Monitoring the Mass Standard via the Comparison of Mechanical to Electrical Power

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***Abstract*—This paper presents the current status of the NIST SI watt experiment. Included are goals for the near future as well as projections regarding the viability of monitoring and/or replacing the kilogram mass standard. Although several significant systematic errors have yet to be evaluated, the standard deviation of the mean of our present measurement distributions is 0.05 ppm.**

I. Introduction

The last remaining artifact standard in the SI system of units is the century-old cylinder of platinum–iridium alloy stored in a vault at the International Bureau of Weights and Measures (BIPM) in Sèvres, France. All indications are that this artifact, defined to be the kilogram, is in fact a very stable and practical standard. Intercomparisons with similar kilogram prototypes are routinely made with accuracies of 1 part in 10^9. However, the masses of such prototypes are known to increase with time due to absorption of water vapor and other material. A special cleaning procedure is thought to return the masses to a uniquely defined value, but the long-term stability at the 1 part in 10^8 level is less certain [1]. Only relative drift rates can be established without reference to an invariant of nature such as a fundamental constant. In order to make a significant contribution to monitoring the absolute stability of the kilogram, a measurement of its value in terms of fundamental constants would be needed with a precision of about 1 part in 10^8/year or better. In this paper we examine the possibility of using our watt experiment to achieve this goal.

The National Institute of Standards and Technology (NIST) SI watt experiment measures the ratio of mechanical work (kilogram-meter^2/second^2) to electrical work (volt-ampere-second). It is based on a concept originally proposed by Kibble [2]. The electrical quantities are measured in terms of voltages and resistances that are maintained with respect to fundamental constants. At the present time we use this experiment to measure these constants in SI units as defined by the kilogram artifact. We believe that the electrical quantities as maintained by the Josephson volt and the quantum Hall ohm are in fact more stable than the kilogram itself. However, these highly stable electrical standards will have little impact on the kilogram until a measurement of the SI watt or work ratio can be made to an accuracy comparable to the present mass stability.

In a recent version of this experiment [3] at NIST we achieved an accuracy of 1.33 ppm in the watt using a conventional electromagnet of modest field strength (2 mT). We have now begun making measurements at 50 times this field strength, using a superconducting magnet. We expect that this new version of the experiment will eventually provide an increase in accuracy by a factor of 10.

II. Theory

Consider the circuit of Fig. 1(a). Two coils carry currents I_1 and I_2. The vertical, z-component of the force between them, F_z, is given by the derivative of the mutual inductance: $F_z = I_1 I_2 (dM_{12}/dz)$. This vertical force can be compared to a gravitational force, mg, using a balance. Now consider the same two coils in Fig. 1(b), where coil 2 is open-circuit and a voltmeter measures the EMF generated across it as it is moved along z with respect to coil 1. The generated emf is given by $\varepsilon = I_1(dM_{12}/dt)$. Combining the expressions for F_z and ε we have

$$f_z v = I_2 \varepsilon \tag{1}$$

where $v = dz/dt$. This simply expresses the equivalence of mechanical and electrical power, all quantities being expressed in SI units.

To express the electrical quantities in our laboratory units we define $K_A = A_{90}/\mathrm{A}$, the ratio of the 1990 ampere international representation [4] to the SI ampere. K_V is defined in a similar way. Taking I_{90} to mean the current as measured in the 1990 representation and similarly for ε_{90}, we have $I_2 = I_{90}K_A$, and $\varepsilon = K_V \varepsilon_{90}$. Substituting these expressions in (1) we have

$$K_W = K_A K_V = \frac{F_z v}{I_{90}\varepsilon_{90}}. \tag{2}$$

Because it is difficult in practice to measure an instantaneous velocity or voltage accurately we do not use (2) directly to determine K_W. Instead, we use an integral form of (2), obtained by integrating the expression for the generated EMF over time and the expression for the force over distance. The expression then becomes a ratio of mechanical to electrical work. Experimentally, we realize these integrals by (a) measuring the EMF as a function of time while moving coil 2, and (b) measuring the current required in coil 2 to maintain a constant force between the coils for various static positions of coil 2. This integrated expression for K_W is given by

$$K_W = \frac{mg \int_{z_1}^{z_2} [I_0/I(z)]\, dz}{I_{0-90} \int_{t_1}^{t_2} \varepsilon_{90}(t)\, dt} \tag{3}$$

where t_1 occurs at z_1 and t_2 occurs at z_2. Here $\varepsilon_{90}(t)$ is the voltage generated when the movable coil is moved along some path in the field of the fixed coil. The product mg is the force on a

