Superconducting Gravimeters: Past, Present and Future

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GWR Instruments, Inc.

INSTRUMENTS, INC.

Colloque G2, Strasbourg, 19 November 2014

Why Use Superconductivity?

- Coils of superconducting wire produce a magnetic field levitating a superconducting test mass: hence the Superconducting Gravimeter (SG)
  - Magnetic levitating field provides a massless spring
  - Spherical test mass is the only moving part

- Stability of persistent supercurrents enables low (in principle, zero) drift
  - In practice, a few μGal/yr, and constant (linear)

- Noise from mechanical deformation and creep is largely frozen out at 4 K
  - Calibration constant remains constant in time over decades, to < 0.01%
  - Environmental sensitivity (ambient temperature, pressure, humidity) also largely eliminated

- However, SG requires liquid helium (LHe) for operation
  - Performance justifies the effort
  - Developments to reduce cost and complexity

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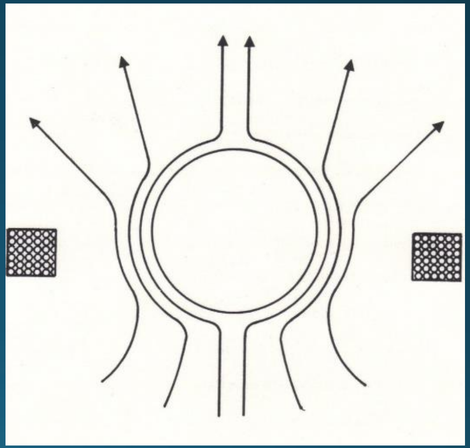
The Prehistoric Past

- University of California, San Diego: Prof. J.M. Goodkind
- W.A. Prothero: Ph.D. dissertation (1967) describing first instrument
  - Experimental results: a single 10-hour time series!
  - Sensor physics and fundamentals of design remain unchanged to this day
    - Persistent currents in perfectly diamagnetic sphere generate stable levitating force
    - Must ensure that magnetic field at surface of sphere << $H_c(T)$, the critical field of the material
      - For niobium, H_c at 4.5 K ≈ 1300 Gauss
    - A single coil is inappropriate: force gradient is too strong



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Control of Levitating Force Gradient

- Two coils, one approximately in plane of sphere and another below, enable adjustment of the force gradient

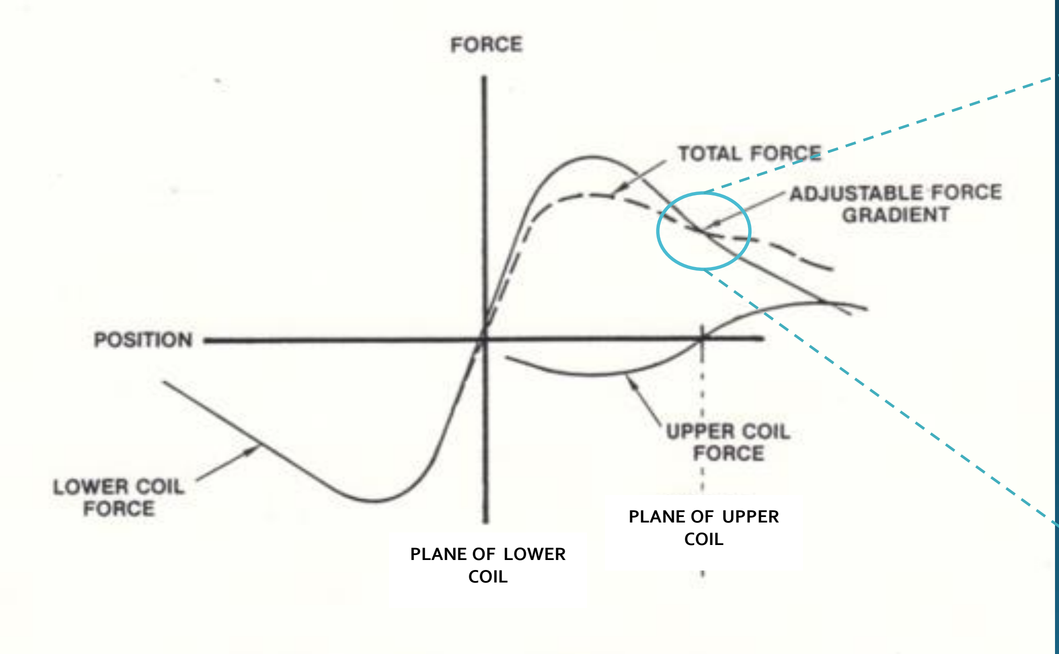
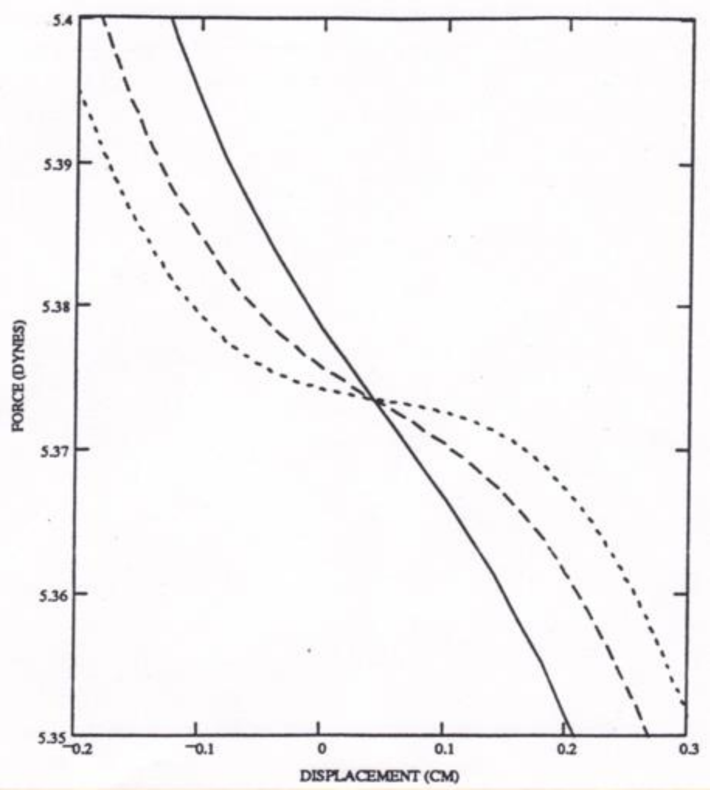


FIGURE 1-3. FORCE VS. SPHERE POSITION



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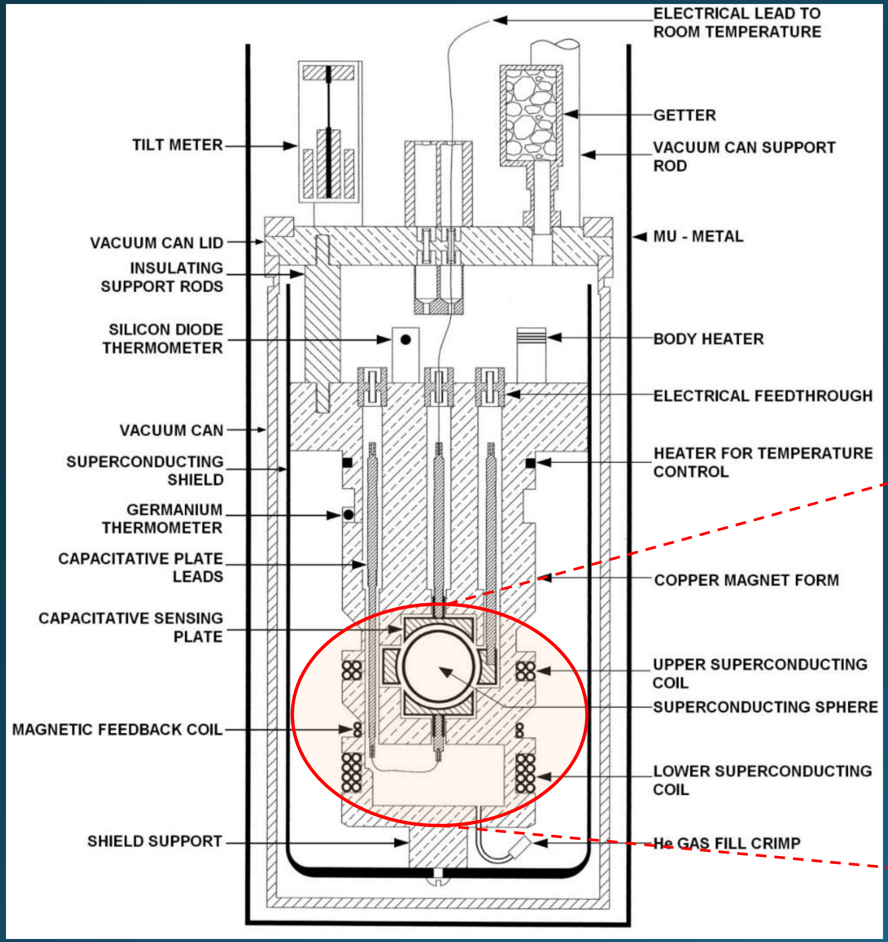
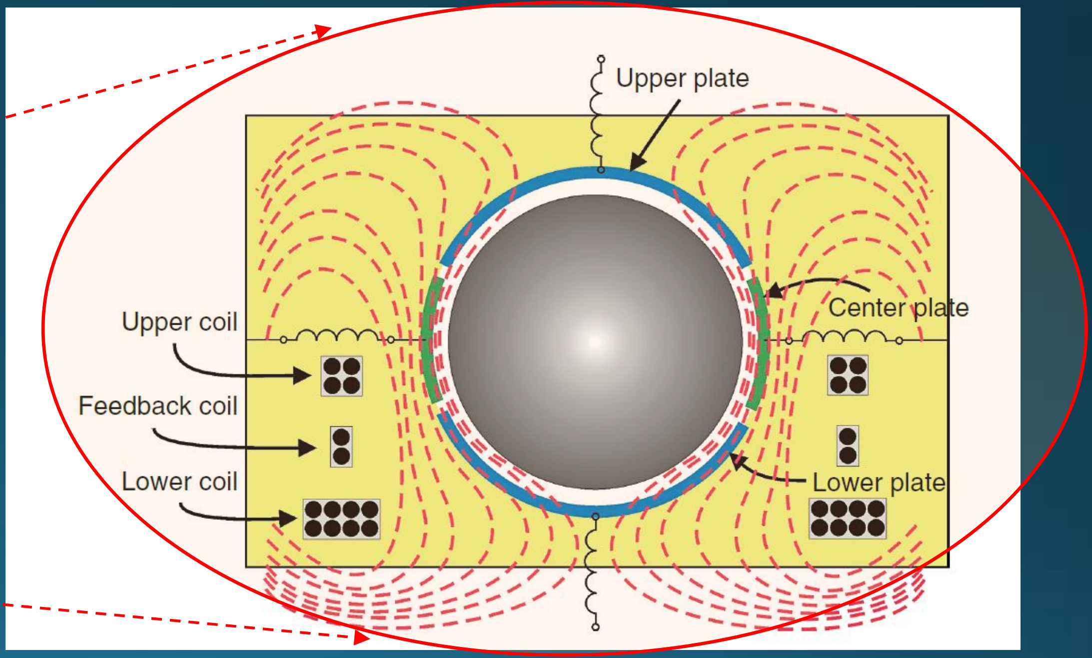
Basic SG Design: Invariant since Prehistory



