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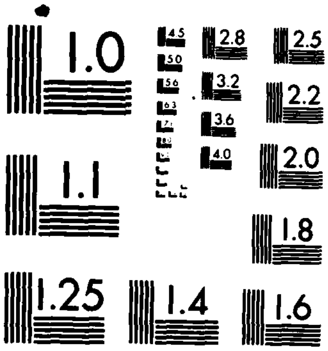
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The AFGL Absolute Gravity System's Error Budget Revisited

ROBERT L. ILIFF
ROGER W. SANDS, MSgt, USAF

8 May 1985

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IN-HOUSE REPORTS

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The error budget for the ~~Air Force Geophysics Laboratory~~'s absolute gravity measuring instrument has been reevaluated for the purpose of locating and correcting an apparent bias that appeared in the data at the ~~Hanscom AFB~~ gravity lab early in 1981. The results of this analysis reveal a major equipment-induced error and minor data reduction errors. Revised gravity values at various sites across the U.S. and Sevres, France are given along with values obtained with other instruments at collocated sites.

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The AFGL Absolute Gravity System's Error Budget Revisited

1. INTRODUCTION

The Air Force Geophysics Laboratory (AFGL) has been involved in research for the development and improvement of a transportable system to measure absolute gravity for several years. Several absolute gravity stations have been established in the United States and cooperative gravity projects have been pursued, both nationally and internationally. A description of the system and its operational and data reduction techniques has been described earlier.[1] Following the October 1980 absolute gravity measurements for the calibration line, Great Falls, Mont., Sheridan, Wyo., Boulder, Colo., Trinidad, Colo., and McDonald Observatory, Tex., the AFGL absolute gravity measuring system acquired an apparent bias in the measurements at the AFGL site. Although equipment problems precluded immediate verification of a systematic shift in the measured value, efforts were finally made to locate and rectify errors that could influence the data.

Plausible causes of a shift in the measurements are:

(1) Laser wavelength change (length standard)
(2) Time standard change
(3) Verticality shift

(Received for Publication 3 May 1985)

[1] Iliff, R.L., and Sands, R.W. (1983) The Absolute Gravity Measuring System A Final Report and Operating/Maintenance Manual, AFGL-TR-83-0297, AD A147853.

Plausible causes of a shift in the measurements (Contd)

(4) Shift of the optical center with respect to the center-of-mass of the dropped object

(5) Real gravity change

(6) Equipment change

(7) Pressure gauge error

A detailed analysis of the cause and effect of errors that could be introduced by the first four error sources can be found in References 1 through 3.

2. LASER WAVELENGTH

The standard of length is based on the wavelength of light from the Spectra Physics Model 119 stabilized He-Ne laser. A change in the wavelength of the laser of nearly a part in 10^7 would be required to cause a change of 80 μgal in the measurement of g. The normal drift rate of this laser has been measured[1] to be about one part in 10^8 per year (a correction is made for laser wavelength drift). The Spectra Physics specification[4] for long-term stability is 1 MHz/day with servo control to lock the laser to the Lamb dip and 75 MHz/day without servo locking. The data taken both with and without locking the laser showed no significant difference in the resultant measured value of gravity. No unexpected change had occurred in the laser wavelength at the time it was checked and the standard of length was therefore dismissed as a cause of error.

3. TIME STANDARD

The system timing is derived from a Tracor Model 304A Rubidium frequency standard which is locked to an atomic transition yielding a frequency accuracy of one part in 10^{11} and a drift rate of less than three parts in 10^{11} per month.[5] A change of about five parts in 10^9 would be required to cause an 80 μgal shift in our measurements. One of the equipment problems encountered after the October 1980 field trip was the inability to lock the frequency standard to the atomic transition. Therefore, the frequency standard was considered a candidate for causing an error. Upon acquisition of a newer Tracor Model 308A Rb standard, the old

---

2. Hammond, J. A. (1970) A Laser-Interferometer System for the Absolute Determination of the Acceleration of Gravity, Joint Institute for Laboratory Astrophysics (JILA) Report No. 103.
3. Zumberge, M. A. (1981) A Portable Apparatus for Absolute Measurement of the Earth's Gravity, Ph. D. Thesis, University of Colorado.
4. Spectra Physics Model 119 Gas Laser Operation and Maintenance Manual.
5. Tracor Operation and Service Manual (for theory of operation of the Rubidium Frequency Standard).

standard was checked out and found to be accurate to better than three parts in 10^{11} even when not locked, so it is concluded that this could not have been a large enough source of error to be concerned about.

4. VERTICALITY

If the laser light path is not vertical, that is, not coincident with the direction of free-fall, the measured value of g will be greater than when it is vertical. A departure from verticality was therefore considered a possible contributor to the apparent bias. The method used to align the light path, as described elsewhere,[1] uses the reflection from a mercury pool as a self-leveling horizontal surface. The light is reflected back through a 5-micron pinhole at the focal point of the collimator. Since the returning light can be very well centered in the pinhole aperture, the error introduced is negligible. However, a verticality error of such magnitude to produce an 80 μgal shift could possibly be introduced by the meniscus at the mercury-container interface, but care has always been taken to center the light beam on the mercury pool; further we were unable to align the system at all when attempts were made to use the edge of the mercury pool. Non-verticality then is not considered a source of the problem.

