Side event on metrology SE01-O9

Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

S. Kristoffersen[1], S. Demeyer[2], P. Vincent[1], D. Rodrigues[2], A. Le Pichon[1], M. Schwardt[3], N. Fischer[2], F. Larsonnier[1]

[1]CEA, DIF, DAM, F-91297 Arpajon, France; [2]LNE, F-78197 Trappes, France; [3]BGR, B4.3, D-30665 Hannover, Germany

Presentation Date: 10 September 2025

S. Kristoffersen *et al.*

Infra-AUV project

Metrology for low-frequency sound and vibration (Sept 2020 – Dec 2023)

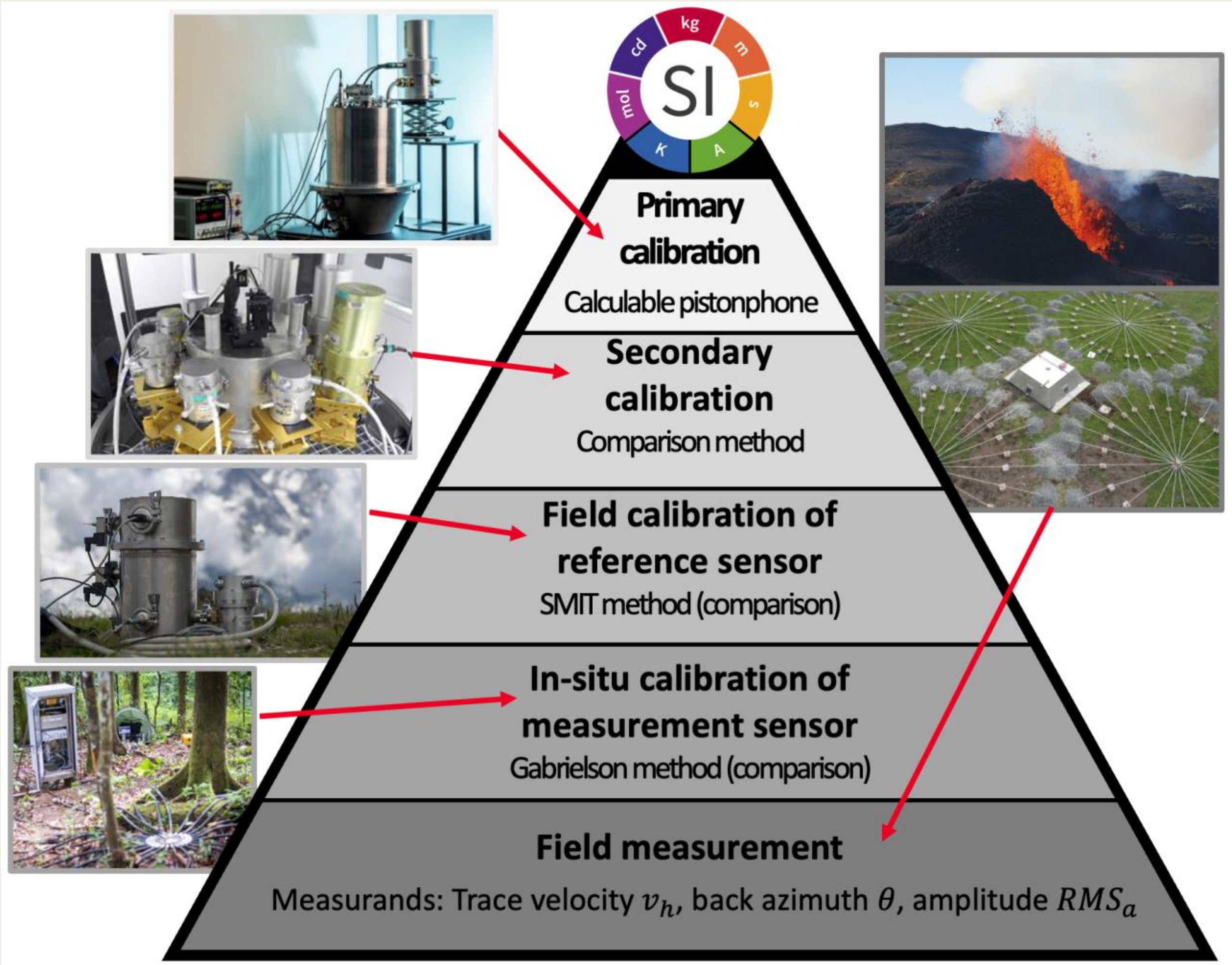
- To develop primary and secondary calibration methods in the low frequency range
- To specify devices suitable for transferring measurement traceability to sensors deployed in the field, e.g. at IMS monitoring stations
- To develop new methods or augment existing methods of on-site calibration, incorporating full measurement traceability
- To illustrate the impact of metrology considerations, such as traceability and measurement uncertainty, in AUV monitoring
- To maximise impact by engaging widely with stakeholders
  - station operators and other scientific users of data
  - sensor manufacturers
  - standardisation committees
  - regulators

Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

S. Kristoffersen *et al.*

Metrological traceability – International System of units (SI)

The **Primary method** of measurement provides the essential first link in the chain of traceability from the definition of a unit of the International System of Units (SI)



Metrological traceability

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Kristoffersen et *al.* (2025) https://doi.org/10.1121/10.0036380

Wave parameter estimation

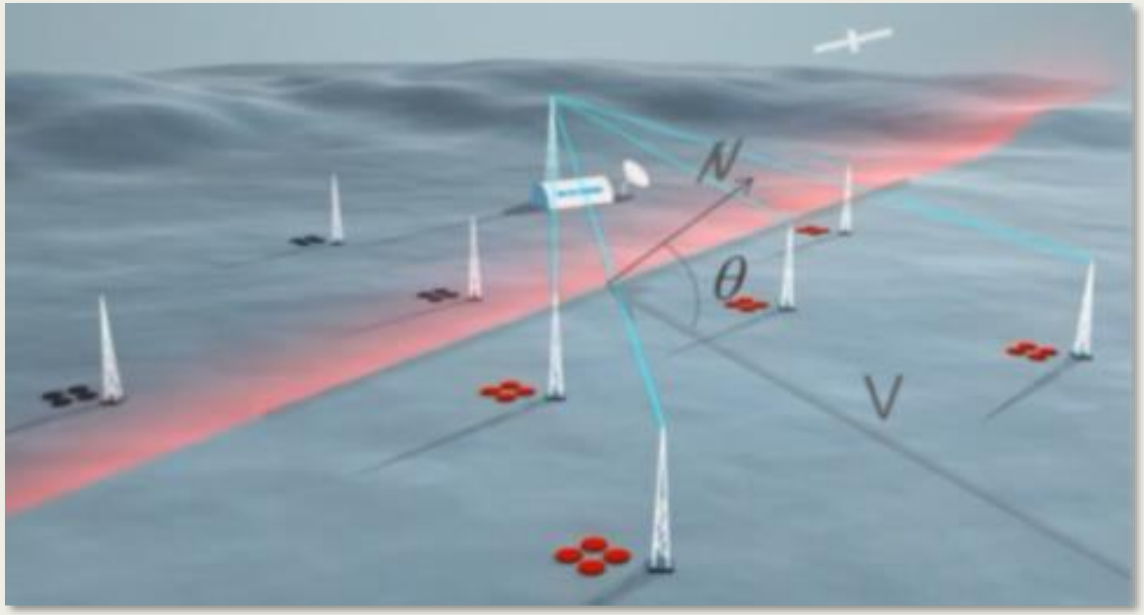
Principle of Progressive Multi-Channel Correlation (PMCC) is to determine the time-delay of arrival (TDOA) at each detector.