- Persistent currents in pair of coils generates magnetic field expelled from superconducting, spherical test mass
- Field produces levitating force with weak, adjustable gradient (spring constant)
- Sphere position sensed via 3-plate capacitance bridge
- Position maintained at null via current in feedback coil; restoring force extremely linear in the current



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Late Prehistory at UCSD

- R.J. Warburton and R. Reineman joined Goodkind lab to refine SG and deploy instruments for geophysical observations
- SG cooled with LHe in passive Dewars with hold times ≥30 days
  - Refilling Dewars is laborious and causes disruptions in data quality
- Sensors deployed at sites in California and Colorado for studies including:
  - Earth tide spectroscopy (ocean/atmosphere loading, nearly diurnal free wobble, search for effects of gravitational anisotropy, etc.)
  - Hydrology (reservoir depletion/recharge at The Geysers, CA, geothermal site)
  - Earthquake prediction (search for pre-seismic crustal deformation)
  - Modeling of atmospheric loading (R.S. Spratt, Ph.D. 1981)
  - Metrology: test of the gravitational inverse square law at ~1 m mass separations (P.V. Czipott, Ph.D. 1983)

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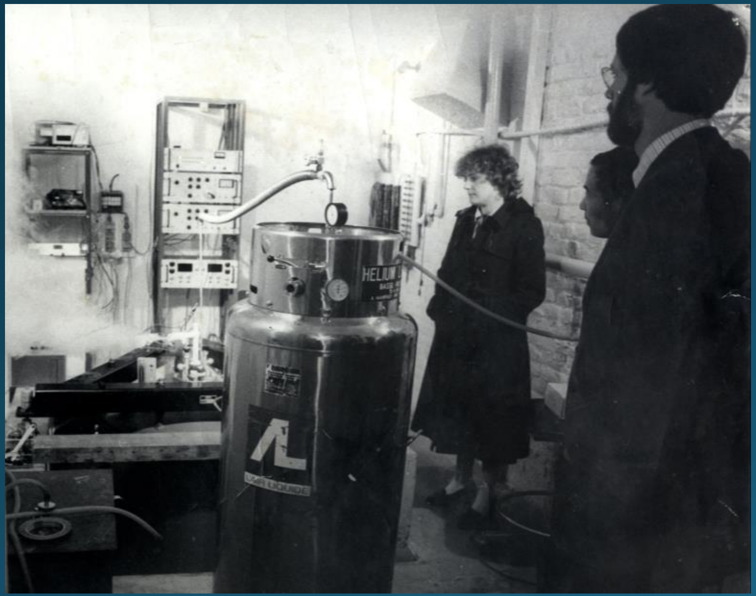
The Historical Past: GWR Instruments

- GWR founded in 1979 to deliver two instruments:
    - P. Melchior, Royal Observatory of Brussels
    - R. Brein and B. Richter, Institut für Angewandte Geodäsie (today, the BKG)

ROB instrument (1980) resembled UCSD cryogenics (passive Dewar)



IfAG requested active refrigeration to reduce expense: first step (1981) on long road to liquid-free operation

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Parallel Development Paths

- Sensor enhancement
- Cryogenic improvement
- Other steps to reduce size, cost and complexity

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Sensor Improvements, 1981-2005

- Proprietary selection and treatment of superconducting materials
  - Greatly reduced spontaneous signal offsets (tares) that occurred on older instruments
  - Reduced start-up (exponentially decaying) drifts
  - Reduced residual linear drifts (2-6 μGal/yr)
- Integrated capacitive tiltmeters and active tilt control
  - Eliminated spurious signals caused by slow tilting of support structures
- Higher test mass
  - Leads to reduced noise
- Slight redesign of magnetic suspension circuits
  - Greatly simplified setup and operation

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Cryogenic Improvements, 1980-1992

- 1980 Baseline: passively cooled Dewar
  - 200 liter capacity, ~4 l/day boiloff (loss) of LHe
  - LHe refills needed every 30-50 days: logistics, labor, expense and data disruption
- First cryocooled Dewar, 1981 (Bad Homburg, Germany)
  - Two-stage cryocooler with 65 K and 11 K stages attached to Dewar thermal shields
  - Time between refills extended to 400 days
  - Direct attachment required Dewar warm-up to remove and service the cryocooler
- Mechanically isolated cryocooler, 1988-1992: the TT70
  - Cold head thermal contact is via He vapor in the neck of the Dewar
  - Cryocooler removable for service without sensor interruption
  - Maintained time between refills at 400 days

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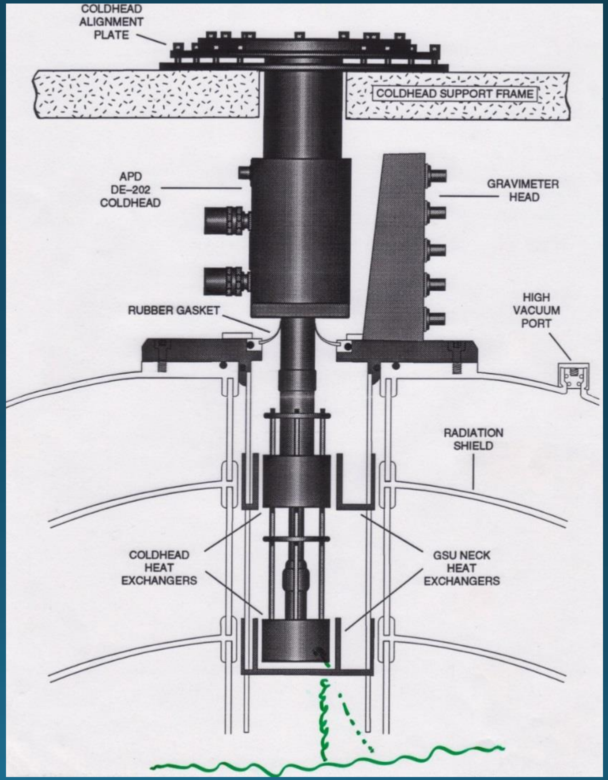
The Model TT70 in Operation

Installation at Cantley, Canada (1989)

Schematic of the Removable Cold Head



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Cryogenic Improvements, 1993-2002

- Compact SG, 1993
    - Smaller, 125 liter Dewar
    - SG built directly into Dewar belly, allowing much better thermal efficiency
    - TT70-style cryocooler enables >1 year interval between refills
    - Structural changes to SG mount enable lower noise than previous SGs
    - Eliminates need for large concrete pier
    - "Assembly-line production": 11 units made, 1994-2002; 9 are still operating today

Example Installations:

Institut de Physique du Globe de Strasbourg

Mt. Stromlo Observatory, Australian National University

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Cryogenic Improvements, 1998-2002

- Ultra Long Holdtime Dewar, 1999
  - Based on 125 liter Dewar of the Compact SG series
  - Used newly available cooler with a 4.2 K cold head
  - Reliquefies He vapor and drips the liquid back into Dewar belly
    - The first closed-cycle system
    - Very reliable: ~3 years between servicing
  - Cryocooler requires 8 kW power (for compressor and water cooler)
  - 3 systems manufactured before supplier *discontinued making the cryocooler!*

Ultra Long Holdtime Dewar installed at Wetzell, Germany.

Support cranes to insert and remove cold head shown in background.

Instrument inside the Dewar is one of the first dual-sphere SGs

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Cryogenic Improvements, 2003-2012

- Observatory SG, OSG
  - Sumitomo Heavy Industries released new closed-cycle cryocooler just in time
    - Smaller cold head easily handled by one person, without cranes
    - Compressor power usage only 1.3 kW (air-cooled)
  - Enables still smaller Dewar: 35 liter capacity
    - Allows 20 days of operation following a cryocooler failure
    - Can liquefy He gas at >1 liter/day
  - Allows essentially indefinite operation after initial fill

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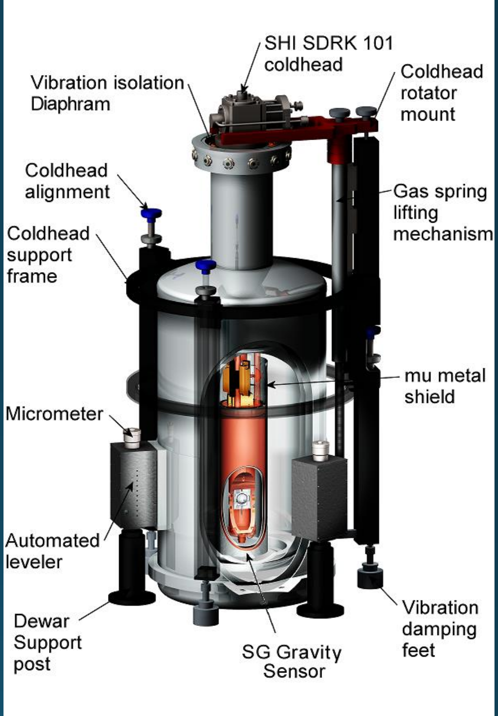
The OSG

- Available in single- and dual-sphere configurations
- Gravimeter Electronic Package
- Data Acquisition System
- GWR User Interface for Personal Computer (GWR UIPC software)
- Remote access to the data system



GWR OSG T048 at Hsinchu, Taiwan

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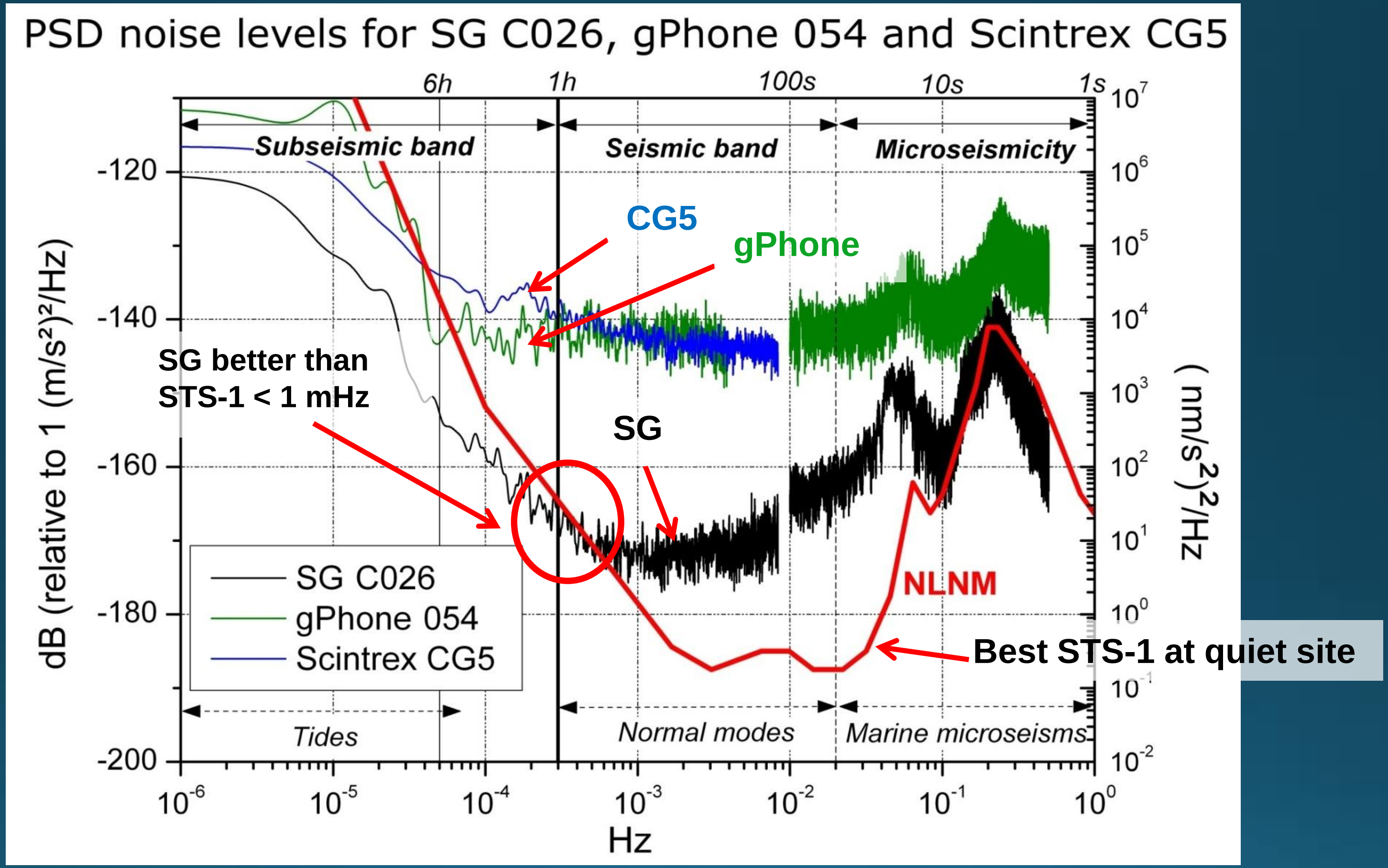
How Good Had the SG Become?



