# Nano-Torque Induction System based on Watch's Hands Rotation in Gravity Field

Justine Lebrun [(1)*], Michel van Ruymbeke [(2)], François Wielant [(1)], Sébastien Naslin [(2)], Jean-Pierre Raskin [(1)], Sébastien Toussaint [(1)]

(1) Université catholique de Louvain, ICTEAM, B-1348 Louvain-la-Neuve, Belgium

(2) Royal Observatory of Belgium, Avenue Circulaire, 3, B-1180 Brussels, Belgium

* corresponding author: ju.lebrun@uclouvain.be

## MOTIVATION

Provide an accessible alternative for **torque calibration and generation**

Current techniques range from ~ $10^{-4}$ [Nm] to $10^{6}$ [Nm] [1,2].

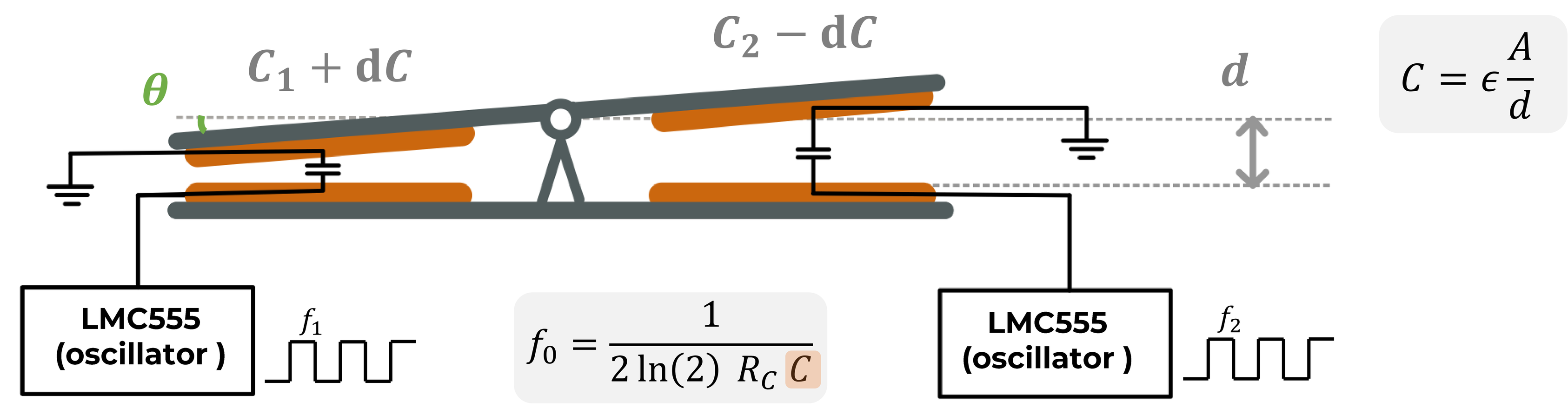
⇨ Design of a device for calibrated torque generation on the micro- to nano-Nm range with long term stability

⇨ Detection of narrow tilts thanks to capacitive detection

⇨ Ease of reproduction

## WORKING PRINCIPLE

The approach uses the mechanical displacement between the movable and fixed electrodes of the horizontal pendulum for **capacitive detection** of tilt $\theta$.




$$C = \epsilon \frac{A}{d}$$

$$f_0 = \frac{1}{2\ln(2)\, R_C\, C}$$

Two **astable oscillators** are used to detect the **capacitance change** by observing a shift in their output frequency, $f_1$ and $f_2$.

