Field Calibration of Weak Motion Sensors using a Strong Motion Accelerometer as Reference

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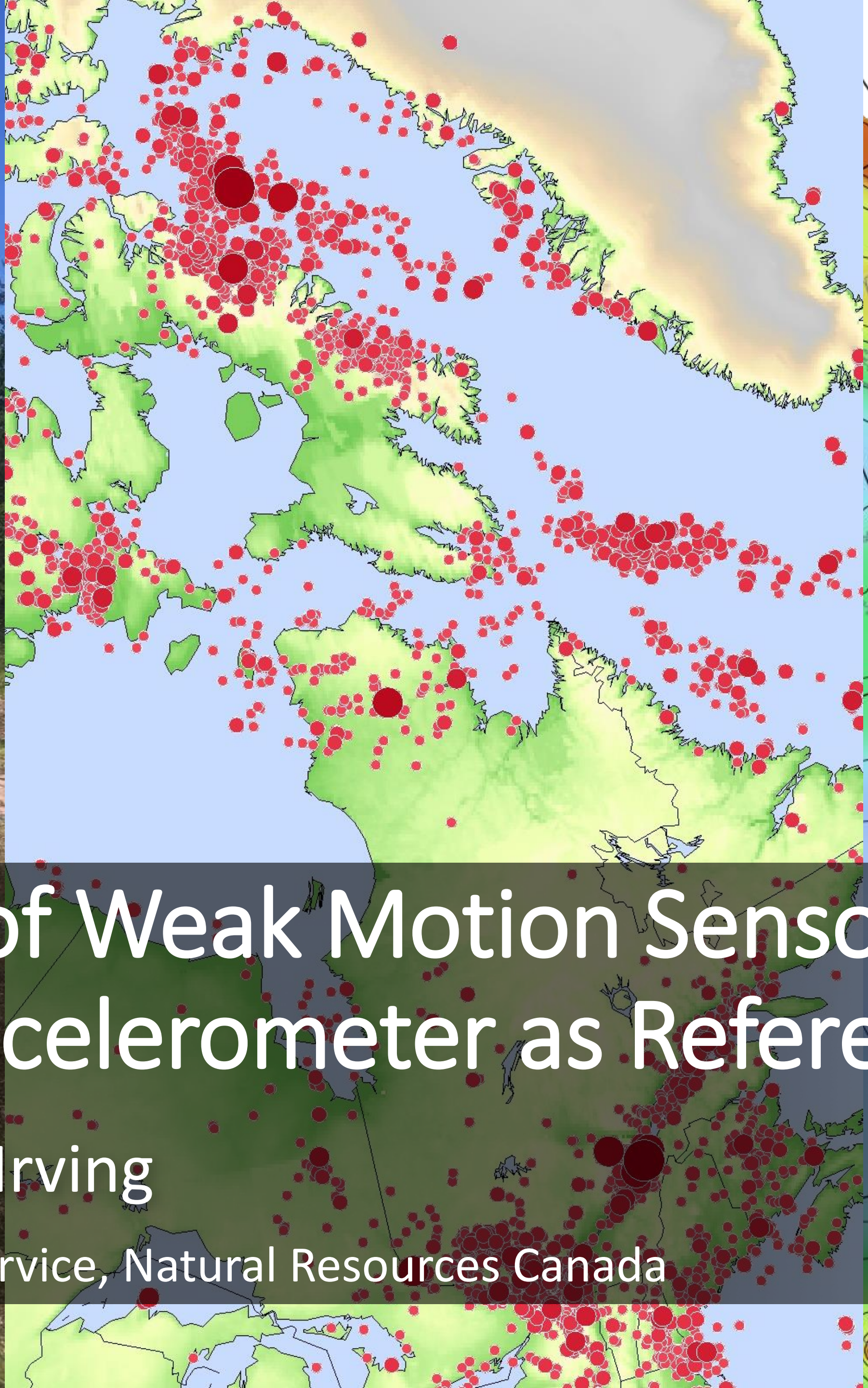
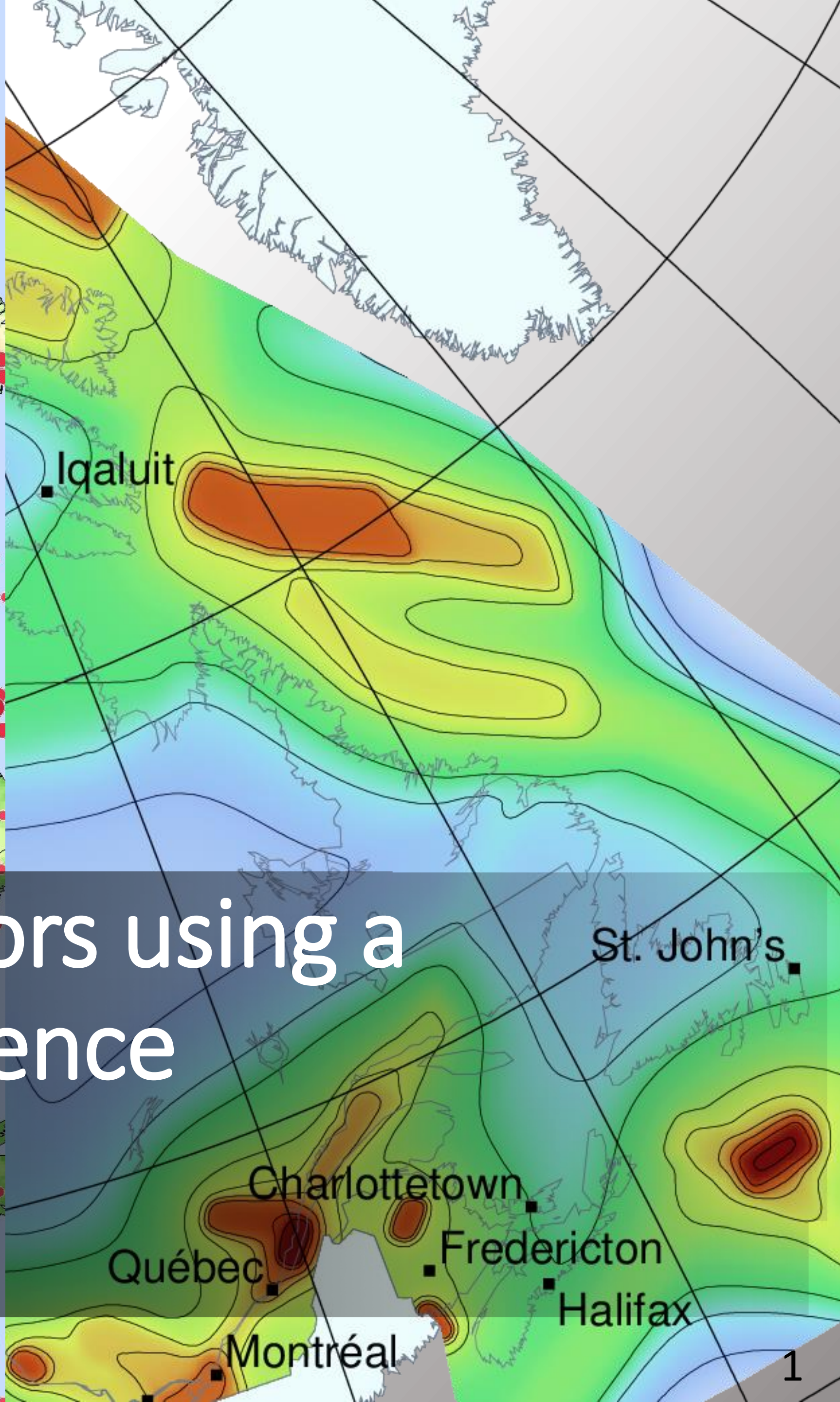