Reference: Riccardi U., Rosat S. , Hinderer J.: *Metrologia* **48**, 28-39 (2011)

The Present: the *i*Grav® SG, 2012-

- Significant reductions in size, cost and complexity
    - Dewar capacity reduced to **16 liters**
    - Total power consumption reduced to 1.5 kW
    - No LHe required for start-up: initial cooldown starts with room-temp compressed gas
    - Weight of system – excluding compressor – reduced by factor of 3.4
        - From 230 kg for OSG to 68 kg for *i*Grav
    - 90% of electronics in sealed enclosure on head of Dewar
        - Enclosure filled with He gas to prevent oxidation over time
        - Provides immunity to humidity
        - Can be temperature-regulated, as needed
    - Two changes to sensor simplify setup and operation
        - Two suspension coils now connected in series in factory-set force gradient
        - Final positioning of test mass (in center of capacitance bridge) performed via small persistent current adjustment in a centering coil

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The *i*Grav®: Small and Cute

10,000 m³ He gas cylinder for resupply in case of power failure

1.3 kW compressor driving 4 K cold head

DC-UPS: 24-hr battery backup in rugged outdoor enclosure

***i*Grav**

Integrated electronics

Cooldown to 4 K in 5 days <u>without use of LHe</u>; Dewar filled in additional 5 days

Zero use of LHe in operation

>7 days operation in event of power failure or cryocooler malfunction

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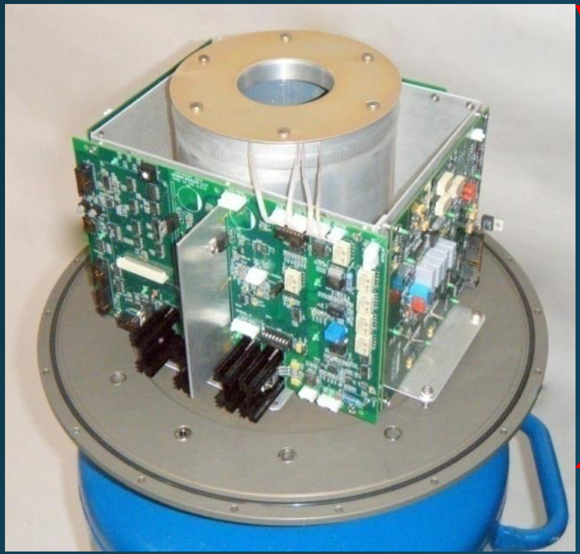
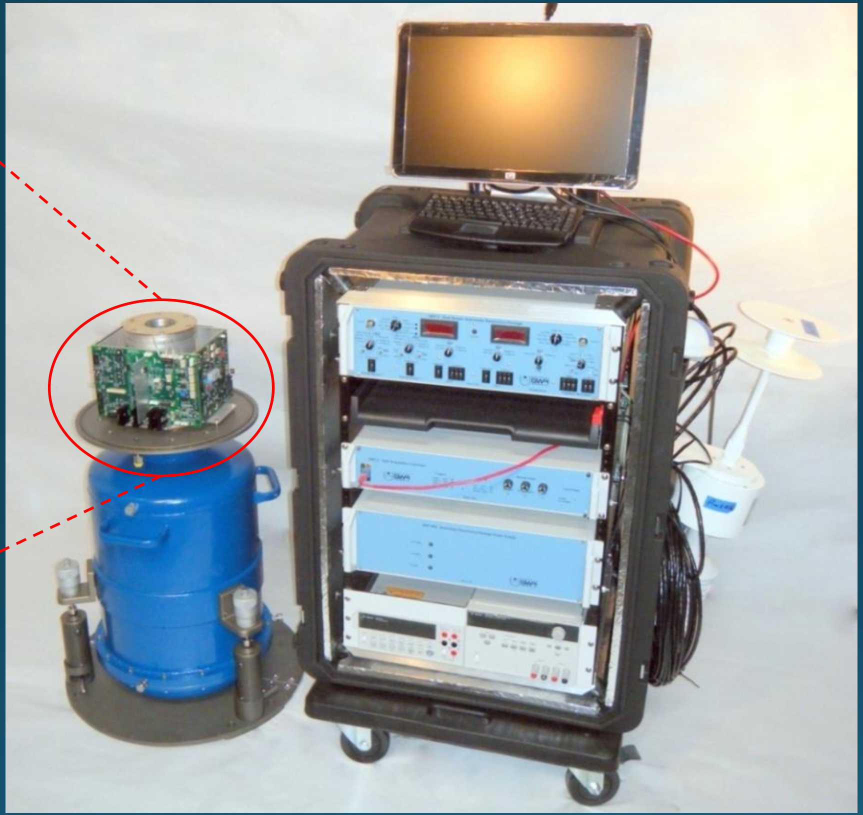
Electronics Comparison: OSG and *i*Grav®





*i*Grav sensor *and* electronics

OSG electronics *alone*

Electronics	*i*Grav®	OSG TREE4
Power (W)	15	250
Voltage (VAC)	28	100-220

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Operating Specification Comparison

Specification	*i*Grav®	OSG
Vibration isolation system		
Weight (kg)	2.3	42.8
Weight with cryocooler cold head installed (kg)	9.5	47.7
Leveling system		
Weight of heavy thermal levelers (kg)	n/a	29.5
Weight of lighter levelers on separate base plate (kg)	8.2	n/a
Cryocooler compressor		
Height x width (cm)	42.8 x 40.6	42.8 x 40.6
Weight (kg)	61.4	61.4
Dewars	*i*Grav	OGD-42
Capacity (liter)	16	42
Height x diameter (cm)	61.0 x 30.5	139.7 x 40.6
Weight (with SG and levelers installed) (kg)	22.7	69.1
Cooldown time with refrigeration only (days)	5	7
Hold time with no cryocooler installed (days)	18	28
Hold time with cryocooler installed but off (days)	10	21
No. of He gas cylinders (10,000 l) to fill Dewar from empty	1.2	3.0

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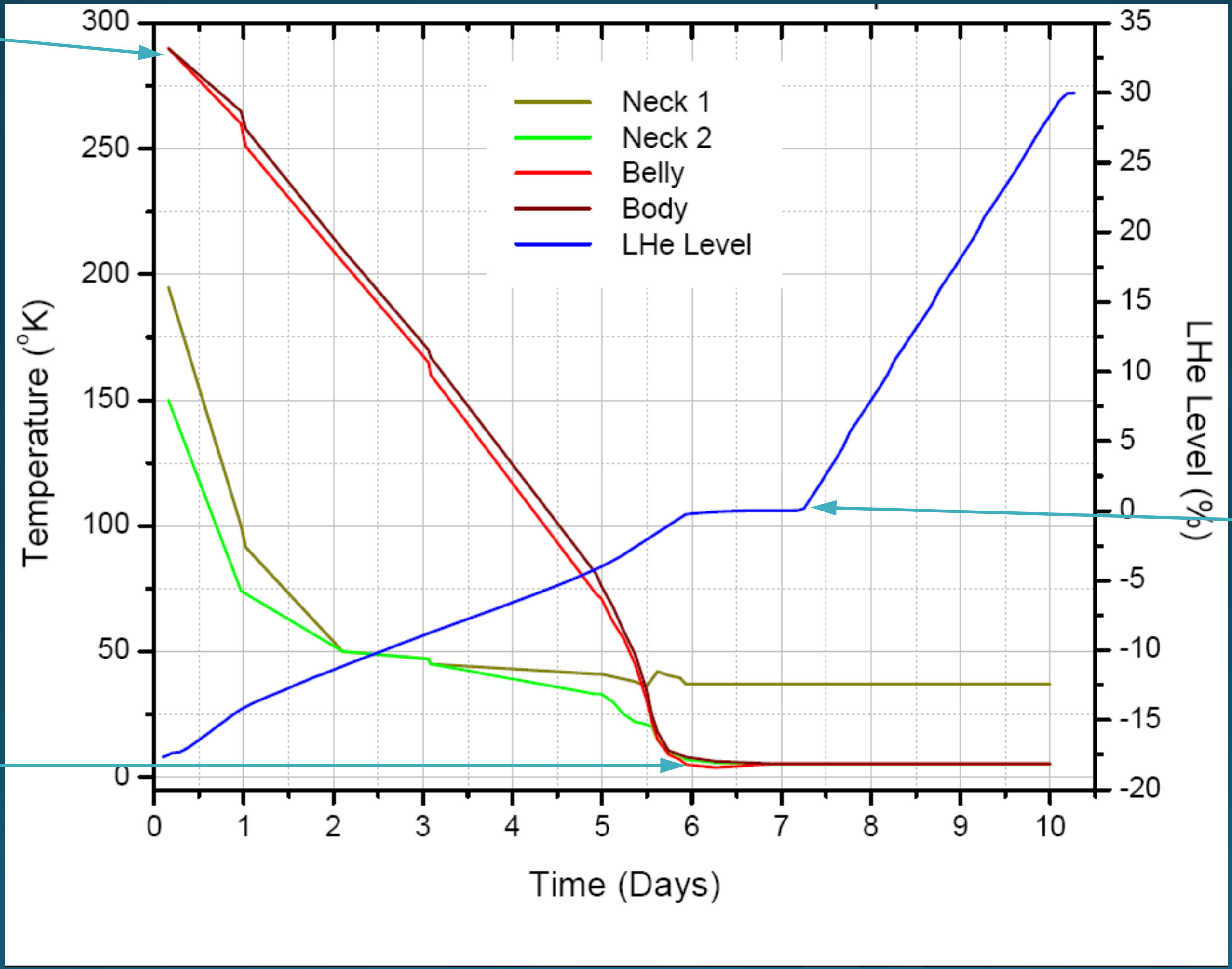
Liquid He-Free Operation

Start at room temp

Apparent negative liquid accumulation is artifact of LHe level sensor at temperatures >4 K

