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in

Proceedings of the 1983 International School and Symposium on Precision Measurement and Gravity Experiment, Taipei, Republic of China, January 24 - February 2, 1983, ed. by W.-T. Ni (Published by National Tsing Hua University, Hsinchu, Taiwan, Republic of China, June, 1983)

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During the past several decades, scientific interest in gravity has continued to be strong. Some of the reasons for the present-day interest in "g" are suggested by the first few slides. Slide 1 points to the use of gravity as a prospecting tool. Slide 2 reminds us that surface measurements of gravity can be used to construct subsurface density structures. Finally gravity can be used as an alternate method to classical leveling (slide 3) to look for vertical height changes. An instrumental accuracy of 6 parts in 10^9 in g (6 μgal) provides a sensitivity to vertical motions (e.g. of the Earth's crust) as small as 2 cm.

At the Joint Institute for Laboratory Astrophysics (JILA) we have recently designed and built a new and highly-portable absolute gravity apparatus based on laser interferometry.

The basic principle (slide 4) of the instrument's operation 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 our new 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 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 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/sec^2). 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 outgasing -- 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 2-3 × 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.

The next slide (slide 5) 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 is completely isolated from the Earth's microseismic motion and other man-made noise during its free fall. The reference corner cube (in the other arm of the interferometer), however, is not isolated. In the past, use has been made of an astable spring system as employed in commerically 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 (ν = 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.

The next slide (slide 6) shows 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 photodiode are amplified and differenced, producing an analog signal that is proportional to the displacement of the mass. This signal is processed by a servocompensated amplifier that drives a loud speaker voice coil. This coil then supplies the needed force on the bracket to make it track the motion of the bottom weight. The top of the spring, which is attached to the bracket, moves then 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.

The next slide (slide 7) 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 frequency-swept interference fringes (slide 8) 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.

On the next slide (slide 9) 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.

The next slide (slide 10) 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 μgal 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 meterological effects.

The fundamental problem involved in measurements of this sort is that of recognizing and eliminating systematic error sources. The next slide (slide 11) gives a concise summary of the sources of error that have been recognized and considered to date.

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. Repeatibility is nevertheless a necessary -- though not sufficient -- condition.

The next slide (slide 12) asks the question: When do you stop inventing and take this instrument (which was designed and developed with portability in mind) out of the warmth and comfort of the laboratory into the field? The next slide (slide 13) points out that even though the JILA absolute gravimeter is still not completely out of the development stage, its 6-10 μgal reproducibility suggests that while it may not be perfect, it is nevertheless, good enough to be tried in the field. It may not be perfectly round, but it will surely roll.

The first thing we did was to pack it in 18 (mostly yellow) boxes (slide 14) and take it (in Oct. 1981) to the Bureau International des Poids et Mesures in Sevres, France (near Paris) to participate in an international comparison of absolute gravimeters. The next slide (slide

15) shows a photograph taken of the apparatus at that (crowded -- at least not as spacious as the Grand Hotel) site.

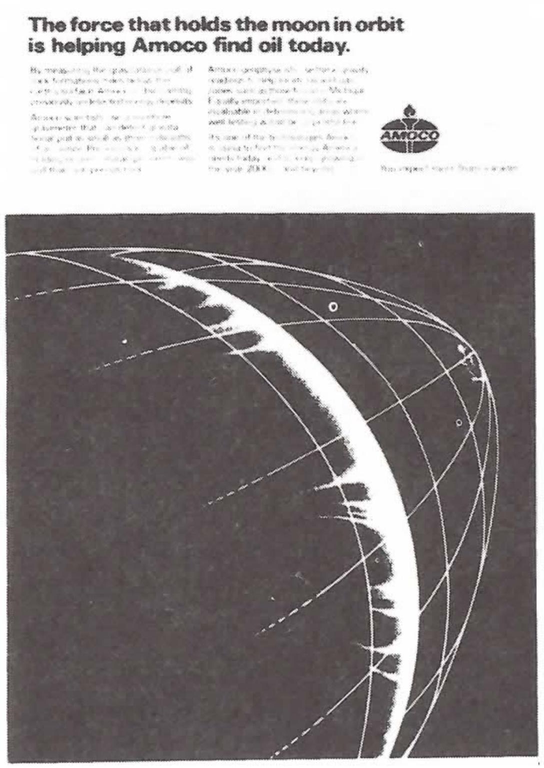
Sometime after its return from Paris, we compacted it further so as to permit it to nicely fit in a small van. The next slide (slide 16) shows the back of the packed van, and the next slide (slide 17) shows the dropping chamber and super spring as they were stowed directly behind the front right seat of the van. One significant instrumental change was made during this period; an ionization-type vacuum pump was permanently attached to the top of the dropping chamber (slide 18). This permitted us to "carry the vacuum with us" by the simple expedience of plugging a 12 V to 3 kV high voltage inverter into the cigarette lighter in the van and using the 3 kV to keep the ion-pump operating while in transit. During a period of 1 1/2 months, measurements were 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) 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. The next slide (slide 19) shows the field modification that was made to allow for this sort of contingency.