5. SHIFTING OF CENTER-OF-MASS AND OPTICAL CENTER

Unlike non-verticality, a bias introduced by rotation of the dropped object when the optical center and the center-of-mass are not coincident can be either positive or negative depending on the direction of non-coincidence. The drop-to-drop scatter would also be expected to be high since the release in a mechanical system such as this is not uniform. No evidence of a shift of sufficient magnitude to cause an 80 μgal change was found, thus ruling this out as the source of bias. The procedure for aligning and checking the locations of the optical center and center-of-mass is explained in Reference 1.

6. REAL GRAVITY CHANGE

A real change in gravity at a particular site could be caused by a change in the water table or tectonic shift; neither has been detected to the extent that would be required to cause a shift of 80 μgal. Note that there is a 28 μgal difference in gravity between two piers at the Hanscom absolute gravity site. The Geodetic Survey Squardron (DMAHTC-Frances E. Warren AFB, Wyo.) also observed this difference using relative gravity meters. The centers of these two piers are separated by only 2 m. This anomaly remains unchanged. Although a short-lived gravity change may have existed early in 1981, it is highly unlikely and is dismissed as a cause of the gravity discrepancy.

7. EQUIPMENT CHANGES

Errors, both random and bias, can be introduced when electronic equipment is changed since each can have its own peculiarities in such areas as rise time, phase shift, time delay, threshold, etc., while still meeting published specifications (this also applies to models with identical specifications). These differences can be important when the equipment is being pushed to the accuracy limits as is in these measurements.

A routine was devised* to investigate error sources exclusive of the mechanical portion of the equipment. The exclusion of this section allows checks to be made without concern for random or bias errors introduced by seismic noise, shock of the mechanical release of the dropped reflector (the moving arm in the Michelson interferometer), air drag, gravity gradient, earth tides, correction for the wavelength of light, and the correction for the finite velocity of light. These tests also eliminated concern for any phase shift that might be introduced by the photomultiplier.

The absolute gravity measuring system is shown in block form in Figure 1. The signal that is generated in the mechanical portion and converted to an electrical signal by the photomultiplier (shown inside the dashed lines in Figure 1) is replaced by a Hewlett Packard Model 3325A sweep frequency generator (synthesizer). The synthesizer can be programmed to generate a sweep frequency from 0 up to 20 MHz, which is used to simulate the signal generated by the dropped reflector in the Michelson interferometer. The initial portion of this accelerating sine wave is shown in Figure 2. The advantage of using the synthesized signal is its reproducibility. Real data have scatter and therefore the system requires literally hundreds of drops to arrive at a statistically significant value, while synthesized data allow the equivalent of a few drops to observe a difference in the resultant data. A change (in signal threshold for example) can be made and the effect can be immediately observed.

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*This routine was jointly devised with The Joint Institute for Laboratory Astrophysics (JILA) of the University of Colorado.

