The View from the Ground: Absolute Instruments and Networks

Derek van Westrum, Ph.D.
NGS Observations and Analysis Division
derek.vanwestrum@noaa.gov

NOAA's National Geodetic Survey
geodesy.noaa.gov

Outline

- Motivation
- Review of common relative instruments
- Absolute Instruments
    - Historical methods
    - Current “classic” freefall gravimeters
    - Gradiometers and Cold Atom Instruments
- Networks
    - Historical networks
    - Modern networks
    - Regional and International (key) comparisons
- Outlook

Motivation

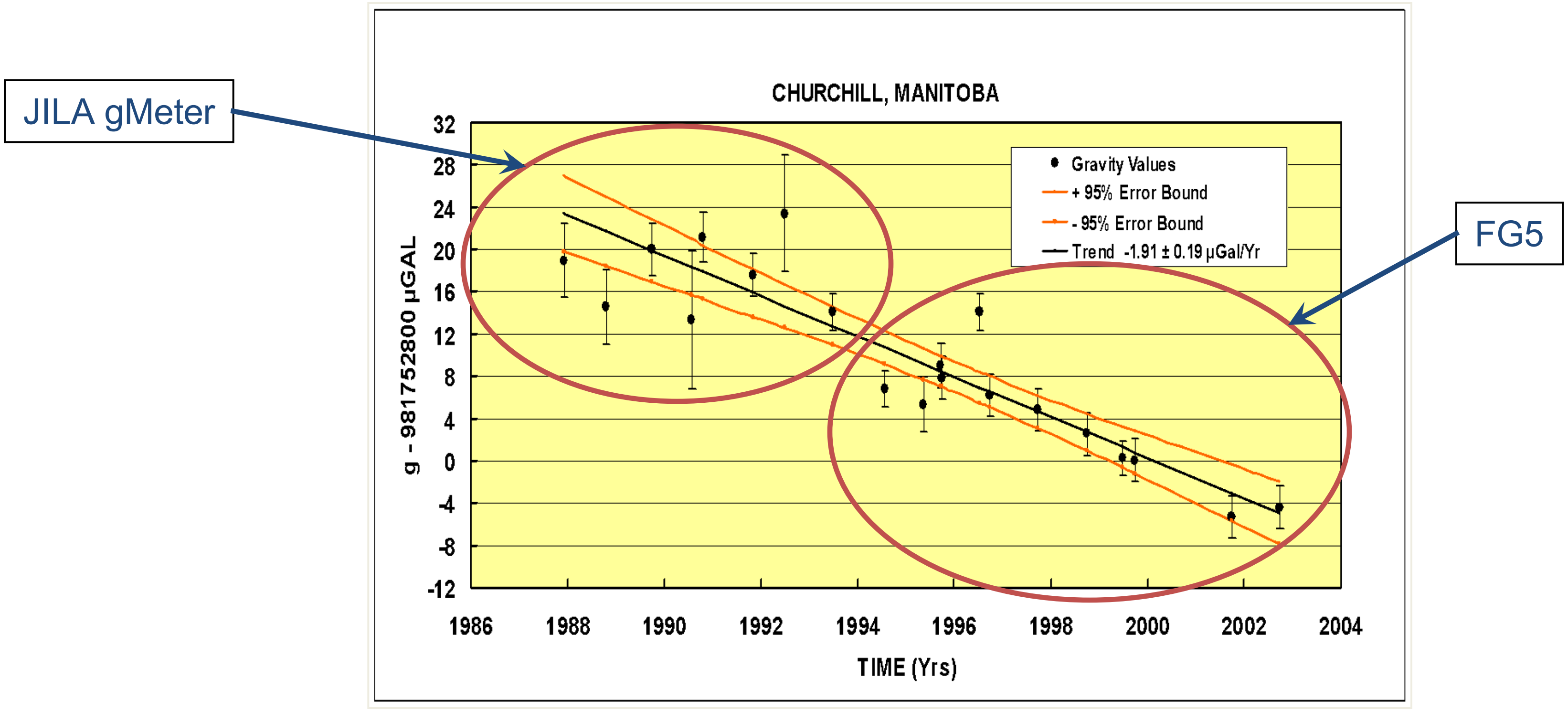
- Relative instruments can tell you about the difference in gravity at different locations or over time.
  - Typically, each instrument is optimized for one or the other.
  - The instruments must be calibrated (separate from the survey)
  - The survey must be performed with the same instrument (often, multiple instruments in parallel).
- Absolute instruments are based on standards of length and time.
  - Inherently calibrated*
  - The absolute gravity value at a site is fundamental and can be measured at any time, with any instrument
  - Current absolute instruments are portable (worldwide range), but – with a few exceptions – static and ground based

*More on this later…

Airborne Gravimetry for Geodesy summer school

Example:

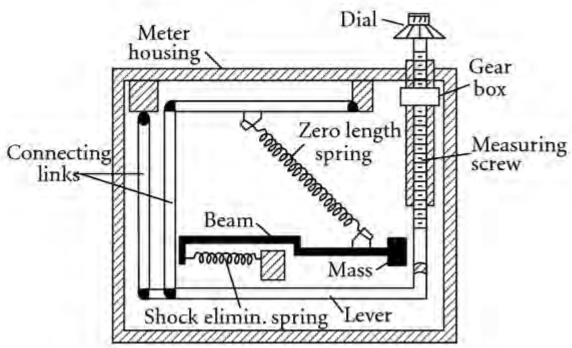
Absolute Gravity Application to Glacial Isostatic Adjustment

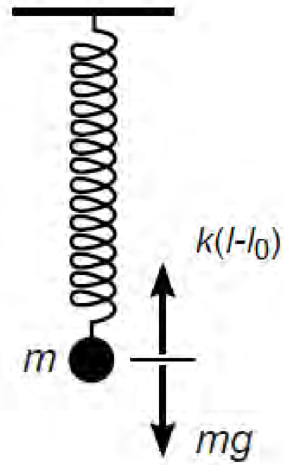


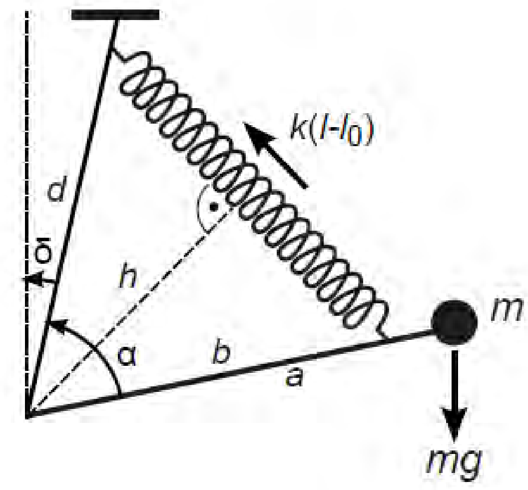
A. Lambert *et al.*, "New constraints on Laurentide postglacial Rebound from Absolute Gravity measurements," Geophysical Research letters, Vol 28, No. 10, pp. 2109-2112, May 15, 2001.

Review of Relative Instrument Principles

LaCoste & Romberg g-Meter





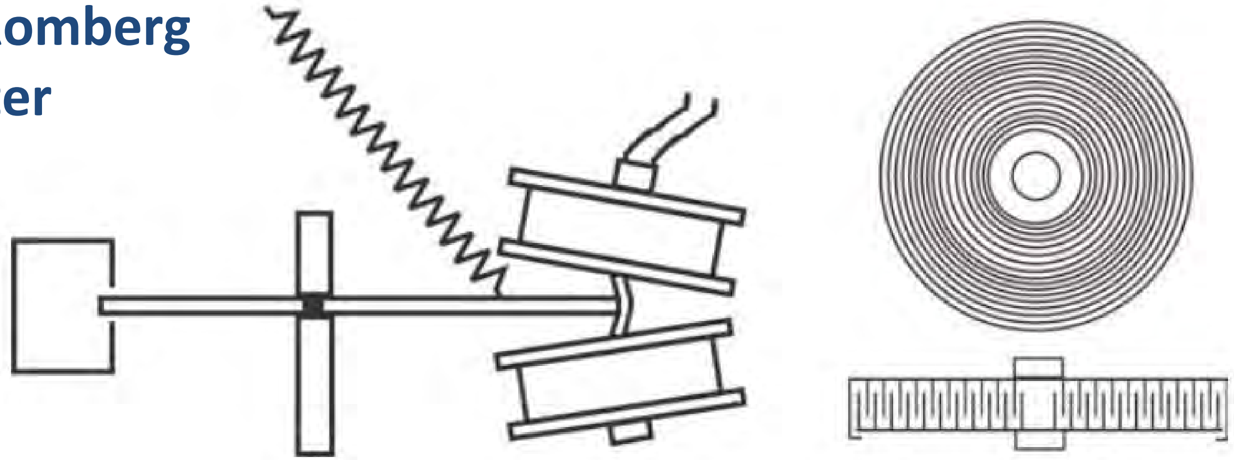


$$mga\sin(\alpha+\delta) = k(l-l_0)\,b\frac{d}{l}\sin\alpha.$$

- The force of gravity stretches a calibrated spring, and the displacement is proportional to gravity. Roughly: mg ~ kx
- Geometric "tricks" (zero length springs) allow a small change in gravity to cause a larger displacement of the test mass.
- Modern systems use an electric force to keep the mass position fixed, and the electric force required is proportional to gravity.
- Both the spring and feedback unit must be calibrated and are subject to drift and offsets (tares) over time.