A number of the sites occupied during this field trip had previously been occupied by one or at most two absolute instruments. Comparison of the different absolute measurements made at the common sites (though complicated by the fact that they were separated by up to three years in time), generally agreed at the 20-40 μgal level; however, given the quoted errors of the various measurements, one should have expected agreement at the 10-15 μgal level. This suggests that one or more of the instruments may have an as yet undiscovered source of systematic errors.

The next slide (slide 20) shows the two-year span of data we have from our JILA laboratory. Although we have no guarantee that this laboratory is (gravitationally) stable, the agreement of our measurements is within ±6 μgal over this extended period -- a period in which the instrument was modified, taken apart and re-assembled, taken to Paris and then later taken to the twelve U.S. sites, etc.

So what is next? Our aim over the next several years, 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 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 under optical path change errors in our error budget.

Finally, 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. Thank you very much for your kind attention.



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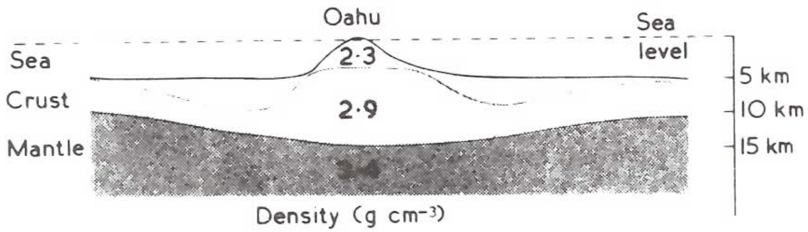


Figure 3 Structure of Hawaii inferred from variation of gravity

(2)

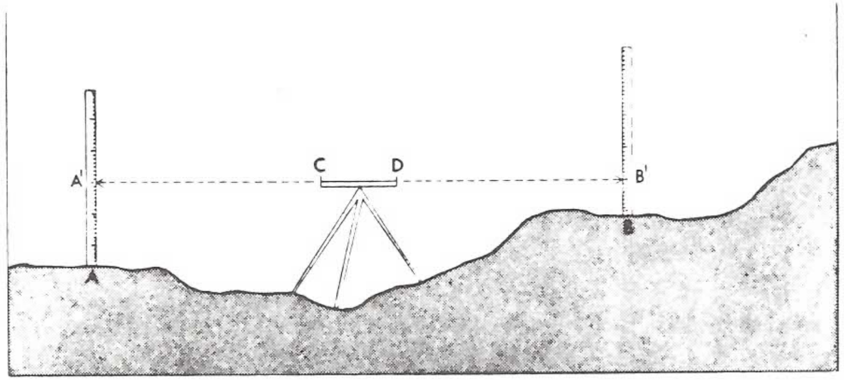
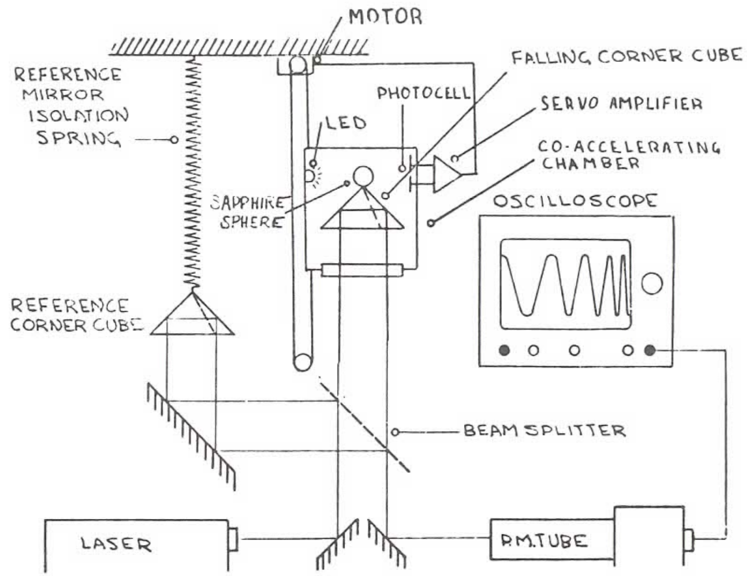


Fig. 1—**ANCIENT METHOD OF LEVELING**, or the determination of heights. A trough of water is placed halfway between two graduated rods, A and B. Sightings are made across the surface of the water, which is always level, first, from C to D to B' and then from D to C to A'. The difference between A-A' and B-B' is the difference in height of the ground levels upon which the rods A and B are standing.

