Published in International Association of Geodesy (IAG) Symposium Proceedings
IAG SYMPOSIUM on TERRESTRIAL GRAVIMETRY: STATIC and MOBILE MEASUREMENTS (TG-SMM2010)
22 - 25 June 2010, Russia, Saint Petersburg

INITIAL RESULTS WITH THE NEW GWR *i*Grav™ SUPERCONDUCTING GRAVITY METER

R.J. Warburton, H. Pillai, and R. C. Reineman
GWR INSTRUMENTS, INC., 6264 FERRIS SQ., SAN DIEGO, CA, 92121 USA
warburton@gwrinstruments.com, Fax: +1 858 452 6965, Tel: +1 858 452 7655

Abstract

Keywords: Superconductive gravimetry, Relative gravimetry, Gravity meter

Many geophysical studies presently using spring-type gravity meters could be significantly improved by replacing these instruments with superconducting gravimeters (SGs). The SGs are far superior with their extremely low drift rates and low noise. However, SGs would have to be much less expensive, portable and much simpler to use before they will be used in many existing and new applications. This year, GWR Instruments is introducing a new iGrav™ SG Meter that is designed to be portable, easy to use and much less expensive than the GWR Observatory SGs (OSG) that are used at most stations in the Global Geodynamics Project. Nonetheless, the iGrav™ SG Meter retains many of the characteristic of the Observatory SG. The iGrav™ has an ultra-low drift of less than 0.5 microGal/month and a virtually constant scale factor. In its cryogenic environment, the iGrav™ is totally insensitive to local changes in temperature, relative humidity, or pressure. With these properties, the iGrav™ provides a precise and continuous record of gravity variations that occur over periods of days, months, years, or even decades with a stability and precision that sets the highest industry standard. The iGrav™ is designed specifically for geophysical applications that require much higher stability and precision than provided by mechanical spring-type gravity meters, but can be set up easily and quickly without the need for an expensive platform, housing or infrastructure. In this paper, we discuss the new design features of the iGrav™; demonstrate both its simplicity and capabilities, and show first results that compare its performance to the Observatory SG.

1. Introduction: Why the new *i*Grav™ SG Meter?

Several factors restrict the operation of Superconducting Gravimeters (SGs) primarily to Observatory locations. These include the high cost of the SG itself, the complexity of the equipment, and the perceived difficulty of operation and maintenance. These factors, in addition to the high cost of preparing the observatory site, severely limit the use of SGs. Most commonly, SGs are used at sites where geophysical noise is small, so that nanoGal ($0.01 nm/s^2$) signals of interest to the Global Geodynamics Project (GGP, IAG Inter-Commission Project IC-P3.1) are more likely to be observed.

The primary goal of the new *i*Grav™ Superconducting Gravity Meter is to expand the use of SGs (and arrays of SGs) to new applications, which include: volcano monitoring, hydrological, geothermal, and non-invasive ground-water monitoring, measurement of subsidence caused by oil, gas, or water extraction, measurement of long-term tectonic effects: post-glacial uplift and/or subsidence, measurement of "silent earthquakes" and precise ocean-load corrections for improving global ocean tide models

The second goal is to enable the expansion of the GGP network of SGs to a more uniform world-wide distribution. The new *i*Grav™ will continue to provide an ultra-high precision continuous gravity reference for studying geophysical phenomena with periods from one second to decades, but at a lower cost. In addition, the new *i*Grav™ will operate without the need for liquid helium, which will allow its introduction into regions of the world where liquid helium is difficult or impossible to obtain.

2. SGs vs. Mechanical Spring Gravity Meters

2.1. Mechanical spring-type gravity meters:

Mechanical spring-type gravity meters are designed to be portable and to make measurements quickly in surveys over a spatially defined network. In general, these meters are less expensive than SGs and easier to use. However, when used as "tidal gravity meters" and left at one location to measure continuous gravity versus time, they are far inferior to SGs. Recent data recorded at the J9 site in Strasbourg and reported by U. Riccardi et al. at the European Geophysical Union meeting 2010; clearly demonstrate the problems with modern spring gravity meters. In these experiments, a Microg-LaCoste gPhone (gPH54) spring gravity meter and a Scintrex CG3M were operated side-by-side with the GWR Superconducting Gravimeter (SG-C026) for several months and a comparative analysis was undertaken to measure resolution, accuracy, noise level and long term stability (drift) with respect to the SG-C026.

The results were conclusive:

- **Scale factor**
  - The gPhone 54 scale factor variation exceeded +/- 0.1% over several months (Figure 1).
  - The CG3M scale factor variation was larger than the gPhone and approached +/- 0.2%.
- **Drift**
  - The gPhone 54 had a large initial exponential drift of 25 μGal/day, which decreased to a quasi-linear drift after six to seven weeks. However, the linear drift portion required modeling with a 5th order polynomial to reduce the drift variation to about +/- 2 μGal over several months (Figure 2).

- The Scintrex CG3M had a large quasi-linear drift of 500 µGal/day, which, after correction with a 2nd order polynomial fit, left a drift variation of about +/- 5 µGal over several months.