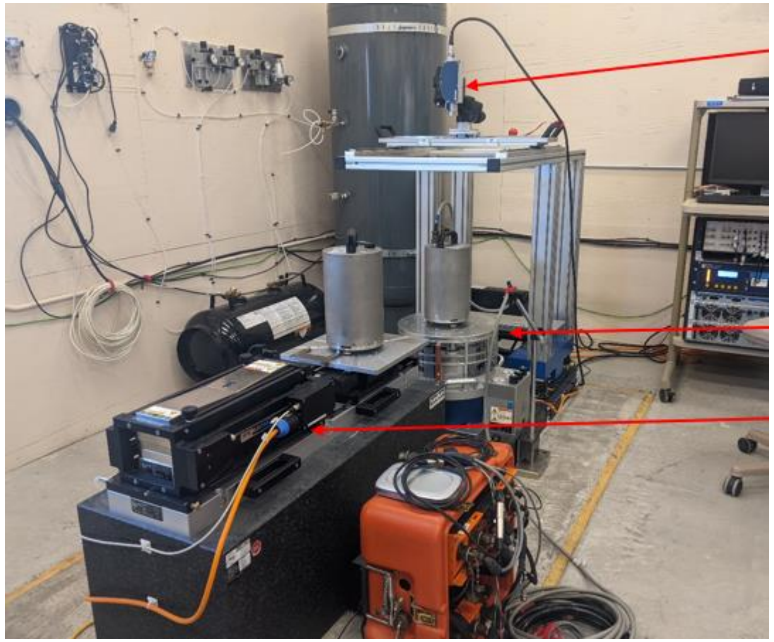
Current absolute seismometer calibration methods have issues at frequency band edges and in transportation of reference

1. Traceable lab-calibration of broadband seismometers

- Accuracy decreases at upper and lower corners (100 s, 100 Hz)
- Not yet accounting for temperature

2. Transportation of lab-calibrated sensor to field for side-by-side testing

- Accuracy decreases away from mid-band
- Requires that transfer function does not change in transport

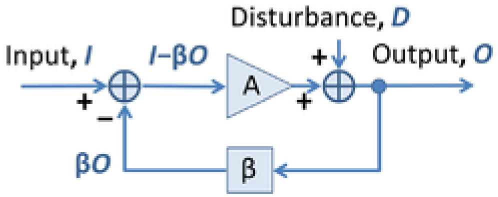


Laboratory absolute calibration setup with shake table and laser (Bloomquist, Merchant, & Slad, 2023)

Klaus, Bruns, Canu, Larsonnier, Winther (2023) “Challenges of Low Frequency Seismometer Calibrations”
Bloomquist, Merchant, Slad (2023) “High Frequency Ground Motion Calibrations of Seismometers used at IMS Stations”
Schwardt et al. (2023) “Determination of the Frequency Response of Seismic and Infrasonic IMS Station Sensors Using an On-Site Calibration Approach”

The main benefit of a mechanical calibration is to verify operation of the force transducer

A feedback control system has a forward path A and a feedback path β:

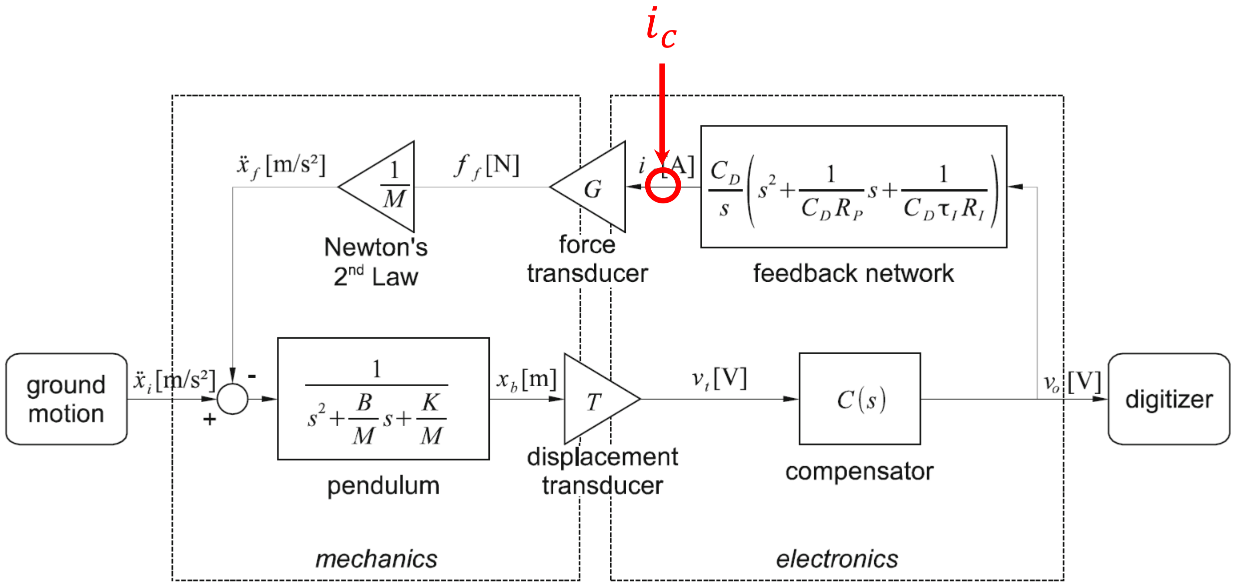


A basic property is that for sufficiently high loop-gain, the transfer function is determined by the feedback path alone:

$$\frac{O}{I} = \frac{A}{1 + A\beta} \cong \frac{1}{\beta}$$

In a force-feedback inertial sensor, an electrical calibration:

- Should not alter the loop gain
- May introduce a low-pass filter
- Injects current into the force transducer



During electrical calibration, the force transducer becomes part of the forward path. It is not part of the closed-loop response.

