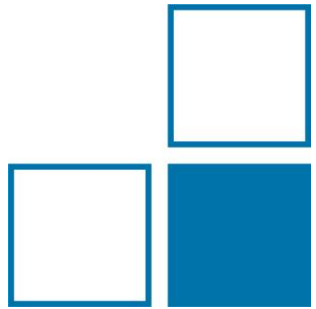
Dynamic calibration of sensors with exclusive digital output

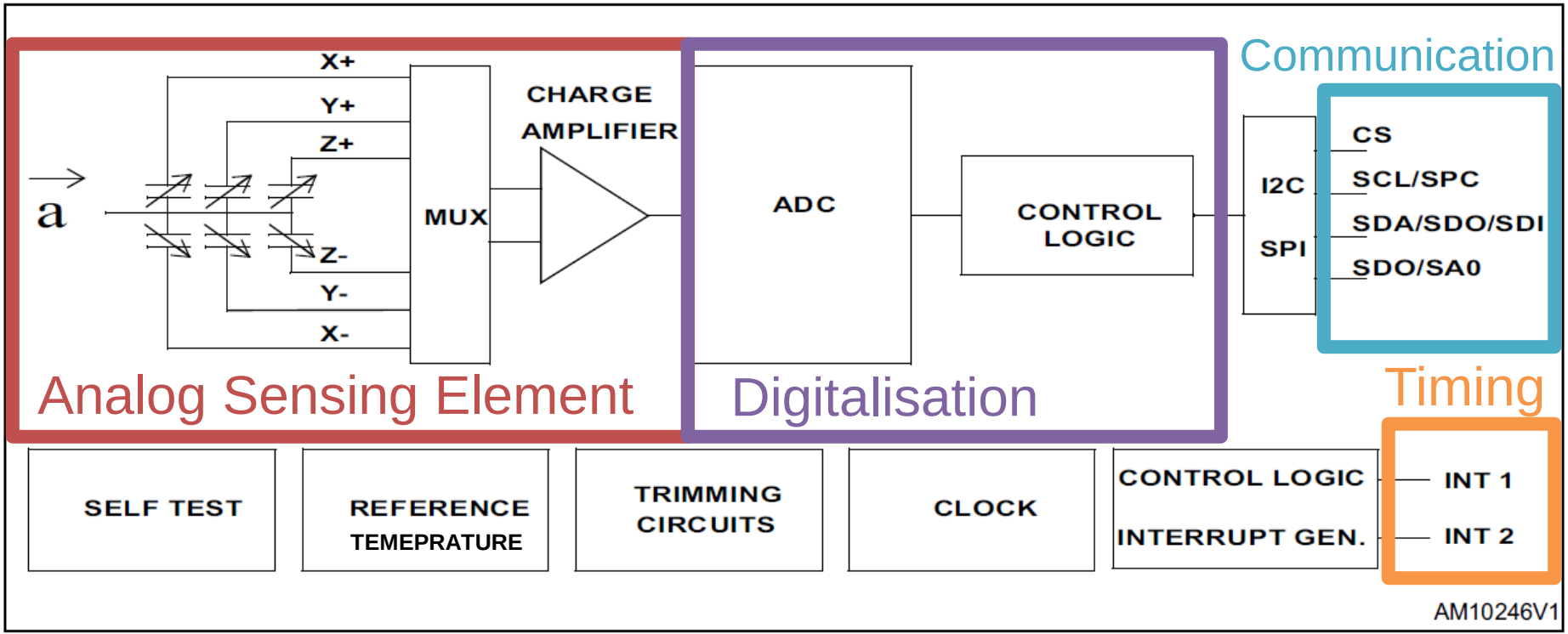
Benedikt Seeger (PTB), Yasin Durgut (Tübitak UME),
Salustiano R. González (CEM)



Braunschweig

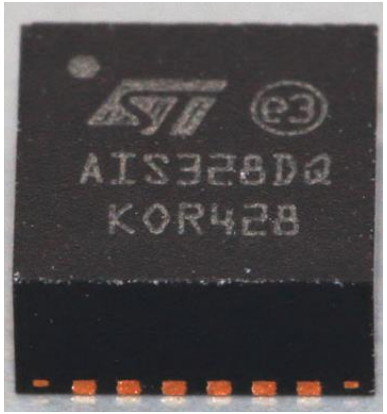
- 1 Mechanics and Acoustics
- 2 Electricity
- 3 Chemical Physics and Explosion Protection
- 4 Optics
- 5 Precision Engineering
- 6 Ionizing Radiation
- 9 Legal and International Metrology
- Q Cross-Sectional Services
- Z Administrative Services
- quest QUEST Institute at PTB
- FPM Fundamental Physics for Metrology

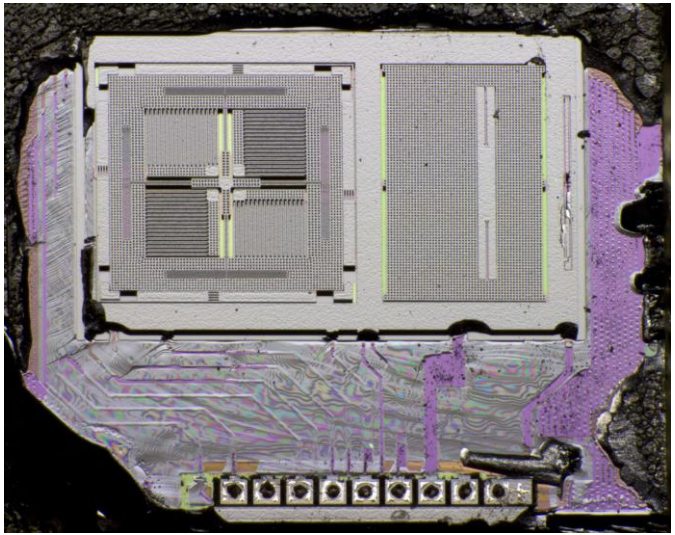
Acceleration MEMS Sensor Overview



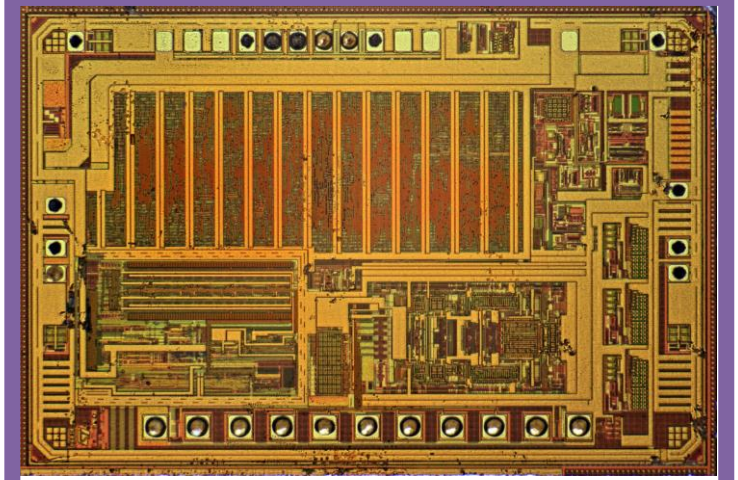
IIS328DQ High-performance ultra-low-power 3-axis accelerometer with digital out-put for industrial applications, STMicroelectronics (2015), https://www.st.com/resource/en/datasheet/iis328dq.pdf