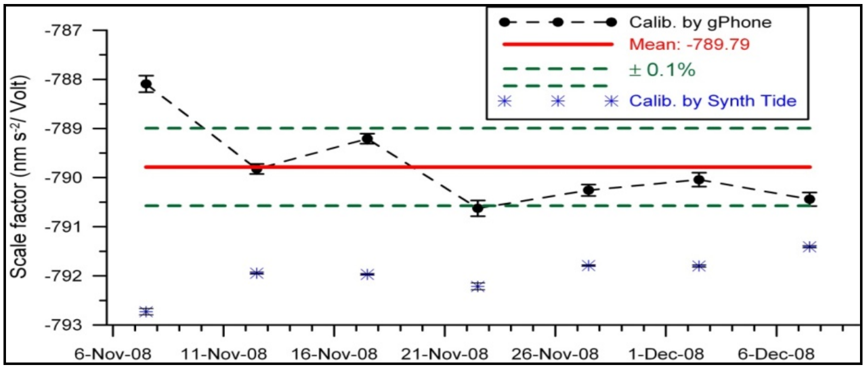

Figure 1: Variability of gPhone Scale Factor. Scale factor varies by more than +/- 0.1% over a two month time span. (U. Riccardi et al. (2010A)

U. Riccardi et al. (2010B) conclude that ***"the gPhone instrumental drift remains a critical point preventing the study of long-term gravity changes. Even after fitting to a high degree (>4) polynomial, it was difficult to distinguish real gravity changes from time-varying instrumental drift."*** Clearly, these scale factor variations and drift problems obscure and interfere with measurement and analysis of continuous gravity signals for periods above few days, which are vital for interpreting and analyzing geophysical processes.

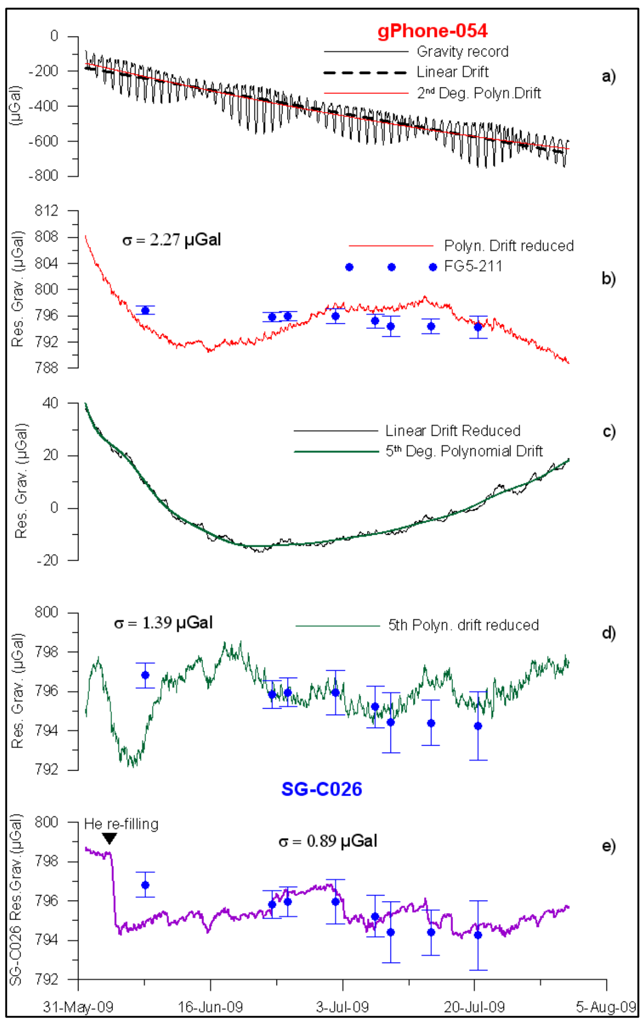

Figure 2: **Typical drift behavior of gPhone vs. SG residuals.** This figure shows the modeling of the gPhone 054 drift curve after the larger exponential drift had decayed over six to eight weeks ((U. Riccardi et al. (2010A). After the initial exponential decay, the drift becomes somewhat linear.

(a) Shows gPhone 054 record with a linear (black dotted line) and polynomial (red line) estimate of the drift;

(b) AG measurements and gPhone054 compared to AG measurements after a 2nd degree polynomial drift correction;

(c) gPhone 054 residual gravity (black) after a first linear drift reduction and further 5th order polynomial drift modeling (green line);

(d) AG measurements and gPhone 054 residual after the 5th degree polynomial drift correction.

(e) AG measurements and SG C026 residual gravity after subtracting **a linear drift reduction of only 2 µGal/year**.

2.2. Superconducting gravity meters:

SGs cannot be used as portable survey gravity meters because they suffer magnetic offsets when they are moved. Nonetheless, the number of SG applications will dramatically increase when scientists choose to use SGs in place of spring gravity meters that are used as "tidal gravity meters" to measure continuous variations of gravity. SGs have higher precision, lower noise and lower drift.

The advantages of SGs are well known:

- Their drifts are much less than 6 µGal/**year.**
    - After the first month, drifts are extremely linear over many years, so annual or semi-annual AG measurements are sufficient for determining the linear drift rate.
- Scale factor is constant to much better than 1 in 10^4.
- SGs are insensitive to the environment (pressure, humidity, etc.)
- SGs utilize an automatic leveling system to keep them aligned along the vertical, to sub µradian precision.

In order to replace spring-type gravity meters, SGs must be made less expensive and simpler to use.

