KBTM

Kibble Balance Considerations for Mass and Gravity

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Kibble Balance Technical Meeting special session “knowledge transfer”
20 November 2025, BIPM

Introduction

1. **Mass:**
    a. Process for disseminating mass from the Kibble Balance
    b. Transfer mass selection
    c. Considerations for vacuum to vacuum transfer
    d. Vacuum to air transfer

2. **Gravity:**
    a. Absolute and Relative Gravimetry
    b. Tide Models
    c. Gravity Transfer

Realization of a Mass value

How do we ensure the mass realized in the balance is the same as the one disseminated out to the world?

Three Steps to mass dissemination from a Kibble Balance

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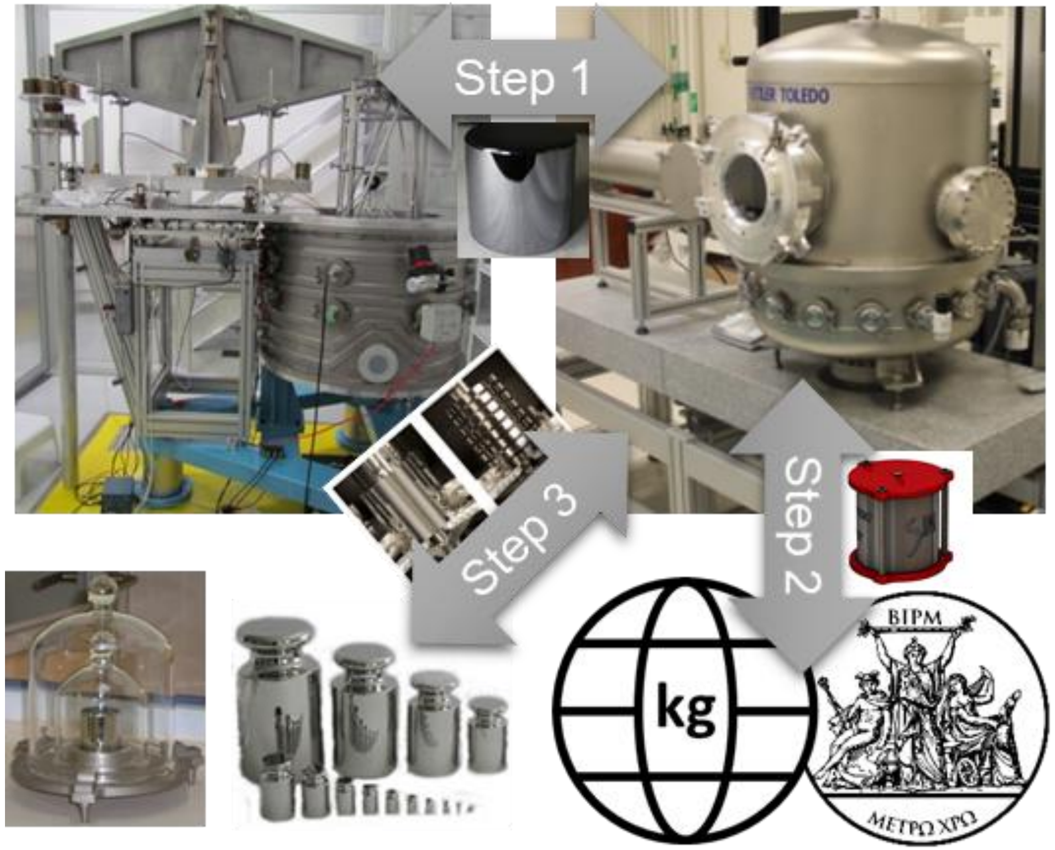

1. **Realization of the mass of a transfer standard using the Kibble balance**
2. **Transfer standard is used to calibrate traveling standard for participation in ongoing key comparison for CV-kg**

And/Or

3. **The value of the transfer standard is disseminated from vacuum to air to calibrate national standards that maintain the mass unit at NRC between realizations.**

STEP 1: Considerations for KB mass artefacts

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- **Mass changes mostly occur through surface mediated processes**
  - **Adsorption/Desorption**
  - **Particle contamination/wear**

  Consider low surface area→ Higher density, lower roughness

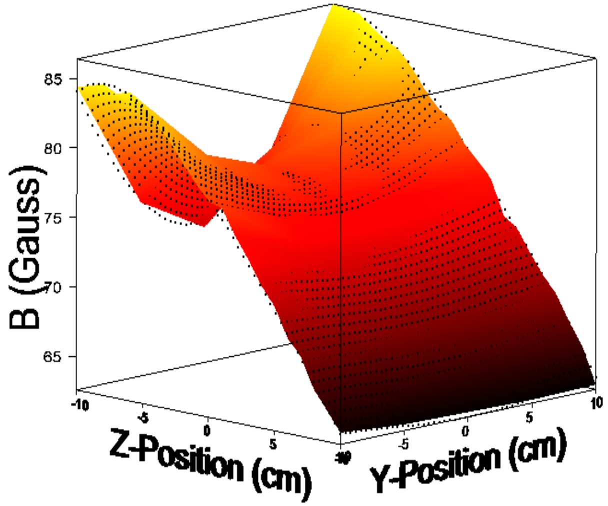
- **Shape: Surface area is minimized for spheres, and when h=d for cylinders, centre of mass is easy to determine**
- **Is the residual magnetic field at the balance pan significant?**

  Consider material magnetic susceptibility requirements

- **At low residual field: Can use stainless steel or platinum iridium**
- **At higher fields: low susceptibility materials should be used: copper, tungsten (+low SA, +hard), silicon (-high SA)**

Step 1) Magnetic properties

KB residual field



The magnetic force is dependent on the KB residual field profile, the mass shape, and its magnetic susceptibility.

For NRC, the mass pan can be positioned so as to minimize these corrections

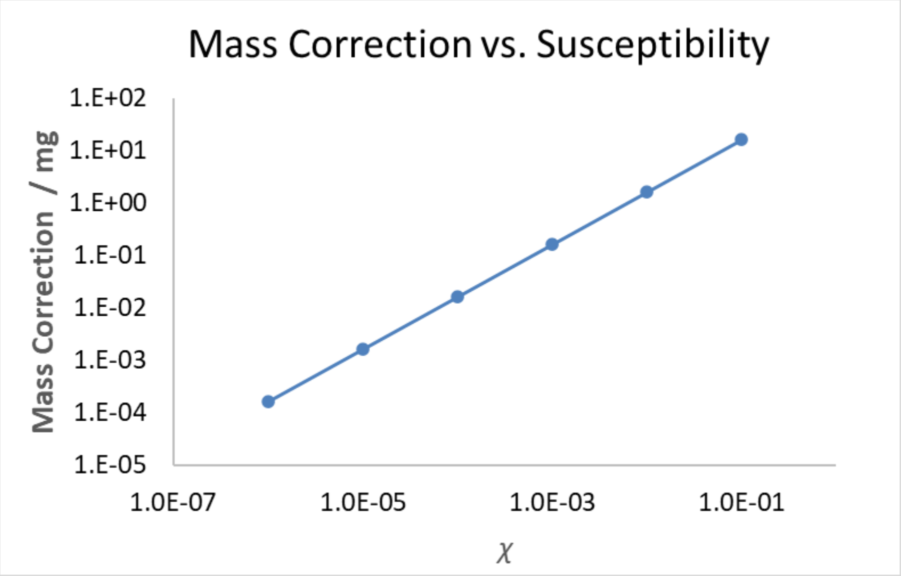
The residual field at the mass pan should be known

$$F_z = \frac{\chi}{\mu_o} B_o^2 \, \pi \left[\left(1 + f_1 h + f_2 h^2\right)^2 - 1 \right] \frac{1}{6 g_2} \left[\left(1 + g_2 r^2\right)^3 - 1 \right]$$

Or approximately

$$F_z = \frac{\chi}{2\mu_o} \pi r^2 \left[B^2(z = h) - B^2(0) \right]$$

h=d=52 mm



Step 1) Vacuum Balance

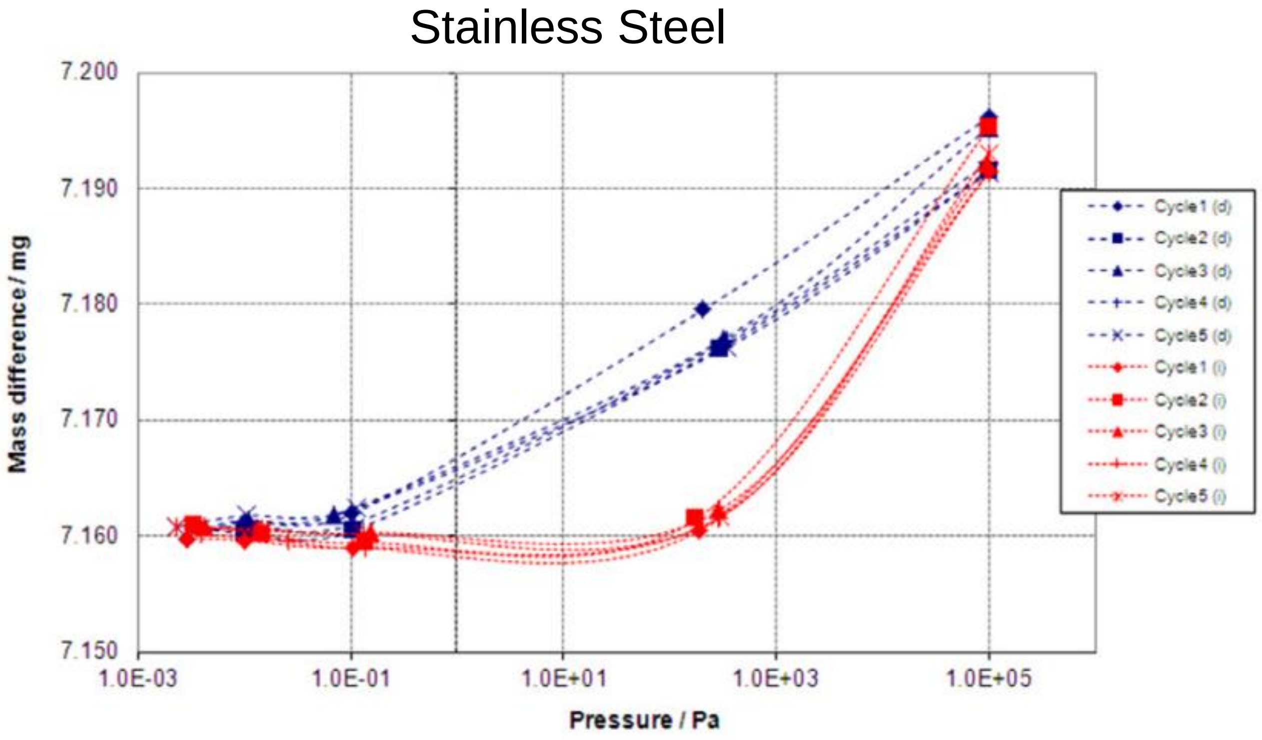
- 1 kg Mass comparator
- 0.1 µg resolution
- Typical comparison weighing uncertainty is 3 µg or less (1 kg)

