Side event on metrology SE01-O7

Seismometer Field Calibration Approaches

John Merchant

bjmerch@sandia.gov

Sandia National Laboratories

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Cleared for release

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Why have traceable field calibrations?

- **Manufacturers and expert laboratories increasingly have the capability for performing traceable calibrations of seismometers:**
  - Need metrologically traceable to the International System of Units (SI)
  - It’s not a calibration without a quantified estimate of uncertainty
- **Once a seismometer is installed, how to ensure it continues to operate properly?**
  - Instruments can fail in unpredictable ways, while still appearing to be functional
  - Electronics and mechanics can degrade over time, causing shifts in performance
  - Environmental conditions can impact seismometer performance (Wielandt, 2012):
    - Barometric Pressure
    - Temperature
    - Magnetic Fields
- **How to transfer calibrations from the lab to the field, for the seismometer lifetime?**

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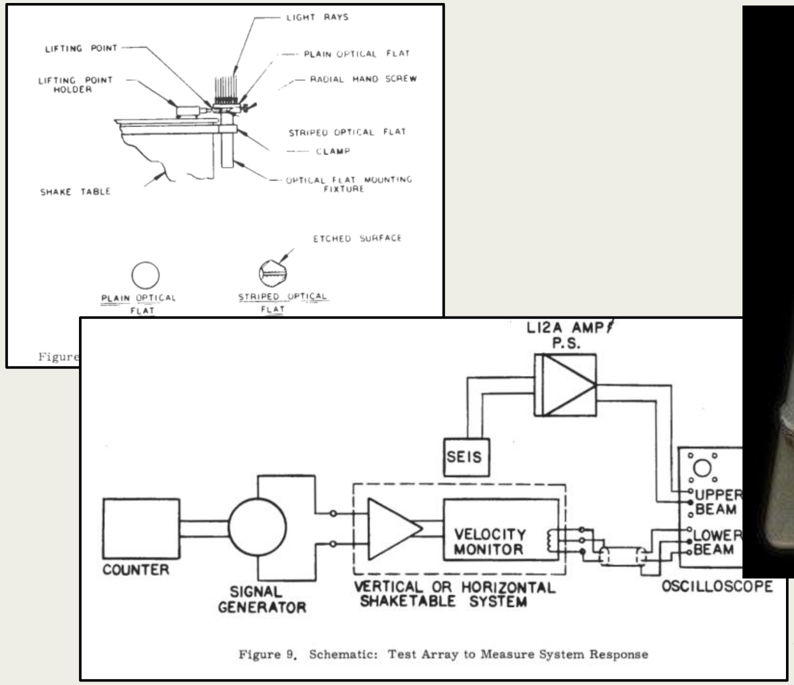
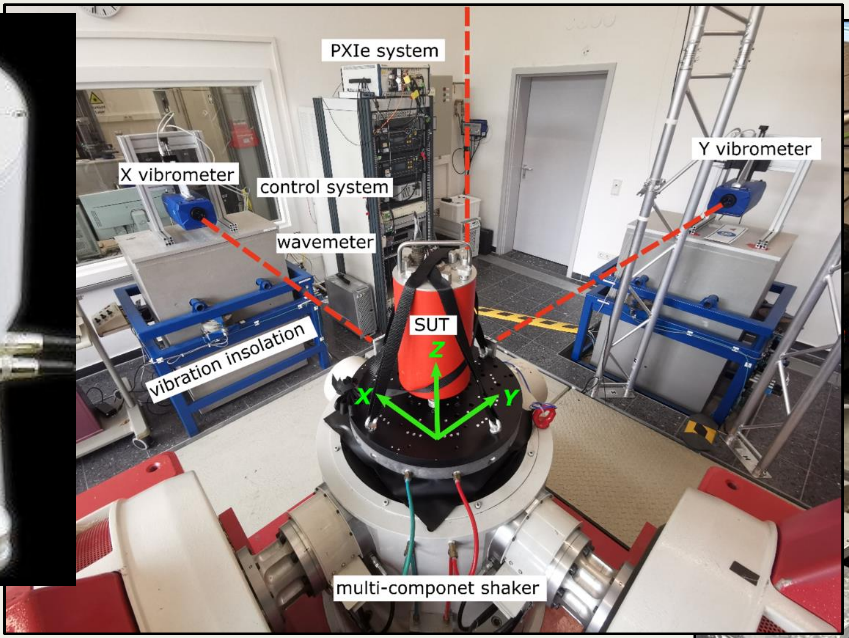
Potential Methods of Field Calibration

Method	Regular Laboratory Recalibration
Pros	• Results in the most accurate calibration with the least amount of uncertainty
Cons	• It removes the seismometer from operation • It will take additional time to ship back and forth • Removal, shipping, and reinstallation risks damage to the seismometer

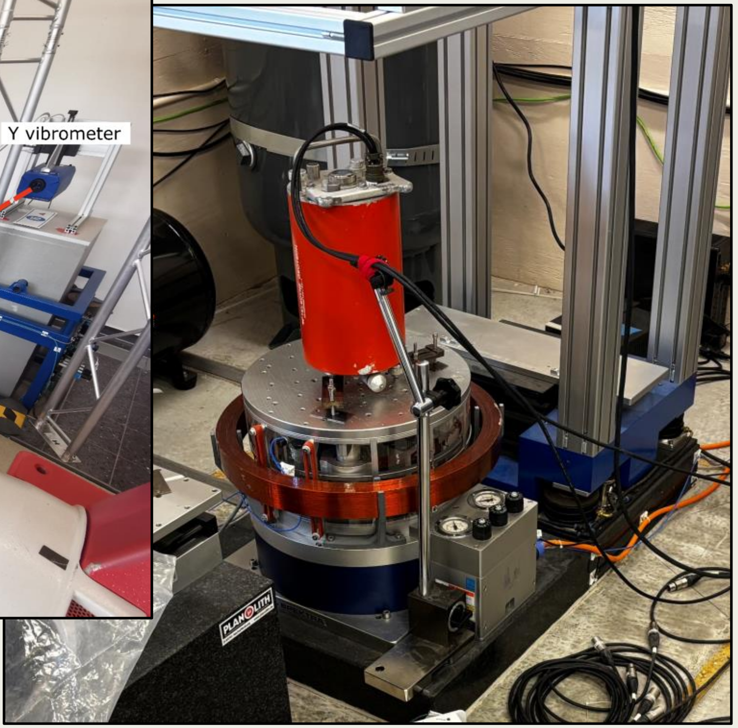


Teledyne Geotech interferometer shake table (Brady, 1974)

