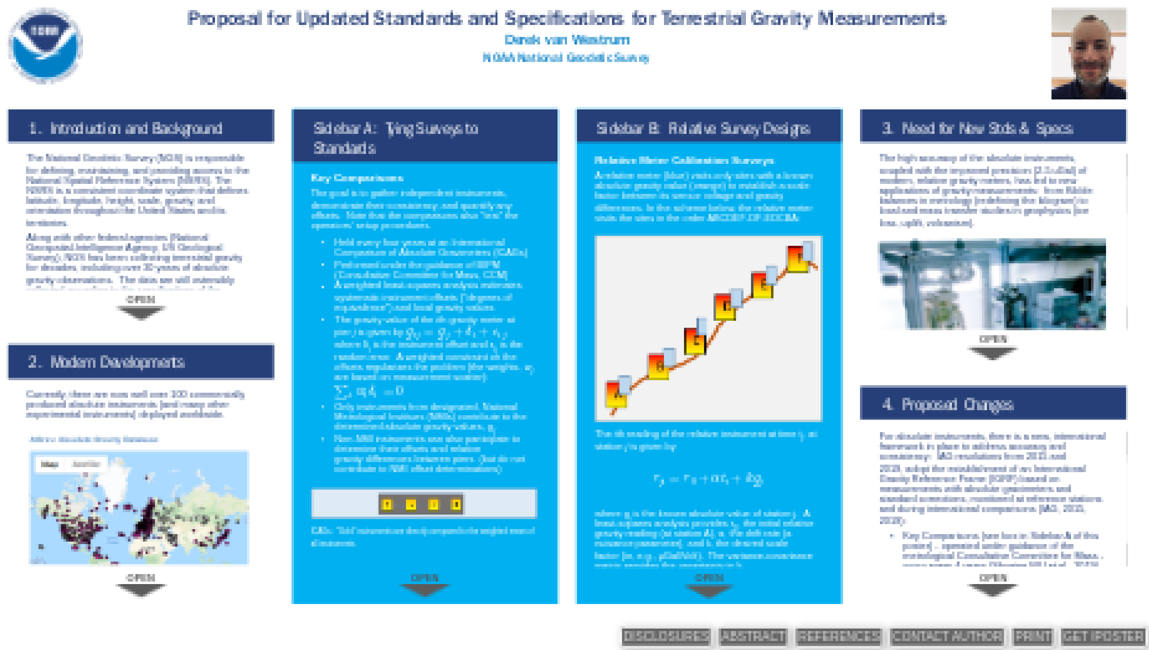
Proposal for Updated Standards and Specifications for Terrestrial Gravity Measurements



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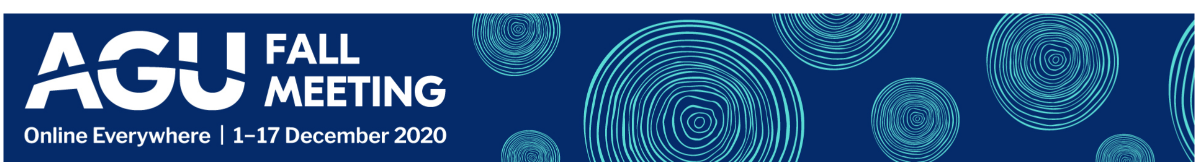
PRESENTED AT:



1. INTRODUCTION AND BACKGROUND

The National Geodetic Survey (NGS) is responsible for defining, maintaining, and providing access to the National Spatial Reference System (NSRS). The NSRS is a consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the United States and its territories.

Along with other federal agencies (National Geospatial-Intelligence Agency, US Geological Survey), NGS has been collecting terrestrial gravity for decades, including over 30 years of absolute gravity observations. The data are still ostensibly collected according to the specifications of the Federal Geodetic Control Committee (FGCC) of 1984 (FGCC 1984). Absolute instruments had just been invented, and the precision of relative measurements was solely determined from least-squares statistics on repeat measurements.

Standards and Specifications for Geodetic Control Networks

Federal Geodetic Control Committee
Rear Adm. John D. Bossler, Chairman

Rockville, Maryland
September 1984

Table 2.3—Gravity accuracy standards

Classification	*Gravity accuracy (μGal)*
First-order, class I	20 (subject to stability verification)
First-order, class II	20
Second-order	50
Third-order	100

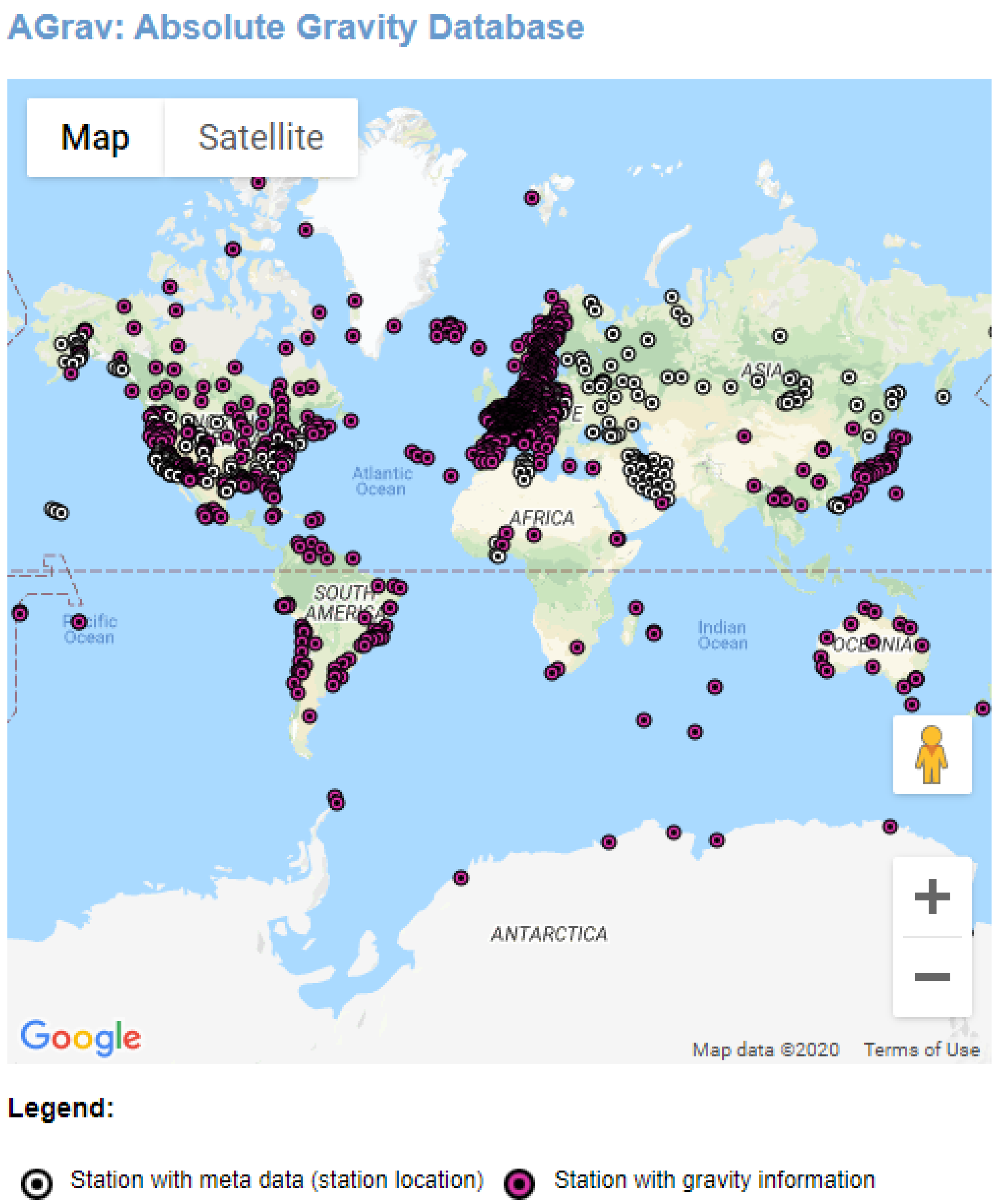
Basically, the standard (accuracy or precision) that a survey was trying to meet dictated the specifications (procedures) that were to then be followed.