(3)



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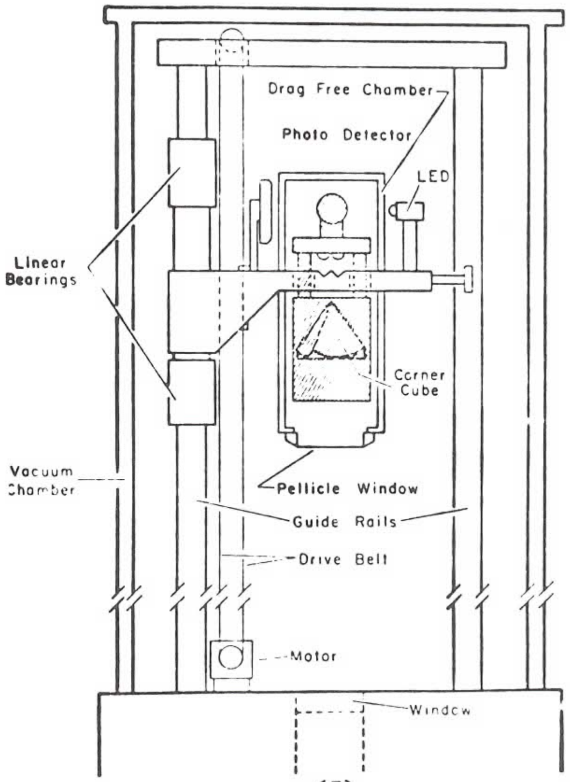
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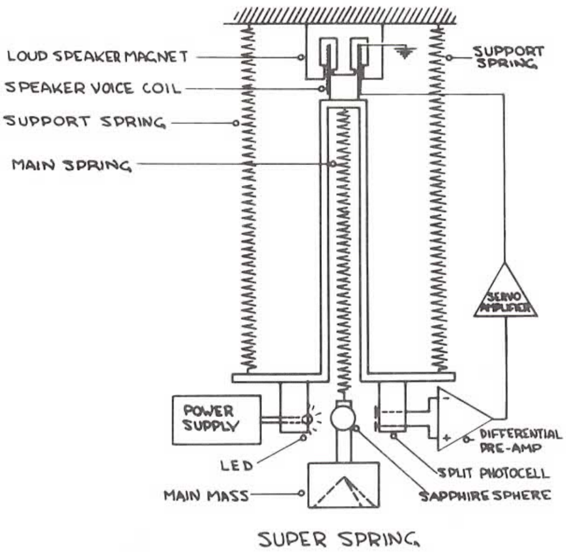
Photo Detector
LED
Linear Bearings
Corner Cube
Vacuum Chamber
Pellicle Window
Guide Rails
Drive Belt
Motor
Window

(5)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SPEAKER VOICE COIL
SUPPORT SPRING
MAIN SPRING
SUPPORT SPRING
SERVO AMPLIFIER
POWER SUPPLY
DIFFERENTIAL PRE-AMP
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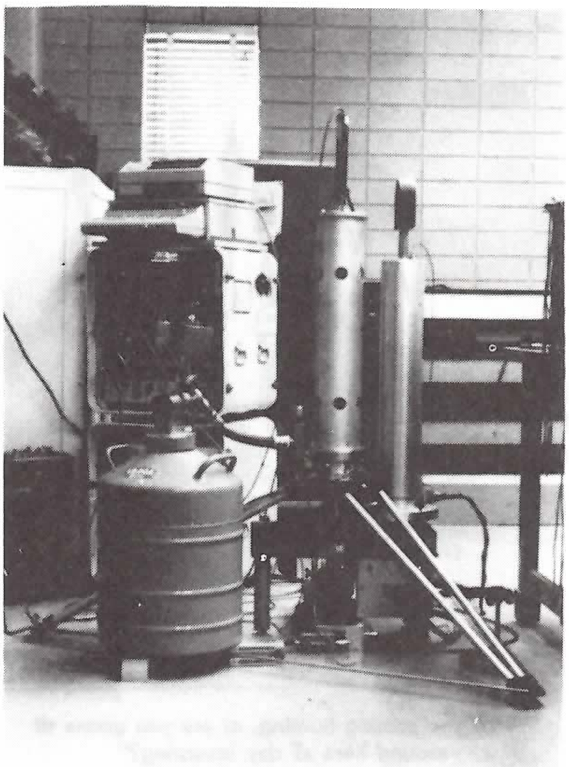
SPLIT PHOTOCELL
MAIN MASS
SAPPHIRE SPHERE
SUPER SPRING

