# 10 Measurement of the gravitational constant $G$

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The gravitational constant $G$ is the least accurately known fundamental constant of nature. The value presently recommended by CODATA[1] with an uncertainty of 128 ppm was measured by Luther and Towler [1] in 1982.

The goal of our experiment is a measurement of $G$ with an uncertainty ten times smaller than at present. The experiment uses a beam balance to measure gravitational forces and has became feasible due to recent progress in the construction of beam balances with extremely high sensitivity. The principle of the experiment will be explained in the following section.

The experiment is set up and running. A first result for $G$ with an uncertainty of 230 ppm was published recently [2]. F. Nolting completed his dissertation and obtained a value $G = (6.6749 \pm 0.0014) \times 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}}$ (relative uncertainty 220 ppm). His result is completely dominated by systematics and the statistical error with 10 ppm is comparatively small.

During the last year we were mainly be occupied with improvements of the experiment and with investigations of systematic uncertainties. These will briefly be described in this annual report.

## 10.1 The principle of the experiment

The experiment has been set up in a 4.8 m deep pit at the Paul-Scherrer-Institute. A schematic view is shown in figure 10.1.

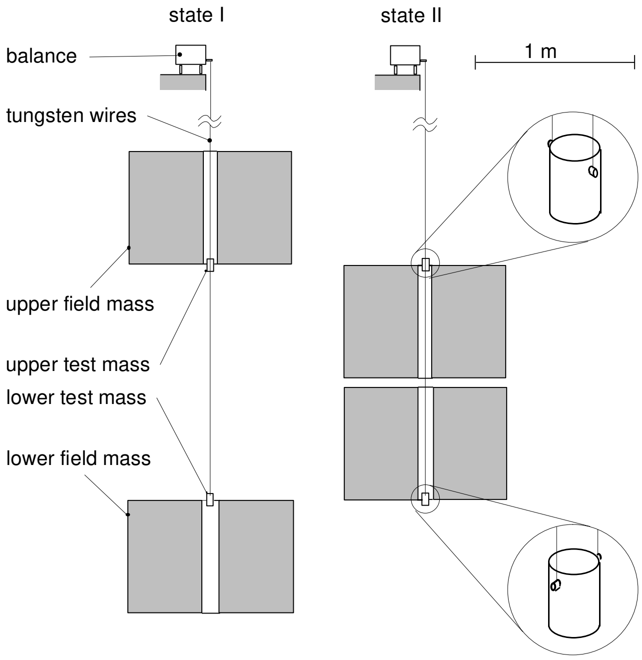


Figure 10.1: *Schematic view of the experiment to measure the gravitational constant. See main text for explanation.*

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

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

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 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 principle of measurement very promising. The test masses are placed at positions where the gravitational force of the field masses has a local extremum. Therefore the relative position of the masses is quite uncritical. The value of $G$ is computed from a double difference and many disturbing forces and drift effects cancel in the result. The field masses are vessels made of stainless steel with a volume of 500 l each. They can be filled with a liquid, either water or mercury. Compared with solids, a liquid is much to be preferred. This is because the density of a liquid is homogeneous, provided its temperature is homogeneous and this can be measured. The effect of compressibility is negligible. The effect of the vessel walls can be measured with empty vessels and subtracted if necessary.

## 10.2 Measurements with mercury

During most of 1998 the experiment was in operation and measurements with mercury filled vessels were performed. The measurements were frequently interrupted and various changes in the set-up were made to investigate systematic effects. The measured signal amplitude is

