Report on the meeting of the CCEM working group on electrical methods to monitor the stability of the kilogram – June 2002

30th August 2002

This was an informal meeting which was held after the CPEM 2002 conference on the morning of the 23rd June 2002 at NRC in Ottawa Canada.

Participants

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Observers

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Watt Balance Technical Meeting

The meeting was held on the 22nd June 2002 at the NRC in Ottawa Canada. All four groups (BNM, METAS, NIST and NPL) which are active in this field were represented. The aims of the meeting were to prioritise topics for future meetings and discuss the laboratory environment needed to operate a watt balance and discuss techniques for the mechanical alignment of the apparatus.

The meeting provided a useful forum for the discussion of detailed issues of the operation of watt balances and the participants agreed that the meetings should be continued at least annually. Priority for hosting the meeting would be given to laboratories actively pursuing the design, construction or operation of a watt balance. The next meeting will be hosted by BNM in June 2003 and will precede the next meeting of the kgwg. The topics chosen for the next meeting were:

1) Generation and measurement of the magnetic field: including magnet design, hysteresis and stability.
2) Aspects of vacuum mass measurement: including storage, transportation, surface and pressure effects.

Zagreb Electrostatic Watt Balance

This balance is operated using the same virtual work principal as the Watt balances described below. Its aim was to weigh a kilogram mass with an uncertainty of 1 part in 10^8 using electrostatic rather than electromagnetic force. Unfortunately funds for the project are no longer available and work on the experiment has stopped.

NMIJ/AIST Levitated Mass

This apparatus measures the increase of gravitational potential energy of a superconducting body when the magnetic flux supporting it is increased by a measured amount. Over the last two years work has been aimed at reducing the uncertainty in the measurement towards 1ppm by measuring the attitude of the floating body. Funds for the experiment have been reduced and now support one scientist.

PTB Ion Beam Deposition

This experiment is a modern version of the determination of the electrochemical Faraday constant. A 20kV Ion source and a dipole magnet are used to select singly charged Gold ions and direct them towards a collecting cup. If the ions are collected carefully, one electron per ion enters the cup allowing the number of gold atoms collected to be determined from the integral of the current flowing from the cup. The mass of Gold collected is determined by weighing.

A successful preliminary test of the system has been made at the 1% level using a reduced ion current and a quartz microbalance. Present work is focussed on increasing the ion beam current either by designing a new source for gold ions or a source for Bismuth ions which may give the twin advantages of allowing beam currents up to 30mA and eliminating the use of Argon in the ion source. The increased ion current would allow 10g of Bismuth to be collected in 6 days. The success of the experiment depends on retaining the neutralised ions in the collector. An array of quartz microbalances, placed in front of the collector, will be used to determine the quantity of atoms reflected from it. The in-vacuum balance for weighing the collector has been made and is now under test.

The project is fully funded for the next three years with 2 permanent staff and others when needed (equivalent to 0.5 person). Their aim is to produce a 0.1 ppm result by 2007

Avogadro - Silicon Crystals

This technique relates the kilogram to the Avogadro constant N_A by precise measurements of the lattice constant, density and molar mass of a silicon crystal. The technique is being actively pursued by a large number of groups around the world. The present uncertainty of the technique has been improved from 0.4 ppm to 0.17 ppm over the last two years.

The 3 ppm discrepancy in the molar volume of the silicon crystal NRLM3 is still under investigation. Improvements have been made in the understanding of the void formation mechanism and hydrogen, present during the growth of the crystal, is implicated in the formation of large numbers of nm scale vacancies. A search for the voids using X-ray scattering from an intense collimated source has so far proved inconclusive. All other 17 different crystals prepared at NMIJ, PTB, and IMGC have shown consistent values of the molar volume, that are lower than the present CODATA recommended value by about 1 ppm. Infrared scattering data on size-evaluated voids have shown that the effect of voids on the molar volume of a properly grown crystal is less than 0.01 ppm.

Future work is focussed on the production of an isotopically enriched crystal having a purity greater than 99.99 % ^{28}Si to reduce the uncertainties associated with the measurement of the molar mass. By improving measurement techniques in each contributing measurement, the group plan to reach an uncertainty of 5 parts in 10^8 by 2005 and 2 parts in 10^8 by 2008.

The project has about 25 full time scientists at various laboratories around the world.

Watt Balances

The experiment is carried out in two parts: firstly a mass *m* weight *mg* is weighed against the force acting on a conductor carrying current *I* in a magnetic field; secondly, the geometrical properties of the conductor and strength of the field are measured by moving the conductor in the field at a measured velocity *u* and measuring the voltage *V* so generated. The measurements are combined to equate virtual electrical power *IV* to virtual mechanical power *mgu*. By measuring *V* and *I* by suitable combinations of the Josephson and Quantum Hall Effects *m* can be equated to Planck's constant h, the metre and the second. The gravitational acceleration *g* is measured using an absolute gravimeter.

BNM Watt Balance

The project is in the middle of its design phase. The system will use a Samarium cobalt magnet generating a radial field of 1T at the coil radius of 130mm. The coil will have 600 turns and will remain fixed to balance at all times. During the weighing of their Au/Pt alloy 500g working mass 5mA will flow in the coil. Voltages and resistances will be measured by direct comparison against Quantum Hall Effect and 1V Josephson Effect devices. For the moving part of the experiment the balance and coil will be moved together on flexible strips at 2 mm/s. The velocity of the coil will be measured with a laser interferometer using heterodyne techniques. The acceleration due to gravity will be measured with a gravimeter which employs cold atoms as the test mass.