And conversely, the extent to which a survey actually met the standard dictated the ultimate classification (specification) of the survey project.

This poster summarizes the developments since the 1980s - especially with regards to absolute instruments - and proposes changes to the above scheme that include relative instruments as well.

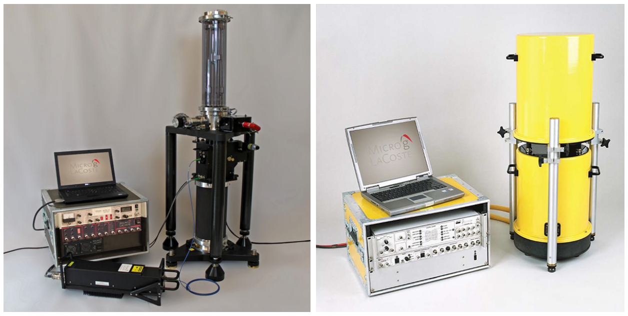
2. MODERN DEVELOPMENTS

Currently, there are now well over 100 commercially produced absolute instruments (and many other experimental instruments) deployed worldwide.



Absolute measurements are completely independent of each other and must provide their own total uncertainty estimates: these are based on measurement precision (statistical scatter in repeat measurements) and a formal systematic error budget analysis.

The laboratory-based FG5 (Niebauer et al. 2012) and field-deployable A10 (Micro-g LaCoste, Inc 2008) of Micro-g LaCoste* are currently the most ubiquitous absolute instruments. Typical total uncertainty values are 2uGal for laboratory measurements and ~10uGal for field observations.



FG5-X (left) and A-10 (right) absolute gravity meters

Final, total uncertainty estimates for each observation are provided by the instruments' software, and these are the values typically reported by the operators - irrespective of what actual setup procedures were followed.

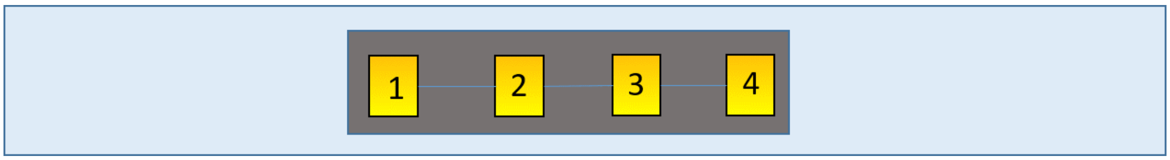
How can we insure that results from disparate instruments are accurate, repeatable, and consistent?

SIDEBAR A: TYING SURVEYS TO STANDARDS

Key Comparisons

The goal is to gather independent instruments, demonstrate their consistency, and quantify any offsets. Note that the comparisons also "test" the operators' setup procedures.

- Held every four years at an International Comparison of Absolute Gravimeters (ICAGs)
- Performed under the guidance of BIPM (Consultative Committee for Mass, CCM)
- A weighted least-squares analysis estimates systematic instrument offsets ("degrees of equivalence") and local gravity values
- The gravity value of the *i*th gravity meter at pier *j* is given by $g_{ij} = g_j + \delta_i + \epsilon_{ij}$ where δ_i is the instrument offset and ε_{ij} is the random error. A weighted constraint on the offsets regularizes the problem (the weights, w_i, are based on measurement scatter): $\sum_i w_i \delta_i = 0$
- Only instruments from designated, National Metrological Institues (NMIs) contribute to the determined absolute gravity values, g_j.
- Non-NMI instruments can also participate to determine their offsets and relative gravity differences between piers (but do not contribute to NMI offset determinations)

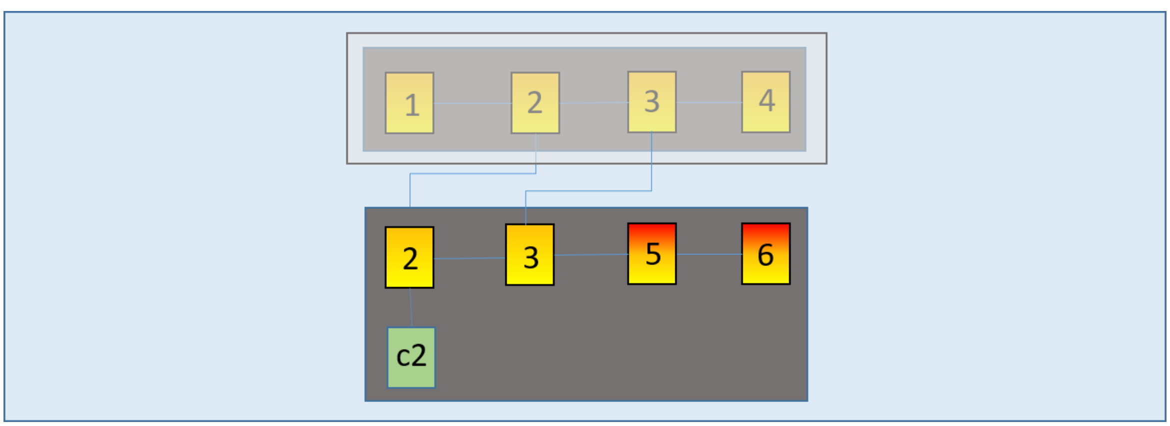


ICAGs: "Gold" instruments are directly compared to the weighted mean of all instruments