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standard mass in a known gravitational field against which the magnetic force is balanced. This simple proportionality between K_W and m is the reason this measurement could be useful for monitoring possible changes in prototype mass standards. For details concerning the link to fundamental constants, see [5].

$I(z)$ is the current in the moveable coil needed to create a magnetic force equal to mg at a position z. The current I_0 is $I(z_0)$, where z_0 is some convenient reference point about which $I(z)$ is measured. The quantity $\int [I_0/I(z)]\, dz$ is called the force integral and is a quantity which depends only on the geometry of the coils and on the path of integration, but not on the current in the coils. Equation (3) requires that the current in the fixed coil (i.e., the field coil) and the geometry of all the coils remain constant between the time that $\int \varepsilon_{90}(t)\, dt$ and I_0 are measured.

If the path of integration for the voltage is different from that of the force, then errors will occur. The suspended coil, as a rigid body, has 6 degrees of freedom that may contribute to the total work done over an integration path. A generalized form of (3) may be written in terms of summations over a chosen set of six coordinates:

$$K_W = \frac{\sum \int_{q_{i1}}^{q_{i2}} F_i\, dqi}{I_{0-90} \sum \int_{t_1}^{t_2} (\partial \Phi/\partial qi)\dot{q}\, dt} \tag{4}$$

where $\Phi = I_1 M_{12}$ is the flux linking the suspended coil, q_i are the three linear coordinates x, y, z and their respective angular coordinates θ_x, θ_y, θ_z and $\dot{q}_i$ are their time derivatives. F_i represents both forces and torques in these directions. Each of the six individual force–torque terms in the numerator has a one to one correspondence to voltage terms in the denominator because they are caused by the exact same geometrical variations. We discuss methods to evaluate the relative contributions of these additional terms below.

III. Apparatus

The apparatus used to make the measurements required in (3) has been described in some detail previously [6]. A brief review of the apparatus is made by referring to the schematic in Fig. 2. The moveable, suspended coil is equivalent to coil 2 in Fig. 1. A superconducting magnet, with segments above and below the suspended coil, provides the fixed field and is equivalent to coil 1 in Fig. 1. In addition to providing a much stronger field, we find the superconducting magnet to be much more stable dimensionally than the room temperature magnet that we have previously used. The details of its construction may be found elsewhere [7].

The suspended coil is attached to the balance wheel through the spider. The spider also supports a pan for the standard mass. The wheel is an aluminum disc with a knife edge at its center. A band consisting of 50 fine wires hangs from the wheel on both sides. As the wheel rotates, it acts like a pulley, raising or lowering the suspended coil. The advantage of this arrangement, compared to hanging the coil from one arm of a conventional beam balance, is that the translation of the coil is almost perfectly vertical. This allows force measurements to be made all along the vertical at any vertical displacement.

An auxiliary drive coil and a set of auxiliary permanent magnets, provides the means by which the balance wheel is made to rotate. A servo feedback to this drive coil controls the motion