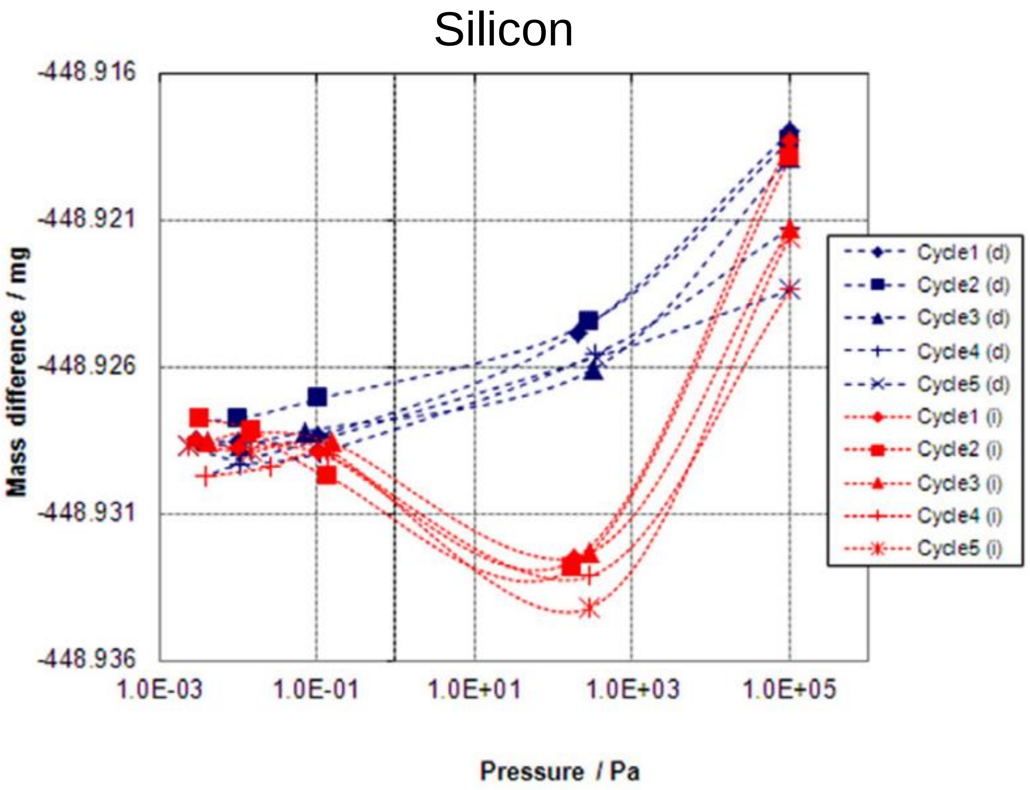
- Operation at constant pressure from 10^{-6} mBar to 1000 mBar
- Used for transferring mass value between vacuum and air

Mettler Toledo Mone

Sartorius CCL1007

Step 1) Mass in Vacuum: Pressure dependence



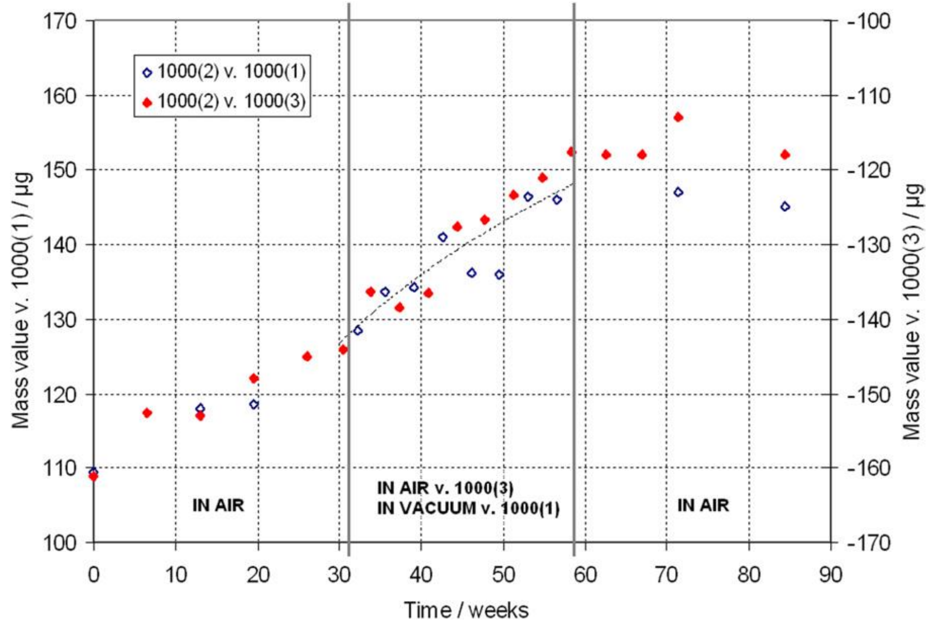


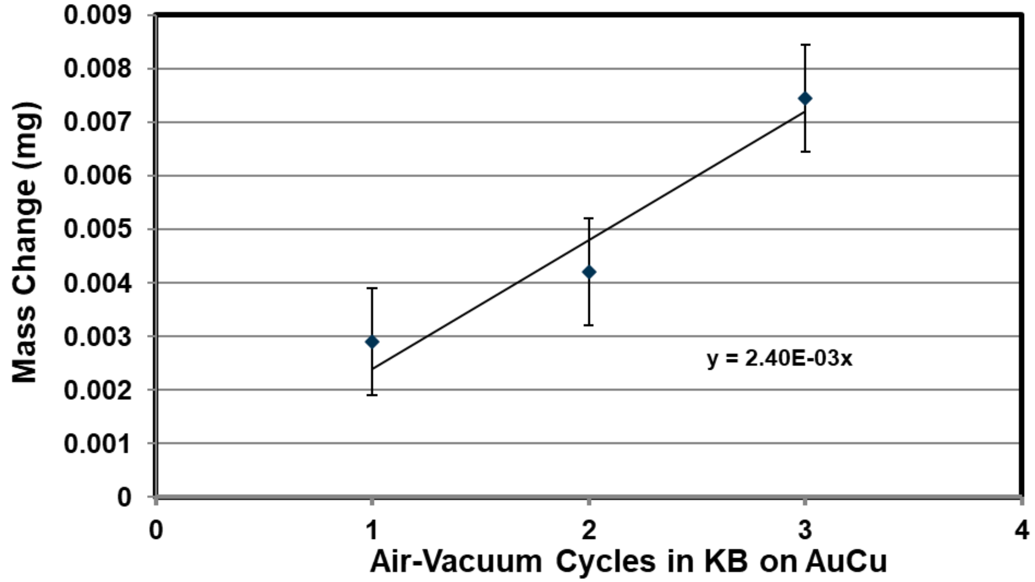
Sorption is typically repeatable between atmospheric pressure and less than 0.1 Pa. Within the same vacuum environments.