Review of Relative Instrument Principles

LaCoste & Romberg Air-Sea Meter



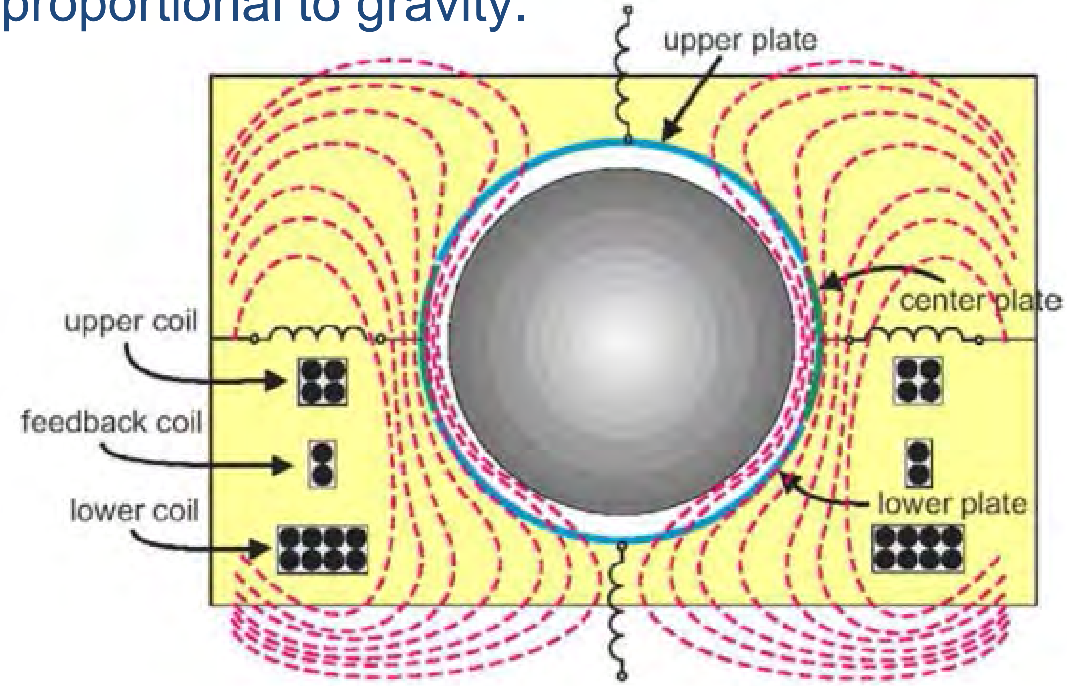
$$g_{Meter} = SM = S(SpringTension + kBeamVelocity + CrossCouplingCorrection)$$

- (Using the LaCoste & Romberg dynamic sensor as an example)
- Again, a calibrated spring is used, but in addition, there is also a calibrated damping factor in which gravity is proportional to beam velocity
- Motion of the sensor requires monitoring and correcting for “cross couplings”
- Again, modern systems use “force feedback” to hold the beam fixed, and the electrical force is proportional to gravity. Some also use magnetic damping instead of the air dampers

Review of Relative Instrument Principles

Superconducting gravimeter (SG)

- Permanent currents in superconducting coils are used to levitate a sphere magnetically.
- Field design gives a large change in position for a small change in gravity
- But again, adjustments in the feedback coil keep sphere position constant. This current is proportional to gravity.
- Very low, linear drift (5μGal/year)
- Typically used to measure changes in gravity at a single location over time.



Review of Relative Instrument Principles

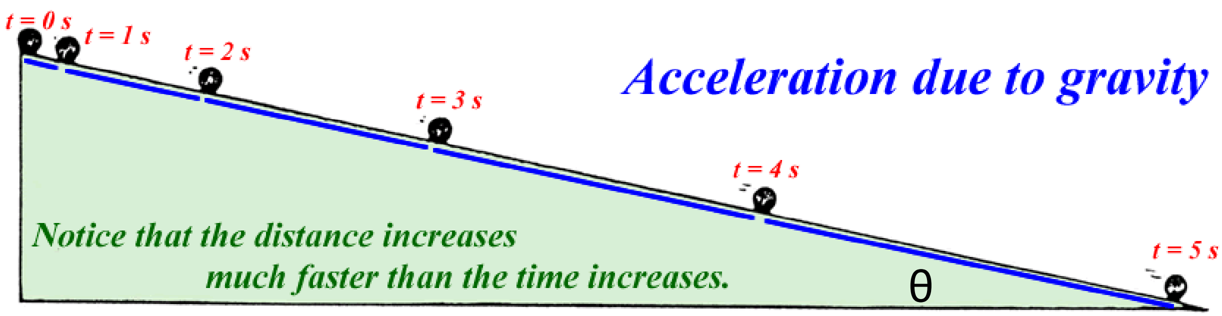
- Each relative instrument has its own
  - Test mass
  - Spring Constant
  - Damping coefficient
  - Etc.
- These parameters can change with
  - Time
  - Temperature
  - Pressure
  - Magnetic fields
  - Humidity
  - Etc.
- To measure g at the μGal level, each parameter (or overall combination of parameters) must be known, controlled, and monitored to a precision of 10^{-9} or better.
- (Note though that these parameters often change lineally with time and are easily corrected for.)

Review of Relative Instrument Principles

- Advantages of relative instruments include
  - No (or few) moving parts
  - Small, portable size (portable survey units: gMeter, CG-5, etc.)
  - Continuous, high rate measurements (SG)
  - High precision (but low dynamic range)
  - Operable in dynamic applications
- The disadvantages include
  - Long term changes in calibration factors
  - Un-modeled sensitivity of calibration factors to environmental conditions
  - Possibility of nonlinear drift
  - Offsets (tares)
  - Difficult to transport
  - “Memory” after an anomaly. For example, the “decay” of an offset after a dynamic meter encounters an air pocket.

Absolute Gravity Meters

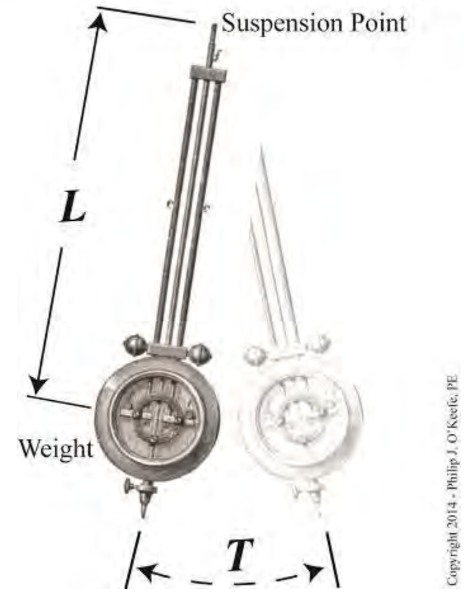
- g is measured “directly” in meters / second^2
- First absolute gravity instruments were Galileo’s inclined planes

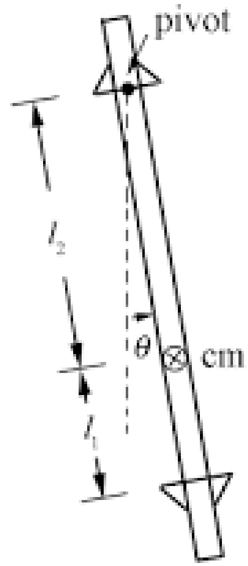


$$g = \frac{2x}{t^2 \sin\theta}$$

Pendulums

- 1656. Huygens makes a pendulum clock
- 1749. Bouguer measures g
- 1817. Kater introduces the reversible pendulum
- (Kater also introduces relative gravity: keep L fixed and $\Delta g \sim \Delta T^{-2}$)
- Vacuum chambers and multiple pendulums were state of the art through 1940s.
- Best accuracy ~100 µGal
- Eventually spring gravity meters had significantly better precision, indicating problems and "absolute offsets" in the pendulum results