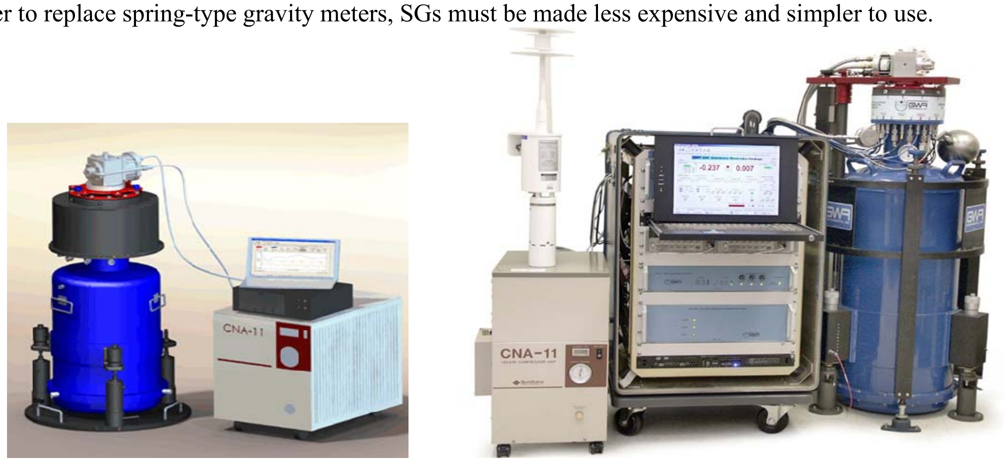

Figure 3: Comparison between ***i*Grav™** and **OSG.** iGrav™ system is much less complex than the Observatory SG shown on the right side.

Dewars	**OSG 42**	***i*Grav™**
Capacity	42 liters	16 liters
Diameter	0.41 m	0.30 m
Height	1.40 m	0.61 m
Weight (with SG and levelers installed)	69 kg	23 kg *
Cooldown time with refrigeration only	7 days	3 days
Hold time with no Cryocooler installed	28 days	18 days
Hold time with Cryocooler installed but off	21 days	7 days
Helium gas cylinders (10,000 m^3) to fill dewar from empty	3	1.2

Table 1: Comparison of OSG and *i*Grav™ Dewars

3. Design Goals of the *i*Grav™

The *i*Grav™ is designed to reduce the cost, size, and weight of the SG and to make it more portable. The *i*Grav™ consists of three systems: the Dewar and base plate, the cryogenic refrigerator, and the control box and portable computer. The *i*Grav™ Dewar is smaller and lighter, making it easier for one person to move around. Smaller and lighter thermal levelers are integrated into the base plate (separate from the Dewar), which can either be placed upon a flat concrete surface or bolted in place, for long-term measurements. The pictures of the *i*Grav™ compared to the Observatory SG (Figure 3) dramatically show the new instrument's reduced complexity. Table 1 compare most of the parameters of the *i*Grav™ and the Observatory OSG. The *i*Grav™ Dewar capacity is only 16 L, compared to the 42 L of the OSG. This contributes to a significant reduction in the *i*Grav™ Dewar height and diameter, but most significantly reduced is the weight, by a factor of three, from 69 kg to 23 kg. In the event the coldhead fails, the smaller dewar has only a 7 day emergency hold time versus 21 for the OSG. Since the SHI cold heads are very reliable such failures are very rare.

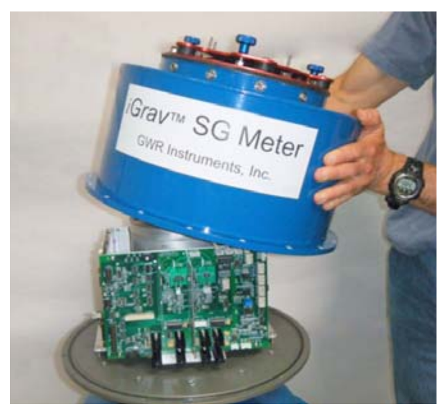

Figure 4: **Integrated data acquisition and control electronics.** Microprocessor-controlled electronics with A/D converter reside in Dewar head. Real-time controller for high-resolution data logging with 7.5 digit DVM for Gravity Signal and Barometer with GPS time stamp. Electronics are sealed in He gas and immune from atmospheric oxidation and humidity.

The elimination of the OSG coldhead alignment frame simplifies the *i*Grav™. In place of the frame and thin isolation diaphragm, the *i*Grav™ uses only a thick rubber bellows to seal the Dewar and to partially vibration isolate the coldhead from the Dewar. This dramatically reduces the complexity and the weight (the OSG frame weighs 39 kg) but allows some transmission of coldhead vibrations to the sensor. This may slightly increase the noise level in the long-period seismic band. For this reason an optional coldhead frame will be offered to users interested in this frequency band.
A main innovation of the *i*Grav™ is the reduced size and power consumption of the electronics. The electronics are smaller and simpler to manufacture and to use (Table 2). This reduction allows the electronics to reside in the head of the Dewar, which lies directly above the sensor (Figure 4).

Electronics:	**OSG TREE3**	**OSG TREE4**	***i*Grav™**
Height/Width/Depth	1.40m X 0.76m X 1.11m	1.00m X 0.55m X 0.74m	0.10m X 0.48m X 0.33m*
Weight	164 kg	68 kg	4 kg*
Power	600 watts	250 watts	15 watts
UPS	2.5 KVA	1.5 KVA	36 hrs with 12V Battery
Voltage	100-220 VAC	100-220 VAC	12 VDC
Operating System	UIPC	FIT UIPC	LabView

Table 2: Comparison of specifications of *i*Grav™ electronics to two Temperature Regulated Electronics Enclosures used by OSGs. *All control electronics are built into the Dewar top. A small external box contains power supplest and a computer for storing the data.

