ADVANCED ABSOLUTE GRAVITY DETERMINATION

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ABSTRACT

During the past twenty years, a number of absolute gravimeters based on laser interferometry have been developed. At the Joint Institute for Laboratory Astrophysics (JILA) we have recently designed and built a new and highly-portable absolute gravity apparatus based on these principles for the purpose of surveying tectonically interesting regions. The status of this new instrument and our future plans for it as well as the general status of absolute gravity determinations will be discussed.

Just as the 19th century witnessed the development of the theory and practice of observations with pendulums for the determination of absolute and relative values of gravity, the second half of the 20th century saw the development of free fall methods for the absolute determination of g. During this period, a number of absolute gravimeters based on the method of free fall have been developed. The earliest determinations [1-5] used the methods of geometrical optics to define the position of the falling object while during the past twenty years, the methods of interferometry — often with a laser light source — have been directly used [6-15].

In the new and portable instrument which we have developed at JILA, we interferometrically determine the acceleration of a freely falling corner cube. In the design and development of this instrument, particular attention was paid to those aspects which would affect its performance in the field. The resulting instrument, we believe, provides a viable new tool for the study of tectonic motions. The system is very small; it can be transported in a small van and requires only two hours for assembly. A high rate of data acquisition is available; if necessary, a single measurement can be made every 2 sec. Further, we have made a concerted effort to detect and eliminate systematic errors. The results of extensive tests indicate that the achievable accuracy for g is about six parts in 10⁶. This instrument therefore provides a sensitivity to vertical motions (e.g., of the Earth's crust) as small as 2 cm.

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The basic principle (see Fig. 1) of the instrument's operation [16-19] is the same as has been used successfully in several other absolute gravity meters. One arm of a Michelson interferometer is terminated by a corner cube retroreflector which is allowed to be freely accelerated by the Earth's gravity, and the times of occurrence of certain interferometer fringes are measured and used to calculate the acceleration of this falling object. A stabilized laser, used as the light source in the interferometer, provides the length standard while an atomic frequency standard provides the time standard.

Two aspects of this instrument account for its ability to achieve high accuracy without sacrificing small size and, hence, portability. First, a new dropping mechanism has been developed which eliminates several sources of systematic error while providing a rapid means of repeatedly releasing the dropping object. Second, a long-period isolation device [20] is used to greatly decrease the instrument's sensitivity to ground vibrations. This avoids the large drop-to-drop scatter that would otherwise result from our comparatively short dropping length (20 cm) — a consequence of the instrument's small size.

In the free fall method, air drag makes it impossible to approach any reasonable accuracy without dropping the corner cube in a vacuum. In our instrument the dropped object is contained in a servo controlled motor-driven drag-free evacuated dropping chamber which moves inside the main vacuum system. This dropping chamber effects the release and then tracks the falling object — without touching it — during the measurement. As

![Figure 1. Schematic of absolute gravity apparatus.](image-url)
a result, the object falls with the residual gas molecules rather than through them. Initially we had hoped to be able to work at $10^{-3}$ 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 µgal transient (1 gal ≅ 1 cm/sec²). 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, still moderate, operating vacuum of $10^{-5}$ mm of Hg, the problems introduced by a dynamic temperature situation were found to be greatly reduced. Further, at this pressure, we still avoid vacuum-welding and the other materials-related problems usually associated with ultrahigh vacuum systems.

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 freely floating inside. Near the bottom of the drop the chamber is first servoed 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. This rapid turnaround capability is primarily responsible for the system's ability to acquire data at a very high rate.

The falling chamber also serves to remove other nongravitational 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.

If one is to achieve a few parts in $10^9$ accuracy in g, an effective method for isolating either the entire system or the reference cube (hung vertically so that vertical motion of the base shortens both arms equally) must be achieved. The need for this isolation stems from the fact that during a measurement, the dropped cube during its free fall is completely isolated from the Earth's microseismic motion and other man-made noise. The reference corner cube (in the other arm of the interferometer), however, is not. In the past, use has been made of an astable spring system as employed in commercially available long-period vertical seismographs. These systems, however, are somewhat awkward to use and suffer from internal (violin-string) modes in the main system spring.