(6)



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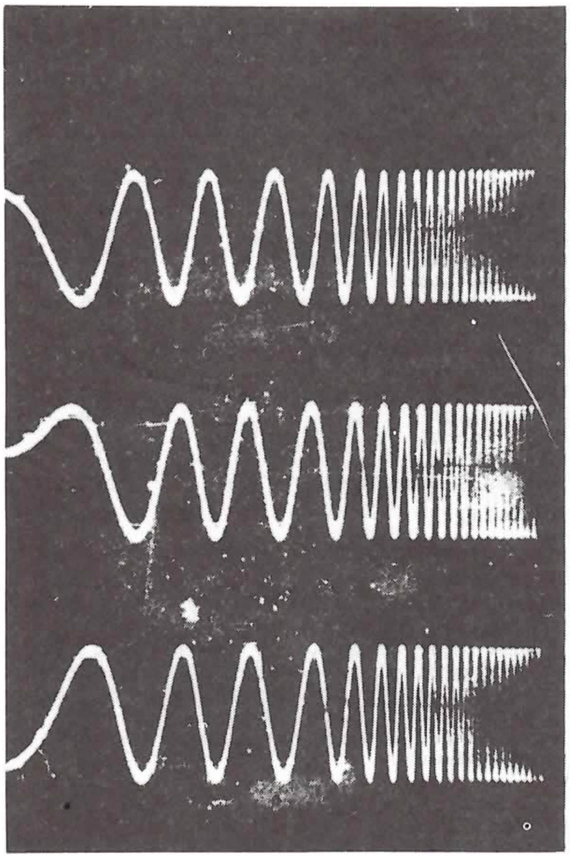

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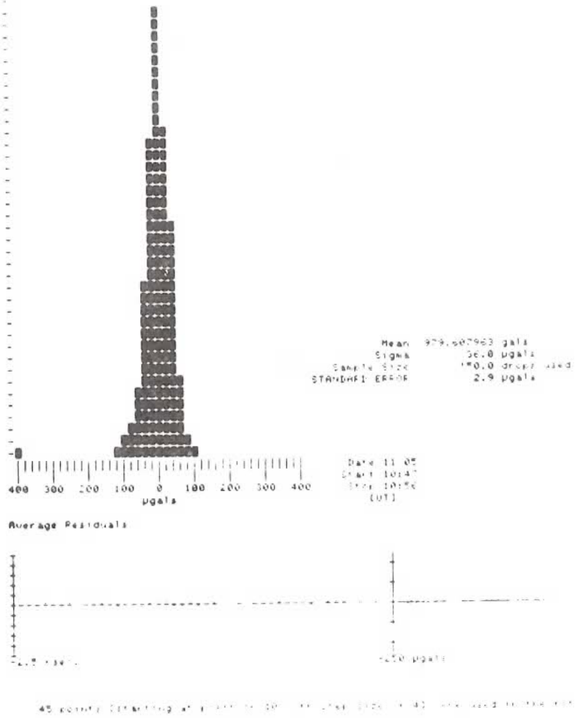

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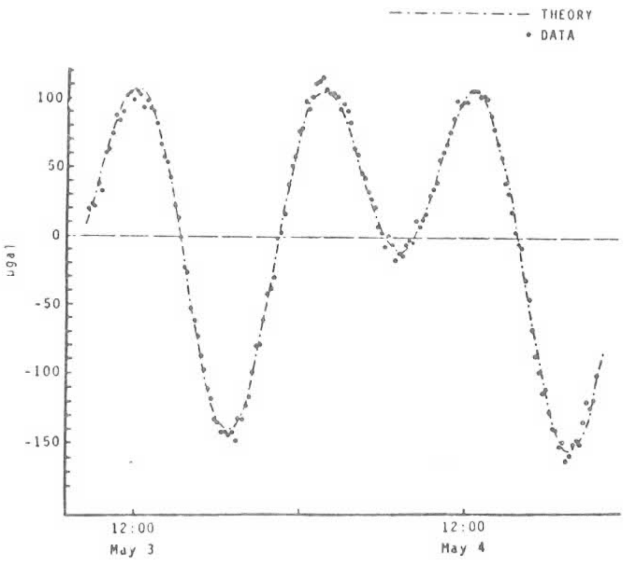


