7 The Gravitational Constant

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We have started a new experiment to measure the gravitational constant G by means of a beam balance. The set-up of our experiment has been completed, the experimental investigations have been started, and we have performed first measurements of G. The aim of our experiment is to measure G with an uncertainty of 10 ppm or less, in order to remove the shameful fact that Newton's gravitational constant is the least precisely measured fundamental constant of physics.

7.1 The principle of the experiment

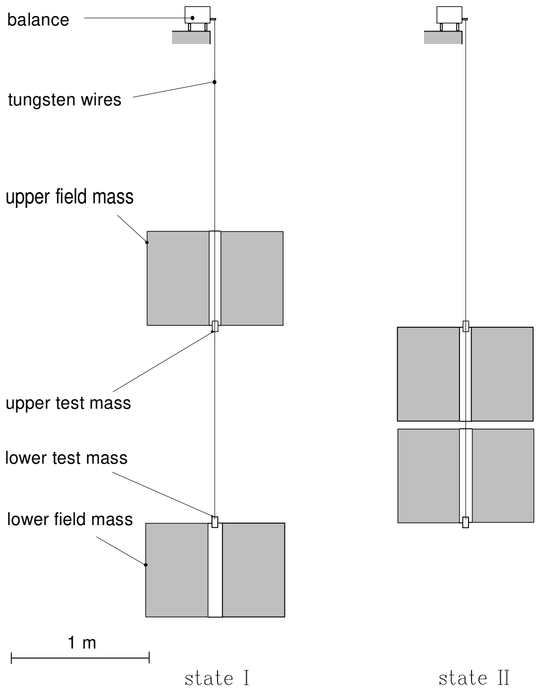


Figure 7.1: The two states of the field generating masses where measurements of the weight difference of the test masses are made.

Two small test masses, which are suspended on wires, are alternately connected to a single-pan beam balance and weighed with high precision (Fig. 7.1). Two large masses are moved vertically and in opposite direction. Their gravitational field acts on the test masses and changes the weight difference of the test masses. This is directly measured by means of the balance.

In our experiment we use a special arrangement of field masses and test masses (Fig. 7.1). The field masses are cylinders with a central bore. Close to the ends of this bore the gravitational field has an extremal point. The field masses are moved between two states in such a way that in each state both test masses are located at an extremal point. Therefore, the gravitational force of the field masses is to first order independent of their positions.

The field masses are vessels of stainless steel with a volume of 500 l. They will be filled first with water, later with mercury. The weight signal is expected to be about

50 μg when the vessels are empty, 110 μg with water and 780 μg with mercury. We can thus make three different measurements of the gravitational force. The comparison of the results enables important consistency checks and should allow us to investigate possible sources of systematical uncertainties. The result with the best statistical uncertainty will of course be obtained with mercury.
The balance has been made available by Mettler-Toledo and is one of the most precise balances in the world. It has been developed to compare 1-kg masses with high accuracy. The resolution of the balance is 100 ng and is further improved to 10 ng by averaging many weighings. A differential measurement with such a mass comparator is advantageous, since many disturbing forces and drift effects cancel in the weight difference. The balance can be calibrated *in situ* with a standard weight. This enables to relate the strength of the gravitational force directly to a accurately known standard force (i.e., the weight of a standard mass). Weighing the gravitational force with an uncertainty of a few nanograms is very ambitious, but a measurement of G with a total uncertainty of 10 ppm and with less systematical errors than the traditional G-measurements seems to be within reach.

7.2 The experimental set-up

A good location for the experiment was found at the Paul Scherrer Institute in Villigen. It is a pit in a machine hall, 4.5 m deep, and with appropriate mechanical and thermal stability. In order to prepare the pit for our experiment, a partition wall and a working platform for the balance were built (Fig. 7.2). A chamber mounted above the pit separates our set-up from other activities in the surrounding.
The heavy steel girders carrying the field masses and the mechanical drive (the 'tower') were built in our machine shop (Fig. 7.2). The vessels are suspended on three spindles with left- and right-handed threads. The vessel moving down pulls the other vessel up. Therefore, the mechanical drive needs a comparably small power. The three spindles are coupled by a gear-drive to ensure a synchronous motion. The 'tower' was first set-up in our institute to test the mechanical components. Then the set-up was moved to PSI and completed in its main components as shown in Fig. 7.2. The characteristic properties of the new set up have been investigated and first measurements of the gravitational force of the empty vessels have been performed.
In order to keep the thermal expansion of the mercury small, we have aimed at a very stable and homogeneous temperature in the pit. Nevertheless, the results show that the requirements for the temperature of the vacuum tube enclosing the test masses are much higher than expected. The weight of a test mass was found to depend on the temperature with a typical sensitivity of 1 μg/K and the temperature is affected by the position of the field masses. To reach a sufficient temperature