Example: 3-Axis MEMS Accelerometer





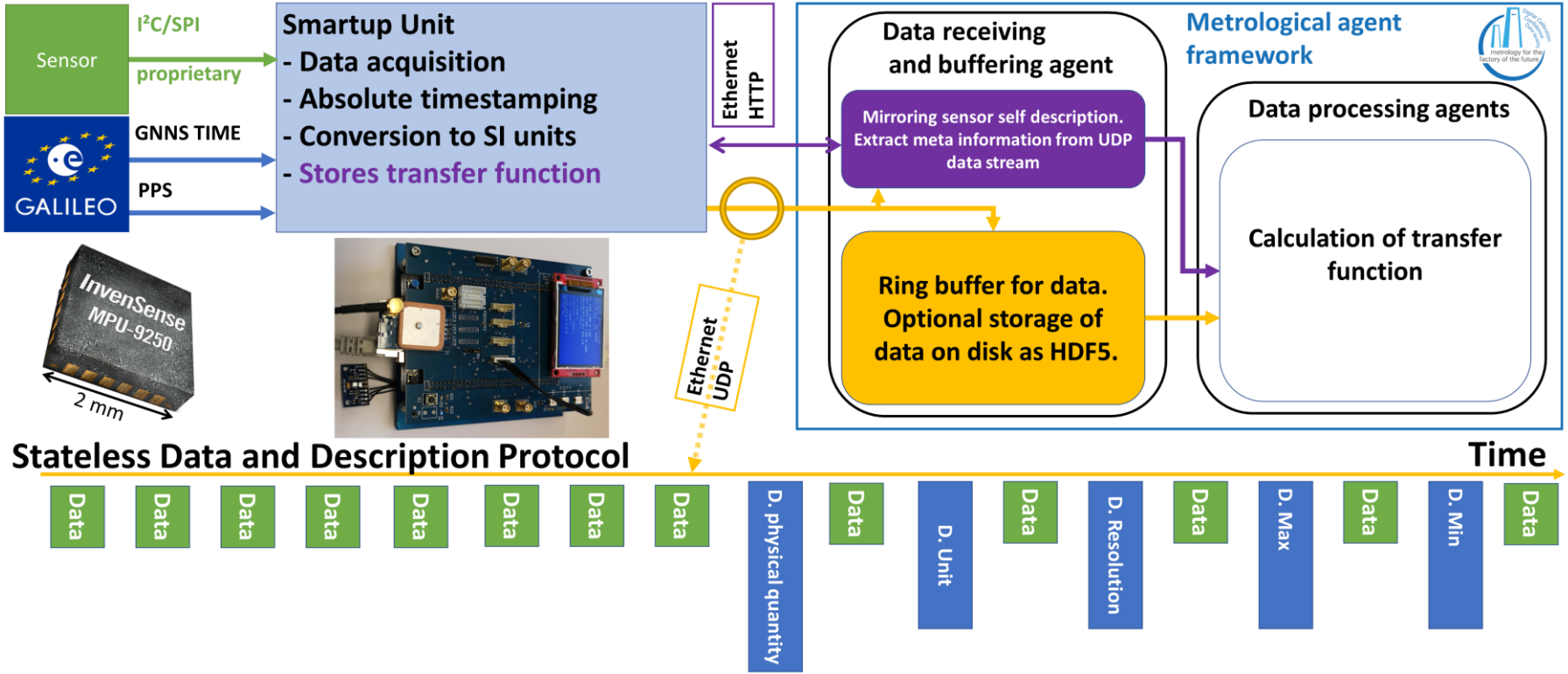
Analog Sensing Element



Digitalisation

Image source https://www.richis-lab.de/MEMS_02.htm

Data flow in the Smartup Unit

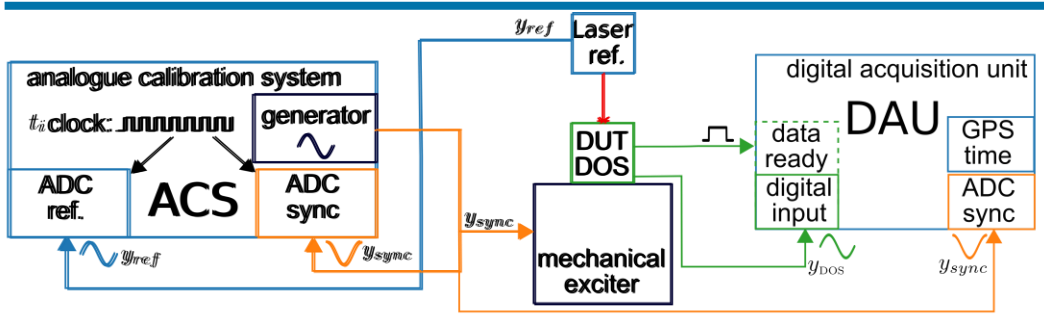


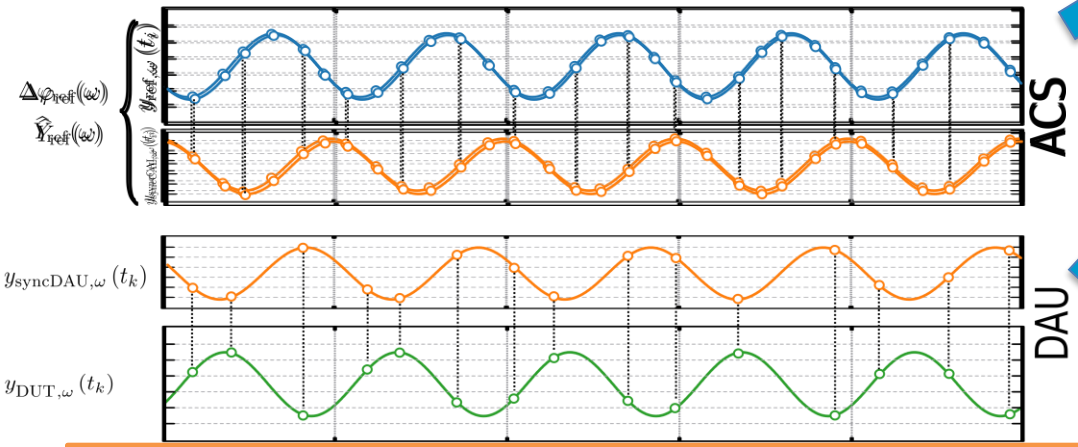
Stateless Data and Description Protocol

Key	Data	Data
ID	123	123
Samplenumber	100	101
Unix time	1594224567	1594224567
Unix time nsecs	123456000	12356012
Time uncertainty	155	156
Data_01	0.234	0.235
Data_02	0.125	0.127
Data_03	9.634	9.602
Data_04	0.005	0.004
Data_05	0.006	0.007
Data_06	-0.005	-0.007
Data_07	-50.62	-50.42
Data_08	10.12	10.02
Data_09	2.35	2.00
Data_10	23.54	23.55

