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STATUS OF THE NIST "ELECTRONIC KILOGRAM" EXPERIMENT


NIST
100 Bureau Dr M/S 8112
Gaithersburg, MD 20899-8112
USA

Abstract
The National Institute of Standards and Technology (NIST) has rebuilt the apparatus and facilities for the watt balance experiment. The goal is to electronically monitor the SI Kilogram at an uncertainty of 10 nW/W. We discuss the design changes and available test results to illustrate the improvements of the system.

Introduction
In 1998, the National Institute of Standards and Technology (NIST) completed the data analysis of the watt balance experiment for an evaluation of the Planck constant [1]. Based on the lessons learned in operating the watt balance, a new system was designed to obtain a factor of ten better uncertainty for a goal of 10 nW/W. The electronic kilogram experiment compares electrical power to mechanical power in a method proposed by Kibble [2], and has been described elsewhere in greater detail [3]. It is pictured in Figure 1. To summarize, this measurement of the unit watt uses the principles of an electric generator, an electric motor, and a mass balance, relying on quantum standard references for length (lasers), time (cesium clocks), voltage (Josephson effect), resistance (quantum Hall effect), and the SI Kilogram artifact. By assuming the universality of the watt definitions and the constancy of the fundamental physical constants defining the representations of the quantum standard references, any variations in the ratio of an electrical to mechanical watt unit must signify a drift in the artifact Kilogram. The electronic kilogram design differs from the previous watt balance mainly by its operation inside a vacuum chamber to nearly eliminate several correction factors based on temperature, pressure, humidity, etc. There are also reductions in the uncertainty contributions from measurements traceable to the quantum references and reductions in several noise sources, both mechanical and electrical.

Design Improvements

General Apparatus. The entire experiment is housed in a new room, with copper sheet lined walls for RF screening, and physically isolated from the main building for vibration isolation. The vacuum chamber is fiberglass, chosen to avoid eddy currents in conductors or induced magnetic fields in ferrous metals. The inside surface is covered in copper screen to avoid static charge buildup while allowing efficient pump down. An achievable pressure of 0.3 Pa is sufficient to eliminate significant air-related correction factors (350 μW/W refractive index and 60 μW/W buoyancy corrections at STP, with standard relative uncertainties of 43 nW/W and 23 nW/W respectively). The main induction coil carries 10 mA current, and with a resistance of 480 Ω proved to have minimal heating problems. Mass balance tests at 28 mg have shown that the lack of air currents should reduce these fluctuations in the balance by a factor of 3.

[Diagram of the NIST electronic kilogram experiment apparatus]

Figure 1. A schematic of the NIST electronic kilogram experiment apparatus.

The balance assembly is almost completely new, with only the balance wheel being reused. The support structure design addresses difficulties in aligning the induction coil with the superconducting magnetic field and gravity. By incorporating fixable flexures at the support points, horizontal forces on the induction coil can be decoupled from torques, which otherwise confuses the difference between misalignment of the coil angle
or the coil's center of mass. Preliminary tests conclude that configuring the alignment is better controlled than on the previous system, and it seems stable in going from air to vacuum. The long-term stability is still undetermined.

Several unsuspected benefits occurred from testing for hysteresis-related noise from the knife edge pivot in the mass balance [4]. It was believed that balance wheel rotation caused mechanical distortion in the knife edge pivot, which in turn caused a hysteretic, time-dependent force on the wheel. Tests showed that the mass balance with a tantalum-tungsten knife edge and boron nitride flat had 10 times more hysteresis than an independent testing system with tungsten carbide ceramic materials with diamond-like coatings. About 70% of this hysteresis was directly attributable to the knife edge materials. However, 30% was occurring from magnetically impure brass in a permanent magnetic field on the counter mass side of the mass balance.

There are other enhancements that have been obtained or installed but not yet evaluated. For placing the mass on the balance in a highly controlled fashion, we have a stepper motor controlled translation table with optical position encoder. This should reduce wheel rotation and thus further reduce knife-edge hysteresis. All voltages will be measured directly against a programmable Josephson array voltage standard [5], which should reduce the Type B standard relative uncertainty in tracing back to a volt reference from 30 nV/V to less than 5 nV/V. The vacuum chamber has embedded heating wires for temperature control, and improved electronics and faster computers are being brought on-line to reduce measurement noise or improve the servo control of such systems as coil velocity and the superconducting magnet current.

Induction coil design and excess noise The original redesign of the induction coil system focused on better rejection of 60 Hz AC voltage pickup and reducing the amplitude change in the DC voltage generation over the range of coil motion, what we refer to as the magnetic field profile. To accomplish the first objective, the fixed coil is split and centered over and under the moving coil at a position of zero mutual inductance between the fixed coils and the superconducting coils. The AC rejection with the moving coil at the center is better by about a factor of 10, about 10 mV. For the second objective, the moving coil was resized to make it smaller radially and longer axially. This successfully reduced the field profile from 380 μW/W equivalent variation to about 80 μW/W. The smaller profile should reduce the uncertainties in curve fitting to estimate the field at the center point for the mass balance.

A first design of the moving coil consisted of #24 wire wound on a fiberglass form but not potted in epoxy. Testing revealed far more high frequency noise (about 20 Hz) in the voltage/velocity ratio than the previous system. This noise was finally diagnosed as the result of flexing of the coil. (This also explains a long-standing noise problem in the previous system.) Parity because of the split fixed coil, which required the support rod mounts to be offset from the center of the coil as they were in the previous design, and partly from a looser construction, the new coil had a large amount of flexing motion. The laser interferometer corner cubes were located at positions that exaggerated the flexing, which had a wave-like distortion pattern around the coil while also twisting. Ordinary ground vibrations continuously stimulated this flexing, so that the velocity signals near the resonance frequencies were highly uncorrelated with the motion of the electromagnetic center of the coil. At worst, the voltage was 180° out of phase with the velocity.

To remedy this problem, a second coil was made with #26 wire to reduce the coil mass to raise the resonant frequency, and potted with epoxy and long carbon fiber strings to stiffen it. The corner cubes are also relocated to a position halfway between the maximal motion and the nodes. Tests on both coils and the previous coil showed a factor of 50 improvement in the mirrors tracking the wire voltage than the first new coil, and about a factor of 10 less than the previous coil. The newest coil now has a flexing resonance at 34 Hz, but the mismatch between voltage and velocity at this frequency is less than 0.5%. Preliminary profile recordings indicate that the voltage/velocity noise is significantly reduced over the previous system. Since this was one of the larger noise sources in the previous experiment, the resolution of the electronic kilogram experiment is expected to improve accordingly.

Conclusion

The new electronic kilogram system has been completely rebuilt and is on its second phase of procedure development and evaluation testing. The investigations so far found that the largest of the uncertainty components in the previous experiment, the air correction factors, volt reference traceability, and several measurement noise problems, are greatly reduced. One unexpected problem, so far, the excessive flexing of the coil, has been improved. This investigation actually led to solving a long-standing problem in the watt balance and a greater appreciation of the subtleties of measuring the position and alignment of the induction coil.

References