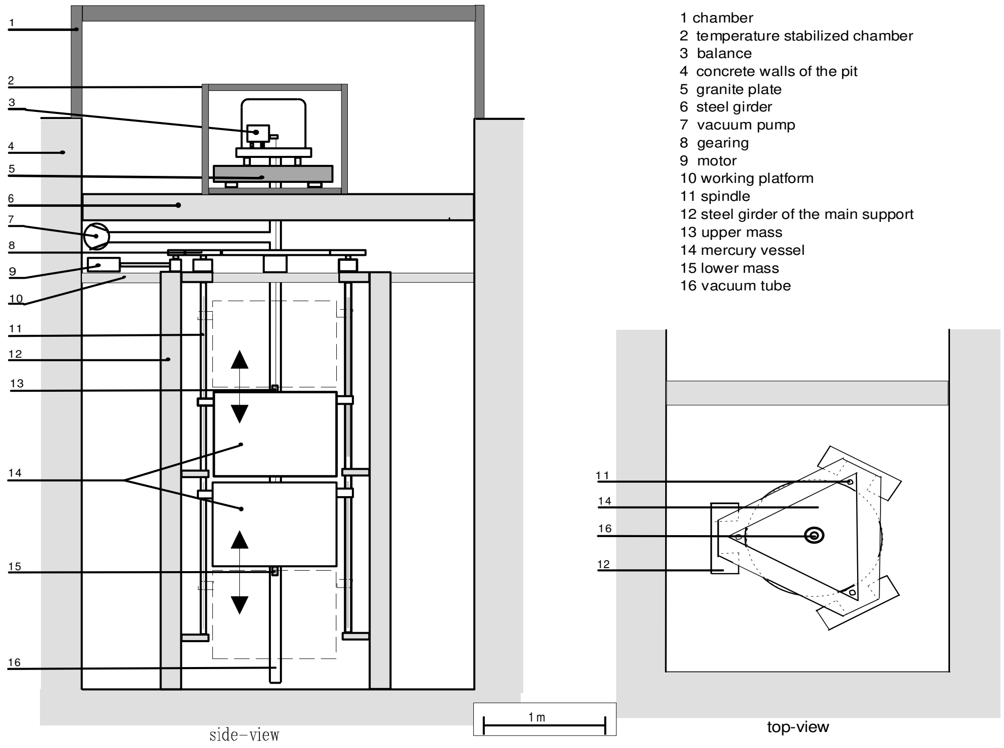


Figure 7.2: The experimental set-up as it is installed at PSI.

stability, a ventilating system has been set-up which circulates the air in the pit and controlls the mean temperature. All local sources of heat are outside. The concrete walls of the pit have been additionally isolated with foam glas and the 'tower' has been covered with radiation shields. With these provisions, the temperature gradient between the field masses has been reduced to 50 mK and the temperature of the vacuum tube is independent of the field mass positions within 4 mK. The remaining systematical error of the weight difference is less than 10 ng.

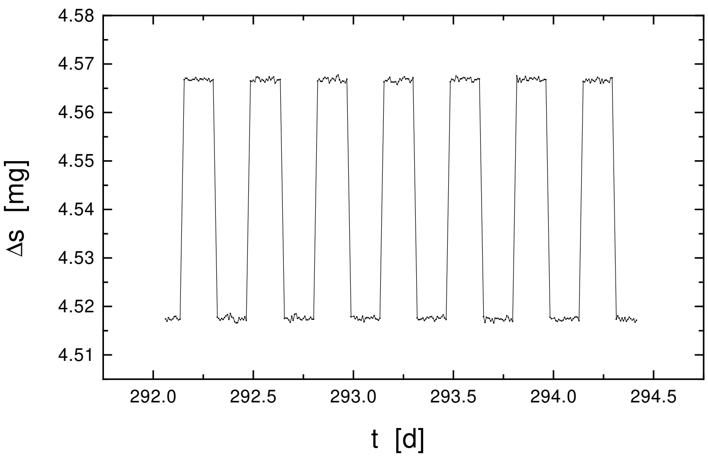
7.3 The beam balance

In our experiment we use a modified version of a Mettler AT1006 Comparator. In order to avoid buoyancy, convection, and other gas pressure forces, we operate the balance in vacuum. The test masses are suspended inside of a vacuum tube which passes through the central bore of the field masses. They are automatically weighed and exchanged. Valuable experience in operating such a balance was gained during our experiment at the Gigerwald-storage lake [1].
The temporal and spatial temperature gradients of the balance have to be very small. Therefore, the balance is mounted inside of a massive copper box. This box and the

