Progress on Vacuum-to-Air Mass Calibration System Using Magnetic Suspension to Disseminate the Planck-Constant Realized Kilogram

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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 the National Institute of Standards and Technology (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 suspension to couple the kilogram in air to a high precision mass balance in vacuum. Technical details of the suspension technique, the vacuum-to-air calibration system, and vehicles for transferring masses into and out of vacuum will be presented.

Keywords: Magnetic suspension, mass metrology, Planck constant, revised SI, SI units, watt balance

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 (IPK), 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 (NMIs). The NMIs maintain traceability to IPK through periodic comparisons of their 1 kg standard(s), which in most cases are also made of the same platinum-iridium alloy, with 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.

Redefinition of the kilogram based on Planck's constant will take place in 2018 [1, 2]. This will complete the redefinition of base units in the SI from artifacts to fundamental constants. When this happens both the watt balance and the International Avogadro Coordination (IAC) project will realize the kilogram in a vacuum environment. In order to use the new kilogram realization to calibrate mass artifacts in air, methods of transferring the vacuum realization to atmospheric pressure will have to be developed.

2. NIST METHOD FOR TRANSFERRING VACUUM MASS CALIBRATIONS TO AIR

2.1 MAGNETIC SUSPENSION

The Mass and Force Group at the National Institute of Standards and Technology (NIST) is building an apparatus which will enable a direct mass comparison between a mass in air and a mass in vacuum.[3] A commercial mass comparator will be installed inside a vacuum chamber and kept under vacuum. This mass comparator will be modified to locate a second mass pan in air underneath the vacuum chamber. This will be accomplished using permanent magnets to create magnetic fields which will pass through the vacuum chamber wall and suspend the lower mass pan as shown in Fig 1. It will then be possible to compare the mass of a weight placed on the mass pan in vacuum with a separate weight placed on the suspended mass pan in air. It therefore does not rely on any empirical modeling, such as that required for calculating the amount of water that is adsorbed onto a mass moved from vacuum conditions to atmospheric pressure. This is currently the only such direct vacuum-to-air mass comparison apparatus being developed in the world.

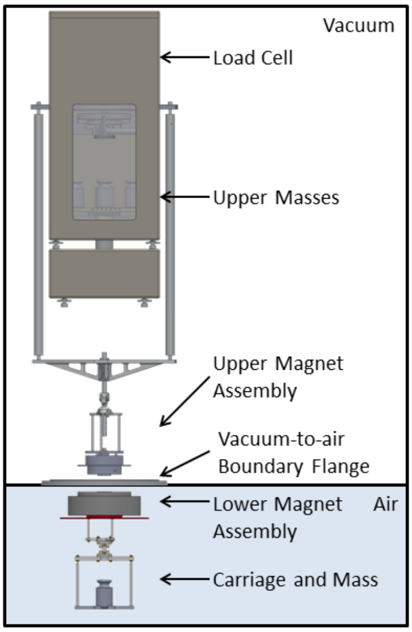

Figure 1: Schematic of the magnetic levitation principle used in the vacuum-to-air mass comparison system. The all-aluminum vessel has an upper chamber containing a vacuum compatible mass balance and a lower chamber for the artifact to be compared to the mass in vacuum.

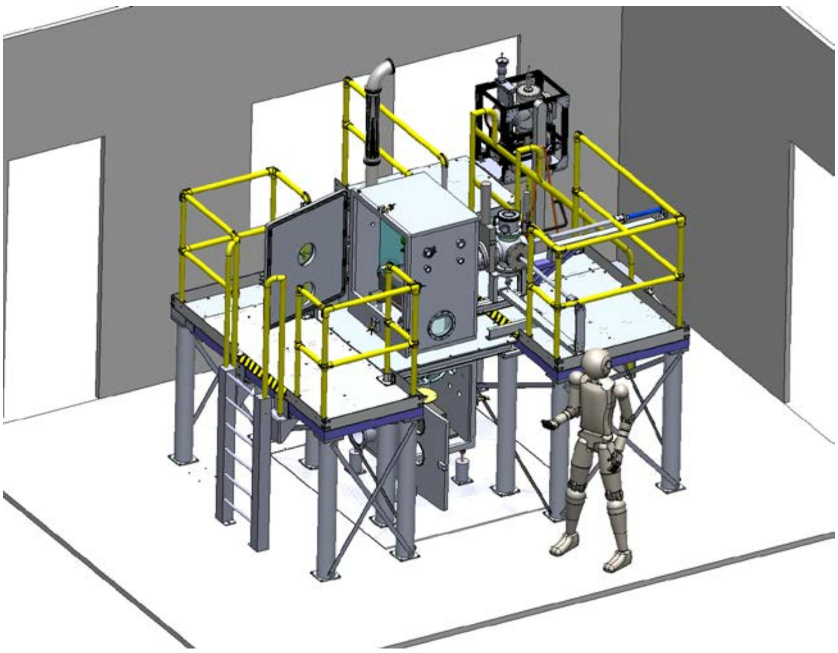

Figure 2: Illustration of magnetic suspension apparatus with vacuum doors opened.