Regional Comparisons (RCAGs)

Because not every absolute instrument can take part in the ICAG, regional comparisons are held.

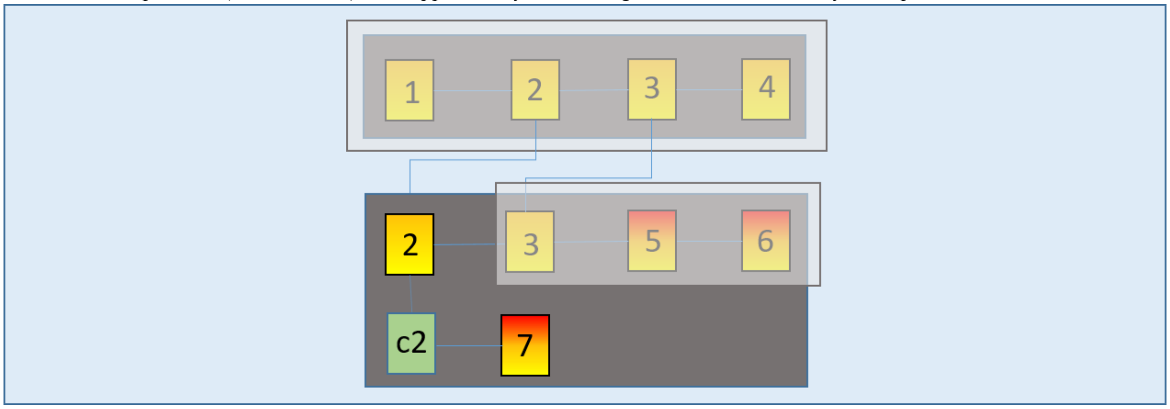
- At least every two years
- Currently in North America, Europe, and Asia
- Results reported to the CCM
- The ICAG-determined instrument offsets are carrried through and used to determine offsets of other (usually non-NMI) instruments
- The absolute meters can also calibrate and control the drift of continuous relative meters



RCAGs: Biases on-NMI instruments (5, 6) are estimated by comparing with ICAG instruments (2, 3). The offsets of 2 and 3 are made to sum to their values at the ICAG.

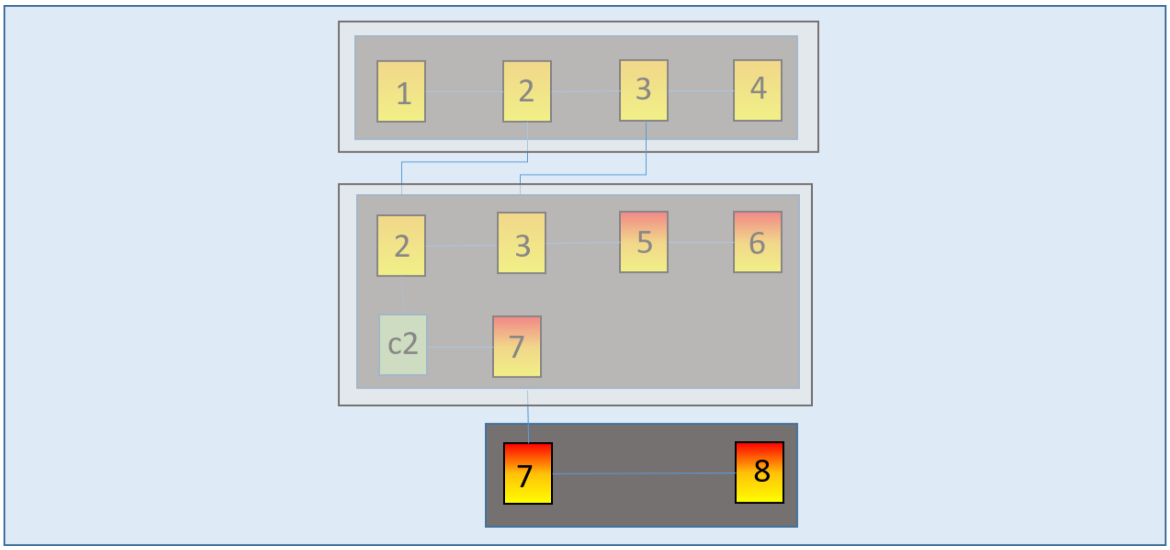
Ad Hoc/Additional Comparisons

Additional comparisons (mini-RCAGs) can happen at any time, though the results are usually not reported to the CCM



Ad hoc comparisons: Here, instrument 7 is compared either directly with 2 or with a time series from the continuous, relative meter c2