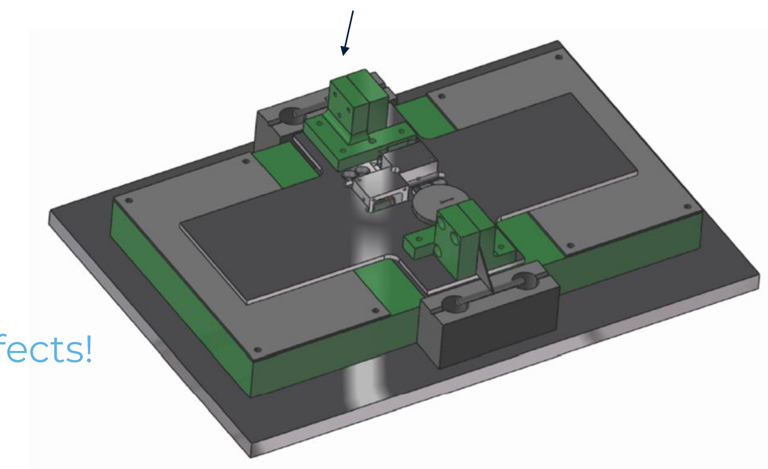
**Environmental factors**, primarily atmospheric pressure and temperature variations can cause electrode dilation and electronics drift - inducing an error $e$ in the signal.

Both sides are equally subjected to these noise effects!

$$f_1 \sim f_0 - \mathrm{d}f + e_1$$

$$f_2 \sim f_0 + \mathrm{d}f + e_2$$

Knife-edge bearing for minimal friction



⇨ Analyzing the **difference between the two signals** ensures the **rejection of common-mode noise** while enhancing sensitivity when measuring **tilt**.

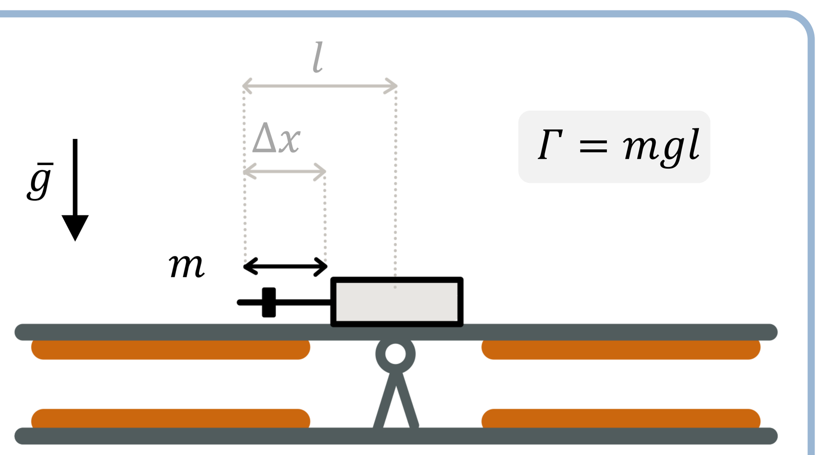
$$f(\theta) \qquad \frac{f_1 - f_2}{f_0} \sim \frac{2\mathrm{d}C}{C} + (e_1 - e_2)$$

⇨ Analyzing their **addition** is a good indicator of **thermal and random noise** ($e$).

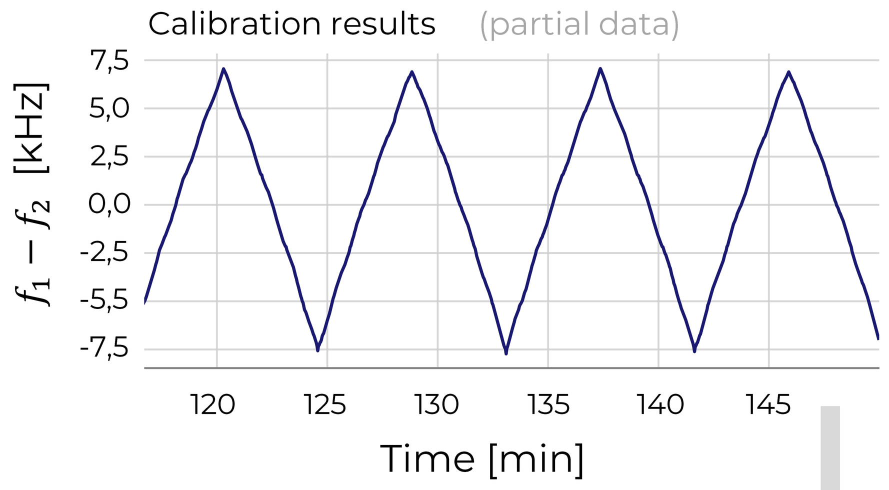
$$f(T, p, \ldots) \qquad \frac{f_1 + f_2}{f_0} \sim \frac{C_1 + C_2}{C} + (e_1 + e_2)$$

## CALIBRATION

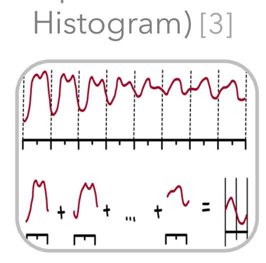
The **system calibration** is based on repetitive cycles of a **lever-arm modulated known torque**, with a known mass.