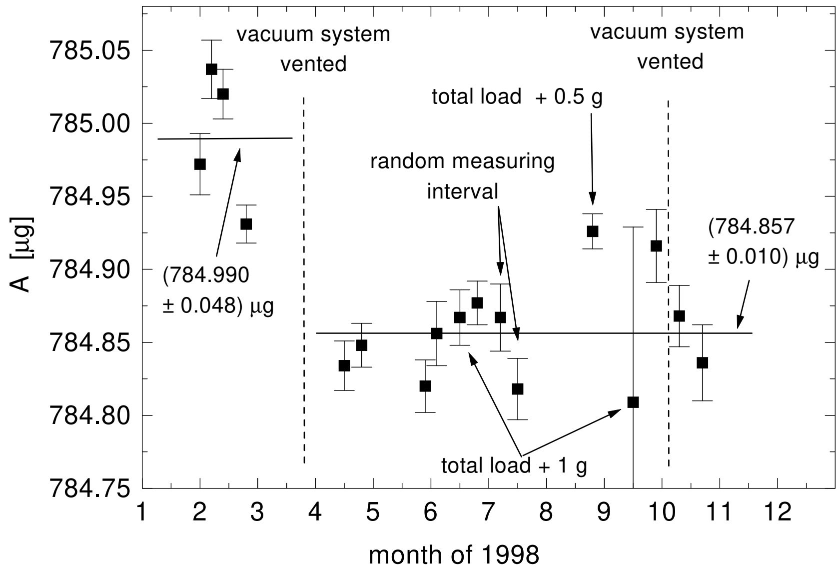


Figure 10.2: *Signal amplitude as measured during 1998 with mercury filled vessels. The error bars are statistical standard deviations. Various changes of the measurement and operations performed are indicated. There are obvious systematic deviations are which presently not well understood.*

plotted in figure 10.2. The error bars are statistical standard deviations with a typical value of 20 ng. During March and October the vacuum system was vented to fix problems. Such operations are big disturbancies as the system needs a rather long time until the residual gas pressure reaches a stable equilibrium value. Although still not clear, gas pressure effects might be one possible explanation for the systematic difference between the first set of data (January, Febuary) and the remaining data.

Initially, the vessels were moved periodically with a period of about eight hours. To investigate whether periodic external disturbances (day–night or weekly) interfere with the measurement period, measurements were performed were the time interval between vessel movements were chosen at random. No significant effect was observed.

To investigate a possible nonlinearty of the balance response, additional loads were placed on the pan of the balance. Such loads should cancel presicely in the first difference which, however, seems not to be the case. This effect is expected to be smaller with the modified balance (see below).

## 10.3 Improvements of the experiment

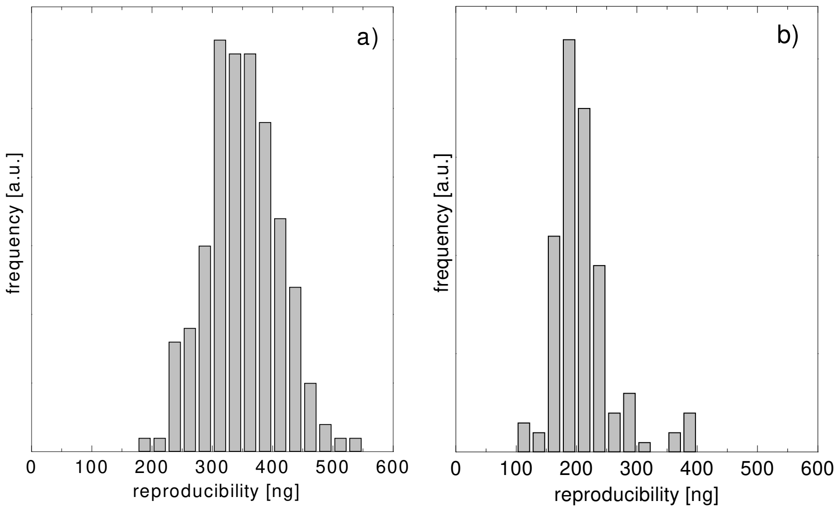


Figure 10.3: *Histograms of the reproducibility of the balance before the modification (left) and after (right).*

Various improvements of the experiment have been made during the last year, mainly aimed at an increased stability and a higher resolution of the balance.

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 originally set to 20 g and recently further reduced to 4 g. The flexure-strips, supporting the beam of the balance, were replaced by thinner ones. The result of these modifications can be seen in figure 10.3, showing histograms of the reproducibility, defined here as the standard deviation of 22 measured test mass differences. Before (left), the average was 360 ng and after the modification (right), its value decreased to 220 ng. This is not as good as we had hoped. There are indications that a significant part of the noise is caused by numerical rounding errors. This would seem to be a simple problem to correct, but it requires access to the internal software of the balance, which we do not have at present. Noise, external to the balance, is certainly also present and needs further investigations.

To monitor the positions of the vessels, a precision measuring system was installed. It has a resolution of $0.5\,\mu$m, which is quite sufficient.

With the present set-up, drifts due to changing temperature, residual gas pressure, etc., are quite large. Due to the double difference, these should cancel. However, this does not seem to be precisely the case and extra noise is induced, in a indirect way, by a changing temperature. Preparations have been started to install a better temperature controlling system and to improve the vacuum.

## Acknowledgement

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## References

[1] G.G. Luther and W.R. Towler, Phys. Rev. Lett. 48, 121 (1982).
[2] J. Schurr, F. Nolting, and W. Kündig, Phy. Rev. Lett. 80, 1142 (1998).
[3] F. Nolting, Dissertation, Uni. Zürich 1998.