HIGH PRECISION GRAVITY MEASUREMENTS

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ABSTRACT:

The measurement of the gravity acceleration is of interest in a broad area of physical sciences: metrology, geophysics and geodesy. High precision gravity data are required to study gravity variation with time, the motion of the Earth's core and mass redistribution in the mantle and crust. In this paper measurement techniques employed in high precision gravity devices are discussed.

INTRODUCTION

The highest accuracy in measuring gravity is required for studying geodynamical and tectonic processes. Phenomena such as land uplift, dilatancy in seismic areas, geothermal activity, water table depth variations, motion of the Earth's core and mass redistribution in the mantle and crust, all result in changes of g which, to be detected, require gravity measurement of the highest accuracy (few parts in $10^{-9}$).

A typical field instrument capable of such accuracy is the La Coste Romberg mod. D relative gravity meter. In order to achieve these limits, however, the meter needs a very accurate calibration to remove effects of non-linearities and periodical errors.

In the past 25 years, progress in the technology of measuring time and distances has allowed the realization of absolute transportable gravity meters with accuracies comparable to that of the best relative meters.
In this paper we will discuss some of the technical aspects of high accuracy gravity devices.

1. THE LA COSTE ROMBERG MOD. D GRAVITY METER

As all the spring-type gravimeters, the La Coste Romberg mod. D is essentially a long period seismometer.

It is well known that the sensitivity of this kind of gravimeter is proportional to the square of the proper period of oscillation.

In the La Coste Romberg devices, the extremely high sensitivity is acquired by using a "zero length" spring in the mechanical setting depicted in Fig. 1.

This spring is characterized by the fact that the force is directly proportional to the length of the spring. It might be seen that at equilibrium

\[ M g d = k b a \]

so that the instrument is insensitive to the angles \( \phi \), \( \phi' \), \( \lambda' \). Thus it can be in equilibrium over a small range of angles and consequently its period can be theoretically infinite. In the LCR meter however it is normally adjusted to 15 sec. Carefully measurement can result in a precision of 2-3 \( \mu \)Gal. The factory provides for each meter a calibration factor. In order to achieve an high accuracy, however, it is necessary to remove any source
Fig. 1. Schematic of a zero length spring gravimeter.

Fig. 2. Calibration curve for LaCoste Romberg D-18.
of systematic errors, which are associated with non-linearities in the calibration function and periodical errors due to mechanical imperfections in the reading screw. Fig. 2 is an example of a calibration curve of a D meter from where it appears clearly that the non-linearities are important. As regards the periodical errors, amplitudes as high as 4.5 μGal for periods of 3.25 counter units have been observed.

Another source of systematic error may rise from the sensitivity of the meter to pressure and temperature gradients.

To gain the high accuracy required for geodetic networks, the systematic error budget for each individual meter has to be carefully studied.

2. ABSOLUTE TRANSPORTABLE GRAVITY METERS

It was after the second World War that the newly developed techniques for the measurement of short time intervals were first employed in gravity measurements.

The most successful absolute gravity meters developed since 1950 employ either the simple free fall or the symmetrical free fall of a body in a vacuum chamber.

In both methods the idea consists in measuring the time and distance along the trajectory and computing g from the basic relationship
\[ s = \frac{1}{2} gt^2 \]

To gain the high accuracy required in geodesy, the distance has to be measured with the accuracy at least of 1 mm and the time at least of 1 n s. Moreover, in order to allow for the transportability, stable (and easily transportable) standard units of distance and time are necessary.

2.1 Distance measurement.

Common device for distance measurement to all the absolute gravity instruments is a Michelson interferometer (Fig. 3). The radiation of a stabilized He-Ne laser is used both as light source and standard unit of distance. The short term stability, of the order of \(10^{-9}\), of a commercially available stabilized laser assures an accuracy in the distance measurements corresponding to few \(\mu\text{Gal}\) in g.

One arm of the interferometer is terminated by a corner cube retroreflector which is freely accelerated by the earth's gravity field.

The second arm is terminated by the reference corner cube. During the free fall, the moving cube is completely isolated from the Earth's microseismic noise, but the reference one is not. To isolate the reference cube, it has been used the fact that the mass of a long period seismometer is effectively isolated for all frequencies greater than the natural resonance of the system.
Fig. 3. Schematic of the Michelson interferometer used in the IMGC absolute gravimeter.
An interesting long period seismometer has been developed by JILA. It is based on the suspension of a mass from a long spring.

In practice, a tractable length (i.e. 30 cm) of spring has been electronically terminated so that it behaves exactly as if it were, for example, 1 km long (fig. 4). The mass on the end oscillates up and down with a period of 60 s and therefore is isolated for all periods shorter than this. To understand the principle of this electronically generated "superspring" imagine that you have a 1 kg mass hanging on the end of a weak coilspring which extends 1 km vertically. This mass will oscillate up and down (with a period of 60 s) and as it does, the coils of the spring will oscillate as well. The coils very near the mass will have an amplitude nearly equal to the amplitude of the mass and the coils far away will have an amplitude less 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 of 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 the super spring a servo system, to generate such a virtual point of suspension, has been used. The degree of tracking is determined by the gain setting of the servo
Fig. 4. Schematic of the "Super Spring" (JILA absolute gravimeter)

Fig. 5. Schematic of a "multiple station" measuring system (JILA)
system and this in turn sets the effective length of the spring and thereby the achieved period. While periods in the range of 10 to 100 s can be easily achieved, the normal period used is about 40 s.