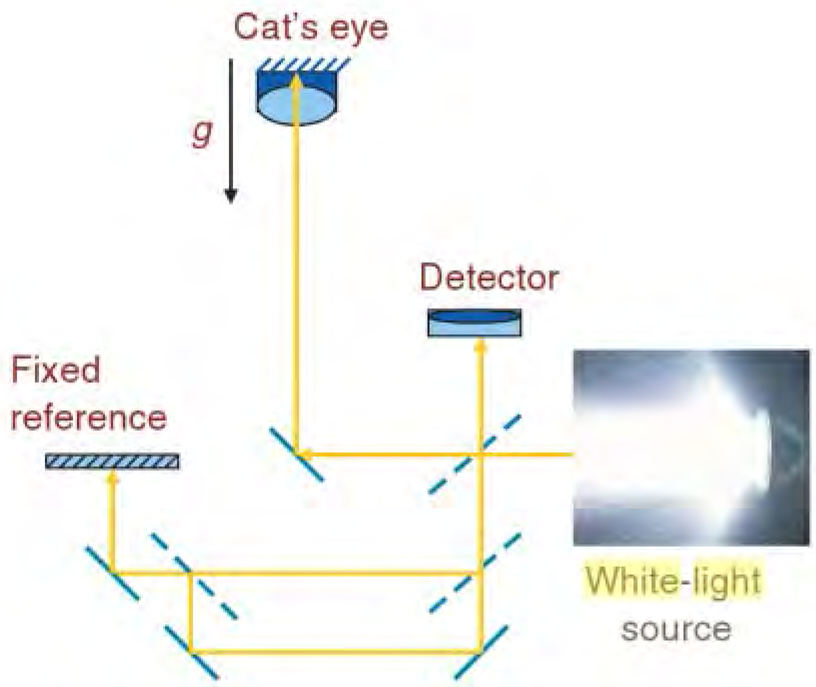




$$g = \frac{4\pi^2 L}{T^2}$$

Freefall Absolute Gravity Meters

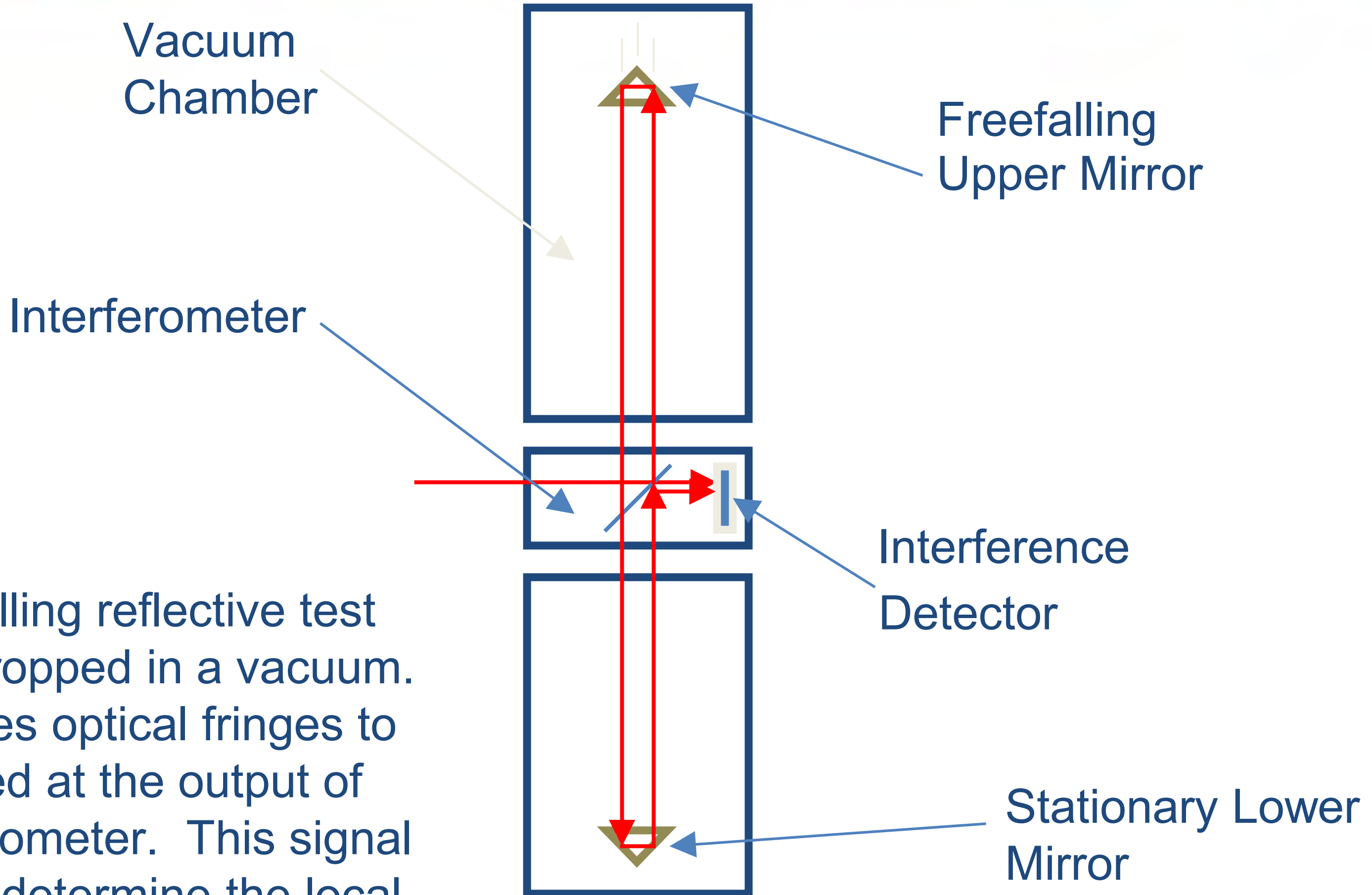
- 1963. Faller and Dicke introduce white light interferometer
- White light makes interference "flashes" when the path **length** of the "test beam" is equal in length to the reference beam.
- This occurs 3 **times** during free fall. The timing of the flashes and the measured path lengths serve to determine g.
- Initial accuracy ~700 µGal



"Classic" Contemporary Freefall Absolute Gravimeters

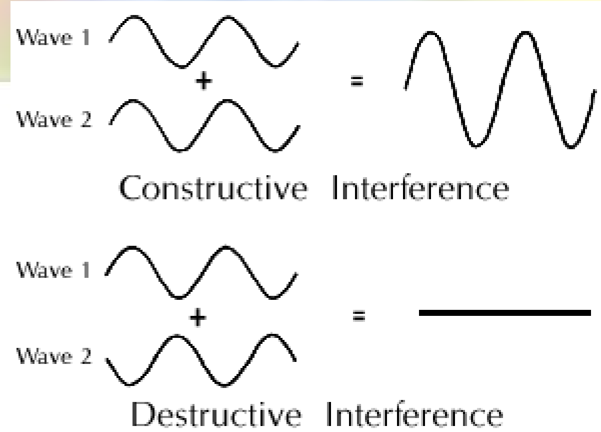
- Through the 1970s and 1980s, the freefall method was improved using lasers, active seismic isolation, precise timing, etc.
- Current state of the art is ~2uGal accuracy (observed agreement between absolute instruments).
- JILA-g, IMGC, FG5(X), A10, GABL, NIM, MPG…
- These devices all drop macroscopic objects and use conventional mirrors and beam splitters
- **Length** (lasers) and **time** (atomic clocks) are stabilized by being tied to atomic transitions (primary frequency standards in most cases)
  - Lasers accurate to ~1×10^{-12}
  - Clocks accurate to ~1×10^{-10} (calibrated to Cesium, 1×10^{-15})

FG5 Principle of Operation



A freely falling reflective test mass is dropped in a vacuum. This causes optical fringes to be detected at the output of an interferometer. This signal is used to determine the local gravitational acceleration.

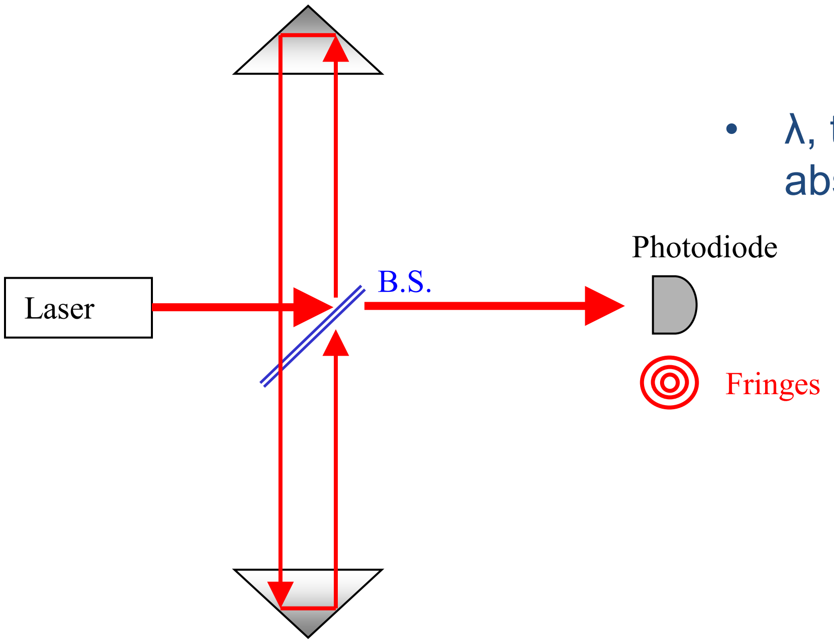
Interferometry



MAX

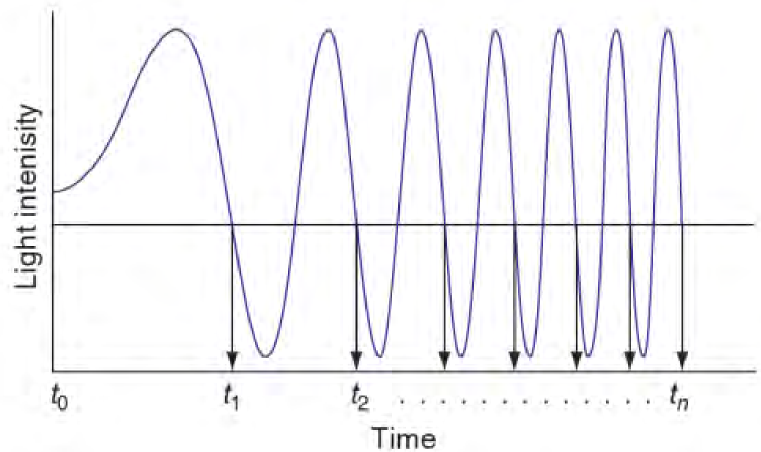
$\lambda/2$

min



Michelson’s interferometer

- λ, the wave**length** of the laser light, can be tied to absolute atomic transitions frequencies.



