A New, Portable, Absolute Gravimeter

M. A. Zumbeuge, J. E. Faller, and R. L. Rinker

Joint Institute for Laboratory Astrophysics, National Bureau of Standards and University of Colorado, Boulder, CO 80309

We report on the performance of a new and easily portable apparatus for the absolute measurement of the acceleration of gravity. Rapid acquisition of data and high accuracy result from the use of a drag-free dropping chamber that descends with the falling object whose acceleration is measured interferometrically. Preliminary results indicate an absolute accuracy of 6 parts in 10^6.

Key words: absolute gravity meter; freely falling corner cube; stabilized laser interferometer.

1. Introduction

The absolute determination of g, the acceleration due to the earth's gravity, has long been a measurement of considerable importance. While g continues to play a significant role in the determination of certain physical constants and standards, with the accuracies obtainable today, this measurement now has broad applications to geophysics. The gravimeter that has been developed at JILA is based on the free-fall interferometric method which has undergone many refinements since it was first used in the 1960s [1-4]. A freely falling mass that contains a corner cube serves as the mirror in one arm of a Michelson-type optical interferometer. The times of occurrence of selected interference fringes give its position as a function of time, and from this the acceleration of gravity, g, can be calculated.

Over the surface of the earth the value of g varies by less than 0.5% from its nominal value of 980 cm/sec^2. This variation is due primarily to the earth's rotation which produces a centrifugal term causing g to decrease toward the equator. This rotation also causes the earth's shape to deviate from a sphere which in turn produces a further dependence on latitude. Local topography and density variations are two other important factors.

The vertical gravity gradient near the surface is approximately 3 μGal/cm (1 Gal = 1 cm/sec^2). Because of this, cm-sized vertical motions of the earth's crust will show up as variations in g of a few parts in 10^6. Since such motions often occur very slowly, the long-term stability in any instrument—if it is to detect them—is of utmost importance. Relative gravimeters which are sensitive to μGal level changes in gravity have existed now for a decade or more; however, they must be operated continuously at a single site if unambiguous results are to be obtained. Furthermore the sensitivity of relative measurements is often limited by instrumental drifts that are not simply linear in time. For these reasons, a portable absolute instrument whose measurements depend on atomic standards and whose absolute accuracy approaches 3 parts in 10^6 would be a very useful tool in the study of tectonophysics. We have successfully built an instrument that appears to approach this accuracy while maintaining the highly portable character necessary for field applications.

2. Design

Figure 1 is a schematic representation of the system. A Michelson interferometer is arranged in such a way that one of the corner cubes is allowed to fall freely. An interference fringe results from each half wavelength of the laser light traversed in the dropped object's descent.

![Figure 1. Schematic of absolute gravity apparatus.](image)

Over the 20 cm length of free-fall during which the measurement is made, 600 000 fringes are generated. The zero-crossing time of every twelve-thousandth fringe is carefully measured and then stored in a computer. The resulting 50 data points are fitted to a quadratic curve which then gives the dropped object's acceleration. This process, which requires only a few seconds, can be repeated many hundreds of times in one hour.

The quantity actually measured is the second time derivative of the optical path difference between two optical elements, one of which is in some way attached to the earth's surface while the other (the falling one) is accelerated by gravity as well as by the vector sum of all other forces acting on it. The interpretation of this measu-
urement as the absolute value of local gravity requires that we fully understand the limitations set by all other forces and processes involved. This entails four fundamental considerations: one, non-gravitational forces on the dropped object must be eliminated or reduced to an acceptable level; two, the optical path difference must be translated into a physical length based on an accurate knowledge of the laser’s wavelength and the index of refraction appropriate to the residual gas at the operating level of vacuum; three, the acceleration of the reference frame from which the measurement is made must be close to zero; and four, the electronic system that counts and times the occurrence of interference fringes must do so without introducing any systematic errors. The design of the instrument proceeded with these four considerations as the underlying guidelines.

Three recent innovations have contributed to the successful development of this instrument: One, a drag-free dropping chamber has been built to shield the dropped object from non-gravitational forces; it is described in detail later. Two, a long period isolating spring developed at JILA [5] has been used to isolate the interferometer’s reference corner cube from vertical motions in the laboratory that would otherwise accelerate the reference frame with respect to which the \( g \) measurement is made. [Note that with a freely falling corner cube and a vertical inertially suspended reference corner cube, the interferometer input is differential in that vertical motions of the rest of the instrument cancel out.] Three, a newly implemented Zeeman stabilization scheme also devised at JILA [6] has been used to stabilize the He-Ne laser that serves as the light source in the interferometer. Its wavelength is periodically (for example on a monthly basis) compared with an iodine stabilized laser developed and built for us by the Length and Mass Measurements and Standards Division of NBS. This absolute wavelength standard, taken together with a rubidium frequency standard (used as the basis of our measurement electronics), lets us base our gravity measurement directly on secondary length and time standards whose accuracy provides the requisite stability for the study of long-term changes in gravity resulting, for example, from tectonic deformation of the earth’s crust in seismically active regions.

3. The Instrument

Air drag makes it impossible to approach any reasonable accuracy without dropping the corner cube in a vacuum. Some years ago at NBS, Tate [7] developed a technique in which the dropped object fell in a vacuum chamber that was dropped simultaneously, minimizing the force due to momentum transfer between the falling object and residual gas molecules in the chamber. To avoid the vacuum welding and other materials-related problems associated with ultrahigh vacuum systems, we have invoked a similar technique. In our instrument the dropped object is contained in a servo controlled motor-driven elevator which moves inside the main vacuum system. This elevator effects the release and then tracks the falling object—without touching it—during the measurement. As a result, the object falls with the residual gas molecules rather than through them, while the differential motion between object and elevator is minimized. This results in a substantial reduction in air drag and allows the \( g \) determination to be carried out in a more moderate vacuum.

