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Progress on the BIPM Watt Balance

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Abstract

In view of the future redefinition of the kilogram, the BIPM has recently started work on a watt balance to link the kilogram with the Planck constant. This paper presents an overview of the existing experimental set-up as well as the essential ideas of the BIPM watt balance and reports the progress to date.

Key words: Planck constant, kilogram, watt balance.

1.   Introduction

The kilogram is the unit of mass in the International System of Units (SI). It is defined through an artefact known as the international prototype, which is kept at the BIPM. The international prototype was manufactured in the 1880s of an alloy of 90 % platinum and 10 % iridium. Four of the six official copies of the international prototype date from the same period. The international prototype is kept with its six official copies in a vault at the BIPM. In addition, copies of the international prototype have been manufactured by the BIPM for use as 1 kg national prototypes. The first of these were distributed in 1889. Since the 1880s, the BIPM has produced more than eighty 1 kg prototypes in Pt/Ir.

The major disadvantage of the present definition of the kilogram is that artefacts such as the international prototype age at a rate, which often cannot be known with a high degree of precision. Unknown changes in the mass unit would also influence, for example, electrical units, because the definition of the ampere is related to the kilogram.

On three occasions, roughly 40 years apart, the mass of the official copies, the national prototypes and the working standards of the BIPM have been compared with the mass of the international prototype. On the last of these occasions (1988-1992), 34 standards from national laboratories were cleaned before the definitive mass comparisons. The results of comparisons between the official copies and the international prototype show some divergence with time. Figure 1 shows the relative changes of about 5×10^{-8} in the mass of the standards since their first calibration. All measurements are represented with respect to the international prototype. For this reason, the mass of the international prototype defines the x-axis of this graph.
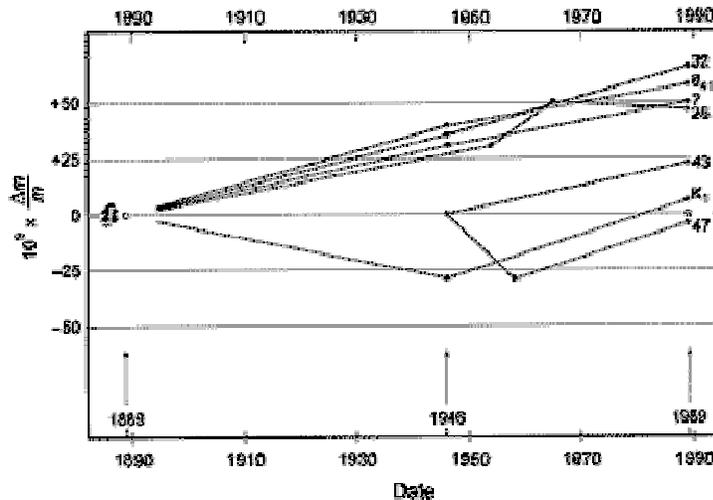
Figure 1. Relative change in mass $\Delta m/m$ of national prototypes Nos. 2 to 20 and of official copies No. 8(41) and No 32, with respect to the international prototype K

The 21st General Conference for Weights and Measures (CGPM) held in 1999 therefore recommended, in its Resolution 7, that efforts continue to refine experiments linking the unit of mass to fundamental constants with a view to a future "quantum-based" redefinition of the kilogram. Any new definition would need to have a relative uncertainty of about 1 part in 10^8 to be consistent with the current definition within its uncertainty of realization.

