PROGRESS ON A VACUUM-TO-AIR MASS CALIBRATION SYSTEM USING MAGNETIC SUSPENSION TO DISSEMINATE THE PLANCK-CONSTANT REALIZED KILOGRAM

Patrick J. Abbott, Ronald C. Dove, Eric C. Benck, and Zeina J. Kubarych

National Institute of Standards and Technology (NIST), USA
100 Bureau Drive MS 8221
Gaithersburg, MD 20899

Abstract: The kilogram is the unit of mass in the International System of Units (SI) and has been defined as the mass of the International Prototype Kilogram (IPK) since 1889. In the future, a new definition of the kilogram will be based on precise measurements of the Planck constant. The new definition will occur in a vacuum environment by necessity, so NIST is developing a mass calibration system in which a kilogram artifact in air can be directly compared with a kilogram realized in a vacuum environment. This apparatus uses magnetic levitation to couple the kilogram in air to a high precision mass balance in vacuum. Details of the levitation technique, vacuum mass metrology, and a roadmap to dissemination of the new kilogram definition will be presented.

1. INTRODUCTION

The kilogram is the only remaining base unit in the International System of Units (SI) that is still defined by an artifact, the International Prototype Kilogram (K), which is made of a platinum- iridium alloy and is maintained at the International Bureau of Weights and Measures (BIPM) in Sevres, France. Therefore the quantity of mass can only be realized at the BIPM, and must be disseminated to the rest of the world through a chain of comparison calibrations through the world's National Metrology Institutes (NMI). The NMIs maintain traceability to K through periodic comparisons of their 1 kg standard(s), which in most cases are also made of the same platinum-iridium alloy, through the working standards of the BIPM. The NMIs then realize a mass scale from approximately 1 mg up to several thousand kilograms through multiple and sub-multiple calibrations involving their 1 kg standard(s) and working standard artifacts. There are several good arguments for replacing the artifact definition of the kilogram. Among these are: a) artifacts can be damaged by accidents or wear and tear; b) a definition that would permit the convenient realization of the unit of mass in places other than the BIPM would solve many logistical problems in the dissemination chain; c) the K has been found to be unstable with respect to official copies that were made at the same time [1]; it has been estimated that the mass of the K has decreased about 0.050 mg over the past 100 years. For these reasons, and to harmonize the unit of mass with the other SI units that are defined in terms of natural constants [2], the General Conference on Weights and Measures (CGPM) has recommended [3] that the magnitude of the kilogram be set by fixing the numerical value of the Planck constant, h,

to be equal to exactly $6.626\ 06\text{X} \times 10^{-34}$ when it is expressed in the SI unit $\text{m}^2\ \text{kg s}^{-1}$, which is equal to J s (the symbol X represents one or more additional digits to be added to the numerical value of h using values based on the most recent CODATA adjustment).

In order for a redefinition of the kilogram based on Planck's constant to occur, the Consultative Committee for Mass and Related Quantities (CCM) has recommended to the International Committee for Weights and Measures (CIPM) that stringent conditions [4] be met regarding the defining experiments. These conditions have not been fulfilled by the experiments that are measuring the Planck constant, the watt balance [5] and the International Avogadro Coordination (IAC) project [6]. Improvements to each of the experiments are anticipated that will allow the conditions for redefinition of the kilogram to be met in the coming years. When this happens, an interesting dilemma in the dissemination of the kilogram will result from the fact that both the watt balance and the IAC project will realize the kilogram in a vacuum environment. In order to use the new kilogram realization to calibrate mass artifacts in air, some method of transferring the vacuum realization to atmospheric pressure will have to be employed.

2. NIST Method for transferring vacuum mass calibration to air

NIST is currently involved in research to develop an instrument that is capable of directly comparing the known mass of a kilogram in a vacuum environment to an unknown mass of another kilogram in air using the same high precision mass comparator [7]. In this scheme, an all-aluminum vessel containing two
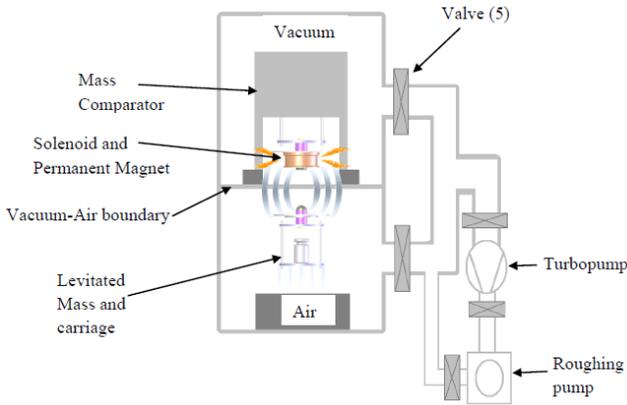
Figure 1. Schematic of the magnetic levitation principle used in the vacuum-to-air mass comparison system. The all-aluminum vessel has an upper chamber containing a vacuum compatible mass balance and a lower chamber for the artifact to be compared to the mass in vacuum.