Operational analysis method used at IDC.

From the TDOA's, back azimuth and trace velocity of the source wave-vector is determined.

PMCC relies on the relative arrival times, errors in sensor phase will result in errors in direction of the source.

Sensitive to phase errors introduced by sensor response (correctable using calibration).

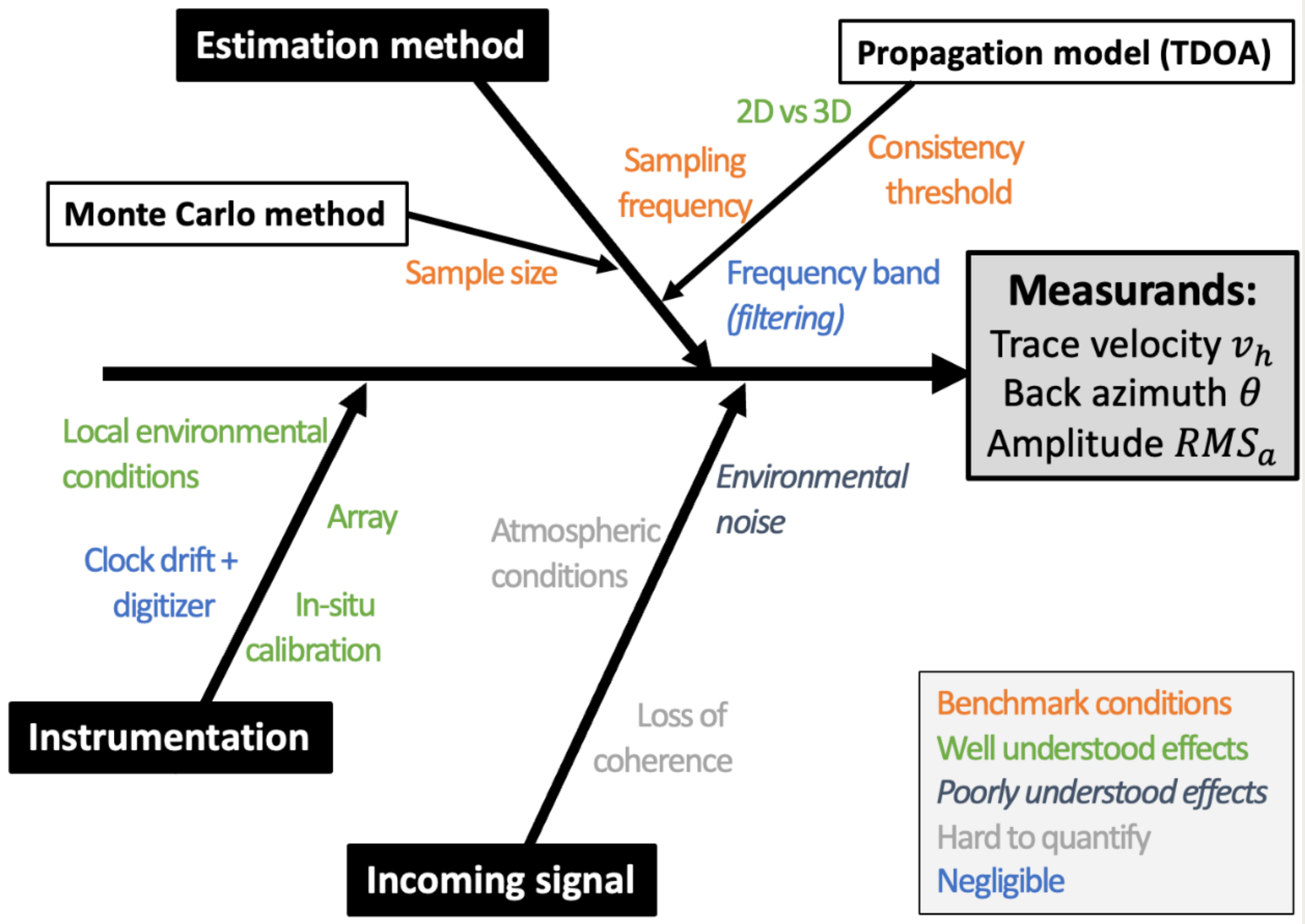


https://www.ctbto.org/our-work/monitoring-technologies/infrasound-monitoring

S. Kristoffersen *et al.*

Comprehensive uncertainty budget

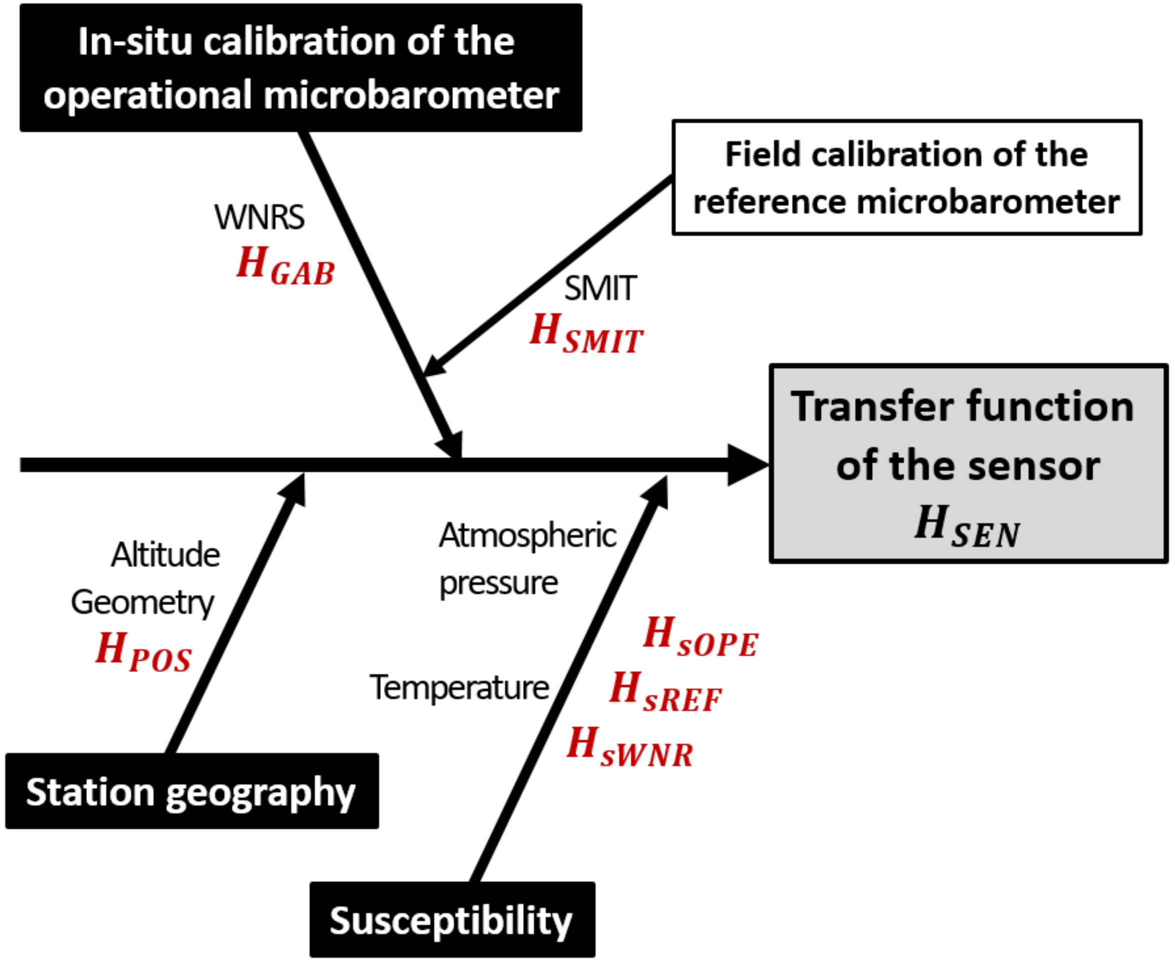
- Three main sources:
  - Estimation method (TDOA/PMCC)
  - Instrumentation (calibration etc.)
  - Incoming signal (atmospheric conditions etc.)
- Three measurands:
  - Back azimuth
  - Trace velocity
  - RMS amplitude