The existing experiments fall mainly into two classes, according to the fundamental constant to which the kilogram could be linked:

- In one type of experiment, the number of atoms in a weighed quantity of matter is determined (Avogadro project [1], ion accumulation [2]), thus establishing a relationship between the kilogram and an atomic mass.
- A second class of electro-mechanical experiments (watt balance, magnetic levitation [3]) links the kilogram to the Planck constant h.
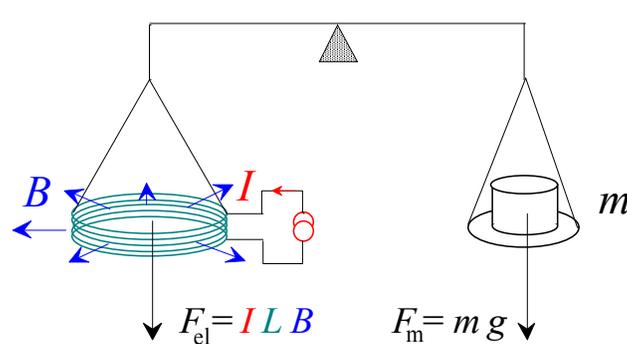
Taking into account the required uncertainty mentioned above and the levels of performance reached up to now by the different techniques we believe that the watt balance is a very promising candidate for a future redefinition of the kilogram.

One of the principle roles of the BIPM is to promote world-wide compatibility in mass measurements by providing calibrations traceable to the international prototype. Research and development are carried out in several areas in order to improve our services and understanding of the fundamental problems of mass determinations at the kilogram level. As a consequence of this and the promising results obtained recently on the determination of the Planck constant by means of the watt balance [4,5] the BIPM decided in late 2 002 to begin work on its own watt balance. The principle of the watt balance and the an overview of the existing experiment set-up as well as the essential ideas of the BIPM watt balance and reports on the progress to date will be outlined in the following sections.

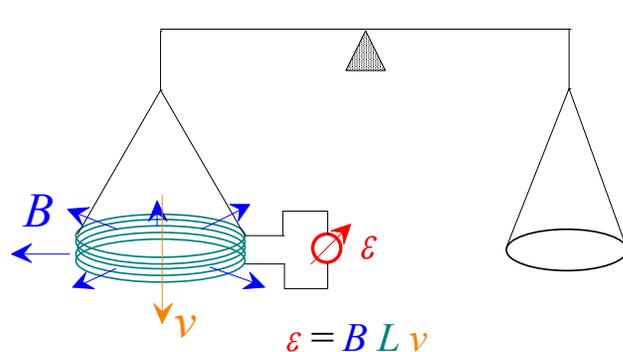## 2. Watt balance

a) Principle

The concept of the watt balance experiment was proposed by Bryan P. Kibble in 1976 [6] from his work on the gyromagnetic ratio of the proton experiment in strong magnetic field, carried out at the National Physical Laboratory (NPL). The apparatus developed measures the electromagnetic force (Fig. 2.) produced when a current I flows through a coil, with wire length L, suspended from a balance (static phase) and dived into a flux density B of a large permanent magnet. This force is balanced by a mass m subject to the earth's gravitational acceleration g. At the equilibrium state the relation is given as:

$$m\,g = I\,L\,B \tag{1}$$

Figure 2. Static phase: equilibrium between gravitational force and electromagnetic force is established by setting the appropriate current *I*.

In a separate measurement (dynamic phase), the same coil is moved vertically (Figure 3.) with a constant velocity *v* and the emf ε induced in it is measured. A second relation is then obtained as:

$$\varepsilon = v\,L\,B \tag{2}$$

Figure 3. Velocity phase: A voltage is induced by moving the coil with a constant velocity through the magnetic field.

Equations (1) and (2) can be combined to eliminate the unknown quantities describing the coil, *L*, and the magnetic field, *B*, and the resulting equivalence of mechanical and electrical power can then be written as:

$$m\,g\,v = \varepsilon\,I \qquad (3)$$

Imperfect equivalence between the two types of power can be due to the assigned value of the Planck constant. The most common errors are caused by a drift of the magnetic field between the two phases and by alignment errors.