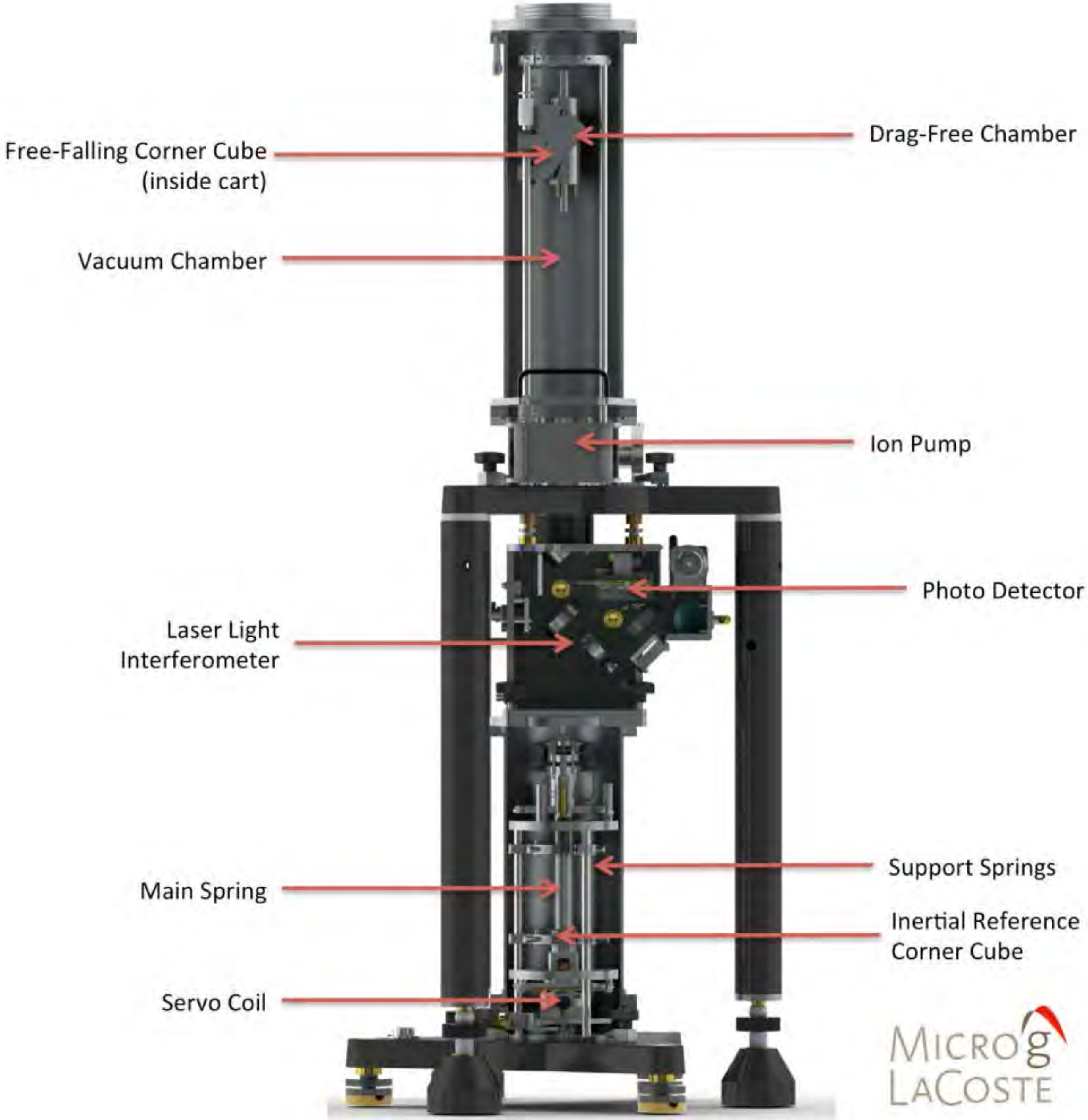
- fringe signal sweeps in frequency as test mass falls under influence of gravity
- **time** recorded (w.r.t. rubidium oscillator) at each zero crossing, creating (t,x) pairs at every λ/2

g Determination

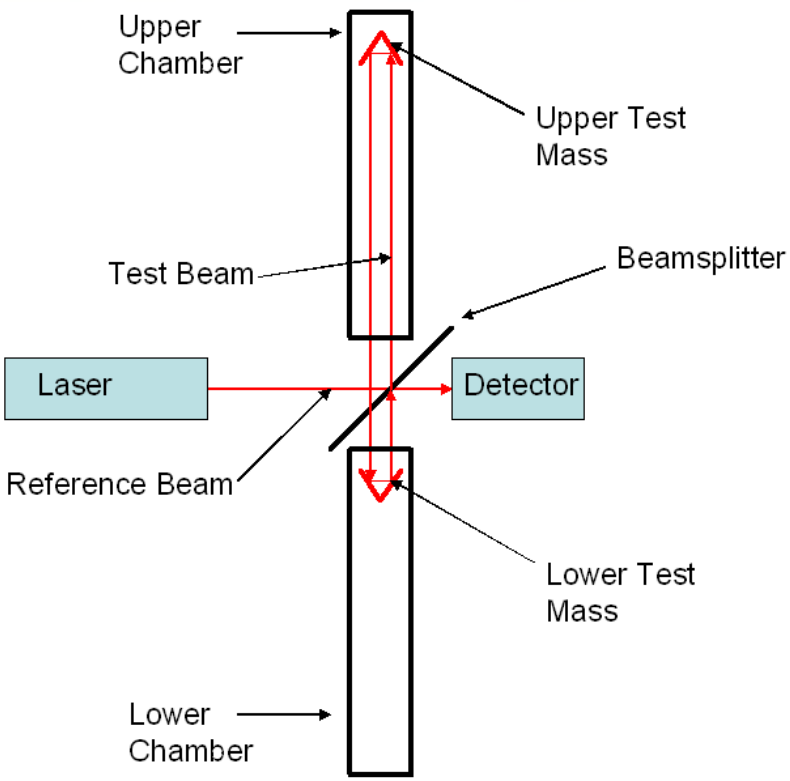
- Fringe = 1/2 x_i
- For each $\boldsymbol{x_i}$, a measured time $\boldsymbol{t_i}$,
- The following function is fitted to the data $\boldsymbol{x_i}$, $\boldsymbol{t_i}$:

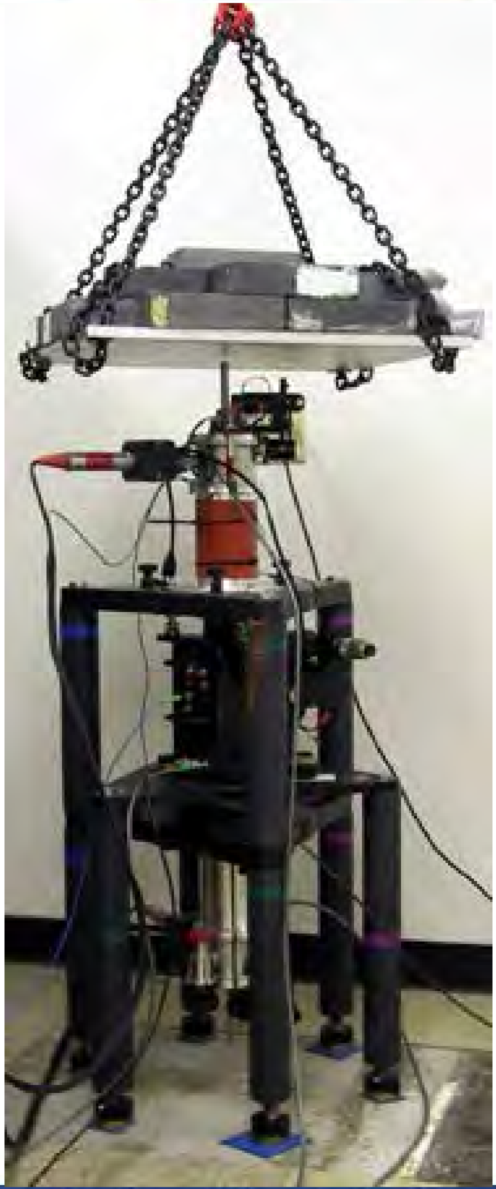
$$\left.\begin{array}{r} x_i = x_0 + v_0\tilde{t}_i + \dfrac{g_0\tilde{t}_i^{\,2}}{2} + \dfrac{\gamma x_0\tilde{t}_i^{\,2}}{2} + \dfrac{1}{6}\gamma v_0\tilde{t}_i^{\,3} + \dfrac{1}{24}\gamma g_0\tilde{t}_i^{\,4} \\ \tilde{t} = t_i - \dfrac{(x_i - x_0)}{c} \end{array}\right\} \quad x_i\,,\ t_i\,,\ \mathrm{i} = 1,\ \ldots,700$$