2.2 VACUUM CHAMBERS AND MASS COMPARITOR

The apparatus will be housed in two separate aluminum vacuum chambers mounted above one another as shown in Fig 1. The upper chamber will house the mass comparator and will be kept under vacuum while the lower chamber will normally be kept at atmospheric pressure. These vacuum chambers are constructed out of non-ferromagnetic aluminum so that stray magnetic fields from the magnetic suspension system will not couple to the wall and interfere with the mass measurements. The vacuum chambers are rectangular in shape with the upper and lower chambers being 88 cm x 67 cm x 111 cm and 77 cm x 67 cm x 80 cm, respectively. Large rectangular doors will provide easy access to components in the vacuum chamber when necessary. Although a maximum pressure of 0.1 Pa would be suitable for removing buoyancy corrections, other factors such as the adsorption of water on to the masses require a lower target pressure on the order of (10^{-3} to 10^{-4}) Pa.[4] A 900 l/s turbo pump will be used to evacuate the system. The ports and windows will be sealed with Viton o-rings.[1] The large door seals have a differentially-pumped dual o-ring design. Although normally filled with air, the lower chamber can also be evacuated or filled with an inert gas.

Figure 3 shows the actual upper chamber which is currently undergoing leak testing. The chambers will be mounted on a concrete pillar underneath the floor in order to vibrationally isolate the apparatus from the rest of the room. The laboratory in which the apparatus will be installed has a temperature and humidity stability of 0.01 °C and 1% respectively. Two raised platforms provide access to the upper vacuum chamber.

Figure 3: Upper Vacuum Chamber under construction.

As mentioned previously, a high precision commercial mass comparator (10 kg capacity with 0.010 mg resolution) will be contained in the upper vacuum chamber. The mass comparator has a turntable so that up to 4 separate masses can be kept under vacuum for comparisons. In the lower chamber, in addition to the magnetically suspended mass pan, there will be an additional turntable to hold up to 4 masses in air for comparisons.

2.3 SUSPENSION SYSTEM

Two SmCo permanent disk (3.81 cm diameter) magnets with a residual field of 1.16 T provide the necessary magnetic field to suspend both the carriage and mass in air. According to Earnshaw's theorem it is not possible to stably suspend an object with only ferromagnets [5]. Therefore dynamic control is required and will be provided by a solenoid (75 Ω) wound around the upper magnet.[6] A proportional-integral-derivative (PID) control algorithm will then be used to stabilize the suspended mass. The PID control system will operate with a field programmable gate array (FPGA) that can operate independently of the computer control system. The position of the suspended mass will first be determined using a Hall probe mounted on the vacuum chamber wall between the two magnets. This will provide a feedback signal

[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

to the PID circuit to roughly stabilize the suspended mass by modifying the current sent to the solenoid. Greater stability can be obtained from a second PID circuit using a laser interferometer to provide feedback on the velocity of the suspended mass pan.

Mass comparisons of the type "A-B-B-A" will be done between masses in the upper vacuum chamber and the lower air chamber. During the actual measurements the carriage will always be suspended, even when there is no mass on this pan. In this way the mass of the lower mass pan will cancel out of the comparison between the vacuum and air masses. When masses are being transferred on or off either mass pan during a measurement comparison cycle, the carriage is not suspended. This is necessary to insure that the mass on the carriage is not dropped during the transfer process.

2.4 GRAVITATIONAL FIELD GRADIENT

One significant difference between the magnetic suspension measurements and a typical mass comparison measurement is that the two masses in the suspension system are being compared at different heights. The local gravitational gradient will need to be accounted for to accurately compare the different masses. The gravitational gradient in the room which will house the magnetic suspension apparatus was measured with a portable commercial gravity meter. The results of these initial measurements are shown in figure 4. The masses in the final apparatus will be located at positions corresponding to 53 cm and 165 cm. The resulting gravitational gradient is 2.82×10^{-6} s^{-2} and would result in a correction on the order of 300 μg. A final gravitational gradient will be measured again when the vacuum chamber and all the surrounding structures are installed in the lab.

