

ELECTROSTATIC PRIMARY REFERENCE FOR MILLIGRAM MASS METROLOGY

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Abstract: Recent advances in the field of mass metrology allow the use of non artifact-based primary references. This enables the creation of a primary reference that determines mass at the scale of interest without the need for subdivision. In this work, the use of an electromechanical balance allows direct metrology of mass at the milligram to microgram scale using electrical metrology traceable to the International System of Units (SI). The comparison between the electrostatic method and subdivision from the kilogram indicates the mass values produced by these two approaches are in agreement after applying a correction for the surface adsorption of water; only the electrostatic measurements are performed in vacuum. A reduction in uncertainty results from the electrostatic approach at the scale of 10 mg.

Keywords: mass; milligram; International System of Units

1. INTRODUCTION

In the near future, the SI kilogram may undergo redefinition [1]. The International Prototype Kilogram (IPK) will be left behind in favor of a realization based on measuring Planck's constant, h . Although the major thrust of the redefinition efforts has occurred at the kilogram level [2,3], opportunities to improve SI mass metrology exist at other scales as well.

Recent work has shown that measurements of mass from electrostatic force arise from h in the same fashion as other methods used for the redefinition [4], and that mass can therefore be directly realized using electrical metrology independent of scale. This means that there is an opportunity to reduce uncertainty in small mass metrology. Previously, to obtain a milligram, the kilogram artifact had to be subdivided many times, with each iteration adding uncertainty to the measurement [5]. With the direct electrostatic realization, subdivision is no longer necessary, eliminating the progressive accrual of uncertainty inherent in the subdivision methods.

2. EXPERIMENTAL METHODS

The Electrostatic Force Balance (EFB) used in this work is an electromechanical balance consisting of a compliant 4-

bar linkage supporting a precision concentric cylinder capacitor [4,6] as shown in Figure 1. The electrostatic force between the inner and outer cylinder balances an external force, in this case, resulting from gravitational force on a test mass. The magnitude of the balance force is

$$F = \frac{1}{2} \frac{dC}{dz} (V + V_s) \quad (1)$$

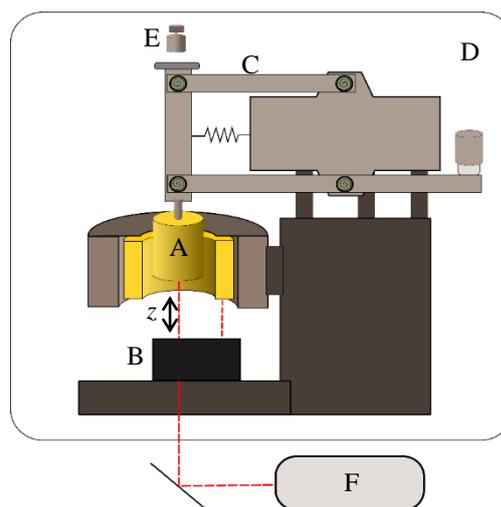


Figure 1. Schematic of the Electrostatic Force Balance (EFB). Shown are: concentric cylinder capacitor (A), laser interferometer (B), 4-bar linkage (C), vacuum enclosure (D), test mass (E), He-Ne laser (F) and z coordinate for measurement of capacitance gradient and electrostatic force.

where C is the gradient of the capacitance between the cylinders with the relative displacement between the fixed outer cylinder and the movable inner cylinder attached to the balance mechanism, z . This capacitance gradient is measured with a capacitance bridge before, between and after weighing experiments by translating the inner cylinder to fixed points across approximately 2 mm using an auxiliary actuator electrode on the opposite side of the balance mechanism. During a weighing experiment, an external voltage is applied to maintain a null position. The true electric potential between the electrodes, V , and the

surface potential from patch effect and surface adsorbates, V_s , both contribute to the force measured. For this reason, the polarity of the external potential is reversed and the mean of the force determined at positive and negative polarity removes the effect of the bias error caused by V_s . An automated stage allows a large number of sequential differential weighings to be conducted in vacuum.

Measurement traceability is required to link the measured electrostatic force to SI mass. Capacitance is determined using a commercial capacitance bridge calibrated traceably to the National Institute of Standards and Technology (NIST) calculable capacitor. This will be linked to h by an AC/DC quantum hall device transfer standard after the upcoming SI redefinition. Voltage is measured using a commercial multimeter, and is traceable to a Josephson junction array. Position is measured by a commercial laser interferometer in which a frequency reference is provided by a stabilized He-Ne laser. Mass is computed from electrostatic force using local gravitational acceleration as determined by an absolute gravimeter measurement performed in the same room as the measurement. In the cases where an EFB measurement is compared to one based on subdivision of the Kilogram, the subdivision value is determined as described previously [4], and is true mass (i.e., the air buoyancy correction has been applied.)