adjacent chambers, one under vacuum and one at atmospheric pressure, is used. A high precision mass comparator (10 kg capacity with 0.010 mg resolution) is contained in the evacuated chamber; this comparator can compare artifacts in the usual way in the evacuated chamber, but can also compare a vacuum artifact to an artifact in the atmospheric pressure chamber by connecting the comparator to the artifact across the vacuum-air boundary via magnetic levitation. This is illustrated in Figure 1.

In the NIST vacuum-to-air mass comparison system, the mass in air is compared directly to the calibrated mass in vacuum using the same high precision mass balance; therefore, it doesn't rely on any empirical modeling, such as that required for calculating the amount of water that is adsorbed onto a mass that is calibrated under vacuum conditions and then removed to atmospheric pressure air.

The mass comparator's weighing pan is coupled to the mass in air (which is situated on an appropriate carriage) by magnetic suspension that uses permanent magnets and a solenoid to create the necessary magnetic field.

3. Magnetic components

The magnetic suspension system designed for this application relies on the mutual attraction of an

upper magnetic pole that is attached to the mass balance through a suitable adapting mechanism and a lower magnetic pole that is attached to a carriage that holds the mass artifact that is to be suspended. Other magnetic suspension balances have been described in the literature [8] and even sold commercially [9]. Shirazee and Basak [10] describe a magnetic suspension system based on the use of an electro-permanent magnet assembly that uses high energy product (BH_{max}) Neodymium-Iron-Boron magnets and Hall sensors to measure and regulate the suspending magnetic field. They were able to achieve suspension of a load of 491 g at an air gap of 61 mm. We have adapted this approach to suspend loads of over 3 kg at an air gap of 15 mm to 17 mm.

Schematics of the magnetic pole assembly are shown in Figure 2. The upper part of the assembly is held together with a centrally located brass screw and contains a solenoid made from approximately 2500 turns of #28 magnet wire insulated with polyimide. The solenoid has a resistance of about 64 ohms, and is concentrically arranged around an SH40 NdFeB ring magnet having an outer diameter of 38 mm (1.5 in) and an inner diameter of 19 mm (0.75 in). To increase the permeability and hence the field of the magnet/solenoid combination, a soft iron ring of the same dimension as the ring magnet is mounted just above (but not attached to) the magnet. Finally, a flat disk-shaped pole piece made of soft iron is used to concentrate and guide magnetic field lines. The pole is 25.4 mm in diameter and has a threaded boss that fits inside the permanent magnet and attaches to the central brass screw. The lower part of the magnetic assembly is identical to the upper part, minus the solenoid. An aluminum spacer is used to separate the iron ring from the permanent magnet
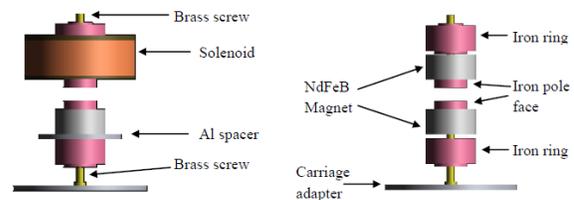
Figure 2. Configuration of permanent magnets and solenoid in magnetic suspension system model. The view shown at right is the same as at left without the solenoid and aluminum spacer

4. Suspension and First Tests

It was proven in the early 19th century by Earnshaw [11] that no stationary object made of charges, magnets and masses in a fixed configuration can be held in stable equilibrium by any combination of static

electric, magnetic, or gravitational forces (that is, by any forces derivable from a potential satisfying Laplace's equation). A consequence of this is that stable equilibrium of any object requires its energy to possess a minimum [12]. In the case of magnetic levitation of diamagnetic objects, the magnetization of a diamagnet is not fixed, but depends on the field it is in, meaning that Earnshaw's theorem does not apply, and so an energy minimum can be created. As a result, levitation of such things as water droplets, living creatures, and wood can be achieved in very large magnetic fields of 10 T or more [12]. Suspension of ferromagnetic materials is quite a different matter. Since the magnetization of a ferromagnetic object is fixed, the stable equilibrium of a ferromagnetic object obeys the conditions of Earnshaw's theorem. This requires that its energy possess a minimum, which is impossible since solutions to Laplace's equation have saddle points, but no maxima or minima [12].