S. Kristoffersen *et al.*

Calibration uncertainty budget

- Field calibration of the reference microbarometer (SMIT) – traceable to primary calibration (SI)
- In-situ calibration of operational sensor
- Sensor position uncertainty
  - 15 cm in x, y
  - 1 m in z
- Sensor susceptibility
  - MB3, MB2005 and WNRS
  - Temperature and pressure



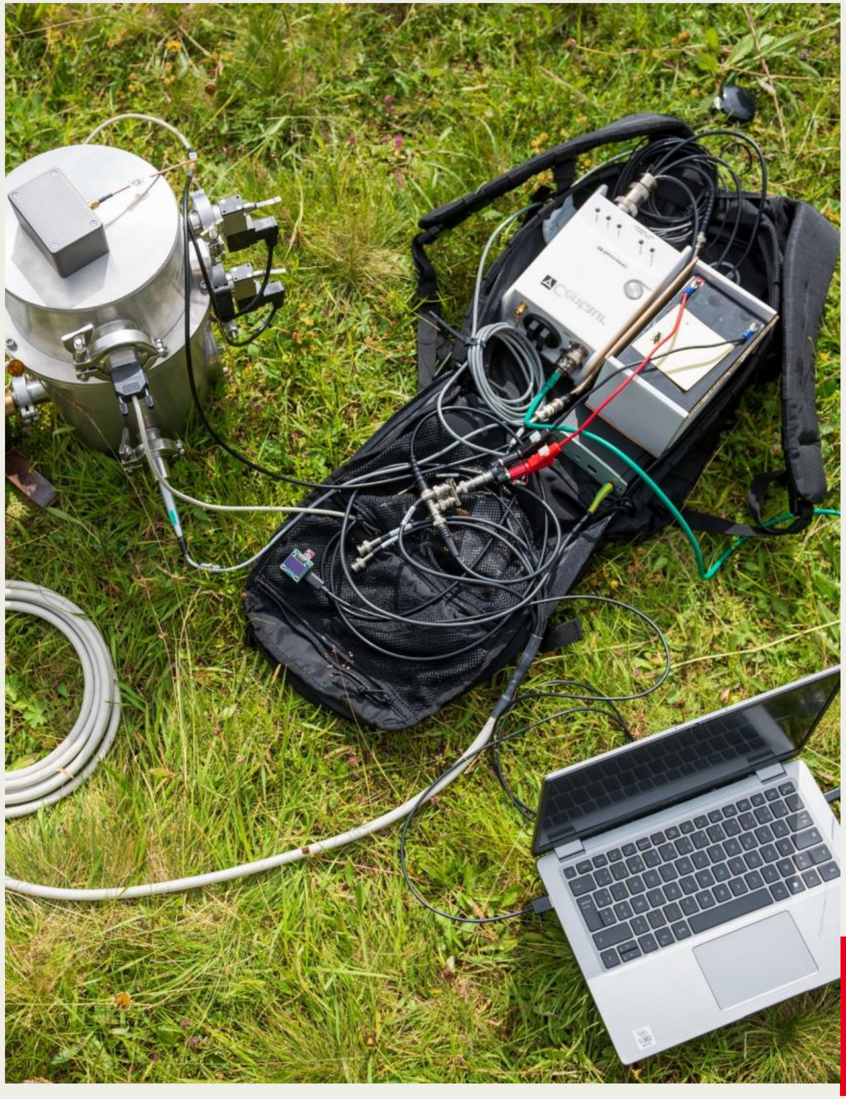
S. Kristoffersen *et al.*

In-situ calibration at local altitude and environment

SMIT – Système de Métrologie Infrasonare de Terrain (In-situ infrasound metrology system)

- Innovative on-field calibration system with comparison with a standard microphone
- Calibration method:
  - Comparison with a HBK4193 standard microphone (calibrated by LNE)
  - Traceable to SI

A. Portable infrasound generator, designed by CEA/DAM;
B. Working standard mic., **calibrated in the laboratory** (knowledge of its susceptibility to P and T);
C. Infrasound sensor to be calibrated ;
D. Commercial field digitizer (Nanometric Centaur);
E. Low frequency amplifier, dev. CEA/DAM ;
F. Solenoid valves, static pressure balancing;
G. Mini weather station ;
H. Computer with *Falcon* software, dev. CEA/DAM ;
I. 12 V battery;
J. Electronic conditioner for the microphone.