4 K

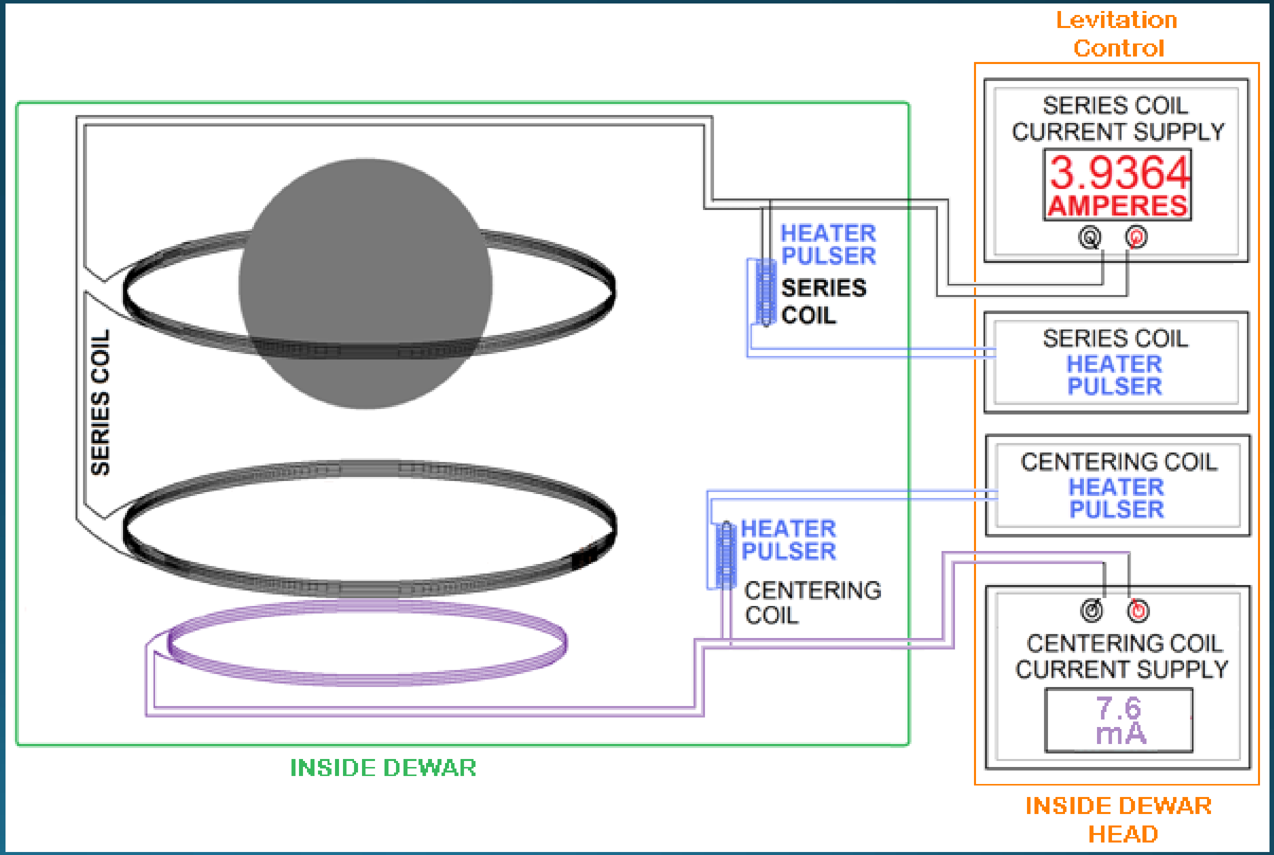


Liquid begins to accumulate; sensor temperature regulation and operation begin

Cooling OSG-60 in 40-liter Dewar using only compressed He gas

Simplified *iGrav*® Test Mass Levitation

- Magnetic gradient set permanently at GWR factory using the turns ratio between Upper and Lower Coils
- Only 2 heat switches needed: (1) series coil heat switch to adjust the current in the series coil, and (2) centering coil heat switch to center the sphere
- Centering the sphere is simple and independent of the series levitation coils; only requires a few mA current
- **Levitation process can be easily learned by new users**



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Revolutionary Transportability of *i*Grav®

Long haul: two *i*Gravs and ancillary materials in a rented panel truck

Short haul: one *i*Grav behind passenger seat in extended-cab pickup truck

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But How Does *i*Grav® Perform?

- Changes yield superior performance at lower cost
    - Smaller initial drift with quicker exponential decay
    - Low linear drifts: ~2-6 μGal/yr (equivalent to the OSG)
- Lack of drift or calibration change in transport: preliminary demonstration
    - Two *i*Grav SGs moved between three locations
        - Initial cooldown in Poway, CA and 4 days' operation
        - 3-day gap
        - Moved to GWR in San Diego, CA for 2.5 days' operation
        - 5-day gap
        - Moved to Tucson, AZ for 6 days' operation
    - Drift rate unchanged at < ~0.1 μGal/day
    - Relative calibrations unchanged at 0.03%

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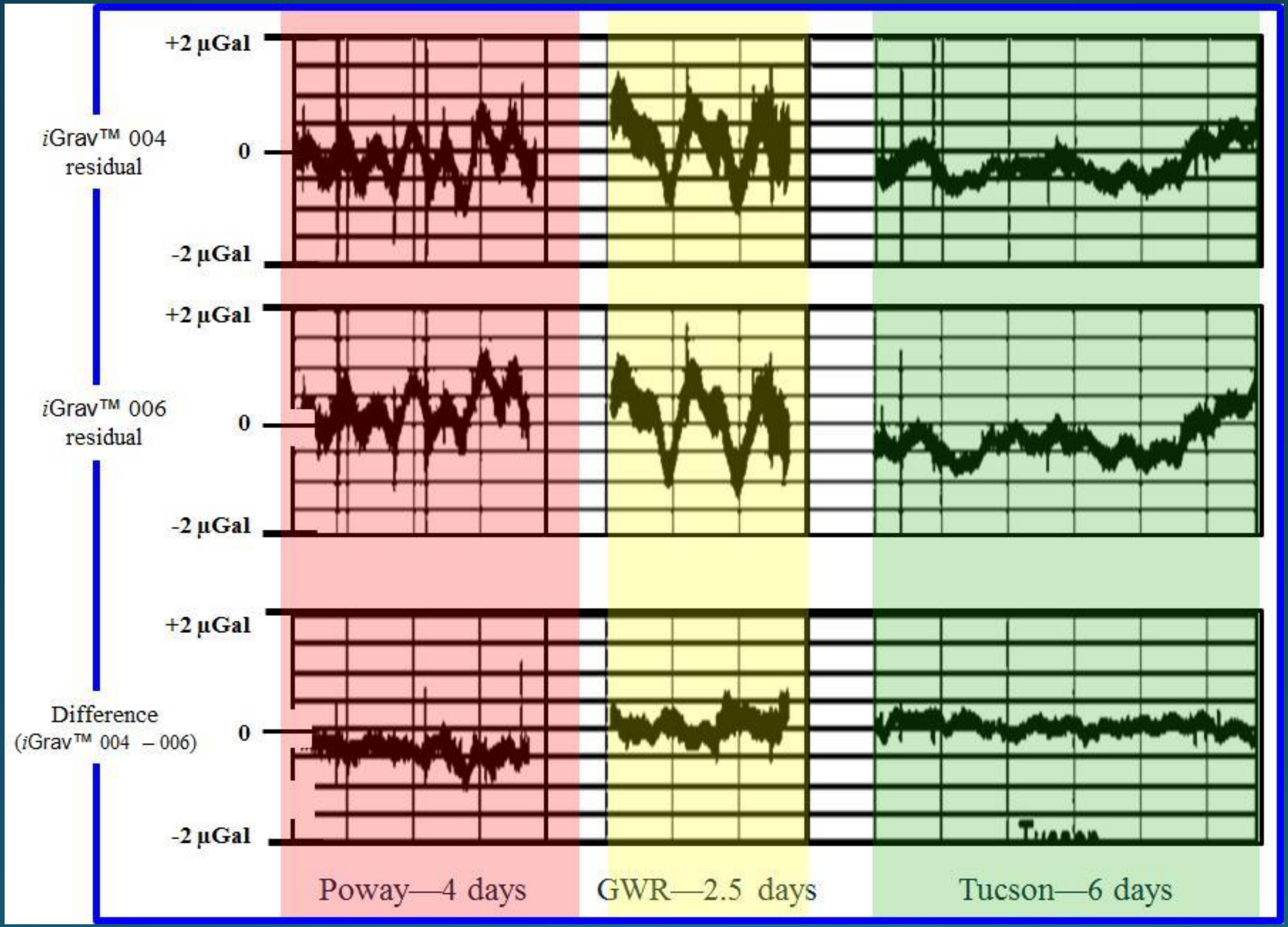
Drift of Two *i*Grav® SGs with Transport

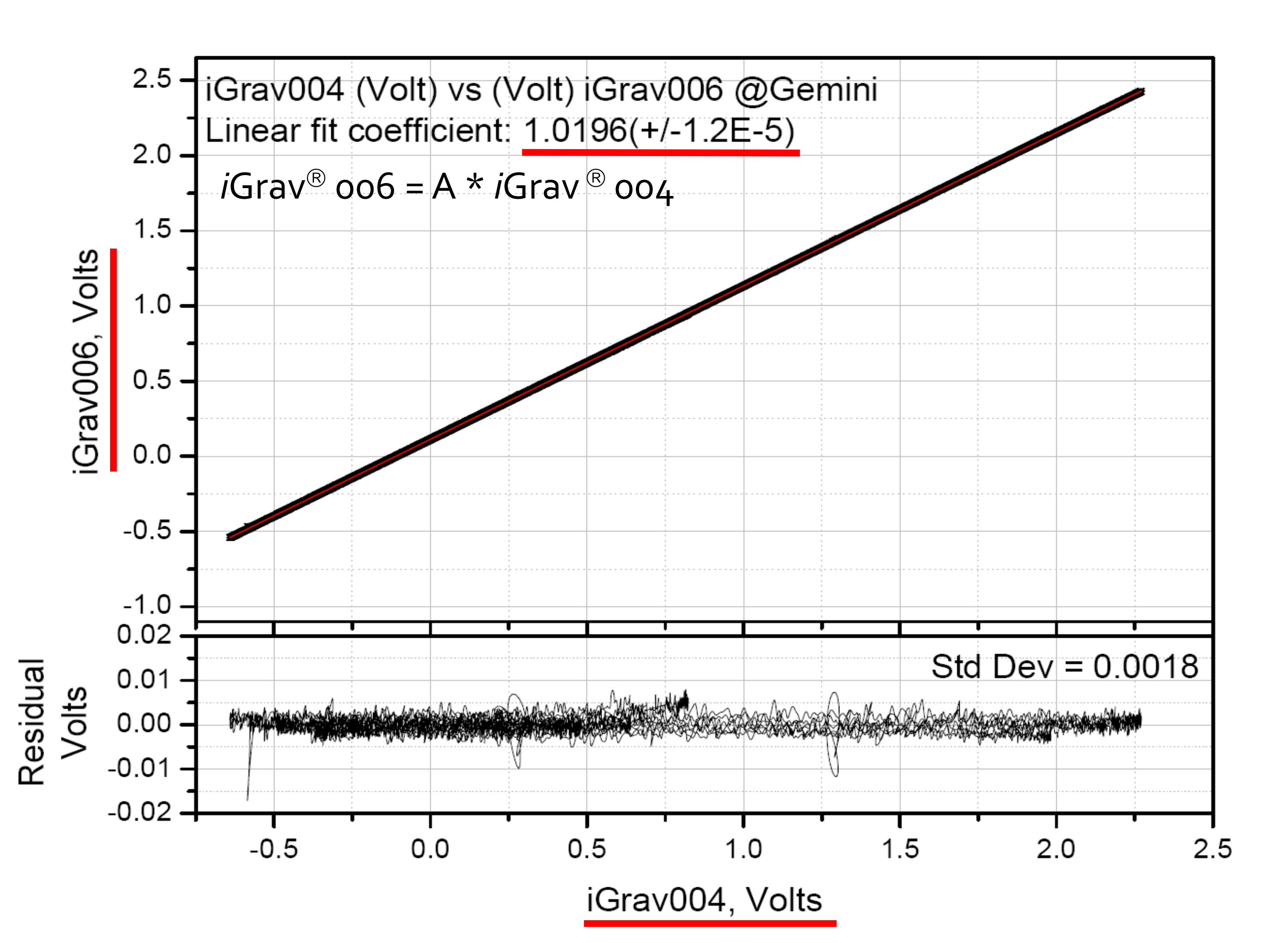


No drifts removed in calculating residuals!