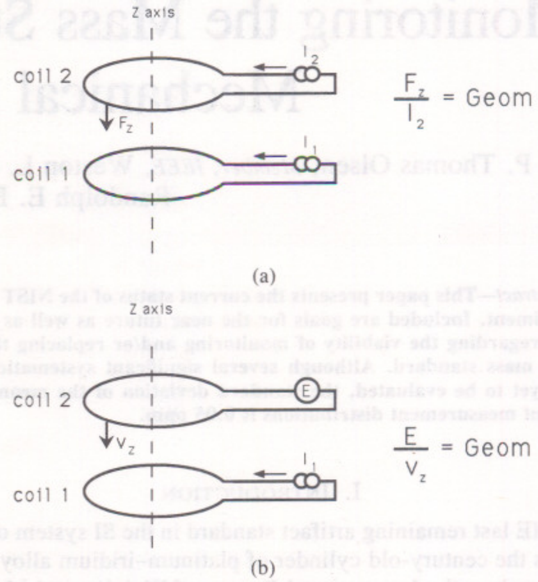

Fig. 1. Conceptual diagram of the experiment showing (a) the force measurement and (b) the EMF measurement. The geometry (Geom) factor can be eliminated by combining the two parts, $F_z/I_2 = \varepsilon/v_z$.

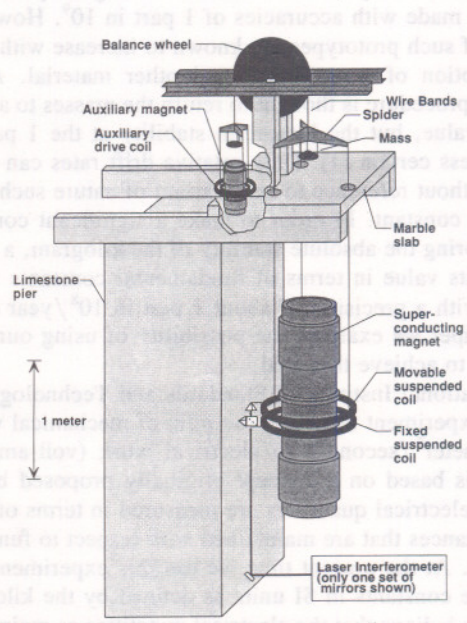

Fig. 2. The apparatus of the NIST SI watt experiment.

of the suspended coil for the generation of the EMF, ε. The position of the suspended coil is measured with a laser interferometer. Servo feedback to the suspended coil maintains this position while we measure the current in the suspended coil required to balance the force mg.

The suspended coil is wound in three separate concentric section with a total of 2355 turns of copper wire with a total resistance of 480 Ω. Reversing a current of 10 mA through this coil changes the magnetic force by about the equivalent force produced by a mass of 1 kg. Gold or brass 1 kg mass standards are used to measure the force. The 10-mA current is passed through a calibrated 100-Ω resistor which allows comparison of the voltage against our working 1-V voltage standard. The 100-Ω resistor is also used to generate 1 V as a reference for the generated EMF when the coil moves. A coil velocity of 2 mm/s generates a 1-V signal across the coil. Thus we are now measuring forces that are 10 times larger and EMF's that are 50 times larger than those previously reported [6]. The vertical travel of the balance has also been extended from 5.9 to 7.5 cm.

1) Magnet Operation: We operate the superconducting magnet in a constant current mode which is *not* persistent. Rather, the current through a temperature regulated, precision resistor is read by a high resolution, auto-zeroing DVM and changes are fed back to a programmable power supply in series with the superconducting coils. The voltage across the sensing resistor is nulled against a standard cell reference to improve the long-term stability of the magnet current. Due to the large inductance (6000 H) of the superconducting magnet, conventional PID (proportional, integral, derivative) feedback is found to be unstable. Instead we use a simple programmed algorithm. The program computes the voltage necessary to account for changing series lead resistances based on the known magnet inductance and the measured time derivative of the current. This correction voltage is then added into the power supply output in an integrated fashion. This technique is found to maintain the average current with less than 0.1 ppm/h drift. Two additional current sources provide small trimming currents to compensate for slight imperfections in the geometry of the various superconducting windings. A current of 5.25 A produces a radial field at the suspended coil of about 0.1 T.

2) Velocity Measurements: Some recent additions to the apparatus include an optical system to monitor the horizontal position of the suspended coil. A pair of corner cubes mounted on the coil reflect laser light to a fixed pair of quadrant photodetectors. The outputs of the photodetectors are read by a computer and combined to yield two horizontal displacements (x and y), as well as any angular displacement (θ_z) about the vertical. In addition, a flat mirror attached to the coil monitors its degree of tilt (θ_x and θ_y) using an autocollimator. These five additional coordinates provide information on their respective contributions to the work done over the integration paths as in (4).