cea

Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

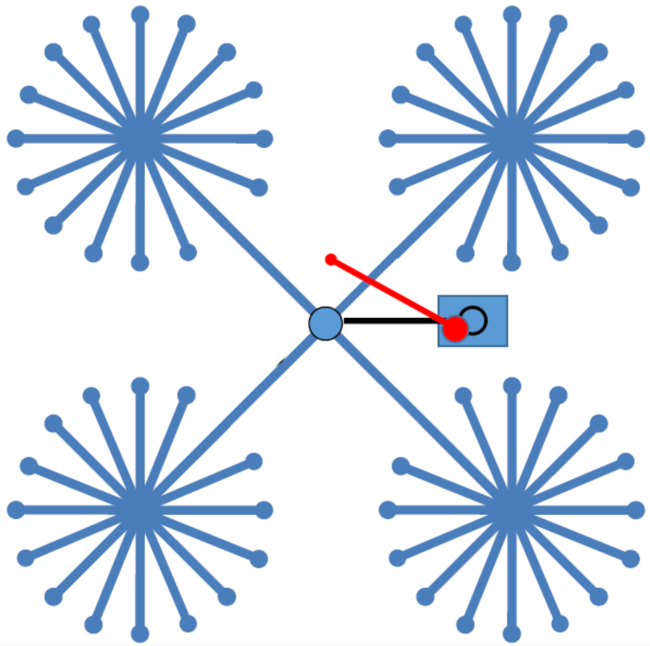
S. Kristoffersen *et al.*

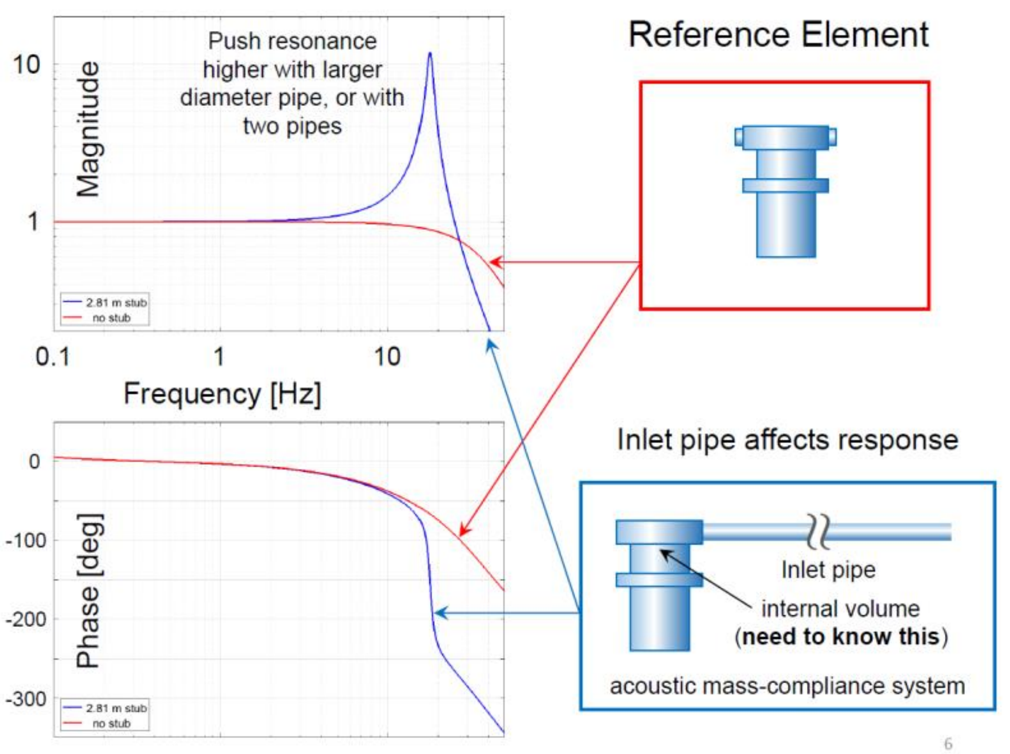
On-site calibration – Gabrielson method

Addition of inlet pipe affects frequency response of reference.

If inlet is offset from phase center of WNRS, both the magnitude and phase will be affected.

If vault is at WNRS center, it may not be practical to align the reference inlet if using a single pipe.





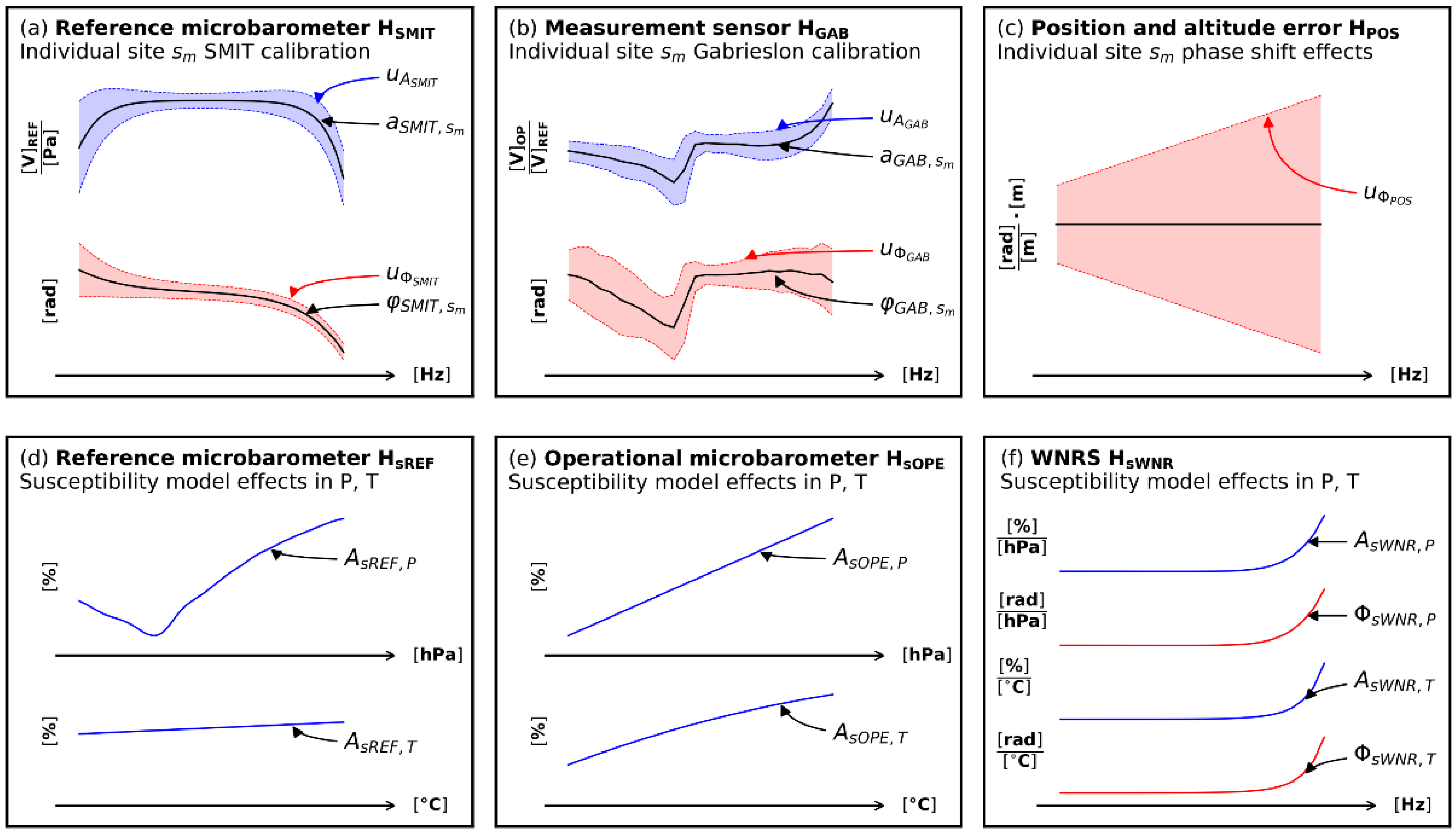
On-site calibration uses ambient signals for a calibration by comparison with the calibrated (primary & secondary) reference sensor.

