

Results from a new interferometric ballistic differential gravity meter

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Abstract. Recently Micro-G Solutions developed an interferometric ballistic differential gravity meter and commenced data collection and analysis. Target accuracies are $\pm 1 \mu\text{Gal/m}$ or 10 EU. The instrument uses ballistic laser interferometer concepts proven on the commercial FG5 absolute gravimeter, with modifications made to accommodate fiber optic interferometer technology. Design principles are explained, with emphasis placed on the advantages of a differential gravity instrument versus a gradiometer. Results from initial experiments conducted with a prototype instrument represent the first time absolute interferometric differential gravity data has been collected and processed. Achieved single drop precision is $\pm 7 \mu\text{Gal}$, while five minute precision drops to $\pm 1.7 \mu\text{Gal}$. These statistics are comparable to the current generation FG5 absolute gravity meters. Conclusions regarding the implications of the data to the geosciences community are made and future research plans are discussed.

1. Introduction

In Stone (1973), an interferometric method to determine the vertical gradient of gravity at a specific point is suggested. Fig. 1 depicts the original Stone drawing. A laser source launches light into a fixed optics system consisting of mirrors and splitters. The split beam is directed into two arms where the light is reflected from two simultaneously falling objects, in Stone's case, two corner cubes. Each reflected beam returns to the beam splitter where they are recombined. The gravity gradient is determined from the interference fringes created by the two falling masses. Though Stone's interferometric gradiometer was never produced, it can easily be constructed using current absolute interferometric gravity meter technology.

2. Interferometric gravity meters

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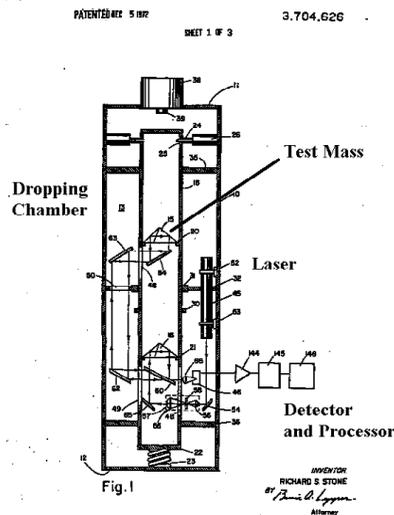


Fig. 1 - The original Stone interferometric gradiometer (Stone, 1972).

Absolute interferometric gravimeters were first developed in the late 1960s (Faller, 1996). This technology has been refined over the past 30 years, and has evolved to the current FG5, which is capable of accuracies at the $2 \mu\text{Gal}$ level (Neibauer, 1995). Fig. 2 depicts a detailed schematic of the FG5 for reference. The system works by sending light to a splitter, where one beam is directed to a corner cube/test mass dropping inside a drag-free chamber, while the other is sent to a corner cube held in isolation. Light from each chamber is recombined at the splitter and the interference fringe signal is sensed at the avalanche photo diode (APD). Time/distance pairs are measured from the zero crossings of the fringe signal and the data are fit to a parabolic trajectory. In order to achieve μGal precision, the instrument must use a frequency stabilized laser source, a precise time standard, and a sophisticated isolation device known as the superspring.

Niebauer (1987) used an earlier version of the FG5 to recreate a modern day equivalent of Galileo's alleged experiment from the Tower of Pisa. However, a disadvantage exists in that the baseline length between the two falling objects is fixed and non-adjustable.

Fig. 3 shows two FG5-type chambers connected via fixed optics. Two proof masses of differing composition (copper and depleted uranium) are used in each chamber and the differential acceleration rate is determined as the proof masses fall simultaneously in drag-free environments. This experiment lays the foundation for using FG5 technology to construct an interferometric gradiometer.