The electrical quantities are measured using the quantum Hall effect and the Josephson effect, thereby relating them to fundamental constants. The Josephson effect allows one to determine an unknown voltage ε as a multiple ε' of a combination of the Planck constant, the elementary charge and a precisely measurable frequency f_J:

$$\varepsilon = \varepsilon' f_J \frac{h}{2e} = \varepsilon' \frac{f_J}{K_J} \qquad (4)$$

The Quantum Hall effect allows one to determine an unknown resistance *R* as a multiple *r'* of a different combination of the Planck constant and the elementary charge:

$$R = r' \frac{h}{e^2} = r' R_K \qquad (5)$$

The application of both effects on the measurement of the voltage and the current in the watt balance equation leads to:

$$m = \frac{\varepsilon_1' \varepsilon_2' f_{J,1} f_{J,2}}{r'} \frac{1}{g\,v} \frac{h}{4} \qquad (6)$$

Where the first component on the right side shows the quantities related to the measurement of the voltage and the current using the macroscopic quantum effects, the second component shows the mechanical measurands such as gravitational acceleration *g* and velocity *v* and the last term is the Planck constant. This equation establishes the link between the macroscopic mass *m* and the Planck constant *h*.

Initially, the experiment would be carried out to determine *h*, based on the present definition of the kilogram. If the uncertainty has been reduced to several parts in 10^8 and the metrology community feels sufficiently confident about the results, the best value obtained could be used to define the value of the Planck constant (without uncertainty), this being equivalent to redefining the kilogram. After an eventual redefinition, a watt balance experiment should permit one to monitor the mass stability of the present international prototype as well as to disseminate the mass unit.

b) Existing experiments

At present, five watt balances are disseminated around the world. The NPL (UK) began to construct the first watt balance soon after the original proposal by Kibble [6] in 1976. The balance is constructed as a classical beam balance and the magnetic field is produced by a permanent magnet. Results obtained with the first version of the apparatus had a standard uncertainty of 2 parts in 10^7 and were published in 1990 [7]. A new result with the Mark II apparatus is expected for 2008.

The NIST (USA) started its experiment only a few years later with an electromagnet, which was subsequently replaced by a superconducting magnet. Instead of a balance beam, a rotating wheel is used which restricts the movement of the coil to the vertical axis. In 1998, results with an uncertainty of 9 parts in 10^8 were published [8]. Further improvements permitted a reduction in the uncertainty to 5 parts in 10^8 in 2005 [9] and to 3.6 parts in 10^8 in 2006 [10]. All results are in good agreement. A further reduction of the uncertainty is expected in the near future.

METAS (Switzerland) started its watt balance project in 1997. The most obvious difference from the other experiments is the small size of the apparatus as a consequence of using a test mass of only 0.1 kg instead of 1 kg [11]. During the velocity mode, the moving coil is decoupled from the mass comparator and replaced on the suspension during the force mode.

The LNE (France) started to develop its watt balance in 1999. This will be a medium-size apparatus working with a mass of 0.5 kg [12]. One of the design criteria was to avoid an unbalance of the mass comparator during the moving mode. This will be achieved by moving the balance together with the coil. Many of the components of the experiment have been developed and assembled in 2007.

The BIPM started to launch the watt balance project late in 2003. The first two years were spent on reflection on the general concept of our apparatus, followed by first developments in spring 2005 [13]. The BIPM watt balance is described in more detail in next section.

3. The BIPM watt balance

The essential and similar characteristic of the four first watt balance experiments is that all of these experiments follows the principle proposed by Kibble in 1976; i.e. the realisation of the mechanical and electrical powers are achieved in two distinct phases of measurements, which are given by the force and velocity modes. Equation (3) which gives the equality of the mechanical and electrical powers is based on the assumption that the geometry of the moving coil and the flux density magnitude of the magnetic source remain stable between the two phases of measurements. The electrical as well as the mechanical orientation regarding the vertical motion of the moving coil and the magnetic circuit must also be kept stable between the two phases. The temperature coefficient of the remnant magnetization of the SmCo magnets, used for the permanent magnets in the existing watt balances, is about 0.035 %/K. Therefore small temperature changes of the magnet lead to significant changes of the magnetic flux density. In addition, the moving coil has six degrees of freedom and during the experiment its