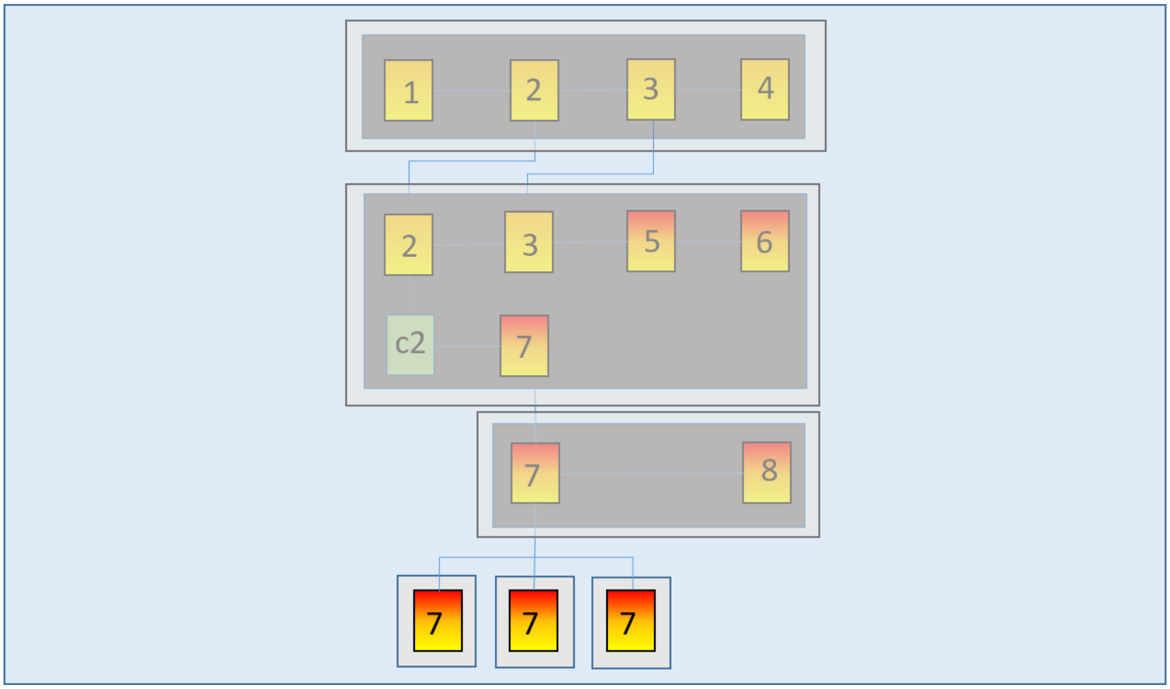
Of course, this chain can be extended indefinitely, with each step taking into account the instrument offsets (with uncertainties) back to the ICAG



Extending the link from ICAG, down to other absolute instruments.

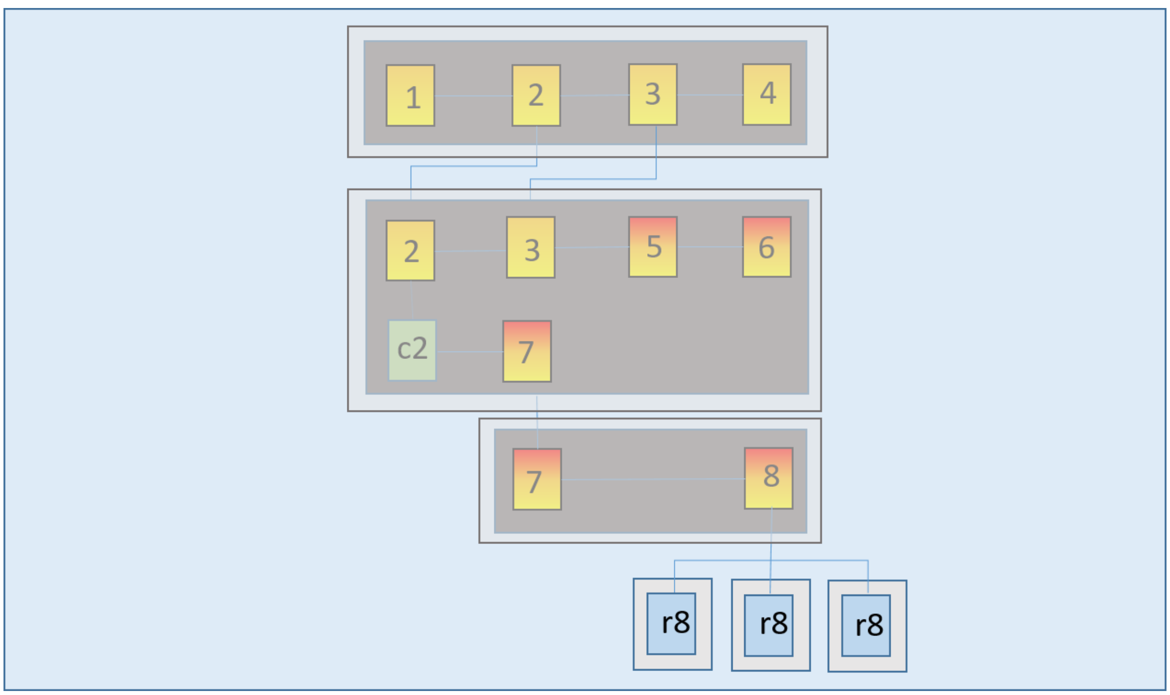
Absolute Field Surveys

With instrument biases controlled and procedures determined to produce consistent results, the absolute instruments can perform field work...



Instrument 7 deployed over multiple field sites.

... or they can be used to calibrate and control relative field isntruments (see "Relative Survey Designs" to the right)