CT-EW1 Lennartz-Weiland Step Table



PTB multi-component exciter



Spektra SE-13 vertical shaker

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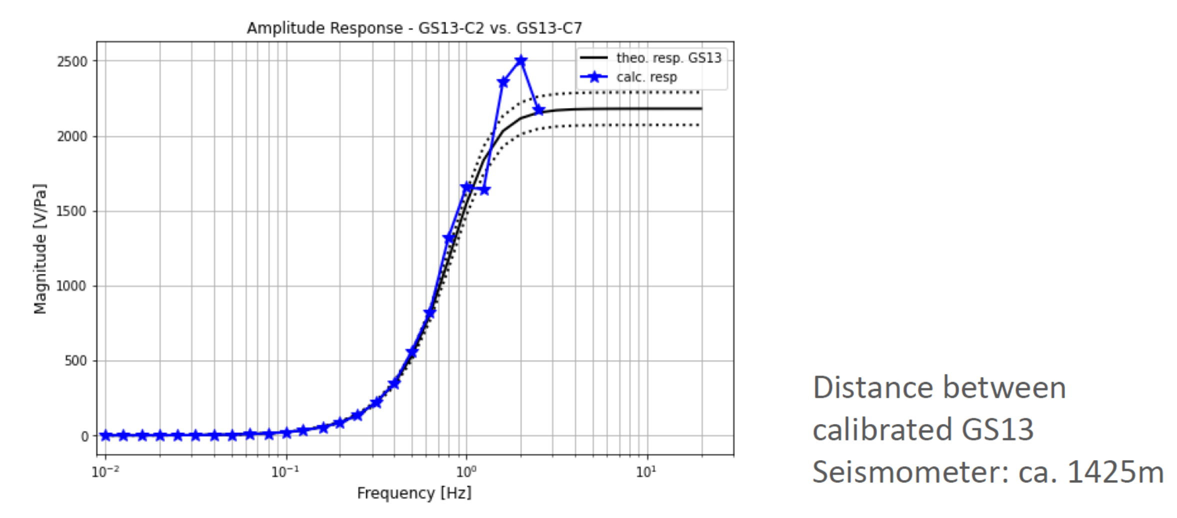
Potential Methods of Field Calibration

Method	Comparison to other seismometers in the network
Pros	• No additional equipment to install • Can be performed without removing the seismometer from operation
Cons	• Difficult to compare coherent ground motion between non-collocated seismometers • Limited to low-frequencies that remain coherent across large distances • Requires a long duration of ground motion to perform, in order to get adequate signal power over the frequency band of interest. • Is the other seismometer calibrated and where is the traceability to the SI?



M. Schwardt, 2022 O&M Workshop, comparing 2 seismometers 1.4 km apart, comparison limited to frequencies < 1 Hz.

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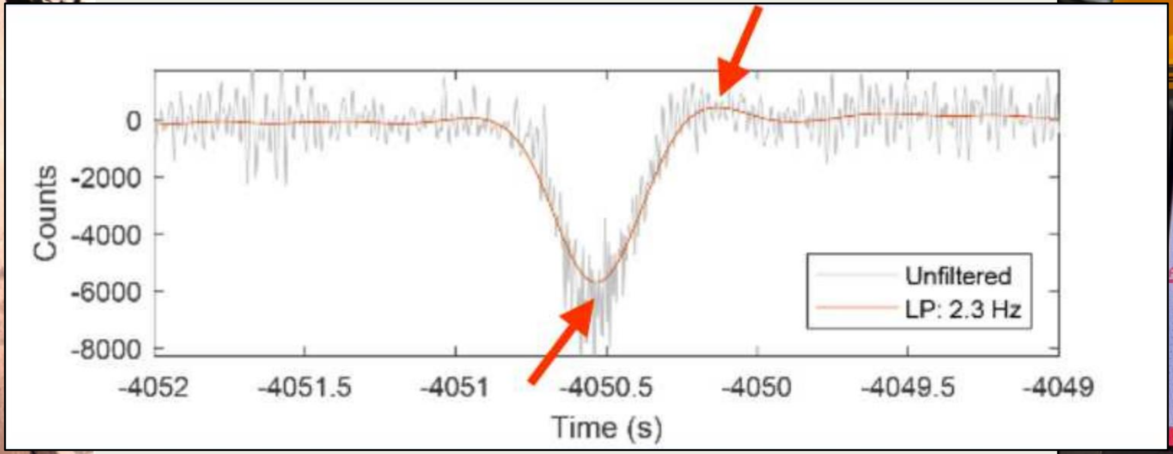
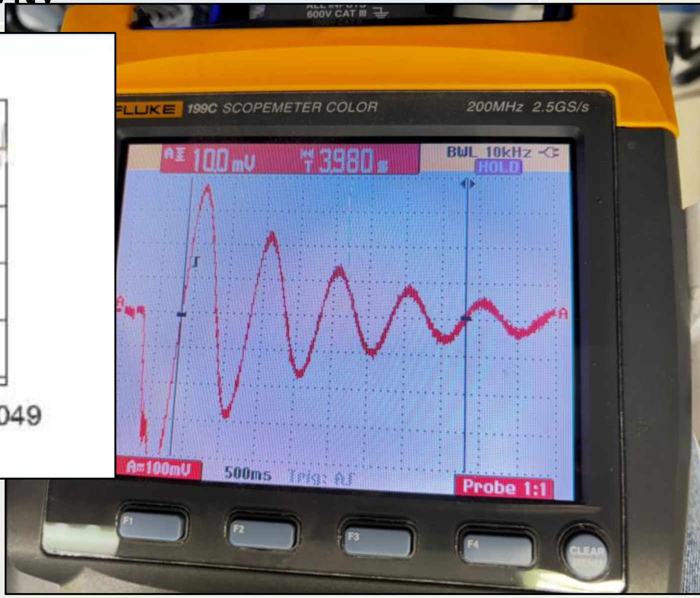
Potential Methods of Field Calibration