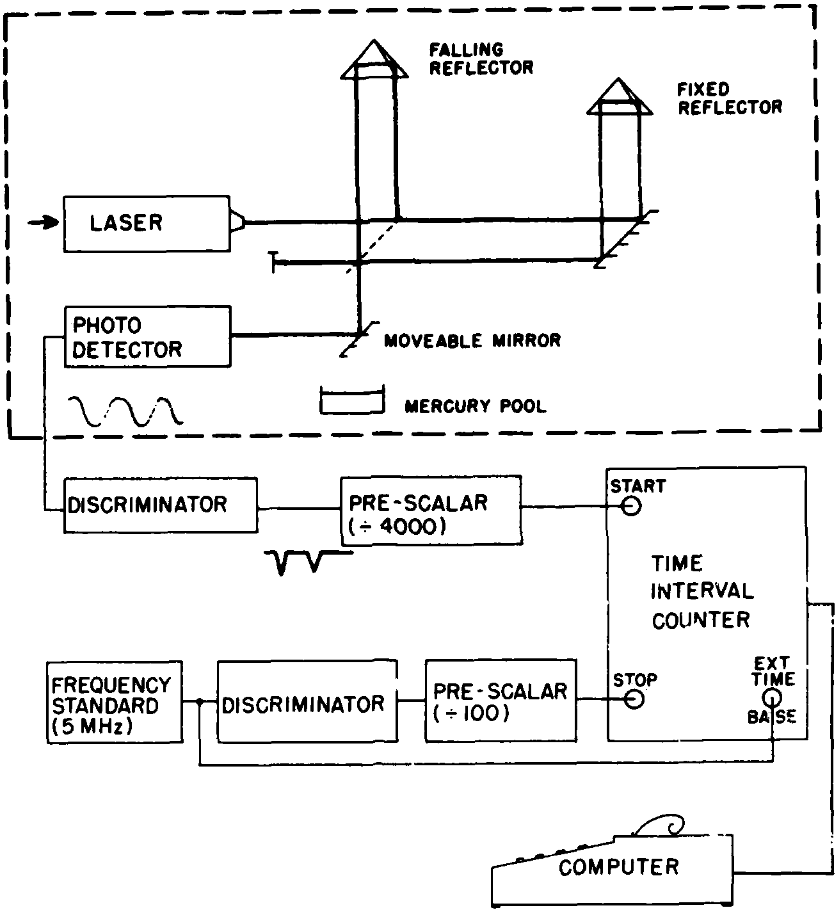

Figure 1. Block Diagram of AFGL Absolute Gravity Measuring System

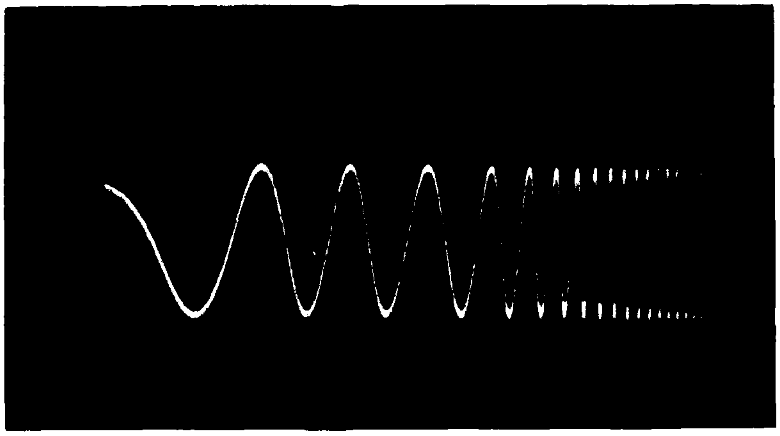

Figure 2. Accelerating Interferometer Fringe Signal

The final frequency (ν) after a specified time (t) is determined by the relationship

$$\frac{\lambda\nu}{2} = v = gt \quad , \tag{1}$$

where

λ = wavelength of the laser light,

ν = final frequency (that is, 0 Hz to ν),

v = velocity of falling object at time t (with no forces other than g acting on the dropped object and zero initial velocity), and

g = acceleration of gravity.

The factor of 2 accounts for two fringe counts per wavelength. For our system we have taken

$\lambda = 6.329914700 \times 10^{-5}$ cm, and

t = 0.4 sec, exactly

and, using $g = 980 \text{ cm sec}^{-2}$, the final frequency is

ν = 12.385632938 MHz .

The signal first goes into the EG&G Model T140/N zero crossing discriminator (Figure 1). The zero crossing discriminator is used to eliminate the problem of skewing, which occurs with amplitude threshold discrimination when the frequency is not constant. Skewing would be severe in this application since the frequency sweeps from 0 to over 12 MHz.

The first test with the synthesized signal was at the input to the zero crossing discriminator using ac and dc coupling. The results of this test showed a difference of 19 μgal, depending on the coupling. The measured value of g was 19 μgal higher with ac coupling than with dc coupling. Data taken with equipment used previously did not show this difference. ac coupling has been used because the dc output level of the photomultiplier is dependent on the ambient light, and the fluctuating dc level made it difficult to observe the signal on an oscilloscope. Since ac coupling was always used this coupling discrepancy had no influence on the higher measured g value.

Next, using the synthesizer, the time (t) and the corresponding frequency (ν) [Eq. (1)] were changed such that the swept frequency corresponded to the correct frequency for $g = 980$ cm $\sec^{-2}$ after falling 0.4 sec in vacuum. The frequency was changed from $\nu = 12.385632938$ MHz for $t = 0.4$ sec to $\nu = 18.578449404$ MHz corresponding to $t = 0.6$ sec. The measured value of g remained constant, verifying that the synthesized signal was repeating the frequency from 0 to 12 MHz regardless of the final programmed frequency.

The output amplitude from the synthesizer was varied from just above the discriminator threshold of 0.4 V peak-to-peak to five times threshold, 2 V peak-to-peak with no change in the resultant calculation of g.

Next the signal is divided by 4000 by the prescalers, the division of which was checked and verified to be accurate using the constant frequency from the rubidium frequency standard.

Next the signal goes into the HP Model 5370A time interval counter. Using the synthesized signal as input, the trigger levels of the start and stop inputs were varied from 0.00 to -0.70 V with no variation in the resulting value (the outputs from the zero crossing discriminator and the divide by 4000 scalers are negative going and therefore the counter trigger is negative). This was not the case with similar equipment at JILA. JILA not only observed variations with threshold settings but found differences when different time interval counters were substituted, even though all six counters were the same HP Model 5370B's.

Another test that was made to check the overall performance of the electronic and computational portion of the system was to vary the value of g with the simulated signal. The value of g, and the corresponding frequency [Eq. (1)], was varied from 960 cm $\sec^{-2}$ to 1000 cm $\sec^{-2}$ with the resulting computation of g changing as it should (±1 μgal).

The linearity of the frequency sweep of the HP Model 3325A used in these experiments was checked and found to be adequate for our purpose. The calculated value of g was not exact as predicted from Eq. (1), but this was of no consequence since we were looking for changes in g as we varied different electronic conditions. The value of g is calculated using 440 data points during the 55 cm free-fall of the dropped reflector and is therefore an average value. Figure 3 is a plot of the residuals as a function of distance the object has fallen. If the sweep frequency was linear the residuals would follow a straight line centered around zero. The calculation of g was also measured by using 100 data points starting at data point 99, 100 starting at 199, etc. for the full drop. This exercise also showed the nonlinearity of the frequency sweep. Even with this limitation the synthesized signal proved to be a valuable tool for evaluating the electronics.

