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THE BIPM *G* EXPERIMENT – FINAL RESULTS

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Abstract

This paper gives the final results of the Mk II version of the BIPM torsion-balance *G* experiment. Results of the Mk I version were published in 2001 and the apparatus was entirely rebuilt in the years 2001 to 2003. The key feature the BIPM approach is that a value of *G* can be obtained by up to three different methods. The 2001 result came from two methods, which agreed with each other closely. The present work is producing results from three different methods and the considerable challenge to be described in this paper is to obtain agreement among the three.

Summary

It is well known that the results of measurements of the Newtonian constant of gravitation, *G*, have been plagued by systematic errors, often much larger than the stated uncertainty. The problem is that the magnitude of the gravitational forces between laboratory sized masses is extremely small, in many classical torsion balance experiments typically around 10^{-12} Nm, and thus very susceptible to non-gravitational perturbing influences.

One of the special features of the BIPM torsion balance is its suspension, which is a wide but thin strip. We showed in our first paper [1] that the restoring torque of a heavily loaded torsion strip is almost wholly gravitational and thus largely immune to the usual problems of drift and anelasticity, that depend on the material properties of the strip. A wide but thin strip also allows the weight of the test masses to be much larger than for a thin wire suspension. The mass of the four Cu-Te test masses of the BIPM torsion balance amount to a total of nearly 5 kg which together with the four 12 kg source masses of the same material results in a maximum gravitational torque of some 3×10^{-8} Nm. The nearly ideal nature of the suspension results in a Q for free oscillation of 10^5, possibly limited by the minimum vacuum pressure that we can attain. The period is 120 s.

The other special feature of the BIPM apparatus is that a value for *G* can be obtained by three different methods:

1. Free deflection (Cavendish) method. In this method the source masses, which rest on a carousel, are moved to produce a gravitational torque on the suspended torsion balance and the angle through which the balance moves (31.5 arc seconds or about 150 μrad) is measured with an autocollimator. The torsion constant of the strip is then found from measurements of the period of free oscillation and the value calculated or measured of the moment of inertia of the torsion balance. Measurements of angle and timing are thus critical in this method.

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2. Electrostatic servo-control. In this method, the torsion balance is electrostatically maintained in its zero position when the test masses move. The electrostatic restoring torque is obtained from measurements of the change in capacitance as a function of angle. Measurements of capacitance, angle and ac voltage are this critical in this method.

3. Time of swing. In this method the small change in free period (some 37 ms) is measured as the source masses are moved between two positions that respectively increase and decrease the small gravitational restoring torque of the torsion balance from the source masses. This method relies upon accurate measurements of period.

Common to all three methods is the requirement for dimensional metrology of the test and source masses, a knowledge of their density homogeneity and the calculation of the gravitational coupling between them. A photograph of the apparatus is shown in figure 1.

We showed in our first paper that there is a large measure of independence between the three methods and this is a strong point of the apparatus. But it is evident that for the results to be persuasive, the three methods must lead to the same value for *G* within their respective uncertainties.

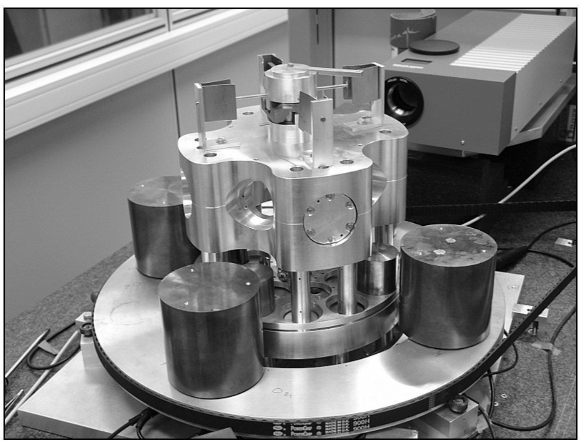

Figure 1. Photograph of the *G* apparatus with the vacuum can removed. The autocollimator is seen in the top-right.

All experimenters embarking on a measurement of a fundamental constant are faced with the problem that they cannot avoid an *a priori* knowledge of what the result is likely to be. Thus they are all subject to the same extreme psychological pressure to continue the search for systematic errors until the result is about what they expect. Various subterfuges have been adopted to overcome this problem, one of these is to carry out all the measurements but keeping one critical parameter needed to calculate the final result hidden until the very end. To adopt this method and actually carry it through to the end requires considerable courage and strong will.

In this experiment we have the advantage that it is first necessary to eliminate all those systematic errors that lead to differences among the three methods. This is already a great advance over an experiment that uses just one method. It is thus wholly justified to continue the search for errors until this condition is satisfied. There remains the problem of the parameters that are common to all three methods, notably the properties of the source and test masses and dimensional metrology.

We have also, however, used the strategy of carrying out many of the measurements before calculating certain critical parameters that would allow us to compare the results of the three methods and to deduce a value for *G*. The conclusion from this exercise, which was not wholly intentional from the beginning, is contrary to what one might expect. We found that when the parameters in question become known we discovered that there were serious, and in at least one case easily avoidable, systematic errors that could have been uncovered at a much earlier stage and much time thereby saved.

In our presentation, therefore, in addition to what we expect will be the final results of the experiment we shall make some remarks on the strategy to be adopted and pitfalls to be avoided in carrying out experiments such as these.

References

[1] T. J. Quinn, C. C. Speake, S. J. Richman, R .S. Davis and A. Picard, "A New Determination of *G* Using Two Methods," in *Phys.Rev.Lett*., vol 87, 11101, 2001.