James Berry and Stuart Davidson 2014 *Metrologia* **51** S107

Step 1) Mass cycling (Vacuum-Air-Vacuum)

Stuart Davidson 2010 *Metrologia* **47** 487

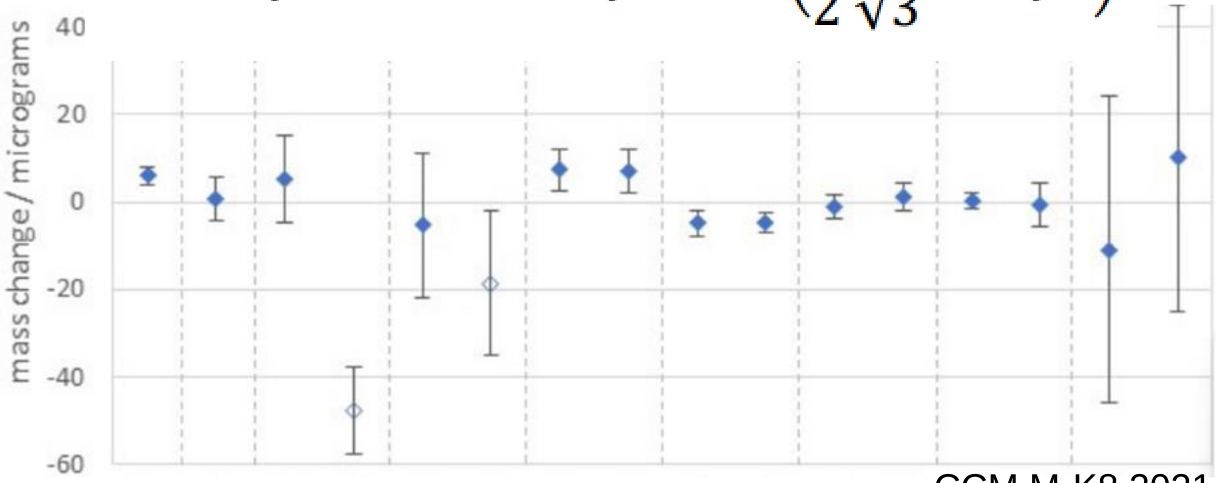




- Cycling in different environments can sometimes cause mass changes
- Typical maximum changes ~2-3 ug per cycle
- Compare to stable masses stored in vacuum before and after realization to track any changes

Step 2) Transport (Vacuum-Air-Vacuum)x2

$$\left(u_{\text{stab},i,j}^{\text{NMI}}\right)^2 = u\left(\Delta m_{i,j}^{\text{NMI}}\right)^2 + \left(\frac{1}{2\sqrt{3}}\Delta m_{i,j}^{\text{NMI}}\right)^2$$



CCM.M-K8.2021

- **Multiple different traveling enclosures were used before settling on a hermetic design which has resulted in highest mass stability during transport**
- **Travel stability less than 2 µg regularly achieved.**

Step 3) Vacuum to Air Transfer Sorption Artefacts

Disks	Integral
Surface area	125 cm^2
Ratio	1
Water Res.	0

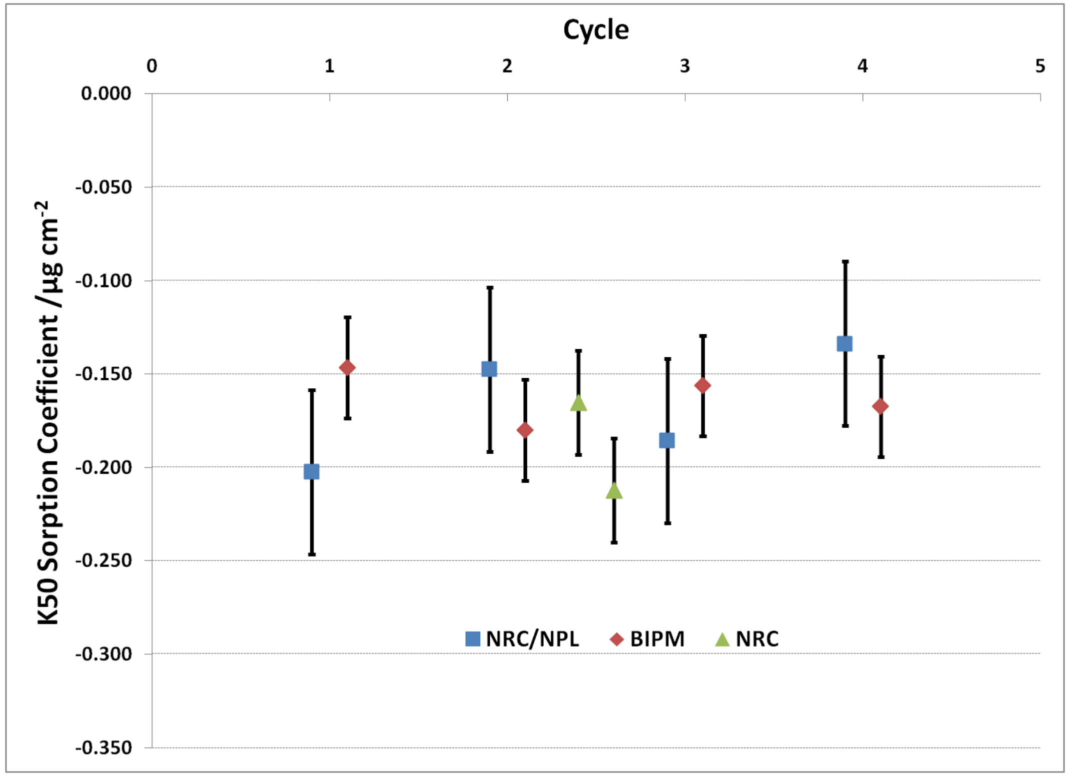
10 Stack
563 cm^2
4.5:1
0.01 ML

20 Stack
1262 cm^2
10:1
0.0003 ML

1 ML~ 0.3 ug/cm^2

- Measure the mass difference of the pair in air and vacuum
- The sensitivity increases with ΔSA,

Step 3) Surface equivalency



$$s = \frac{\Delta m_{\mathrm{vac}} - \Delta m_{\mathrm{air}}}{A_{\mathrm{stk}} - A_{\mathrm{int}}}$$

Sorption on PtIr artefact as determined by 3 sets of sorption artefacts over several years and laboratories

Step 3) Sorption Values

Author(s)	Material	Surface roughness (Rz)[b] (nm)	Sorption Value (µg cm^{-2})	Pressure (P)a	Time between cleaning and measurement
Schwartz [12]	Stainless steel	120	−0.030[a]	0.1	<8 months
Schwartz [12]	Stainless steel (uncleaned)	120	−0.076[a]	0.1	—
Picard and Fang [13]	PtIr	10–100	−0.080	0.1	<1 month
Picard and Fang [13]	Silicon	<10	−0.030	0.1	<1 month
Picard and Fang [13]	Stainless steel	10	−0.040	0.1	<1 month
Davidson [14]	PtIr	10	−0.162	10^{-4}	<6 months
Davidson [14]	Stainless steel	60	−0.154	10^{-4}	<6 months
Berry *et al* [15]	Stainless steel	60	−0.13 to −0.25	$0.05–10^{-4}$	<3 years
Mizushima *et al* [16]	PtIr	5–25	−0.013	$0.1–10^{-3}$	<1 year
Berry and Davidson [17]	PtIr	10	−0.070	$0.1–10^{-3}$	<5 years
Berry and Davidson [17]	Silicon	<10	−0.050	$0.1–10^{-3}$	<5 years
Sanchez *et al* [5]	PtIr	10–100	−0.162	$0.1–10^{-3}$	>20 years

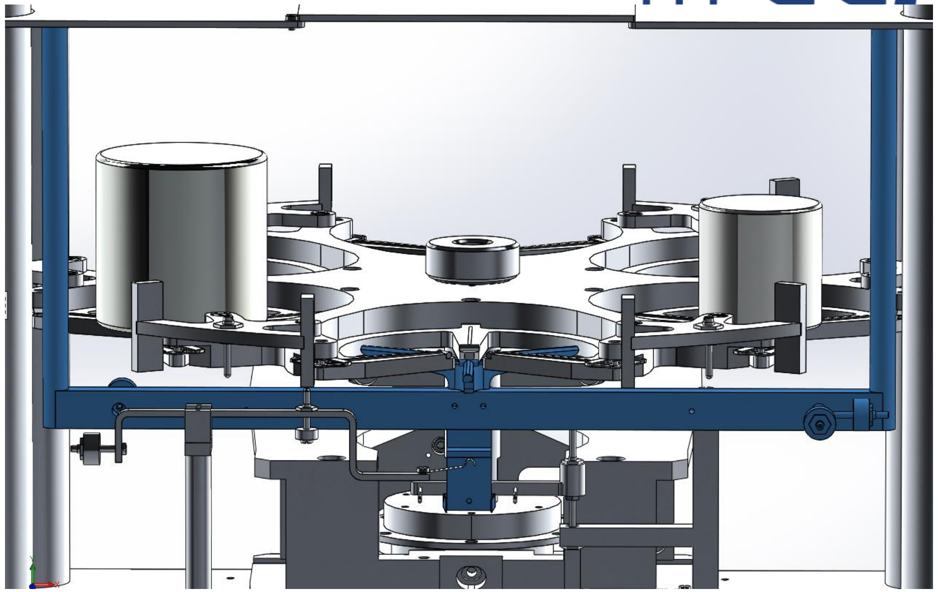
[a]Corrected to 50% RH using equations (1) and (2) in [18].
[b]Surface roughness values are indicative and may have been converted to Rz from Ra or RMS values.