Key	Description	Description	Description	Description	Description
ID	123	123	123	123	123
Type	PHYSICAL_QUANTITY	UNIT	RESOLUTION	MIN_SCALE	MAX_SCALE
Description_01	X Acceleration	\metre\second\tothe{-2}	65536	-156.914	156.909
Description_02	Y Acceleration	\metre\second\tothe{-2}	65536	-156.914	156.909
Description_03	Z Acceleration	\metre\second\tothe{-2}	65536	-156.914	156.909
Description_04	X Angular velocity	\radian\second\tothe{-1}	65536	-34.907	34.906
Description_05	Y Angular velocity	\radian\second\tothe{-1}	65536	-34.907	34.906
Description_06	Z Angular velocity	\radian\second\tothe{-1}	65536	-34.907	34.906
Description_07	X Magnetic flux density	\micro\tesla	65520	-5775.43	5775.43
Description_08	Y Magnetic flux density	\micro\tesla	65520	-5775.43	5775.43
Description_09	Z Magnetic flux density	\micro\tesla	65520	-5775.43	5775.43
Description_10	Temperature	\degreecelsius	65536	-77.208	119.080

Calibration System for „digital Sensors“





IEEE 1057 Sine Fit

$$y_{\mathrm{ref},\omega}(t_i) = \hat{Y}_{\mathrm{ref},\omega} \cdot \sin(\omega \cdot t_i - \varphi_{\mathrm{ref},\omega})$$

$$y_{\mathrm{syncCAL},\omega}(t_i) = \hat{Y}_{\mathrm{syncCAL},\omega} \cdot \sin(\omega \cdot t_i - \varphi_{\mathrm{syncCAL},\omega})$$

$$\Delta\varphi_{\mathrm{ref-sync}}(\omega) = \varphi_{\mathrm{ref}}(\omega) - \varphi_{\mathrm{syncCAL}}(\omega)$$

IEEE 1057 Sine Fit

$$y_{\mathrm{DUT},\omega}(t_k) = \hat{Y}_{\mathrm{DUT},\omega} \cdot \sin(\omega \cdot t_k - \varphi_{\mathrm{DUT},\omega})$$

$$y_{\mathrm{syncDAU},\omega}(t_k) = \hat{Y}_{\mathrm{syncDAU},\omega} \cdot \sin(\omega \cdot t_k - \varphi_{\mathrm{syncDAU},\omega})$$

$$\Delta\varphi_{\mathrm{DUT-sync}}(\omega) = \varphi_{\mathrm{DUT}}(\omega) - \varphi_{\mathrm{syncDAU}}(\omega)$$

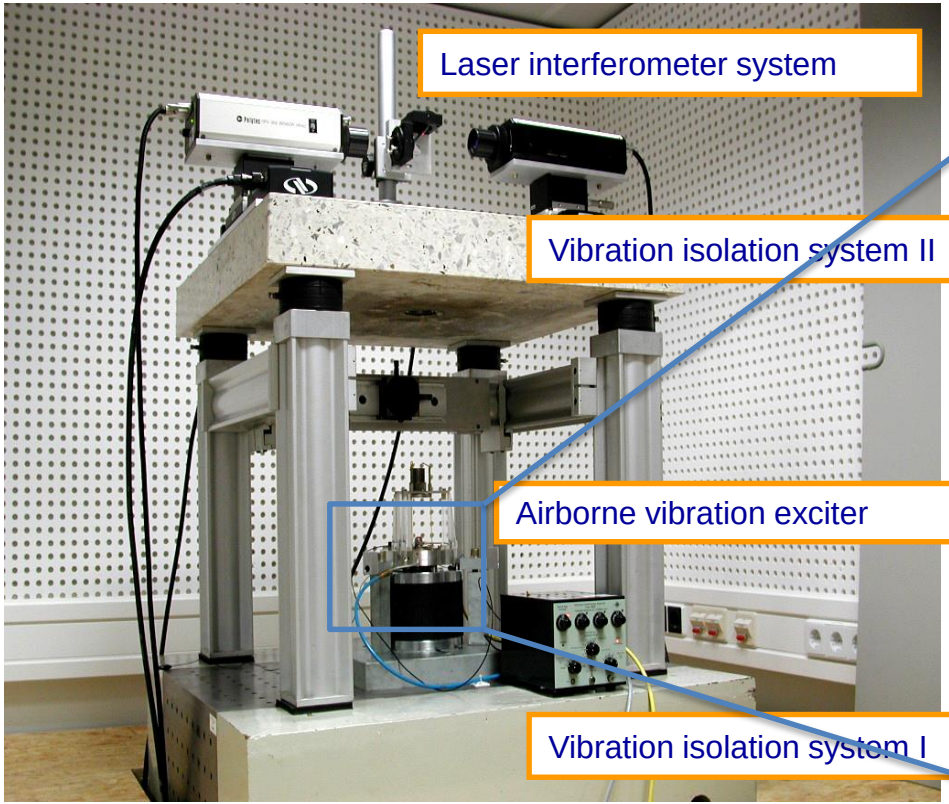
$$|S(\omega)| = \frac{\hat{Y}_{\mathrm{DUT}}(\omega)}{\hat{Y}_{\mathrm{ref}}(\omega)}$$

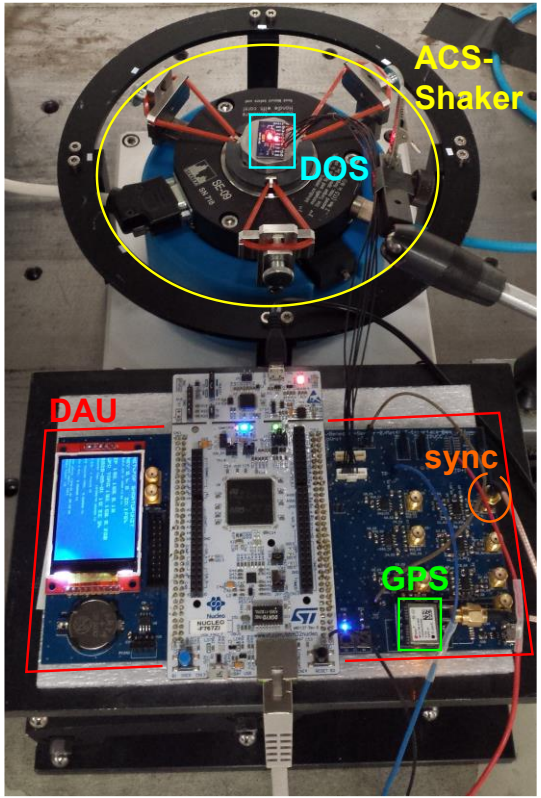
$$\Delta\varphi(\omega) = (\Delta\varphi_{\mathrm{DUT-sync}}(\omega) - \Delta\varphi_{DAUADC}(\omega)) - \Delta\varphi_{\mathrm{ref-sync}}(\omega)$$