orientation must be kept as stable as possible between the velocity and the force phases of measurements. If both measurement phases are carried out sequentially, at a time interval of typically one hour, the magnetic flux density as well as the alignments of the moving coil can therefore be significantly different. From these two main constraints we plan at the BIPM to carry out both parts of measurements simultaneously. A constant current will be injected into the coil to create a magnetic force to balance the weight, while the coil is moving at constant velocity through the magnetic field. The induced voltage will be superimposed on the voltage across the coil due to the current flow. Both types of voltages need to be separated with an uncertainty of the order of 1 part in 10^8. Most critical in this respect is the large temperature coefficient of the electrical resistance of the coil, 0.4 %/K. Resistance changes due to temperature fluctuations of the wire during the time of a measurement (of the order of 1 minute) would mask changes of the induced voltage. We therefore plan to ultimately use a superconducting coil in which the resistive voltage drop would not exist. In this "cryogenic watt balance" the permanent magnet will also be held at cryogenic temperature. Another advantage is that the nominal value of the current applied to the superconducting coil can be adjusted, for example to work with a larger test mass than the 100 g mass planned, without creating additional Joule heat. The drawback is, of course, that in such an environment, alignments are more difficult to carry out due to the restricted accessibility of the magnetic circuit, and maintaining alignment when going from room to cryogenic temperatures is also much more difficult. We therefore plan to maintain the alignment dynamically by servo-controlling the coil position with respect to the magnetic field.

We have started to develop a room-temperature experiment to test the feasibility of simultaneous force and velocity measurements and to test the alignment procedure. We expect to reach a relative uncertainty below 10^{-5} with this version of the experiment.

I. General design

For force measurement, the watt balance experiment needs a balance from which a moving coil is hung via a suspension. A pan is integrated in this suspension in order to receive the test mass of 100 g whose weight is balanced by injecting 1 mA constant current in the coil to create a magnetic force. A motor is also integrated in the suspension to generate the vertical displacement of the moving coil in the total range of 20 mm at constant velocity. The velocity measurements of 0.2 mms^{-1} are carried out by means of a Michelson interferometer. To generate the electromagnetic force, the moving coil is dived in permanent magnetic circuit having a flux density of about 0.5 T. In opposition to the NPL, NIST and BNM watt balances, the design of the BIPM experiment has the balance and the magnet fixed and the coil displacement is carried out by contracting or extending the coil suspension hung from the balance. Further details as well as some preliminary results are reported in the next sections.

II. Coil suspension

The coil suspension (Figure 4) was designed and assembled at the BIPM, which includes electrostatic motor, expander, the coil and the suspension itself permitting one to generate a vertical displacement of the moving coil.

The upper part of the suspension (spider) is designed to support the electrostatic motor and the expander. This part will be hung from the balance via a universal joint made of cross Cu-Be flexures. The gimbal is essential in order to lock the resulting force, coming from the coil suspension, at the same point of application of the balance connection. The connection to the expander is carried out by means of three other Cu-Be flexure-strips, they are tightly clamped to the spider and to the expander (three beams at 120°).The spider includes mechanical stops to limit beam rotations to ±100 mrad and supports the electrostatic motor.

The expander is composed by an electrostatic motor to generate a vertical motion of the moving coil via the three beams connected to the lower part of the suspension.