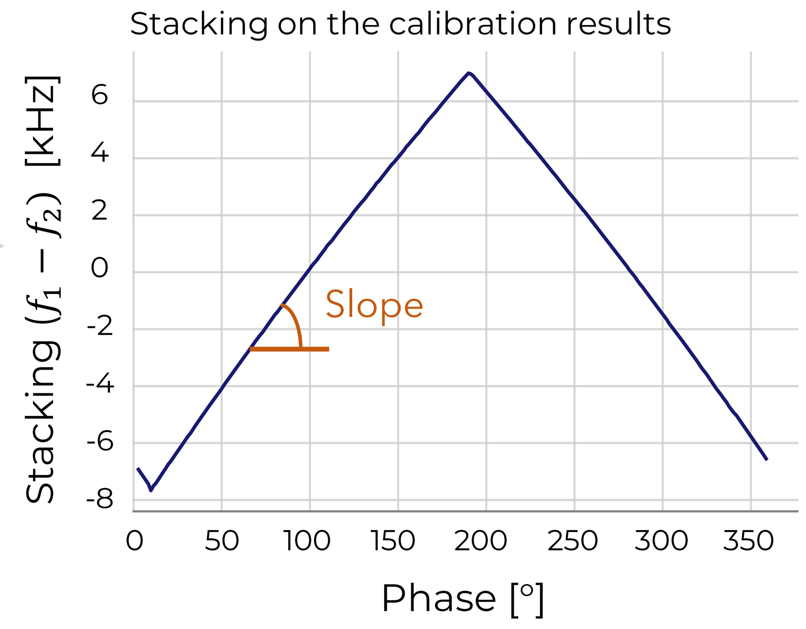

Calibration results (partial data)



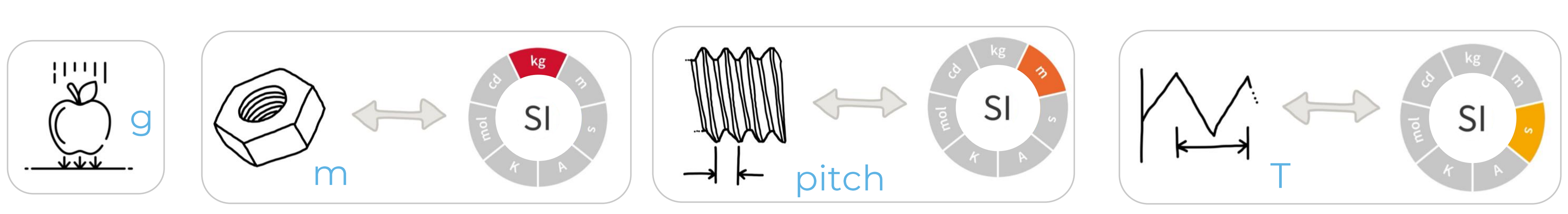

'HiCum' Stacking (Output cumulative Histogram) [3]



Stacking on the calibration results




Calibration is **linked to the fundamental SI standards** as the pitch and mass of the nut (used as the mass) are measured with reference instruments. Local earth gravity field $g$ is a secondary standard.




$$\text{Slope} \quad \frac{\mathrm{d}\Delta f}{\mathrm{d}t} = \frac{1}{S}\frac{\mathrm{d}\Gamma}{\mathrm{d}t} \qquad \Gamma = mgl$$