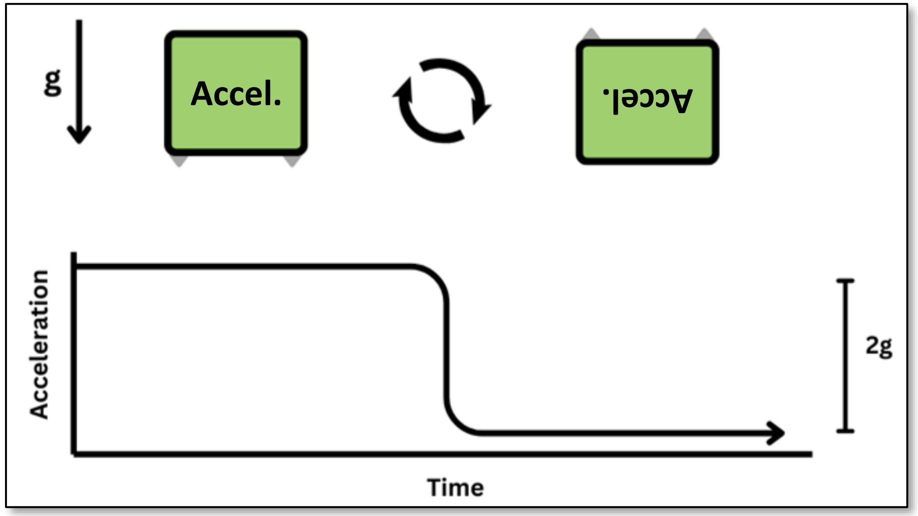
Left: https://en.wikipedia.org/wiki/Negative_feedback. Right: Fig. 6 from Ackerley, N. (2015). Principles of broadband seismometry. In *Encyclopedia of earthquake engineering* (pp. 1941-1970). Springer, Berlin, Heidelberg.

Your reference sensor can be calibrated in the field, and immediately compared to a sensor under test

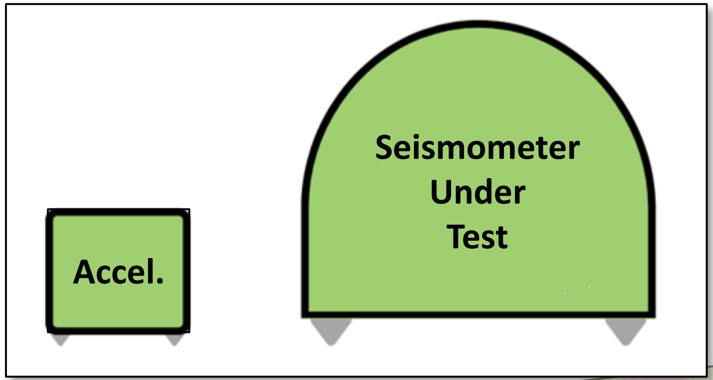
Method:

1. Absolute calibration of reference strong-motion accelerometer using gravity (slide 4)
   - Sensitivity is affected by temperature (slide 5)
   - Need to account for local gravity (slides 6-8)
2. Side-by-side relative calibration of instrument under test at mid-band (slide 9)
   - Only valid where SNR is high, around 0.2 Hz (slide 10)
   - Trade-off between duration x SNR and accuracy (slide 11)
3. Electrical calibration of both sensors across full frequency band (slide 12)
4. Combine results and propagate errors (slides 13-16)

1.



2.

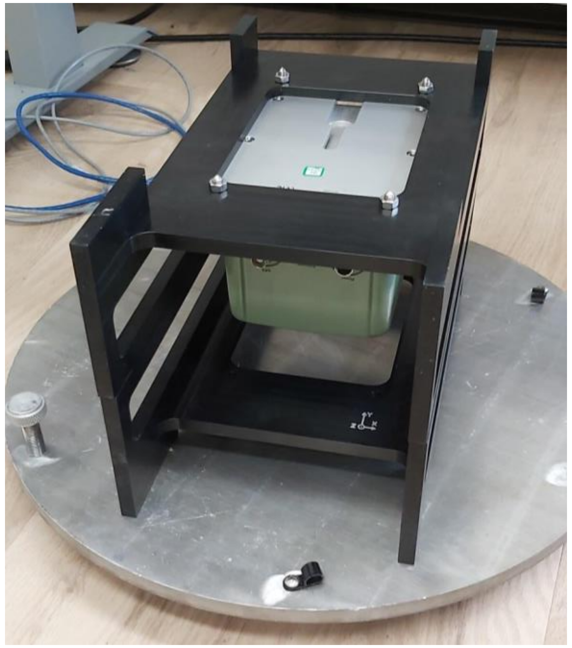


Step 1: Absolute Accelerometer Calibration

- Difference between upright and upside-down readings gives twice the sensitivity to gravity