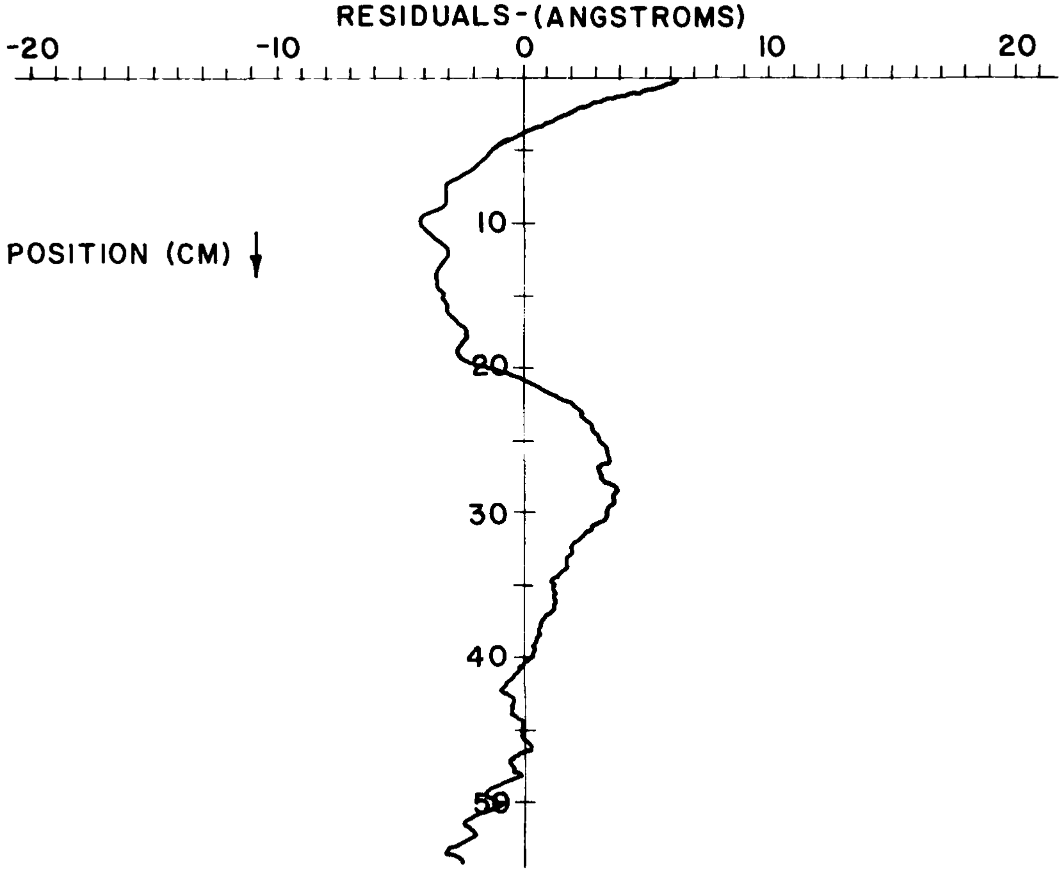

Figure 3. Residuals in Position for Least Squares Fit of Synthesized Signal

Errors can also be induced by equipment not associated with the system. A systematic bias of 68 μgal was observed by the Istituto di Metrologia "G. Colonnetti" (IMGC) during a field trip to the United States. This bias was determined[6] to be caused by a gyroscope that was being tested in another room a few meters away. We investigated this type of interference at the Hanscom AFB Gravity Laboratory and found no evidence that any interference of this nature was present.

8. PRESSURE GAUGE

A Varian Model 845 power supply and controller, and a Model 564 nude ionization gauge tube are used to monitor the vacuum chamber pressure. If the filaments on the vacuum gauge tube become contaminated, an outgassing condition can exist in the area of the tube's sensing grid resulting in a pressure reading that is higher than the actual pressure inside the chamber. Since the correction for air drag vs pressure is logarithmic in the region of our concern,[1] the pressure reading is an increasingly critical measurement as the pressure rises. An 80 μgal error would result due to the pressure correction if the gauge read 7×10^{-6} Torr, while the actual vacuum was 10^{-7} Torr. After the October 1980 field trip the recorded pressure was higher than usual but since a correction was made for this we were not concerned at that time. During the reevaluation this became the prime suspected error source. Installation and check-out of a new gauge tube showed that the old vacuum gauge tube was in error. This resulted in a gravity correction of about 65 ± 10 μgal too high. The resulting error in the corrected value of gravity of 65 μgal led to questioning the validity of the October 1980 field trip results.

During the period in question absolute gravity measurements were made at sites previously occupied by AFGL and other instruments. The stations were: McDonald Observatory, Tex., Trinidad, Colo., Boulder, Colo. (JILA), Sheridan, Wyo., and Great Falls, Mont. The reevaluation of the raw data revealed minor reduction errors of unknown origin, but the final results compared favorably with previous and subsequent data. Also the pressure readings had not shown a high value until returning from the field trip. The data log book showed that the pressure readings during the field observations were in the range of 5×10^{-7} Torr and nearly 6.5×10^{-6} Torr after the trip. From this and the close agreement of previous gravity values we conclude that the October 1980 absolute gravity values are valid. This was not the case for the international gravity comparison made in Sevres, France, at the Bureau International des Poids et Mesures (BIPM) in

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[6] Marson, I., and Alasia, F. (1980) Absolute Gravity Measurements in the United States of America, AFGL-TR-81-0052, AD A099017.