DAU ADC needs calibration

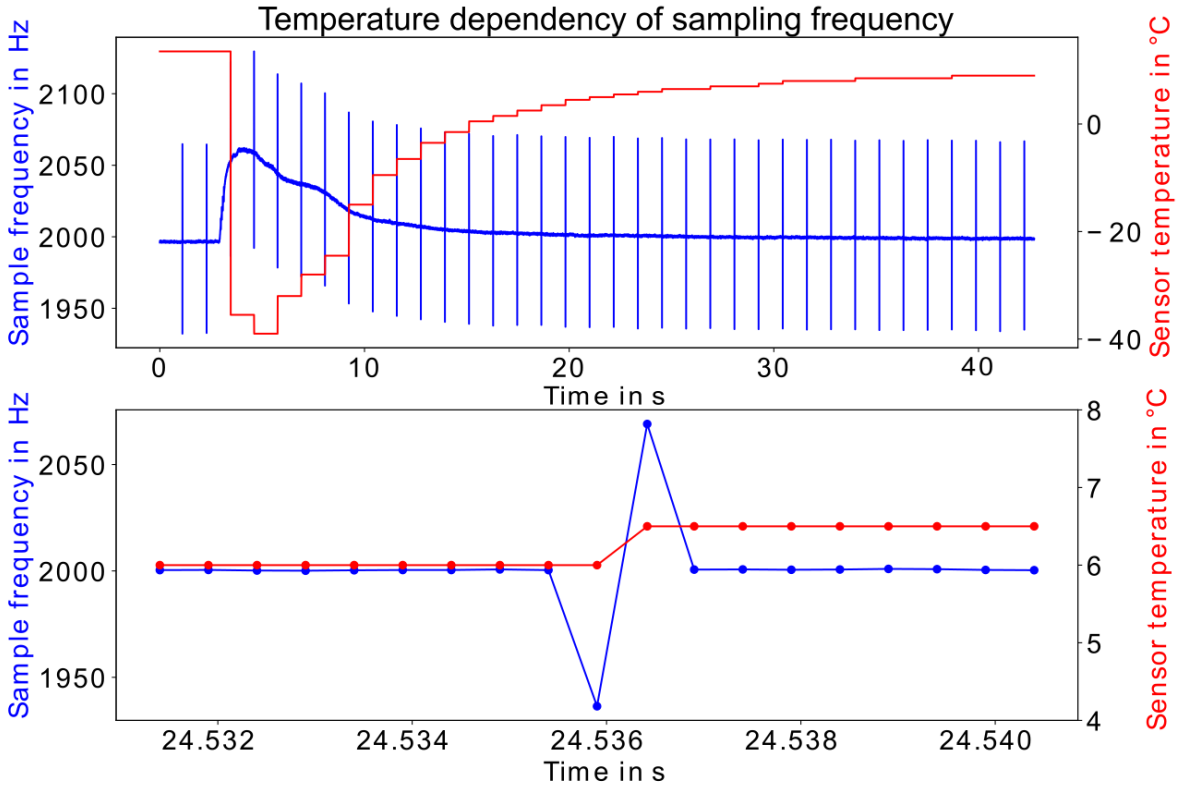
http://dx.doi.org/10.21014/acta_imeko.v9i5.1008

Calibration System for „Digital Sensors“





Sensor Sample Clock Example

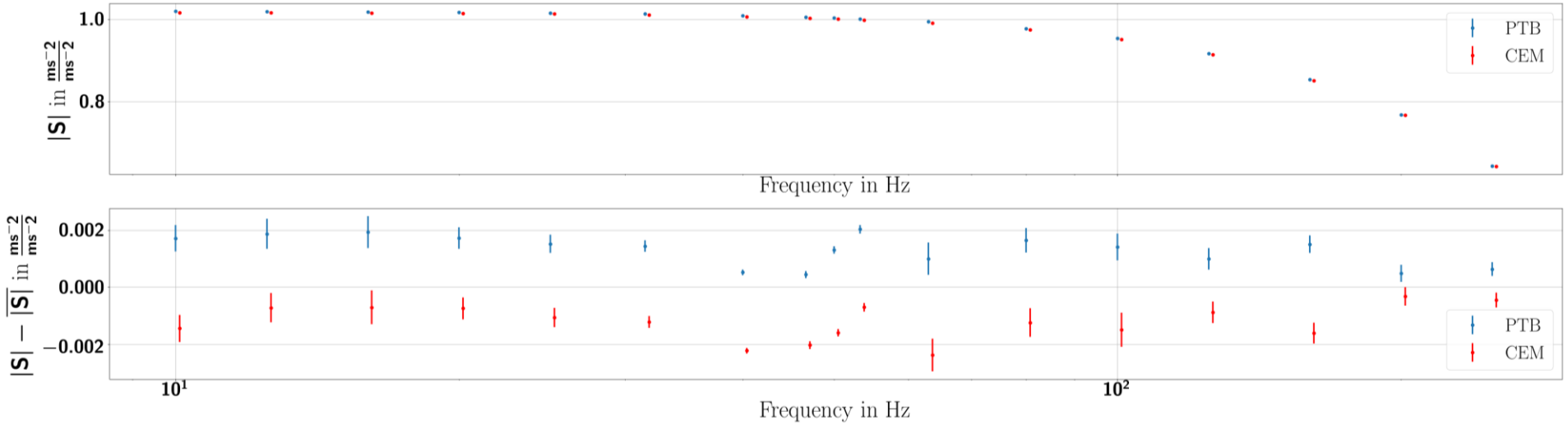


- Many sensors generate the sample clock internally.
- Deviations in the % range are possible.
- Precise phase evaluation is not possible without knowledge of the sample clock.

In contrast to the FFT, the IEEE1057 Sine Approximation does not require equidistant samples.

Example Measurements at CEM and PTB

PTB 10 repetitions
CEM 9 repetitions
Uncertainties were calculated from the weighted repetitions