Following a recent suggestion [8] we have introduced a new method to measure the velocity using a standard two-frequency orthogonally polarized commercial He–Ne laser with a frequency difference of 1.6 MHz. In the usual manner two difference frequencies are obtained: 1) a hetrodyne reference signal directly from the laser and 2) a hetrodyne signal from one polarization going to the corner cube attached to the moving coil and the other polarization going to the mirror on the stationary coil. Instead of using a conventional mixer to measure the difference frequency, we use a time interval measuring instrument capable of recording the time and count of each zero crossing of each cycle of the 1.6-MHz frequency. From the count information we compute the integral part of the phase difference and from the time difference we compute the fractional part of the phase difference. Thus we can measure the interferometer position at any rate up to a rate of 1.6 MHz, limited only by the rate that we can transfer blocks of data to the computer. Presently we store 4096 such positions during one direction of the velocity, then read it into the computer during turnaround and compute and store the data while taking the other velocity direction. We have the position reading synchronized with a precision DMM by using the start-integrating pulse of the DMM to prevent a data hold-off signal in the time interval instrument. We believe this new position measurement technique will greatly improve our flexibility in taking data as well as provide improved reliability and accuracy. The time interval instrument has an inherent noise (phase error) of less than 0.0005 of a fringe, but the optical detector noise is about 0.005 of a fringe and vibrations in the wire band cause a 0.3 of a fringe noise at the band resonance of 28 Hz. This unwanted noise averages out but is a major limitation in our velocity measurements. We believe we can greatly improve the weighing portion to the experiment resulting in this vibration becoming our largest source of noise. This new time interval measurement system has already proved valuable in diagnosing our velocity measurement problems. While we are not yet presenting measurements of K_W obtained with this new method, we are beginning to change our system over for this purpose.

In addition to our newly installed time interval measurement system, we are ready to install a new interferometer, consisting of corner cubes, directly mounted on the moving and stationary coils as originally planned. Until now, we found it convenient to have only one interferometer mounted on the axis of the coil with the mirror mounted on the mass pan, even if it was removed from the coils by a distance of more than two meters. The new corner cubes (the location of one is shown in Fig. 2) must, of course, be symmetrically located around the coils so we can measure the velocity of the center of the coil. We expect a significant reduction in noise because some unwanted motion between the coils and their corresponding mirrors in the present, interferometer location produces a measured velocity that does not appear in the simultaneous voltage measurement. Fortunately, many of the vibrations seen in the velocity are not observed in the ratio of voltage/velocity, because we measure the voltage difference and the velocity difference between the two coils. The closer the mirrors are to the coils, the more likely this cancellation will occur.

IV. Procedures

The measurement of K_W is divided into three phases, corresponding to the three key measurable quantities in (4). In the first phase, the suspended coil moves under servo control so as to generate a nearly constant EMF. Data accumulated during this ''voltage'' phase are used to compute the time integral of the voltage. In the second, or ''force'' phase, we measure the current, I_0, which balances the force, mg, at a specific position of the suspended coil. These two measurement phases are repeated many times in succession. At a different time, often separated from the first two phases by several days, we perform the third phase or ''force integral'' measurement. This is accomplished by comparing the current needed to balance mg at a variety of vertical positions of the suspended coil.

1) Voltage Measurements: In the voltage phase of the measurement, the EMF generated by the moving coil is servoed to a null against a reference voltage. This is accomplished by adjusting the velocity using a small current in the auxiliary drive coil. After each traversal the 10-mA current source is reversed, reversing the reference voltage. Under servo control, this reverses the direction of travel of the suspended coil, and another measurement is taken going in the opposite direction. Some computation of the time integral of the generated EMF, including digital filtering of the time data, is performed during the period when the coil turns around for another traversal. The compressed data are stored for later analysis. The integral is taken over a path whose length is 7.5 cm or a time interval for the voltage integral of about 37 s. A set of 12 traversals in each direction is measured, which, with the turning around time, requires about one-half hour. To eliminate the effect of drift and of zero offsets, we interpolate the voltage integral obtained for two up (down) traversals to the time of a down (up) traversal and compute the up/down difference in voltage integrals.