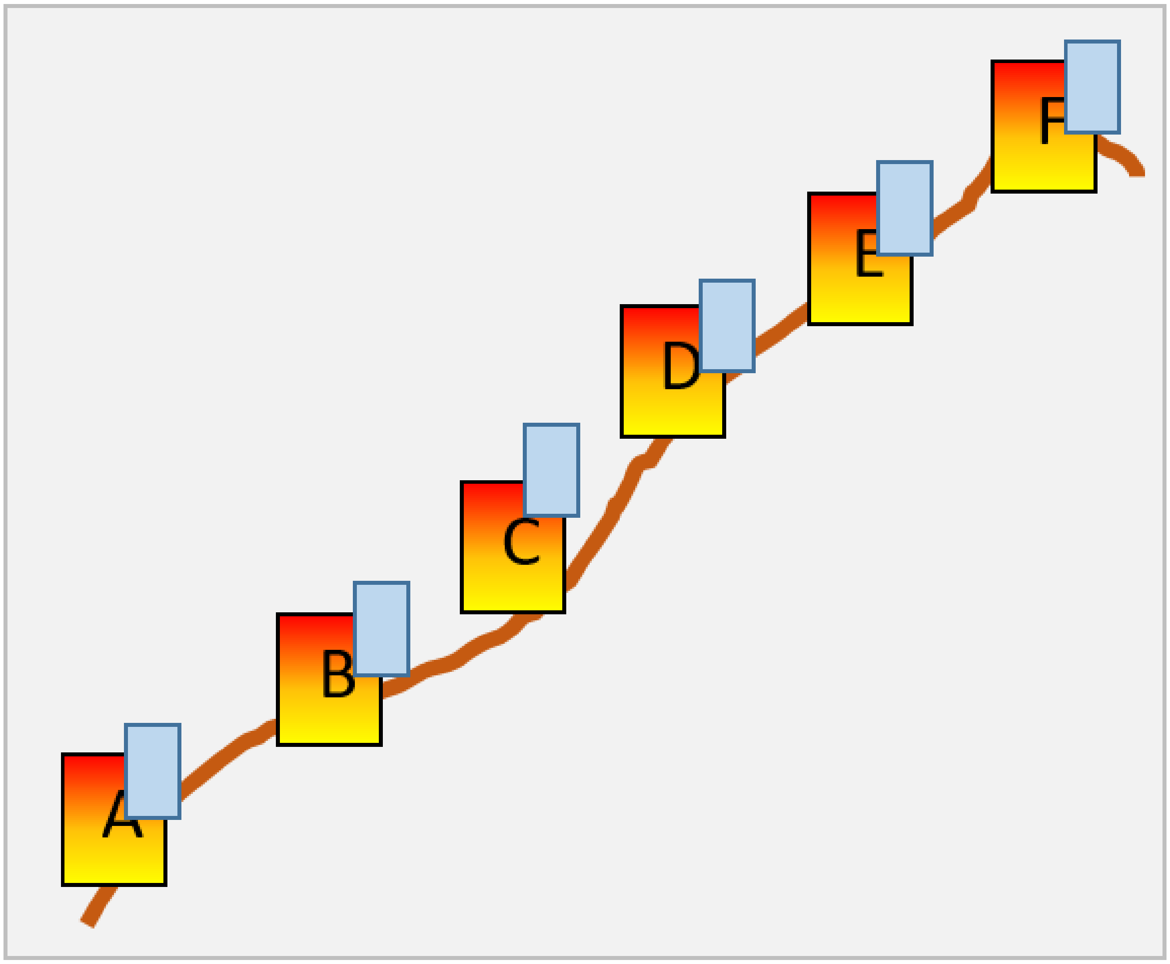


Relative instrument, r8, deployed at multiple field sites.

SIDEBAR B: RELATIVE SURVEY DESIGNS

Relative Meter Calibration Surveys

A relative meter (blue) visits only sites with a known absolute gravity value (orange) to establish a scale factor between its sensor voltage and gravity differences. In the scheme below, the relative meter visits the sites in the order ABCDEF-DF-EDCBA:



The *i*th reading of the relative instrument at time t_i, at station *j* is given by

$$r_{ji} = r_0 + \alpha t_i + k g_j$$

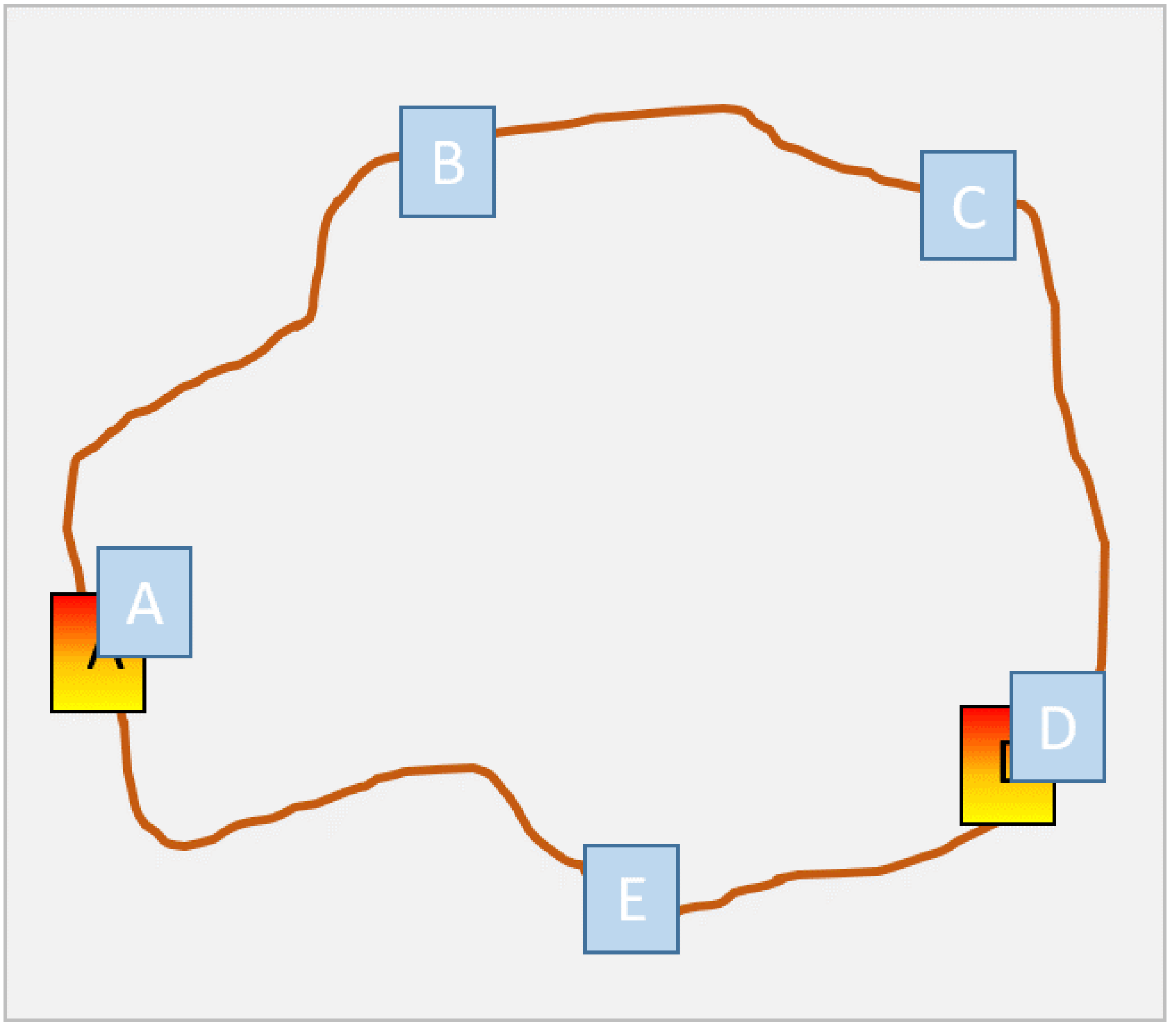
where g_j is the known absolute value of station j. A least-squares analysis provides r_0, the initial relative gravity reading (at station A), α, the drift rate (a nuisance parameter), and k, the desired scale factor (in, e.g., μGal/Volt). The variance-covariance matrix provides the uncertainty in k.