(10)

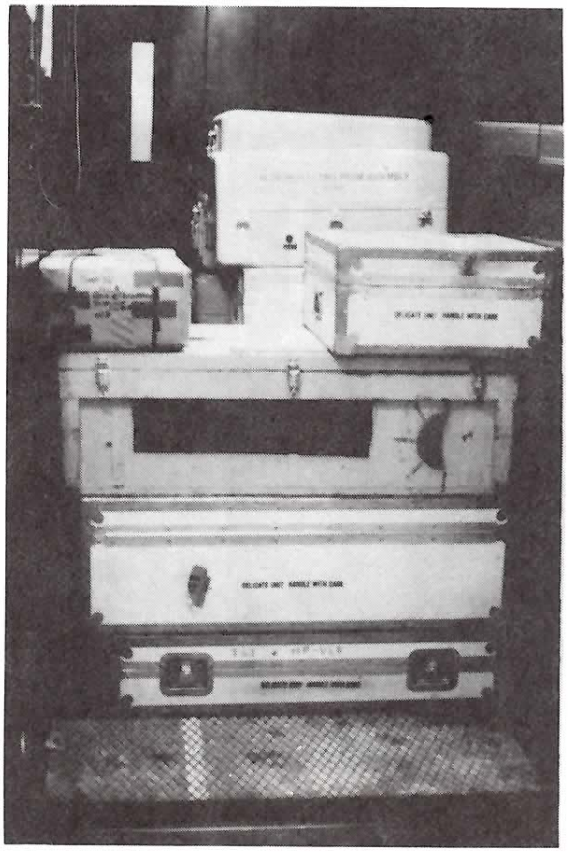
KNOWN SYSTEMATIC ERRORS

Source	Error
Differential Pressure	1.0 µgal
Differential Temperature	1.0
Magnetic Field Gradient	0.5
Electrostatics	1.2
Attraction of Apparatus	0.5
Vertical Reference	0.8
Optical Path Changes*	3.8
Laser Wavelength	1.0
Rotation	1.0
Translation	1.0
Floor Recoil	1.0
Phase Shift	1.0
Frequency Standard	0.5
rms Total	4.2 µgal

*This error is primarily due to problems associated with the pellicle on the bottom of the drag-free chamber having a finite wedge angle. At the present time we are exploring a number of possibilities (including the possibility of completely eliminating the pellicle) with the aim of reducing or eliminating this error source.

(11)

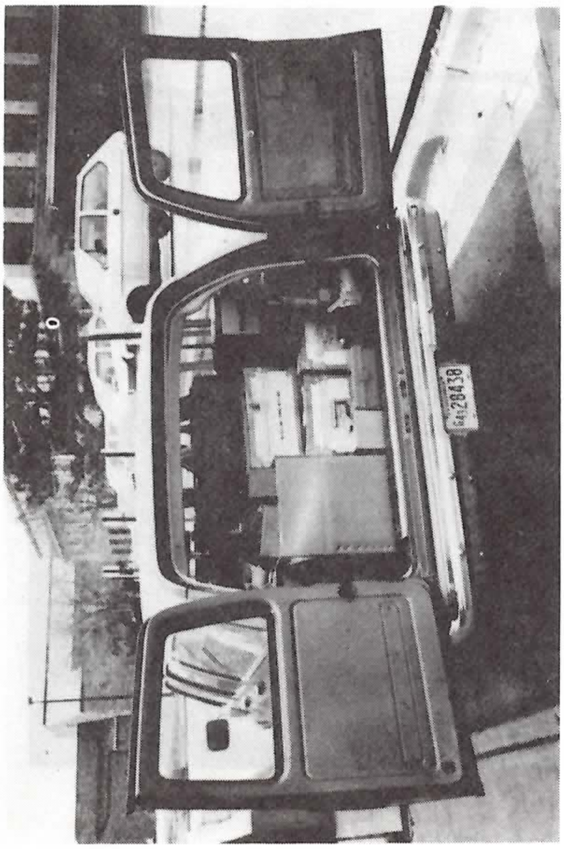
(12)



(14)

"It may not be a perfect wheel, but it's a state-of-the-art wheel."