2) Force Measurements: During the force phase, the suspended coil position is servoed to a fixed location by feeding back the interferometer measurement as a current to the coil. This current is measured with the standard mass alternately on or off the pan which is connected to the spider from which the coil is hung. A force measurement typically consists of eight reversals when the mass is lowered onto or raised from the suspended pan. For each positioning of the mass, the coil current is measured by passing it through a 100-Ω resistor and comparing the voltage drop to the 1-V reference. The balance is arranged so that when the mass is lifted or replaced, the current in the coil must reverse in order to maintain the servo position. Current is measured for about 2 min in each mass position. Including the time for raising and lowering the mass and stabilizing the servo, the elapsed time for force measurements is about 25 min. To eliminate the effect of drift and zero offsets we interpolate between two measurements with the mass off (on) to the time of a measurement with the mass on (off) to obtain the on/off current difference.

On a typical day of taking data, we obtain 12 to 20 pairs of voltage and force measurements, at the rate of about one pair per hour, including the time required to automatically reconfigure the apparatus when changing from voltage to force measurements and vice versa.

3) Force Profile Measurement: The final phase of the measurement, the determination of the "force profile," is very similar to the force measurements described above. Here, we simply make repeated force measurements, but at various vertical positions of the suspended coil. To eliminate the effect of drifts, we continually measure the reversal current at the reference position used in the force phase. Thus we obtain the ratio of the reversal current at various positions, $I(z)$, to the current at the reference position, I_0. The measurements are repeated at different positions continuously for several days. The ratios obtained are fitted to a polynomial and analytically integrated over the same interval used for the voltage integral.

In order to minimize the influence of choosing a particular set of end points for the integration interval, we calculate the voltage integral for 20 to 50 overlapping regions with different sets of end points. The end points of the fixed-length intervals used are changed by about a third of the total distance used in the analysis. From each voltage integral, and the appropriate force integrals for each interval, we obtain a value of K_W. To reduce noise and to eliminate effects which contributed at the end points of the integral, such as variations in the velocity which might be due to servo errors, we average these with equal weight. (This process tends to weight measurements of voltage and time taken near the ends of the analyzed region less than those in the central region, since the integrated region always includes one or two centimeters of the region nearest the center.)

V. Recent Measurements

Fig. 3 shows a histogram of 45 values of K_W obtained over a period of several days. Each value contributing to the histogram is obtained as follows. From the values of two successive voltage integrals, typically taken an hour apart, we interpolate a voltage integral at the mean time of the intervening weighing measurement and calculate K_W from the actual weighing and the interpolated voltage integral. Similarly, we interpolate between two successive weighings to the time of a voltage integral measurement and obtain K_W from those values. The values in the histogram are averages of two successive values of K_W, one from two voltage integrals and a weighing and one from two weighings and a voltage integral. The next two values of K_W so obtained are used to produce another point on the histogram. Each point, therefore, contains information from two weighings and two voltage integrals, corresponding to approximately 2 h of elapsed time. While some of the information is used in adjacent points, they are reasonably independent. The standard deviation of these K_W values is 0.29 ppm with a standard deviation of the mean of 0.043 ppm. Because there still exist several unevaluated systematic errors, we do not report any new value for K_W at this time.

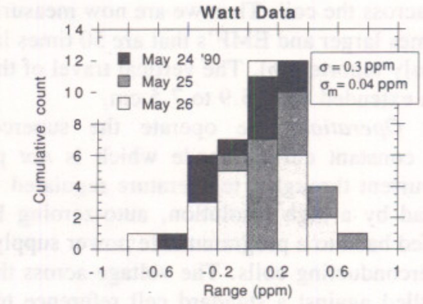

Fig. 3. A histogram showing the distribution of 45-w measurements taken over three days (45 h of data taking) in May 1990. The number of measurements obtained are represented by the lengths of the unit block; the value of the watt for these measurements is given in ppm with respect to an arbitrary offset.