Method	Weight Lift Test (obsolete)
Pros	• No removal of equipment and only a short interruption to operational use • Can be traceable to the mass of the weight and local gravity
Cons	• Can only be performed on older passive/open-loop seismometer, e.g. geophone • Must be performed in-person, requires expert training, and is invasive to the seismometer • Short duration, with poor SNR • Realistically, only provides corner frequency, and in-band sensitivity

Benioff Seismometers, Leo Brady Seismic Network (June 1985)



Weight lift test signals, damped (Young, 2019)



Weight lift test, undamped

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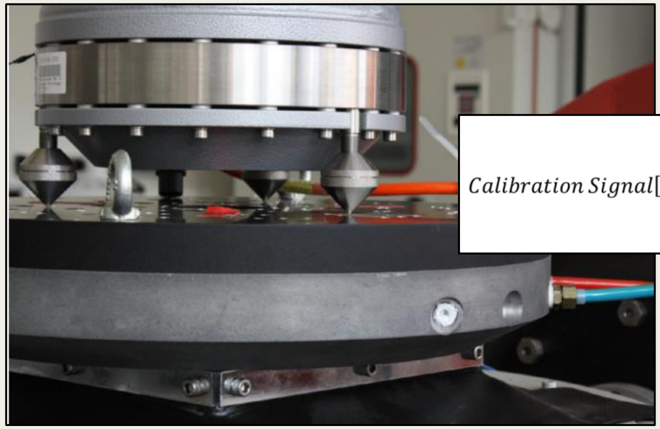
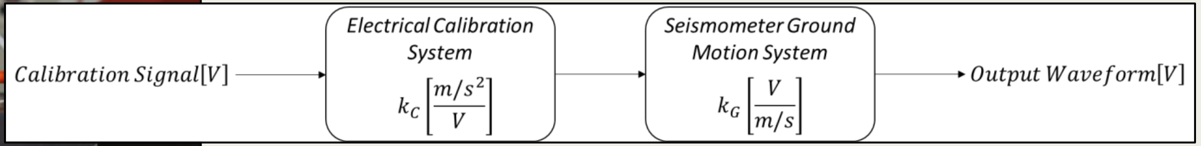
Potential Methods of Field Calibration

Method	Electrical Calibration
Pros	• No removal of equipment and only a short interruption to operational use • Easy to perform remotely
Cons	• Digitizer and seismometer must support this, but most do • Assumes the response of the sensing and calibration subsystems are known accurately • Cannot distinguish between the seismometer, calibrator, or environmental impacts. • Moves the seismometer proof-mass and not the frame, does not account for the mechanical response of the frame or its coupling to the ground. • Lack of traceability to the SI, best considered a consistency check

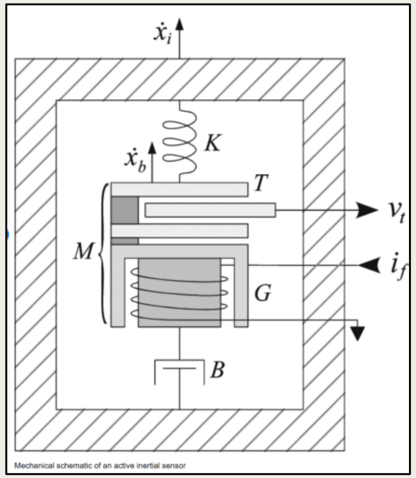
CMG-3T Internal Structure



Seismometer Mounting Feet (Bruns, 2024)



Electrical Calibration and Ground Motion Subsystems



Active Seismometer Sensing and Calibration
Principles of Broadband Seismometry (Ackerly, 2014)

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Electrical "Calibration" Traceability

6.1. Accuracy Limitations of the on-site calibration

The "calibration" input, contrary to what the name expresses, is not calibrated, i.e. the transducer constant (see section 13, *Specifications*) is not internally adjusted to a specified value. The tolerance limits given in the specifications are those the calibration constants can naturally scatter at the maximum.

!

Therefore, the calibration constants cannot be used in order to verify the absolute calibration of the instrument!

Yet, the transducer constants remain stable through time on the same level as the absolute calibrations. So, executing excitation through the calibration coils at regular intervals (e.g. once a week) and comparing the outputs with reference output data collected after deployment can help assess the health status of the seismometer. Provided that the temperature is about the same as at the time of reference data acquisition, any deviation exceeding these approved drift values indicates a severe fault within the feedback loop. Value and tolerance limits for the calibration constant are given in section 13, *Specifications*.

Unfortunately, the feedback transducer system (coil and magnet) lies outside the component checking scope of regular on-site calibration, because it is actor (acceleration generator) and re-actor (acceleration meter) at the same time. Any fault-induced parameter shift is canceled out, therefore.

When applying an input source function containing the adequate frequency range, it is possible to evaluate the low-frequency corner period and damping constant with high accuracy.

