1 Measurement of the Gravitational Constant G

St. Schlamminger and E. Holzschuh

The goal of this experiment is a precision measurement of the gravitational constant G with a projected uncertainty of 10 ppm. The experiment is located at the Paul-Scherrer-Institute (PSI). All major parts are set up and are functioning. Descriptions may be found in previous annual reports or in more detail in the dissertation of F. Nolting [1]. The measurements of G, which he made, demonstrated the potential of the method but the size of his systematic error (200 ppm) also indicated the need for further developments.

During the last year we have made extensive investigations of possible systematic effects. Also solutions had to be found for the necessarily large improvements. Below we will describe what we have achieved so far. Unfortunately, our work at PSI had to be stopped at the end of September. This is because the building at PSI, where the experiment is located, is being reconstructed. We received first information about this plan in July 2000 and the final decision by PSI was made on 16. August. Hence we could do little changing our experimental plans. The reconstruction is still in progress.

The essential components of the experiment are a single-pan beam balance (Mettler Toledo, type AT1006), 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 and defined to be the signal. The field masses (two stainless steel vessels, filled with 6.7 tons of mercury) are moved between two positions and their gravitational force on the test masses modulates the signal.

The key measuring device of the experiment is thus the balance, and in fact, the dominant systematic uncertainties of the early measurements of G were related to the balance. Therefore, our work concentrated on understanding and reducing external disturbances, lowering the noise of the balance, and improving the calibration procedure.

The balance's reading is directly affected by variations of temperature or tilt. We have installed highly sensitive tilt meters with a resolution of 0.1 μrad or 0.02 arc seconds in two orthogonal directions. Observations made so far indicate a slow drift (of order 10 μrad per week) and a day-night modulation with a typical amplitude of 2 μrad. It seems that at least the periodic change of the tilt is induced by changes of the ambient temperature. To first order a change of tilt shifts the zero point of the balance which if cancelled by taking differences. We foresee no problems here.

The temperature of the balance is of prime importance. In last year's report we have described the design of an elaborate stabilisation system. After some minor modifications

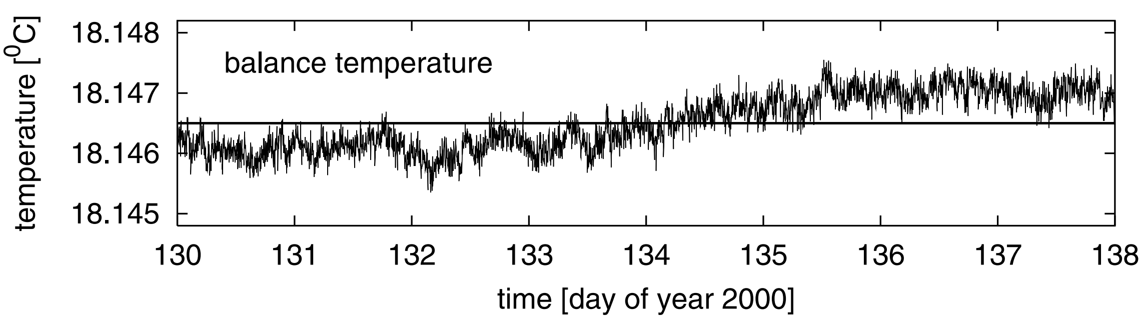

Figure 1.1: *Temperature of the balance during an eight day period in 2000.*

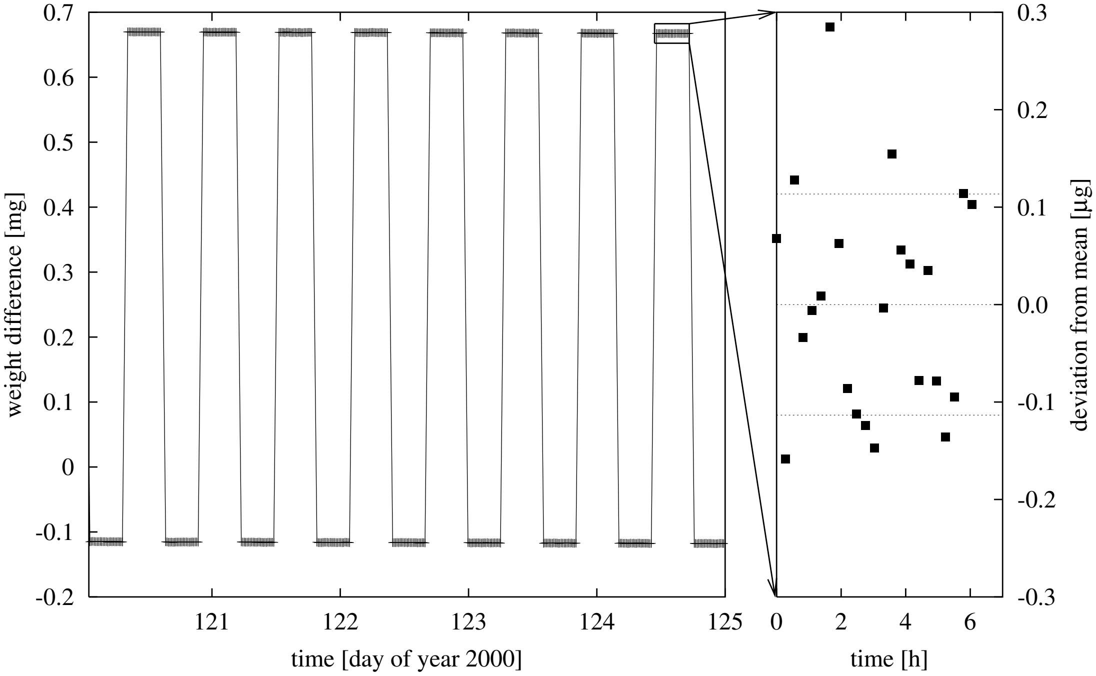

Figure 1.2: *Signal (measured weight difference) from five days of data during 2000. The right part shows the last half-cycle expanded by a factor 700.*