Stability of Relative Calibration

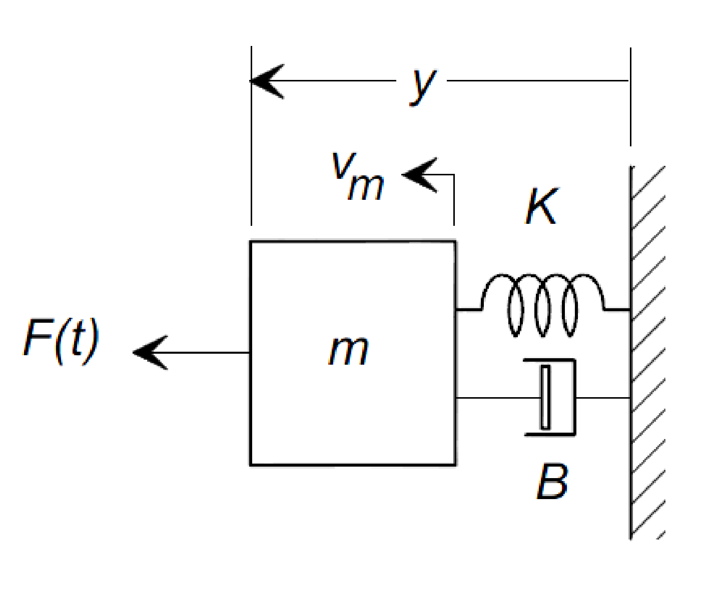
Location	Coefficient
Gemini, Poway, CA	$1.01964 \pm 1.2 \times 10^{-5}$
GWR, San Diego, CA	$1.02023 \pm 5.6 \times 10^{-5}$
SAVSARP, Tucson, AZ	$1.01982 \pm 1.0 \times 10^{-5}$
Mean value	$\mathbf{1.01989 \pm 3.0 \times 10^{-4}}$

Peak-peak variation of relative scale between sites <0.06%



From the Present to the Future

- Can we further reduce the noise of the SG?
  - SG as a damped harmonic oscillator
  - Noise given by $P_A = 4\, k_{Boltzmann}\, T\, (B\, m^{-2})$
    - Increase mass of levitated sphere
      - As long as field at surface of sphere remains << H_C
    - Increase the Q of the sensor by decreasing damping coefficient B



- The *i*Grav®: from 4D to 4C gravimetry
  - Low, stable drift and improved transportability can enable combination of continuous base station and coverage of multiple sites
  - Continuous measurements at multiple locations provide real-time spatio-temporal observation of changing mass distributions

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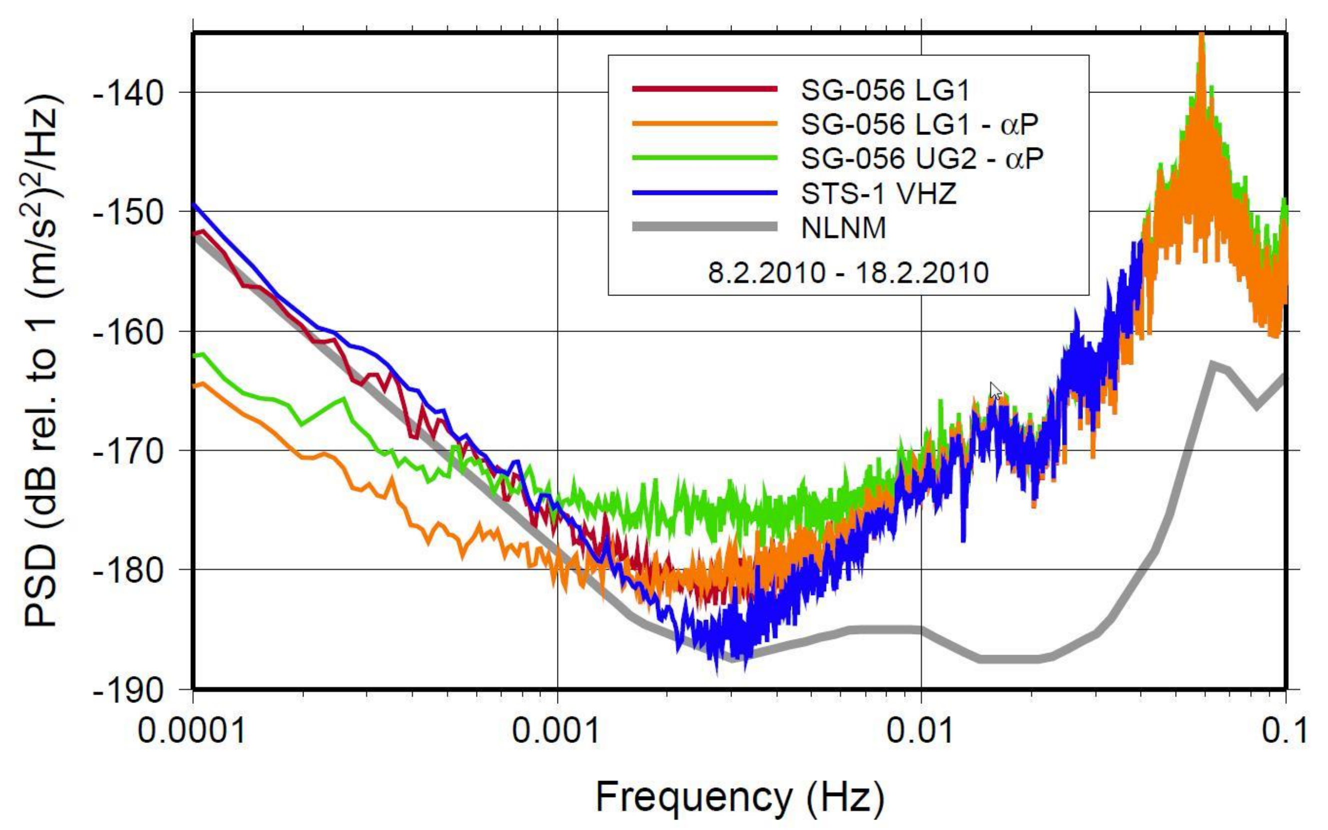
Increased Levitated Mass

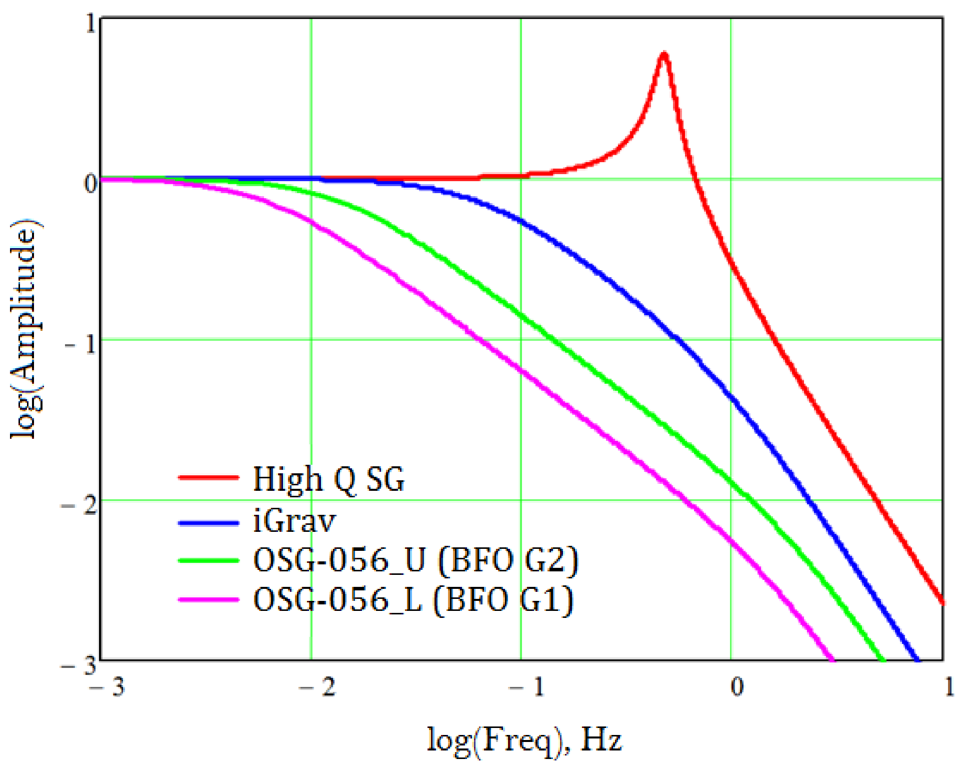
- Dual-sphere OSGs with one standard mass (4-6 g) and one higher mass (17 g)



Comparison of dual sphere OSG with STS-1 seismometer and NLNM: 10 quiet days at Black Forest Observatory, Germany.