Metrologia **53 (2016) A95**

- **Sorption values depend on surface area, cleanliness, roughness, surgace and environmental chemistry**
- **Without measurement, 1 kg PtIr cylinder can be assumed to have a sorption correction of approximately 8 µg +/- 7 µg to span the range of reported values.**

Step3) Dissemination to Air

$$M_t \approx d + \rho_a \Delta V_{t-r} + M_r(1+(\Delta g_{t-r}/g))$$

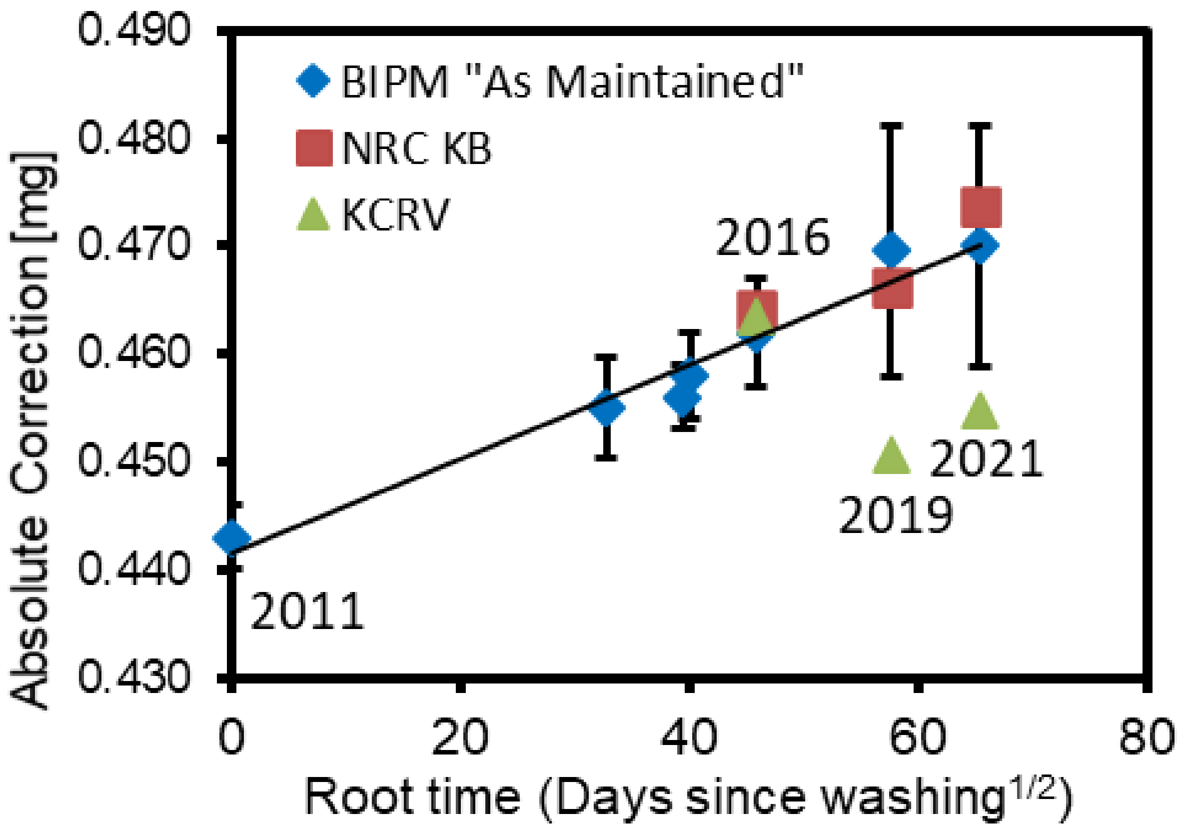


- **Once in a vacuum comparator, sorption artefacts can used to transfer the realized value to any type of mass in air:**
- Compare the realized mass to sorption artefacts in vacuum, then the same sorption artefact to a stored mass in air

A large buoyancy correction can be replaced by a small sorption correction

Eg. PtIr-SS Buoyancy correction is 98 mg u~9.8 ug→ 12 ug u=2 ug

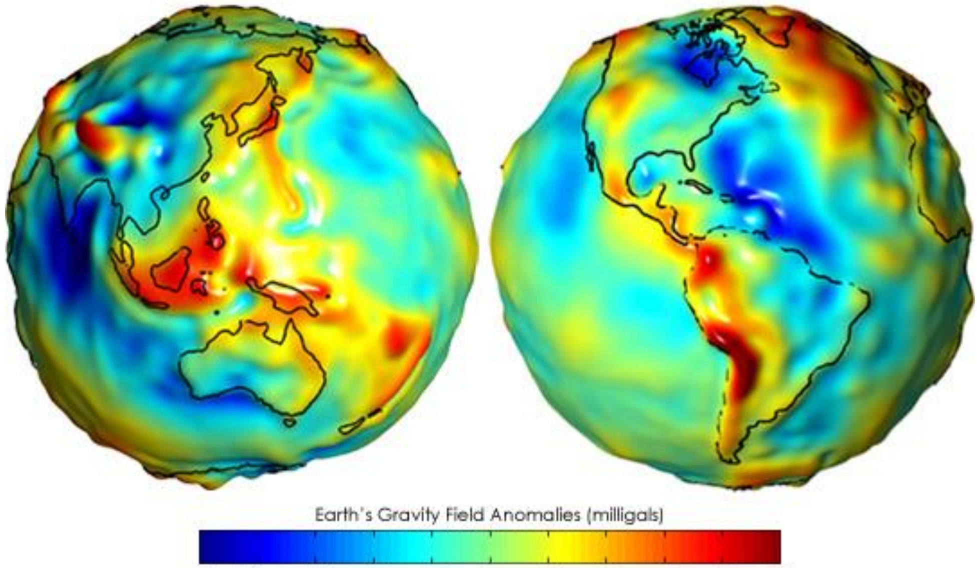
Canadian National Standard since 2011



Predictable physical drift, can be used to store the realized value

Can be disseminated through traditional mass methods

Gravity



NASA/Goddard Space Flight Center Scientific Visualization Studio

Kibble Equation

$$mg = \frac{IV_c}{v}$$

$$g = G\frac{M_\oplus}{r^2}$$

Universal Gravity

$$F = G\frac{m_1 m_2}{r^2}$$

$$g = G\frac{M_\oplus}{r^2} = 6.67 \times 10^{-11}\ \mathrm{m^3{\cdot}kg^{-1}{\cdot}s^{-2}} \times \frac{5.98 \times 10^{24}\ \mathrm{kg}}{(6.38 \times 10^6\ \mathrm{m})^2} \approx 9.8\ \mathrm{m{\cdot}s^{-2}}$$

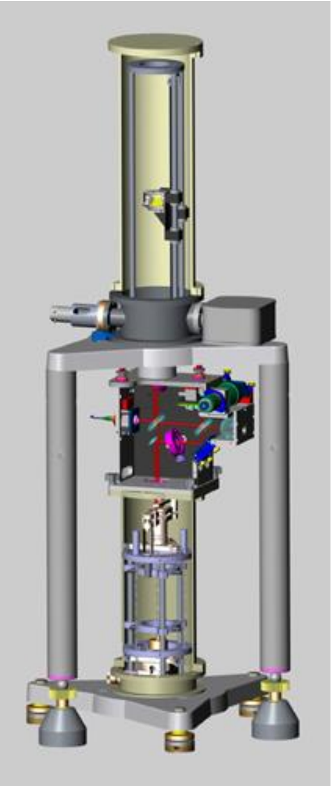
- **Gravitation is a fundamental interaction, which for our purposes (Newtonian) scales the force of attraction between massive bodies.**
- **Earths gravity varies globally ~100 mGal**