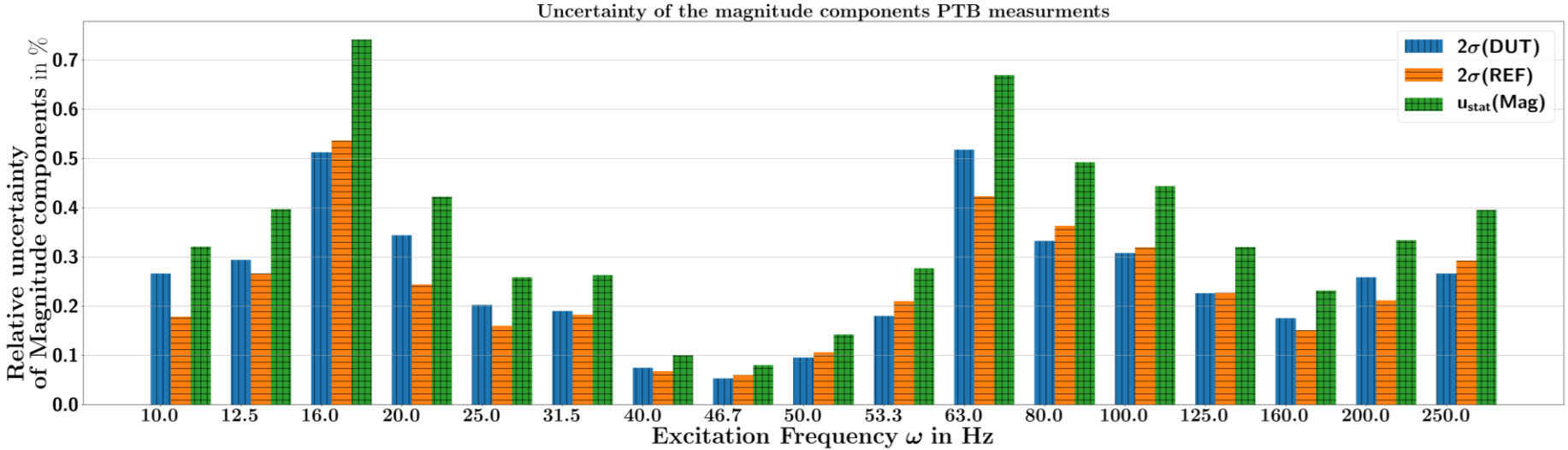
Statistical uncertainty one run PTB

The uncertainty does not yet include systematic influences such as

- temperature
- mounting.

$$|S(\omega)| = \frac{\widehat{Y}_{\mathrm{DUT}}(\omega)}{\widehat{Y}_{\mathrm{ref}}(\omega)}$$

The seven cables of the sensor can lead to resonances and other mechanical disturbances.



Example Measurements at CEM and PTB

PTB 10 repetitions
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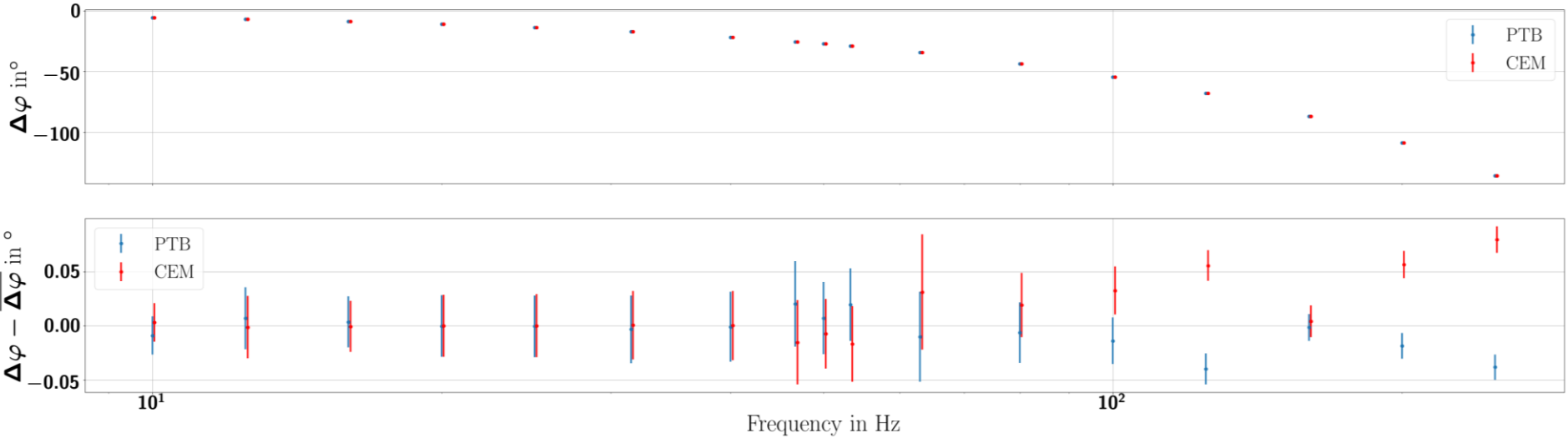


Statistical uncertainty one run PTB

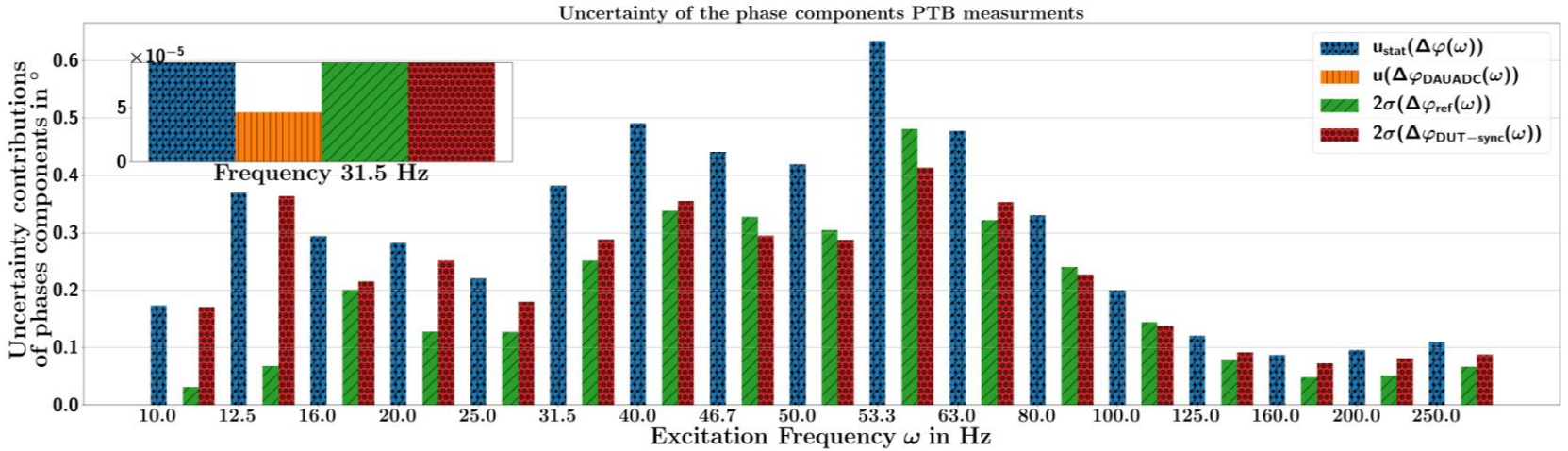
The uncertainty does not yet include systematic influences such as

- temperature
- mounting errors.

PTB's analog reference signal does not have a constant amplitude over frequency.

- source of phase uncertainty.