4. *i*Grav™ Sensor Design

The fundamental principles and design remain the same in the *i*Grav™ as for the OSG. A spherical superconducting mass is levitated using a magnetic force that exactly balances the force of gravity. The magnetic force is produced by trapping supercurrents in magnetic coils using heat switches. The superconducting property of zero resistance and the perfect stability of the supercurrents produce an ultra-stable magnetic spring (Figure 5).
The *i*Grav™ sensor is very similar to the OSG's, however, many design changes were made to simplify its manufacture. These changes include: Aluminum magnet body reduces weight and cool-down heat capacity; magnet body is shorter to reduce dewar height; magnet coils are wound in series; and rugged Nb shield attachment increases durability during shipping.
In a typical OSG, the magnetic gradient is set through a careful adjustment of the ratio of Upper Coil current to Lower Coil current. Four (4) heat switches are used and the current is adjusted to 0.1 mA out of 4 A. This is difficult to accomplish even with "stable" current supplies. The force gradient must be checked several times during initialization, and the sphere is centered by inducing a small current into the lower guard coil. This is a tedious process, and very few users have the skill and/or confidence to levitate the sphere or to re-center it.
An important goal for the *i*Grav™ is to simplify initialization and sphere levitation so that users are fully capable at mastering all aspects of operating the SG without needing assistance from GWR. To achieve this goal, the Upper and Lower coils (as shown in Figure 6) are connected in series and the magnetic gradient is permanently set at GWR by fixing the ratio of turns in the Upper Coil to the number of turns in Lower Coil. The series coil is connected to a four (4) ampere current supply and current is trapped in the coil using a single heat switch. In strong feedback, the current in the series coil to set so that the levitation force balances local g at the site of operation. No further action is required to adjust the gradient! When the sensor is switched from strong feedback to Run, the sphere must be more precisely adjusted to the center of the capacitance bridge. This adjustment uses a separate small centering coil that operates independently from the series coil and is controlled by a second heat switch and small current supply. Centering the sphere is simple and only requires a few mA. The entire levitation process can be easily learned by new users and in the future will be automated in the software.

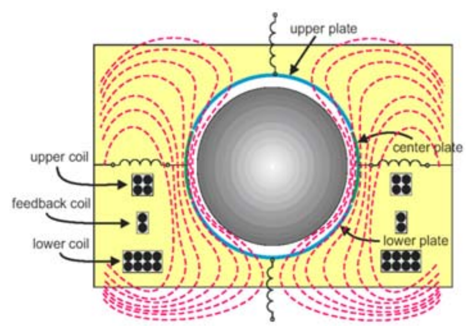

Figure 5: Drawing showing magnetic flux distribution from Upper and Lower coils, In response to the magnetic field that results from the currents in the coils, currents are induced in the surface of the sphere that prevent flux from entering sphere. The interaction between the induced currents in the sphere and the currents in the coils produces the force that levitates the sphere.

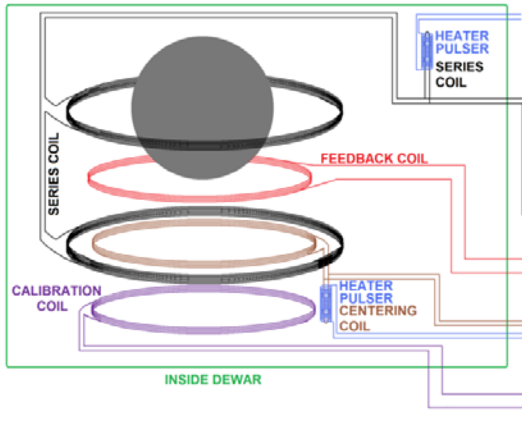

Figure 6: Schematic of series coils used in the *i*Grav™, The Upper and Lower coils (**black**) are wound in series and are energized using one current supply and one heat switch. The sphere is centered using a small current through the Centering coil (**brown**) and a second heat switch. The Feedback coil (**red**) provides the force that keeps the sphere at the null of the capacitance during operation. An additional "Calibration" coil (**purple**) is added to help verify that the scale factor (μGal/volts) has remained constant after the gravity meter has been moved.

5. First Results with *i*Grav™ SG Meter

5.1. Magnetic force gradient of *i*Grav™ versus OSG

Figure 7 shows a comparison of a "typical" gradient in the OSG versus the set gradient in the *i*Grav™. [A typical gradient is set by adjusting the ratio of the UC to the LC currents until the response of the capacitance bridge is about 2 V for 10 mA, with the capacitance bridge drive set to unity (BD = 1)]. Of course, the gradient of OSG 061 could be set to almost any value (weaker or stronger); however, the gradient shown is within the guidelines set by GWR for the OSG. The *i*Grav™ gradient is about three times stronger than the OSG. Interestingly, decreasing the Lower Coil by one turn will weaken the *i*Grav™ gradient to be about equal to the OSG 061 gradient. This option was not chosen because the stronger gradient makes the *i*Grav™ much easier to operate and to date shows no detrimental effects.