3. Interferometric gradiometers

To construct a gradiometer using FG5 technology, rather than placing only one corner cube/test mass in freefall and using the other as an inertial reference, both are placed in complete freefall in a single dropping chamber. The optical interference provides a fringe signal with frequency f as given by

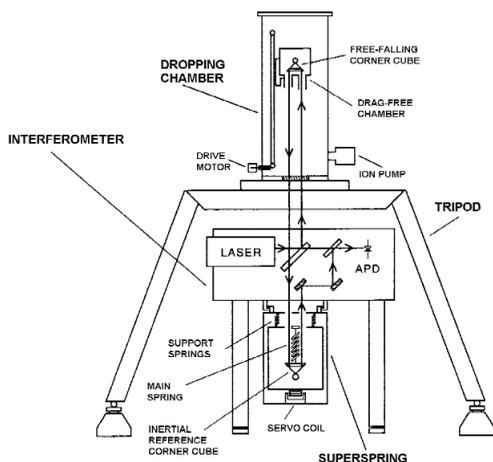


Fig. 2 - Schematic of FG5 gravity meter.

$$f = 2(\Delta V_0 + \Delta g x t) / \lambda.$$

where f is a function of both initial velocity difference ΔV_0 and the gradient Δg . With ΔV_0 equal to zero, virtually no fringe signal (less than 1/3 of a fringe for a typical 200 ms drop) would occur. One way to induce a signal is to create a small time lag between the release of each object. For example, a delay of 20 ms could be set to yield a base fringe frequency of 190 kHz. Deviation from this base fringe frequency caused by the gravity gradient is on the order of 1-2 Hz. Similar to the FG5, time/distance pairs (t, d) are determined from the zero crossings of the interference fringe signal and the data is fit to a parabolic equation:

$$d_i = x_0 + v_0 t_i + 1/2 \delta g t^2$$

using least squares. It is important to emphasize that the gradient δg is determined directly from the interference fringes caused by both test masses dropping simultaneously. In other words, the gradiometer version of the instrument does not measure a gravity value at each individual chamber, but the gravity difference between the two.

Though Stone's gradiometer was never constructed, the Galileo experiment conclusively proved a fixed optics gradiometer would work. The key advantage of a Stone-type interferometric gradiometer includes elimination of common mode dynamic platform errors. This implies that any type of common mode vibration as well as even the Eötvös correction in dynamic applications can be cancelled. Furthermore, error cancellation extends even further in that unstabilized lasers and imprecise clocks may be used with accuracies still well within the 0.1 EU range. These elements imply a simple instrument when compared to the complex FG5. For example, this type of instrument would be ideal for airborne applications because of the inherent insensitivity to platform noise and the Eötvös correction. However, a disadvantage exists in that the baseline length between the two

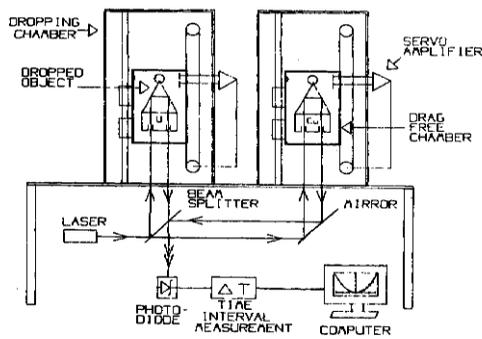


Fig. 3 - FG5 chambers in Galileo experiment (Niebauer, 1987).

falling objects is fixed and non-adjustable.

4. Differential gravity meters

As Fig. 3 shows, in a bulk optics system the distance between the two dropping masses is fixed. If an application calls for either a longer baseline or different orientation, a new system must be created. This problem can be addressed if fiber optic cables are used to construct the interferometer rather than fixed optics. Fig. 4 shows a rough concept of an absolute interferometric differential gravity meter using fiber optic technology. Light enters the input arm and is split at a 2x2 coupler connected to the two dropping chambers. The reflected light returns along the second input arm and is output to a photo diode detector where the time/distance pairs are measured and processed. This instrument, based on a fiber optic interferometer, would be more appropriately labeled a differential gravity meter, rather than a gradiometer. The two chambers connected with fiber optics can be placed into any arbitrary orientation and will simply measure the absolute difference in gravity between the two free-falling test masses. Furthermore, the two sensors can be placed an arbitrary distance apart. This has important implications in terms of observing the gradient signal.