Gabrielson, https://doi.org/10.1121/1.3613925
Green, https://doi.org/10.1093/gji/ggab155

Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

S. Kristoffersen *et al.*

Complete calibration chain

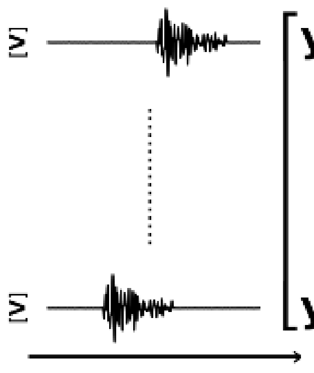


Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

S. Kristoffersen *et al.*

Monte Carlo

(1) Raw measurement signals
Time domain



$$\begin{bmatrix} \mathbf{y}_{\mathbf{RAW}}^{s_1} \\ \vdots \\ \mathbf{y}_{\mathbf{RAW}}^{s_m} \end{bmatrix}$$

FFT →

(2) Raw signals
Frequency domain

$$\begin{bmatrix} \hat{\mathbf{y}}_{\mathbf{RAW}}^{s_1} \\ \vdots \\ \hat{\mathbf{y}}_{\mathbf{RAW}}^{s_m} \end{bmatrix}$$

$\circledast_{\mathbf{n}}$ →

(3_n) Transfer function, $\mathbf{n^{th}}$ run, $\mathbf{H_{SEN} = H_{POS} \cdot H_{sOPE} \cdot (H_{SMIT} H_{sREF})^{-1} \cdot (H_{GAB} H_{sWNR})^{-1}}$
Frequency domain, $\varepsilon \sim \mathcal{N}(0,1)$, $n \in [0;N]$, $N = 10^5$ runs

$$\mathbf{H}_{\mathbf{SEN}}^{\mathbf{n},\,\mathbf{s_1}} \quad A_{SEN}^{n,s_1} = \frac{1}{a_{SMIT,s1} + u_{A_{SMIT}} \varepsilon^*_{A_{SMIT}}} \cdot \frac{1}{a_{GAB,s1} + u_{A_{GAB}} \varepsilon_{GAB,s1}} \cdot \frac{A_{sOPE}(P_{s1}, T_{s1})}{A_{sREF}(P_{s1}, T_{s1})\, A_{sWNR}(P_{s1}, T_{s1})}$$

$$\Phi_{SEN}^{n,s_1} = -(\varphi_{SMIT,s1} + u_{\Phi_{SMIT}} \varepsilon_{\Phi_{SMIT},s1}) - (\varphi_{GAB,s1} + u_{\Phi_{GAB}} \varepsilon_{GAB,s1}) - \Phi_{sWNR}(P_{s1}, T_{s1}) + u_{\Phi_{POS}} \varepsilon_{\Phi_{POS},s1}$$

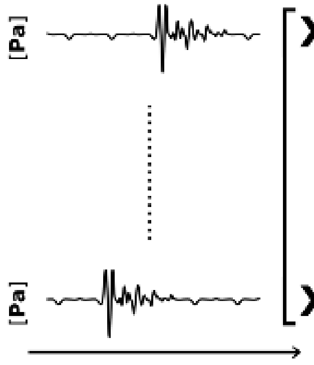
$$\vdots$$

$$\mathbf{H}_{\mathbf{SEN}}^{\mathbf{n},\,\mathbf{s_m}} \quad A_{SEN}^{n,s_m} = \frac{1}{a_{SMIT,s_m} + u_{A_{SMIT}} \varepsilon^*_{A_{SMIT}}} \cdot \frac{1}{a_{GAB,s_m} + u_{A_{GAB}} \varepsilon_{GAB,s_m}} \cdot \frac{A_{sOPE}(P_{s_m}, T_{s_m})}{A_{sREF}(P_{s_m}, T_{s_m})\, A_{sWNR}(P_{s_m}, T_{s_m})}$$

$$\Phi_{SEN}^{n,s_m} = -(\varphi_{SMIT,s_m} + u_{\Phi_{SMIT}} \varepsilon_{\Phi_{SMIT},s_m}) - (\varphi_{GAB,s_m} + u_{\Phi_{GAB}} \varepsilon_{GAB,s_m}) - \Phi_{sWNR}(P_{s_m}, T_{s_m}) + u_{\Phi_{POS}} \varepsilon_{\Phi_{POS},s_m}$$

$\mathbf{iFFT_n}$ ↓

(4_n) Deconvoluted signals, $\mathbf{n^{th}}$ run
Time domain



$$\begin{bmatrix} \mathbf{X}_{\mathbf{SEN}}^{n,s_1} \\ \vdots \\ \mathbf{X}_{\mathbf{SEN}}^{n,s_m} \end{bmatrix}$$

$\mathbf{TDOA_n}$ →

(5_n) $\mathbf{TDOA_n}$ and $\mathbf{RMS_{a,n}}$ amplitude, $\mathbf{n^{th}}$ run
Back azimuth $\boldsymbol{\theta}_\mathbf{n}$, trace velocity $\mathbf{v_n}$, amplitude $\mathbf{RMS_{a,n}}$

$$\begin{bmatrix} \boldsymbol{\theta}_\mathbf{n} : \ \mathrm{TDOA}_n\left(\{\mathbf{X}_{\mathbf{SEN}}^{n,s_m}\}\right)_\theta \\ \mathbf{v_n} : \ \mathrm{TDOA}_n\left(\{\mathbf{X}_{\mathbf{SEN}}^{n,s_m}\}\right)_v \\ \mathbf{RMS_{a,n}} = \frac{1}{\mathbf{M}} \sum_{\mathbf{i=1}}^{\mathbf{M}} \sqrt{\left\langle \left(\mathbf{X}_{\mathbf{SEN}}^{n,s_m}\right)^2 \right\rangle_\mathbf{t}} \end{bmatrix}$$

$\langle \cdot \rangle_\mathbf{n}$ →

(6) Monte Carlo propagation result
Back azimuth $\boldsymbol{\theta} \pm \mathbf{u_\theta}$, trace velocity $\mathbf{v} \pm \mathbf{u_v}$ and $\mathbf{RMS_a} \pm \mathbf{u_{RMS}}$

