What can we measure with an Eötvös balance?

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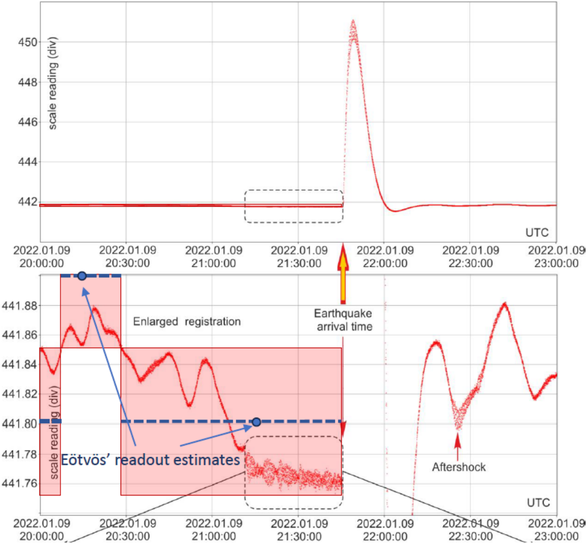
Short answer: almost everything

Eötvös balance measures force difference, therefore

- gravity gradient,
- equivalence principle,
- fifth force, therefore e.g. extra dimensions,
- temperature,
- atmospheric pressure,
- seismicity,
- ...,
- bus schedule,
- Newtonian noise?
- earthquake signals?

Signal, noise and sensitivity

- Improved sensitivity
- Equilibrium vs time series



Differential and compensation measurements

Elimination of the bias.

$$\begin{aligned} x_1 &= \text{noise} + A \\ x_2 &= \text{noise} - A \end{aligned} \qquad \rightarrow \qquad \frac{x_1 - x_2}{2} = A$$

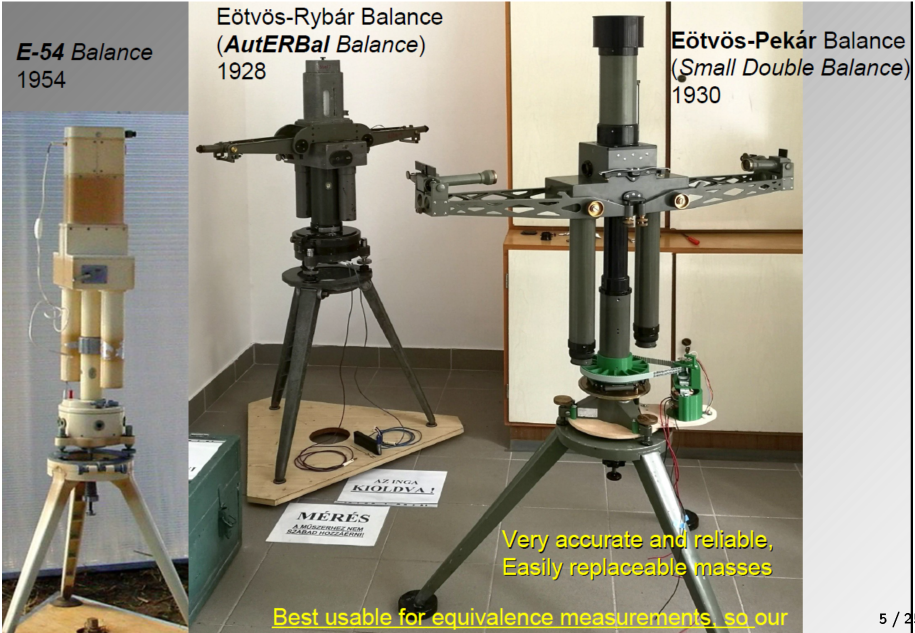
Example: GPS. Typical measurement errors are about 5-10m. With corrections (accelerometer, map matching, etc.) the accuracy is about 1m. With differential measurement relative to a fixed station, accuracy is 1cm.

Eötvös balance: equilibrium for EP. Differential in several respects. There are two independent and opposite balances.