3. RESULTS AND DISCUSSION

The results of a weighing performed on a stainless steel 10 mg mass are shown in Figure 2. As in previous studies [4], the mass determined by the EFB is slightly smaller than that determined by Kilogram subdivision. The mass values determined are 10.00070(13) for subdivision and 10.000512(73) for the EFB, where parentheses indicate combined standard uncertainty. The difference in the mass values for these techniques is 0.19 μg , consistent with desorption of a surface water layer from the mass artefact's surface. Water desorption from uncleaned stainless steel surfaces account for mass changes of 0.74 $\mu\text{g}/\text{cm}^2$ of exposed surface area for artefacts stored at 40 % relative humidity [7]. The stainless steel artefact tested here has a surface area of 0.17 cm^2 , which indicates approximately 0.12 μg is expected to desorb under vacuum. This places the difference between the measurements well within experimental uncertainty.

A full description of the uncertainty analysis for the EFB [4] and subdivision methods [5] can be found in previous work. Table 1 provides a summary of the uncertainty components in the EFB measurement, which are broken down into type A for statistical uncertainty and type B for other types of uncertainty [8]. Uncertainty in transfer of length is dictated by the characteristics of the laser interferometer. The voltage and capacitance uncertainties are related to the electrical metrology. The alignment of capacitor cylinders, corner loading and alignment of balance travel are all dictated by the balance mechanism, and are

measured directly as the EFB is set up. Hysteresis is caused in the balance mechanism by the small impulse forces resulting from dropping the mass onto the balance. This effect is measured in a separate experiment, but introduces a small amount of Type B uncertainty. The temperature dependence of dC/dz results from a small amount of heating introduced by the automated mass handling stages. The type A uncertainty in weighing is taken as the standard deviations of the daily weighing results, which are themselves an average of 50 weighings. This term includes uncertainty from both the weighing and capacitance gradient measurements, as the dC/dz determinations bracket the mass determinations at regular intervals and the average value of dC/dz from before and after a weighing is used to compute force from Equation 1.

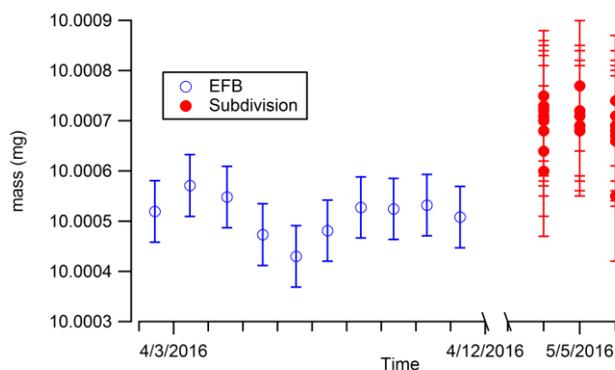


Figure 2. Comparison of EFB to Kilogram subdivision for the determination of a 10 mg mass value. Error bars on the EFB results, reported at $k=1$, are determined from the Type B uncertainties from Table 1 and Type A uncertainty calculated from the standard deviation of the mean for the mass measurements collected during each daily trial. Error bars, reported at $k=1$, for the subdivision results are determined as per published protocols [5].

In contrast to previous measurements, the type A uncertainty is no longer dominant at the milligram level. Systematic uncertainties such as the temperature dependence of the capacitance gradient contribute more overall to the combined standard uncertainty. This indicates that further reduction of uncertainty is possible. It is important to consider, however, that practical concerns dictate the stability of the mass is of great importance for dissemination of the standard. It will be important to evaluate the effects of repeated use and repeated cycling between vacuum and air on the mass value of reference artefacts.

4. CONCLUSION

The use of electrostatic force has been shown to provide a primary reference for mass that is equivalent to or better than subdivision from the kilogram. Combined standard uncertainty of the electrostatic method is shown to reduce the uncertainty of a 10 mg stainless steel wire artefact's mass value by a factor of 2 while providing the same mass value as subdivision. A submicrogram difference between

the results in the two methods is consistent with the effects expected from desorption of a water layer in the vacuum environment used for the electrostatic method. The uncertainty analysis applied to the electrostatic method yields a combined relative standard uncertainty of 7.3×10^{-6} , and further improvements are possible pending an examination of the stability of the mass artefacts calibrated.

Uncertainty components	Relative Uncertainties
<u>Type B uncertainties</u>	
transfer of length	1×10^{-7}
transfer of Voltage ($2\delta V/V$)	4.0×10^{-6}
transfer of capacitance ($\delta C/C$)	1.2×10^{-7}
alignment of capacitor cylinders	1.2×10^{-7}
corner loading	6×10^{-7}
stray capacitance	8.2×10^{-7}
hysteresis	2.2×10^{-7}
alignment of balance travel	7.3×10^{-7}
temperature dependence of dC/dz	4.4×10^{-6}
<u>Type A uncertainties</u>	
Weighing	4.1×10^{-6}
Combined standard uncertainty	7.34×10^{-6}

Table 1. Components used to determine calibration uncertainty in EFB measurement.

5. REFERENCES

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