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Prospects for a truly portable absolute gravimeter

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Abstract

We are in the process of developing a small portable absolute gravimeter that employs a cam-based dropping mechanism. The resulting high data rate (100 drops in 30 s) serves to compensate for the short (2 cm) dropping distance. We hope to achieve a measurement accuracy with this instrument of ±5 μgal.

> With few exceptions, the most convenient means for imparting a specific motion to a member is by means of a cam-and-follower mechanism. Not only can the motion be completely specified, but the resulting physical configuration is both rugged and compact (Fundamentals of Mechanical Design, third ed., by Richard M. Phelan. McGraw-Hill, p. 70).

Absolute gravity measurements offer the possibility of measuring vertical height changes (the subject of this meeting) at the centimeter level. Today's absolute instruments (Faller, in press), though capable of achieving the requisite level of accuracy (1–2 μgal, $1\text{–}2\times10^{-8}$ m/s^2), are still fairly bulky in comparison with relative instruments. Relative instruments can be used to study uplift phenomena but their use requires multiple repeat-measurements at each of a number of sites in order to establish the gravity differences whose changes in time are then indicators of vertical motion. A smaller and simpler absolute gravimeter, provided it has the requisite accuracy, would therefore be of considerable interest for the study of crustal deformation; for being absolute, it avoids the problems associated with multiple measurements at a variety of sites.

One possible approach to developing a ‘‘small’’ field-usable absolute instrument would be to measure g by dropping atoms and measuring their rate of fall using atom interferometry (Peters et al., 2001). (Since atoms are small they would also have the advantage of producing negligible instrumental recoil when they're dropped.) However, up to this point, the bulk of the necessary

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associated "electronics"—required to sense the atoms and to provide for the still-required seismic isolation—has resulted in working instruments that are somewhat larger than atoms, or for that matter anything approaching a field-usable size. Nevertheless, there is little doubt that atom interferometry will prove to be the wave of the future. In the meantime (and we believe there will be a reasonable meantime), let us describe a new "old fashioned" instrument that we are presently working on that is intended to meet this measurement need.

The reader should recognize that no matter how you measure g, you run into a "wall" of geophysical and man-made noise sources at the parts in 10^9 level of accuracy.

Accordingly, the challenge is not to have exquisite sensitivity (much better than 1 in 10^9) to changes in gravity (as is already presently achieved using cryogenic gravimeters) but to make the simplest and most user-friendly yet easily portable instrument that will measure to an accuracy of a few parts in 10^9. With this in mind, we have developed a simple cam-driven dropping mechanism (see the quote at the beginning of this paper) that creates a free-fall drop every 0.3 s. The instrument is "inertially compensated" (our instrument's answer to the fact its dropped piece weighs a lot more than does an atom) by using a second cam to drive a balancing mass whose motion keeps the center of mass of the instrument fixed throughout the entire release–drop–catch–return cycle. As a result, there is no appreciable phase-related-to-the-drop recoil effect—something that very often can systematically bias a result. The problem is simply that the measurement process (the free fall of the dropped object and the other motions required to effect this) causes the instrument to both recoil and shake—and both effects result in acceleration noise. And because these effects occur nearly identically for each drop, this noise contribution does not average out. The cam's rotation rate is adjustable so that the cam can be set in sync with the free-fall rate that is dictated by the (local) value of gravity. The beauty (we feel) of this instrument is its simplicity as well as its relatively small size. In addition, because it is an absolute instrument, it neither drifts nor suffers from tares as do relative gravimeters.

In the instrument we are developing, a double cam mechanism (Faller et al., 2001) controls the motion of two carts (Fig. 1). At the start of a drop, the (corner-cube-containing) dropped object sits kinematically on the upper cart. On this cart being accelerated down faster than g, the dropped object, having lost its support, goes into free fall. The shape of the cam is such that after release, the upper cart then maintains a (nearly) constant "lift-off" (separation between it and the dropped object) until the end of the free-fall period. At the end of the drop, this object is gently caught, slowed down, and returned to the top position at which point the entire process repeats itself again. The release–drop–catch–lift cycle occurs in one revolution of the cam. The measurement is made during 2 cm of undisturbed free-fall during the 3.4 cm total drop length. One consequence of this short drop is that 200 measurements are made every minute. Another is that the dropping chamber's height, presently 38 cm, can be reduced to about 30 cm.