Streckeisen STS-2.5 Manual

Seismometer Field Calibration Approaches

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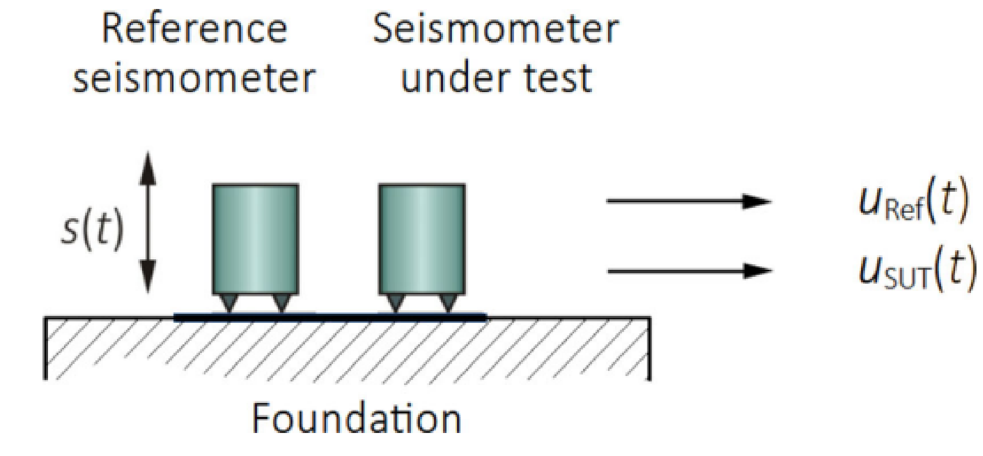
Potential Methods of Field Calibration

Method	In-Situ Comparison Calibration
Pros	• No removal of operational equipment and no impact to operational use • Easy to perform remotely
Cons	• Requires a second seismometer be co-located with the operational sensor, which may be challenging for borehole seismometers. • Requires ground motion above instrument self-noise, can be difficult to get coherence Traceability to the SI still requires a procedure for re-calibration of the reference • Environmental influences may still have an impact



Linking Seismic Measurements to the International System of Units (Klaus, et al, 2024)

Geotech GS13 and Nanometrics Trillium Horizon seismometers

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Examples of Electrical Calibration
and
In-situ Comparison Calibration

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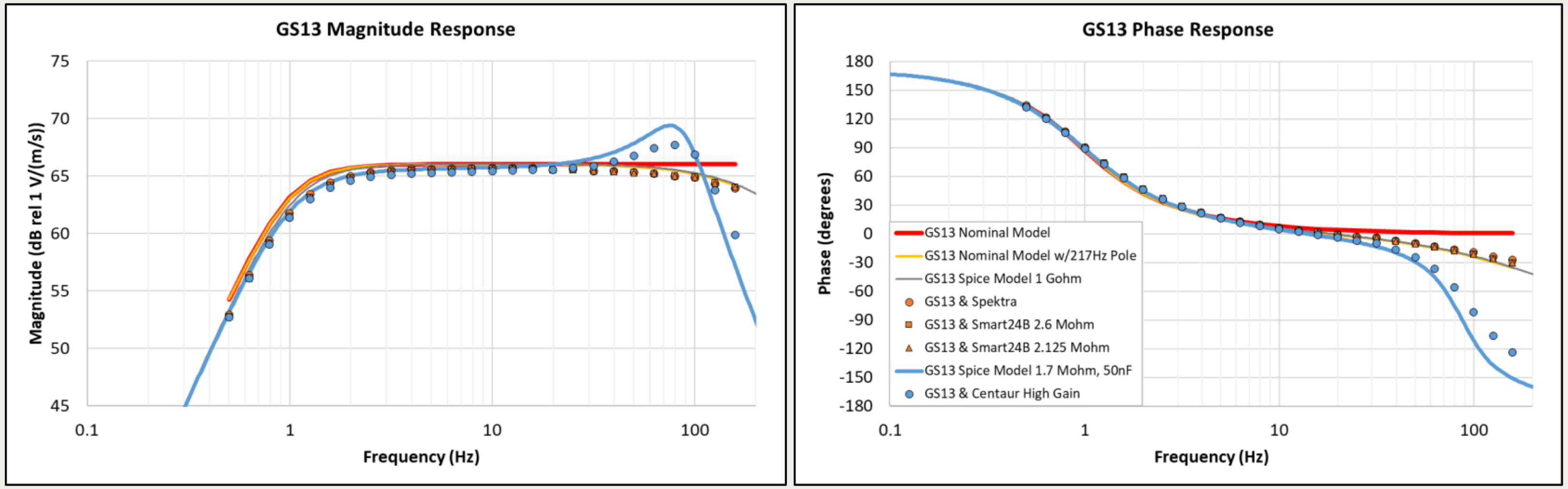
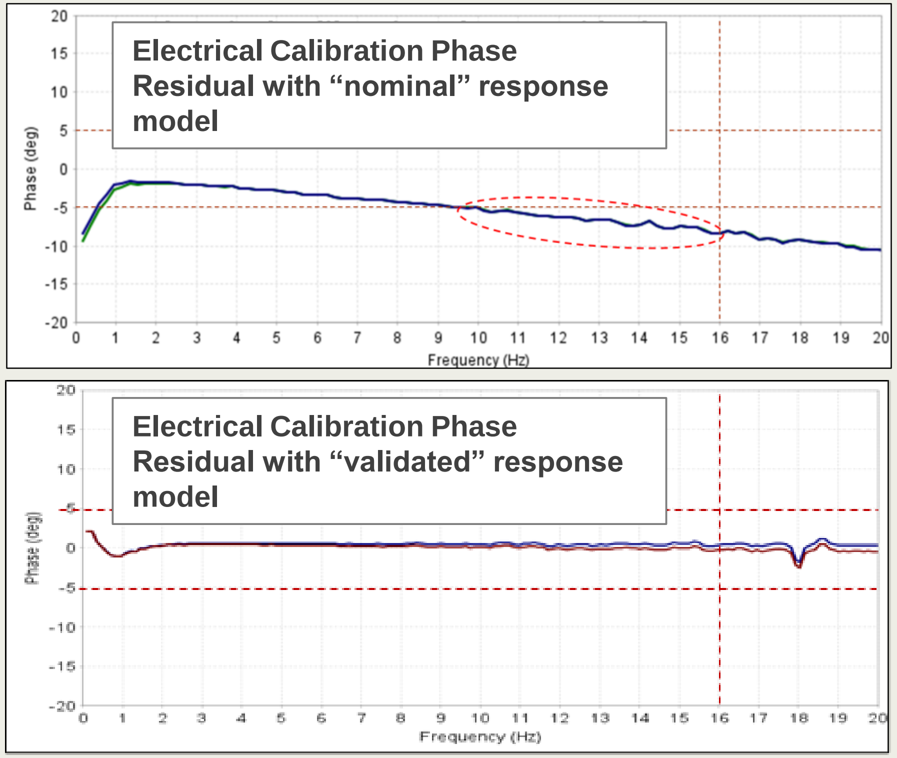
Electrical Calibration: Assumptions about responses