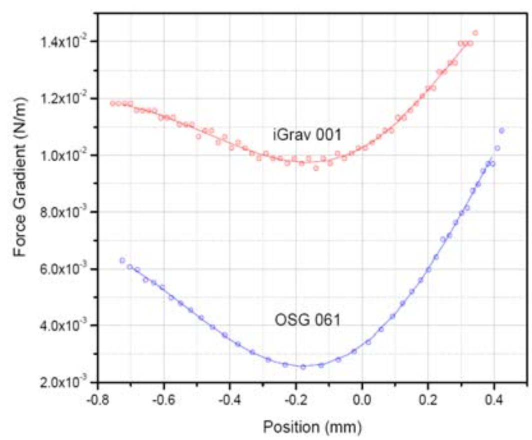

Figure 7: Magnetic force gradient versus position: *i*Grav™ vs. OSG, The X-axis is a measure of the sphere position with respect to the center of the capacitance bridge. The Y-Axis is the gradient (spring constant) measured in Newtons/meter.

5.2. Transfer function: *i*Grav™ versus the OSG

The motion of the mass in a mass–spring system is described by a second-order differential equation:

$$F(t) = -kz(t) - b\frac{dz(t)}{dt} - m\Delta g(t)$$

This also applies to the SG, where z is the relative displacement of the sphere with respect to its equilibrium position in the capacitance bridge; k is the spring constant that results from the magnetic gradient; b is the damping constant proportional to velocity, m is the mass of the sphere; and $\Delta g(t)$ is the deviation of gravitational field from the value with the sphere at its equilibrium position.

For the SG, the spring constant can be determined by knowing the sensitivity of the capacitance bridge and the scale factor of the SG. GWR has measured the sensitivity of the capacitance bridge to displacement, G_c, to be 3.9 x 10^7 m/V, which corresponds to 4 Angstrom/mV. The scale factor, S_G (in units of nm/s^2/V) can be determined to 1% by fitting the output of the SG to a good theoretical tide model. In normal closed-loop operating conditions, the scale factor is a measure of the acceleration (force divided by the mass of the sphere) that is produced by the current in the feedback coil. The gravity signal itself is the feedback voltage, which is applied to a 100 K resistor in series with the feedback coil. The spring constant is determined by operating the SG in an open-loop configuration and applying a few volts to the 100 K resistor and feedback coil and measuring the output of the capacitance bridge.

For example, if V_I is applied and the SG output voltage is V_O; then the spring constant k is:

$$k = \frac{V_I m S_G}{V_0 G_C}$$

With knowledge of the mass and spring constant, one can then calculate natural frequency of the oscillator:

$$\frac{1}{\omega_0^2} = \frac{m}{k}$$

The values for the mass, scale factor, spring constant and frequency are given in lines 3 to 6 of Table 3. Equating the force to the kinematic acceleration in an inertial frame results in the following equation:

$$m\frac{d^2 z(t)}{dt^2} = -kz(t) - b\frac{dz(t)}{dt} - m\Delta g(t)$$

The complex amplitude (or frequency response) of such a system (see for example: Y. Imanishi et al., 1996) to a driving force in the form of $f(t) = me^{i\omega t}$ is well known to be:

$$S(\omega) = \frac{1/\omega_0^2}{1 + i\omega/Q\omega_0 + \omega^2/\omega_0^2}$$

Where Q is defined by the equation:

$$Q = \frac{\omega_0 m}{b}$$

Of additional interest, the spectral acceleration-noise power density due to Brownian motion in a simple mechanical oscillator is give by:

$$P(\omega) = \frac{4kT\omega_0}{Qm} = \frac{4kTb}{m^2}$$

Following the methodology of Van Camp (2000), the frequency response was determined by analyzing the instruments response to a repeated series of voltage steps applied to the 100 K resistor and feedback coil. Even though the gravity signal was filtered using the standard GGP low pass filter, there were considerable micro seismic signals that interfered with the analysis. These were attenuated by averaging over many steps. The resulting frequency response for the OSG (light green), *i*Grav™ (light blue) and the GGP filter (dashed red line) are shown in Figure 8. From these data it is clear that the *i*Grav™ has a much higher resonance frequency, f_0, and Q than the OSG. However, it is also clear that the attenuation of the GGP filter will interfere with measuring the Q. In this analysis we have corrected for the filter by dividing the response curves by the filter attenuation. The corrected responses for the OSG (dark green) and *i*Grav™ (purple) are also shown. These data are then fit to the real part of the frequency response equation above; and the fitted functions (black) are superimposed on the OSG (dark green) and *i*Grav™ (purple) traces. As shown, a very good fit is obtained using only the Q as a variable. The resulting Q's and the damping factors are shown in line 8 and 9 of Table 3; and the theoretical noise is shown in line 10.

Parameter	Unit	iGrav™	SG061
Gradient (BD=1)	V/10mA	1.1	2.0
Capacitance Bridge Gain G_C	m/V (BD=7)	3.9×10^{-7}	3.9×10^{-7}
Mass m	Kg	4.37×10^{-3}	3.85×10^{-3}
Scale Factor (Run) S_G	$nm/s^2/V$	972	728
Spring constant k	N/m	0.0102	0.0033
ω_0	Rad/sec	1.531	0.933
f_0	Hz	0.243	0.148
Q		0.254	0.056
b	Kg/sec	0.027	0.064
P_a (Noise)	$(nm/s^2)^2/Hz$	0.342	1.073

Table 3: Comparison of harmonic oscillator parameters from function fit to *i*Grav™ and OSG.