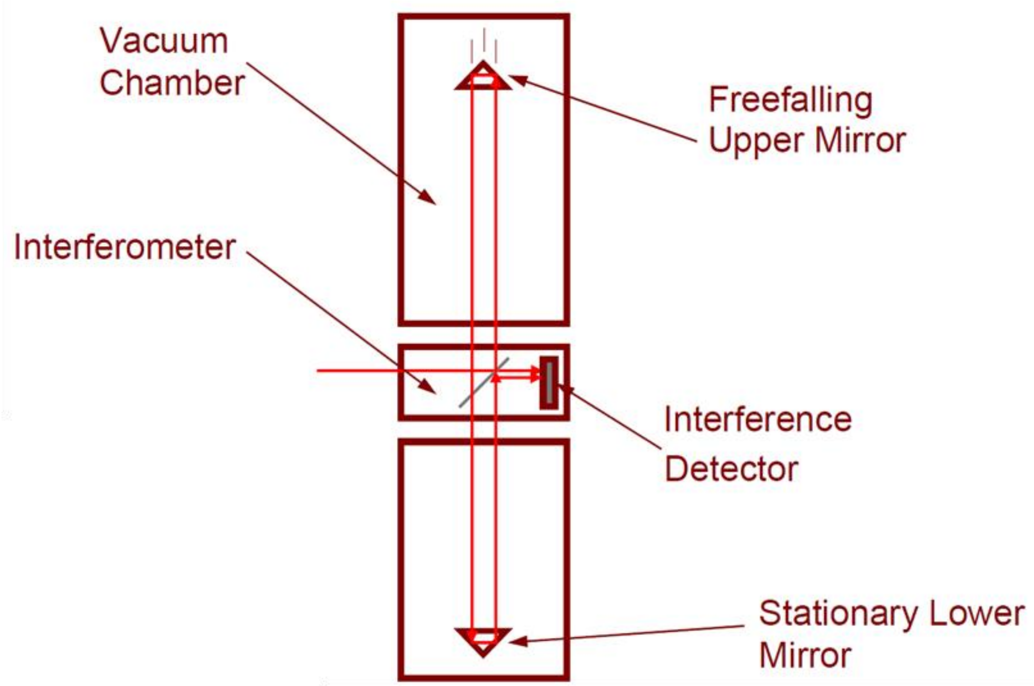
Absolute Gravimeters

Accuracy <5 ppb,

Accuracy <5 ppb,

Micro G FG5X



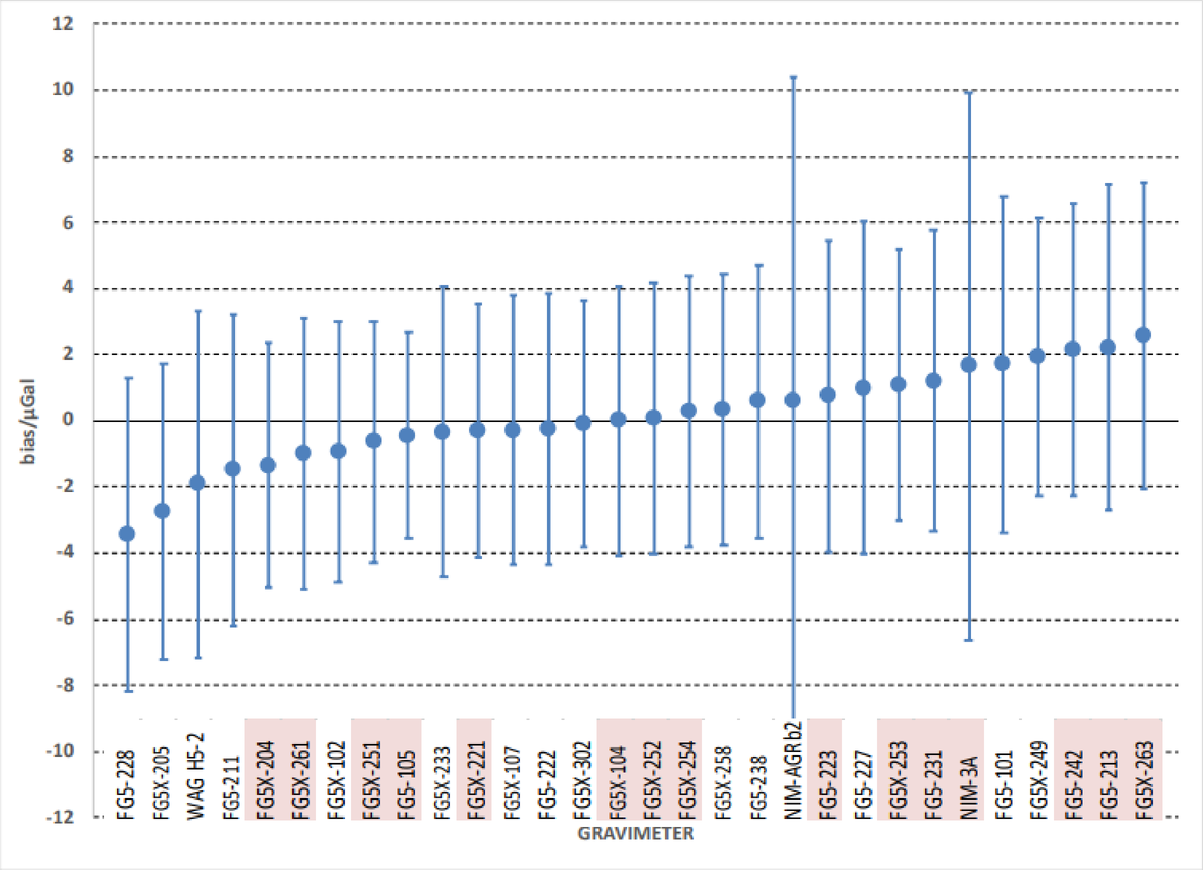


Exail AQG

Optical Interferometry of a dropped retroreflector. Not for continuous long term monitoring

Based on atom interferometry
Higher sampling rate, no moving parts, long term monitoring

Comparison of absolute gravimeters



David Newell *et al* 2024 *Metrologia* **61** 07009

CCM.G-K2.2023: Good agreement across all absolute gravimeters

All within ~+/- 4 µGal

Relative Gravimeters: Change in g

Measure change in g

iGrav SG

Super conducting gravimeter
Sensitive and Stable, used for long term change monitoring

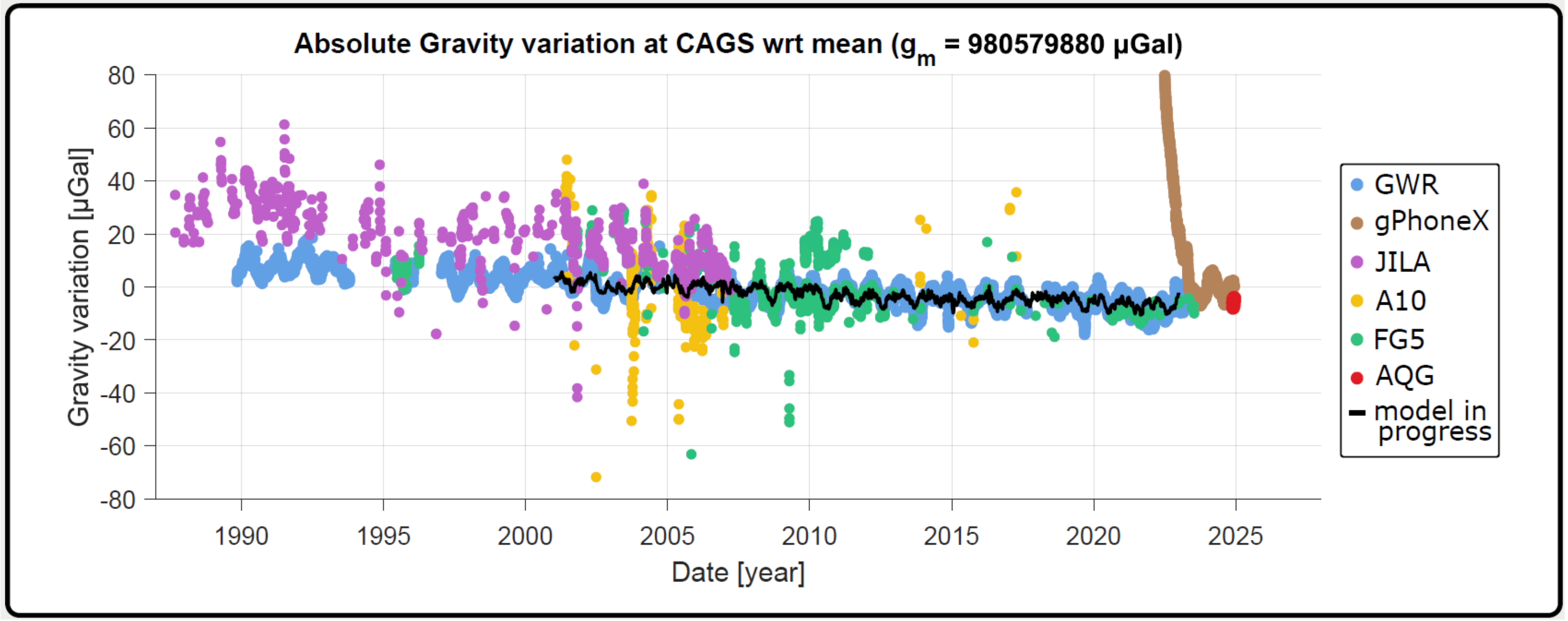
Scintrex CG6

Small and portable
Not for long term monitoring

gPhoneX

<5 µGal, long term measurement

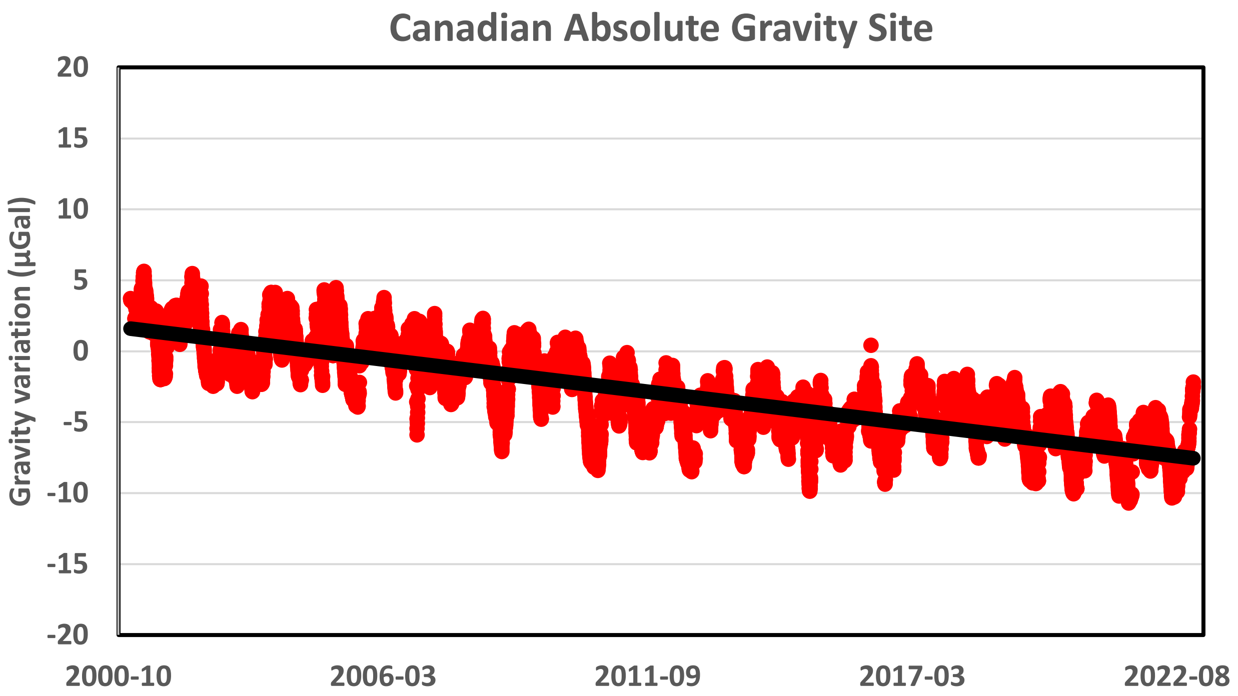
Canadian Absolute Gravity Station (CAGS)