- Interpreting the results of an electrical calibration assumes the nominal responses are known accurately
- Traceable calibrations (SnT 2025, P3.1-178, Merchant) have shown that "nominal" can be incorrect, especially at high frequencies
- Assuming an incorrect response can result in discrepancies in the electrical calibration results



Geotech GS13 primary calibrations on a traceable shake table, Spektra SE13, and comparison again Nominal Amplitude and Phase Response (Red), with Inductive Pole (Yellow), and accounting for digitizer impedance (Blue)



Residual in Electrical Calibration Phase Response when using an incorrect "nominal" response model

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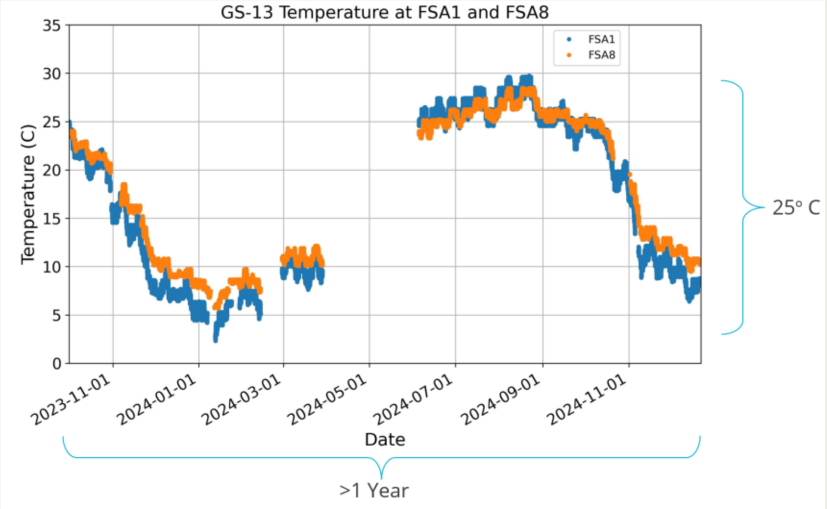
Electrical Calibration and In-Situ Comparison, Example Application

- Motived by SnT 2023 presentation on temperature effects at Yellow-Knife (NRCan, Ackerly), SNL undertook to perform a similar study using GS13 Seismometers (SnT 2025, P3.1-182, Bloomquist)
- Temperature probes were attached directly to seismometers and for 1 year performed:
  - Daily broadband electrical calibrations for 1 hour at 03:00 Local
  - In-Situ comparison between co-located seismometers, Geotech GS-13 and Guralp CMG-3T
  - Compared results using PTS CalxPy software