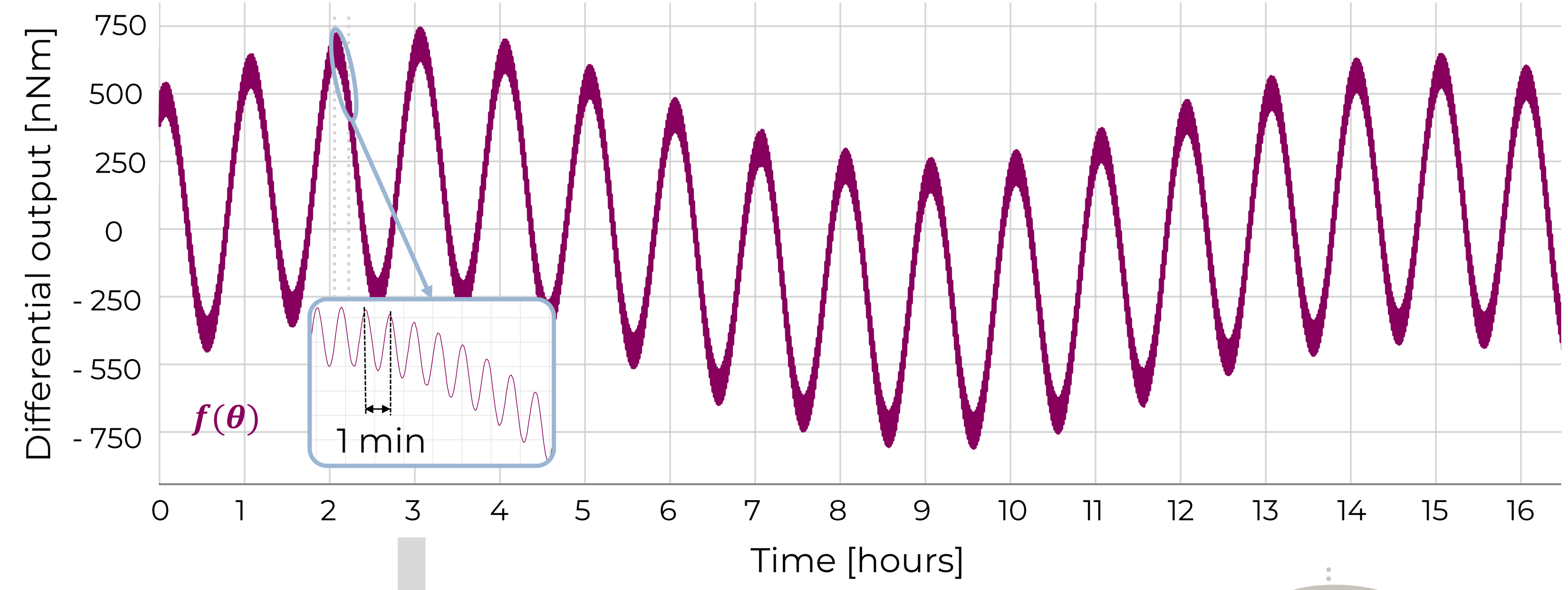
⇨ **Sensitivity** to the applied torque:

$$S = 209 \times 10^{-12}\ \mathrm{Nm/Hz}$$

## ROTATION OF WATCH'S HANDS IN GRAVITY FIELD

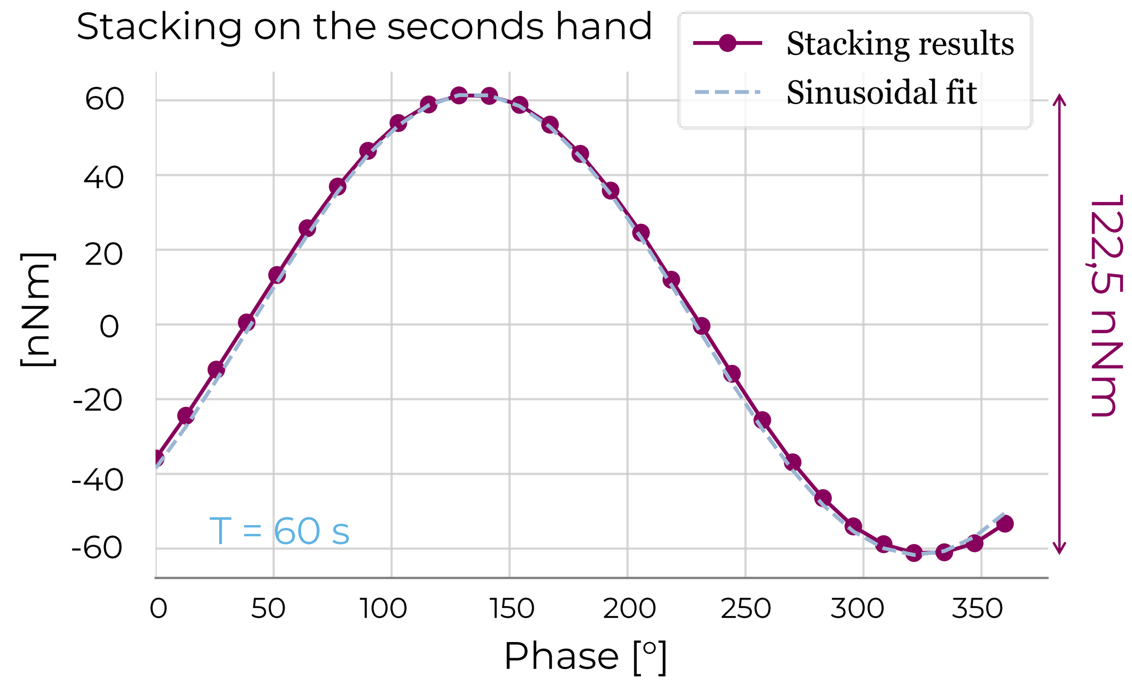
Once calibrated, the device directly **translates the tilt of the movable electrode into physical quantities**.

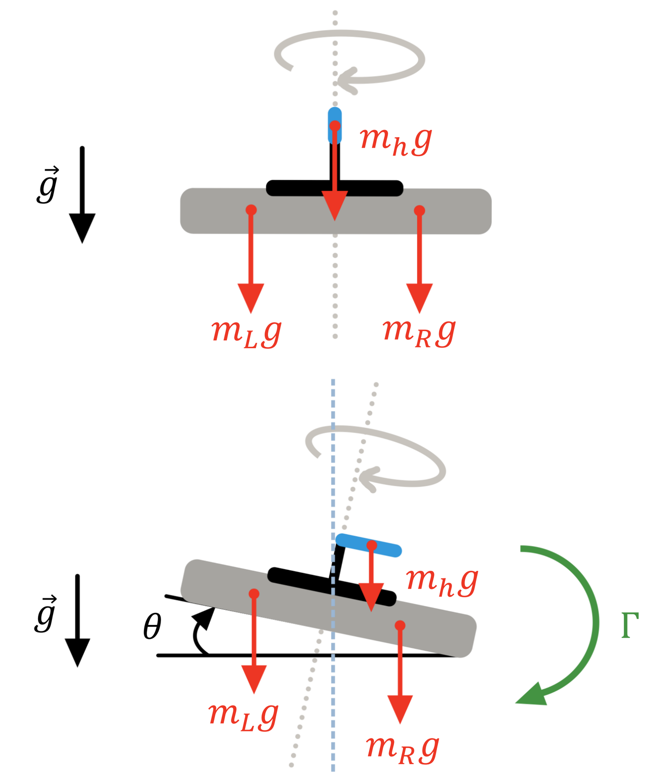
If a quartz watch mechanism is placed on top, the tilt caused by the shifting center of mass as the hands rotate can serve as a **calibration torque inducer**.