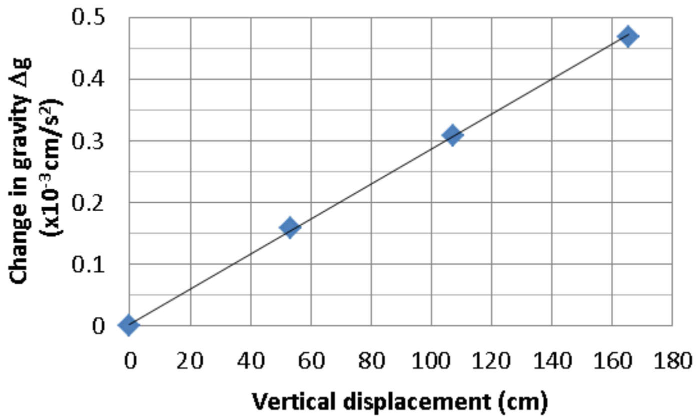

Figure 4: Variation of gravity vs height in the magnetic suspension laboratory. The air and vacuum masses will be located at approximately the vertical displacements corresponding to the 53.2 cm and 165.5 cm data points.

3. VACUUM MASS TRANSPORT

3.1 MASS TRANSPORT VEHICLE

NIST will realize the new kilogram with the NIST-4 watt balance.[7] The watt balance and the magnetic suspension system are located in different labs at NIST and it will be necessary to transport masses in vacuum between the two apparatus. This will be accomplished with a mass transport vehicle (MTV) which is essentially a mobile vacuum chamber (See Fig. 5). It is built mainly out of copper-gasket-sealed stainless steel vacuum components. It is not necessary to use non-ferromagnetic components since the MTV will not be attached to the magnetic suspension apparatus during measurements. Only the viewport door and gate valve have Viton o-ring seals. The MTV connects to the other vacuum chambers with an ISO band clamp so that it can easily be connected and disconnected. A cold cathode ion gauge is used to monitor the vacuum and a getter pump is used to maintain the vacuum ($<1 \times 10^{-3}$ Pa) during transport. The getter pump can be battery operated, but even without pumping a suitable vacuum has been maintained in the MTV for over 60 minutes which is sufficient time to move between the different labs. Both the ion gauge and the getter pump are oriented so there is no direct line of sight between them and the mass to prevent possible ion sputtering onto the mass.

Figure 6 shows a cutaway view of the interior of the MTV. Masses being transported will sit on a slotted block in the center of the chamber. Circular indents designed to match several different types of masses keep the mass from sliding sideways during transport. Three triangular wedges made from polyether ether ketone (PEEK) on top prevent the mass from tipping over. All surfaces which could come into contact with the mass are coated with a diamond-like carbon film to prevent material from being transferred to the mass. The slotted block and triangular wedges can be independently raised and lowered so that the mass can be placed on a transfer fork from the load lock which enters the MTV through the gate valve. The transfer fork when fully inserted into the MTV will vertically sag by approximately 1 cm when supporting a 1 kg mass. In order to vertically and horizontally align the transfer fork with the slotted block, a PEEK ramp will support the fork at the proper height.