Fig. 4 can be further generalized into a 2xN splitter connecting N multiple chambers rather than only two. Fig. 5 shows a possible configuration whose measurement would yield a vector gradient

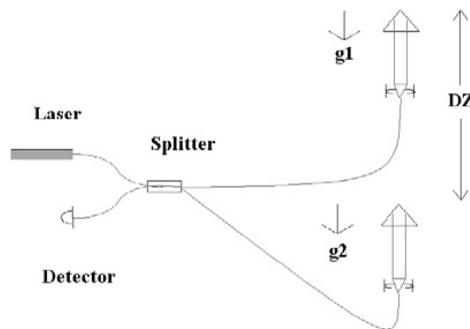


Fig. 4 - Schematic of fiber optic differential gravity meter.

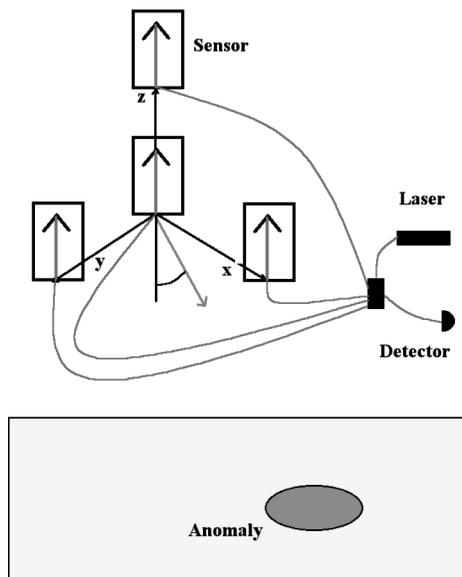


Fig. 5 - Vector gradiometer using multiple sensors.

that pointed directly at a source anomaly. The four chambers would be inter-connected via a 2x4 splitter. To understand how the six differential gravity pairs can be extracted, it is important to understand how the gradient fringe signal differs from the gravity. The former appears as a swept sine wave moving from 0 to 6 MHz during a typical 200 ms drop while the latter appears as a nearly constant frequency determined by the initial velocity difference. If the objects are in freefall during the same time span, individual gradients may be extracted among all nodes simultaneously by demodulating the complex carrier signal. Fig. 6 shows the resulting power spectral density plot for a system of four sensors. The differential gravity associated with each pair would be contained within ± 2 Hz of each individual peak and could be extracted using common signal processing

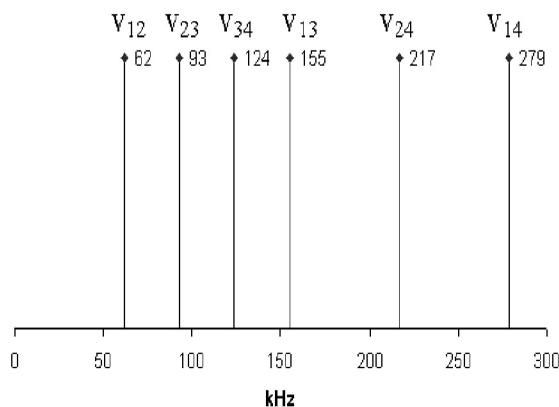


Fig. 6 - PSD plot of fringe signal from multiple chamber system.

methods.

5. The prototype differential gravity meter system

A freefall interferometric gradiometer (FIG) prototype was constructed to test some of the basic interferometric differential gravity meter and fiber optics ideas presented. The prototype works by simultaneously dropping two test-masses in a vacuum and using a laser interferometer to measure the differential acceleration (gravity) between the two objects. The instrument consists of two separate dropping chambers, each of which contains one of the test masses. The dropping chambers of the FIG are arranged with a vertical separation of about 91cm, as shown in Fig. 7. Using standard FG5 chambers, the prototype instrument stands approximately 2.3 m high. Each dropping chamber is evacuated to remove the effect of air resistance. Inside each dropping chamber is a “drag-free” cart (DFC) that is used to lift and drop the test mass. During the free-fall measurement the DFC tracks the test-mass and provides a mechanism for dropping and catching as well as shielding the masses from electrostatic and air-resistance forces.

