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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1109/CPEM.2014.6898445>

2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), pp. 434-435, 2014-08

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Recent Improvements of the NRC Watt Balance

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Abstract — We describe the modifications and improvements that have been made over the past two years to reduce the uncertainty of the NRC watt balance.

Index Terms — Planck's constant, watt balance, electronic kilogram, measurement uncertainty.

I. INTRODUCTION

In 2011, after completing the assembly of the NRC watt balance in Ottawa and its re-alignment, an initial measurement of Planck's constant was performed with a relative uncertainty of 65 parts in 10^9 [1]. The goal at that time was to duplicate the NPL experiment as closely as possible. From this experience a number of limitations were identified and a program began to reduce the most significant uncertainty components and to improve the overall accuracy of the experiment. The following are the most significant changes.

II. SUMMARY OF THE MAIN MODIFICATIONS

A. Mass Exchange Errors

In 2011, the largest uncertainty component was due to the correction of the mass exchange errors [2]. Two effects associated with the weighing process produced significant systematic errors and the uncertainty in the applied corrections was evaluated at 59 parts in 10^9 . The first effect, the tilting of the beam during mass exchanges, was minimized by replacing the original coil support with a more rigid structure and by adjusting the center of mass of the beam. The second effect, the tilting of the central flat, was eliminated by building a new mass lift which is detached from the balance support plate. These modifications reduced the size of the effects to about 2 parts in 10^9 . These modifications had two additional benefits: First, the tilting of the balance during mass exchanges caused a displacement of the coil and, as this effect was eliminated, alignment uncertainties associated with this displacement were also reduced. Second, the reproducibility of the results and therefore, the type A uncertainty, was greatly improved.

B. ADC non-linearity

The accuracy of the voltage measurements was limited by non-linearity of the ADC that was originally integrated with the nanovoltmeter [3]. The issue was eliminated by replacing the ADC with two Agilent 3458 voltmeters. Besides reducing linearity errors to less than 1 nV over a 1 mV range, this modification also improved the voltage-velocity synchronization of the moving phase measurement and

allowed for the reduction of the gain of the nanovolt-amplifier, which increased its bandwidth.

C. Modification of the coil suspension

The original coil suspension consisted of a top section, the stirrup, which pivots about the end-knife of the beam, parallel to the y-axis, and a bottom section comprising the coil and its supporting structure. The top and bottom sections were joined by two sets of flexural gimbals that allow pivoting about the x and y axes [4]. The suspension was modified by inserting a middle section between the stirrup and the coil. The middle section is joined to the stirrup by a set of flexural gimbals to give one additional pivoting axis parallel to the x-axis. This modification allows for the measurement of the coil horizontal forces during normal balance operation and resulted in reduced uncertainty due to these forces.

The length of the middle section was chosen so that, after the addition of the middle section, the mass pan would be positioned at the turning point of the magnetic field, where the gradient is minimal. Due to this change, the force due to the magnetic susceptibility of the test mass represents only a few parts in 10^9 of its weight, and the uncertainty of this correction is negligible.

D. Improvement of the angular velocity measurement

The autocollimators used to measure the coil angular velocities, ω_x and ω_y , were characterized to determine their accuracy [5]. The tests revealed that the autocollimator that was originally used for this measurement had a distance dependence that resulted in a measurement uncertainty of about 60 nrad/mm. By replacing the autocollimator we reduced this uncertainty to 20 nrad/mm. This figure affects the alignment uncertainties due to the coil torques ($\omega_x \tau_x$, $\omega_y \tau_y$) and the uncertainty due to the correction of the Abbe error. The combined uncertainty of these effects is now on the order of 4 parts in 10^9 .

E. Mode leakage

Until 2011, the interferometer used a polarization stabilized laser. This type of laser produces two different modes whose frequencies are typically different by about 700 MHz. Ideally only a single frequency should reach the interferometer. However, a small fraction of the unwanted mode leaks into the interferometer and produces an error in the velocity measurement. For a typical leakage of about 1 % of the total power, the error is about 14 parts in 10^9 . This problem was eliminated by replacing the original laser with one that uses

transverse-Zeeman frequency-stabilization. This laser produces two modes as well but their frequencies differ only by 500 kHz, which results in negligible mode leakage error. Other modifications to the optics include coupling the laser into fiber optics. This allowed us to use a fiber collimator to launch the laser into the experiment, thereby improving the pointing stability, and enabled us to have our laser calibrated in-situ by the NRC time and frequency laboratory through the use of a fiber optic link that connects with the watt balance laboratory.

F. Mass calibrations

The test mass used to obtain the 2011 results was calibrated in vacuum at NPL. The uncertainty in the value of the mass was dominated by changes that occurred during transport between NPL and NRC. In 2012, a new M-one vacuum mass comparator was commissioned at NRC and the air-to-vacuum traceability chain, to link the watt balance test masses to our Pt-Ir prototype K74, was investigated. Furthermore, another Pt-Ir mass, K50, was sent to BIPM for calibration in 2013. These improvements achieved an uncertainty for the watt balance reference mass of about 9 parts in 10^9 at 1 kg.

G. Gravitational corrections

In 2013 we modified the watt balance control software to make use of more accurate models to calculate geophysical gravitational effects (earth tides, polar motion, ocean loading and atmospheric pressure) [6]. The uncertainty of these models was assessed at the Canadian Absolute Gravity Station (CAGS) using a superconducting gravimeter and it was deemed to be smaller than $1 \mu\text{Gal}$.

III. THE 2013 MEASUREMENT CAMPAIGN

A measurement campaign was run from September to December, 2013 to obtain a new measurement of Planck's constant with improved uncertainty. We measured four different masses: m_1 (1kg Au-plated Cu), m_2 (0.5 kg Si), m_3 (0.5 kg Au-plated Cu) and m_4 (0.25 kg Si). The masses were calibrated at the NRC mass laboratory before and after watt balance measurements.

The full alignment state of the watt balance can now be measured in vacuum [5] and it was determined for each of the test masses at least twice during the span of the measurements. Other supporting measurements include:

- The 50Ω standard resistor was measured three times during the campaign using a portable Quantum Hall resistance standard and a portable cryogenic current comparator [7].
- The laser frequency was calibrated in-situ three times, at the beginning, middle and end of the campaign.
- The average gravitational acceleration in the laboratory was measured in June and December 2013.

The results of these measurements will be presented at the time of the conference

ACKNOWLEDGEMENT

This work has benefited from the support of many people. From NRC, Dave Inglis has been involved with the project since its inception, Jacques Laird has conducted the gravity modeling, Richard Green has performed our vacuum mass measurements and Alan Madej has provided laser frequency measurements. From NPL Stuart Davidson and Keith Berry provided mass calibrations for our earlier measurements and have loaned us the use of several silicon masses. Ralph Behr and Luis Palafox of PTB have provided the programmable Josephson chip. Finally, we wish to thank Ian Robinson of NPL for his enormous contribution to this project and his continued support

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