FSA8 Vault – contains collocated GS-13 and CMG-3T seismometers

PT-100 adhered to side of CMG-3T

PT-100 adhered to vertical GS13



In-vault temperature variability from 4 C to 29 C over the 1 year period

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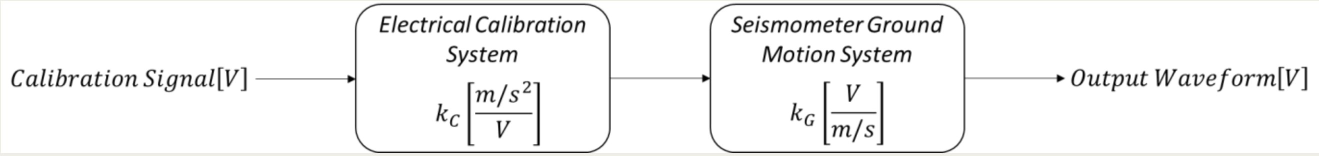
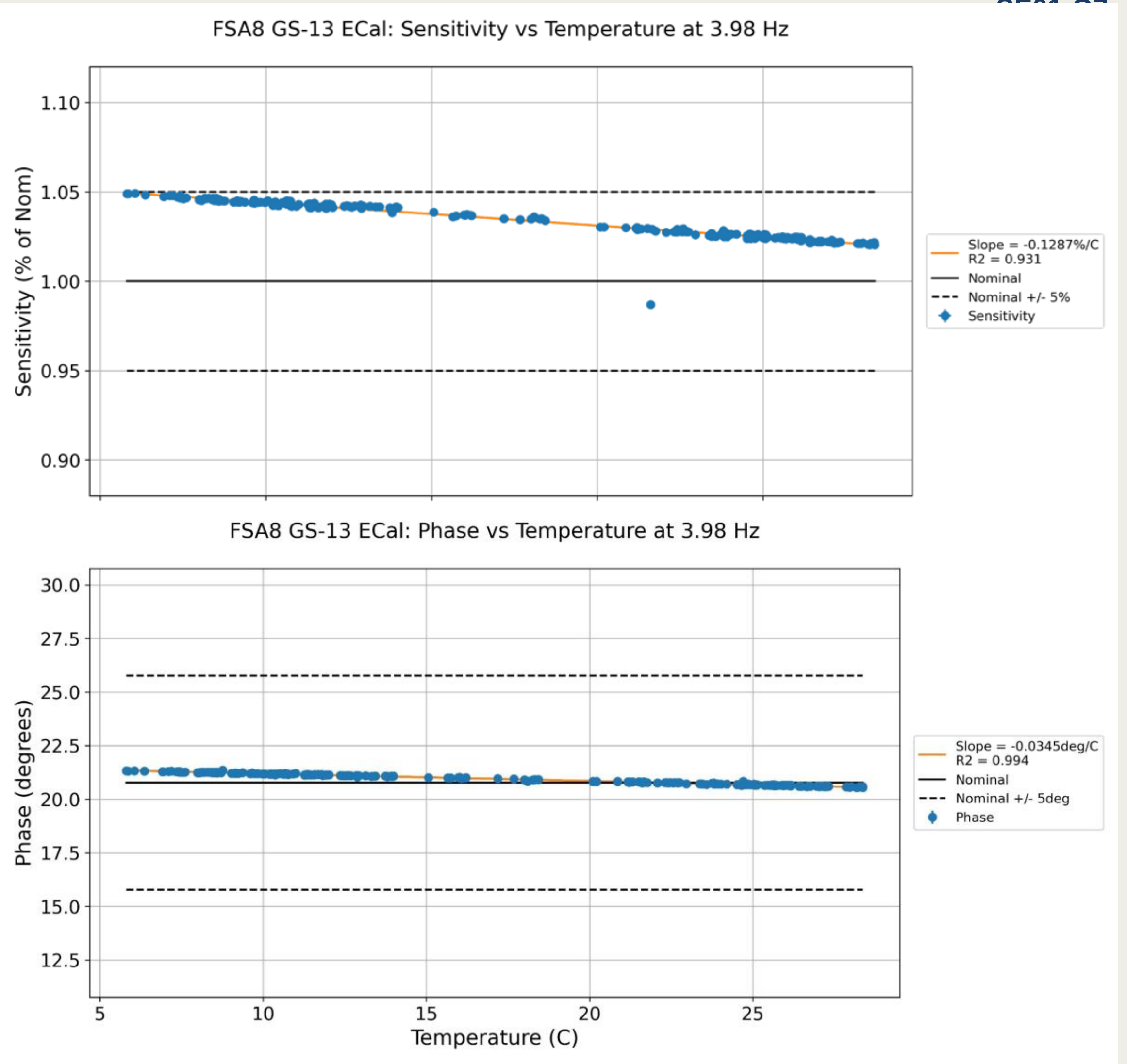
Electrical Calibration Results: Geotech GS13

- Electrical calibrations generally have high SNR and are highly repeatable
- The Geotech GS13 demonstrates a clear temperature correlation, as shown in figures of amplitude and phase versus temperature at 3.98 Hz
- This temperature dependence is the combination of both the sensing and calibration subsystems of the seismometer, **they cannot be separated!**
- Results at high frequency are consistent with modelling of temperature dependence.



Lumped Electrical Calibration and Sensing Subsystems



GS13 Electrical Calibration Amplitude and Phase Variability vs Temperature at 3.98 Hz

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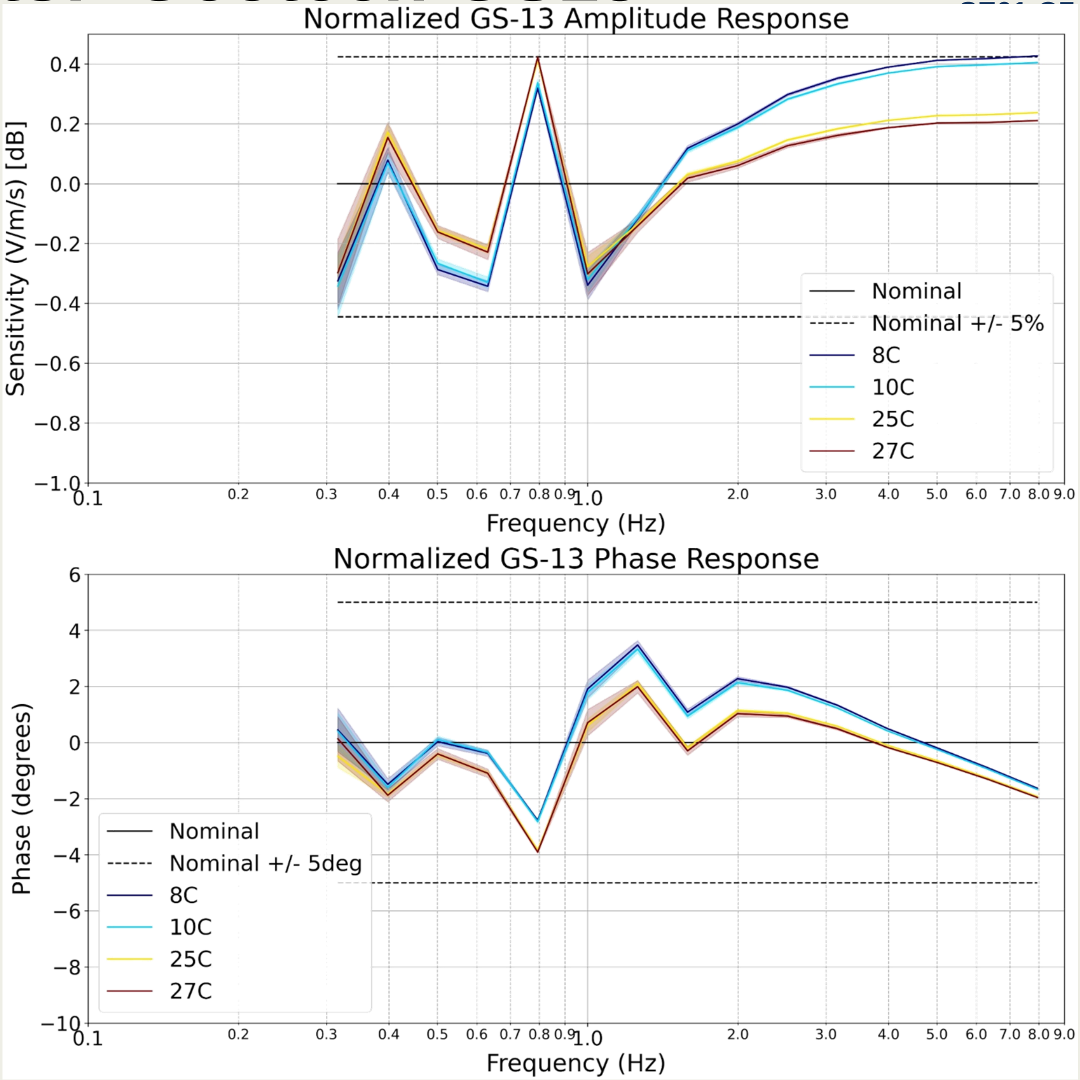
Electrical Calibration Results: Geotech GS13