Differential elimination of

- material inhomogeneities and differences (torsion spring constant),
- small differences in instrument parameters due to manufacturing,
- drift and uncertainties in equilibrium,
- changes in the environmental conditions,
- etc.

Geophysical Eötvös balances



Gravity-gradiometer

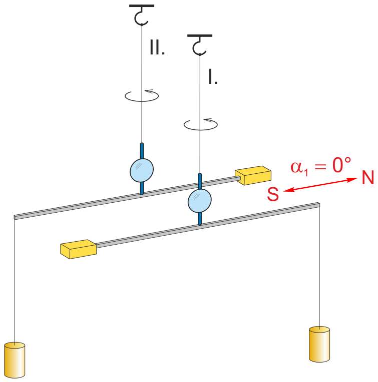
Eötvös balance measures the gradient of the gravity:

Eötvös tensor:

$$W = -\nabla^2 U = \begin{pmatrix} W_{xx} & W_{xy} & W_{xz} \\ W_{xy} & W_{yy} & W_{yz} \\ W_{xz} & W_{yz} & W_{zz} \end{pmatrix}$$

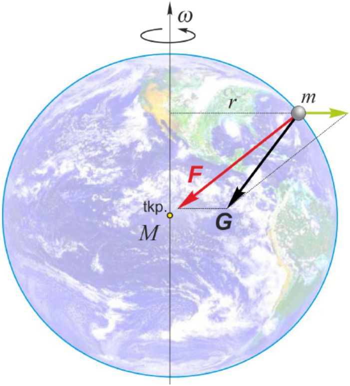
Eötvös formula:

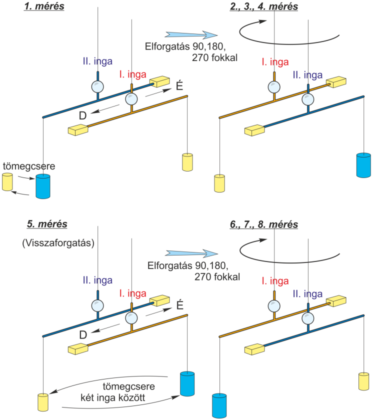
$$\phi - \phi_0 = \frac{K}{\tau}\left((W_{yy} - W_{xx})\sin(2\alpha) + 2W_{xy}\cos(2\alpha)\right) - \frac{2mhl}{\tau}\left(W_{xz}\sin(\alpha) - 2W_{yz}\cos(\alpha)\right)$$



Measurement of the equivalence principle

Earth based and Sun based protocols.

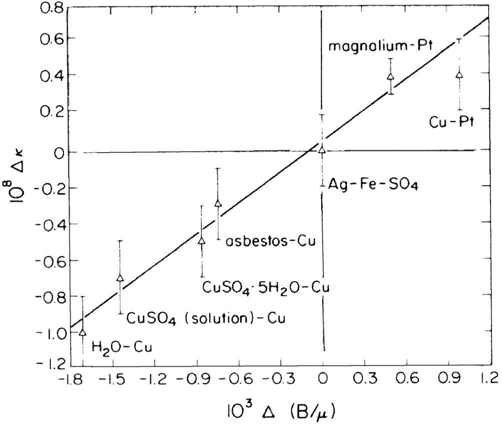




Earth: rotation, test mass exchange.
Sun: balance is fixed, Earth is rotating.