The lower cam of the instrument, that drives an auxiliary mass, is designed so as to compensate for all of the various accelerations of the upper cam that are required to create the lift-off and catch as well as to compensate for the dropped objects and the upper carts zero weight when they are in free fall. Our "old fashioned" answer to the fact that, in an atom interferometer, the weight of the dropped object is negligible is that we inertially compensate for the dropped object's weight so as to keep the weight supported by the floor constant. Removing recoil effects on the measurement is particularly important for this instrument because the short drop length requires that both times and lengths be measured to a higher precision if one is to achieve an accuracy comparable to that obtained in longer-drop instruments. Incidentally, to create a drop comparable in length to

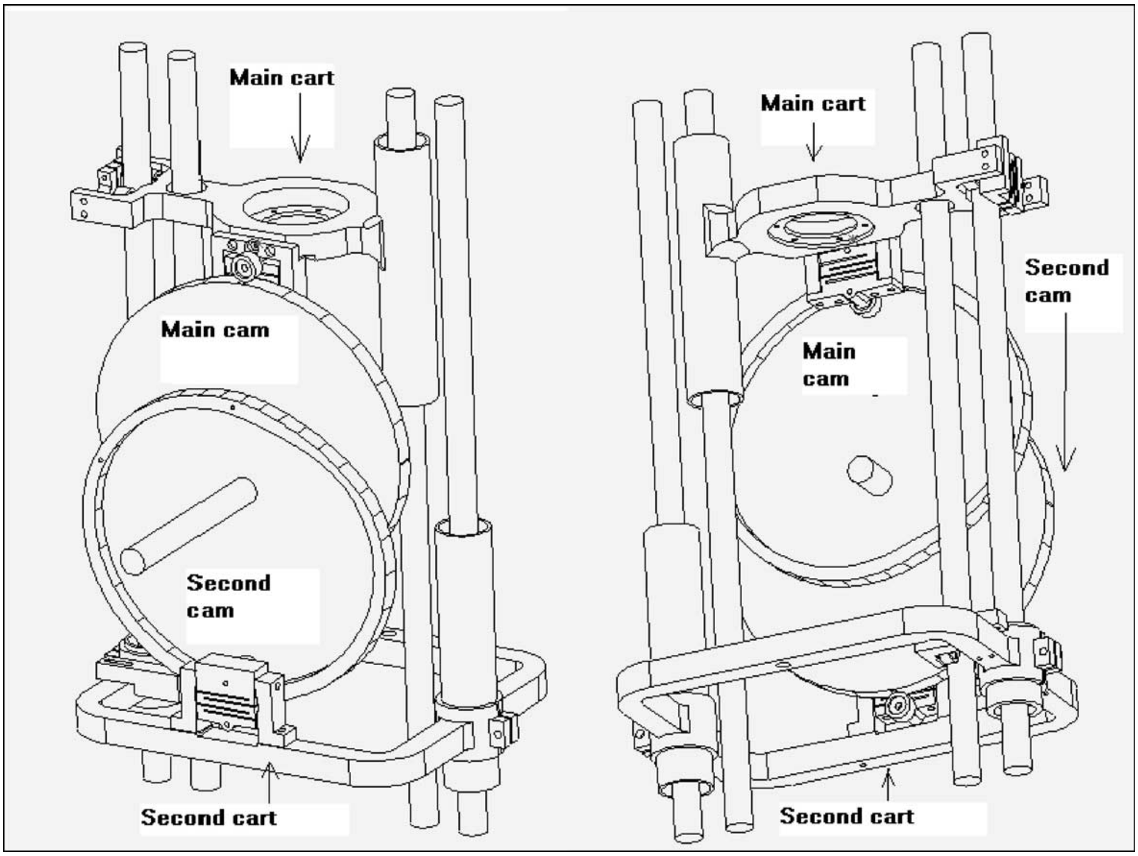

Fig. 1. Schematic drawing of how the two carts are each driven by a cam.

the 20 cm used in the FG-5 (Niebauer et al., 1995) and GABL (Russian Instrument) absolute gravimeters, the cam would need to be 10 times larger.

Because one was available, for this prototype instrument we used the interferometer from an FG-5 (Faller et al., 2001) absolute gravimeter. This is essentially a modified Mach-Zender interferometer. In the final instrument, this ‘‘borrowed’’ FG-5 interferometer base will be replaced with a much smaller one.

A schematic view of the present instrument is presented in Fig. 2. The vacuum chamber (1) containing the dropped test mass (2) is positioned under the interferometer (5). The vacuum is maintained at a pressure 10^{-4} Pa (1 μTorr) by a miniature ion pump. A passive spring with a corner cube (3) is mounted directly on top of the interferometer. Because the high data rate results in four measurements being made during each period of the spring (spring period = 1.2 s), the scatter caused by the inevitable motion of the spring in its fundamental mode cancels out. (The *average* of any four sequential measurements will be very close to the ‘‘connect value.’’)