A laser interferometer is used to monitor the differential free-fall distance of the two objects with a precision of better than 1 nm. A stabilized laser is guided into an optical fiber and split by a 2×2 fiber-optic coupler and sent to each dropping chamber. The light from each fiber bounces off a retro-reflector which is currently a corner cube mounted on each free-falling test mass, and then re-enters the fiber. The optical signals are recombined in the same beam-splitter and directed to the photodiode by the return fiber of the fiber-optic splitter.

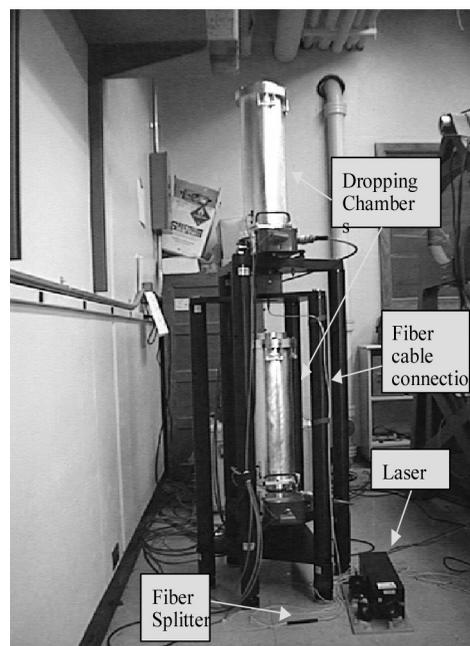


Fig. 7 - Photograph of prototype differential gravity meter.

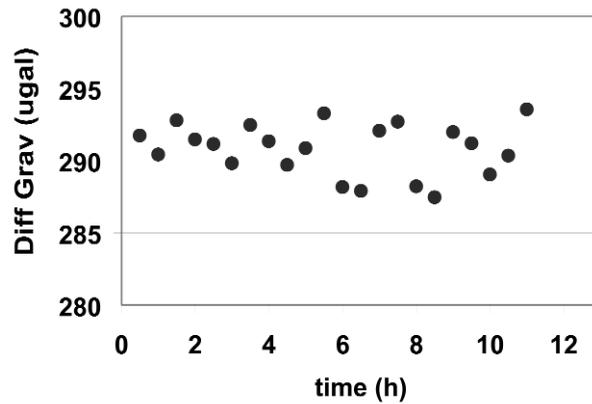


Fig. 8 - Set averages from JD 240 experiment.

One object is dropped a short time before the other so that it has a non-zero initial velocity with respect to the second test-mass. The differential velocity between the test masses generates a nearly constant optical fringe frequency that is easy to detect with a photodiode. The vertical gravity difference decreases (or increases) the base fringe frequency as the two objects fall. The times for the zero-crossings of the optical interference fringes are measured and stored. This data represents time-distance pairs for the differential path of the two freely-falling test-masses. Theoretically, the gravity difference is obtained by a linear least square fit to a parabolic trajectory.

6. Experimental results

Several sets of experimental data have been collected during the past few months. The most

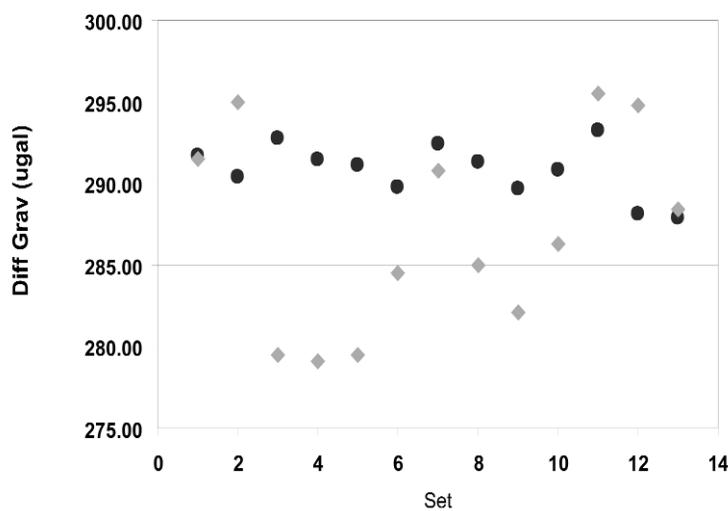


Fig. 9 - Comparison of FIG data (circles) with L&R Super G (diamonds).