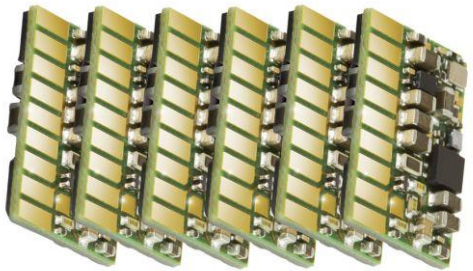
$$\Delta\varphi(\omega) = (\Delta\varphi_{\mathrm{DUT-sync}}(\omega) - \Delta\varphi_{DAUADC}(\omega)) - \Delta\varphi_{\mathrm{ref-sync}}(\omega)$$



Pulse pressure transducer calibration

- MG-Sensor Analog-Digital-Module
  - Time series recording
  - 20 kHz Sample rate
  - 4 wire bridge (4.8 V)
  - times 100 gain
  - 16 bit resolution

https://www.mg-sensor.de/de/Aktuell.html

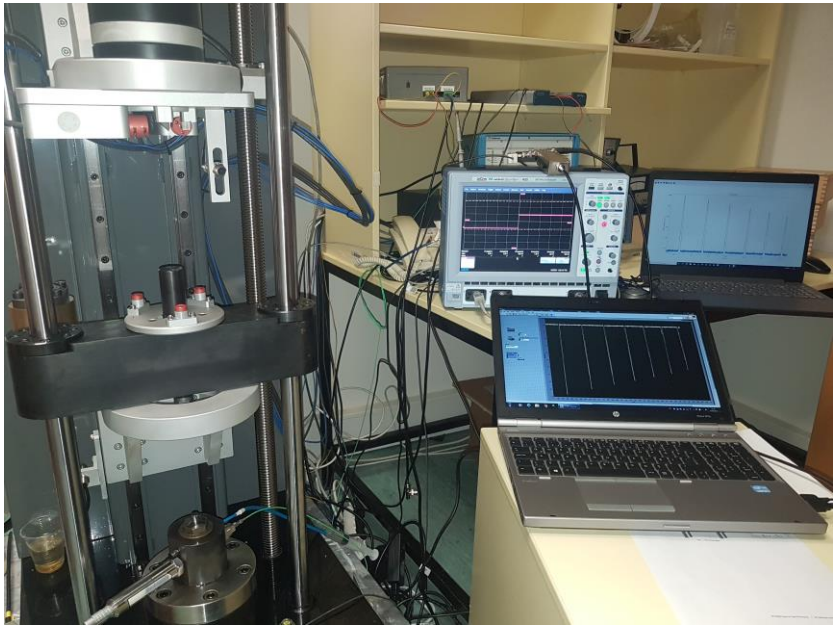


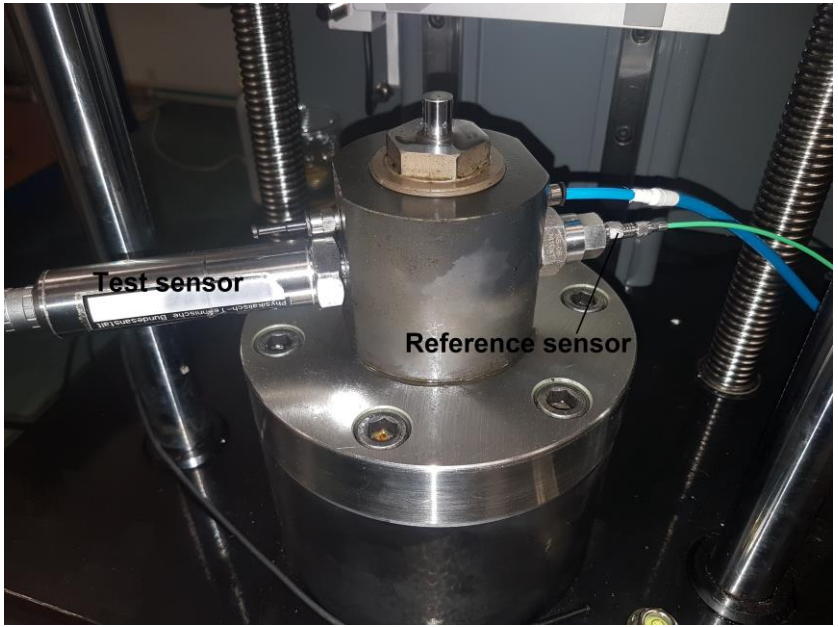
- P3MBP BlueLine Pressure Transducer
  - 10000 bar/mV/V

https://www.hbm.com/en/2477/p3mbp-blueline-high-pressure-transducer-up-to-15000-bar/

Pulse pressure excitation at Tübitak UME

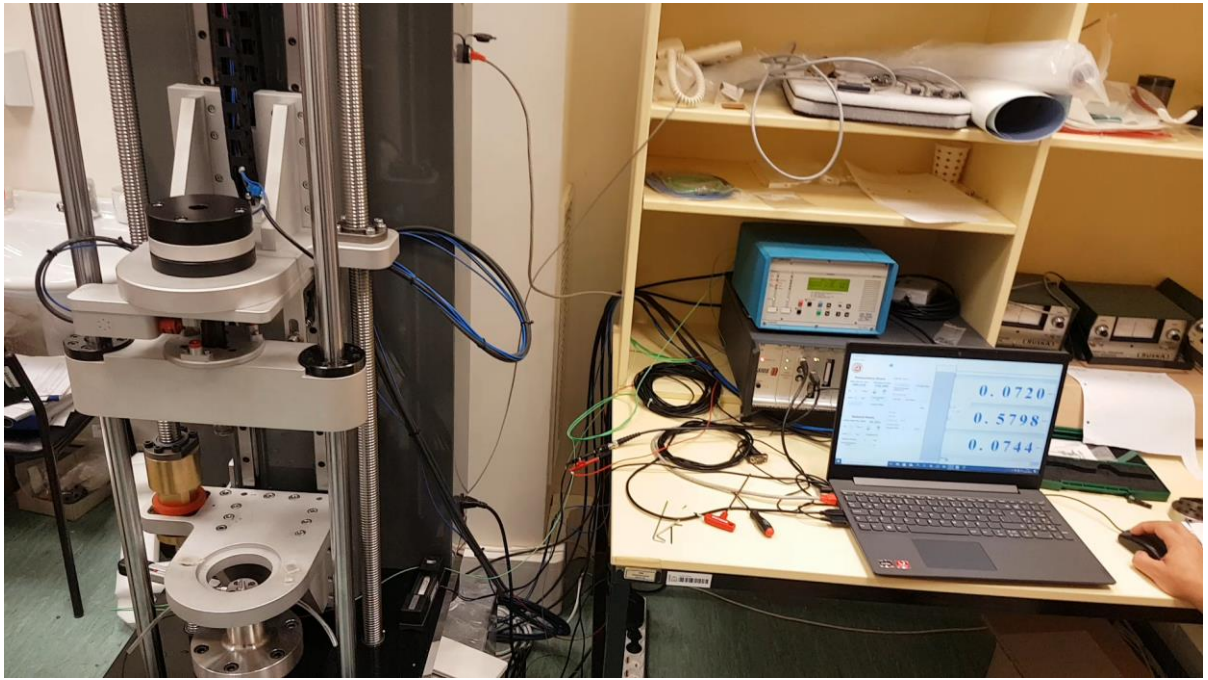
Comparison of pulse peak values
similar to ISO 16063-21
„Methods for the calibration of vibration and shock transducers“