- γ is the vertical gravity gradient (~3 μGal/cm),
- c the speed of light
- x_0 the initial position
- v_0 the initial velocity
- g_0 the initial acceleration


Free-Falling Corner Cube
(inside cart)
Vacuum Chamber
Drag-Free Chamber
Ion Pump
Photo Detector
Laser Light
Interferometer
Main Spring
Support Springs
Inertial Reference
Corner Cube
Servo Coil
MICRO g
LACOSTE

Aside: Absolute Gradiometers

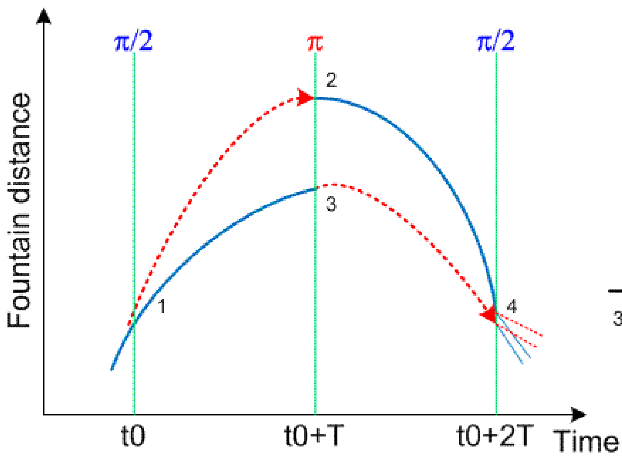


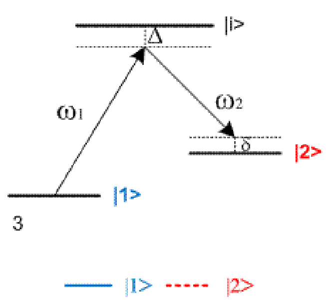


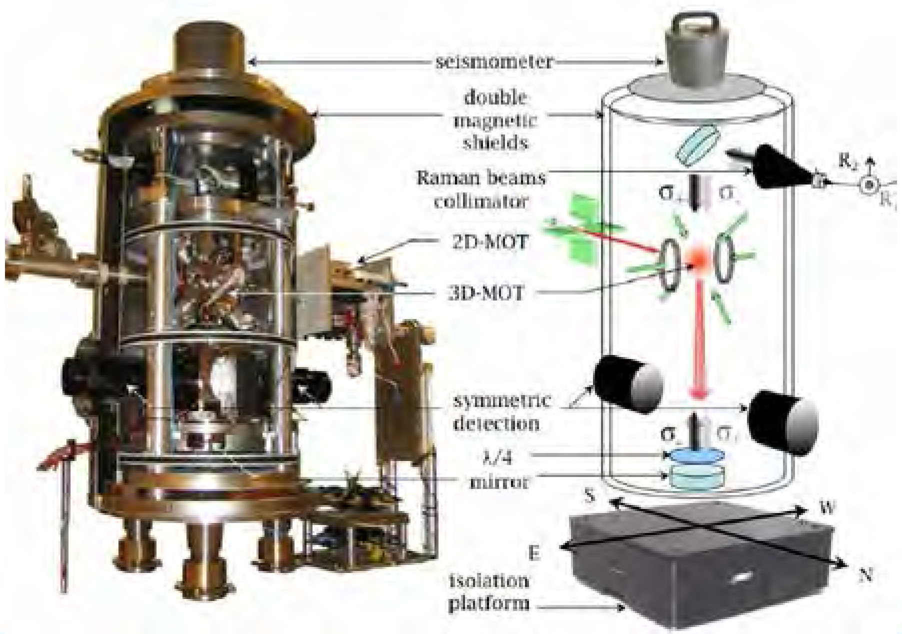
The lower reflector is also placed into freefall. It (typically) falls more quickly due to the gravity gradient.

Cold Atom Gravimeters (A Preview!)

- Also a free fall method, but the role of matter and light is reversed: atoms are split into two paths, and light is used to form “mirrors” and “beam splitters”
- Length and time standards are still provided by ties to atomic transitions
- Advantages: no recoil force into the ground (low noise), no moving parts, fast and continuous measurements