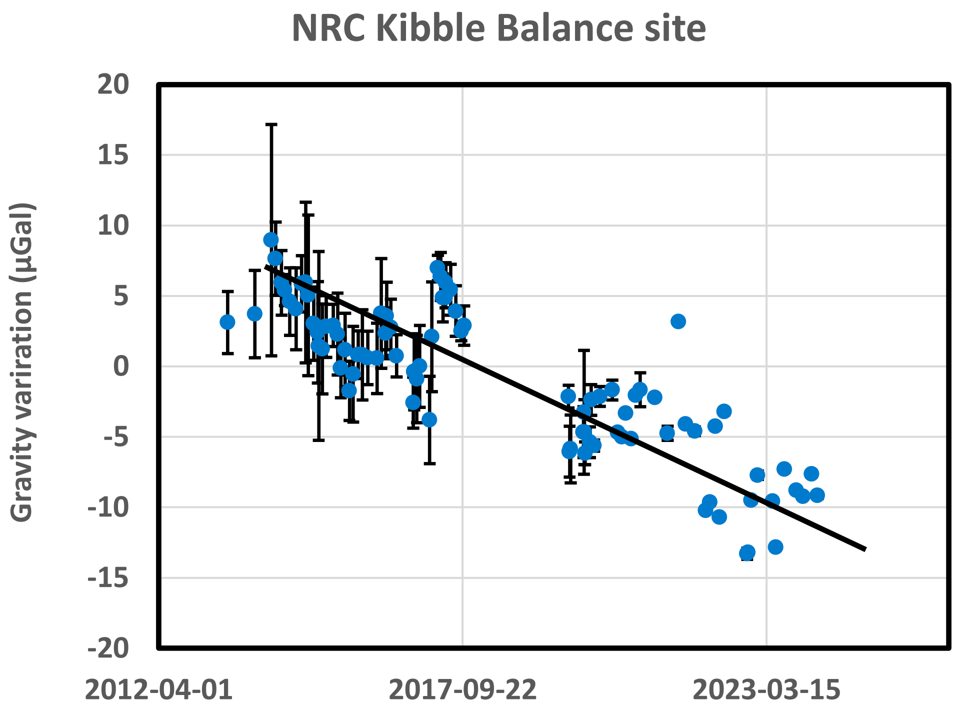


Station Coordinates (Scaled)			
Latitude	**Longitude**	**Elevation**	**Description**
N45° 35' 7" ± 20.0 m	W75° 48' 27" ± 20.0 m	269.20 ± 1.00 m	CAGS SITE A - CANTLEY

Gravimetric Information		
Gravity	**HI**	**Gradient**
980579.9292 mGal	0.91 m	0.3770 mGal/m

Long term and seasonal variation





Glacial Rebound ~-0.5 µGal/yr

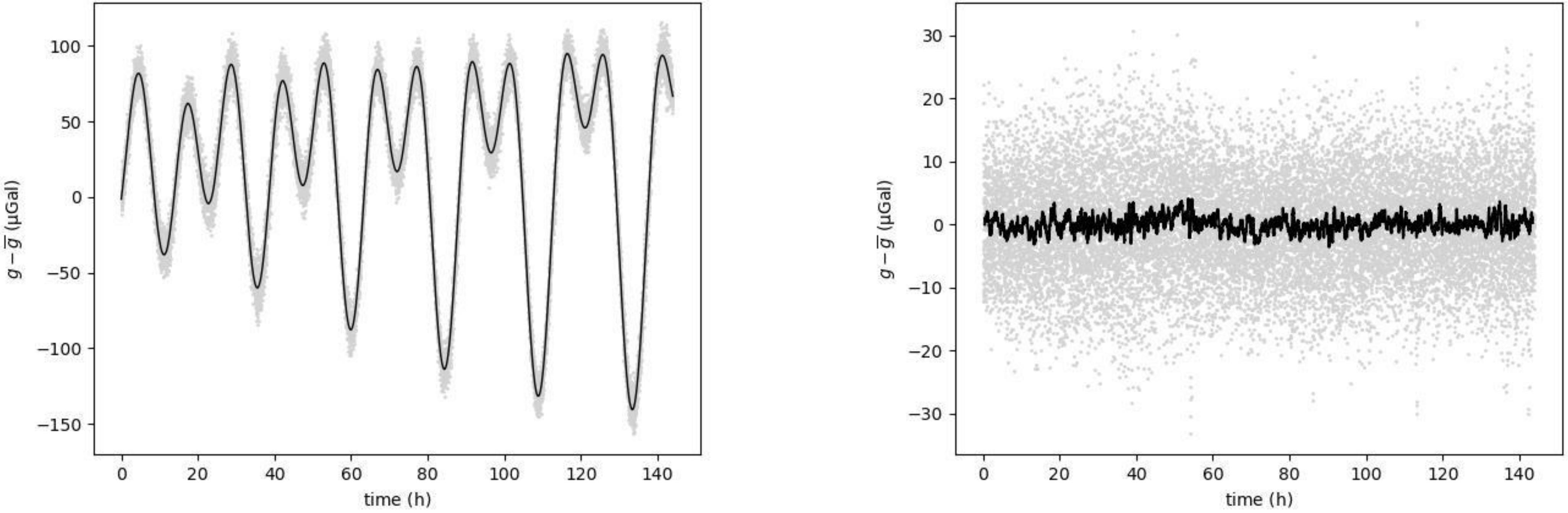
Max deviation: 6 µGal

Glacial Rebound ~-1.3 µGal/yr

Max deviation: 7.8 µGal

stdev =2.4 µGal FG5 data only

Daily Variation from FG5



6 days of measurement data, peak to peak variation of about 250 ppb

Combination of models can be used to extract tides to better than 1 µGal

Eg. Tamura (1987). See https://eterna.bkg.bund.de/

Daily Variation

Tidal Models (Impact of celestial bodies)

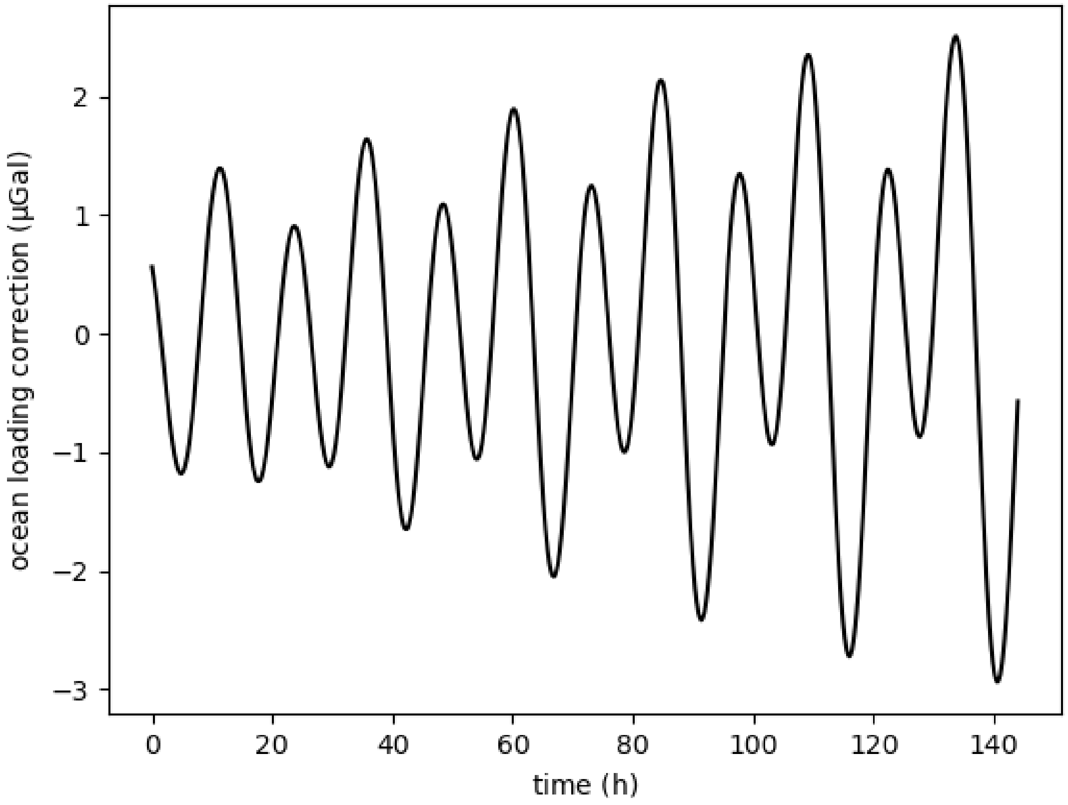
- Earth Tides: Movement of the earth (largest contributor)
- Ocean loading: Movement of ocean water

Polar motions : Due to movement of poles (earth axis of rotation)