October 1981. Reevaluation of these data revealed an omission in the original data reduction. The original preliminary value for the BIPM site, point A4, was 980926.617 mgal, and the recalculated value is 980926.645 mgal. After applying the correction of 0.065 mgal for the pressure gauge error, the final gravity value for point A4 is 980926.580 mgal.

Table 1 is a listing of the final AFGL gravity values at all the sites where this instrument has made measurements along with the values obtained by the JILA and IMGC instruments.

List of Agencies Referred to in Table 1

Instrument	
AFGL:	Air Force Geophysics Laboratory, Hanscom AFB, Mass.
JILA:	Joint Institute for Laboratory Astrophysics, Univ. of Colo., Boulder, Colo.
IMGC:	Istituto di Metrologia "G. Colonnetti", Torino, Italy

Table 1. Absolute Gravity Values at Various Sites in the U.S. and Sevres, France as Determined by Different Instruments

Instrument	Hanscom AFB, Mass.	g (mgal)
AFGL	1978-1980	980378.685
JILA	May 1982	980378.697
IMGC	Dec 1977	980378.659
	NBS Gaithersburg, Md.	
AFGL	Mar 1980	980103.257
JILA	Apr 1982	980103.259
	McDonald Observatory, Tex.	
AFGL	Oct 1980	978820.074 (978820.087)*
IMGC	Jun 1980	978820.097

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*Denotes previous published AFGL gravity values.

Table 1. Absolute Gravity Values at Various Sites in the U.S. and Sevres, France as Determined by Different Instruments (Contd.)

Instrument	Holloman AFB, N. Mex.	g (mgal)
AFGL	Jul 1979	979139.600
	May 1980	979139.600
JILA	Mar 1982	979139.615
IMGC	Jun 1980	979139.584
	Trinidad, Colo.	
AFGL	Jul 1979	979330.370
	Oct 1980	979330.384 (979330.393)*
	Denver, Colo.	
AFGL	Apr 1979	979598.277
JILA	Dec 1981	979598.322
	Mar 1982	979598.302
IMGC	Oct 1977	979598.268
	Mt. Evans, Colo.	
AFGL	Jul 1979	979256.059
	JILA - Boulder, Colo.	
AFGL	Oct 1980	979608.583 (979608.601)*
JILA	Dec 1981	979608.568
	Apr 1982	979608.565
IMGC	May 1980	979608.498
	Casper, Wyo.	
AFGL	Jul 1979	979947.244
	Sheridan, Wyo.	
AFGL	Jul 1979	980208.912
	Oct 1980	980208.925 (980208.964)*
JILA	Apr 1982	980208.952
IMGC	Jun 1980	980209.007
	Great Falls, Mont.	
AFGL	Jul 1979	980497.311
	Oct 1980	980497.325 (980497.367)*
IMGC	Jun 1980	980497.412

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*Denotes previous published AFGL gravity values.

Table 1. Absolute Gravity Values at Various Sites in the U.S. and Sevres, France as Determined by Different Instruments (Contd.)

Instrument	Vandenberg, Calif.	g (mgal)
AFGL	Jun 1980	979628.190
JILA	Mar 1982	979628.137
	Lick Observatory, Calif.	
AFGL	Jun 1980	979635.503
JILA	Mar 1982	979635.503
	Sevres, France	
AFGL	Oct 1981	980926.580
BIPM (A4 transfer)	Oct 1981	980926.577

The A4 transfer gravity value[7] is relative to the gravity value at point A, obtained by Sakuma at the BIPM. These relative measurements were made with three Model D and three Model G La Coste-Romberg gravity meters. These instruments were operated by the following agencies.

Institut fur Angevandte Geodasie (IFAG), Frankfurt FRG
Defense Mapping Agency (DMA), Cheyenne, Wyo.
Institute fur Physikalische Geodasie (IPG), Darmstadt FRG

9. GRAVITY CORRECTION VS PRESSURE

A correction is applied to the measured value of gravity (g_m) due to air drag, which is a function of chamber pressure. As stated earlier, the vacuum gauge tube was found to be defective and gave an incorrect value of chamber pressure reading, which resulted in assigning a correction to g_m that was about 65 μgal too high. Replacement of the gauge tube necessitated a recalibration of the gravity correction vs the new pressure readings. Note that the absolute pressure need not be known since the correction is made based on the pressure reading that must only be a repeatable reading at the same pressures for a given calibration. Further, we have an accepted absolute gravity value at this site and a priori information that the correction will be on the order of 1 μgal at a pressure of 10^{-7} Torr.

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7. Becker, M., and Groten, E. (1983) Relative Gravimeter Measurements at the 1981 Absolute Gravimeter Campaign in Paris-Sevres, Bureau Gravimetrique International Bulletin D'Information No. 52.

Although we were not able to achieve a vacuum as high as we would have liked, extrapolation of the correction curve yields a gravity correction of about 1.5 μgal at 10^{-7} Torr, which is consistent with theory and our experience.

The pressure was varied from 7.9×10^{-7} up to 5×10^{-5} Torr. The data are plotted in Figure 4 along with the previous calibration curve. Although it is not immediately obvious, since the curves are nearly parallel, the slopes of the lines are different. The old (dashed) line has a slope of 12 μgal/μTorr, while the new calibration line has a slope of 20 μgal/μTorr. Since our gravity measurements are made with a vacuum in the 10^{-7} Torr range there is very little difference in the corrections from the old and new calibrations.