(13)



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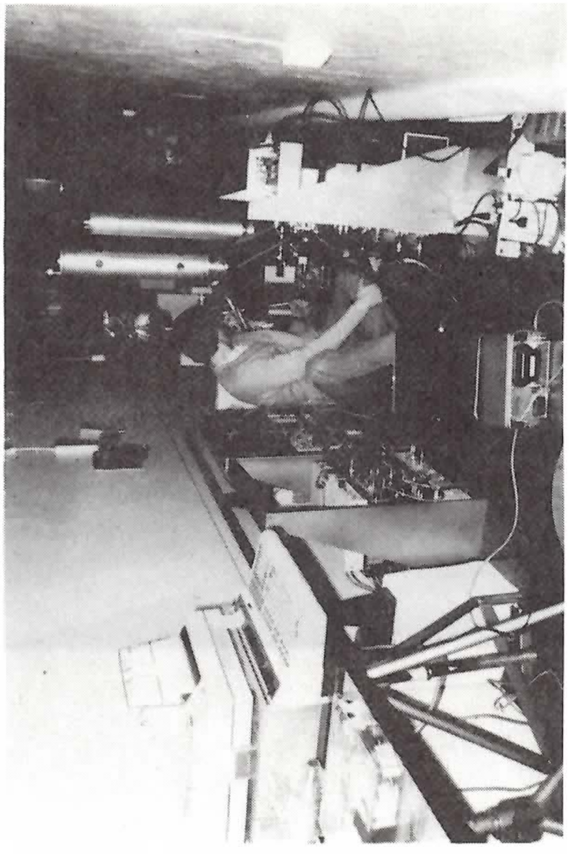

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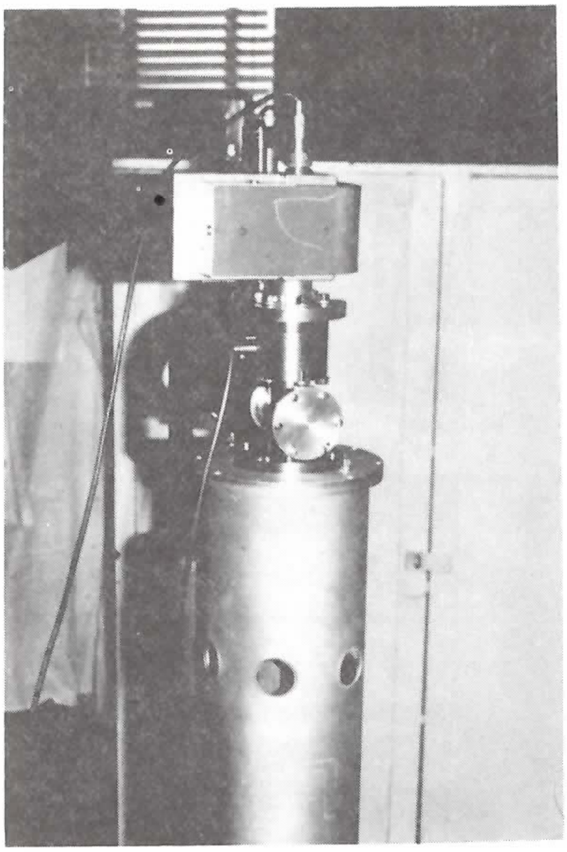
(17)



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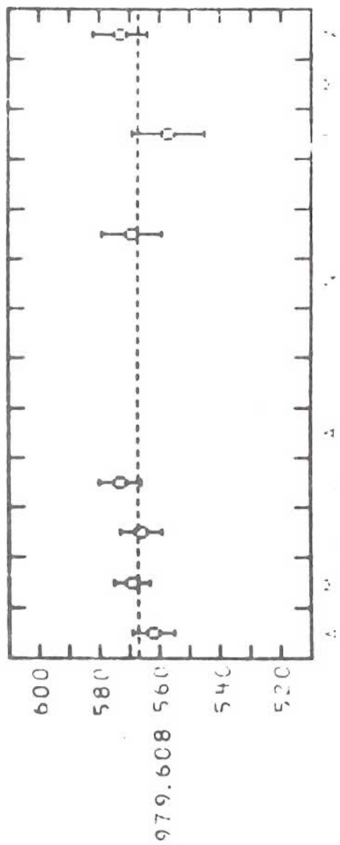

(20)