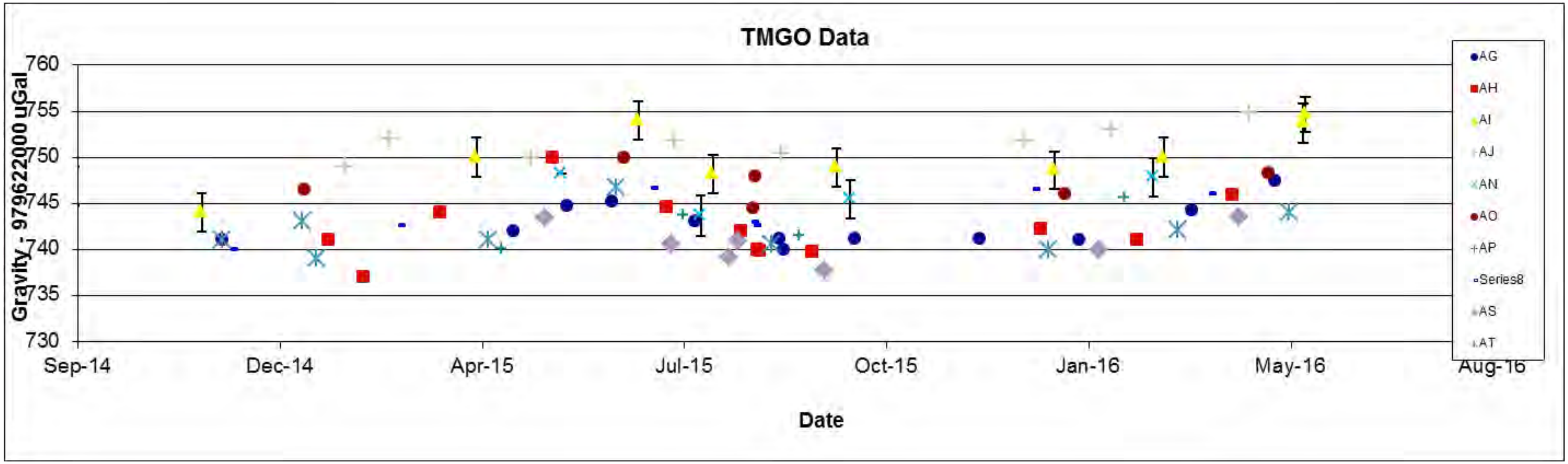




Practical Limitations on Absolute Accuracy

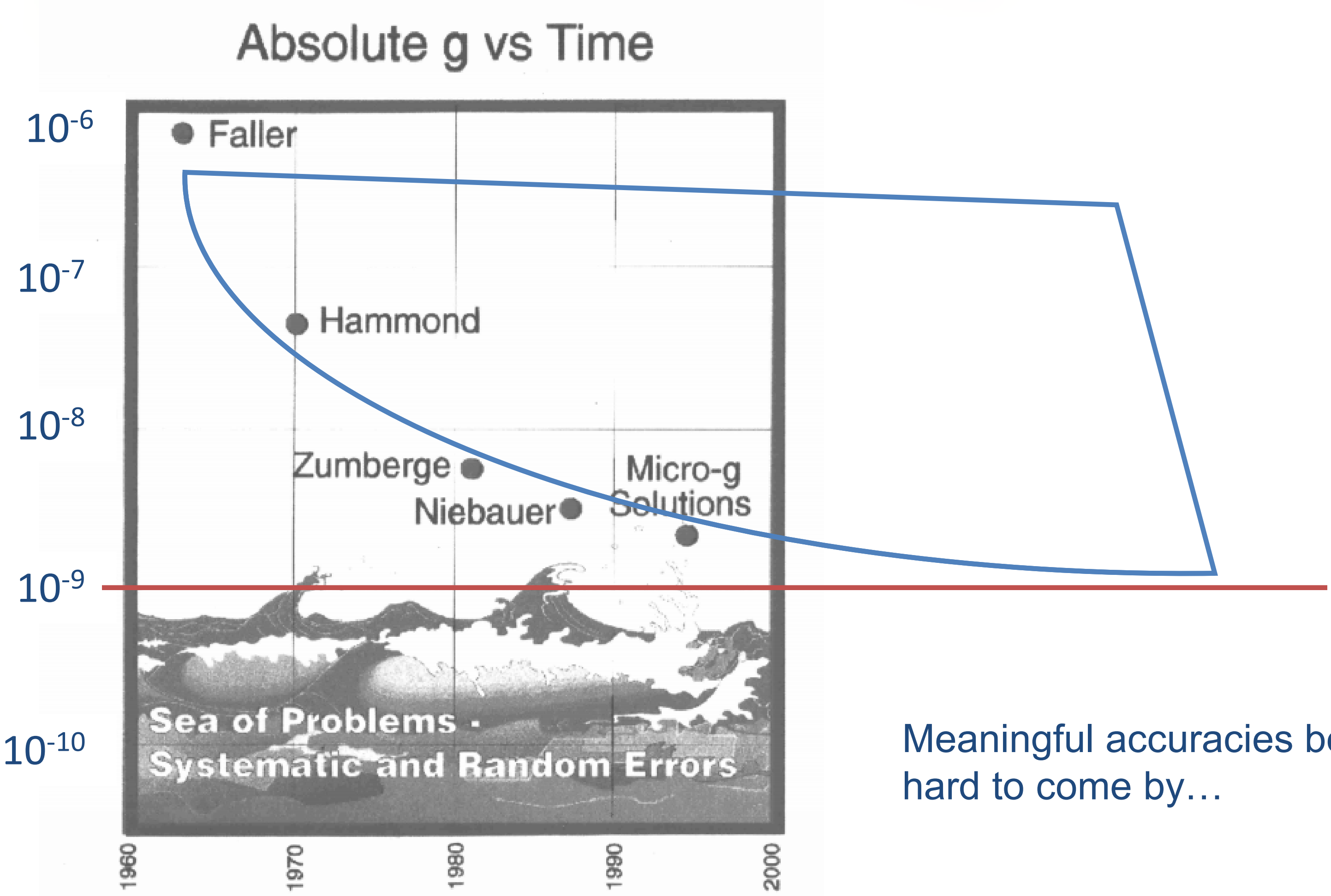
- Absolute measurements routinely corrected for
  - Earth tides (changing shape of dry earth due to sun and moon)
  - Ocean loading (loading on continental plates due to sloshing of oceans from earth tides)
  - Barometric pressure changes (more or less mass above the instrument)
  - Polar motion (changes in centrifugal force as the earth's axis changes orientation)
- All are known to about 1-2 μGal, and these uncertainties add in quadrature
- Other phenomena can affect gravity meters at this level
  - Water table fluctuations
  - Volcanic activity
  - Subsidence, uplift
- To get to sub-μGal accuracies, it becomes necessary to monitor small and complicated signals and/or create complex models
  - For example: barometric loading (tilt caused by differential atmospheric loading across a continental plate) can be observed, but is very difficult to model accurately

Hydrology* Signal at TMGO



*We assume…

Jim Faller's "Sea of Problems"



Meaningful accuracies below 1μGal are hard to come by…

Myths and Misconceptions

- *Certain components still need to be calibrated in absolute gravimeters, therefore "it's all relative"…*
    - No. As long as the components' characteristics are directly traceable to an absolute standard (time or distance – usually frequency, in practice), the measurement is absolute.
- *Relative gravity meters could be absolute if one were more careful.*
    - No. This would require knowledge of all relevant parameters (spring constant, test mass, spring properties, …) to ~$1x10^{-9}$. And it would require constant knowledge of any change to any of those (with time, temperature, pressure, etc.)
- *Okay then, absolute gravimeters are "perfect".*
    - No! They can (easily?) be set up incorrectly (wrong height, wrong laser mode), components can become contaminated, magnetized…

Historical Gravity Networks

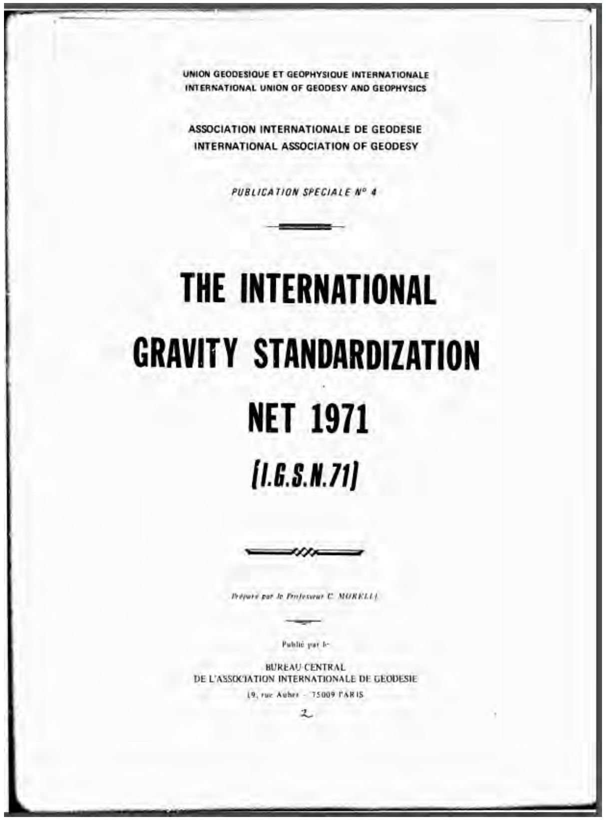
- 1671. Richer notices his pendulum clock runs slower near the equator. It's now interesting to measure gravity everywhere!
- 1900. Vienna Gravity System (by Helmert), relative accuracy of 10 mGal
- 1909. Potsdam Gravity System, relative accuracy of 3mGal
  - (corrected Vienna by -16mGal)
  - Based on reversible pendulum measurements at Geodetic Institute Potsdam (a single datum point)
  - Transferred worldwide via relative pendulums
  - Problems revealed as early as 1930: the datum itself was about 14mGal too high, and transfers had errors of many mGals.
  - New spring-based gravimeters revealed discrepancies between absolute sites.

IGSN71

International Gravity Standardization Net of 1971 of Morelli *et al.*

"It would seem that a solution would be impossible : we need the gravity-meters to be sure of the pendulums and the pendulums to calibrate the gravity-meters. "

- 1854 gravity stations worldwide
- 500 "primary" stations
- 10 absolute stations (mostly Faller)
- ~25,000 relative measurements (mostly LaCoste)
- Mean accuracy ~ 100 μGal



UNION GEODESIQUE ET GEOPHYSIQUE INTERNATIONALE
INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

ASSOCIATION INTERNATIONALE DE GEODESIE
INTERNATIONAL ASSOCIATION OF GEODESY

PUBLICATION SPECIALE N° 4

THE INTERNATIONAL GRAVITY STANDARDIZATION NET 1971

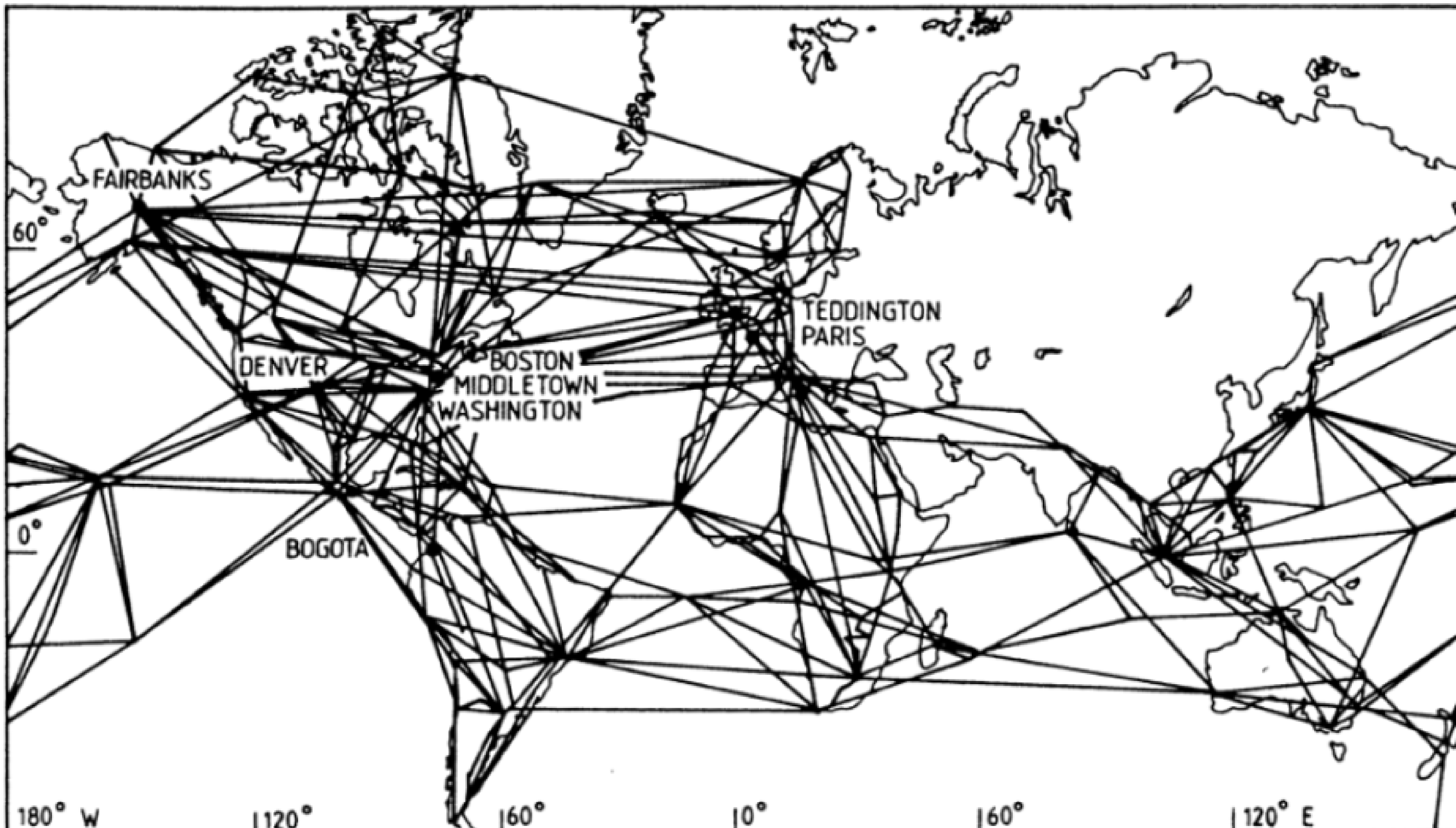
(I.G.S.N.71)