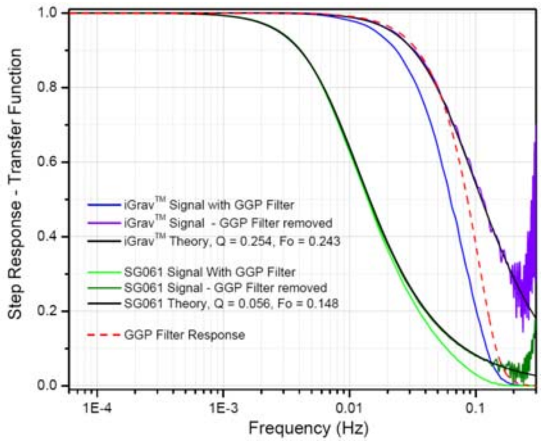

Figure 8: A comparison of the open loop transfer functions of the *i*Grav™ and the OSG

5.3. Noise comparison of *i*Grav™ and OSG061

The noise spectra for the *i*Grav™ 001 are compared to the OSG and the NLNM (orange trace) in left side graph of Figure 9. These data indicate that the noise of the *i*Grav™ 001 (red trace) is slightly lower than OSG 061 (blue trace) when operated at GWR. This is consistent with the lower value of the damping constant, b, which was discussed in the previous section. Also, we show the noise level of the gPhone 054 (purple dashed line) that was measured at Strasbourg (U. Riccardi, 2010). The instrumental noise of the gPhone is about 30 times higher than the *i*Grav™.

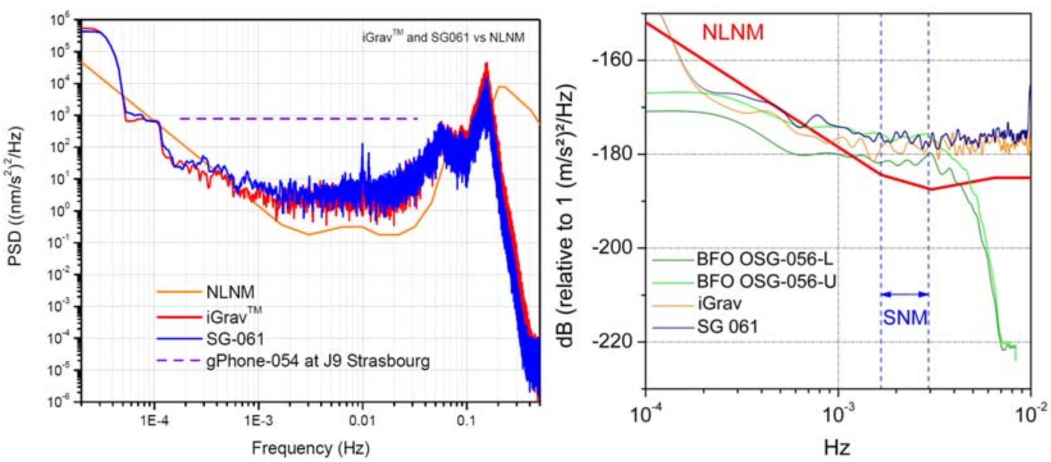

Figure 9: On the left side - Noise comparison of *i*Grav™ and OSG061 compare to NLNM. On the right side - Noise comparison of *i*Grav™ and OSG061 compare to Black Forest Observatory OSG-056 Dual Sphere SG and NLNM

To confirm our result, we sent the same data to Severine Rosat (private communication) for her analysis. Her results are shown on the right side of Figure 9 and compare the *i*Grav™ and OSG data—not only to the NLNM but also to data from both the Upper sphere (light green) and the Lower sphere (dark green) of the Dual Sphere OSG-056. This provides a stringent test, since OSG-056 is operating at the Black Forest Observatory (BFO), which is known to be one of the quietest sites in the world. One second data was used to analyze the SGs operating at GWR; while the BFO data was digitally filtered to one minute samples. This accounts for the attenuation of the BFO data above 5 x 10^{-3} Hz. However, in the critical Signal-Noise-Measurement (SNM) band, it is clear that the OSG 061 noise level is as low as the Upper sphere at BFO, while the *i*Grav™ has a slightly lower noise level. The lowest noise level is achieved by the heavier 17 g ram sphere in the Lower sensor of OSG-056 at BFO.

From these data we conclude that design changes to the *i*Grav™ sensor have certainly not degraded its sensitivity or increased its noise. Longer tests are now being performed to measure the drift characteristics of the *i*Grav™.

5.4. Can a portable *i*Grav™ be used to calibrate the European network of SGs?

It has been common practice for years (O. Francis et al., 1998) to use an AG to calibrate the SG by operating them both simultaneously side-by-side over a period of at least five days, preferably when Earth tides are near their maximum amplitude. This procedure can attain a scale factor calibration precision that is better than 0.1% and can approach 0.05% under very quiet operating conditions. The precision of the calibration is limited by the noise of the AG (30 to 50 μGal Hz $^{-1/2}$) which is more than two orders of magnitude greater than the noise of the SG (0.1 – 0.3 μGal Hz $^{-1/2}$) (M. Van Camp et al., 2005). As a result of the AG noise, the standard deviation of the residuals of the linear regression fit between the SG and AG typically is about +/- 1 μGal.

