1 Measurement of the Gravitational Constant G

S. Schlamminger, E. Holzschuh, and W. Kündig

The gravitational constant G is defined by Newton's law of gravity. Although known for a long time, it is still the least accurately measured fundamental constant of nature. In 1987, the CODATA[2] committee recommended a value with an uncertainty of 128 ppm [1], largely based on the measurement of Luther and Towler [2]. In the meantime some new measurements have been published with rather discrepant results and recently, the same committee has increased the uncertainty for G to 1500 ppm [3]. There is clearly a need for more accurate and reliable measurements.

The goal of our experiment is a measurement of G with an uncertainty of order 10 ppm. The experiment uses a beam balance to measure gravitational forces and has become feasible thanks to recent progress in the construction of beam balances with extremely high sensitivity. The principle of the experiment will be explained below.

All major parts of the experiment are set up and are functioning. A first result for G with an uncertainty of 230 ppm has been published [4]. A detailed description of the experiment may be found in the dissertation of F. Nolting [5], who obtained a slightly improved value,

$$G = (6.6749 \pm 0.0014) \times 10^{-11}\,\mathrm{m^3kg^{-1}s^{-2}} \qquad \text{(relative uncertainty 220 ppm).}$$

These early results were completely dominated by systematic uncertainties.

During the past year we were mainly occupied with upgrades and improvements of the experiment. These improvements, which will be briefly described in this annual report, were primarily aiming at an increased stability of the experiment. Progress has also been made in achieving higher resolution and lower noise of the balance.

The experiment is located in a 4.8 m deep pit at the Paul Scherrer Institute. A schematic view is shown in Fig. 1.1. The essential components of the set-up are a single-pan beam balance, two test masses and two large field masses. The test masses (1 kg each) are suspended with thin tungsten wires and alternately connected to the balance. The difference of their weights is measured with high precision and taken as the signal. The balance and the test

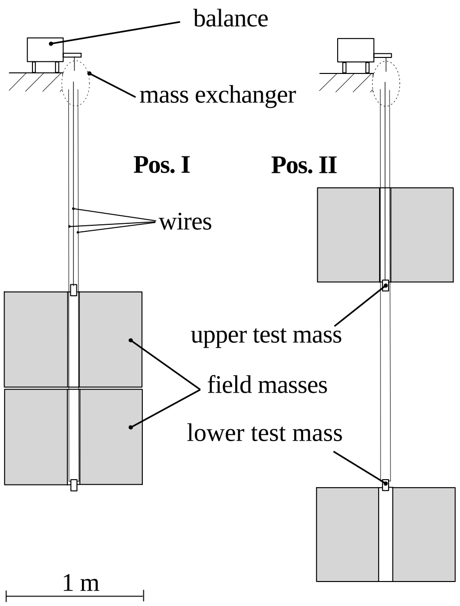

Figure 1.1: *Schematic view of the experiment to measure the gravitational constant. See main text for explanation.*

---

[2] The Committee on Data for Science and Technology of the International Council of Scientific Unions

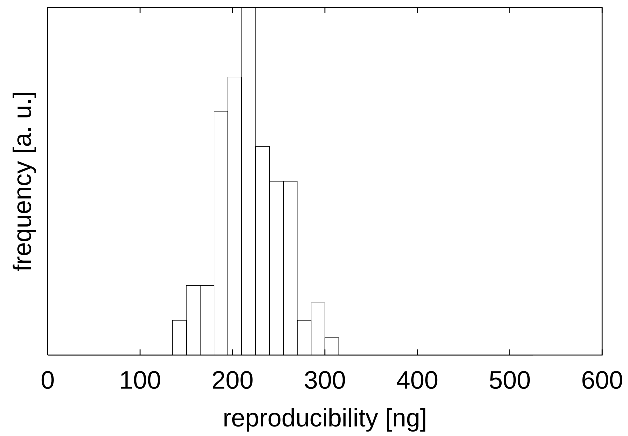

Figure 1.2: *Histogram of the reproducibility of the balance.*

masses are inside a vacuum system. The field masses are cylindrical in shape and have a central bore such that the test masses can pass through. By moving the field masses between the two positions shown, their gravitational force on the test masses changes the signal. From the difference of the signal for the two states and from known values for the masses, densities, and distances, the gravitational constant G can be computed.

There are several features which make this measurement principle very promising. The test masses are placed at positions where the gravitational force of the field masses has local extrema. Therefore the relative positions of the masses are quite uncritical. The value of G is computed from a double difference and many disturbing forces and drift effects should cancel in the result. The field masses are vessels made of stainless steel with a volume of 500 l each. Presently, they are filled with mercury because of its high density. Previously, a measurement with water filled vessels has also been performed [4].