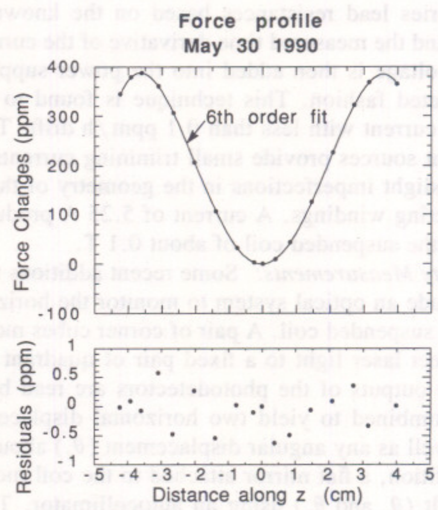

Fig. 4. A set of force measurements at seventeen vertical positions of the movable coil (shown as points) and a sixth-order fit (curve) to these force profile points.

Fig. 4 shows the results of a typical measurement of the force profile, along with the polynomial fit to the measured points. A similar profile can be obtained by integrating the voltage data over appropriately small time intervals. Because of the short time intervals, such a profile is noisier than the directly measured force profile, but it has the same shape, as expected.

VI. Discussion

In our current effort to push the accuracy of this measurement beyond the parts-per-million level, the following matters are of primary concern.

1) Alignment: Since we are comparing a magnetic force with a gravitational force, the measured force is strictly in the vertical or z direction. The force integration path in the numerator of (4) is thus well defined. However, the path followed for the EMF-time integration is not necessarily equivalent, and the corresponding extra work terms in the denominator of (4) can cause serious errors in K_W. The superconducting magnet is designed to produce an axially symmetric, purely radial field that ideally does not produce the extraneous voltages that appear in these extra terms. This can be seen most easily in Fig. 5. In this drawing of the magnetic field lines the region where the moving coil is used has only radial field lines that are uniformly spaced. If the radius of the moving coil is changed, it is easy to see that $\delta \Phi / \delta z \sim F_z$ does not change. Similarly, horizontal displacements cause only second-order changes in the force. In reality, small imperfections in the magnet construction, as well as misalignment between the magnet coils and the moving coils, can compromise this feature. There are two alignment parameters responsible for large first-order effects on the moving coil. Specifically, the "magnetic axis" of the superconducting magnet should be both parallel to the local vertical and coaxial with the suspended coil. In practice, this axis is defined as that orientation of our magnet which produces no horizontal forces or torques on the suspended coil. We then expect that the corresponding error voltages are likewise not produced.

If the magnetic axis is tilted with respect to gravity, horizontal forces will be exerted on the coil. We determine these forces by measuring horizontal deflections of the suspended coil under reversal of a known current through the coil. In this case the horizontal magnetic force is balanced against the gravitational restoring force formed by the 10-kg dead weight of the coil's pendular suspension with a 2.9-m lever arm. We can easily resolve angular deflections of, and align the magnet to within, about 10 μrad in this way.

The coaxial alignment is measured via the torque on the coil, either Γ_x or Γ_y, that is produced when the two axes (magnet and coil) are horizontally displaced. For a relative displacement of x_0 the torque on the coil is simply $\Gamma_y = F_z x_0/2$ and similarly for y_0 and Γ_x. First, the stiffness of the coil suspension is calibrated for tilt under a known torque. Autocollimator readings of the coil tilt angles, θ_x and θ_y, under current reversal are then a measure of these misalignment torques and the corresponding coaxial displacements. With our present coil suspension, a resolution in tilt of 1 s of arc corresponds to a resolution in coaxial displacement of about 60 μm. Once the coils are aligned this well, we can tolerate a rotation of the moving coil from its horizontal plane of only 50 sec over the 7.5-cm vertical integration path in order not to generate errors in K_W larger than 1 part in 10^7. It is also possible to increase sensitivity for measuring these quantities by relatively minor changes in the coil suspension, if necessary.

In addition, we must measure displacements in the velocity-EMF phase in a strictly vertical projection. In this case our laser interferometer must be aligned to within an angle of 400 μrad to avoid errors larger than 1 part in 10^7.