Four laboratories are participating in the project:

BNM-INM/CNAM: optics, masses, balance and mechanics
BNM-LNE: mass transfer between air and vacuum
BNM -LNE/LAMA: electricity and magnetism
BNM-SYRTE/OP: gravimetry

The resources applied to the project are equivalent to 5 full time scientists.

The project has the long-term aim of reaching an uncertainty of less than 1 part in 10^8. By the end of 2003 they intend to have moved into their new building, have a complete specification for the component systems of the apparatus and have constructed a prototype apparatus.

METAS Watt Balance

The METAS Watt balance has been assembled and is operational. The system measures a 100g mass and uses completely separate mechanisms for moving the coil and weighing the force it produces. The system has been assembled and tested in air and has achieved a repeatability of 6 parts in 10^7. The magnet-coil assembly is being redesigned as the existing setup exhibits excessive hysteresis following a weighing. The apparatus is due to move to new accommodation in a class 10000 clean room which will offer an improved laboratory environment in terms of cleanness, vibration isolation and temperature stabilisation. In the meantime, extensive tests are being conducted under vacuum conditions.

The project aims to reach an uncertainty of less than 1 part in 10^8 and has very high priority within METAS. The project employs the equivalent of 3 full time scientists.

NIST Watt Balance

The apparatus has been completely rebuilt, incorporating many improvements learned during operation of the previous system. The measurement systems and basic operating programs were successfully reused with upgraded computers. Extensive velocity and low-mass force measurements in vacuum were conducted in 2000-1, leading to improvements such as an *in vacuo* center-alignment procedure, and the addition of ceramic, diamond-like coated material for the knife-edge and flat. A major noise source was found and reduced by designing a new, stiffer coil to eliminate low frequency resonances that disturbed the relationship between the interferometrically measured velocity and the generated voltage. In early 2002, operations at full magnetic field strength allowed force measurements in air using a kilogram. The group intends to run the apparatus directly against a Josephson series-programmable voltage standard. Preliminary, i.e. uncalibrated, watt values from automatic operation in both velocity and force modes are now regularly obtained. Present work is also addressing further noise reduction with an even more rigid coil, increased stabilization of the magnetic field magnitude, five-room, building temperature control, active vibration control of the balance, and generation of simulated test data. The group is aiming for 1 in 10^7 by the end of 2002 and 1 in 10^8 at the end of 2003, when the project is due to move into the NIST Advanced Metrology Laboratory. Adequate funding is available for the project, which supports 3 full-time staff and 3 part time guest researchers.

NPL Watt Balance

The NPL Watt balance has made over 1000 measurements in vacuum between January 2000 and November 2001. Many of these measurements were part of the search for the origin of the 3 part in 10^7 change in the value which occurred in mid April 2000. The shift is now attributed to slow changes in the angle of the balance support which can introduce a slowly varying error proportional to the product of the horizontal velocity of the coil and the corresponding horizontal force in weighing mode. The major modifications have been made to the apparatus to eliminate this problem by measuring and nulling the horizontal movement of the coil. The apparatus is being realigned and should resume measuring in September 2002. It is intended to obtain a result from this system with a target uncertainty of better than 5 in 10^8 by July 2003. It is then intended to transfer the apparatus into a new vacuum chamber in the new building for NPL.

Funding for the project is guaranteed to September 2005 and supports 1 full time scientist with support from other parts of NPL. There is the possibility that further funding may be made available following the outcome of a review of the project commissioned by the National Measurement System Policy Unit (NMSPU) which funds the work and is a part of the UK Department of Trade and Industry (DTI).

NMIJ/AIST Josephson Array

A Josephson junction array was described which operates at 10 Kelvin and is therefore suitable for use with a small refrigerator. The array operates at 16GHz with a critical current of 1mA at 1V. The arrays may be available from NMIJ/AIST.

Gravimeter Comparison: ICAG 2001

Every three to four years an international comparison of gravimeters is held at BIPM in Paris. A significant number of absolute gravimeters from around the world make measurements at different times and at different sites within BIPM. The results are combined to eliminate the differences in position and time of measurement and assess the underlying differences between the instruments. The gravimeters associated with the METAS, NIST and NPL watt balances took part and so it is possible to assess the differences between them and also their differences from the comparison reference value. The majority of the gravimeters in the comparison are very similar in design, it is hoped that, in future, the BNM ‘atom’ gravimeter will be able to participate to help detect and eliminate any small errors which may remain in either design. The results of the comparison have not yet been published but the preliminary results show that the uncertainty due to the gravimeter will not limit a watt balance in reaching uncertainties of 1 part in 10^8.

Collaborations with other working groups and consultative committees

To foster stronger links between the differing methods of monitoring the kilogram Peter Becker, the chairman of the CCM Avogadro working group, was invited to observe the meeting of this group and Ian Robinson was invited to observe the meeting of the Avogadro working group. The CCM now has a working group on Gravimetry which is of interest to all the watt balance groups. Also there is an interest in coordinating work on vacuum weighing on topics such as surface and pressure effects in different gases and techniques for transporting masses of differing materials either under vacuum or in an inert gas atmosphere. The CCM could be invited to participate in this activity.

Planck's Constant

Considering the present progress in measuring Planck's constant, the working group recommends to the CCEM that no change be made to conventional values, or their uncertainties, that are based on value of Planck's constant and its associated uncertainty.

Conclusions

All the groups engaged in this activity have made considerable progress over the last two years. Within the next two years it is likely that all the Watt Balance groups will have data with uncertainties considerably better than 1 part in 10^7 and will be moving towards the target of 1 part in 10^8. During this period it should be possible to assess the relative agreement between the various groups and the existing CODATA recommendations.

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