$$S_z = \frac{1}{2\ \mathrm{g}}(Z_{upright} - Z_{inverted})$$

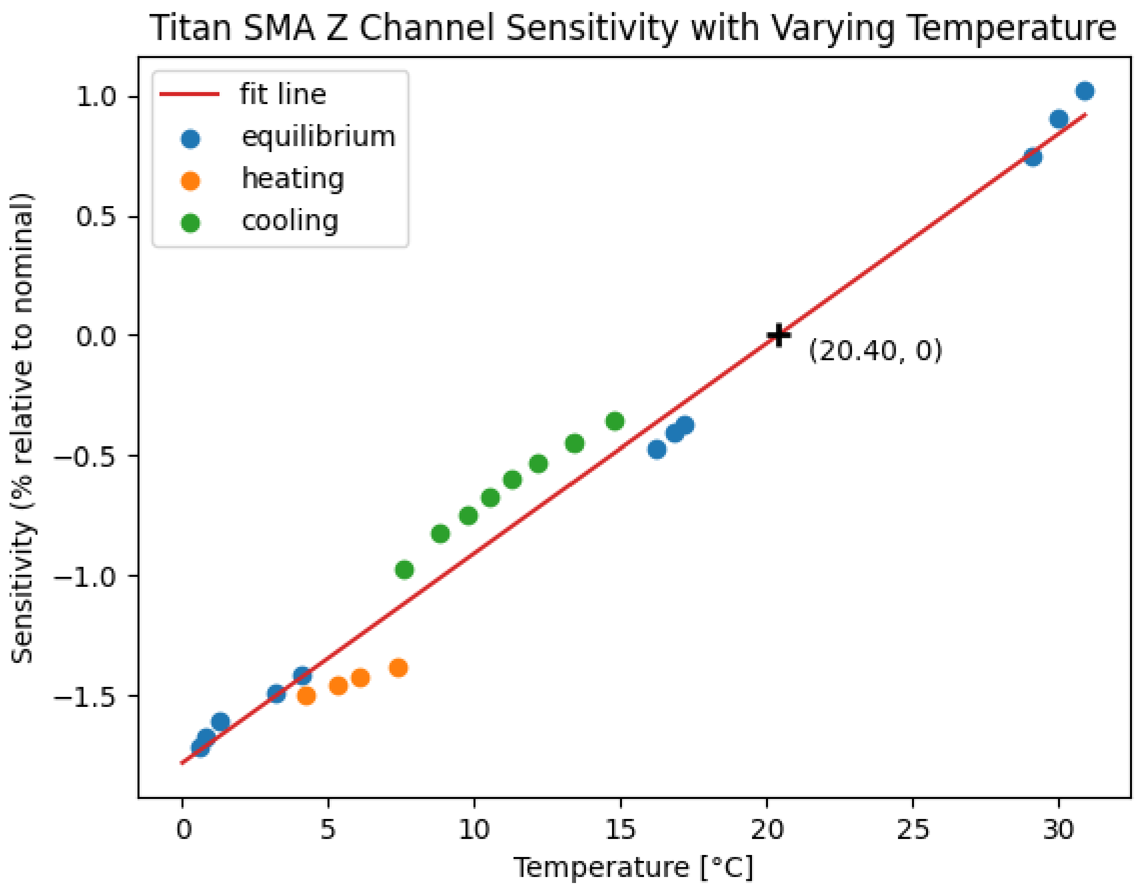
- Instrument must have clip level > 2 g
- Works for horizontal axes as well
- Could be extended to give off-axes sensitivities
- Requires a “six-sided box” jig permitting accurate placement on 6 sides, and a flat & level surface
- We have developed a tool which outputs StationXML with calibrated response



Titan SMA bolted into trimming jig on top of leveling plate

Step 1a: Temperature is important

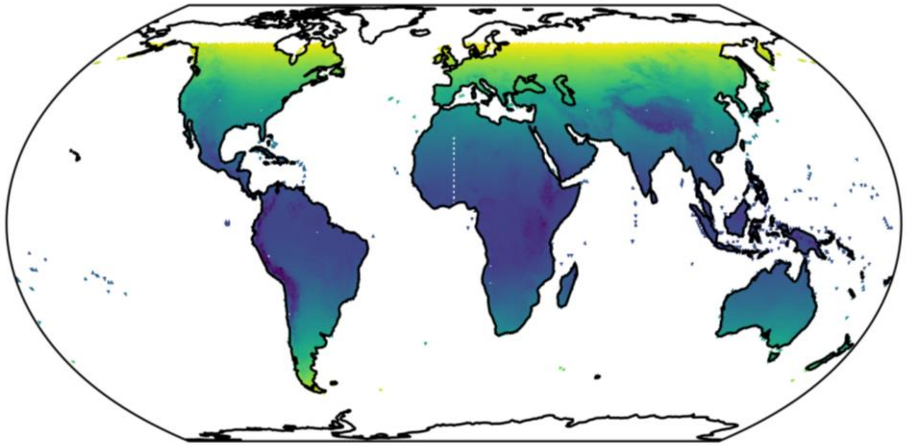
- Sensitivity of the Titan SMA varies ~2.5% from 0 to 30 °C
- Results differ while the instrument is heating or cooling
- Conclusion: Wait for temperature to stabilize before comparing data

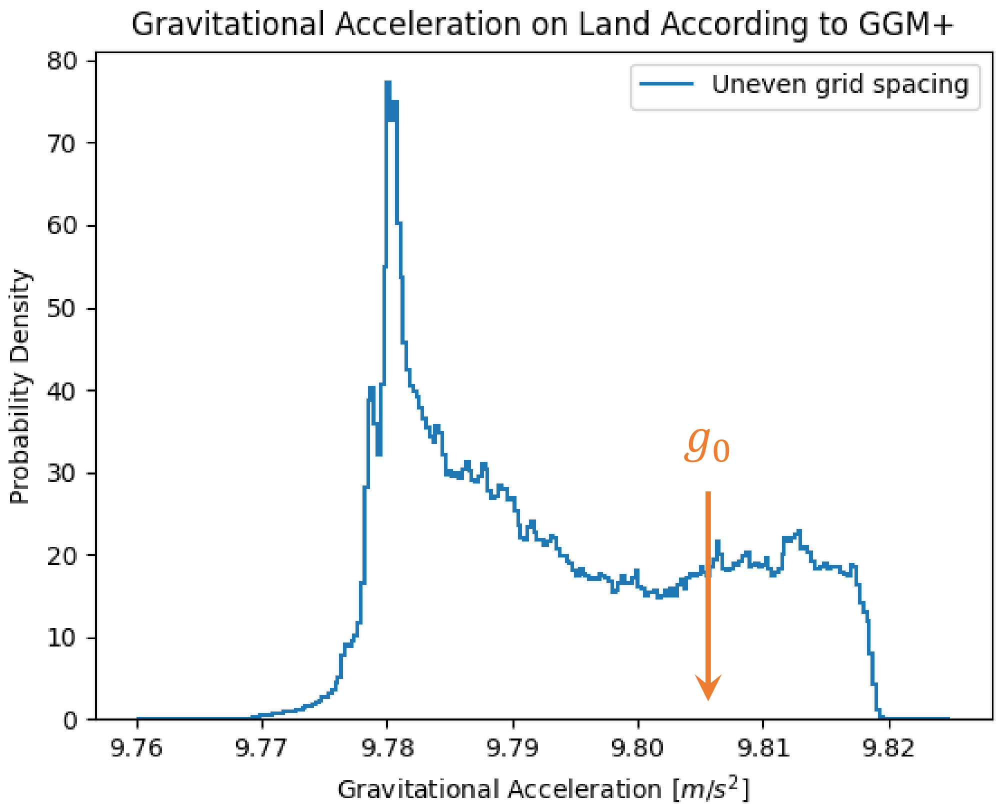


Step 1b: Accounting for Local Gravity

- Using GGM+ model for gravitational acceleration on the Earth's surface
  - GRACE satellite gravimetry
  - Resolution improved by accounting for topography (SRTM)

GGM+ Gravitational Acceleration using 1 Degree Spaced GeoTess Grid





Hirt, C., S. Claessens, T. Fecher, M. Kuhn, R. Pail, and M. Rexer (2013), New ultrahigh-resolution picture of Earth's gravity field, *Geophys. Res. Lett.*, 40, 4279–4283, doi:10.1002/grl.50838.