Pressure: Gravity associated with air column 0.3 µGal/mBar

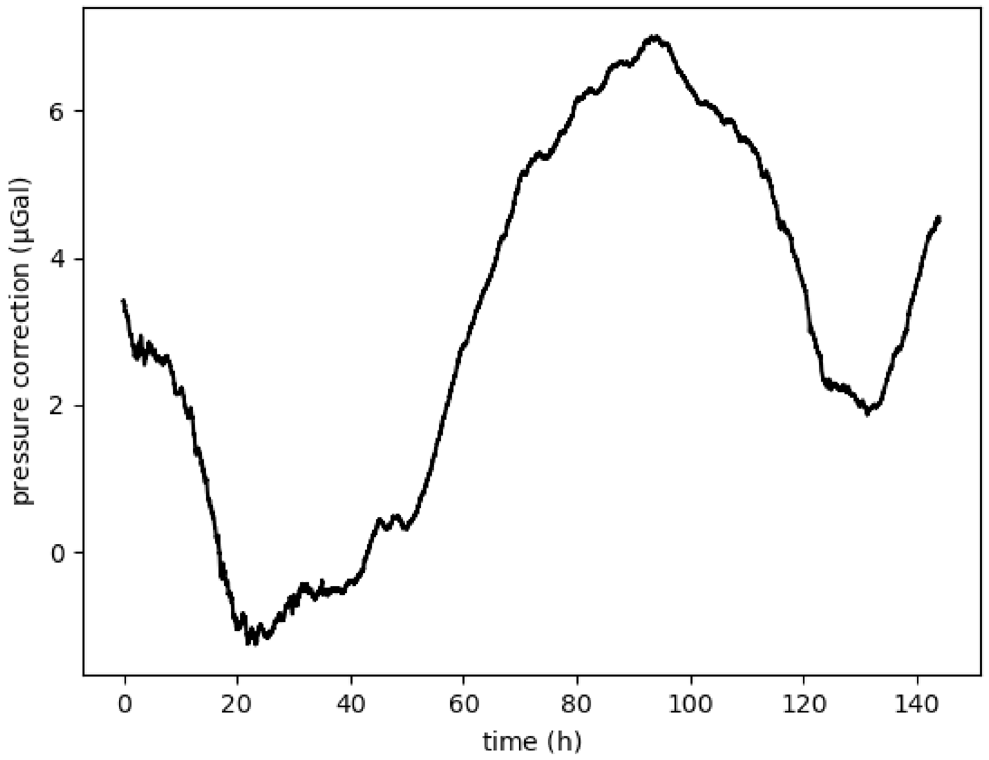
Can be included into KB servo system to predict required coil current

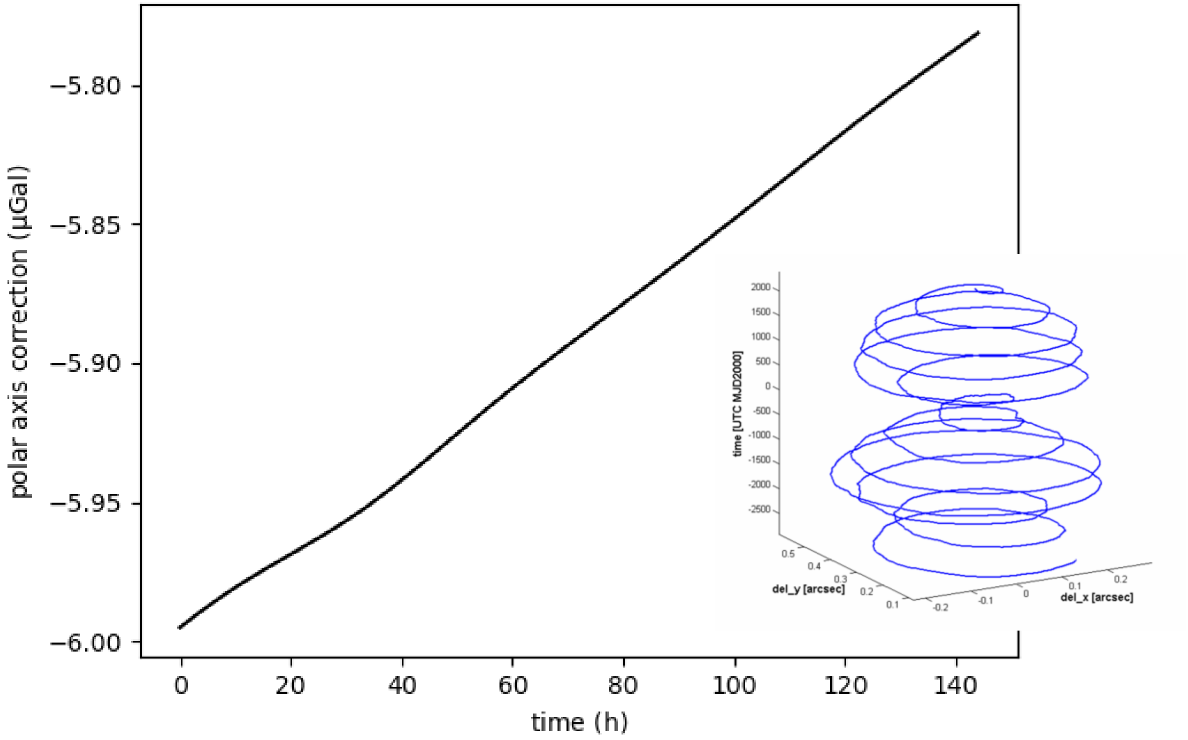
Daily Variation: Ocean Loading



Usually small contribution of a few ppb

Pressure and Polar Motion



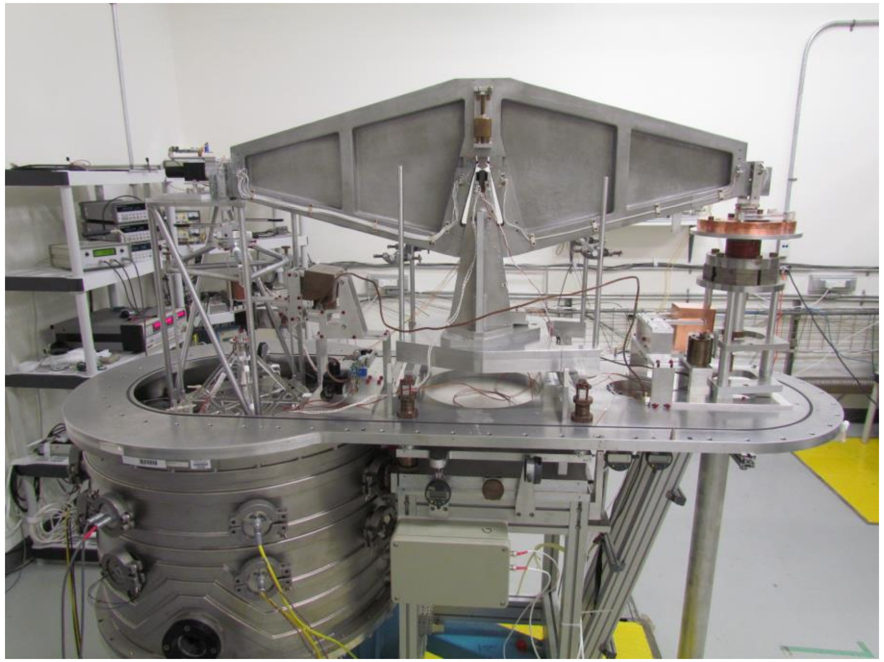


Pressure correction from gravitation attraction of air column 0.3 µGal/mBar

Correction due to polar motion (wobble of earth axis), from IERS

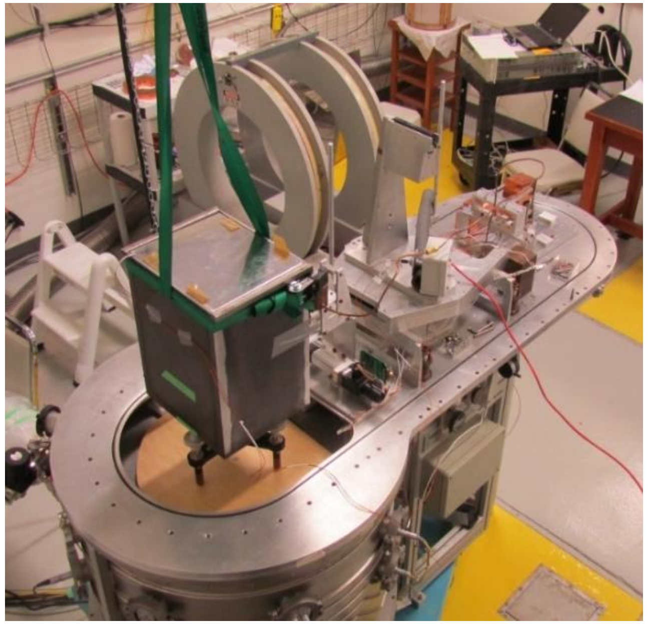
https://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop

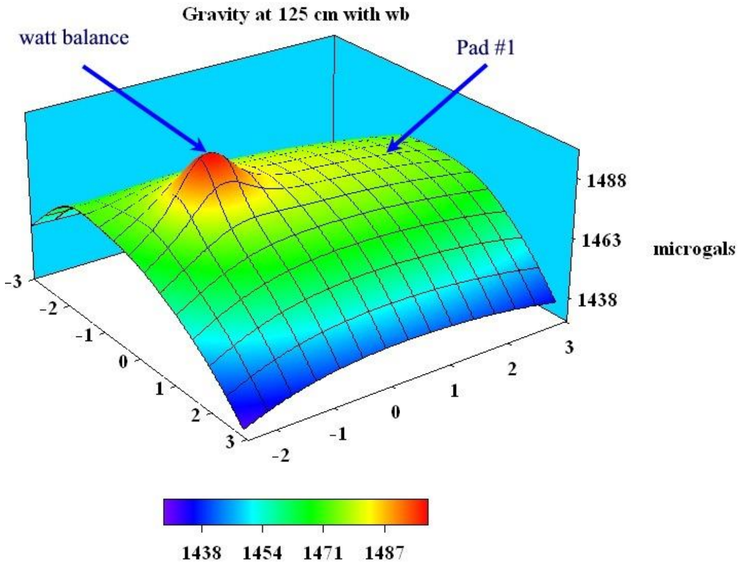
Gravity Transfer



How to transfer absolute g measurement (h~130 cm) to the centre of mass of your artefact for realization?