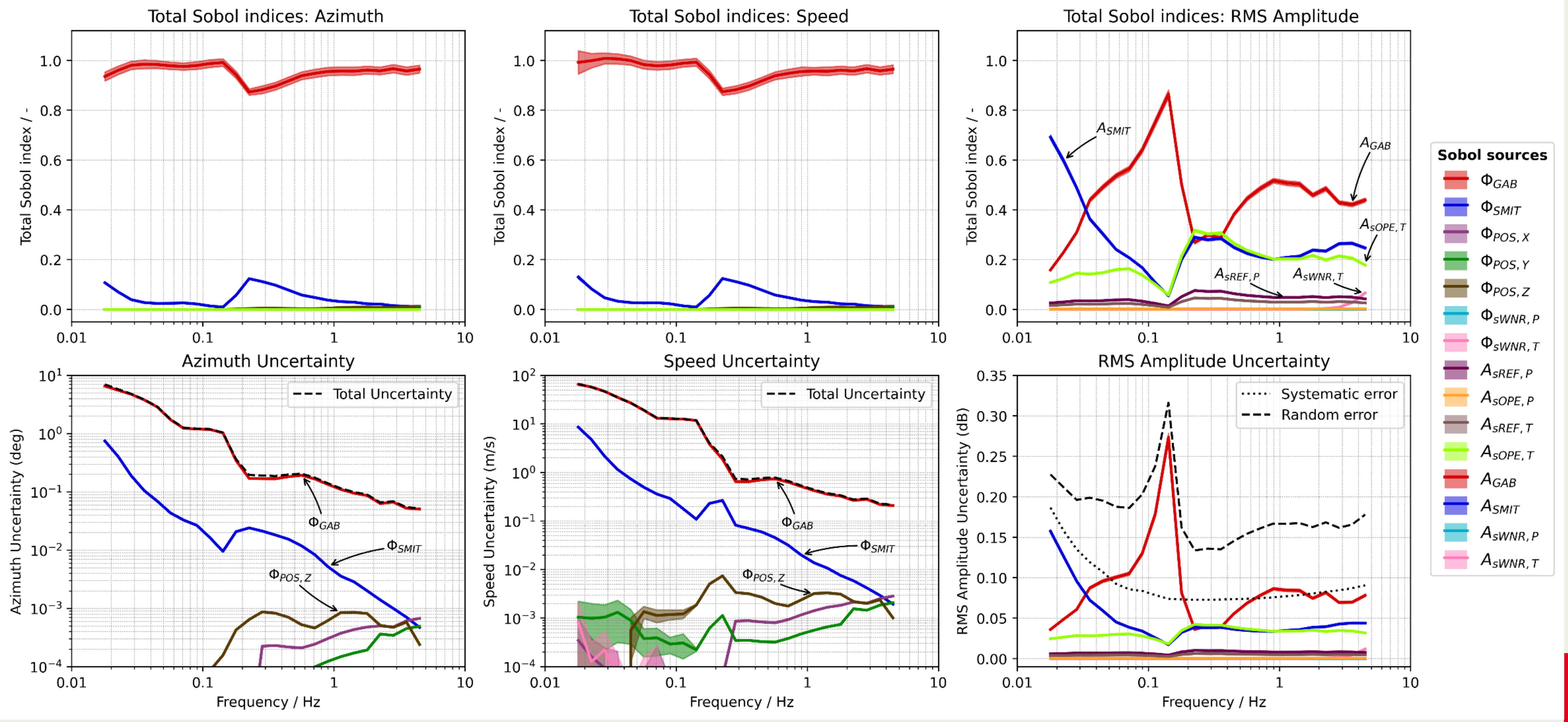
$$\begin{bmatrix} \boldsymbol{\theta} = \langle \theta_n \rangle_n \pm \mathrm{std}(\theta_n) \\ \mathbf{v} = \langle v_n \rangle_n \pm \mathrm{std}(v_n) \\ \mathbf{RMS_a} = \langle RMS_{a,n} \rangle_n \pm \mathrm{std}(RMS_{a,n}) \end{bmatrix}$$

cea

Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

S. Kristoffersen *et al.*

Sensitivity analysis



Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

S. Kristoffersen *et al.*

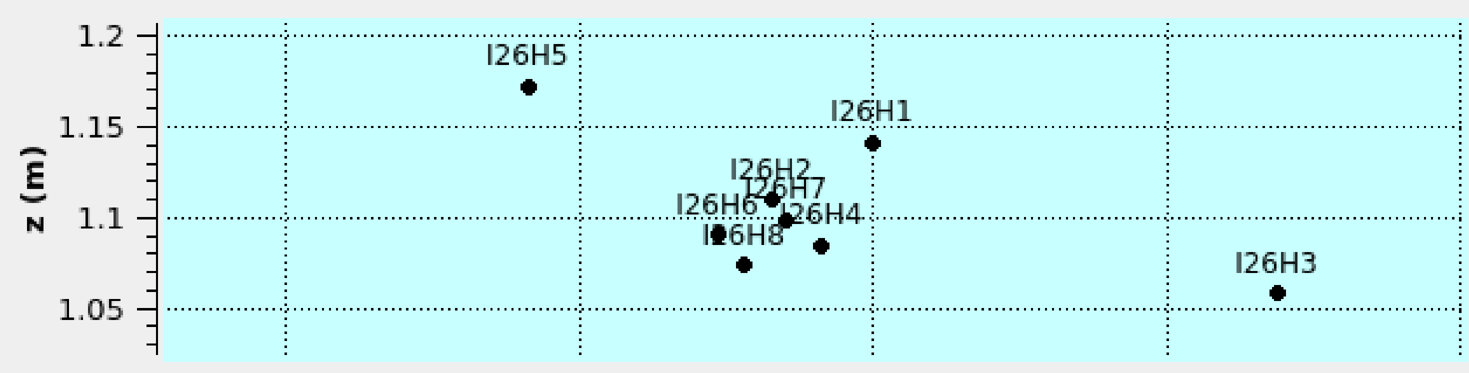
2D Bias

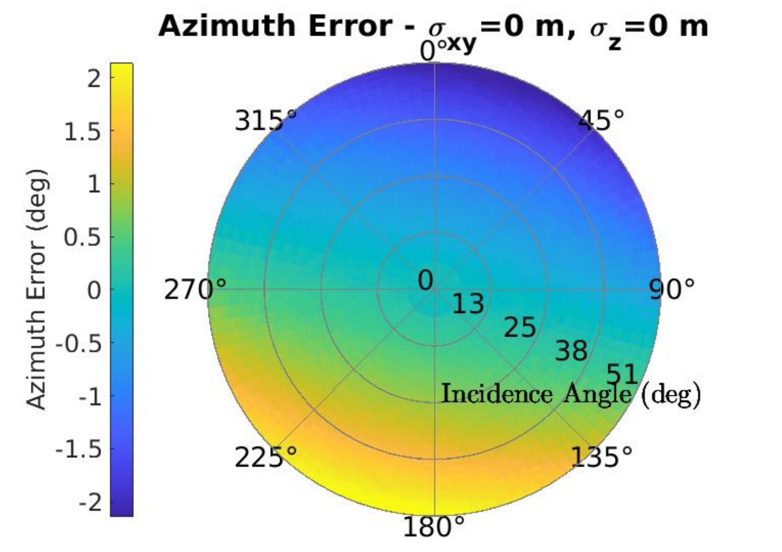
As with many IS stations, IS26 is non-planar.