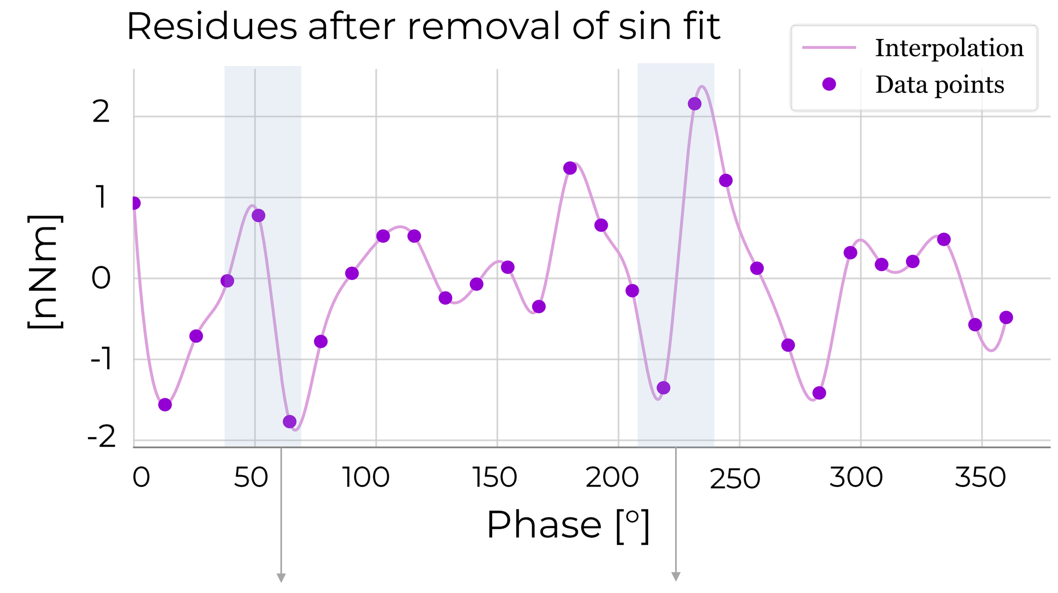

'HiCum' Stacking

Stacking on the seconds hand



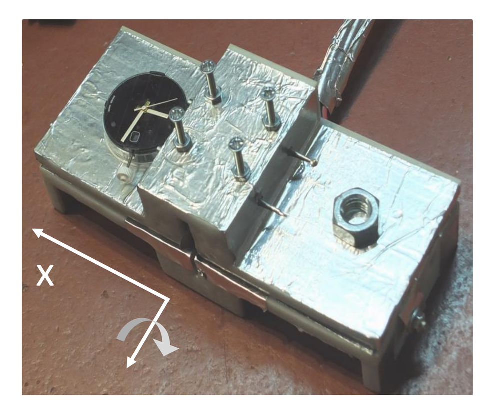




Residues after removal of sin fit




Momentum from the hands' impulse is transmitted when the hands are perpendicular to the axis of rotation

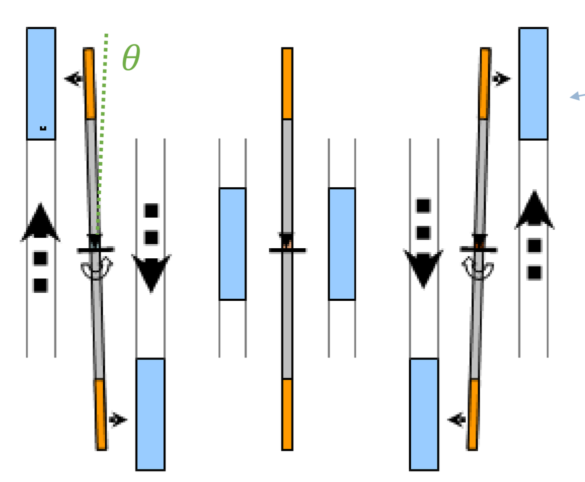
3D printed version of the device proved **ease of reproduction**




Results are independent of the watch's position, as the torque solely depends on its projection along the x-axis.

## APPLICATION – MEASURING THE GRAVITATIONAL CONSTANT

Calibration of the 'GSVP' device dedicated to G gravitational constant measurements.