To achieve isolation, we use the fact that a mass (in our case, the reference cube) suspended from a long spring is effectively isolated from vibrations (which enter at the top) for all frequencies greater than the natural resonance of the system. Thus, one must have a system resonance
of 0.05 Hz or lower (20 sec period or longer), which calls for a fairly long spring. For example, it would take a spring 1 km in length to yield a period of about 60 sec.

In practice, we electronically terminate a tractable length of spring (i.e., 30 cm) so that it behaves exactly as if it were, for example, 1 km long. The mass on the end oscillates up and down with a period of 60 sec ($\nu = 0.017$ Hz) and therefore is isolated for all periods shorter than this. To understand this electronically generated "super spring," imagine you have a 1 kg mass hanging on the end of a weak coil-spring which extends 1 km vertically. This mass will oscillate up and down (with a period of 60 sec) and as it does, the coils of the spring will oscillate up and down also. The coils very near the mass will have
an amplitude nearly equal to the amplitude of the mass and the coils that are far away from the mass will have an amplitude less than that of the mass. In fact the coils near the top will scarcely move at all. Now if one were to grasp the spring 30 cm above the mass and move that point on the spring just as it moved when the lower portion was in free oscillation, the motion of the mass would remain unchanged. Having done this, one could then cut off the top of the spring and be left with a 30 cm long spring that has the same resonance frequency and behaves in all ways exactly as a spring 1 km long. In our "super spring" we use a servo system to generate such a virtual point of suspension.

Figure 3 is a schematic drawing of the system. The two side springs supply the force to support a bracket on which a mass is attached by a central spring; this bracket is free to move in a vertical direction. The light from the LED is focused by the sapphire ball onto a split photodiode. The outputs from the two halves of this diode are amplified and differenced, producing an analog signal that is proportional to the displacement of the weight. This signal is processed by a servocompensated amplifier which drives a loud speaker voice coil. This coil then supplies the needed force on the bracket to cause it to track the motion of the bottom weight. Since the top of the spring is attached to the bracket, the top of the spring moves with nearly the same amplitude as the bottom. The degree of tracking is determined by the gain setting of the servo system and this in turn sets the effective length of the spring and thereby the achieved period. While we can easily achieve periods in the range of 10 to 100 sec, we normally use a period of about 50 sec.

![Diagram of the super spring system](image-url)

Figure 3. The "super spring."
Figure 4 is a photograph of the apparatus. The dropping mechanism is inside a vacuum chamber which is supported by three folding legs. Beneath this is a base that supports the long-period isolation spring and contains the associated optical components that comprise the interferometer. The electronics fit nicely in two packing cases. We no longer utilize the large Dewar seen in the foreground but simply maintain the vacuum by using an ion pump which is now attached to the top of the dropping chamber. One person can disassemble and load the entire system into a small van in about one hour. Reassembly takes one to two hours.

The detection of the interference fringes by 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. This analysis presently requires about 4 sec, so 150 drops can be made in 10 minutes. Analysis of the residuals indicates that the average length measurement errors are about 0.001 wavelength.

Figure 4. Photograph of apparatus.
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 μgals to as high as 70 μgals during unusually noisy periods caused by poor weather or increased human activity nearby.

Figure 6 shows results from two days of continuous operation at about 70% of the maximum possible data acquisition rate. The tidal effects of the sun and moon can easily be seen. The solid line is the theoretical tides calculated without the inclusion of any ocean loading effects (which are small in Boulder). Subtraction of the theoretical tides results in an rms deviation of about 6 μgals for the means of sets of 150 drops. The removal of the theoretical variation due to changes in barometric pressure did not reduce the rms deviation. No attempt was made to correct for other meteorological effects.

The fundamental problem involved in measurements of this sort is the problem of recognizing and eliminating systematic error sources. Table 1 gives a concise summary of the sources of error that have been recognized and considered to date.