In Figure 10 below, we imitate a typical SG–AG calibration, but instead replace the AG with a portable *i*Grav™ to transfer the scale factor from the *i*Grav™ to SG 061. In this preliminary experiment, the *i*Grav™ is calibrated by comparison to a tidal model, but it could also be calibrated with an acceleration platform or an AG. The linear regression fit gives a calibration of 72.869 +/- 0.001 μGal/V, which equates to a precision of 1.4 x 10^{-3} %.This is more than 50 times better than achieved with the AG, but may be an overestimation of the precision. Another estimate of the precision is given by lowest trace of Figure 10, which shows the scatter of the residuals of the linear regression between the *i*Grav™ and SG 061. The standard deviation of the residuals is about +/- 0.04 μGal, which is 25 times lower than those achieved using an AG. This result suggests the possibility of moving an *i*Grav™ to many of the GGP sites and performing a relative calibration of about 4 x 10^{-3} %. For example, the *i*Grav™ could be moved throughout Europe to provide a precise relative calibration of the European network of SGs. (The absolute calibration could then be made by inter-comparison of all of the AG calibrations made throughout Europe.) As another example, an *i*Grav™ could potentially be transported around stations distributed along the coast of Norway to measure Earth tides and ocean loading vectors. With a relative calibration good to 4 x 10^{-3} %, this would result in a big improvement in testing ocean loading models in that region.

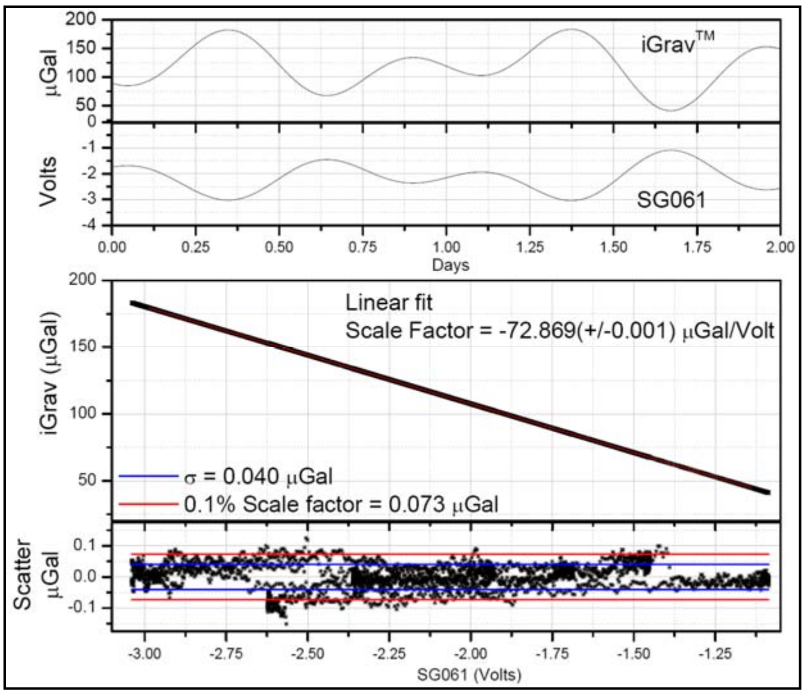

Figure 10: First test of concept of using *i*Grav™ to "calibrate" other SGs Note that the standard deviation of the scatter is 0.04 μGal when two SGs are least squares fit together. This compares to a standard deviation of about 1 μGal when an AG is fit to the SG. This suggests that using an *i*Grav™ to determine relative calibrations between SG sensors will be 25 times more precise than using an AG.

The authors stress two points. 1) This is a relative calibration and not an absolute calibration. 2) To be successful, it requires that the scale factor of the *i*Grav™ remains stable to about one part in 10^5 when the instrument is moved. Careful measurements are now beginning to test the second requirement. For example, how reproducible is the scale factor if the sphere is lowered by decreasing the current in the magnet coils to zero, and then re-levitated at a new location? Does the sphere need to remain levitated to preserve the scale factor? And if so, how well is scale factor preserved under these conditions?

Perhaps the stability of the scale factor can only be determined by comparing to a stationary undisturbed SG. However, as an alternative and as shown in Figure 6, we have added a "calibration coil" to independently measure the constancy of the scale factor. This will be achieved by activated the coil with a precise step function in current and measuring the output of the *i*Grav™.

5.5. Cooling the OSG or *i*Grav™ without using Liquid Nitrogen or Liquid Helium

In the past, all SGs were cooled from room temperature (RT) to 4 Kelvin (4 K) using liquid nitrogen (LN2) and liquid helium (LHe). First the Dewar was partially filled with LN2 and left at least 12 hours (overnight) to cool the SG sensor to 77 K. The next morning, the LN2 was removed by turning the Dewar upside down and pouring the LN2 out. The sensor and Dewar were then cooled to 4 K by transferring LHe from a storage Dewar into the SG Dewar. This was done very slowly to take full advantage of both the cooling power of the LHe and the resultant cold He gas. Such a transfer would take 2 to 3 hours to both cool to 4 K and then to fill the Dewar with LHe.