Note that:

- The uncertainty in the absolute measurements, g_j, should be propagated into the uncertainty of k
- An instrument offset in the absolute measurements will not contribute to uncertainty in k.

Relative Loop Surveys

With a k factor established for a relative meter, the instrument can then be employed to measure gravity differences in a "loop" (below) or "ladder" scheme. These are typically tied to one or more absolute "base stations" (sites A and D in this example).



The ith reading of the relative instrument at the jth station is given by:

$$r_{ji} = g_0 + \alpha t_i + r_j$$

where again, we fit for the initial relative reading, g_0, the drift, α, and the relative gravity differences between stations, r_j. We also include the absolute information using "pseudo observations" that anchor the relative values:

$$g_j = \hat{g}_j$$

for only the absolute sites. We then perform a weighted least squares with the relative site occupation weights including (in quadrature)

- k factor uncertainty
- absolute site uncertainty
- relative meter statistical uncertainty

and the absolute site occupation weights including only

- absolute site uncertainty.

The output is the offset between the relative reading and the first absolute station, g_0, the full field gravity at all stations, tied to absolute values, and the nuisance drift rate value.

An example using our loop above. We solve the matrix equation **y** = **Xa**, for the parameter vector, a:

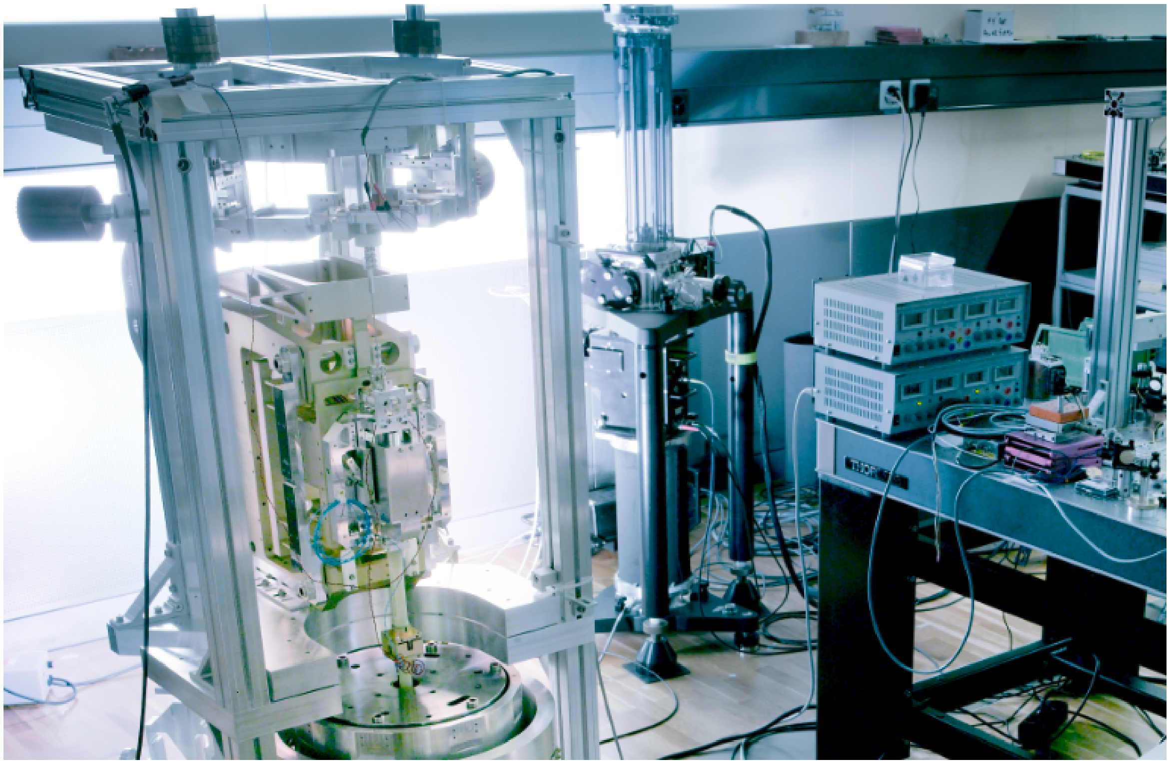
$$\begin{pmatrix} r_{A1} \\ r_{B1} \\ r_{C1} \\ r_{D1} \\ r_{E1} \\ r_{A2} \\ g_A \\ g_D \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & t_{A1} \\ 1 & 0 & 1 & 0 & 0 & 0 & t_{B1} \\ 1 & 0 & 0 & 1 & 0 & 0 & t_{C1} \\ 1 & 0 & 0 & 0 & 1 & 0 & t_{D1} \\ 1 & 0 & 0 & 0 & 0 & 1 & t_{E1} \\ 1 & 1 & 0 & 0 & 0 & 0 & t_{A2} \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \hat{g}_0 \\ \hat{g}_A \\ \hat{g}_B \\ \hat{g}_C \\ \hat{g}_D \\ \hat{g}_E \\ \alpha \end{pmatrix}$$