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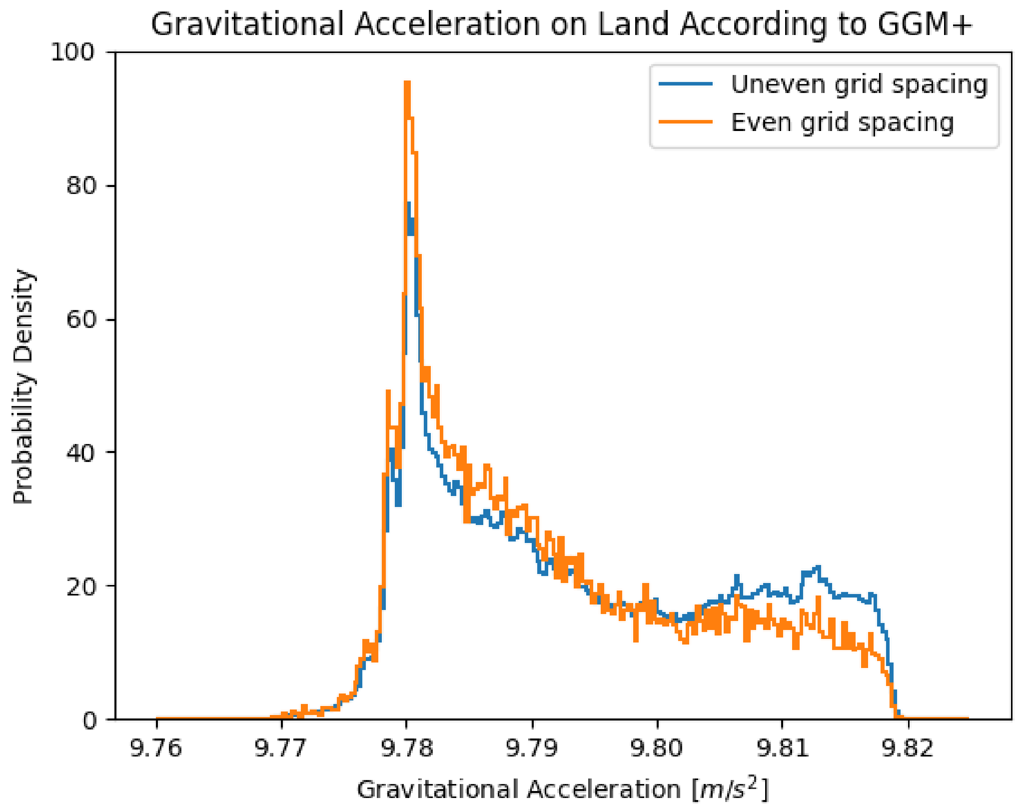
- Re-gridded using GeoTess evenly space grid
  - Saves disk space
  - Better represents likelihood of finding any particular value of *g* on Earth



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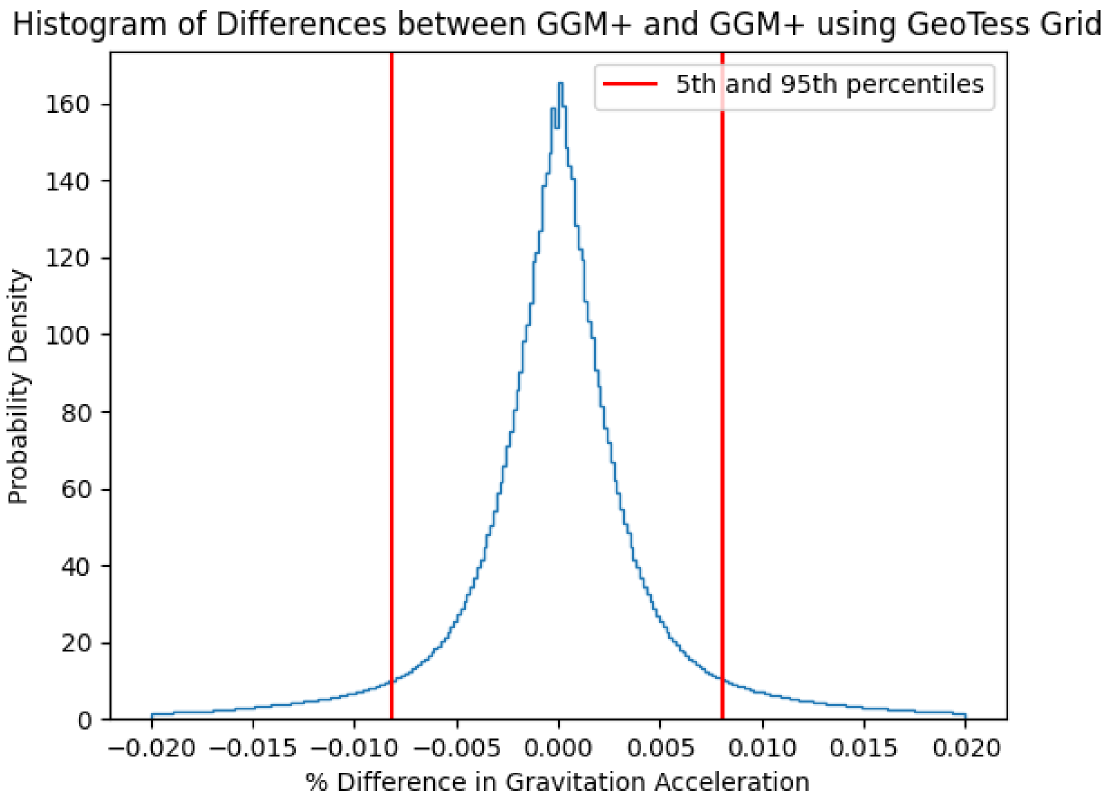