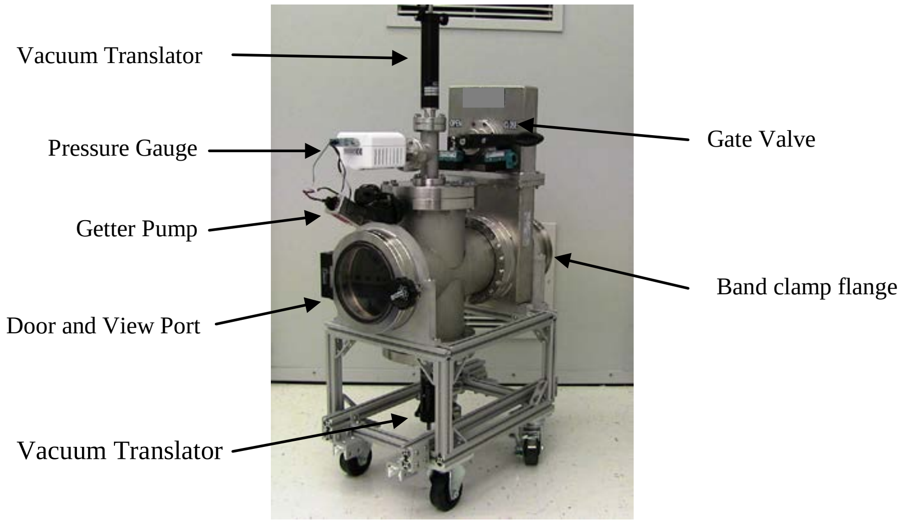

Figure 5: Mass transport vehicle

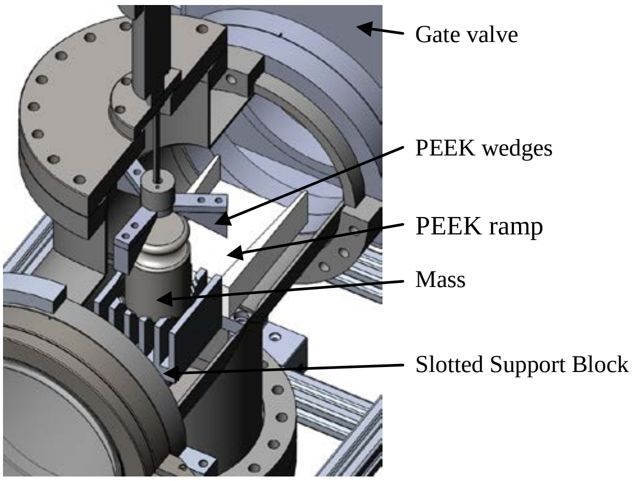

Figure 6: Schematic of interior of mass transport vehicle

3.2 LOAD LOCK SYSTEM

Masses will be transferred from the MTV into the magnetic suspension vacuum chamber through a load lock which will maintain the mass under vacuum during the transfer process. The load lock is built using a 6 way cross as shown in Fig. 7. The front flange of the 6 way cross is an ISO band clamp to which the MTV will be connected. Once the MTV has been attached, the load lock will be evacuated with an independent turbo pump station. Once a suitable (≈10^{-3} Pa) vacuum is obtained in the load lock, the gate valves on the MTV and the load lock can be opened. The mass fork in the back of the chamber, which is attached to a long linear vacuum translator, can be moved into the MTV to transport the mass back to the center of the load lock. The transfer platform which is composed of an array of rectangular posts can then be moved upward to pick the mass off the mass fork. The second mass fork on the right can then be moved into position underneath the mass and the transfer platform can then lower the mass onto the fork. The mass fork can then transfer the mass onto the circular mass turntable of the mass comparator. This second mass fork has tines of different lengths so that the mating slots in the circular mass turntable for different mass positions will not intersect. The mass fork can now be retracted and the gate valves closed. After venting the load lock, the MTV can be detached and removed before the mass comparison measurements are initiated. The surfaces which come into contact with the mass, the mass forks and the transfer platform will be coated with a diamond-like coating.

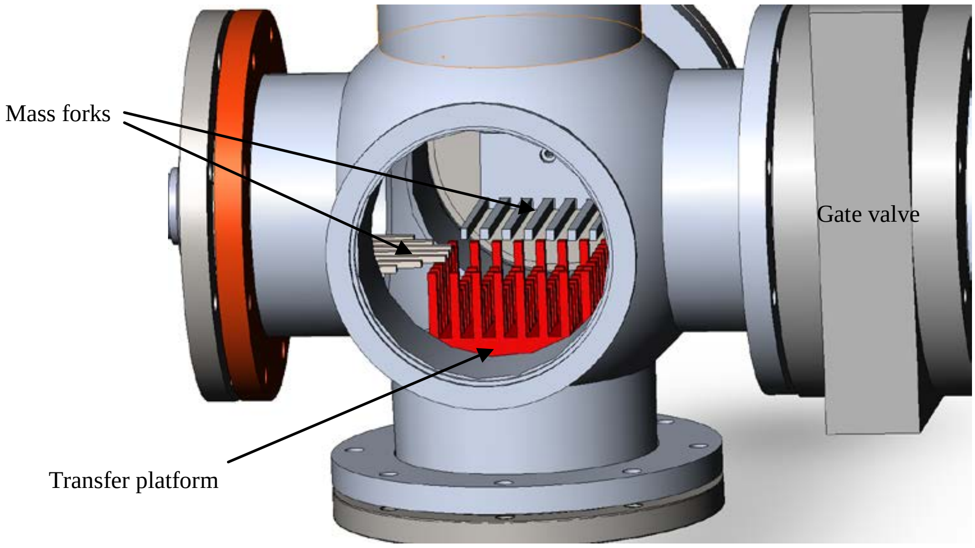

Figure 7: Schematic of load lock interior

4. CONCLUSION

The mass and force group of NIST are in the process of constructing a magnetic suspension system which will enable the direct comparison of a mass in air with a mass in vacuum using the same mass comparator. This will be accomplished by suspending the mass in air beneath the mass comparator using magnetic fields which will penetrate the vacuum chamber walls. This will become part of the *mise en pratique*, the set of instructions for realizing and disseminating the kilogram after redefinition. A mass transfer vehicle and load lock system will enable masses to be transported under vacuum from the NIST watt balance to the magnetic suspension apparatus and to other vacuum storage facilities.

5. REFERENCES

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