where the obsevation weights are given by

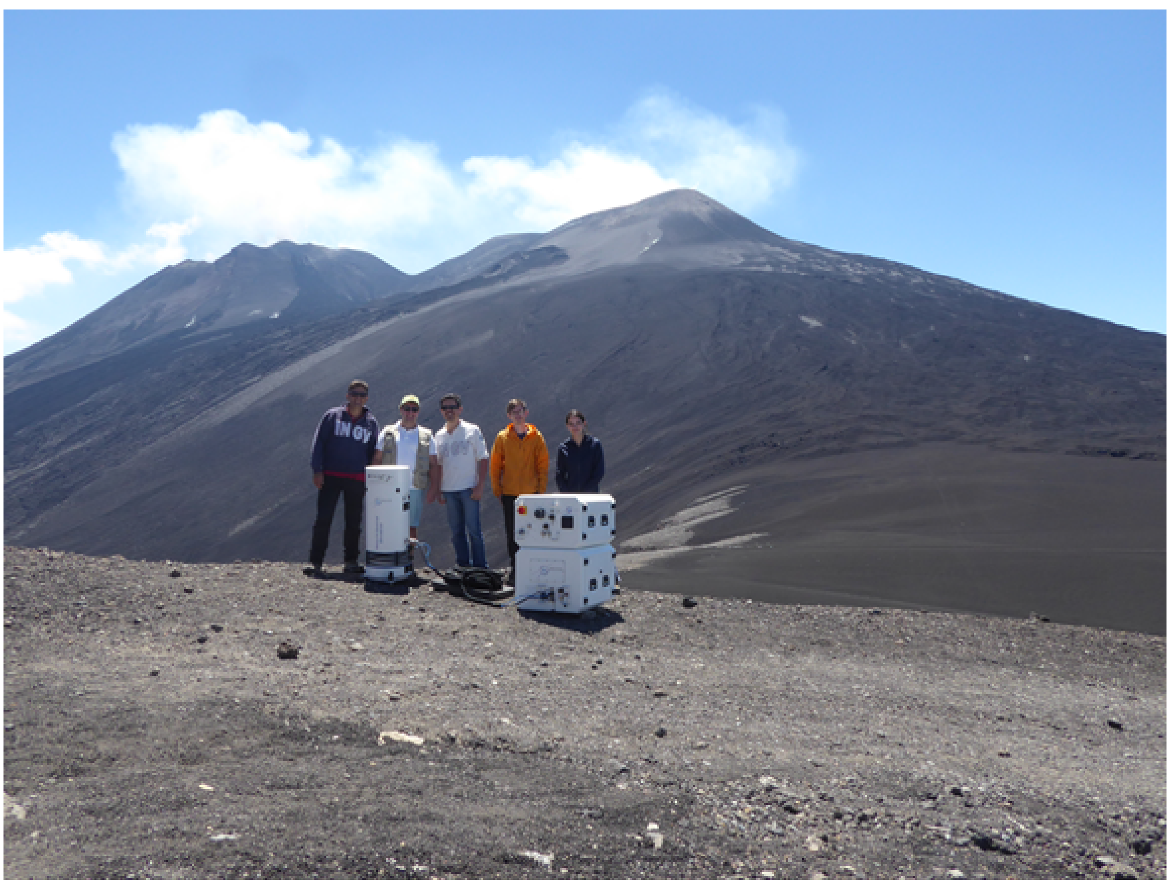
$$w^2 = \begin{pmatrix} u_k^2 + u_{A1}^2 \\ u_k^2 + u_{B1}^2 \\ u_k^2 + u_{C1}^2 \\ u_k^2 + u_{D1}^2 \\ u_k^2 + u_{E1}^2 \\ u_k^2 + u_{A2}^2 \\ u_A^2 \\ u_D^2 \end{pmatrix}$$

3. NEED FOR NEW STDS & SPECS

The high accuracy of the absolute instruments, coupled with the improved precision (2-5 uGal) of modern, relative gravity meters, has led to new applications of gravity measurements: from Kibble balances in metrology (redefining the kilogram) to local and mass transfer studies in geophysics (ice loss, uplift, volcanism).



Kibble balance at METAS, Switzerland with FG5 in background



MuQuans quantum gravity meter on Mt. Etna

These applications require the highest levels of accuracy and precision, and it is clear that consistency among the independent absolute measurements must be insured. Further, the various components of the absolute instruments (laser and clock frequencies) must be tied to international standards for metrological applications.

Finally, a uniform set of processing procedures (luni-solar tide corrections, ocean loading, polar motion, etc.) also need to be prescribed (Makinen 2018).

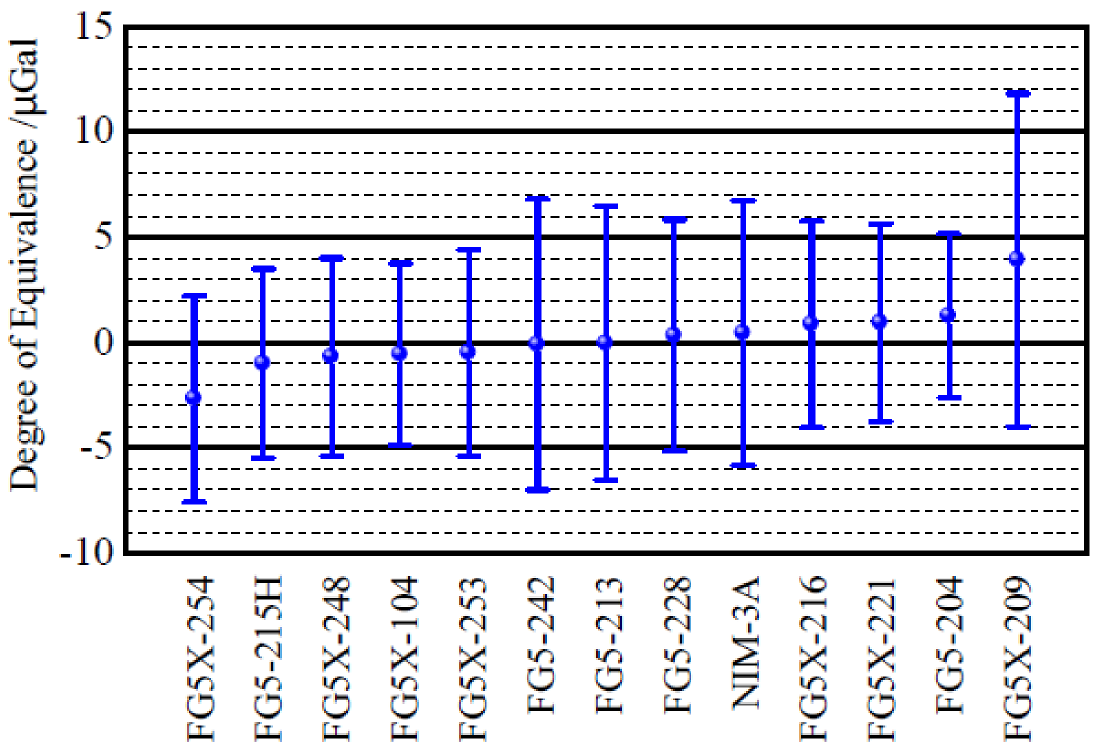
The current FGCC standards and specifications do not address these concerns. There is no mechanism to quantify absolute accuracy and consistency, and no way to rigorously tie relative measurements to absolute standards.