The passive mass-spring system purposely has a period of 1.2 s. Within one period, the system completes exactly four drops. It is because we exactly sample the position of the reference mass four times each spring period that its otherwise data-dominating acceleration ‘‘noise’’ is (nearly) cancelled out.

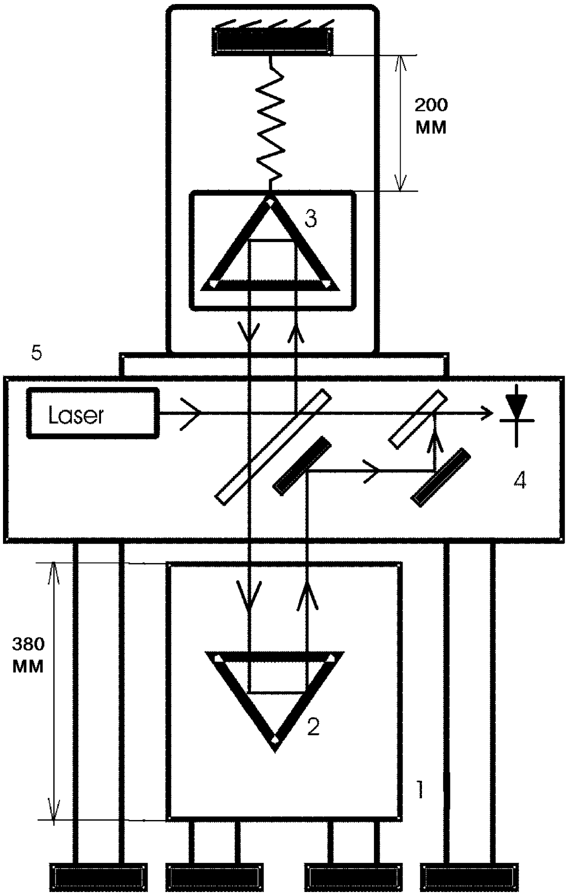

Fig. 2. Schematic view of instrument (gravimeter).

The reference ‘‘mirror’’ consists of a copper mass (with a corner cube inside) hung at the end of the spring (Fig. 3). Eddy currents created by magnets that are placed in a circular manner around the copper mass are used to damp rotation and other spring modes. These magnets, whose poles lie along the inner and outer edges, are twice as long as the copper mass, with the result that they do not significantly damp the vertical motion of the spring. The degree of damping can be altered by changing the distance between the magnets and the copper mass. Though this design is very simple to use and requires only a few minutes of set-up time, it is very effective in reducing the drop-to-drop scatter.

The test mass falls, fringes occur at the output of the interferometer. The maximum frequency of the fringes in the case of this small cam-based instrument is 2 MHz. An avalanche photodiode converts the interferometers optical output to an electrical signal. A high-speed comparator, generates the zero crossing signals. The TTL (square wave) signal is then sent to the time interval counter. The internal clock is slaved to a 10 MHz rubidium frequency standard.

The signal is processed with standard FG-5 software ‘‘Olivia’’ (Micro-g Solutions). That was compiled to suit our system. The data are least-squares fit to a function that uses the known vertical gravity gradient. The software also makes the required corrections for the solid Earth

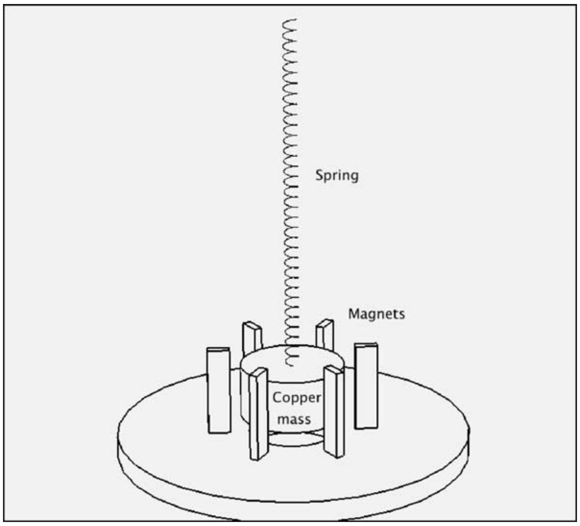

Fig. 3. Reference mirror suspension showing magnetic damping scheme.

tides, polar motion, barometric pressure, speed of light, and ocean loading as well as allowing for the transfer of the measured value to a preferred datum height.