The electrostatic motor is composed of two mobile electrodes placed on each side of a plate connected to ground and fixed to the spider. By applying a high voltage on the electrodes, an electrostatic force is created and the movement of the mobile electrodes is transmitted via the three beams at 120° to the lower part of the suspension (moving coil and test mass pan). In order to work at the most linear part of the motor, the previous distance between the two electrodes has been widened. The quadratic behaviour with the voltage has been linearised by applying identical bias voltages to both high voltage electrodes, and by superposing opposite control voltage to them. The voltages are provided by two power supplies and modulated by means of a digital signal coming from a computer. High voltage of 6.5 kV can be reached with a rate of 10V/ms.
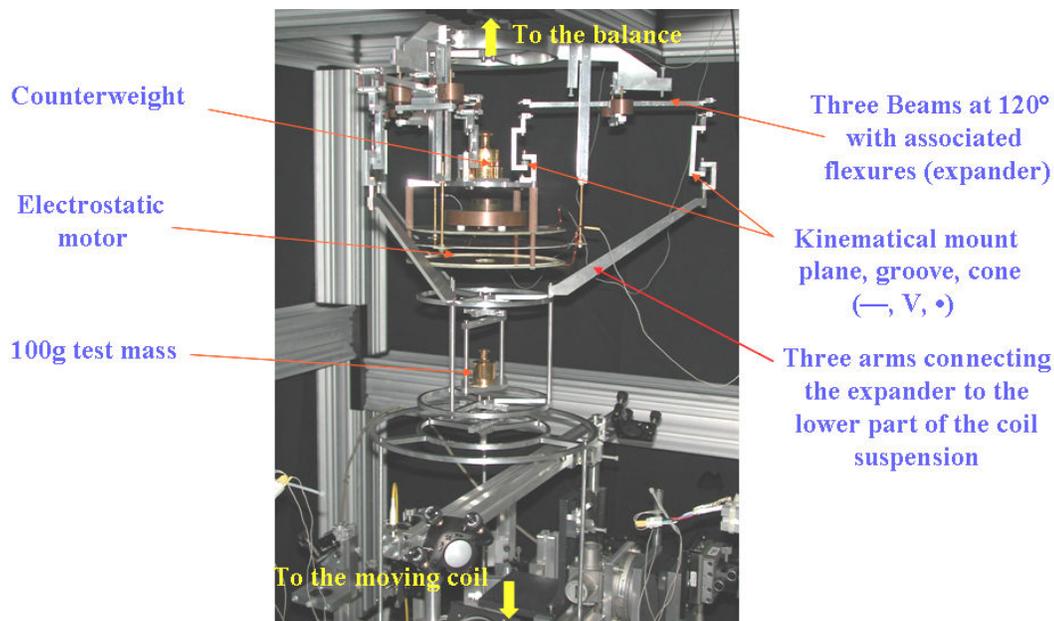

Figure 4. Picture of the coil suspension which allows the generation of a vertical motion of the moving coil at 0.2 mm/s on a total path of 20 mm.

In order to minimise the electrostatic force, the mass of the lower part of the suspension (coil side) is counter weighed within 100 mg by additional masses set on a plate receiver connected to the moving electrodes. So far, the electrostatic motor has the capability to compensate overload up to 1.7 g. The use of flexures for all connections of the expander among the beams, the electrodes and the upper and the lower parts of the suspension permits generation of a frictionless motion and a smooth displacement of the coil. Nevertheless, misalignments of the beams, electrodes and the suspension or imperfect flexures clamping among these three parts could generate instability of the flexures or nonsymmetric restoring force as function of the beam rotation angle. The electrostatic force F_e necessary to generate vertical motion of the moving coil was measured in these both cases: F_e(+10 mm) =22 mN and F_e(-10 mm) = 23 mN.