- The temperature susceptibility is frequency dependent.
- Influence is more significant to amplitude with increased variability at the corner frequency.
- Potential to exceed +/- 5% in electrical calibration if temperatures are too variable

Frequency	Amplitude Coefficient (%/˚C)	Phase Coefficient (Degrees/˚C)
0.5	0.086	-0.027
1	0.041	-0.077
2	-0.086	-0.067
3.9811	-0.125	-0.035
7.9433	-0.134	-0.017

Amplitude and Phase temperature coefficients at various frequencies



Electrical Calibration Amplitude and Phase Variability vs Frequency at temperature points

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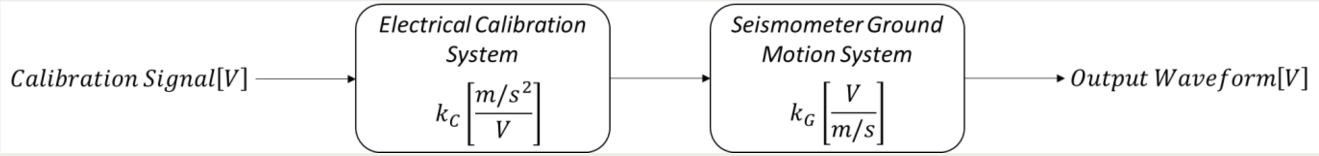
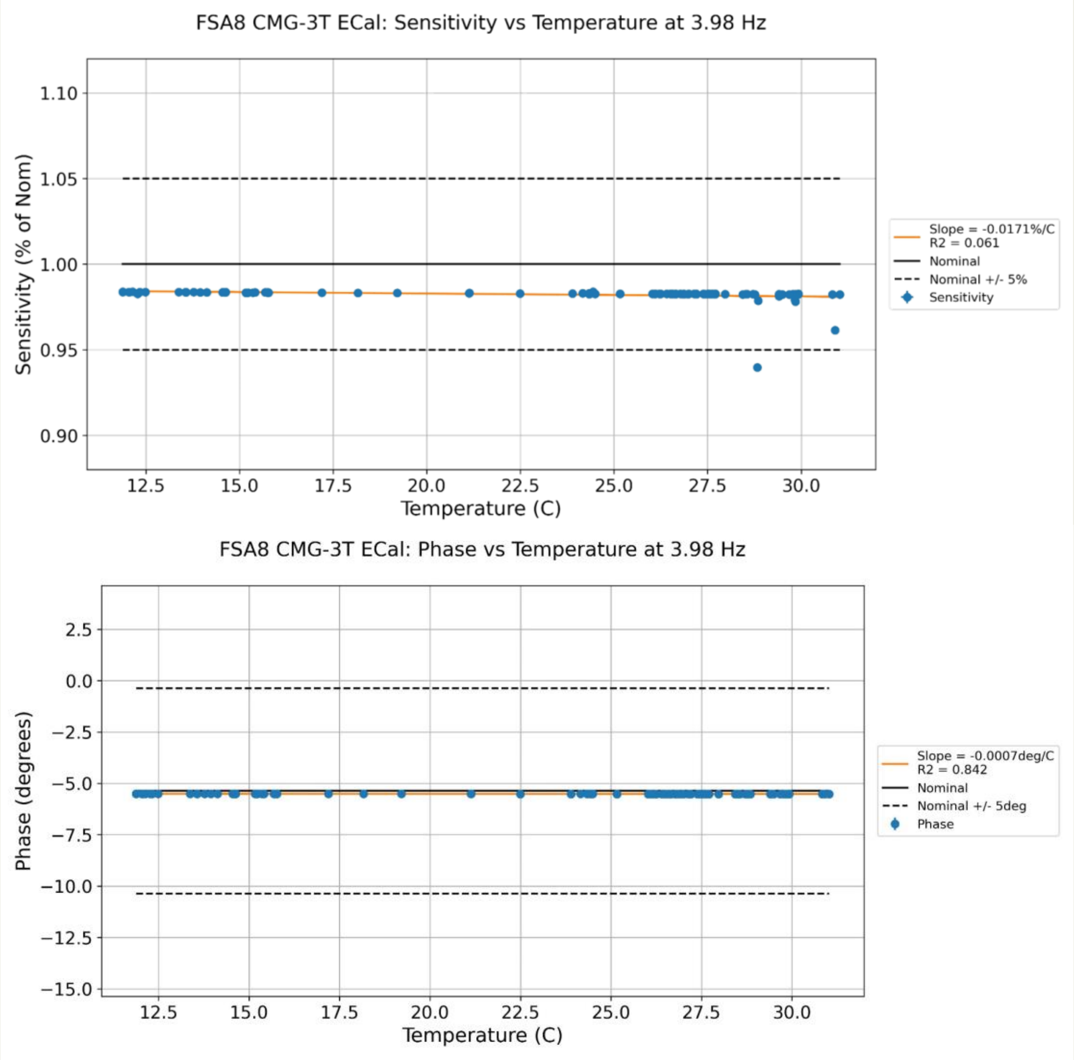
Electrical Calibration Results: Guralp CMG-3T