Relative gravimeter measurements

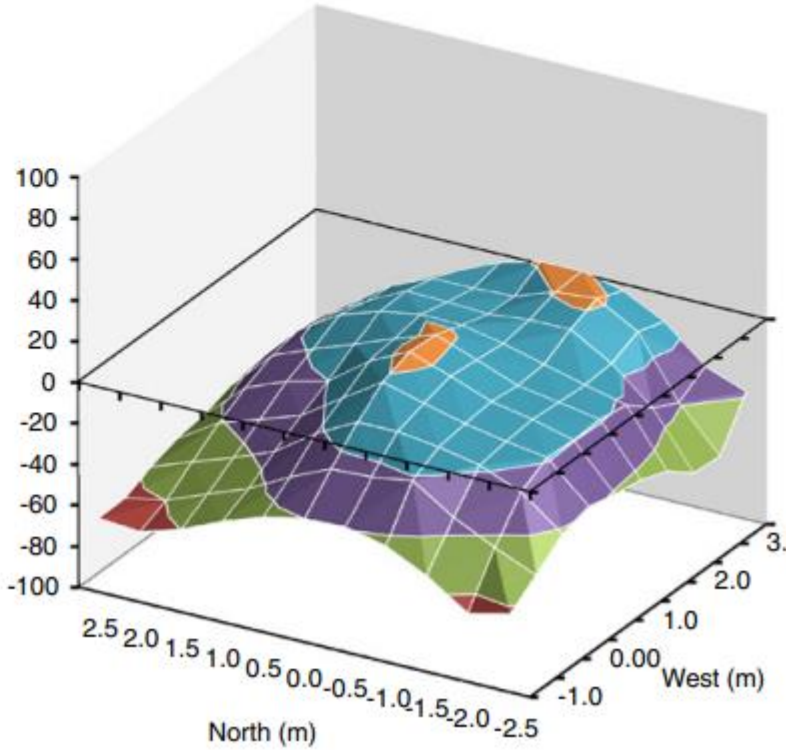




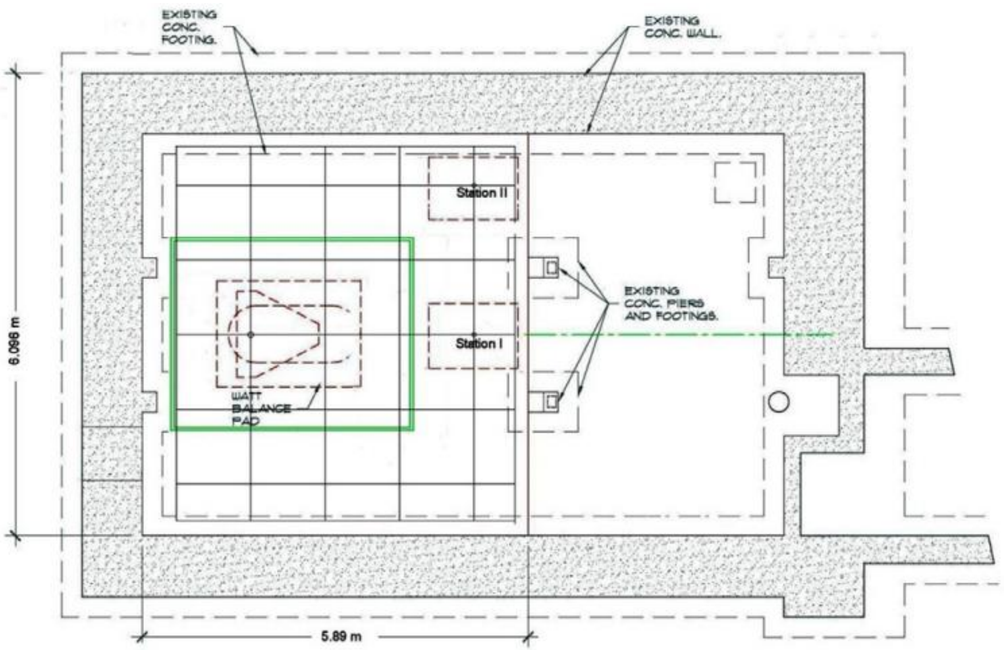
Method 1: Use a relative gravimeter (eg. CG6) to measure the difference between abs g point and Mass artefact position

Method 2: Measure what you can and model what you can't

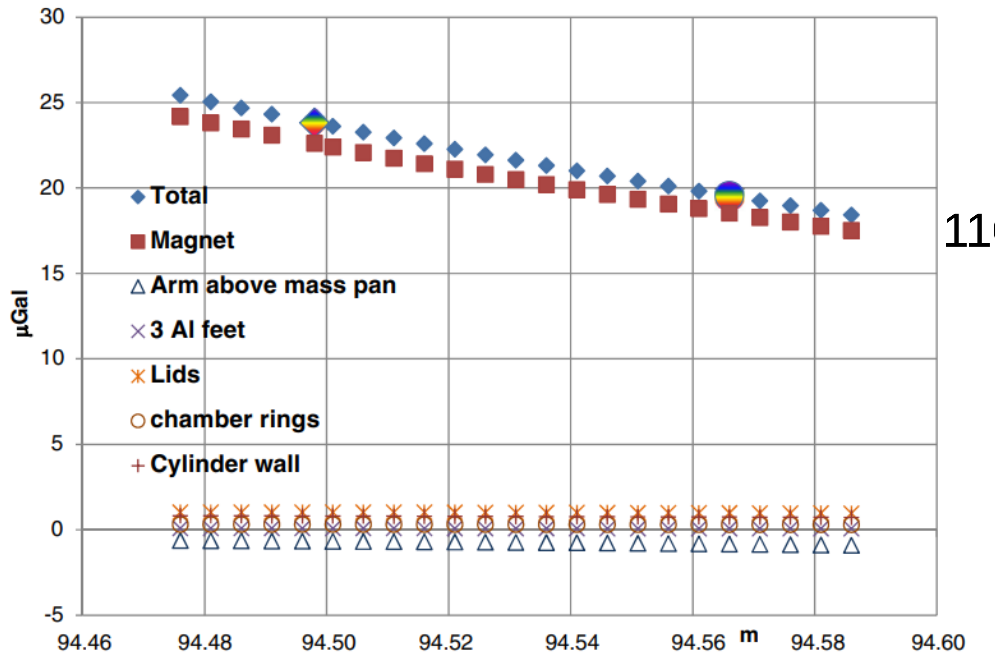
Measure Horizontal and Vertical Gradients



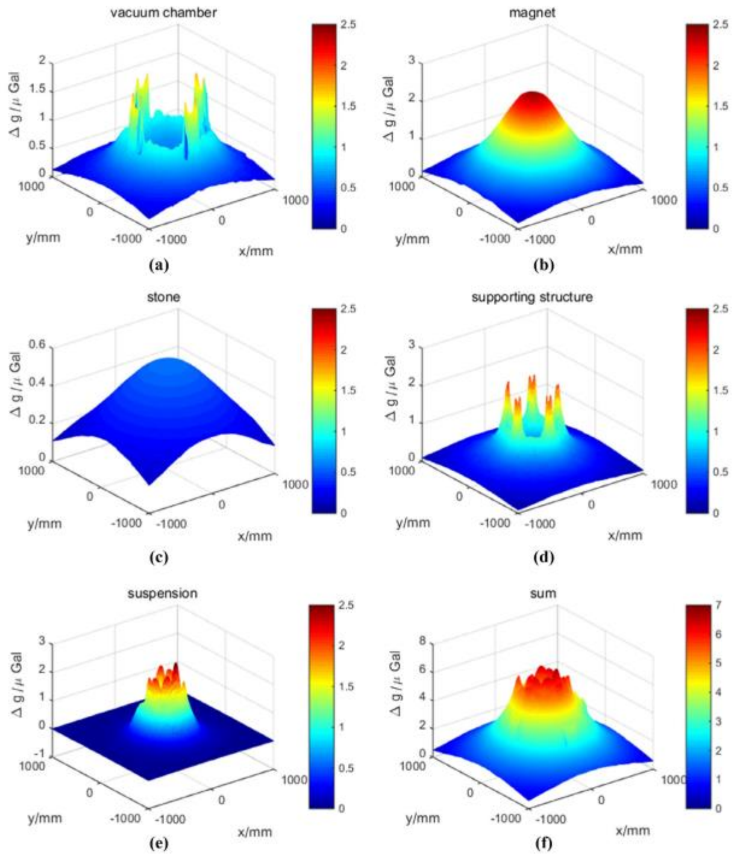
Metrologia 54 (2017) 445



Gravity Modeling of Self attraction



1100 kg



Nagy D 1966 Geophysics 31 362–71

Shisong Li et al 2017 Metrologia 54 445

Metrologia 54 (2017) 445

Summary

1. Mass:

a. **Process for disseminating mass from the Kibble Balance**

3 (2) Steps to disseminate realized values

b. **Transfer mass selection**

Consider mass properties to optimize performance in KB environment

c. **Considerations for vacuum to vacuum transfer**

Pressure minimum, cycling stability, transport

d. **Vacuum to air transfer**

Sorption artefacts to account for water/hydrocarbon ad/desorption

2. Gravity:

a. **Absolute and Relative Gravimetry**

Instruments and seasonal variations

b. **Tide Models**

Daily changes in gravity due to earth tides, ocean loading, polar motions

c. **Gravity Transfer**

Methods for transferring g from measurement position of gravimeter to KB mass pan

Thank you.

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