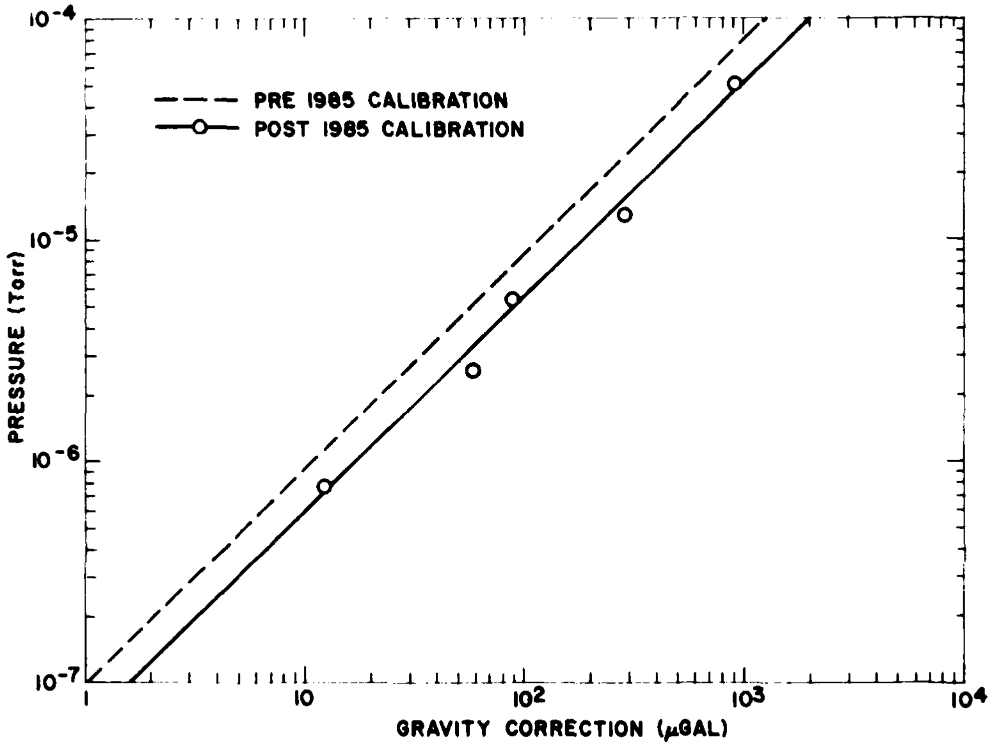

Figure 4. Gravity Correction as a Function of Pressure

The physics of the forces acting on the dropped object is quite complicated, since the predominant forces change with pressure. For this application we are only concerned with the region of free molecular flow, that is, the molecular mean free path is large compared to the dimensions of the confining chamber so that molecules collide much more frequently with the chamber walls and dropped object than with other molecules. Below about 10^{-3} Torr, the interaction of molecules with solid surfaces is the main concern. In this domain a molecule that strikes a surface may undergo an elastic collision with no energy exchange or sustain an inelastic collision whereby the molecule may be permanently absorbed or remain at the surface for a short period of time. The exchange of energy (elastic vs inelastic collisions) is determined by the accommodation coefficient of the material. The dropped object should be made of a material with an accommodation coefficient as small as possible. For more detail on drag forces in the free molecular flow region see, for example, References 8 and 9.

From the foregoing it can be seen that each apparatus requires its own calibration. Here we are concerned with the correction to the measured value of gravity for our system as a function of pressure over the range of interest regardless of the physics behind it.

Each data point on the graph of Figure 4 is the average of 100 or more individual drops. The standard deviations of the data were comparable at all pressures but the residuals as a function of position during the drops deteriorated at higher pressures. The residuals at a pressure of 7.9×10^{-7} Torr (Figure 5) follow the theoretical curve for a freely falling body in a gradient field in a vacuum (smooth curve). Figure 6 shows the deterioration of the residuals at 1.5×10^{-5} Torr. The data plotted in Figure 7 (pressure = 5×10^{-5} Torr) have been reduced by a factor of three (that is, the peak-to-peak amplitude is actually about 50 Å and is completely out of phase with the gradient field).

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8. Heer, C.V. (1972) Statistical Mechanics, Kinetic Theory, and Stochastic Processes, Academic Press, New York.
9. Kauzmann, W. (1966) Kinetic Theory of Gases, W.A. Benjamin Inc.