2.2 Time measurements

The most modern absolute gravity meters of both types use a multiple stations method to measure distances and times. The following is a description of a measuring technique initially developed by JILA for the simple fall gravimeter, which will also be employed in a symmetrical free fall one.

The fall of the corner cube generates an interference fringe which is detected by a photomultiplier for each half wavelength of the falling corner cube's descent.

It takes the dropped object about 0.2 seconds to fall 20 cm resulting in a fringe frequency starting at zero and reaching 6 MHz at the measurement's end, generating about 600,000 fringes in all.

The raw sinusoidal fringe signal is amplified and fed into a zero-crossing discriminator which transforms the signal into a series of pulses. A zero-crossing discriminator insures that no noise fluctuation will be counted as a whole fringe. It produces a pulse when the input crosses zero in a positive going direction, then disables itself until the input voltage has dropped below an adjustable negative arming level. The fringe pulses generated by the zero-crossing discriminator are
too numerous for measuring the time of occurrence of each one, so they are divided down by a synchronous scaler. The synchronous scaler opens a gate that transmits a fringe pulse only after a preset number of fringes have preceded it. A synchronous counter was used as opposed to a ripple counter because of its lower fluctuations in time delay.

Although selectable, the number of fringe pulses required to produce one scaled fringe pulse is usually set to be 4000, corresponding to the dropped object having moved about 1 mm. In the 20 cm drop lasting 200 msec, then, the times of occurrence of 200 scaled fringe pulses need to be measured to within 0.2 nsec, referenced to a common zero. The method is schematically represented in Figure 5. The time from each scaled fringe pulse (input to the start channel) to the earliest following pulse from a constant frequency clock pulse train (input to the stop channel) is measured by the single shot time digitizer. This digitizer generates a logic pulse when it has in fact accepted a clock pulse as a stop and measured a time. This latch pulse is used to signal an external counter to record the current value of its register, which is counting the clock pulses, without interrupting the counter.

Essentially, the amount each scaled fringe pulse proceeds in time a measured integer number of constant periods is measured. The time of occurrence of the Nth scaled fringe pulse is simply
\[ T_N = M_N T - \Delta t_N \]

where \( M_N \) is the number of the clock pulse used in the \( N^{\text{th}} \) measurement, \( T \) is the period of the clock pulse train, and \( \Delta t_N \) is the time from the \( N^{\text{th}} \) fringe to the \( M_N^{\text{th}} \) clock pulse as measured by the single shot time digitizer. For each fringe then, the computer, which is interfaced to both the time digitizer and the external counter, records a \( \Delta t \) and an \( M \). It must do this before the arrival of the next fringe which will produce another \( \Delta t \) and an \( M \).

After each drop, the \( t \)'s and \( M_N \)'s are used to calculate times corresponding to 200 incremental 1 mm (4000 fringe) positions. The resulting table of 200 time-vs-distance ordered pairs is then fit to a quadratic of the form

\[ x_i = x_0 + v_0 t_i + \frac{1}{2} gt_i^2 \]

2.3 Sources of errors.

Recently a very great effort is given by scientists in isolating and eliminating all sources of systematic errors.

They may rise from:

- microseismic noise because of non complete cancellation of this effect by the isolation device.

- Vacuum. To this regard it has to be noted that the effects of residual air resistance are negligible in
the symmetrical free fall to the extent that it is proportional to the velocity of the object.

To avoid this effect in the simple fall method, in the JILA 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.

- Temperature and pressure gradients.
- Magnetic fields.
- Electrostatics.
- Vertical reference.
- Optical path changes.
- Laser wavelength.
- Motion of the corner cube.
- Floor recoil
- Phase shifts
- Frequency standard.

A very great effort is being given by scien
tist in order to contain the overall systematic errors budget within 3 \( \mu \text{Gal} \).
CONCLUSIONS

With both, high accuracy gravity networks and absolute gravity meters it is now possible to achieve an accuracy of few \(\mu\text{Gal}\). It has to be noted, however, that only networks with base stations separated by small gravity differences and short distances are capable of such an accuracy. Each individual gravimeter employed in microgravity nets has to be carefully studied to allow corrections for non-linearities and periodical errors in its calibration functions.

Also in absolute gravimetry an intensive effort must be given in understanding eliminating or compensating for all possible sources of systematic errors. With this regard, site dependent systematic errors represent a very subtle source. Furthermore it is worth while to note that all absolute gravity instruments measure \(g\) at a well defined point in the space, situated at a certain height (dependent from the kind of gravimeter) from the floor. The measure of the vertical gradient for the reduction to the floor of the measured value represent another crucial point in the error budget.

Finally, the high sensitivity of modern gravimetry, if allows the detection of small gravity effects, could introduce a source of noise, in the sense that unwanted local gravity variations (such as water table changes, pressure variations and so on) can be superimposed to the phenomena under study.
It is, therefore, very important a continuous monitoring of this kind of effects in any high precision time dependent gravity survey.

REFERENCES
Marson I., Faller J., 1984: "g" the gravity acceleration: its measurement and its importance. J. of Physics, in press.