Figure courtesy of R. Widmer-Schnidrig

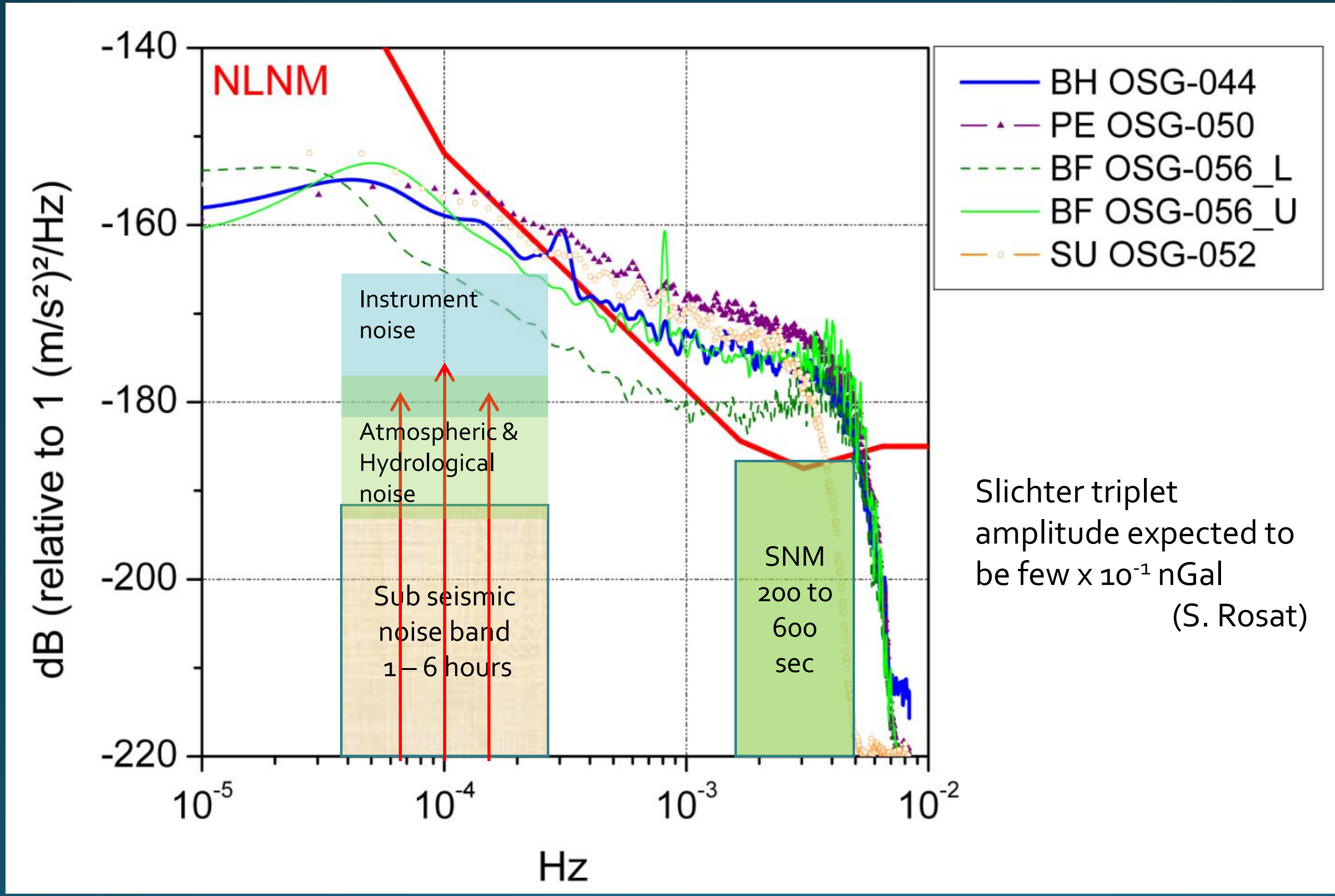
Increasing the Q of the SG



Instrument	Mass of Sphere (grams)	Q (Quality Factor)	ω_0 (Natural Frequency)	b (Damping Factor)	P_a in dB (Noise Factor)
High Q SG	4	6	3	0.0075	-189
High Q SG	18	6	3	0.0075	-202
iGrav™	3.85	0.25	1.5	0.064	-179
BFO OSG-056_U	4.3	0.083	1.06	0.056	-181
BFO OSG-056_L	17.7	0.063	0.63	0.176	-188

Expect High-Q SG noise to decrease by factor of 20 (14 dB) compared to BFO OSG-056_L

Search for the Slichter Triplet



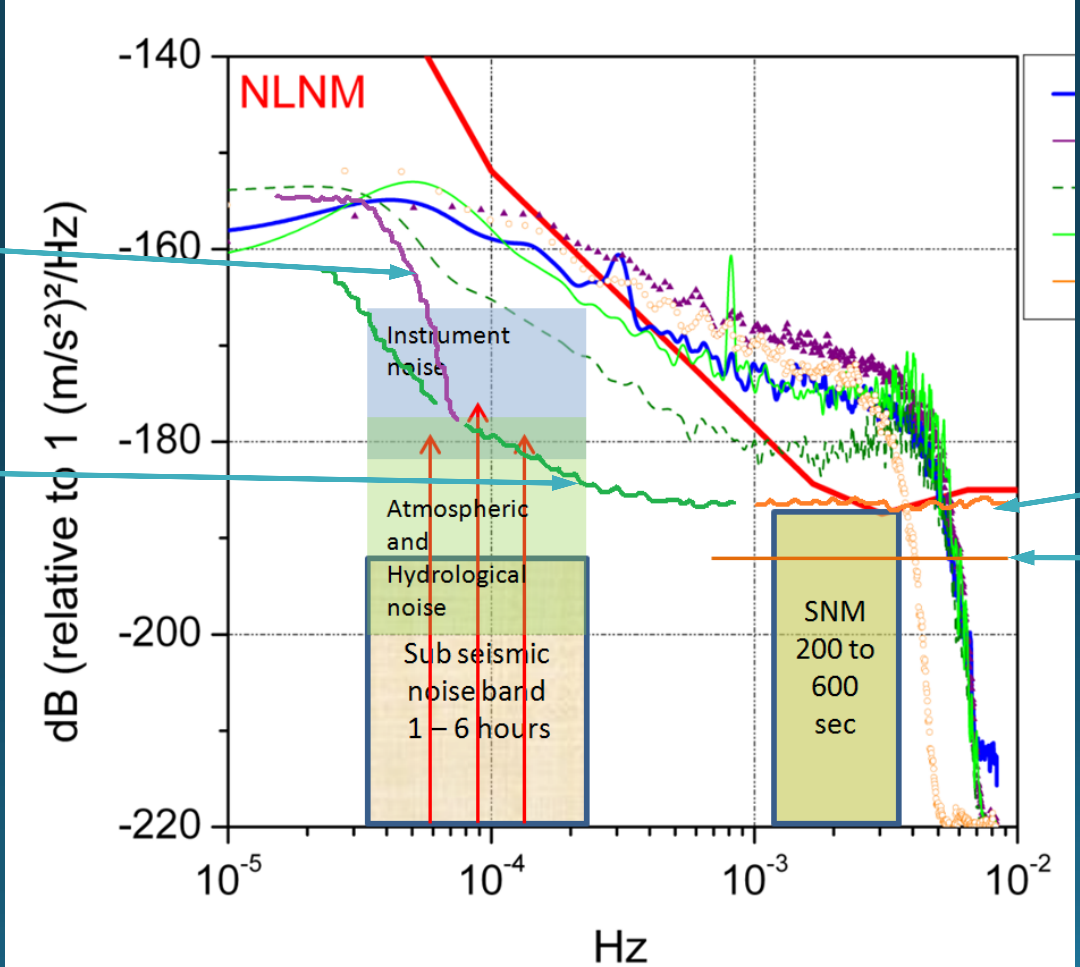
What can be expected of a high-Q SG?

Projected Noise Spectrum of a High-Q SG

- Assume high-Q sensor noise ≅ -195 dB at 1 mHz
- Averaging just a few SGs might capture Slichter modes

Feared excess long-period noise (higher drift) from high-Q sensor

Conjectured spectrum at lower frequencies (artist's conception)



Estimated signal around 1 mHz

Assumed sensor noise at 1 mHz

Increased Mass *and* Higher Q

- BFO dual sensor: fears that higher mass leads to higher drift
    - Because fields on sphere closer to H_C
    - Observed: lower drift than “normal” sphere
- Metsähovi dual sensor: first delivery of a high-mass, high-Q sensor
    - Q ≈ 2-2.5, lower than the 6 imagined earlier
    - Drift is higher than *i*Grav and T020, but still linear
- The *i*OSG™: high-mass, high-Q observatory sensors
    - Lower noise: approach NLNM for 2 mHz < f < 30 mHz
        - Reduce force gradient on sphere to lower resonance below microseisms (from ~0.3 to ~0.1 Hz)
        - Modify feedback board (e.g., to allow user-selectable feedback gain)
    - Linear drift may be unchanged: 2-6 µGal/yr (or a bit more)
    - **Can dispense with the dual-sphere sensor**

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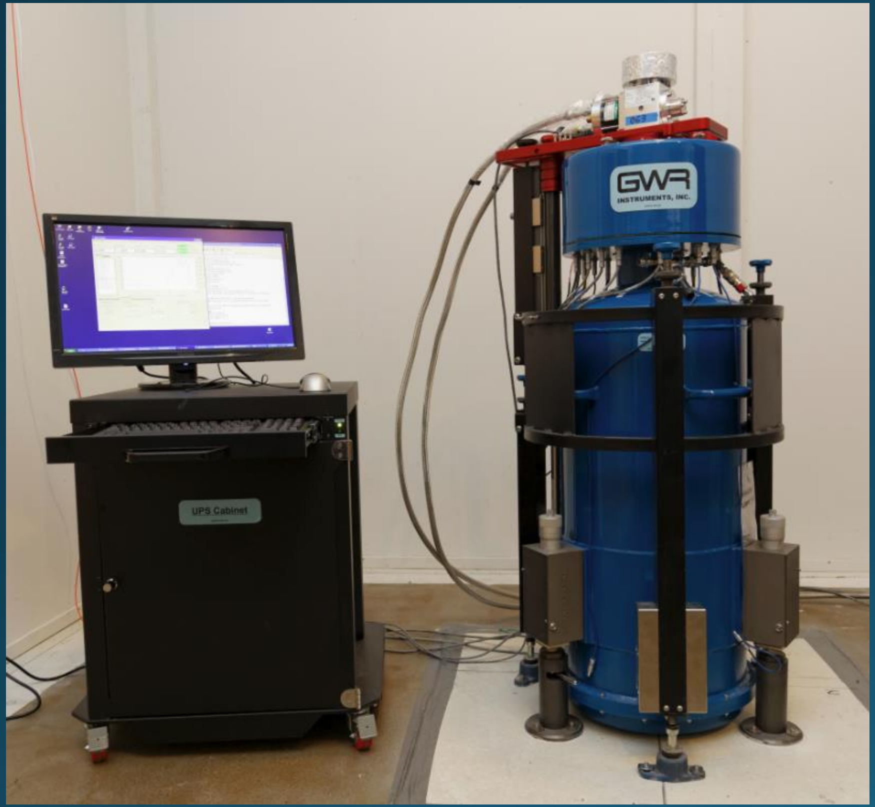
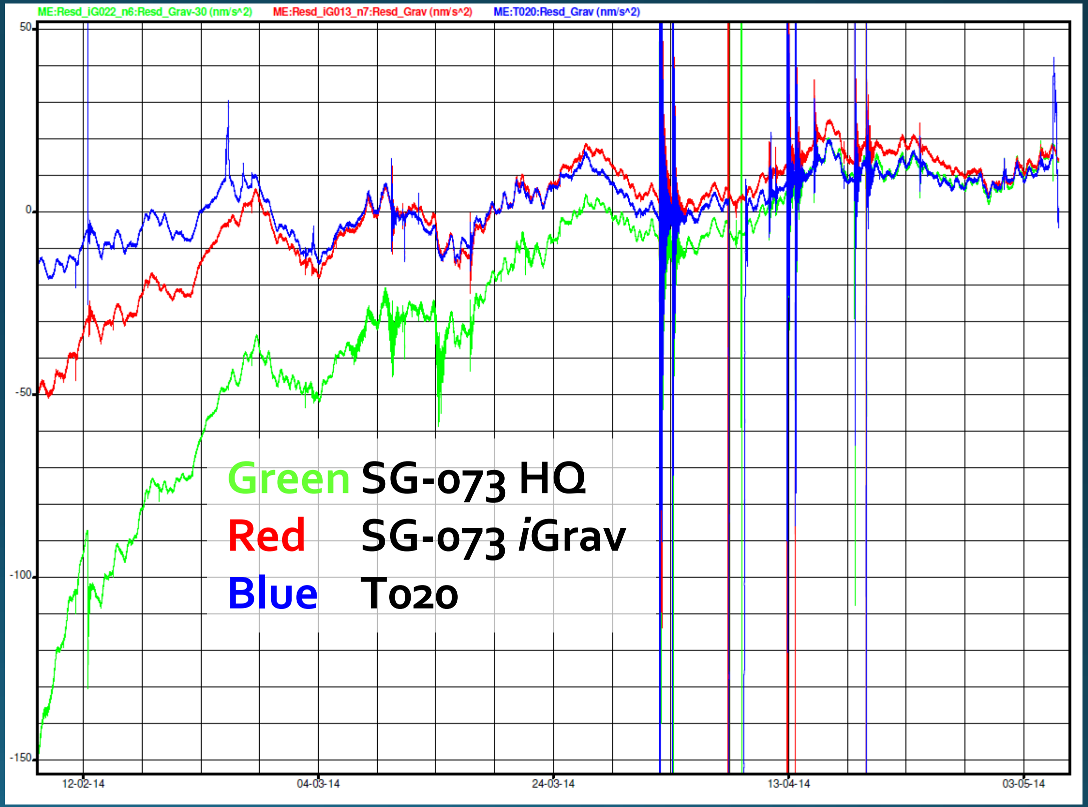
The *i*OSG™: High-Mass, High-Q SG