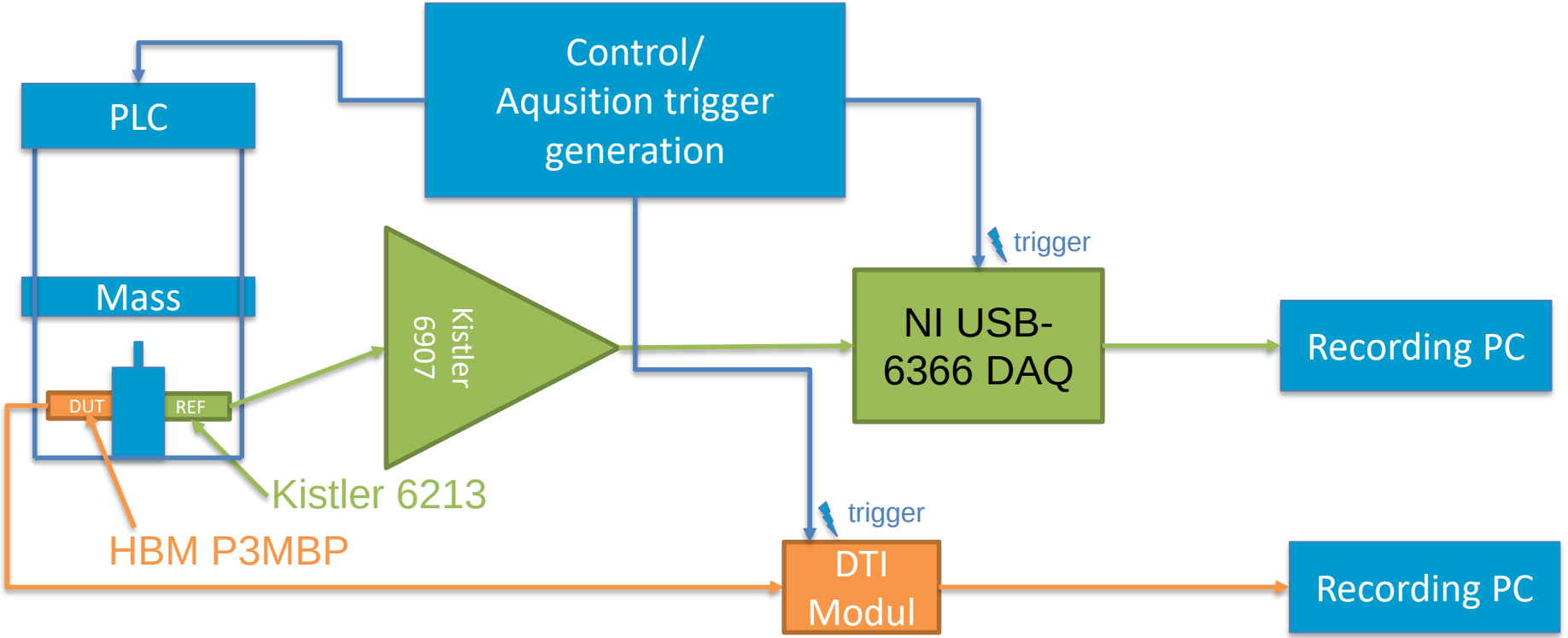


Pulse pressure excitation

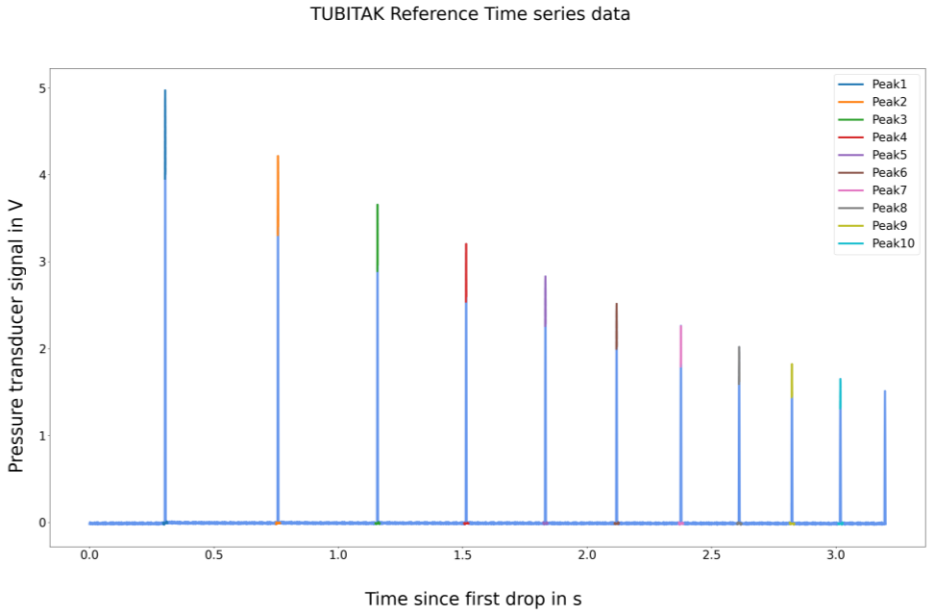
Facility at Tübitak UME

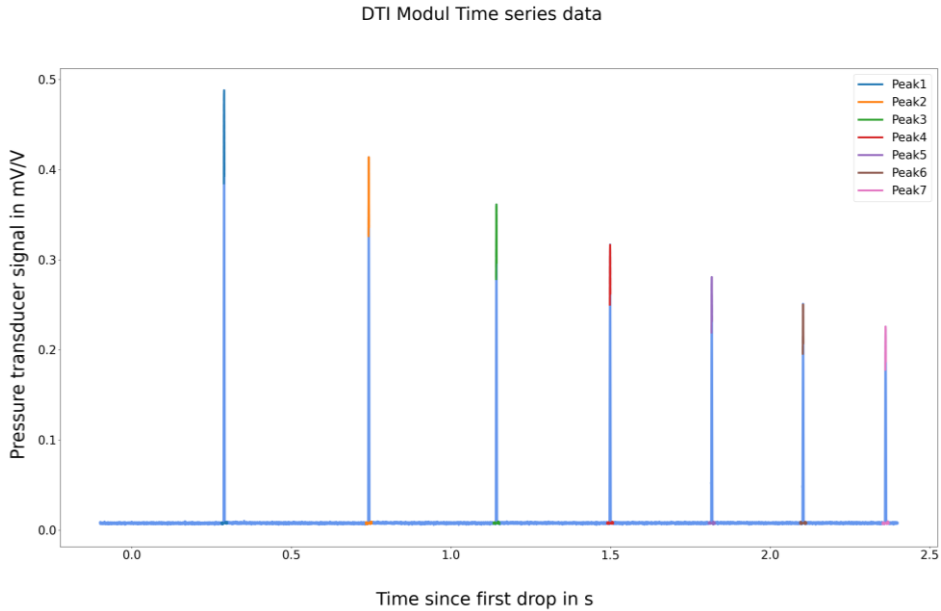


pressure pulse excitation