In September 2001, a series of measurements were carried out at the pillar AG of the Table Mountain Geophysical Observatory (Boulder, CO, USA). This station is known for its very low level of seismic noise. Measurement sets of 120 drops were taken every 3 min during the day and every 15–20 min at night. Fig. 4 shows the data for September 27 starting at 7 pm and then taken every 15 min thereafter.

Standard deviations for the single set of 120 drops (requiring just 36 s to make) ranged from 40 μgal to 200 μgal. The "set to set" standard deviation ranges between 4 and 8 μgal which is somewhat better than a simple square root of *n* analysis would suggest. The reason is that much of the "scatter" results from the acceleration associated with the springs fundamental mode which—because of the data rate—is mostly cancelled out. The *g* value derived from this extended data set was found to show a ±20 μgal sensitivity to the selection of the data start and stop points.

Recently, back at JILA, we have been able to reduce this "cut-off" sensitivity to the level of ±3 μgal by using better metrology in the gravimeter assembly process and at the same time making several improvements in the dropping mechanism. At this point, the latest JILA-taken data appears very promising. We will still need to revisit the Table Mountain site to see if a nearly simultaneous FG-5 determined value there falls within our "cut-off" windowed value. At the present time, we are slightly, but critically, modifying the shape of the cam to reduce in size the necessary direction-changing impulses it applies in the course of creating the necessary cart cut-off motions. We expect that this will reduce the size of the residuals and, accordingly, the magnitude of any residual-related (systematic) effects.

So, what are the prospects for a truly portable absolute gravimeter? At the 1963 IUGG meeting (held in Berkeley, CA) one of us (J.E.F.) asked Lucien LaCoste if he thought that someday small absolute gravimeters would be used instead of his relative gravimeters. He answered, "Yes, . . .but I'm not worried." We believe that were Lucien still alive today he might at least be somewhat worried.

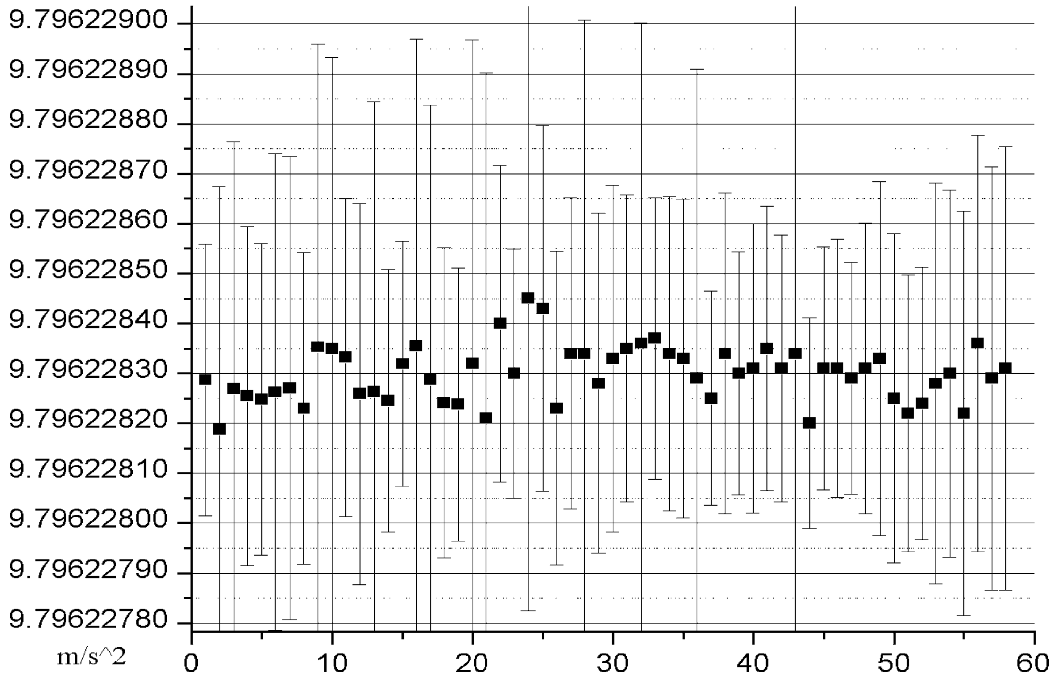

Fig. 4. Extended (overnight) data set (as described in text). Note that at this site, a half-minute is required to get a measurement of 10 μgal.

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Though the trade names of several commercial products are given in the text, this is done for identification purposes only, and does not constitute an endorsement by the authors or their institutions.

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