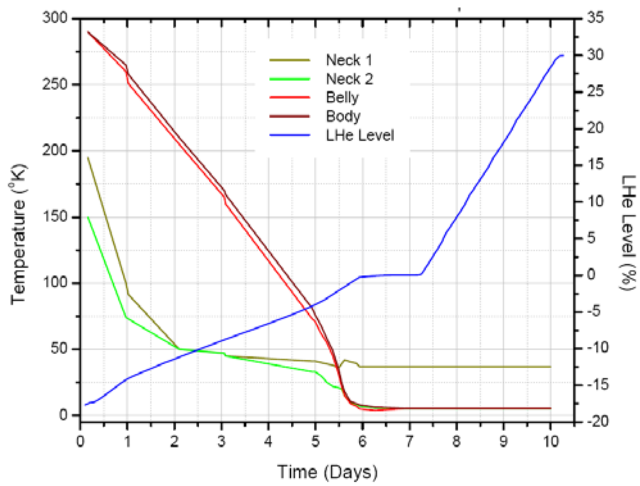

Figure 11: Cooling the OSG using the Cryogenic refrigeration system. It takes about 10 days to cool the OSG using only the Cryogenic refrigeration system and Helium gas. Initial experiments show this time will be halved to less than 6 days for the *i*Grav™

We are no longer dependent on using LN2 and LHe. Improvements have been made in the Coldhead/Dewar system so that only the Cryocooler and helium gas are needed to cool to 4 K. Figure 11 shows the cooling process for the OSG. After turning on the Cryocooler, the Neck 1 (brown) and Neck 2 (green) temperatures drop rapidly to 50 K in the first 2 days. This is expected since these neck thermometers are placed next to the upper and lower cooling stages of the coldhead. In contrast, the Body (dark brown) and Belly (red) temperatures lag the neck temperatures by about 3 days. The Body and Belly are cooled by conduction through the helium gas—more slowly as a result of the large mass and heat capacity of the vacuum can and the gravimeter's magnet body. After about 5.5 days the Neck 2, Belly, and Body all cool to about 4 K and Neck 1 stabilizes to about 40 K.

The level indicator (blue) scale is on the right-hand Y axis. The level indicator is adjusted to read zero percent when it is in cold He gas at 4 K. This happens between days 6 and 7. Up to that point, the negative readings provide a qualitative measure of the temperature of the He gas as it cools from 300 K to 4 K. Most important is that the onset of liquefaction and production of LHe starts just after 7 days and then the Dewar fills at a rate of about 10%/day.

Our first experiment with the *i*Grav™ indicates that it will cool and fill in about half the time of the OSG. Therefore, after inserting and turning on the Cryocooler, the *i*Grav™ will cool and be close to filled with LHe in about 5 days. This process will use about one Helium gas cylinder (containing 10,000 meter^3 of helium gas). Therefore, two such Helium gas cylinders will provide plenty of gas to operate the *i*Grav™ at a remote site and autofill after a total of 7 days of power outages. As a result, the user never needs to purchase, transport, or transfer liquid helium and LHe will be "manufactured" on site to refill the Dewar after power outages.

6. Conclusion

Spring-type gravity meters are still being used to record continuous gravity at many sites. However, their data quality is degraded by temperature and pressure-induced instrumental effects, by variation in scale factor, and by variable drifts that can only be partially approximated by higher order polynomials. With spring-type gravity meters, users end up spending effort trying to make corrections for instrumental effects, rather than focusing solely on the underlying geophysics.

As discussed in this paper, the *i*Grav™ Superconducting Gravity Meter is designed to replace spring-type gravity meters when used for continuous measurements of gravity versus time. With its extremely low drift, constant scale factor, and low noise, the *i*Grav™ will provide a virtually noise-free measurement of continuous gravity with the same low noise and low drift produced by SGs presently used in the GGP network.

The *i*Grav™ is smaller, lighter, and simplified so that it can easily be moved. The size and power usage of the electronics has been greatly reduced—and most of the cables eliminated—by placing the electronics in the head of the Dewar. The *i*Grav™ coils are wound in series with a fixed magnetic gradient. This vastly simplifies sphere levitation and initialization of the sensor, so that new users can easily learn and master all aspects of instrument operation. In addition, the dewar/sensor is cooled from room temperature to 4 Kelvin using the refrigeration coldhead and the coldhead liquefies helium gas supplied from a gas cylinder to fill the dewar with liquid helium. This entirely eliminates the need for purchasing, transporting, or transferring liquid helium, either during the initial installation or for continued operation of the gravity meter.

The lower price, simplicity, and convenience of the new *i*Grav™ will enable users to replace spring-type gravity meters with Superconducting Gravity Meters (SGs) at many sites where high-quality continuous gravity data are essential to understanding complex geophysical problems.

7. References

Francis, O., T. M. Niebauer, G. Sasagawa, F. Klopping, and J Gschwind (1998), Calibration of a superconducting gravimeter by comparison with an absolute gravimeter FG5 in Boulder, *Geophys. Res. Lett. , 25(7)*, 1075 - 1078.

Imanishi, Y., T. Sato and K. Asari, (1996), Measurement of mechanical responses of superconducting gravimeters, *J. of the Geodetic Soc. of Japan, 42(2)*, 115 - 117

Riccardi, U., S. Rosat and J. Hinderer, (2010A), Results from some calibration experiments conducted at Strasbourg superconducting gravity station, EGU Vienna, May 2–7, 2010.

Riccardi, U., S. Rosat and J. Hinderer, (2010B), A 300-day parallel gravity record with the gPhone-054 spring gravimeter and the GWR-C026 superconducting gravimeter in Strasbourg (France): first comparative study, Poster XY399, EGU Vienna, May 2–7, 2010.

Van Camp, M., S. D P. Williams, O. Francis (2005), Uncertainty of absolute gravity measurements, *J. Geophys. Res., 110*. B05406, doi:10.1029/2004JB003497.

Van Camp, M., H.-G. Wenzel, P. Schott, P. Vauterin, O. Francis, (2000), Accurate transfer function determination for superconducting gravimeters, *Geophys. Res. Lett. , 27(1)*, 37-40