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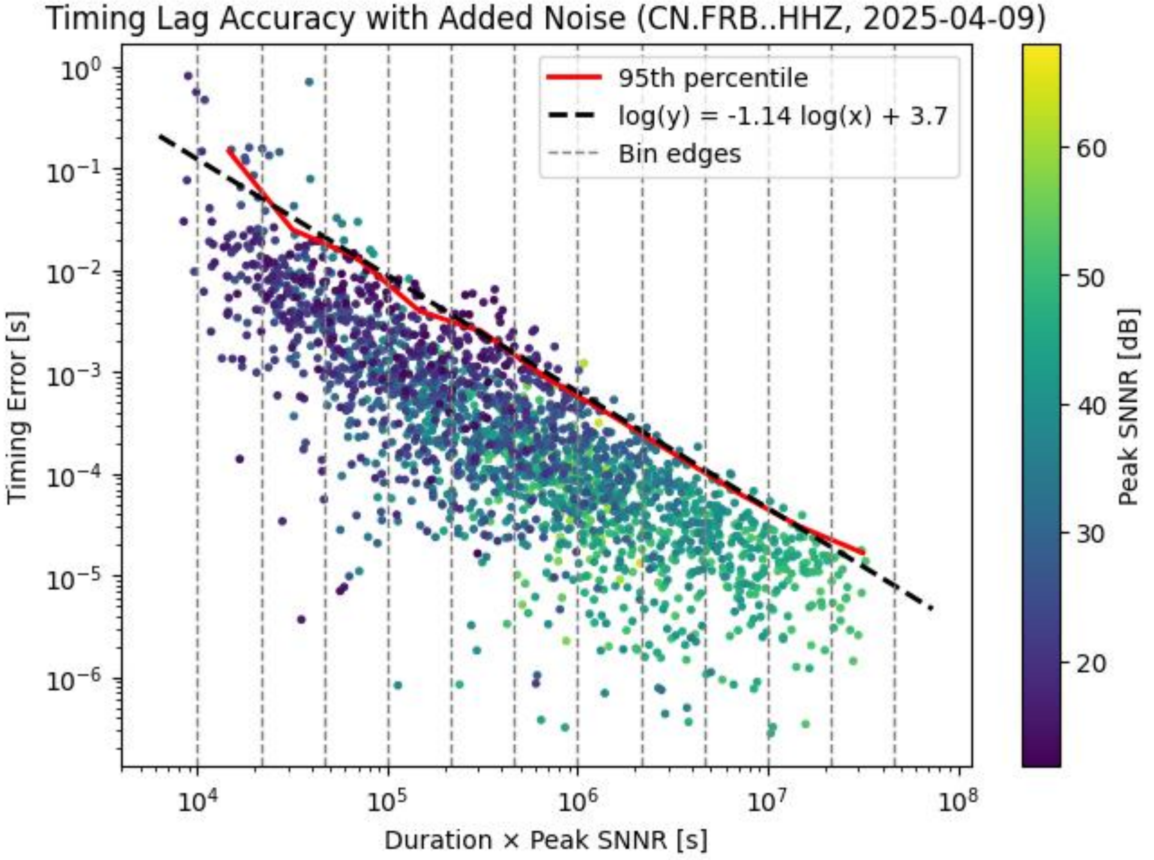
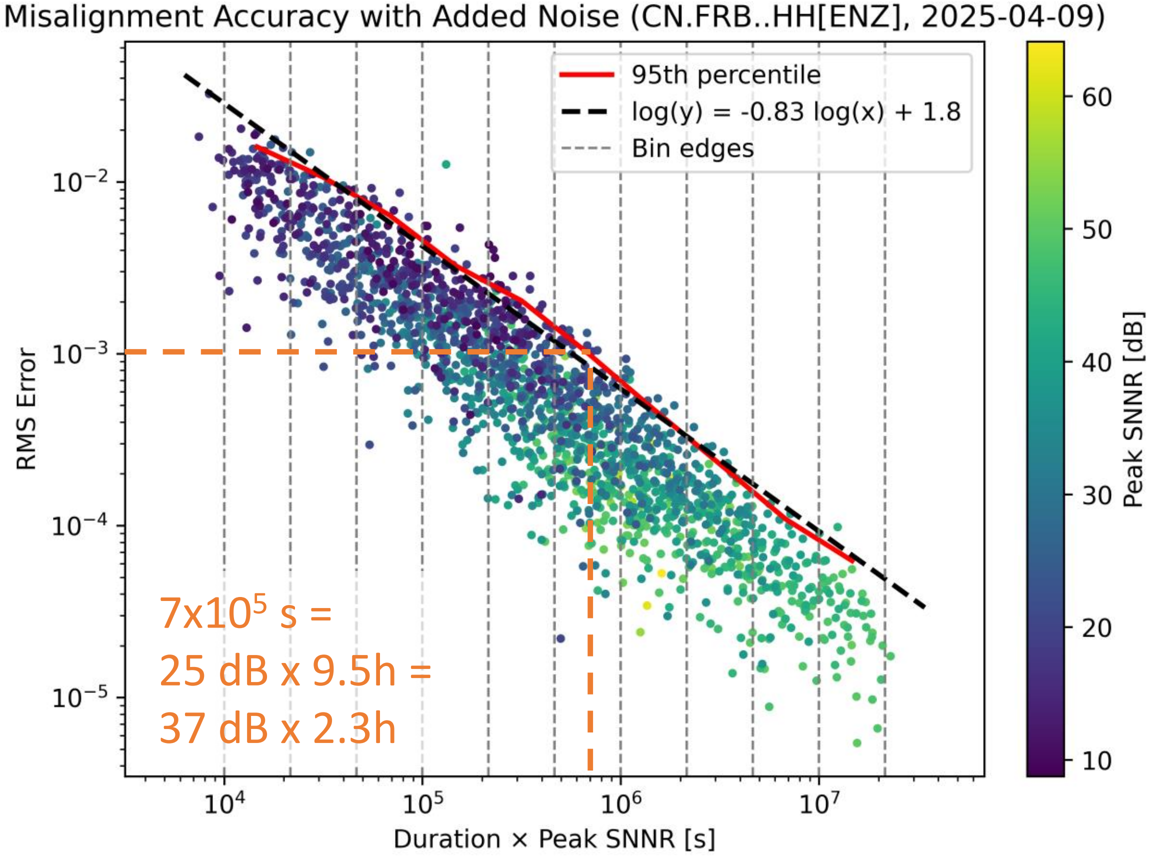
Step 2: Side-by-Side Testing

- Only data with temperature close to the final temperature is used
- Preprocessing:
  - Responses are removed
  - Traces are bandpassed around the microseismic peak frequency
- Linear least squares: $R = (A^T A)^{-1} A^T B$
  - Expect a diagonal matrix where the values represent the sensitivities of each channel

Titan SMA set up beside Trillium 120 QA

Step 2a: Errors in Side-by-Side Timing and Misalignment Estimates Decrease with Increasing SNR and Duration





Plots generated by adding white noise flat in acceleration to simulate the noise floor of an accelerometer

Irving, C., & Ackerley, N. (2025). Estimating Timing Lag and Misalignment using Co-Located Seismographs. CHIS EEW White Paper 63.01, 15 pp.