- What about the Guralp CMG-3T?
- The electrical calibration does NOT show a temperature correlation, but the reason is more subtle:
  - CMG-3T is an active seismometer with feedback control.
  - The same coil and magnet is used for:
    - Ground Motion sensing
    - Electrical Calibration
- This results in cancelling out the observed impact to electrical calibration.
- **This does NOT mean that the CMG-3T is free of influence from temperature.**



Lumped Electrical Calibration and Sensing Subsystems



CMG-3T Electrical Calibration Amplitude and Phase Variability vs Temperature at 3.98 Hz

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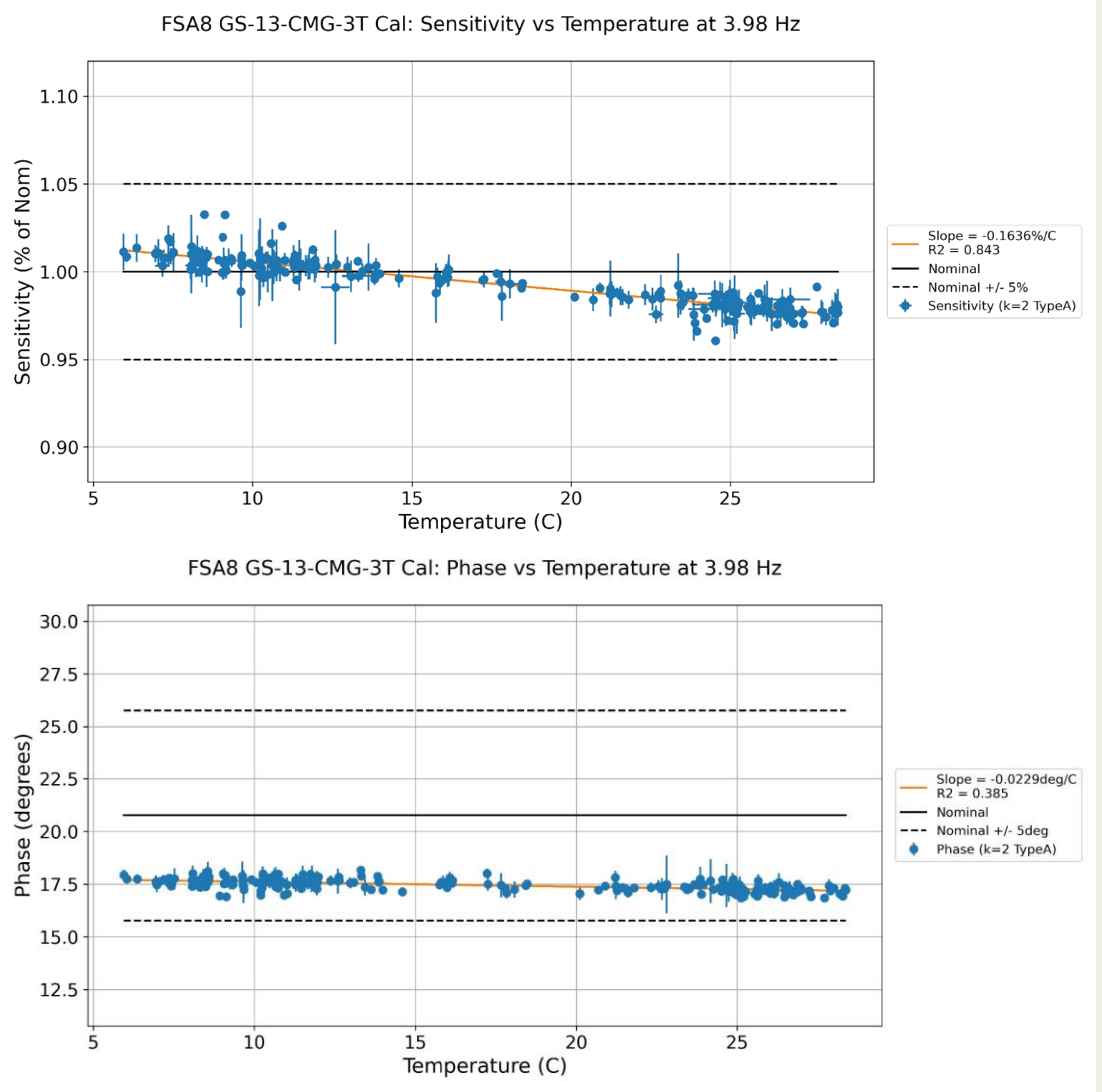
In-Situ Comparison Calibration Results: GS13 vs CMG-3T

- Comparison Calibration results are more variable
  - Lower SNR for In-Situ than electrical calibration
- Results lump the performance of both the reference and operating seismometers.
- A noticeable temperature coefficient for amplitude remains.
  - It's larger than what we modelled for the GS13, possibly due to the unmeasured contribution of the reference CMG-3T sensor.



GS13 in-situ comparison of amplitude and phase variability vs temperature, using CMG-3T as reference.

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Summary

- Traceable calibrations in the field are critical for confidence in the correct performance of the monitoring system
- Electrical calibrations are presently the main method of seismometer calibration
  - Fills an important role for easily checking consistency, that nothing has changed since installation
  - Lacks traceability
  - With modern seismometers, it may mask impacts due to environmental conditions

- Questions to address:
  - How to continually maintain traceability to the SI for operational sensors?
  - How to propagate uncertainty quantification from the laboratory to the field?
  - How to account for unquantified environmental impacts to operational and reference sensors?