- First instrument: Metsähovi, Finland



SG-073: side-by-side *i*Grav® and *i*OSG™ sensors in single Dewar



Superconducting gravimeters 08.02. – 05.05. 2014
First 80 days of data
Figure courtesy of H. Virtanen

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4C: 4D *Continuous* Gravimetry

- Enabled by:
  - Stability and transportability of the *i*Grav®
  - Simpler, smaller enclosures for field use
- Southern Avra Valley Storage and Recharge Project (SAVSARP), Tucson, AZ

Reference: B. Creutzfeldt *et al.*, *J. Geophys. Res.* **117**: D08112 (2012).

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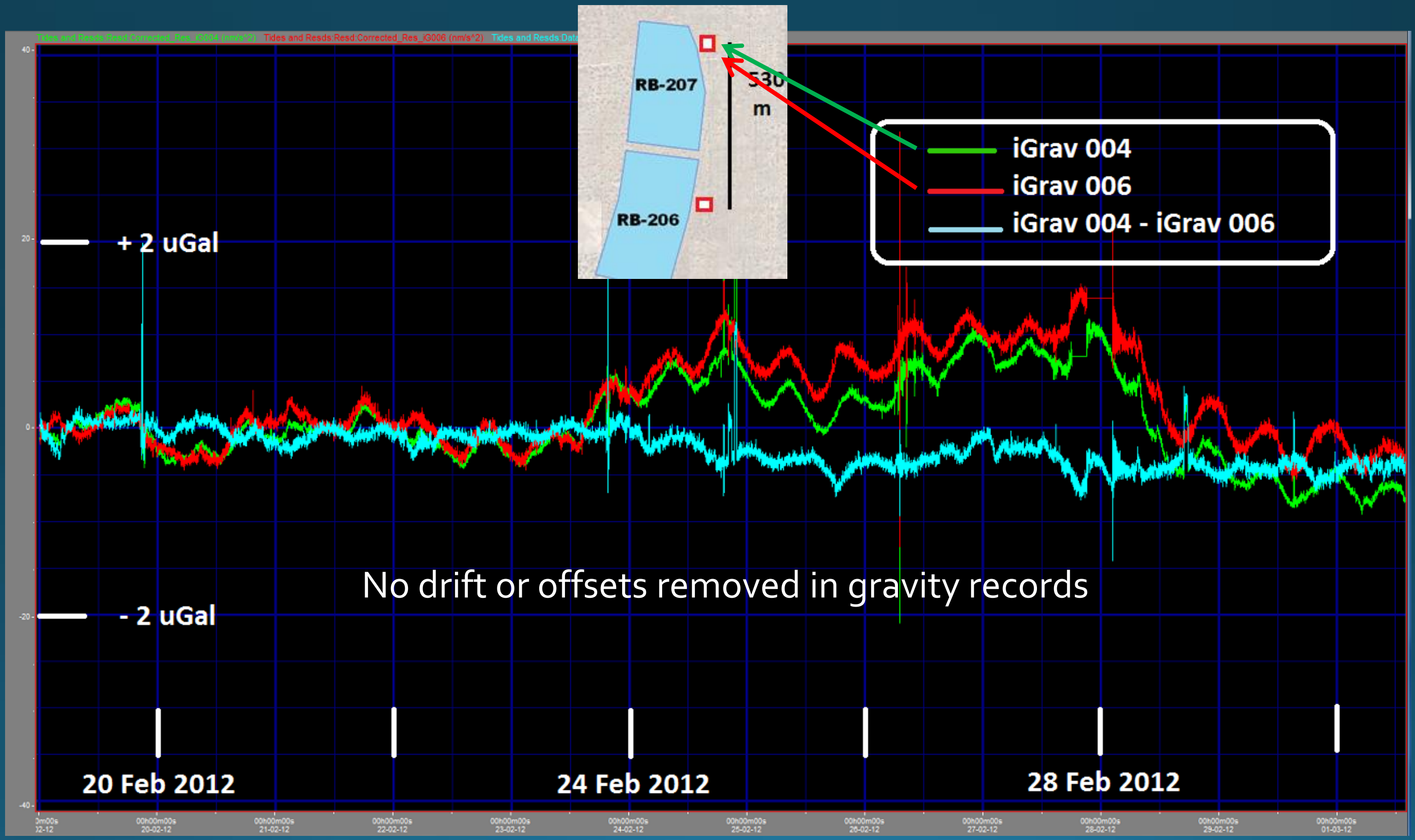
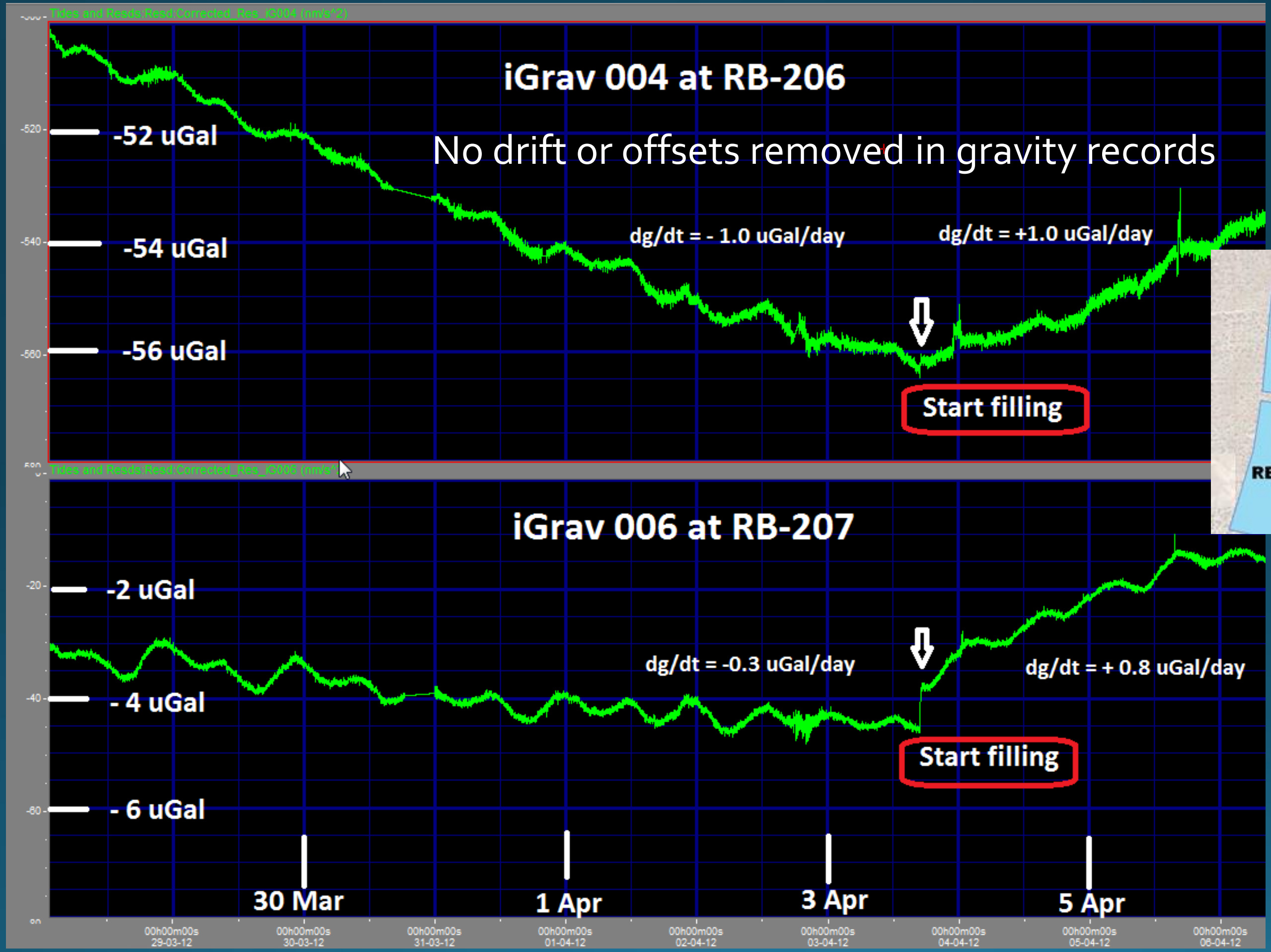
Water Storage Basins Initially Dry

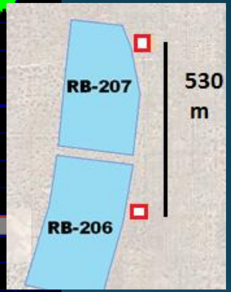
- *iGrav*® SGs 004 and 006 first run side by side next to Basin RB-207