Fifth force: Eötvös-Pekár-Fekete (1904-22)

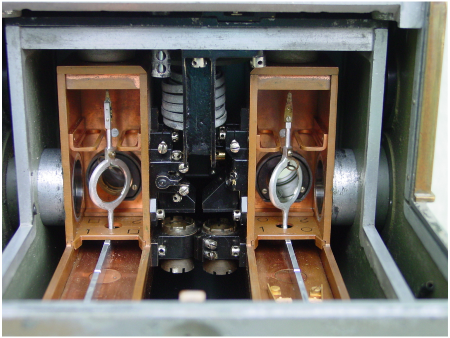
Fischbach-Sudarsky-Szafer-Talmadge-Aronson, 1986

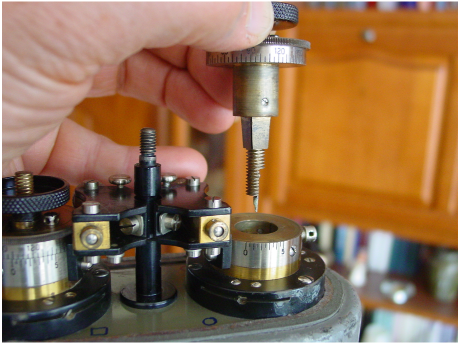


$$\boxed{|F| = \gamma(1+\Delta\kappa)\frac{mM}{r^2}}$$

B - specific barion charge, μ - mass

The Eötvös balance instrument

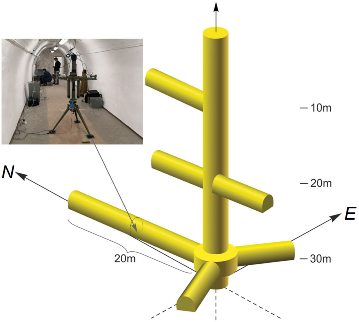


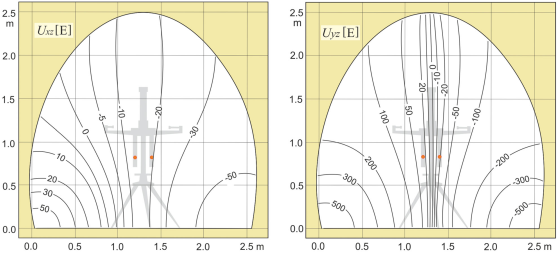


Mirrors, torsion wire and the lower mass

Gravity gradients in JUPL

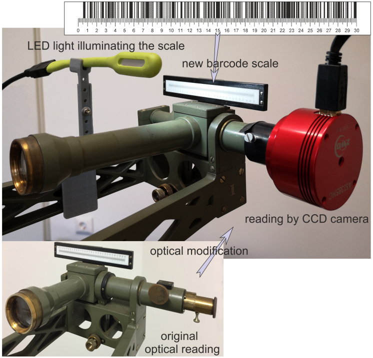
- Calculated with the mass model of the laboratory
- measured: U_{xz} = -15.2 E, U_{yz} = -14.4 E
- the calculated g_{xzz} perpendicular deviation is small
- the measure g_{xzz} perpendiculsr deviation 0.051 nGal/cm^2

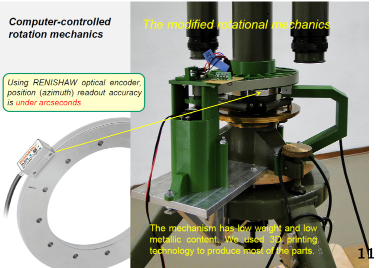




Improved sensitivity

- Automatic readout:
  image processing, direction calculation
- Automatic rotation:
  sensitive motor, accurate position feedback (code ring)
- Stable, calm environment:
  Jánossy Underground Physics Laboratory
- Better statistics, improved evaluation (e.g. simulated damping, self consistent solution of Eötvös equation, etc...)





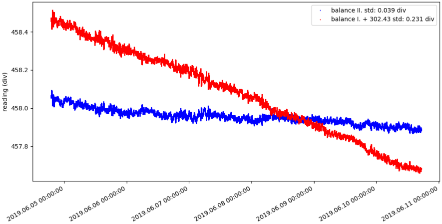
Problems and possibilities

- The accuracy of the EPF measurement of the parameter of equivalence: $\Delta\eta = 3 \cdot 10^{-9}$
- Expected improvement is 3 magnitudes, realised improvement is 1-2 magnitudes. Problems:
  - various drifts of the torsion wire: jumps and slow motion,
  - vibration sensitivity,
  - atmospheric pressure sensitivity ,
  - gravity and azimuth angle should be known exactly,
  - control of various environmental factors (mass effect of rain, moisture, human activity).