Step 2b: Accelerometer sensitivities change as expected between gain modes

- Compared absolute calibrations in 2g and 4g mode:
  - Observed ~0.01% difference in expected sensitivity
- This allows us to perform the side-by-side calibration with the accelerometer in 0.25g mode
  - Lower noise floor means higher SNR ➔ smaller error OR shorter test

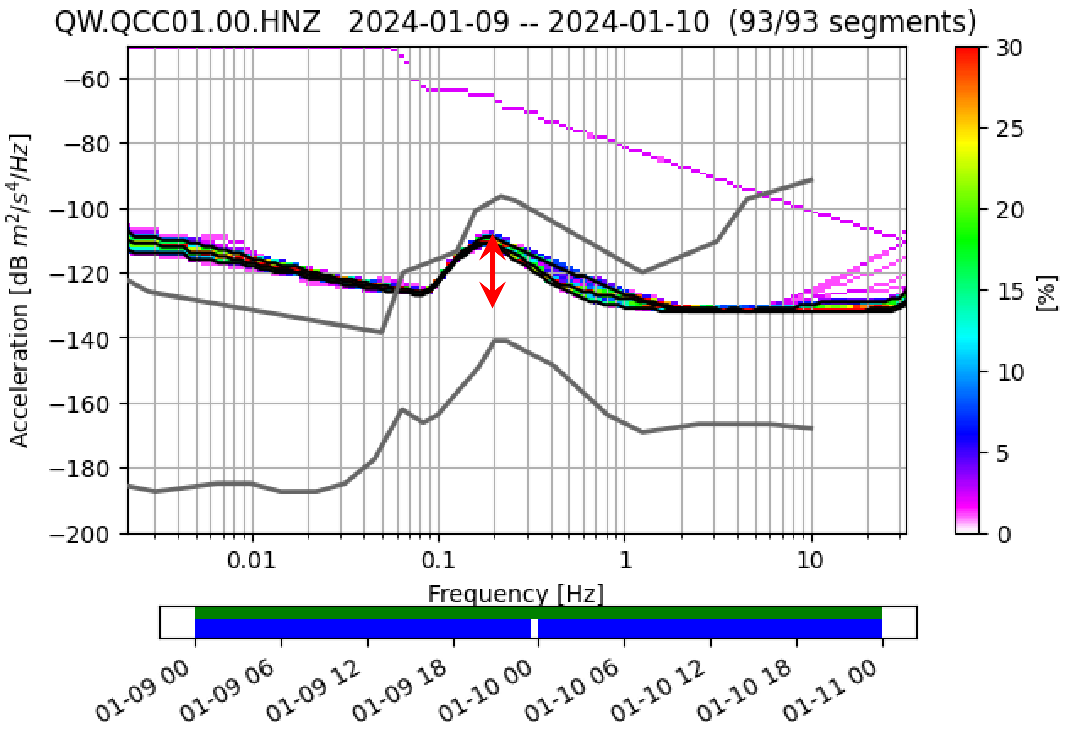
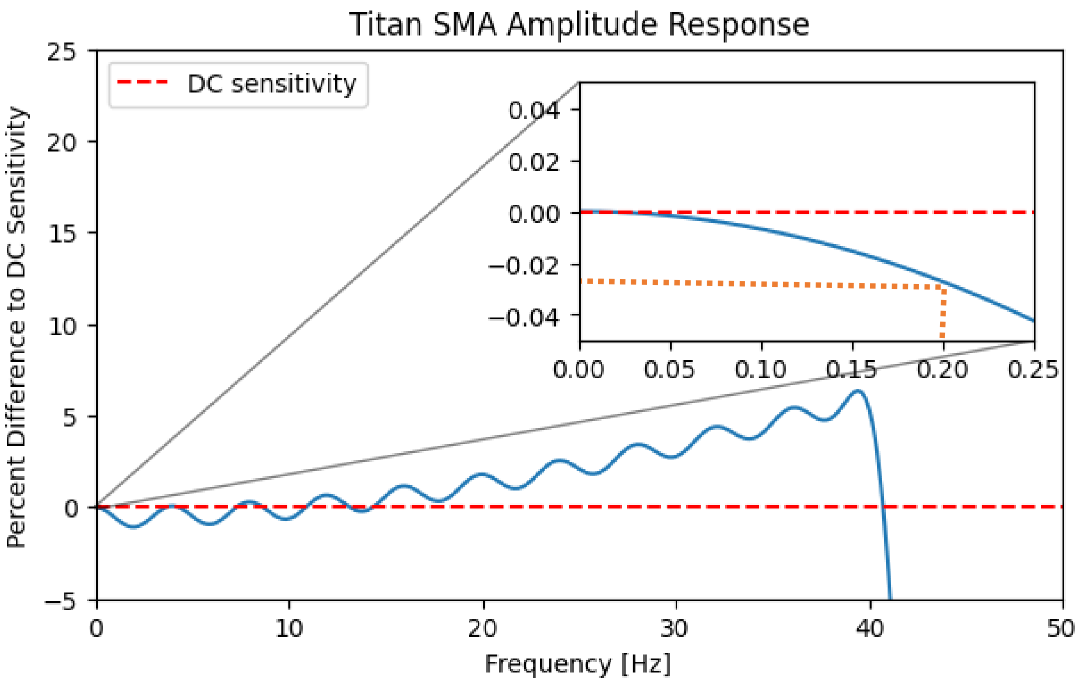
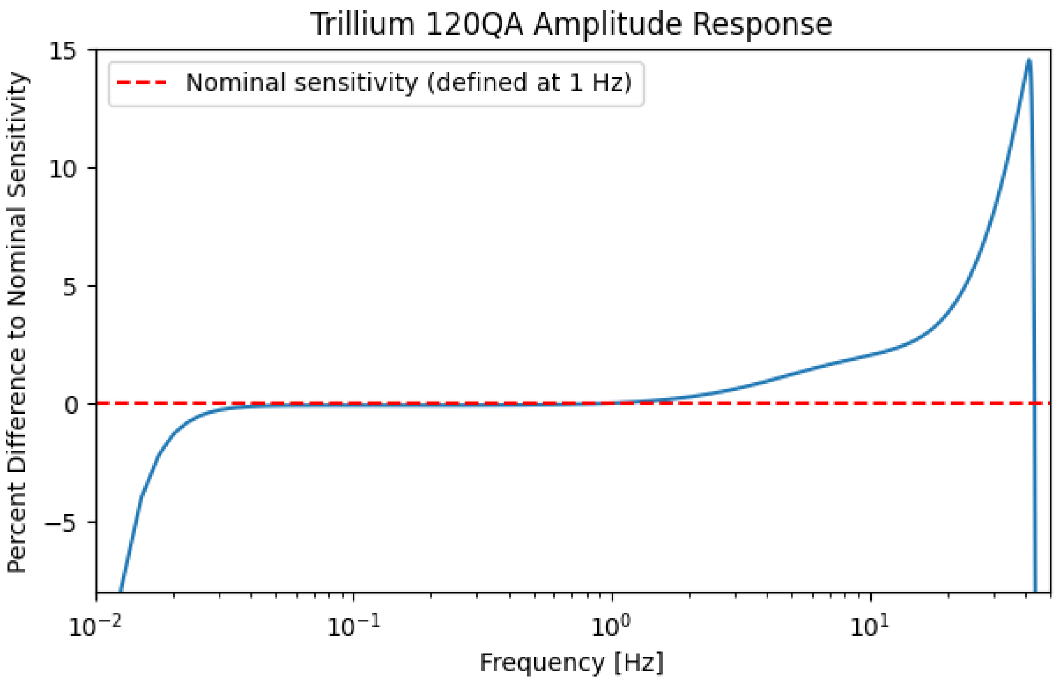