Figure 2 is a schematic representation of the drag-free dropping chamber. The dropped object rests in kinematic mounts on a chamber that can be driven along vertical guide rails by a thin stainless steel belt connected to a dc motor. The position of the dropped object relative to this drag-free chamber is measured by focusing light from an LED through a lens attached to the dropped object onto a position sensitive photodetector. The error signal thus derived is used to control the motor that accelerates the chamber downward, leaving the dropped object floating inside. Near the bottom of the drop the chamber is first served to gently arrest the dropped object’s fall, and then used to return the dropped object to the top of the track for the next measurement. Figure 3 is a photograph of this system.

In addition to shielding the dropped object from drag forces the falling chamber also serves to remove other non-gravitational forces. The chamber provides an electrically conducting shell to completely surround the dropped object so that external electrostatic fields do not affect the measurement. Also, the purely mechanical character of the release removes the necessity for having any sort of magnetic support or release mechanism that might subsequently result in an unwanted magnetic force. Finally, buoyancy effects are removed because a pressure gradient cannot exist in a zero-\( g \) environment.

The detection of the interference fringes using a photomultiplier results in a sinusoidal signal whose frequency is proportional to the falling object’s velocity. A zero crossing detector and a digital scalar are used to convert this signal into a series of about 50 pulses, each of which corresponds to the dropped object having fallen 6000 wavelengths (12,000 fringes) or about 0.38 cm. The times of occurrence of these pulses referred to an arbitrary but common zero are measured to within 0.2 nsec by commercial electronics and stored in a minicomputer. A quadratic least-squares fit to these data determines \( g \). Analysis of the residuals indicates that the length measurement errors are about 0.001 wavelength. The analysis
Most of the data have been taken in the sub-basement of the laboratory wing of JILA on the University of Colorado campus in Boulder. Some data sets, however, have been taken in a building on the outskirts of the National Bureau of Standards grounds in Boulder. This latter site is significantly quieter in that it has less vibration than the JILA sub-basement, but is less convenient in terms of modifications. We plan to reoccupy the NBS site, as well as several others around the Western United States, in the near future.

Figure 5 is a histogram of 150 drops which comprises one 10-minute data set. The standard deviation in such sets varies from as low as 20 μGal to as high as 70 μGal during unusually noisy periods caused by poor weather or increased human activity nearby.

4. Results

Despite the fact that the instrument is portable, it has been moved only a few times thus far in its development. Until now, the primary emphasis has been the detection, understanding, and elimination of systematic errors.
discuss sources of error that have been considered to date.

The effects of possible magnetic and electrostatic forces on the dropped object are as yet undetectable. The addition of magnetic fields larger than those normally encountered by the dropped object have been found not to affect the value of \( g \). The result of changing the separation of the dropped object and the co-falling chamber does not cause a shift in the measured value of \( g \), indicating again that electrostatic or magnetic forces between them are not significant.

Initially we had hoped to be able to work at a pressure of 10^{-3} mm of Hg and were encouraged by measurements in which we purposely introduced a relative velocity between the falling chamber and the dropped object. No significant shift in \( g \) resulted from rather large relative velocities (2–4 mm/sec). However, onset of rapid temperature changes produced a several hundred \( \mu \)Gal transient. Rough calculations of the magnitudes of forces due to temperature and pressure gradients across the dropped object as well as the effects of surface and cavity outgassing—all of which would occur during times of departure from thermal equilibrium—suggested that a lower vacuum was not only prudent but necessary. In our present operating vacuum range of 10^{-5} to 10^{-6} mm of Hg, the problems introduced by changing temperatures were found to be greatly reduced.

Errors that stem from rotation or translation of the dropped object [8], the effect of small rotations in optical elements in the interferometric path, the consequences of optical misalignment, and any effects of optical feedback on the laser, are all believed to be less than 10^{-9} of \( g \). Other considerations, which have thus far yielded no indication that errors are present, include nonrandom mechanical vibrations introduced systematically by the measurement and frequency-dependent time delays in the electronics.

6. Conclusions

Although several of these points deserve further examination, we feel that most of the sources of systematic errors have been recognized and are well in hand. It is, however, always possible that further investigation may reveal other difficulties, but it seems unlikely that our quoted value will change by more than 10 \( \mu \)Gal. To date, we have made 400 sets of 150 drops during which the system appeared to operate correctly (e.g., we were not subjecting it to special test conditions) over a one-month period, yielding a value (reduced to the floor using a gradient of 2.3 \( \mu \)Gal/cm) of 979.608557 Gal. The standard deviation of the results of these 400 sets is 5.9 \( \mu \)Gal or about 6 parts in 10^9 (see Fig. 7), while the standard deviation of the mean of a single 150 drop set ranges from 3 to 7 \( \mu \)Gal. Recognizing the as yet uncompensated meteorological effects, the results are statistically consistent. We feel the one sigma uncertainty of 6 \( \mu \)Gal is a conservative representation of the instrument’s capabilities. Further tests of the instrument’s accuracy are planned, including direct comparison with other absolute instruments.

This work was supported in part by the Air Force Geophysics Laboratory and in part by the National Bureau of Standards as part of its research program on improved precision measurement techniques for application to basic standards.

References