whole exchange mechanism is set up in a vacuum chamber which is located in another thermally insulated box. The room temperature is roughly stabilized. We began with an active temperature stabilization of the balance, but a passive stabilization was found to cause much smaller spatial temperature gradients and gives better results. The very small temperature drift of the balance can be accepted since is has no measureable influence on the weight difference.
The vacuum chamber with the balance is placed on a granit plate which rests on steel girders mounted across the pit (Fig. 7.2). This mechanical decoupling from the surrounding and a simple vibration isolation is sufficient, since the sensitivity of the balance to vibrations is low. Analyzing the measured data, no effects due to vibrations from the motor-drive of the field masses or from the vacuum pumps have been seen. Also effects due to seismic, human, or industrial vibrations have never been observed. At present the stability and reproducibility of a single weight difference is about 250 ng. This value is dominated by the internal noise of the balance and not by external disturbances. To further reduce this noise, the weight difference is measured for a few weeks and modulated by the gravitational force of the field masses.

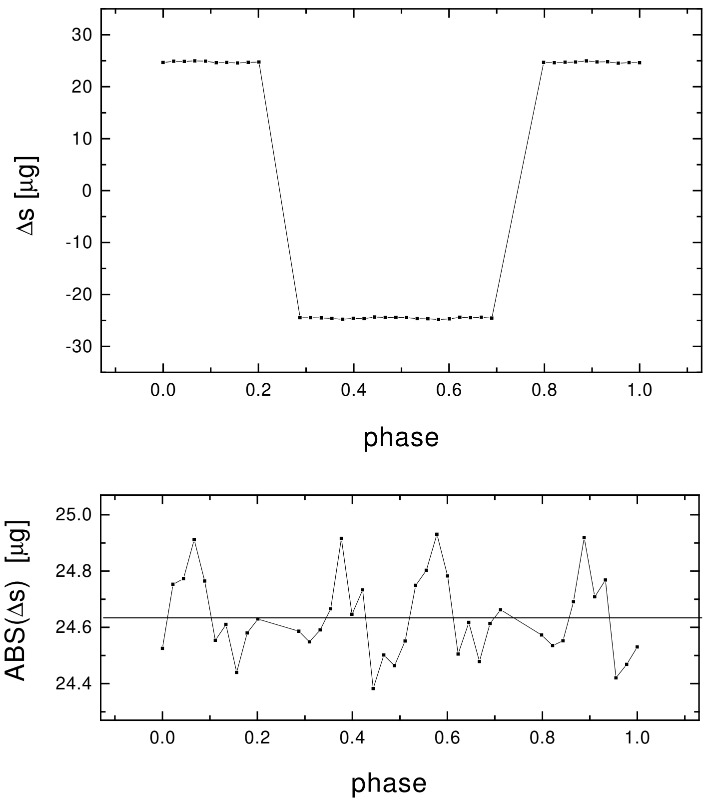
7.4 First results

Figure 7.3: A time series of the weight difference of the test masses, modulated by the gravitational force of the empty vessels.



The gravitational force of the empty vessels has been measured to test the complete set-up and to gain experience about possible systematical effects. Fig. 7.3 shows an example of a time series of the weight difference, modulated by the gravitational force of the empty vessels. In Fig. 7.4 the averaged shape of the modulated signal and the modulation amplitude with the remaining noise can be seen. Using an integration time of ten days, the modulation amplitude is determined with a statistical uncertainty of 10 ng. This is an interesting precision and allows us to in-

Figure 7.4: a) Drift corrected and averaged shape of the modulated signal from Fig. 7.3. b) The mean of the absolute value of the signal gives the modulation amplitude and shows the noise of the measurement.



vestigate various sources of systemtical effects. For example tilt effects of the 'tower' or magnetic forces are already excluded. Weight changes of the test masses due to temperature effects have been reduced to less than 10 ng. A further systematical effect has been found which requires further investigations. However, the small statistical uncertainty should enable to identify this effect within a short time.

7.5 The next steps

The first measurements with empty vessels have provided valuable experience about the performance of our apparatus. The next steps are to fill water and later mercury into the vessels. This enables a larger signal of 110 μg, resp. 780 μg and thus an improved statistical uncertainty of the gravitational constant. Moreover, it will be possible to make important consistency checks and to set upper limits for systematical errors.

Acknowledgement

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References

[1] A. Cornaz, B. Hubler, and W. Kündig, Phys. Rev. Lett. **72**, 1152 (1994) and Phys. Rev. D **51**, 4005 (1995).