![Histogram of one run](image-url)

**Table 1**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>979.607963 gals</td>
</tr>
<tr>
<td>Sigma</td>
<td>36.0 μgals</td>
</tr>
<tr>
<td>Sample Size</td>
<td>150.0 drops</td>
</tr>
<tr>
<td>STANDARD ERROR</td>
<td>2.9 μgals</td>
</tr>
</tbody>
</table>

**Figure 5.** Histogram of one run.
Table 1. Known systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differential Pressure</td>
<td>1.0 μgal</td>
</tr>
<tr>
<td>Differential Temperature</td>
<td>1.0</td>
</tr>
<tr>
<td>Magnetic Field Gradient</td>
<td>0.5</td>
</tr>
<tr>
<td>Electrostatics</td>
<td>1.2</td>
</tr>
<tr>
<td>Attraction of Apparatus</td>
<td>0.5</td>
</tr>
<tr>
<td>Vertical Reference</td>
<td>0.8</td>
</tr>
<tr>
<td>Optical Path Changes</td>
<td>2.8</td>
</tr>
<tr>
<td>Laser Wavelength</td>
<td>1.0</td>
</tr>
<tr>
<td>Rotation</td>
<td>1.0</td>
</tr>
<tr>
<td>Translation</td>
<td>1.0</td>
</tr>
<tr>
<td>Floor Recoil</td>
<td>1.0</td>
</tr>
<tr>
<td>Phase Shift</td>
<td>1.0</td>
</tr>
<tr>
<td>Frequency Standard</td>
<td>0.5</td>
</tr>
<tr>
<td>rss Total</td>
<td>4.2 μgal</td>
</tr>
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</table>

Over the past several years, the primary emphasis has been on the detection, understanding, and elimination of systematic errors. The high repeatability of a measurement (e.g., the precision) is unfortunately not always an indication of the accuracy. Repeatability is nevertheless a necessary -- though not sufficient -- condition. A rather detailed discussion on the question of accuracy is to be published elsewhere [21].

Over the past year, during which many tests and evaluations were made involving both disassembly of and modifications to the instrument, the rms deviation in $g$ as measured in our JILA laboratory amounted to about 10 μgal. We are unable to attribute this increased variation to any specific effect, although we suspect that some part of it may be related to changes in ground water content around and under our sub-basement laboratory. During this period the instrument was taken (in October 1981) to
the Bureau International des Poids et Mesures in Sevres, France (near Paris) to participate in an international comparison of absolute gravimeters and (following its return) to the absolute gravity site at the University of Denver.

Though the JILA absolute gravimeter is still not completely out of the development stage, given that the systematic error budget totals about 4 μgal and the reproducibility is generally 6-10 μgal, it seemed appropriate to begin field measurements with the new instrument. To this end during the past 1 and 1/2 months measurements have been made at six sites in California (selected for their geophysical interest); at three sites along the mid-continental North American gravity calibration line; at JILA, a "check" measurement; and at two sites on the east coast, the National Bureau of Standards in Gaithersburg, Maryland, and the Air Force Geophysics Laboratory in Bedford, Massachusetts. The only major difficulty (damage) we encountered in carrying out these twelve measurements resulted when the large Dewar (which we still carry in the van along with the apparatus in the event it should be necessary to restart the vacuum) tipped over, breaking the high voltage terminal on the ionization vacuum pump. This happened when the driver had to brake suddenly to avoid hitting a cow. We plan to publish the results of these measurements as soon as we have completely reduced the data.

The laser wavelength error, given in Table 1, is based on using a Zeeman stabilized laser [22]. However, for some of the field measurements, as well as the BIPM and Denver measurements, we have experienced some problems with this laser and/or have had to use a Lamb-dip-stabilized laser. Because of this, the accuracy of these measurements may be limited to about 10 μgal. This difficulty should be corrected soon.

Over the next several years, our aim is to see that absolute gravity measurements become both usable and used in the field. To this end, we are in the process of designing (and building) a number of new instruments incorporating several modifications which, based on our experiences to date, should further improve the ease of using the instrument in the field. We also expect to be able to reduce the rss error budget to about 3 μgal, primarily by removing the pellicle from the bottom of the dropping chamber and replacing it with appropriately baffled holes. This will eliminate the bulk of the 2.8 μgal listed in Table 1 under optical path change errors.

Though much work remains to be done, one cannot fail to be impressed with the extraordinary progress that has been made over the past 20 or so years. Today one can make absolute measurements as accurately — possibly even more accurately — than one can make relative measurements. Given continued interest and support, the last 20 years of this century should see absolute gravity mature both as a new geodetic data-type and a useful geophysical tool.

Acknowledgments

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References