.

An important current application of torsion balance in physics is the remeasurement of the former Eötvös-experiment. Lorand Eötvös and his colleagues Dezső Pekár and Jenő Fekete executed a series of measurements (EPF experiment) from 1906 till 1908 to validate the equivalence of gravitational and inertial mass – which is an important basepillar of Einstein's general theory of relativity [19].

Our analysis of the EPF experiment pointed to a possible bias that made it necessary repeating the tests under better conditions and using modern new technology [20]. Planning and preliminary measurements started at July of 2017.

The principle of the EPF experiment is rather simple [6]. Earth's gravity vector $\boldsymbol{g}$ has two main components, the gravitational force $\mathbf{F}_T = m\mathbf{G}$ and the rotational centrifugal force $\mathbf{F}_C = m\mathbf{C}$, where $\mathbf{G}$ is the gravitational and $\mathbf{C}$ is the rotational field intensity. The basic assumption of Eötvös was that the centrifugal force of $\mathbf{F}_C$ is independent of material composition, but that the gravitational force of $\mathbf{F}_T$ might depend on it. Consider the placement of various materials (e.g. gold and aluminum) at the surface of the Earth, as shown in Fig. 8. The two different bodies have exactly the same mass ($m = m'$). It is assumed that both bodies are subject to the same centrifugal force $\mathbf{F}_C$, but the Earth exerts gravitational force $\mathbf{F}_T$ on mass m and $\mathbf{F}'_T$ on mass m'. Accordingly, as shown in Fig. 8, the gravity force on the mass m is $\mathbf{g}$ and the gravity force on the mass m' is $\mathbf{g}'$.

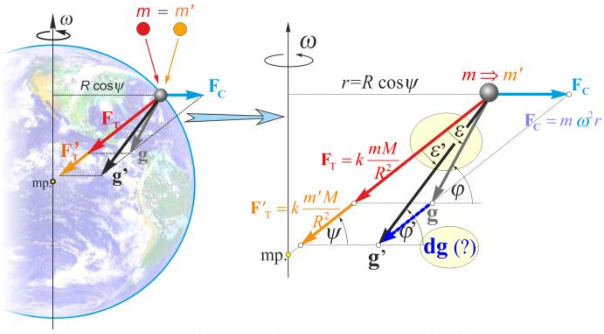

Figure 8. *Assumed difference of gravity in case of different materials*

The idea of the EPF experiment [19] was to compare the horizontal component of gravitational force $m\mathbf{g}$ due to the Earth acting on different materials or samples with the horizontal component of centrifugal force $m\mathbf{C}$. Centrifugal force is assumed composition independent hence if gravitational force depends on material composition, the imbalance of horizontal forces can be detected with a torsion balance.

The $\mathbf{F}_C$ centrifugal force acting on the bodies rotating together with the Earth is perpendicular to the axis of rotation, and on the Northern hemisphere the horizontal component of $\mathbf{F}_C \sin\varphi$ facing south, as shown in Fig. 9.

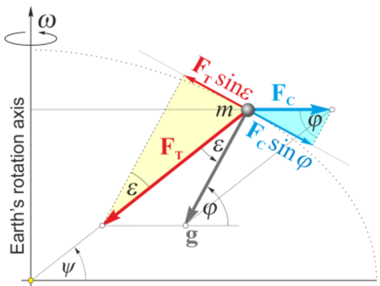

Figure 9. *Horizontal components of forces*

The size of the $\mathbf{F}_C \sin\varphi$ component depends on the geographic latitude φ of the measurement site. This force is in balance with the northward force $\mathbf{F}_T \sin\varepsilon$, which is the horizontal projection of the gravitational force $\mathbf{F}_T$ acting on the body. The angle ε in Fig. 9 is the angle enclosed by the gravity force $\mathbf{g}$ and the gravitational force $\mathbf{F}_T$. Assuming that the gravitational force of $\mathbf{F}_T$ may depend on material composition, Eötvös introduced the notation of material quality factor:

$$\eta = 2\frac{\left(m_g / m_i\right) - \left(m'_g / m'_i\right)}{\left(m_g / m_i\right) + \left(m'_g / m'_i\right)}$$,(2**Hiba! A könyvjelző nem**

Here the t and s indices denote the inertial and gravitational masses, respectively. Thus, if we take $\eta = 0$ for some reference material (eg for water), the force of gravitation on the another body will change according to the relation $(1+\eta)\mathbf{F}_T$.