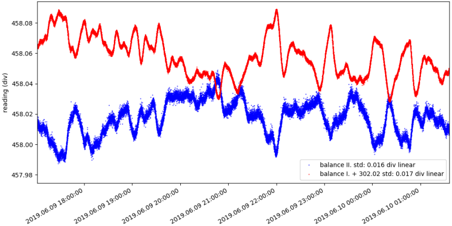
Signal or noise?

Long term drift and a perplexing correlation

- Long term drift: material or environment? Initially 0.01 unit/hour that become a linear 0.005 unit/hour drift (2 μrad/hour), or smaller

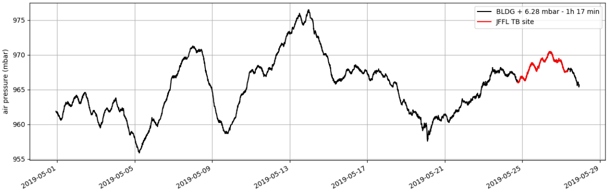


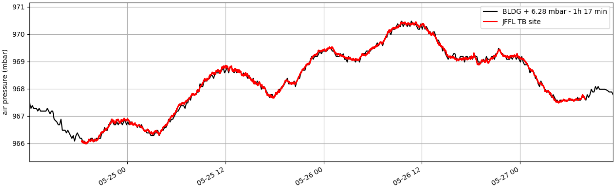
- removing the drift one can observe a characteristic (anti)correlation of the signals



Pressure variation

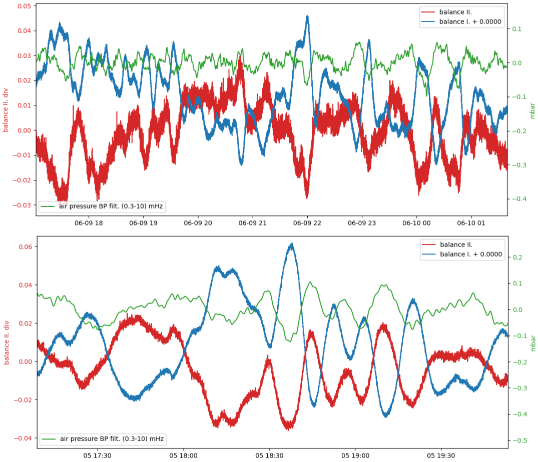
- Atmospheric pressure measured with a simple Bosch BME280 sensor
- Atmospheric pressure measured on the top of a neighbor building
- Pressure variations are correlated





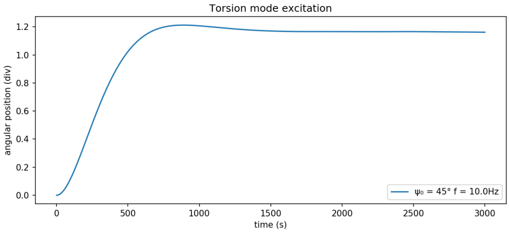
Azimuth angle and pressure

- The filtered (2 minutes - 60 minutes) atmospheric pressure is correlated with azimuth angle - that is why the balances themselves are correlated
- the effect is azimuth dependent



Oscillations of the fixpoint

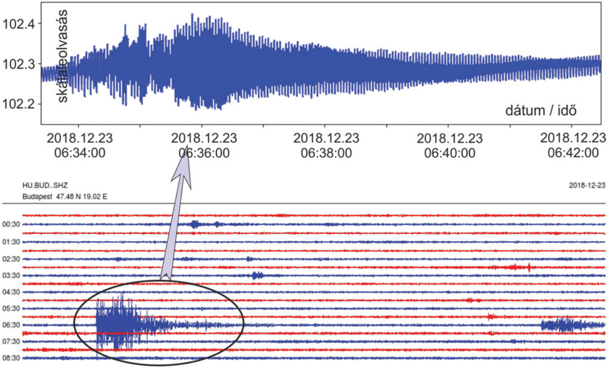
- Speake és Gillies (1987), Karagioz et al. (1975)
- "dumpbell effect": vertical oscillations are coupled to torsion oscillations.
- explanation: kinetic energy is minimal, if the direction of the dumpbell is parallel to the rotation axis of the simplest swing motion
- simulation of the torsional oscillations of a simple Coulomb balance if the amplitude and the frequency of the oscillation of the fixing point 1 μm and 10 Hz