2) Extraneous Modes: The coil suspension has other degrees of freedom which are easily excited when masses are placed on and off the balance. Foremost among these are two nearly degenerate pendulum modes as well as a torsional mode with the wire band acting as a fiber that can twist. These modes move the coil around at non-negligible velocities and to the degree that the magnetic axis is misaligned, generate error voltages at their respective frequencies. To the extent that these

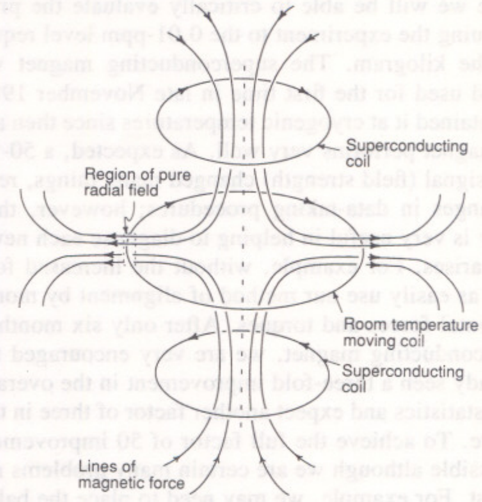

Fig. 5. Field lines in the purely radial geometry.

extra velocities change the voltage–time integration, their oscillations may not average to zero and systematic errors will occur according to (4). The modes are routinely monitored with the optical position detection system described above. We find our best data are in fact generated when these modes have not been recently excited. While we currently have only air damping on the coil, schemes for both passive and active damping of these modes are being considered.

3) Knife Edge Hysteresis: We have found that the zero point (point of zero net torque) of our balance changes systematically according to the direction and magnitude of its most recent excursions. Over the full $\pm 9°$ travel the effect can be as large as a 100-mg (100 ppm) shift. We normally determine this zero point by alternate measurements with the mass on and off the balance pan made at the same reference position z_0. Unfortunately, in order for the balance–equilibrium servo to accommodate the changing weights, the balance moves away from and then back to the reference position before we can make a new measurement. The direction of this excursion is in fact different for mass being taken off the pan than for mass on. The magnitude is typically near 1° with current servo system. This then creates a large systematic error in the weighing. To complicate matters, these excursions are not simply monotonic but exhibit an overshoot (undershoot) before the balance returns to the reference position. We have traced this hysteretic behavior to the knife edge which apparently is yielding under these conditions. Replacement with a virgin knife can reduce the effect but there is apparently a gradual degradation in the elastic behavior over time.

There are two ways this problem may be reduced. First, we are preparing to replace our 2.5-cm long silicon carbide knife with a 7.5-cm sapphire knife. We expect this material to exhibit significantly less hysteresis and the decreased load per unit length will reduce any tendency for yielding. Second, we should be able to reduce the magnitude of the excursions by about a factor of 30 with some changes in the balance–equilibrium servo.

VII. Future Prospects

Our immediate aim is to reach the original design goal of the experiment, namely, a 0.1-ppm or better value for K_W. This goal is likely to be reached within the next year or two. At the same time we will be able to critically evaluate the prospects for continuing the experiment to the 0.01-ppm level required to monitor the kilogram. The superconducting magnet was installed and used for the first time in late November 1989. We have maintained it at cryogenic temperatures since then and find that the magnet performs very well. As expected, a 50-fold increase in signal (field strength) changed many things, requiring many changes in data-taking procedures; however, the extra sensitivity is very useful in helping to diagnose each new problem as it arises. For example, without the increased force we could not as easily use our method of alignment by monitoring the horizontal forces and torques. After only six months using our superconducting magnet, we are very encouraged that we have already seen a three-fold improvement in the overall measurement statistics and expect another factor of three in the very near future. To achieve the full factor of 50 improvement still seems possible although we are certain many problems must be solved first. For example, we may need to place the balance in a vacuum chamber.

We believe the geometry of our experiment, combined with Kibble's two-part approach to equating power, is a very favorable method for an ultra high accuracy measurement.

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