If $\eta \neq 0$, the balance of two forces shown in Fig. 8 is lost due to the difference of gravitational and inertial masses, so the mass m' will be affected by the force η $\mathbf{F}_T \sin\varepsilon$ pointing to northward, which will result in a small turning of the balance beams. Thus, the main question of the Eötvös experiment is whether it is observable a small turning of the balance beams due to the supposed different forces acting on the upper and lower masses inside the torsion balance if we replace the lower mass with another material.

Our improved small original Pekár type Eötvös balance started the weak equivalence principle tests in summer 2019 in the Jánossy Underground Research Laboratory –30 meters underground.

The recent sensitivity of the improved balance is significantly higher than the sensitivity of the EPR device. There are various environmental effects that make harder to achieve the improvement by 2 magnitudes, the objective of our instrument development [21]. One of them is the influence of tidal forces.

5. Tidal effect

Earth tides may disturb delicate gravity instruments in various ways and Eötvös torsion balances are no exception. Sensitive gravitational experiments with the balance are susceptible to these tidal effects. Since to our knowledge these effects are not mentioned the literature, therefore in the following we briefly overview them.

First, there is an obvious direct gravitational pull of the Sun and Moon on the balance. This effect is very tiny, however, because the torsion balance is a differential instrument and the gravitating bodies are very far from it. For example, the maximum torsional moment on a Pekár type balance due to the Moon is about $2.3 \cdot 10^{-17}$ Nm, causing 10^{-5} rotation of the arm in terms of scale divisions, which is unmeasurable.

Second, there are various indirect gravitational effects from earth tides. Tidal deformation of the site may cause differential Newtonian gravitational pull, and the Eötvös balance is known to sensitive to nearby mass variations. In the underground laboratory JFFL, for example, where the instrument is installed in a tunnel, 0.2 mm deformation of the tunnel walls might cause a

0.01 scale division amplitude rotation of the Pekár balance according to our gravity modeling. Groundwater tidal motion in unconfined or confined aquifers is another cause of nearby mass variations. These effects, however, are very site dependent and hence hard to quantify. Groundwater monitoring and modeling at the site may facilitate their evaluation.

Third, somewhat surprisingly, earth tides may disturb the Eötvös balance through a ground tilting effect. Air pressure induced ground tilt is a well-known disturbing effect on long-period seismometers [22], and thus atmospheric earth tides may play a role in case of torsion balances as well. According to a detailed 7-dof mechanical model of the Pekár balance it was estimated that a 0.1 μrad amplitude semidiurnal ground tilt through the motion of the suspension point of the balance may cause a semidiurnal torsional motion of the balance with amplitude of 10^{-4} scale division. The main mechanism of this tilt-induced effect is the offset of the drag force on the balance's arm, which executes semidiurnal pendular motion due to the oscillation of the suspension point. The offset of the drag force with respect to the torsion fiber causes a periodic moment of force and semidiurnal tidal torsional vibrations. The effect may also depend on the azimuthal position of the balance's arm, since according to our tilt measurements with a Lippmann HRTM instrument at JFFL, the tilt is anisotropic in the tunnel over a wide range of frequencies.

The second and third effects are measurable with our improved device. Therefore they represent noise that reduces the sensitivity of the equivalence principle measurements. However, at the same time, they are important signals in site characterisation of underground laboratories like Einstein Telescope or Kagra, where the Newtonian noise is the key element of the low-frequency sensitivity of gravitational wave detectors [23].

6. Summary

Sensitive gravity gradiometers, like Eötvös balance, can collect various geophysical and geodetic information. Those can provide global reference data – as it was surveyed in the first part of this work and also provide sensitive site-specific data about changes in our gravitational environment, like direct and indirect effects of tidal forces.

The mystery of the fifth force detection in the EPF experiment is still unsolved. There is a small chance that the dipole torsion balances are special because gravity is sensitive to rotation [24]. One of the main objectives of our device development is the experimental test of some recent hypotheses.

We can see that the increased sensitivity of this old device, an original Eötvös balance, connect fundamental physics and geophysics again. More than 100 years of its design and 90 years after its construction may open new directions in researches.

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