*i*Grav® 004 Moved to Basin RB-206

- Water then allowed to flow into basins





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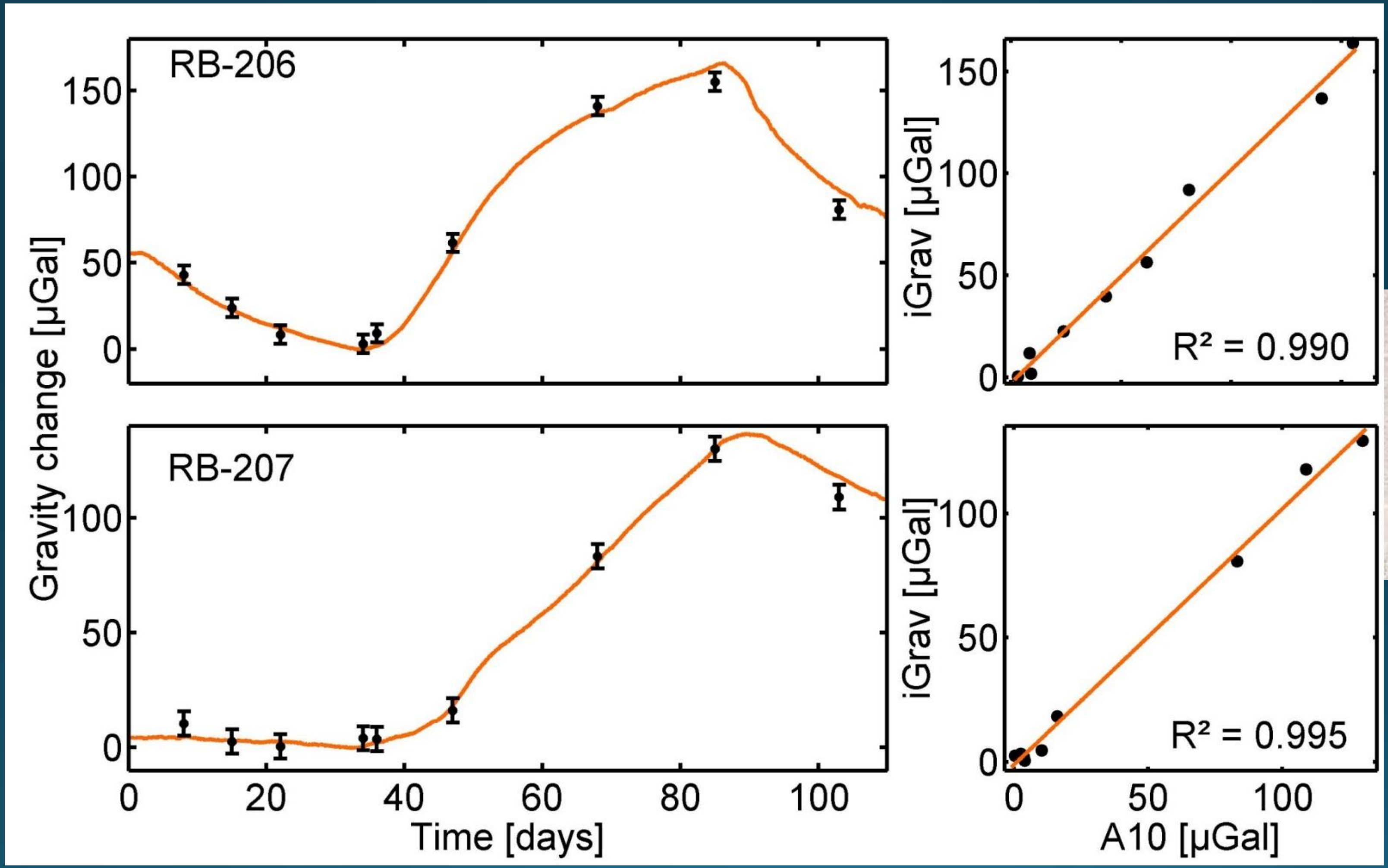
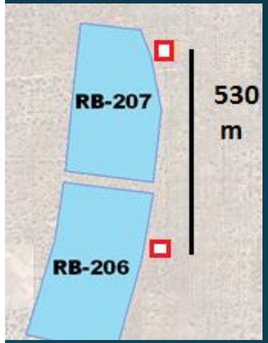
Excellent *i*Grav® Agreement with AG Data





Reference: B. Creutzfeldt *et al.*, AGU Fall Meeting (2012).

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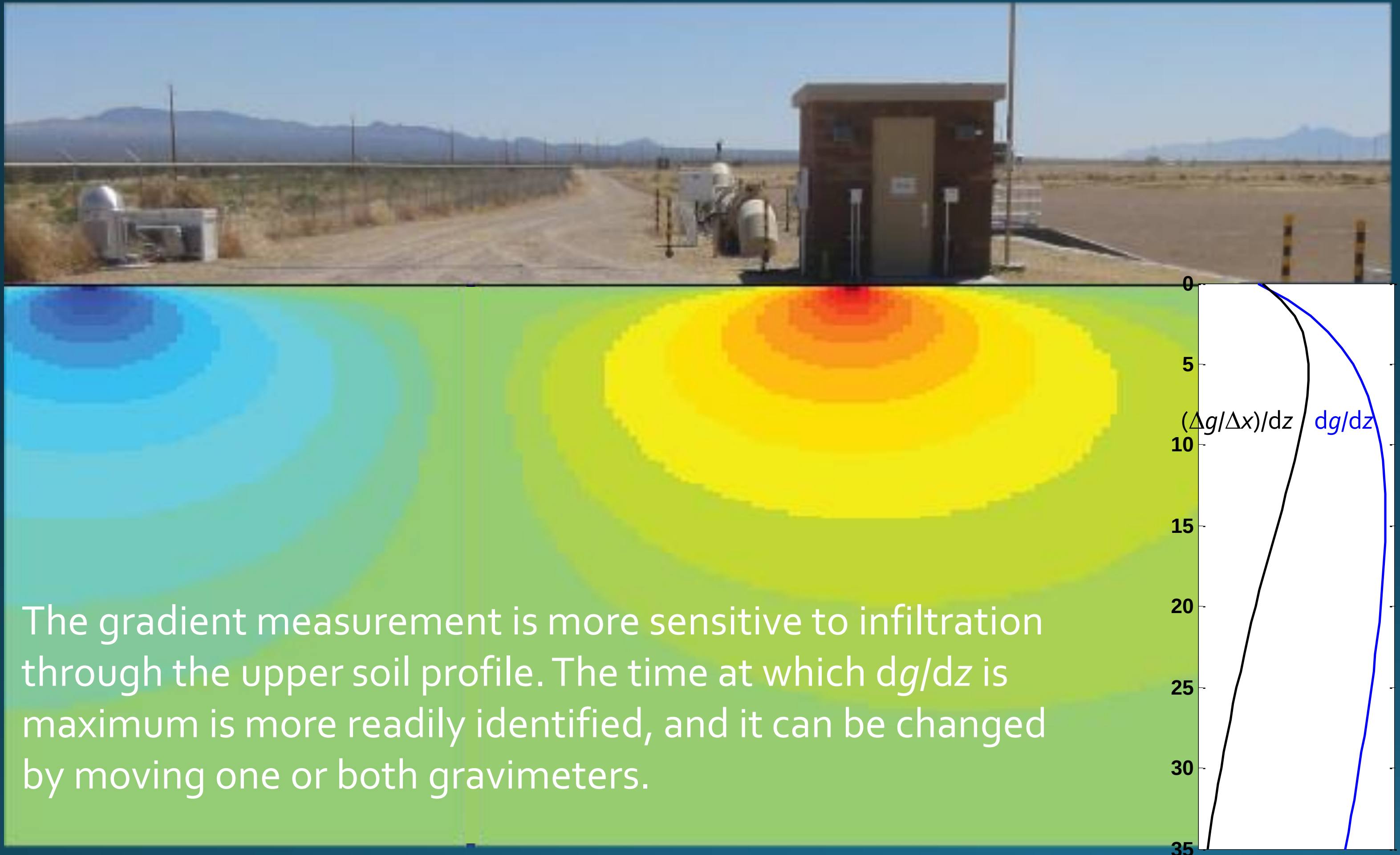
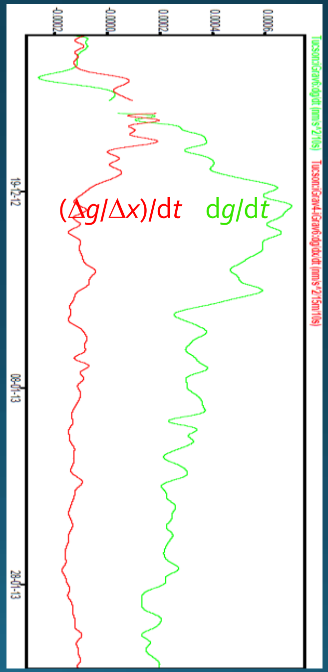
Two Gravimeters at SAVSARP



The gradient measurement is more sensitive to infiltration through the upper soil profile. The time at which d*g*/dz is maximum is more readily identified, and it can be changed by moving one or both gravimeters.

- Modeled effect of wetting front propagation into soil at constant rate
- Observed d*g*/dt and (Δ*g*/Δ*x*)/dt approximately agree with modeled d*g*/dz and (Δ*g*/Δ*x*)/dz



- Measured Δ*g*/Δ*x* as high as 150 nm/s² over 15 m (= 10 Eö)
- Accurate Δ(d*g*/dt) measurement of 1 μGal/day, over 3 days
- Time scale: 20 days per division

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Reference: J. Kennedy *et al.*, *Geophys. Res. Lett.* **41**, doi:10.1002/2014GL059673 (2014).

4C: Truly Continuous 4D Gravimetry

- SAVSARP and other projects confirm utility of *i*Grav® SGs for horizontal differential gravimetry
- Further reduction in sensor and Dewar size opens up borehole (vertical differential) gravimetry
    - *i*Grav already fits existing large-diameter boreholes
    - Cryocooler demonstrated with >100 m cables, so only the sensor need be lowered
- Vertical differential gravimetry gives exquisite resolution of near-surface hydrological phenomena
    - Also useful for monitoring CO_2 sequestration, water displacement

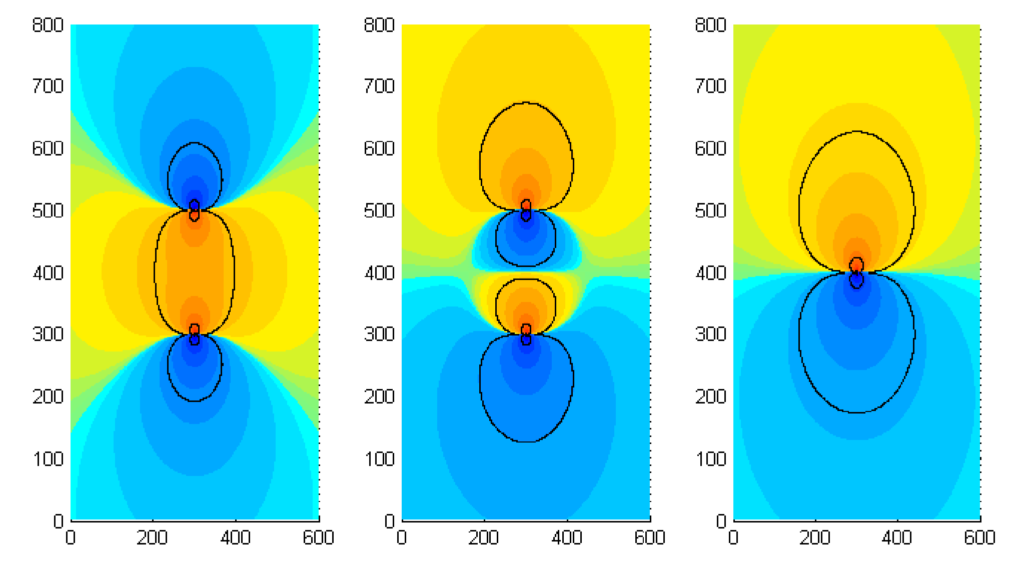

Figure courtesy of J. Kennedy

vertical difference vertical sum single gravimeter

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Further into the Future

- Steady improvements in SG performance enable new applications
- Steady reductions in size, cost and complexity remove barriers
- Further noise reduction – *i*OSG™ development – in progress
  - Enable new observatory measurements elucidating Earth structure and dynamics
- *i*Grav® transportability and stability enable 4C gravimetry
  - New insights into hydrology, volcanism, and other localized processes
  - Small, simple enclosures reduce cost of SG 4C gravimetry
  - *i*Grav not far from ready for shallow borehole applications

Many thanks to GWR's customers and colleagues!

Thank you for your attention!

GWR INSTRUMENTS, INC.