Figure: Typical earthquake early warning station in 2g mode; SNR is 20-25 dB

Step 3: Response removal

There is a slight difference in the accelerometer response at 0.2 Hz and DC …





Step 4: Error Accounting

Source	Error [%]
Temperature ($20 \pm 10°C$)	0.877
Gravity	0.180
Tilt ($\pm 0.3°$)	0.001
Response error	0.027
Noise error (40 dB SNNR, 2.5 hours)	0.068
Quantization error	< 0.001
Total (Root sum of squares)	0.898
Total (Worst case)	1.154

Temperature fluctuations mean that the side-by-side data won't be at the exact same temperature as the accelerometer calibration

Acceleration due to gravity varies slightly depending on location

The surface that the accelerometer calibration is performed on may not be perfectly level

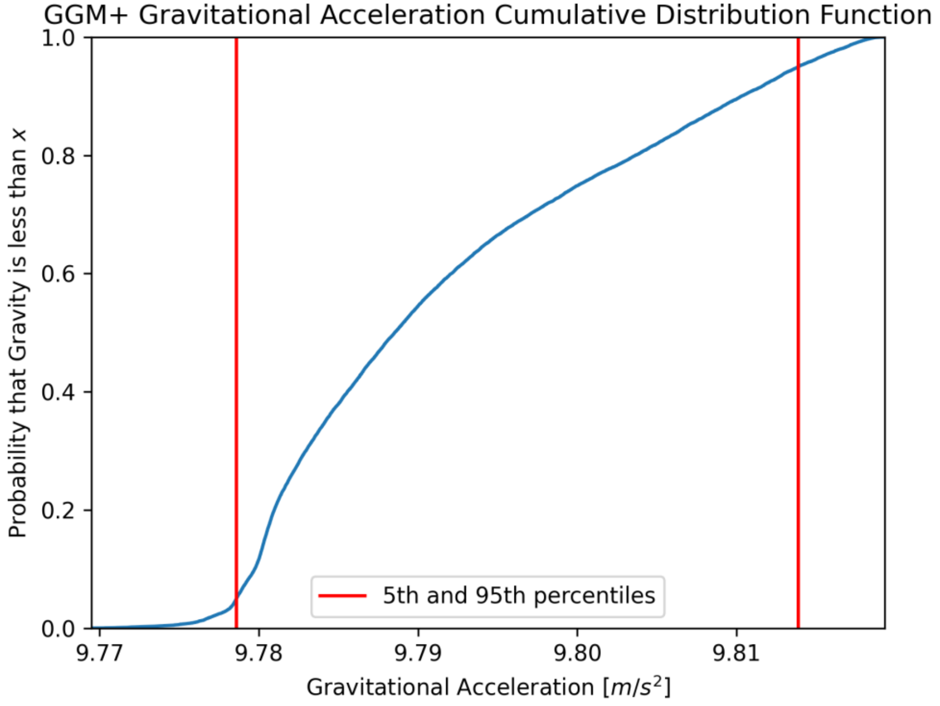
Step 4: Error Accounting

Source	Error [%]
Temperature (20 ± 0.3°C)	0.058
Gravity	0.180
Tilt (± 0.3°)	0.001
Response error	0.027
Noise error (40 dB SNNR, 2.5 hours)	0.068
Quantization error	< 0.001
Total (Root sum of squares)	0.203
Total (Worst case)	0.335

We reduce temperature variance by only using data with temperature near the temperature of the calibration

Step 4: Error Accounting

Source	**Error [%]**
Temperature (20 ± 0.3°C)	0.058
Gravity	0.180
Tilt (± 0.3°)	0.001
Response error	0.027
Noise error (40 dB SNNR, 2.5 hours)	0.068
Quantization error	< 0.001
Total (Root sum of squares)	0.203
Total (Worst case)	0.335



$$\frac{9.81388305 - 9.77859455}{2 \times 9.80665} \times 100\% = 0.180\%$$

Step 4: Error Accounting

Source	Error [%]
Temperature ($20 \pm 0.3°C$)	0.058
Gravity grid inaccuracy	0.008
GGM+ uncertainty	0.002
Tilt ($\pm 0.3°$)	0.001
Response error	0.027
Noise error (40 dB SNNR, 2.5 hours)	0.068
Quantization error	< 0.001
Total (Root sum of squares)	**0.094**
Total (Worst case)	**0.165**

Latitudes and longitudes are rounded to fit on a less dense grid

Uncertainty on provided accelerations in the GGM+ model

Main adjustable parameter: duration-SNR-accuracy trade-off

Summary

Field calibration of strong motion accelerometers:

- Can greatly simplify field calibration of weak motion seismometers
- Cannot replace lab calibration for verification that calibration input and ground motion output responses are as manufacturer states

As far as I know, neither GRACE nor GGM+ nor calibrated in a traceable way, yet gravity itself may be able to serve as an important reference.

Next Steps

- Training of field operations staff in Canada
- Opportunistic calibration of CNSN stations
- Compare calibration results to laboratory calibration?

Questions?

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