To achieve stable suspension, other means besides or in addition to permanent magnets must be found. This can be done in a straightforward way by using the variable magnetic field of a solenoid (refer to Figs. 1 and 2) whose current is continuously adjusted so as to provide the necessary magnetic field that will produce a force on the suspended object that just offsets the gravitational force. This setup requires a servo loop that adjusts the solenoid current by comparing a set value of the magnetic field between the poles to the actual value of the field as measured by a Hall sensor. In our system, permanent magnets provide the required magnetic field, with the "trim" field from the solenoid used for dynamic control in conjunction with a PID control computer algorithm with feedback from the Hall sensor. A pulse width modulation technique based on the design of Marsden [13] is used to drive a variable current through the solenoid.

A proof-of-concept magnetic suspension system was constructed with a mass balance having a maximum load of 10 kg and a resolution of 1 mg. This proof-of-concept system does not have the ability to be evacuated, but served as a testbed for improving the vacuum-to-air system design. With the proof of concept system, we have suspended mass artifacts from 100 g to 1 kg using a "carriage" assembly to hold the mass artifacts. This carriage assembly has a mass of 2.3 kg. In each case, the suspension is stable to better than the 1 mg resolution of the balance. It was found that suspension is easier to achieve and more stable when the Hall sensor is located as close as possible to the magnetic pole on the top of the carriage. The PID control algorithm is mostly proportional control whose magnitude varies with suspended load and is found empirically. Attempts to predict the PID parameters from a mathematical model have not proven useful.

5. Vacuum to air vessel

The knowledge gained from construction and operation of the proof-of-concept apparatus was used to build a similar magnetic suspension rig to mount in a vessel that has adjacent vacuum and air chambers. In the vacuum chamber, a high-precision mass comparator of maximum load capacity 10 kg and resolution of 0.010 mg has been installed. The mass pan suspension of this comparator has been fitted with an adaptor that allows a solenoid/permanent magnet assembly to hang below the chassis of the balance just above the metal barrier between the vacuum and air chambers. On the air side of the barrier, a carriage similar to the one in the proof-of-concept device is attached to a magnetic pole consisting of a soft iron flat pole face and a permanent ring magnet. The Hall sensor is the same type as is used in the proof-of-concept device, but is mounted within a groove on the air side of the vacuum-air barrier.

The mass comparator has been specially designed to operate in a vacuum environment of about 10^{-2} Pa. The improved resolution (by a factor of 100) of this comparator over that used in the proof-of-concept device should allow an accurate evaluation of the stability of the magnetic suspension. The ultimate goal for the uncertainty of the vacuum-to-air calibration system is $\pm$ 0.020 mg, which is the manufacturer's repeatability specification of the comparator, and represents an uncertainty that will not add significantly to the over-all uncertainty for a 1 kg mass calibration. Currently, the standard uncertainty for a 1 kg mass calibration done by the NIST Mass and Force group is about 0.025 mg. Among the experiments under consideration for redefining the kilogram in vacuum, the best standard uncertainty achieved by a watt balance is 0.036 mg by NIST [5], and 0.030 mg for the Avogadro project [6].

Initial results for suspension of a 1 kg mass in the vacuum-to-air vessel produced stability of 0.5 mg or less (the standard deviation of the mass reading). Considering that these results were obtained with atmospheric pressure air in the upper and lower chambers, and neither chamber was completely sealed, the 0.5 mg stability is reasonable. As of this writing (November 2013) preparations are underway for a comparison between a calibrated kilogram artifact in vacuum and an uncalibrated kilogram artifact in air.

6. Dissemination of a kilogram defined in vacuum

When the kilogram is redefined in terms of the Planck constant, the new definition will refer to a kilogram in vacuum, since both the watt balance and Avogadro project experiments take place in a vacuum environment by necessity. In order to ensure

continuity with the current artifact definition, the vacuum-realized kilogram must be transferred to air. Unlike the adsorption/desorption characterization experiments and models, the magnetic suspension apparatus discussed in this paper provides a direct method of comparing an artifact in vacuum with one in air using the same mass comparator. It will also provide a check on the adsorption/desorption method.