The balance was supplied by Mettler Toledo. The commercial version has a large measuring range, unnecessary for our purpose. To increase the resolution and to reduce noise, the range was reduced to a value of 4 g. The replacement of some mechanical parts has been mentioned in the last year's annual report. Various modifications of the internal software of the balance were necessary mainly because the balance was designed for a resolution of $1\,\mu$g, much to coarse for our experiment.

The present performance of the balance is illustrated in Fig. 1.2. Shown is a histogram of the reproducibility which is defined here as the standard deviation of 22 measured test mass differences. The measuring time for one difference, including two exchanges of the test masses, is 11 min. The average value is 220 ng.

The weights of the test masses are measured alternately by connecting one mass at a time to the balance. A special mechanical device is used being labeled mass exchanger in Fig. 1.1. During the past year we have redesigned and partly rebuilt this device in order to minimize the variations in the total load on the balance during the exchange of the test masses. Load changes may result in mechanical stress energy stored in the structure of the balance which will be released subsequently on a long time scale leading to additional noise. The new device was installed very recently. A first test indicates that we can exchange the 1 kg test masses while keeping the load change on the balance below 0.1 g.

The balance is affected by changes of the temperature, causing drifts of the balance's reading. To a large part this effect can be attributed to a drift of the zero point. The calibration of the balance changes little with temperature. Originally, it was therefore believed that temperature induced drifts would cancel in the double difference. However, we had to conclude that this is not the case with the required precision. For this reason an elaborate

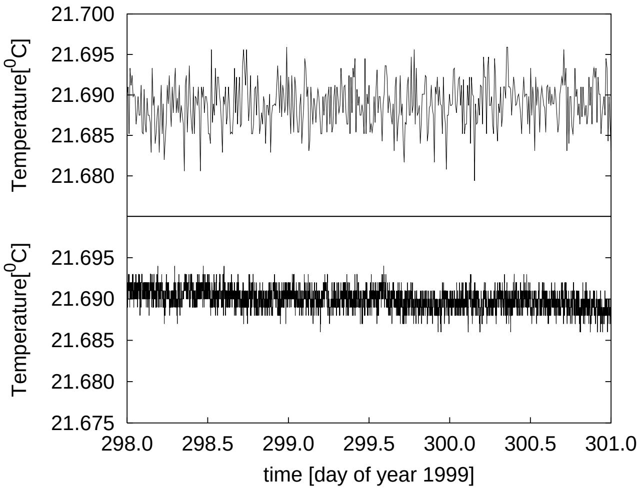

Figure 1.3: *Temperature in the thermally isolated box as measured with two independent thermometers.*

temperature stabilization was installed in 1999.

The system consists of three stages. A new air-conditioning was installed in the barrack housing the balance and the electronics. The cooling power is measured and continuously controlled. Typically, the temperature in the barrack is constant to within 0.1 K. The balance is located in a vacuum chamber which is surrounded by a thermally isolated wooden box. The temperature inside the box is controlled by a second air-conditioner. The temperature sensor for the controller was made of platinum wire wound around the chamber. It averages in space but has a fast response in time. The stability of the temperature inside the box is illustrated in Fig. 1.3 showing measurements with two independent thermometers. The last stage is passive. It is simply a heavy copper case housing the balance inside the vacuum chamber. The case acts like a low-pass filter with a time constant of several days thus averaging fluctuations of the vacuum chamber's temperature. The complete system requires at least a week to reach equilibrium. We have therefore at present no long-term measurements of the balance's temperature but are confident that we can reach a stability of order one milli-Kelvin.

There might be external influences to the experiment which are beyond our control. Tilt of the ground may be an example. We have therefore installed highly sensitive tilt meters with a resolution of 0.1μrad (0.02 arc seconds). We have seen some effects, but so far these seem to have been induced by a changing temperature.

We thank the PSI for its hospitality and Mettler Toledo for the precision balance and the calibration of various standard weights. We are grateful to metrotec engineering for the help modifying and tuning the balance. The experiment was supported by the Swiss National Science Foundation, the Dr. Tomalla Foundation, and the Scientific Research Foundation of the University of Zürich.

References

[1] E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. 59, 1121 (1987).

[2] G.G. Luther and W.R. Towler, Phys. Rev. Lett. 48, 121 (1982).

[3] R.J. Mohr and B.N. Taylor, Rev. Mod. Phys. 72, No.2 (2000).

[4] J. Schurr, F. Nolting, and W. Kündig, Phys. Rev. Lett. 80, 1142 (1998).

[5] F. Nolting, Dissertation, Uni. Zürich 1998.