Préparé par le Professeur C. MORELLI

Publié par le

BUREAU CENTRAL
DE L'ASSOCIATION INTERNATIONALE DE GEODESIE
19, rue Auber - 75009 PARIS

IGSN71

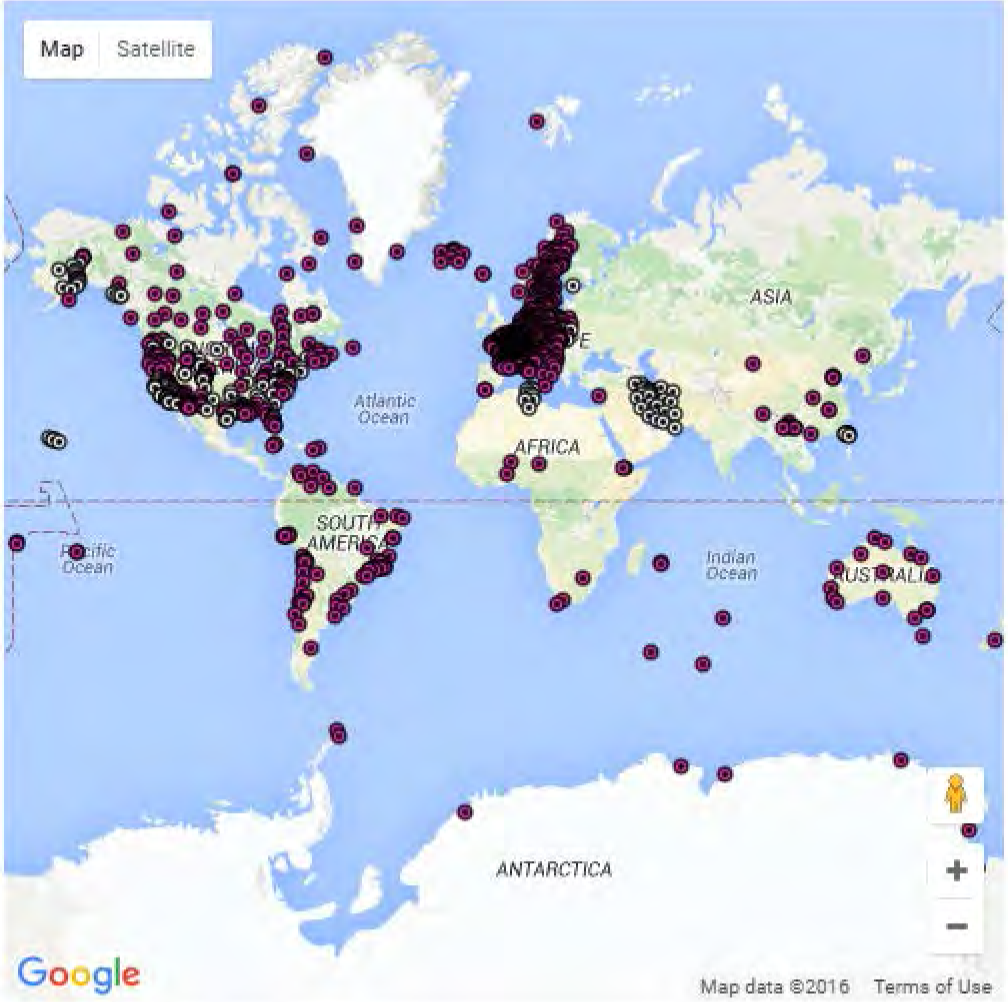

FAIRBANKS
60°
DENVER
BOSTON
MIDDLETOWN
WASHINGTON
TEDDINGTON
PARIS
0°
BOGOTA
180° W
120°
60°
0°
60°
120° E

Absolute Gravity “Networks”

- Currently there are over 100 absolute gravity meters in the world (about 100 from Micro-g LaCoste alone)
- What need is there for a traditional, worldwide network if each absolute measurement is a “network” unto itself?
- The current IAG strategy, in conjunction with the Consultative Committee on Mass (CCM) at the CIPM (International Center for Weights and Measures) is to create an absolute database, Agrav*, of all absolute measurements (volunteer basis)
- The instruments are tied to absolute standards (and thus each other) through validations and calibrations at international or regional comparisons. (ICAGs and xCAGs)

*http://agrav.bkg.bund.de/agrav-meta/

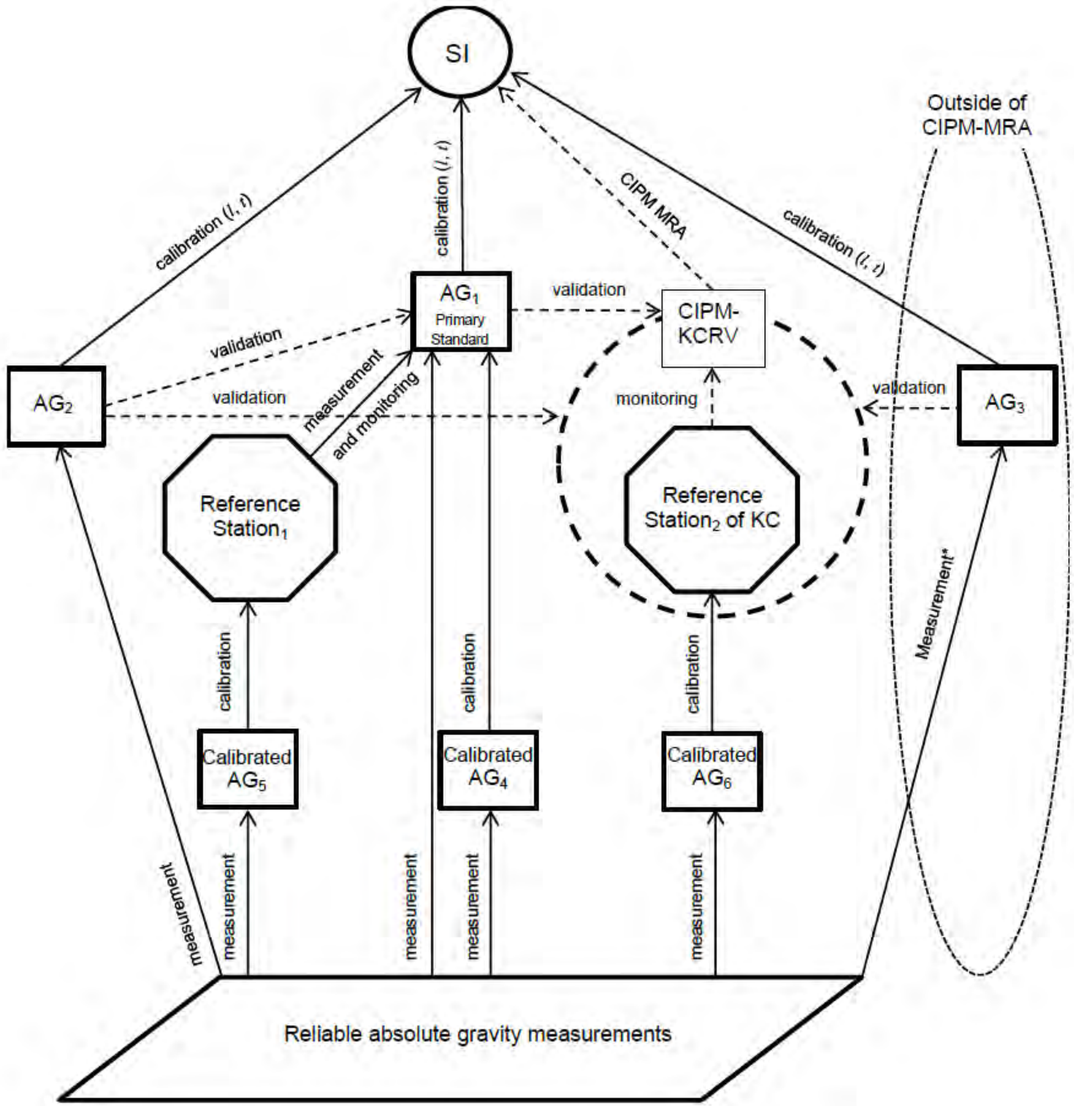
Agrav Holdings (2016)