What is the reason of the oscillation according to the pressure change?

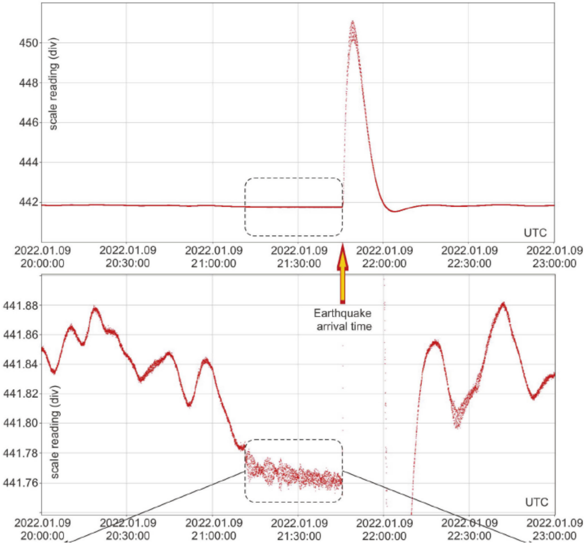
Detection of distant Earthquakes

- M = 4.3 in Serbia, low epicenter 2018.12.23. 06:34.
- balance signal in JUPL
- seismogramm of the same earthquake in the Kövesligethy Radó Seismological Observatory



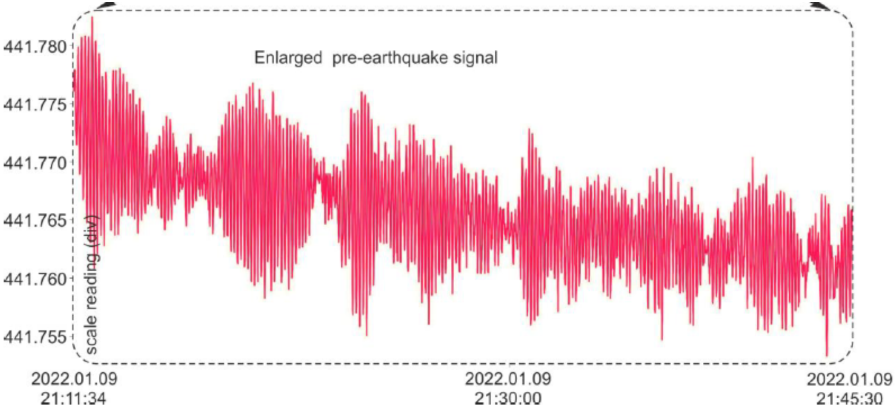
Earthquake signal

- M = 5.6 in Greece, low epicenter 09.01.2022. 21:45.