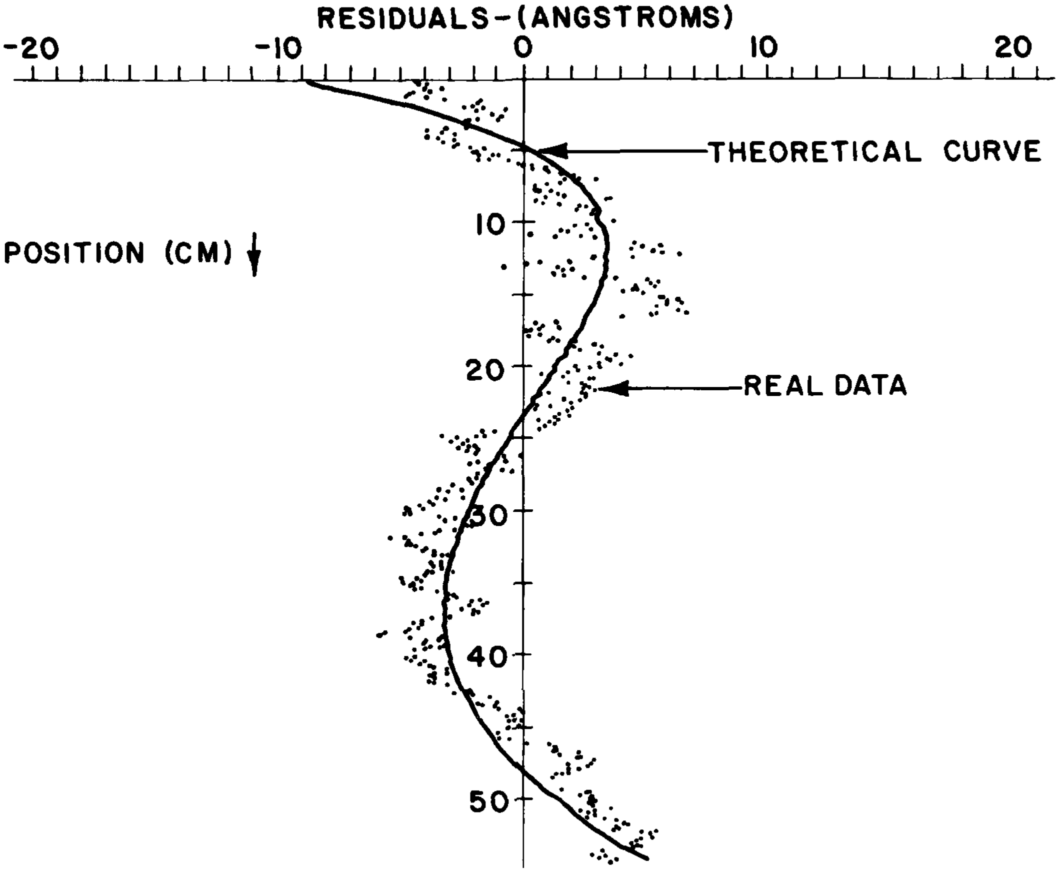

Figure 5. Gravity Residuals (Å) vs Distance After Drop (cm)
Pressure = 7.9×10^{-7} Torr

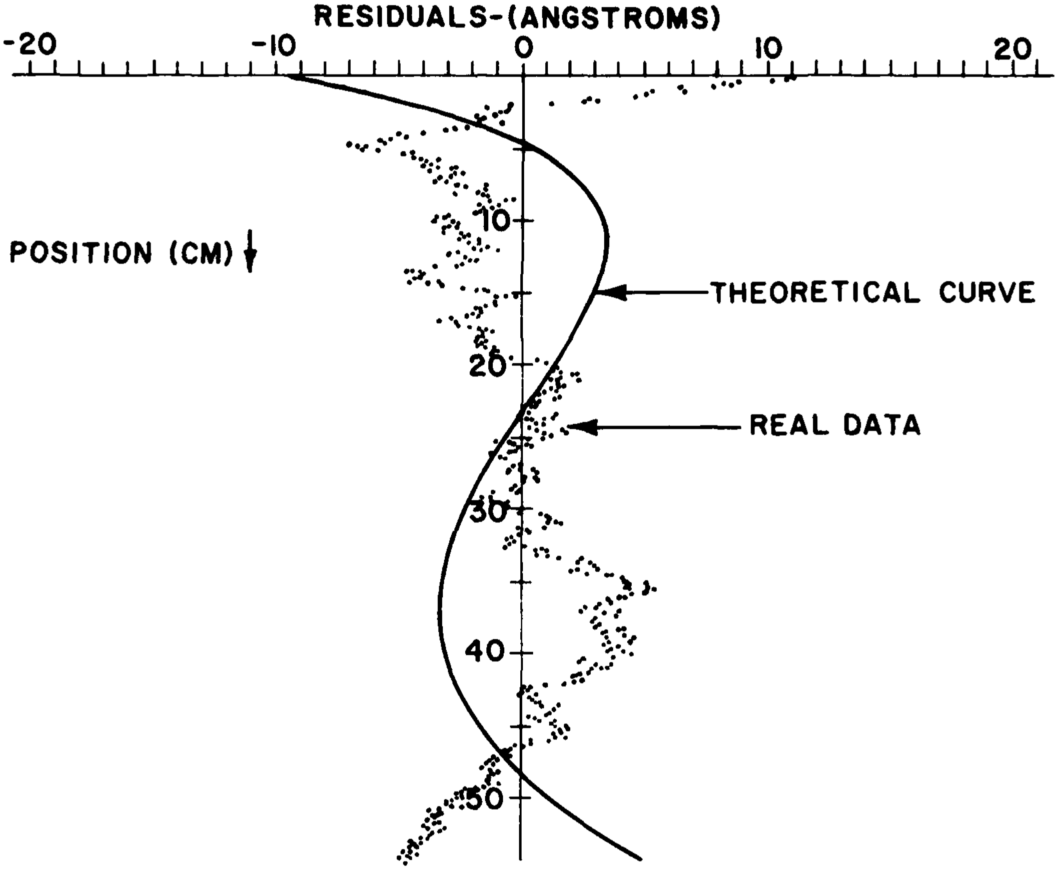

Figure 6. Gravity Residuals (Å) vs Distance After Drop (cm)
Pressure = 1.5 X 10^{-5} Torr