the system now works well. On long time scales the balance's temperature can be kept constant to within about one milli-Kelvin while the ambient temperature changes by several degrees.This is illustrated in figure 1.1 showing data from an eight day run in 2000.

The stable temperature allowed us to investigate the properties of the balance more closely as it was possible before. We found that the zero-point has a linear drift with a slope of 12 μg per day. The cause of the drift could not yet be identified. It may have its origin either in the mechanics or the electronics of the balance. A linear drift of the zero-point is of course no problem as it cancels precisely for the weight difference. The calibration of the balance also has a linear drift, with a slope of order 0.1 μg per gramme and per day. This should also be no problem as the balance can be re-calibrated several times a day.

We have made measurements to investigate and improve the noise of the balance. An example is given in figure 1.2 showing the measured signal (weight difference of the test masses) as a function of time. The signal is modulated by the gravitational force of the field masses. The root mean square deviation is 110 ng. This is sufficient. A further reduction of the required total measuring time is however still possible as the time for one data point in figure 1.2 was dominated by the time needed to exchange the test masses. With some modifications of the exchange mechanics and a new procedure we hope to achieve a reduction by a factor of about three. This work is in progress.

The balance must be calibrated with standard weights. Conversion to force is done using the value of local gravity (g) which we know to eight decimal places. For the required accuracy (5 ppm), a standard weight must be at least 0.2 g which is much larger than the signal amplitude (785 μg). If the response of the balance should not be strictly linear, a serious systematic error may result. We found a simple solution for this problem. It is based on the fact that we need only relate the average slope of the balance's response as determined by a standard weight with the average slope over the signal amplitude. This can be accomplished

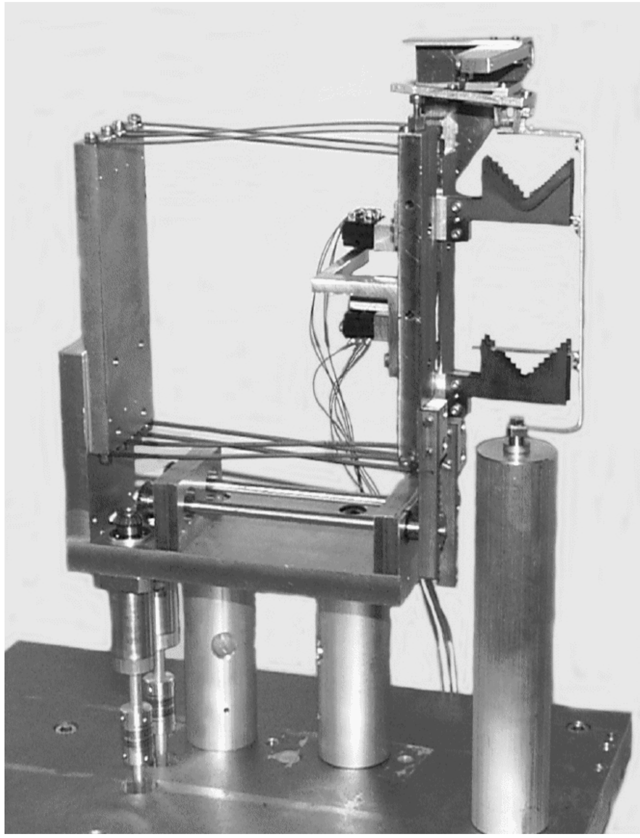

Figure 1.3: *The calibration device, mounted on a test stand.*

by placing a large number of small auxiliary weights on balance and forming an average over the range of the calibration. A device for doing so, in vacuum and under computer control, has been built. A photograph is shown in figure 1.3. The auxiliary weights were made from stainless steel wire and form two sets with 16 pieces each. The masses in one set have nominal values equal to the signal amplitude ($785\,\mu$g) while the masses of the other set are 16 times larger. All pieces have been adjusted such that the deviations from the nominal values do not exceed $3\,\mu$g. By combination we can thus change the auxiliary mass on the balance in 256 approximately equal steps. The auxiliary masses will initially rest on the two V-shaped supports seen on the right in figure 1.3. The supports can be moved in the vertical direction using stepper motors, thereby placing the auxiliary masses in a small frame which will be mounted on the balance's beam.

Initially there were some problems due to adhesive forces, but now the device seems to work well and will be built into the experiment shortly. Provided, the reconstruction at PSI will be finished in due time, we should be able to restart our measurements in the near future.

We thank the PSI for its hospitality and Mettler Toledo for the high precision balance and the calibration of various weights. We are grateful to metrotec engineering for close collaboration. 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] F. Nolting, Dissertation, Uni. Zürich 1998.