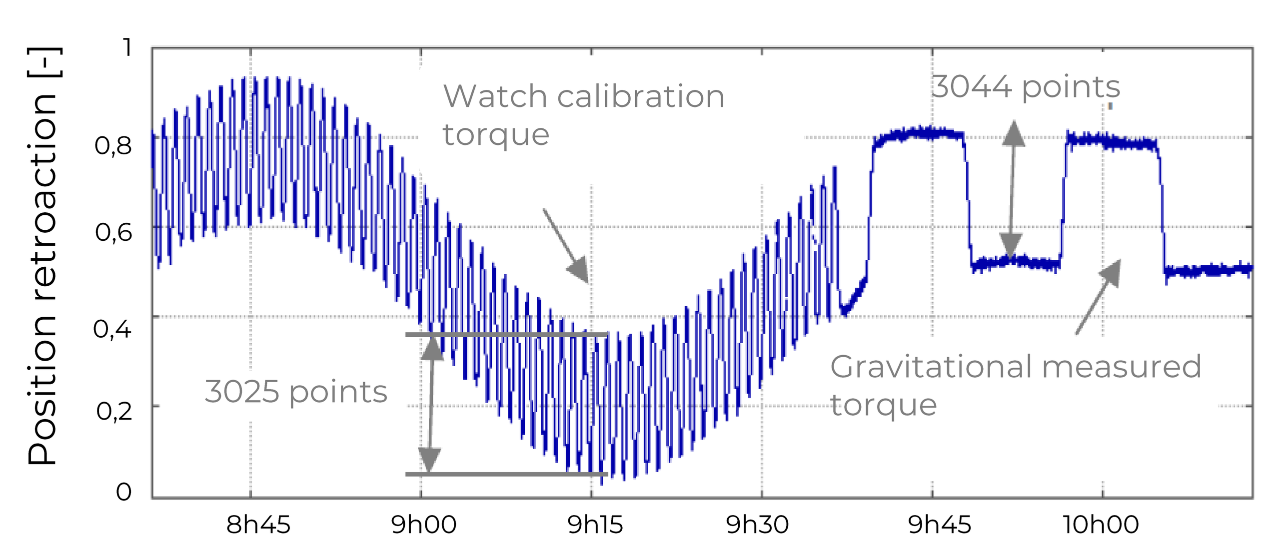



Independent masses move in a periodic motion, applying a gravitational torque on the pendulum's masses.

$$F = G\,\frac{m_1 m_2}{r^2}$$

The sinusoidal torque induced by the watch is of the same order of magnitude as the gravitational effect measured [4,5].

⇨ Continuous calibration with long-term stability.




⇨ The method compares torque ratios without needing to fix the instrument's sensitivity.

## CONCLUSION & PERSPECTIVES

- Device capable of **detecting tilts induced by torques ranging from micro- to nano-Nm**
- **Calibration** linked to **fundamental SI mass, length, and time standards**, with **the local gravity field** as a secondary standard
- Allows calibration of a **torque inducer**
- Demonstration of calibration for a watch mechanism, transforming it into a **portable continuous calibration tool** for various applications in inclinometry, earth tides sensing, and other fields (particularly for challenging narrow geometries)

**Perspectives**

- Inductive detection with the same configuration (instead of capacitive) for electromagnetic feedback positioning, and magnetic measurements
- Application of the calibration methodology for micro-strain gauges

## REFERENCES

[1] BIPM, "Guidelines for Submission and Review of Calibration and Measurement Capabilities", Consultative Committee for Mass and Related Quantities, Working Group on Force and Torque, 2024

[2] Z. Comden *et al.*, "The Design and Performance of an Electronic Torque Standard Directly Traceable to the Revised SI," in *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1-6, 2023.

[3] Ruymbeke, M. & Zhu, P. & Cadicheanu, N. & Naslin, S., 2007, "Very Weak Signals (VWS) detected by stacking method according to different astronomical periodicities (HiCum)", *Natural Hazards and Earth System Science*, 7, 2007.

[4] Naslin Sébastien, "Etude et réalisation d'un procédé expérimental
novateur dédié à la mesure de la constante universelle de gravitation G", 2009, Presse universitaire de Louvain.

[5] Michel van Ruymbeke, Sébastien Naslin, Ping Zhu, Francis Renders & Jean-Philippe Noël, Royal Observatory of Belgium Gravitational balance, *IAG symposium on terrestrial gravimetry*, 2014.

UCLouvain — icteam — Royal Observatory of Belgium