recent experimental results are from data taken at the Table Mountain Gravity Observatory (TMGO), a well known NOAA gravity observation laboratory outside of Boulder, Colorado. Fig. 9 shows the time series for the last TMGO experiment. Standard deviation for the set averages are $\pm 1.7 \mu\text{Gal}$. Typical single drop residuals are below 6nm which translates to a single drop precision of $\pm 7 \mu\text{Gal}$.

In order to verify the absolute accuracy of the FIG, an independent measure of the vertical difference over the 91cm FIG baseline was established using an L&R Super G meter. Thirteen sets of observations were taken over a three hour period. A set consisted of the G meter observing at the top dropping chamber location for three minutes and then moving down to the bottom location. Only the last minute of data was used at each position to account for hysteresis. The L&R meter data collected over the 91cm baseline produced a difference of $290 \pm 8 \mu\text{Gal}$. This can be compared to the FIG value of $293.8 \pm 5 \mu\text{Gal}$. The two compare within their respective error estimates.

Fig. 9 shows a comparison of the 13 sets collected by the L&R Super G with the first 13 sets of the second experiment collected by FIG (JD 240). The FIG set averages remain within an amplitude of $\pm 3 \mu\text{Gal}$ while the L&R data wanders between 279 and 296 μGal .

There is also a considerable advantage in acquisition time for the FIG compared to the standard L&R gravimeter. The 13 sets collected with an L&R at 2 stations separated by 91cm took over three hours to complete and resulted in a gravity difference measurement precision of $\pm 8 \mu\text{Gal}$. With a single drop precision of $\pm 7 \mu\text{Gal}$, the FIG yielded a better gradient estimate in one single drop taking 0.2 s. The time advantage becomes even more apparent over longer permanent baselines where the FIG produces an instantaneous measurement, not a differenced value subjected to set-up and take-down procedures and errors.

7. Conclusions

Interferometric gradiometers offer several benefits in terms of error cancellation and costs. Differential interferometric gravity meters using fiber optic technology offer these same benefits, plus the additional gain of flexibility both in terms of sensor locations and number of sensors deployed. An interferometric ballistic differential gravity meter has been successfully constructed and initial results are encouraging. In a relatively short period of time, single drop precision has gone from 300 to 7 μGal with hardware improvements only. Table 1 summarizes the progress made in the last six months in terms of improvement on single drop and set standard deviations, which are now at $\pm 7 \mu\text{Gal}$ and $\pm 1.7 \mu\text{Gal}$ respectively. Though improvement is expected to continue, it is realized

Table 1 - Summary of experimental progress.

Experiment Julian Day	Drop σ (mGal)	Set σ (mGal)
070	300	55
170	45	6
224	30	5
240	7	1.7

research into these applications progresses, the prototype will be reduced significantly both in terms of size and weight. Toward this end, the production and testing of a dropping chamber 1/10 the volume of the prototype's has recently been completed and will be tested in the near future.

The ability to place multiple sensors within the same system will be further investigated. Once these investigations are complete, it will allow for multiple sensors to be connected and even deployed over a large region. At this point, it would be possible to imagine applications as depicted in Fig. 10. In this scenario, sensors are located over an area of volcanic activity and connected with a fiber optic network emanating from a central monitoring station. Such a system could provide instantaneous real-time changes in the gravity field over a large region and be used to assess deformation and other seismic related movements.

The interferometric differential gravity meter represents a new way of acquiring information about the earth's gravity field. Potential applications are numerous and the flexibility in sensor location and orientation allows many possibilities. The experimental results obtained during the last six months show that the instrument has the potential to significantly impact the research areas of physical, geophysical and metrological science.

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