RECONSTRUCTION AND PRELIMINARY TESTS OF THE NIST ELECTRONIC KILOGRAM EXPERIMENT

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Abstract

The NIST electronic kilogram experiment is being completely rebuilt into a vacuum chamber within a specially designed laboratory room. Major renovations include reference mass positioning equipment, structural alignment flexures, and a redesigned inductive coil. The goal is less than 10 nW/W uncertainty. Preliminary data on measurement capabilities are expected.

Background

The Watt balance experiment at the National Institute of Standards and Technology (NIST) is designed to make a determination of the SI Watt unit. It uses the Kibble concept [1] of calculating virtual power by balancing mechanical force with electrical force via the Olsen design [2] of using a radial magnetic field. Briefly described, the NIST experiment statically balances the weight of a kilogram mass standard against an electrical force, measured as the current in an inductive coil within a magnetic field. The ratio of force to current is proportional to the field, which is separately calibrated by moving the coil vertically through the balance position, measuring a ratio of velocity to generated voltage. Combining these proportionality ratios and rearranging them gives a ratio of familiar equations for mechanical and electrical power (Eq. 1).

$$\frac{F}{I}\bigg/\frac{U}{v}=\frac{(F\bullet v)_z}{U\times I}=\frac{\{mgv\}}{\{UI\}}\frac{\mathrm{W}_{\mathrm{SI}}}{\mathrm{W}_{\mathrm{elec}}}\equiv 1. \quad (1)$$

Here, F is the force of gravity g on a mass m, v is velocity, U is voltage, I is current, W_{SI} is the watt unit in SI, and $\mathrm{W}_{\mathrm{elec}}$ is the electrical watt unit in terms of defined values for the Josephson constant and von Klitzing constant. Since no motion is induced in the current-force mode, and no current is drawn in the velocity-voltage mode, the calculated powers are virtual; frictional and heating losses are essentially eliminated.

The use of the Josephson effect and quantum Hall effect as references for voltage and resistance respectively, allows a determination of the Planck constant h and other fundamental physical values. Of the main reference units in the experiment: mass, length, time, voltage and resistance, only mass is a non-quantum based reference. By improving the precision of the watt balance to 10 nW/W or better, it becomes feasible to monitor the long term drift of the SI artifact mass standard. This essentially ties the SI mass standard (the kilogram) to electronic reference standards that are reliant only on a constant h, thus the name electronic kilogram experiment.

New Construction to Reduce Uncertainty

In our 1998 reported value for Planck's constant [3], the uncertainty was 85 nW/W. To decrease the overall uncertainty for monitoring the kilogram, most of the experiment and its environs were completely rebuilt. We will describe in this paper some of the experimental changes and resulting lowered uncertainty components.

The largest uncertainties arose from operating the previous experiment in air. The refractive index affected the interferometry while air buoyancy complicated the mass' weight calculation. Almost every part of the balance assembly was rebuilt to fit inside a specially constructed vacuum chamber, schematically represented in Figure 1. The upper chamber houses the balance section. A second section houses the inductive coils, 3 m below and centered around the liquid helium dewar containing the magnetic field source, a superconducting solenoid. The chamber sections are fiberglass, connected with PVC tubes -- thus avoiding eddy current or magnetic effects. To eliminate static charge, thin copper screen is attached to the inner walls and balance wheel support structures. The plan is to operate with about 10 Pa helium in the chamber. This will reduce the correction for the refractive index to less than 5×10^{-9} while providing sufficient thermal conduction for the coil when operating with current.

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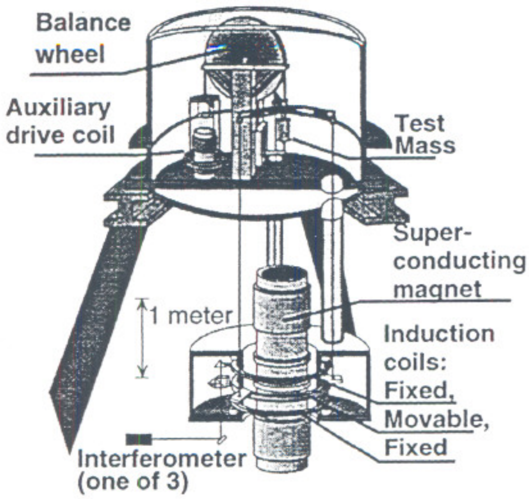

Figure 1. A schematic representation of the electronic kilogram experimental apparatus. The vacuum chamber and support tripod are in cut-away view.

The chamber itself is situated in a room clad internally with 0.4 mm copper plate for rf shielding. The room has features meant to enhance temperature control: thermally insulated walls and floor, separate air flow, and a computerized temperature control system for the building. (The vacuum chambers have additional heating wires built into their sides.) The room is physically isolated from the building's support structure and concrete floor to reduce vibrations.

The dot product of the vector representation for force and velocity in Eq. 1 reflects a critical aspect -- hardware alignment. This may be one of the sources of error most difficult to reduce. The balance only measures vertical forces, so it is essential to properly align the magnetic field, the inductive coil's plane, the coil's line of travel, and the interferometer beams, all with respect to gravity. Alignment is complicated by the free swinging nature of the inductive coil, and made worse by operating everything inside the vacuum chamber. A number of improvements are being tested. 1) The balance wheel and inductive coil support structure sits on a heavy-duty translation stage, allowing centering adjustments while under vacuum. 2) Lockable flexure joints in the coil support structure should isolate coil tilt from coil translation during alignment procedures. 3) In an attempt to reduce vibrations of the coil, stiffer and lighter graphite-composite materials are used in the long lengths of supporting tubes.

Several changes will affect the voltage measurements. A calculation modeling the solenoid's magnetic field revealed that the field's gradient from the inner to the outer side of the old coil deviated from the desired purely radial nature by 0.02 % -- a possible cause of unwanted torques. The new coil is 50 % thinner at 20 mm, reducing the non-radial variation by about a factor of 4. The previous system also had a second coil wired in series opposition, acting as a stationary reference point for the interferometer and compensating the moving coil's pickup of 60 Hz noise. The noise cancelation should be better with a new design of two fixed coils instead of one, each with one half the number of turns and positioned above and below for symmetry. The volt measurement scheme is further enhanced with a new, low thermal-emf switch that has great flexibility in connecting different voltage sources in series with the same voltmeter. These sources can be the moving and/or fixed coils, reference resistor, Zener reference standard, or a programmable Josephson array voltage standard [4] (JAVS). For the ultimate in voltage measurement capability, this high-stability JAVS can be used as the reference in a switching scheme where voltage reversals can be measured without in-circuit switching.

The balance wheel and knife-edge pivot are about the only items reclaimed from the old system. However, we are working to reduce the wheel rotation during mass placement, and thus avoid hysteresis in the flexing of the knife-edge. New motion control motors and linear stages with encoder feedback will allow better positioning of the mass relative to the balance pan. A new VXI laser interferometer will increase the resolution of the pan's position (and balance wheel angle). Combined with a faster computer, the target is to limit motion to within a few micrometers (50 µrad), an improvement factor of 100. Test data on the uncertainty achievable with all these new improvements will be presented.

References

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