4. PROPOSED CHANGES

For absolute instruments, there is a new, international framework in place to address accuracy and consistency: IAG resolutions from 2015 and 2019, adopt the establishment of an International Gravity Reference Frame (IGRF) based on measurements with absolute gravimeters and standard corrections, monitored at reference stations and during international comparisons (IAG, 2015, 2019):

- Key Comparisons (see box in Sidebar A of this poster) - operated under guidance of the metrological Consultative Committee for Mass - occur every 4 years (Shuqing WU et al., 2019). These provide quantifiable offsets of each participating instrument from a weighted mean of all observations (referred to as "degrees of equivalence" between the gravity meters). These define the current international "standards" in gravity.

ICAG2017 at NIM China



Results of the ICAG2017. Instrument offsets are determined relative to the weighted mean of all instruments.

- These metrological instruments then participate in Regional Comparisons to facilitate traceability back to the standard.
- If needed, other ad hoc absolute instruments can, in turn, compare with these, lengthening the chain but still providing a link to the standard.
- Note that these comparisons also inherently account for any operator/procedural setup issues (specifications).

For the US, the FGCC standards and specifications need to be updated to reflect these international developments.

- We propose to abandon the idea that specifications are chosen to meet a predetermined standard. Rather, we will follow the IAG prescriptions for absolute measurements where instrument offsets and uncertainties are traced to absolute comparisons.

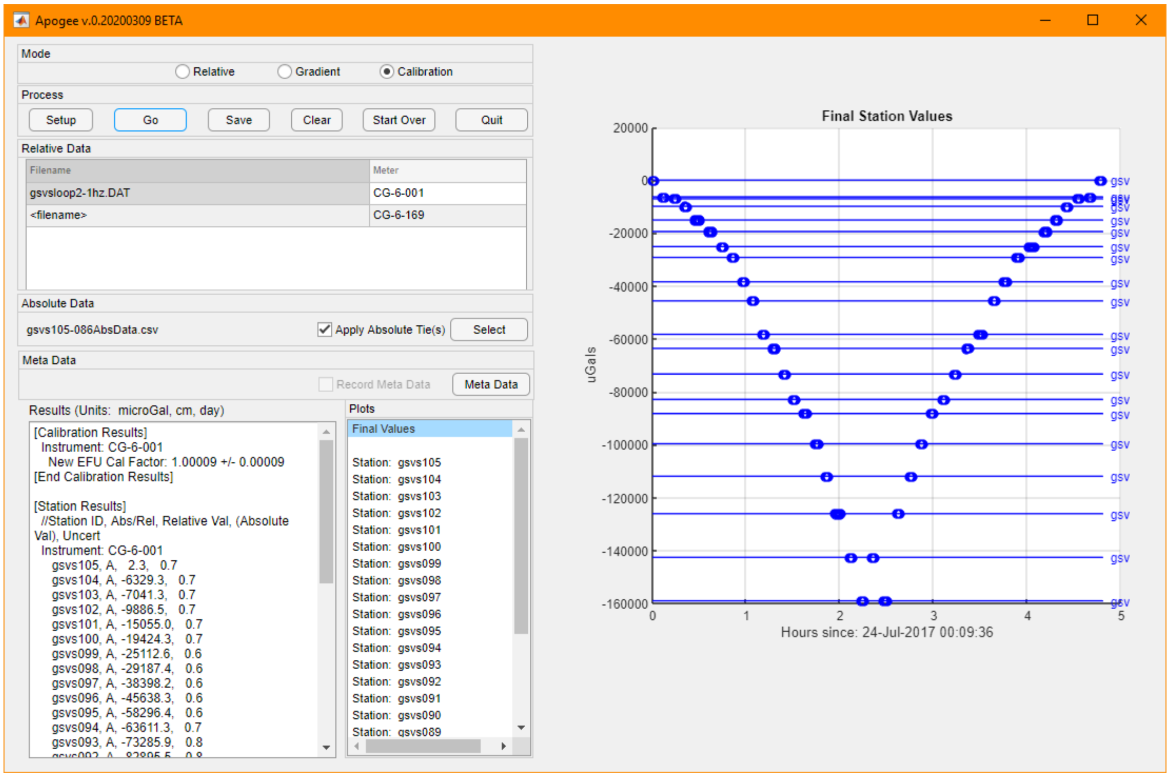
Standards and Specificaitons for Relative Instruments

We propose to expand this traceability to relative gravity observations (see Sidebar B of this poster):

- A relative instrument must have its scale factor (and scale factor uncertainty) calibrated against traceable absolute instrument(s).
- Note that an overall offset in an absolute meter cancels in relative difference measurements, but the scale is critical.
- Further, absolute base stations used in relative "loop" surveys must also be tied to the comparison chain.
- If a measurement cannot demonstrate a link to an absolute comparison chain, its overall uncertainty will be increased by some factor that is still to be determined (2X, 5X?)

NGS has published a beta version of its Apogee relative gravity processing software (van Westrum 2019) that:

- can determine a relative instrument's scale factor (and uncertainty) over occupations of sites with known absolute values
- uses a Gauss-Markov model with fixed constraints to reduce relative survey loops containing absolute base station(s)
- propagates the uncertainty in the scale factor (not normally accounted for).
- can fit for vertical gradients at fixed heights over a bench mark, again properly propagating the scale factor uncertainty
- simultaneously fits for - and removes - instrument drift as well as possible offsets (tares) between site occupations.



Apogee software in instrument calibration mode.

We welcome your questions, thoughts, concerns, and ideas. Contact the author at derek.vanwestrum@noaa.gov

DISCLOSURES

*The use of commercial products does not imply endorsement by NOAA.

ABSTRACT

The mission of the National Geodetic Survey (NGS) is to define, maintain and provide access to the National Spatial Reference System (NSRS). The NSRS provides a consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the United States and its territories. The current standards and specifications for acquiring and processing terrestrial gravity data date back to 1984, long before the now common use of portable absolute gravity meters and modern relative instruments. We present a proposal for a detailed update of these standards and specifications, which is consistent with the latest resolutions of the International Association of Geodesy: absolute gravity meter accuracies will be traced to international comparisons, and these can, in turn, be linked to other instruments through regional comparisons and fundamental gravity sites. Calibration procedures based on absolute observations will also quantify the accuracy of relative instruments as well.

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