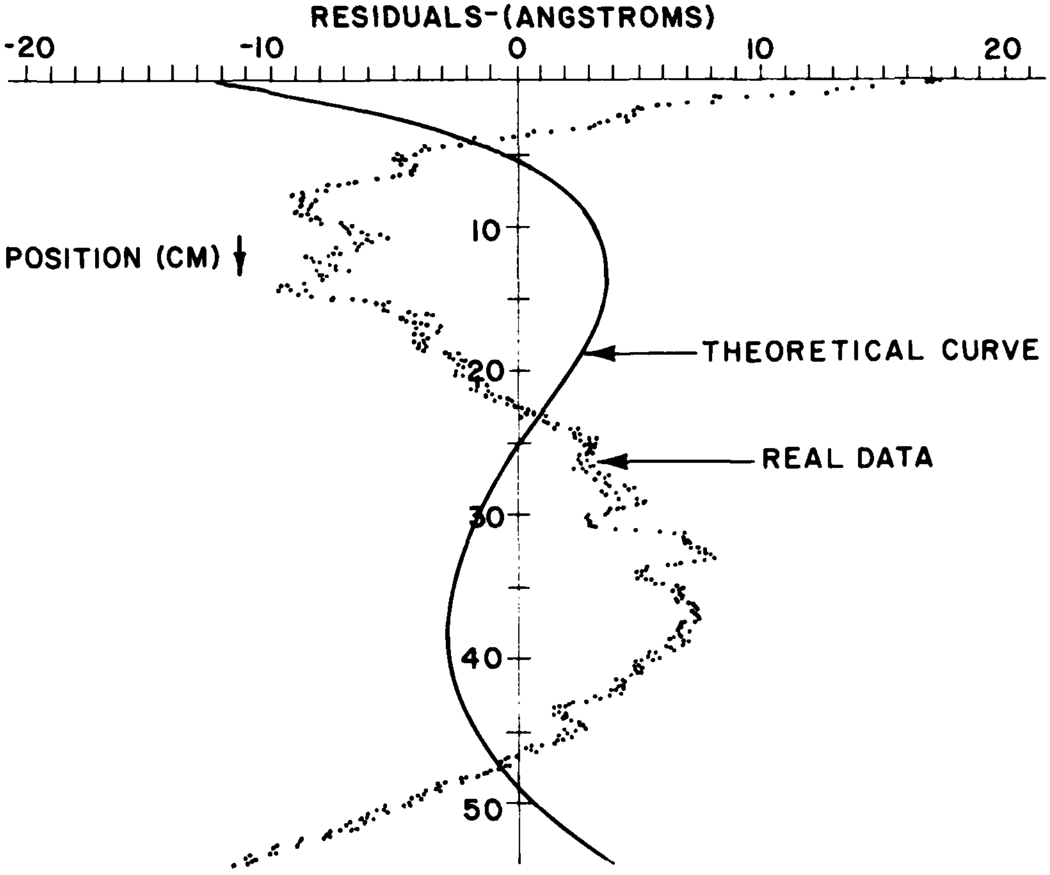

Figure 7. Gravity Residuals (Å) vs Distance After Drop (cm)
Pressure = 5×10^{-5} Torr

10. FINDINGS

The AFGL absolute gravity system has proven to have a sound approach for the measurement of gravity and, as with any system, periodic checks of the various components must be made. For this system six major checks should be performed. First, the laser wavelength should be measured frequently enough to establish the ageing rate so that corrections can be made during extended field trips; second, the time standard can generally be accepted as valid as long as it is in the locked mode; third, verticality should be checked several times a day during the measuring period. This is a simple check and does not disrupt the measurement process; fourth, the displacement between the optical center and the center-of-mass should be checked whenever there is reason to believe it may have shifted such as because of rough handling in shipment or high scatter in the data. This check is made infrequently because it is highly unlikely that there is a shift and an extended period of downtime is required to perform this operation; fifth, a synthesized signal was found to be very helpful and should be available for checking out any electronics and software changes. When electronic components are changed, whether a direct component exchange or an upgrading of the system with a completely new component, errors can be introduced. By using a synthesized signal before and after equipment changes, errors (or differences) can be identified and taken into account. Similarly, the artificial signal can be used to preclude errors that could be caused by software changes. Sixth, since the correction for g as a function of chamber pressure is logarithmic, the system should be operated in a pressure range that requires only a small correction for air drag. This pressure region is dependent on the system's physical configuration and will vary from one system to another. Data should be taken periodically at a higher pressure as a check on the pressure correction calibration.

11. CONCLUSIONS

The cause of the incorrect absolute gravity value obtained at the Hanscom AFB gravity laboratory, Haskell Observatory, during the first few months of 1981 was found to be a faulty component in the vacuum readout portion of the system. This malfunction resulted in assigning a correction to the measured value of g that was 65 ± 10 μgal too high. It was further determined that this component failure occurred at a time such that the absolute gravity calibration line measurements made prior to this failure were not affected, but the pressure gauge error in the original Sevres gravity value has now been taken into account and our final value at this site compares extremely well with the value obtained by Sakuma at the BIPM, Sevres, France.

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