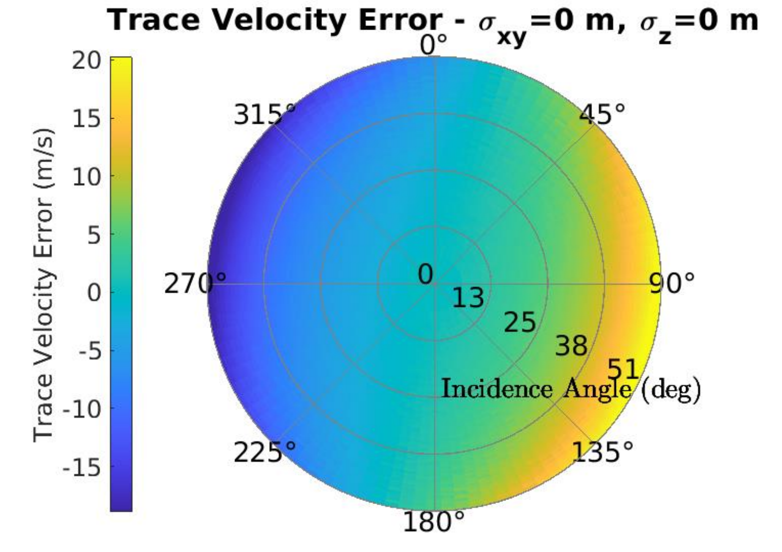
Failure to account for the 3D nature of the station **results in errors** in the back azimuth and trace velocity estimations.

Biases depend on the direction of arrival (back azimuth and incidence angle).

Biases increase with increasing incident angle.



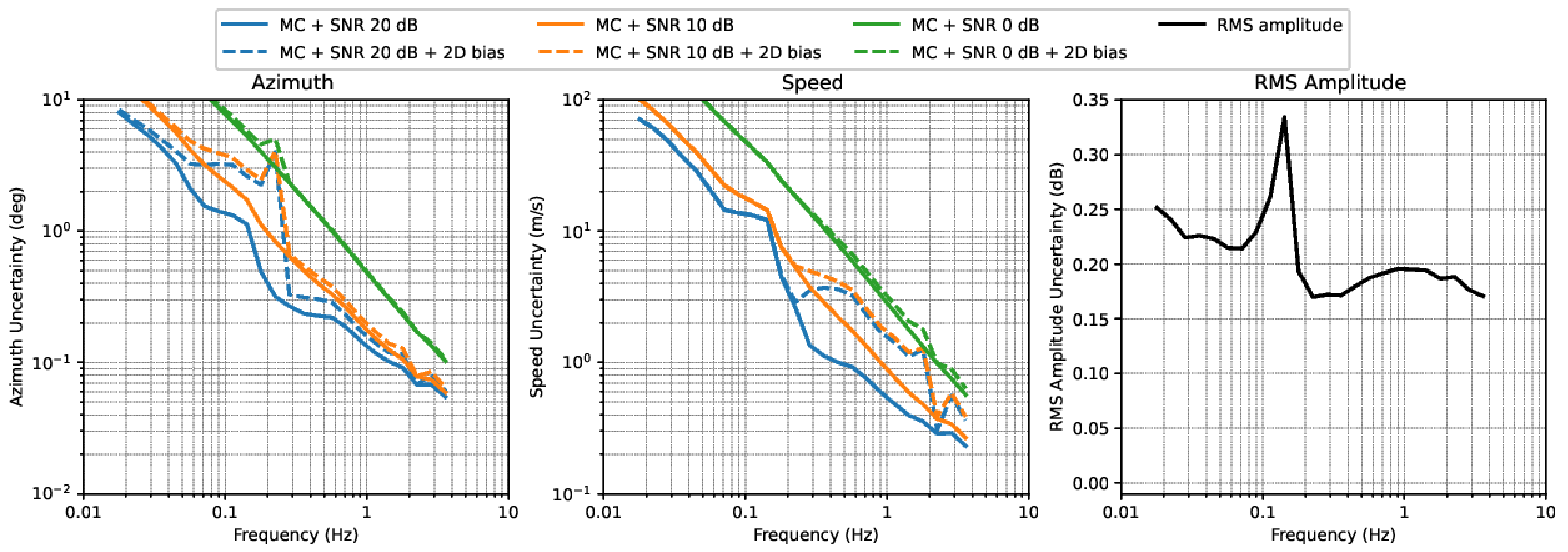




Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

S. Kristoffersen *et al.*

Total uncertainty budget



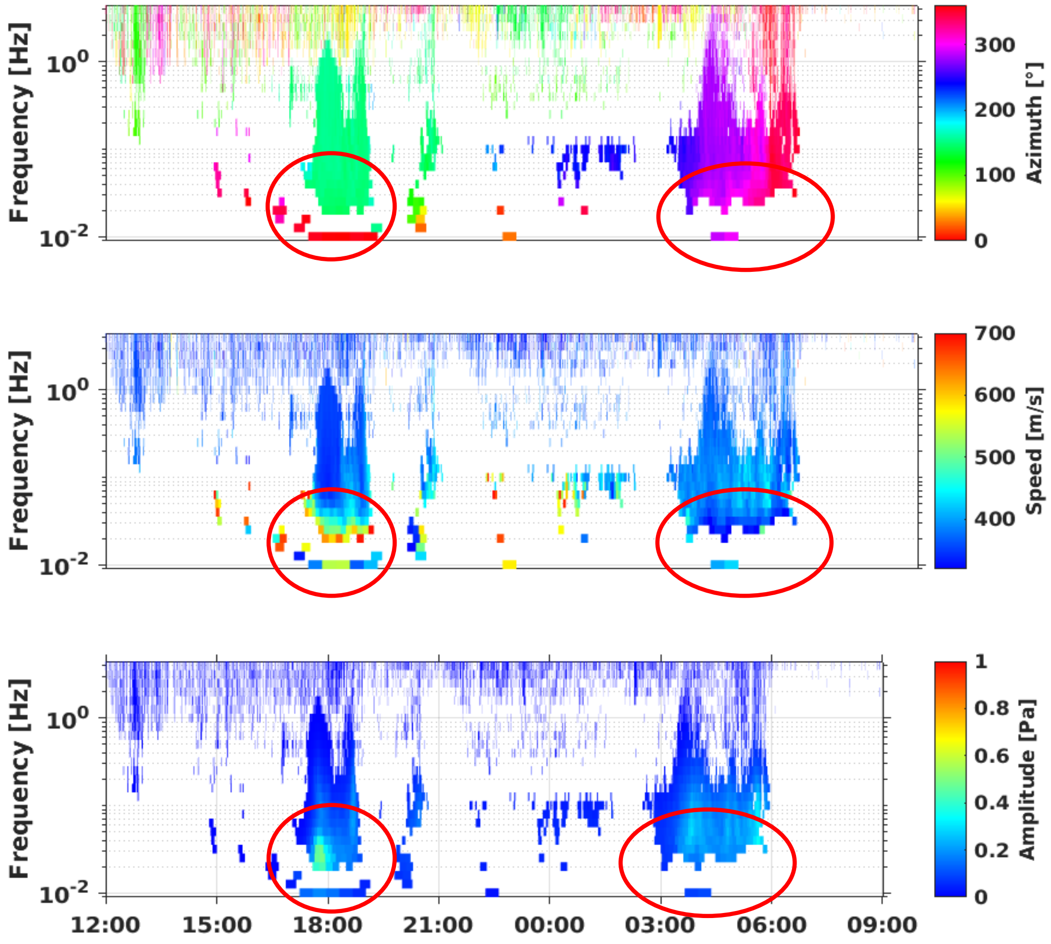
- **2D bias introduces substantial errors relative to the other uncertainty sources**
- At an SNR of 0 dB, uncertainty is dominated by noise, save for a small contribution from the 2D bias
- Even at an SNR of 10 dB, noise has a substantial contribution to uncertainty budget

Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

S. Kristoffersen *et al.*

Calibration of IS47 (South Africa) – Hunga-Tonga Eruption (Jan 15, 2022)

Raw

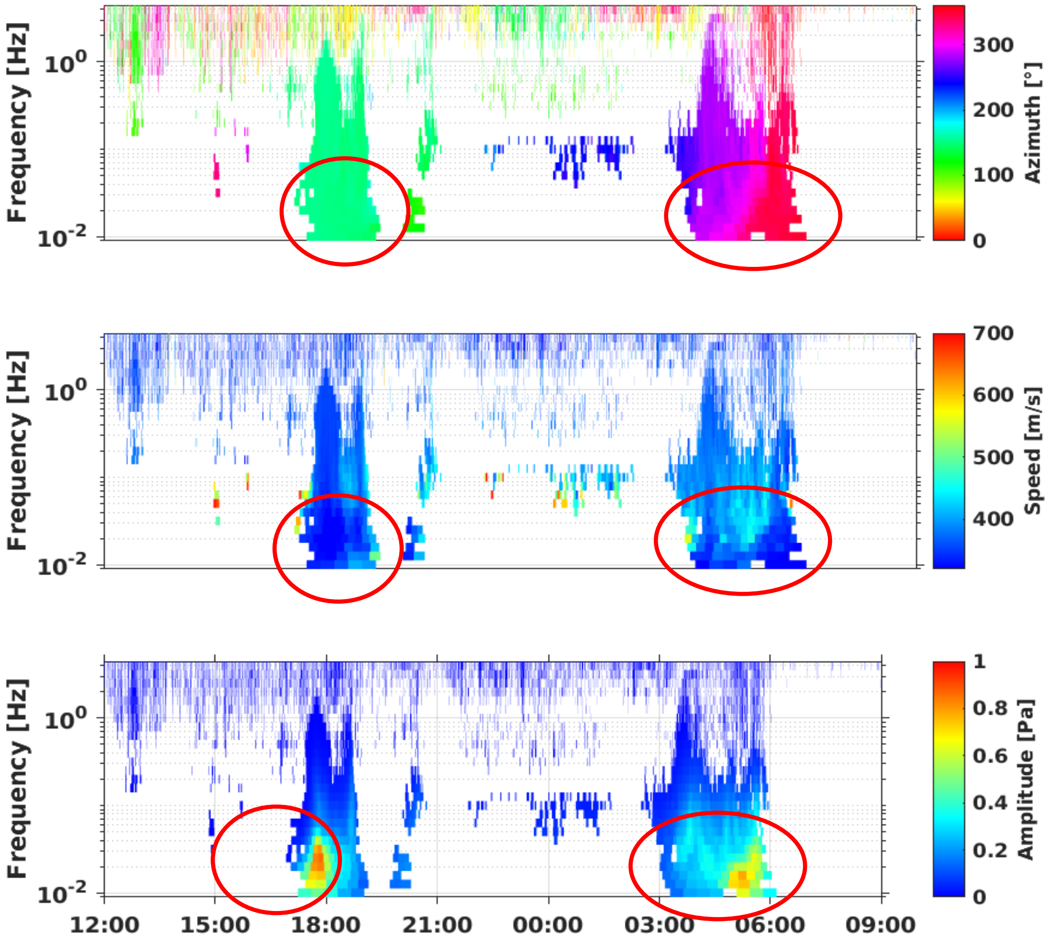


Increase of low-frequency detections

Removal of azimuth (up to 150°) and speed (100s m/s) errors

Increase in RMS amplitude

Calibrated



Kristoffersen et *al*. (2024) https://doi.org/10.1121/10.0025131

S. Kristoffersen *et al.*

Conclusion

- Calibration uncertainties are generally less than the uncertainties associated with noise at SNRs below 10 dB
- 2D analysis introduces measureable biases (dependent on station geometry and the signal DOA).
  - **Back azimuth biases** are between **0.01 and 4°**
  - **Trace velocity biases** are between **0.1 and 5 m/s**
  - 3D analysis should be applied to IMS infrasound stations
- Sensitivity analysis
  - On-site (Gabrielson) calibration is the most influential uncertainty source for all three parameters
  - Sensor susceptibilities to temperature and pressure are important for amplitude uncertainty
  - Further research needs to be done on the phase susceptibilities of the microbarometers.
- Calibration curves can be used both to monitor data quality, and in post-processing to correct defective data over the entire IMS band of interest (0.02-4 Hz).
- Potential for near real-time application using Gabrielson calibration curves (routinely calculated for certain IMS stations) and implementation in PTS environment (CalxPy).

S. Kristoffersen *et al.*

Acknowledgements

- Thomas Gabrielson (Penn State)
- Alfred Kramer and Benoît Doury from the CTBTO
- Julien Marty (UCB)
- Jelle Assink (KNMI)
- Jean-Marc Koenig, Nicolas Tranchant and all other colleagues at CEA
- All of the support from the colleagues at BGR
- Richard Barham (Acoustic Sensor Networks)
- Infra-AUV project

19ENV03 Infra-AUV

References

- Gabrielson (2011), https://doi.org/10.1121/1.3613925
- Green et al. (2021), https://doi.org/10.1093/gji/ggab155
- Kristoffersen et al. (2023), https://doi.org/10.1121/10.0017319
- Cansi (1995), https://doi.org/10.1029/95GL00468
- Alcoverro et al (2005), https://doi.org/10.1016/j.epsl.2022.117639
- Vergoz et al. (2022), https://doi.org/10.1016/j.epsl.2022.117639
- Kristoffersen et *al*. (2024) https://doi.org/10.1121/10.0025131
- Kristoffersen et *al.* (2025) https://doi.org/10.1121/10.0036380