Absolute Comparisons

- First comparison of seven absolute gravity meters was performed at BIPM (Sevres, France) 1981.
- International comparisons every four years, regional comparisons every two years.
- Key comparisons and pilot studies.
  - Key comparison is **validation** between certified metrological institutes (equivalent to comparing kilogram standards owned by different government agencies). Goal is to verify uncertainties
  - Pilot studies are **comparisons** and/or **calibrations** of non-metrological institutes' instruments (geodesists, for example…)
- Least-squares reduction of various meters on various piers over various days provides "degree of equivalence" between instruments measured in μGals.
- Typical agreement ~3 μGals

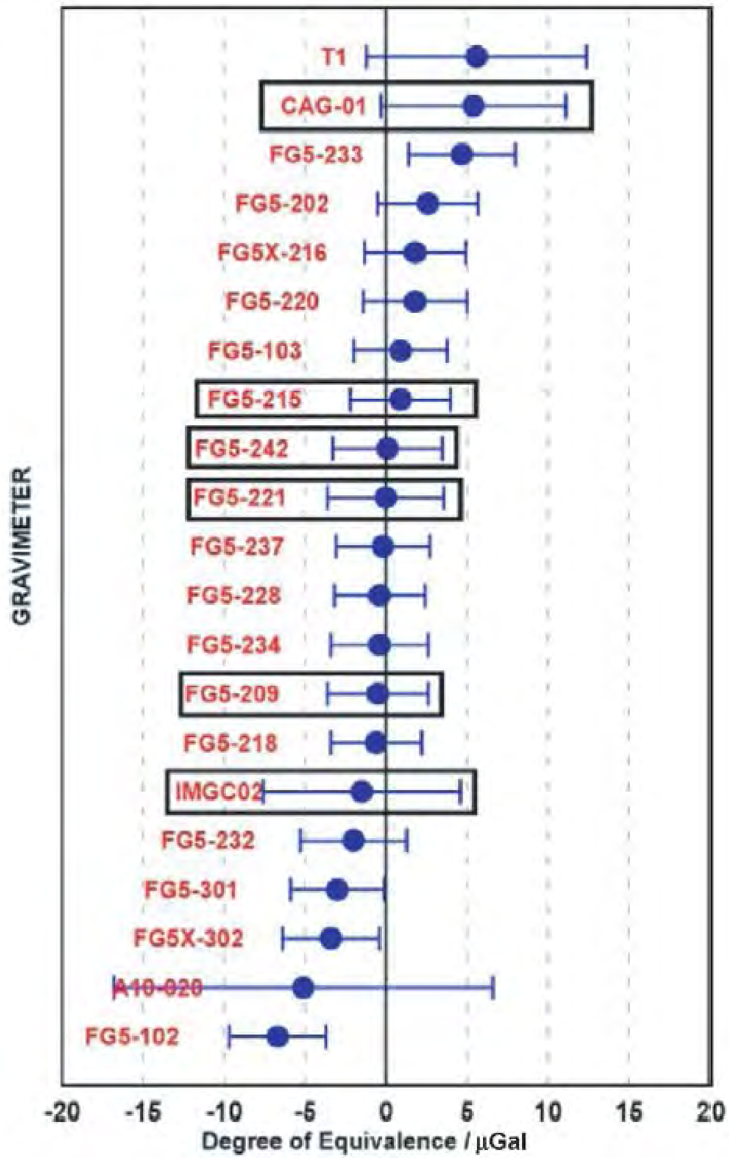
Absolute Comparisons



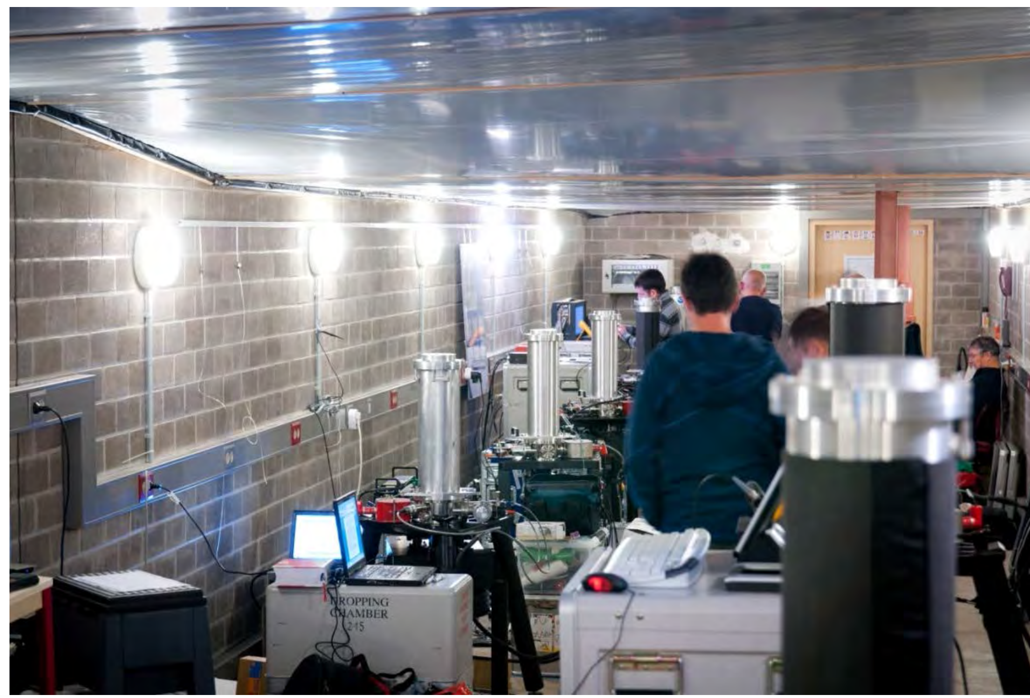
http://www.bipm.org/wg/CCM/CCM-WGG/Allowed/2015-meeting/CCM_IAG_Strategy.pdf

Airborne Gravimetry for Geodesy summer school

Absolute Comparison Results

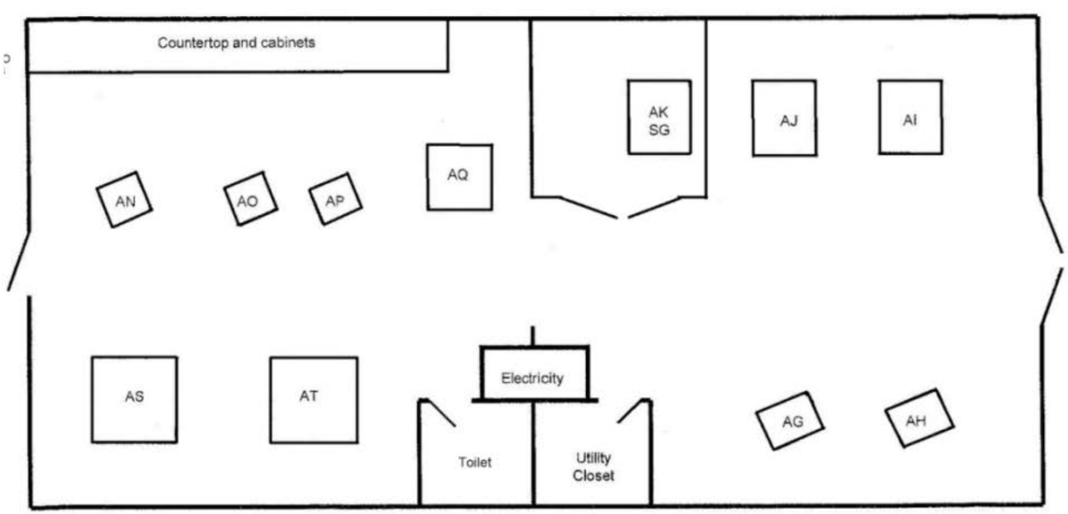


ICAG2011 Luxembourg results: σ=3.1µGal



Regional Comparison Example

- North American Comparison of Absolute Gravimeters (NACAG)
  - 1995, 1997, 2010, 2014, 2016
- 2016 will be the first certified by the CIPM
- 10 piers, ~10 instruments*, 7 countries, 5 days



*Details pending…

TMGO (aside…)

- Isolated location ~15km north of Boulder, Colorado
- Over 20 years of gravity (permanent SG, A10, FG5X, and relative meter calibration base

Going Forward: The Global Absolute Gravity Reference System

- Wziontek and Wilmes: "The global gravity reference system is [now] realized by a network of 'gravity gauges' connected by AG comparisons."
- Mean, worldwide accuracy of ~5 μGal
- Regional comparisons for temporal stability and consistency
- Local *ad hoc* networks as necessary (absolute and/or relative)

The Future

- Cold atom gravimeters
  - Continuous, long-term (~year) measurements with high temporal resolution (>1 Hz).
  - Short term (earthquakes, hydrology) and long term (geodynamics, hydrology) applications.
  - Portable
  - Easy to include in current Absolute Gravity Reference System
- Optical clocks
  - Accuracies of 10^{-18} can measure differences in geopotential directly (equivalent 1cm height resolution)
  - An absolute measurement of relative difference

Thank you for your attention!

Questions, comments?

Please don't hesitate to contact me:

derek.vanwestrum@noaa.gov