To evaluate the misalignment of the moving coil, a study was carried out for the full range (20 mm) of the coil displacement by means of four Position Sensitive-Detectors (PSDs) to measure the six degrees of freedom and preliminary results were obtained during the travel of the moving coil. The horizontal displacements of the coil are within 100 µm and 600µm for X and Y directions, respectively. The horizontal coil inclinations θ_X and θ_Y are within 200 µrad and 50 µrad for X and Y directions, respectively. The vertical rotation θ_Z along the axe $_Z$ is about 1.5 mrad for the complete path. The good reproducibility of the results, obtained for each degree of freedom, shows that it will be possible to lock up the coil position of the moving coil by adding an electrostatic servo control. That will be the next step to improve our coil suspension by applying, for each degree of freedom, a servo-control in order to have dynamic alignment control with respect to the magnetic circuit. So far, electrostatic control of the vertical rotation θ_Z of the moving coil has been integrated and tested. It is composed of three grounded gold-plated glasses fixed on the three rods at 120° connecting the moving coil to the upper part of the suspension. In order to minimise any horizontal force, these cathodes can be adjusted vertically by auto-collimation technique within 0.3 µrad. Each cathode is in a sandwich between two electrodes on which high voltages are applied to generate the necessary electrostatic forces to servo-control the vertical rotation within 50 µrad for the whole 20 mm path of the moving coil. The high voltages applied to the six electrodes are proportional to the error signal given by the already install Position Sensitive-Detector (PSD) and its associate optical bench. This device reduces by a factor thirty the undesirable vertical rotation θ_Z observed without any servo-control.

In addition, work has started on the control of the unwanted horizontal inclinations θ_X and θ_Y of the moving coil during its displacement. The design is based on four piezo-electrics mounted in push-pull mode to transmit horizontal inclinations in both axes of the moving coil having its point of rotation at its centre of mass. A design has been elaborated and theoretical investigations on its servo-control feasibility have been studied. Work needs to be done to improve the ΔX and ΔY horizontal displacements during the vertical travel of the moving coil, which are still too large.

The coil hung from the suspension has been machined at the BIPM. The wire has been wound as perfectly as possible to reduce induced voltages due to a

rotation of the coil. This is difficult because about 30 layers for a total of 1200 turns need to be wound. Different methods of winding and gluing the wire have been tested.

III. Magnetic circuit

The magnetic circuit defines the size of the experiment; we opted for a table-size experiment to ease control of the alignment of the experiment and to facilitate cooling to the cryogenic temperature. The main characteristics of the magnetic circuit are now defined as a result of the study undertaken with help of an engineering company (CEDRAT, Grenoble) . The main feature is that the air gap and the magnets will be surrounded by a soft iron structure, forming a closed magnetic circuit, so that the coil in the air gap will be well protected against external magnetic perturbations. The flux density will be about 0.7 T.

The magnetic circuit is constituted of two central Sm_2Co_{17} permanent magnets (B_r = 1T) inside a symmetrical closed yoke made of FeNi alloy, having large permeability and being compatible with the low temperature. The dimensions of our magnetic circuit were determined by means of a finite element simulation to reach the optimum homogeneity in the pole gap where the measurements are made. The gap will have a diameter of 250 mm and a width of 13 mm to accommodate the coil. The fact that the magnetic circuit is closed provides the great advantage of low stray fields ($<10^{-4}$ T) and good isolation against external fields. In theory, the symmetry of the structure should result in a very uniform field profile in the gap within twenty ppm for the whole of the travel range of the moving coil. Mechanical designs have been studied taking into account the geometric constraints, which are crucial in the realisation of the magnetic circuit. The assemblage of the different parts are designed to take into account the mechanical stability between room and cryogenic temperature for which magnetic circuit will be located. The assembly procedure is also an essential point of the conception of our magnetic circuit due to the fact that the magnetic forces (10 kN) rose during the assembly. The design takes into account that the Sm_2Co_{17} permanent magnets are difficult to machine and to use as a reference surface. In addition, the components are selected in function of their magnetic properties, thermal expansion and cryogenic behaviours. Nine segments of permanent magnets are sandwiched between two FeNi discs. The Vacuumschmelze company, Hanau, Germany, will be able to furnish us with the permanent magnets in sandwich shape. A contract with WZL/RWTH, Aachen, Germany, for a complete evaluation of the machining feasibility has been signed to investigate more carefully the machining procedures and the process needed to assemble the components as a function of the mechanical requirements. The final magnetic circuit will be delivery in the first half of 2008.