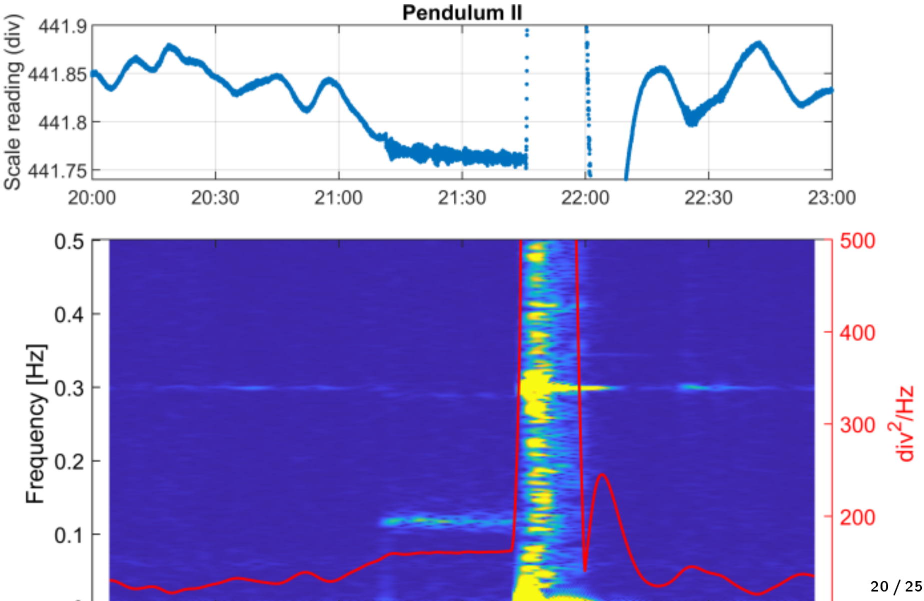
Enlarged pre-earthquake signal

- M = 5.6 in Greece, low epicenter 09.01.2022. 21:45.
- Spectacular resonance.



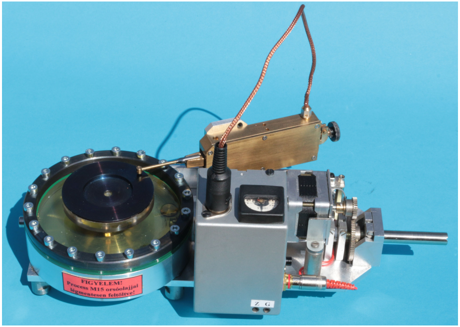
Spectrum of the signal

- Resonance at 0.12Hz .



Recent activity

- Testing resonant environmental effects (pressure, temperature, seismic noise, magnetic field, etc...). Measurement and active exitations.



Low frequency waggler for active testing.

- Equivalence principle measurement. 5th force and gravity gradient.
- Assembling and installing an Eötvös balance network.

Eötvös100-Equivalence Group

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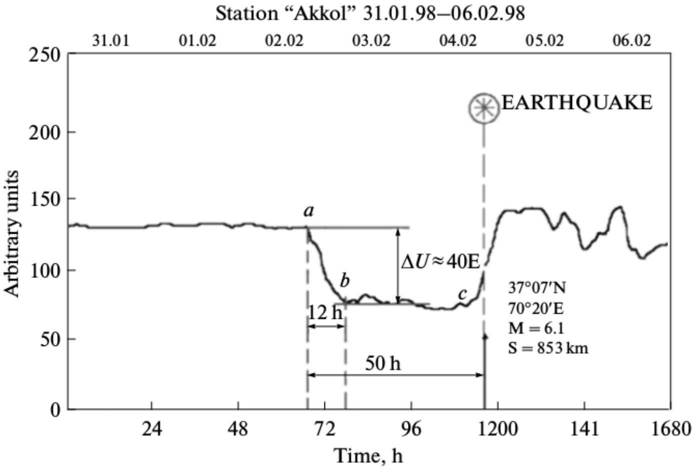
Thank you for your attention!

Earthquake prediction with torsion balances?

- Tipical GV signal due to unknown reasons before an earthquake (Volfson et al. 2011)



Earthquake prediction with torsion balances?

- Gravity variometers (GV) are sensitive to seismic oscillations. An accidental discovery in Sovietunion around 1970 (Volfson et al. 2010)
- Gravity variometers were deviating from equilibrium, typically several 10 hours before an earthquake (Kalinnikov et al., 1992)
- The torsion balance operates according to a maximal resonant energy adsorption due to the horizontal motion in various directions (Kalinnikov, 1990).
- 18 couples of GV were operational in 7 seismological stations in Kazahstan for 15 years (Khaidarov et al., 2003)