A pathway for dissemination under the new kilogram definition is shown in Figure 3. Under this scenario, a watt balance would calibrate a nominal 1 kg artifact in vacuum, which becomes a primary standard; this artifact would be transferred under vacuum to the magnetic suspension system's vacuum chamber. Here, it could be used to calibrate another artifact in vacuum directly, or one of the US national standards using magnetic suspension. By calibrating a U.S. national standard with a watt balance calibrated kilogram, a direct link is made between the Planck constant definition and the artifact definition (K), closing the traceability loop. Note that under the above dissemination chain for the new kilogram, nothing changes as far as customer calibrations are concerned. The magnetic suspension system is used to calibrate the platinum iridium U.S. national standards, which are then used in air to calibrate stainless steel working standards, which in turn are used to calibrate customer artifacts. Assuming a standard uncertainty of 0.030 mg for the watt balance realization of the kilogram at the time of redefinition and 0.020 mg standard uncertainty for the

Figure 3. A roadmap for dissemination of a redefined kilogram in which the kilogram is realized in terms of Planck's constant by a watt balance. The pathway involves transfer from vacuum to air (dotted line) via the magnetic suspension system . Note that the current artifact-based dissemination through the International Prototype Kilogram is shown inside the box with the red dotted boundary.

magnetic suspension vacuum-to-air transfer, the combined standard uncertainty for the NIST national standards (platinum, in air) will be about 0.036 mg. Secondary (working) NIST standards made of stainless steel will have a standard uncertainty of about 0.038 mg, which should allow dissemination to reference

standards of class E1 accredited laboratories [14] with a standard uncertainty of 0.050 g or less. This should be sufficient for the E1 accredited labs to meet the OIML recommended standard uncertainty of 0.083 mg for 1 kg artifacts.

7. REFERENCES

[1] Girard, G.,"The Third Periodic or less for dissemination of mass at 1 Verification of National Prototypes of the Kilogram (1988-1992)", *Metrologia* 31 (1994) 317-336.

[2] Mills, I.M., Mohr, P.J., Quinn, T.J., Taylor, B.N., and Williams, E.R.,"Redefinition of the kilogram, ampere, kelvin and mole: a proposed approach to implementing CIPM recommendation 1 (CI-2005). *Metrologia* 43(2006) 227-246.

[3] "On the possible future revision of the International System of Units", the SI, Draft Resolution A of the General Conference on Weights and Measures (CGPM) at its 24th meeting, 17 – 21 October 2011. http://www.bipm.org/utils/en/pdf/24_CGPM_Convocation_Draft_Resolution_A.pdf

[4] Consultative Committee for Mass and Related Quantities (CCM) Report of the 12th meeting (26 March 2010) to the international Committee for Weights and Measures. Bureau International des Poids et Mesures, Sevres. http://www.bipm.org/utils/common/pdf/CCM12.pdf

[5] Steiner, R.L., Williams, E.R., Fewell, D.B., and Liu, R., "Towards an electronic kilogram: an improved measurement of the Planck constant and electron mass", *Metrologia* 42 (2005) 431-441.

[6] Andreas, B., et. al., "Counting the atoms in a ^{28}Si crystal for a new kilogram definition," *Metrologia* 48 (2011) S1-S13.

[7] Jabbour, Z., Abbott, P., Williams, E., Liu, R., and Lee, V., "Linking air and vacuum mass measurement by magnetic levitation," *Metrologia*, **46** (2009) 339 – 344.

[8] Clark, John W., "An electronic analytical balance", Rev., Sci. Instr. **18** (12) (1947) 915-918.

[9] Abbess, Inc., P.O. Box 498 Ashland, MA USA 01721-0498 http://www.abbess.com/physics/maglev.html

[10] Shirazee, N.A., and Basak, A., "Electropermanent suspension system for acquiring large air-gaps to suspend loads", *IEEE Trans. Mag*., **31** (6) 199, 4193-4195.

[11] Earnshaw, S., "On the nature of the molecular forces which regulate the constitution of the luminiferous ether", *Trans. of the Cambridge Philosophical Society*, vol. 7 (1842), 97-112.

[12] Berry, M.V. and Geim, A.K., "Of flying frogs and levitrons", *Eur. J. Phys*. 18 (1997) 307-313.

[13] Marsden, G., "Levitation!", *Nuts & Volts*, 24 (9), 2003, 58-61.

[14] OIML R 111-1 International Recommendation, Edition 2004 (E), Part I: Metrological and technical requirements.