In the meantime, a simplified magnet system has been constructed at the BIPM, which is being used until the definitive system will be delivered. A flat coil has been also machined, on a circuit board, in shape of spiral having external diameter of about 200 mm. This coil model should be used as pickup coil to align horizontally the solenoid coil coming from the NIST.

IV. Coil velocity measurement

The velocity is measured using a commercial four path heterodyne Michelson interferometer. The frequencies of both orthogonally polarized components of the beam have been calibrated at the BIPM. The quality of the interferometer optics has been evaluated using auto-collimation techniques. We obtained a significant angular deviation between the transmitted beam with respect to the incident beam of about 0.2 mrad. It is therefore necessary to make the vertical alignment of the measurement beam between the interferometer and the moving coil. An optical system to align the beam along the local gravity vector has been developed. The horizontal reference is a mirror whose orientation has been previously aligned using a mercury pool. Its horizontal inclination can be monitored by using two highly sensitive spirit levels. Preliminary measurements of the moving coil velocity using the interferometer have been carried out. We obtained a standard deviation of about 35 μm/s for a total travel range which is relatively high and needs to be reduced. Additional investigations were carried out to evaluate the performance of the interferometric measurements and check possible noise sources coming from the interferometric measurement set-up. From these investigations, the optical system for the velocity measurements was entirely reviewed and found to have a better integration and adaptation for the interferometric measurements of the experiment. The system is directly mounted on the permanent magnet and it also incorporates various elements for commercial and independent frequency detection.

V. Voltage measurements

The accuracy of the room temperature experiment will be limited by the temperature coefficient of the electrical resistance of the coil and by the temperature stability of the magnetic circuit. We plan to use, in addition to the moving coil, a second non-inductive fixed coil, carrying the same current, which should allow us to track the variations of the resistance with temperature. The induced EMF of 0.1 V will initially be measured with a digital voltmeter, and later by opposing it with the output from a programmable Josephson array.

The stability of the ratio from the induced voltage to the velocity gives (equation (2)) the profile of the magnetic circuit. Results of this ratio are strongly dependant on the synchronisation of the velocity acquisition coming from the interferometer and the voltage coming from the voltmeter. The voltage is integrated during 60 ms (3 PLC) whilst the acquisition of the velocity is carried out at 1 kHz. So far, the phase shift between the beginning of the voltage integration and the first acquisition of about 1200 data, for one way travel of the moving coil coming from the interferometer, is about 40 μs with 10 μs jitter at the 1 kHz rate.

VI.   Force measurements

For the magnetic force, which must balance the weight of a 100g test mass, we plan to maintain the current in the coil constant at a nominal 1 mA during the coil movement. We have developed a first version of a current source which delivers 1

mA with a short term stability of about 2 parts in 10^7. A voltage reference of 10 V (integrated circuit) and a 10 kΩ resistor are connected in series between the input terminals of an operational amplifier. The current flows through the resistor and is controlled such that it creates the potential difference necessary to bring the amplifier input to zero.

For gravitational force measurement, we purchased, according to our timetable and in order to save time, a commercial weighing cell having load capability of about 10 kg with a resolution of 10 μg. This weighing cell adapted for our purpose should permit us to start the second phase of our study; i.e. the feasibility of the simultaneous force and velocity measurements. Therefore, the ratio of the gravitational force to the current (equation (1)) will be investigated in 2008; this ratio should be in agreement with the voltage velocity ratio.

4.   Acknowledgements

5.   Conclusions

Since the beginning of the development in spring 2005, considerable progress has been made on the BIPM watt balance. We have started to develop a room-temperature experiment to test the feasibility of simultaneous force and velocity measurements. Moving coil displacement is at present servo-controlled in vertical Z direction as well as in vertical Z rotation. We are able to simultaneously acquire the velocity and voltage and deduce their ratio. We expect in the next two years to reach a relative uncertainty below 10^{-5} with this version in room temperature but under vacuum.

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