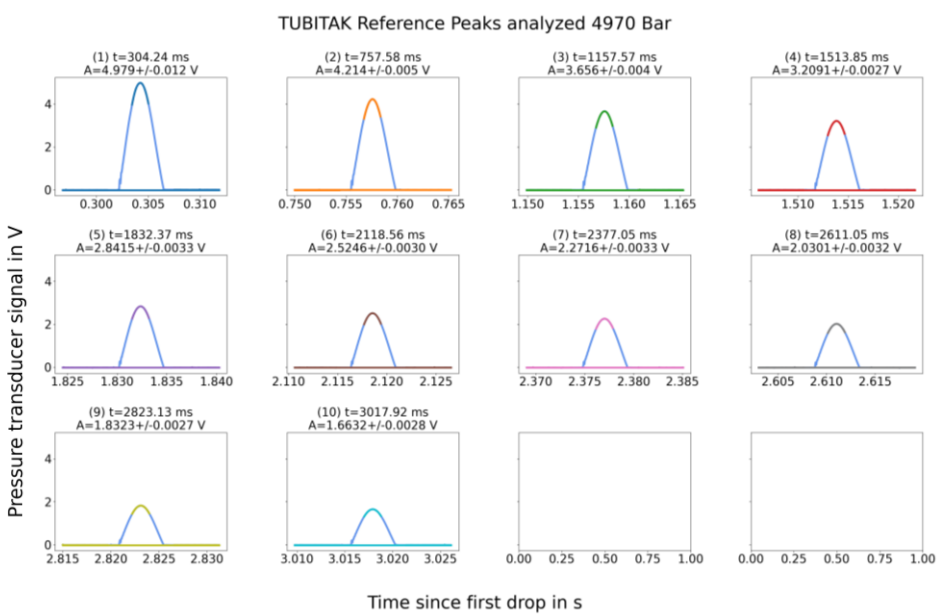


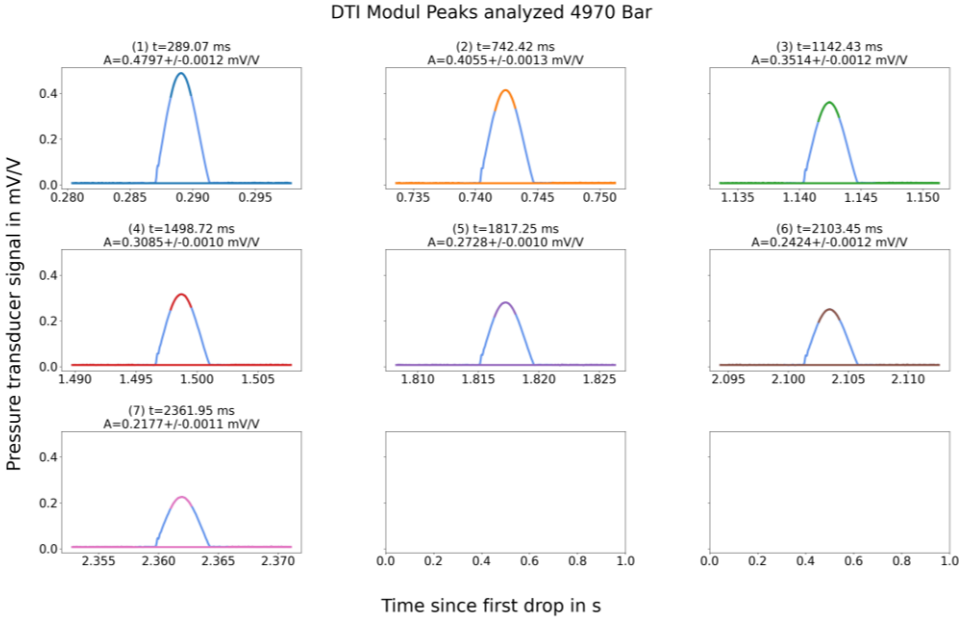
Timeseries 4970 bar first pulse



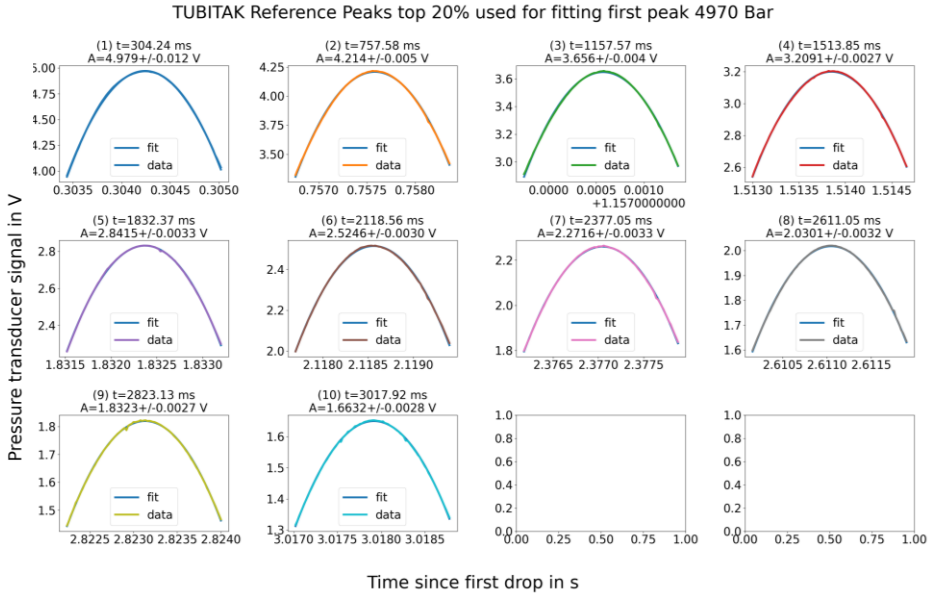


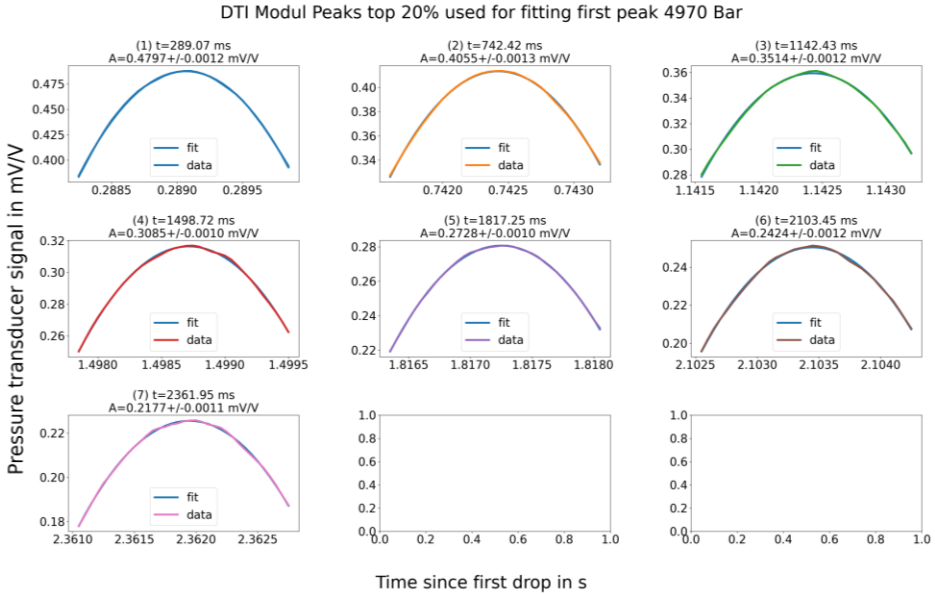
Full pulses 4970 bar first pulse



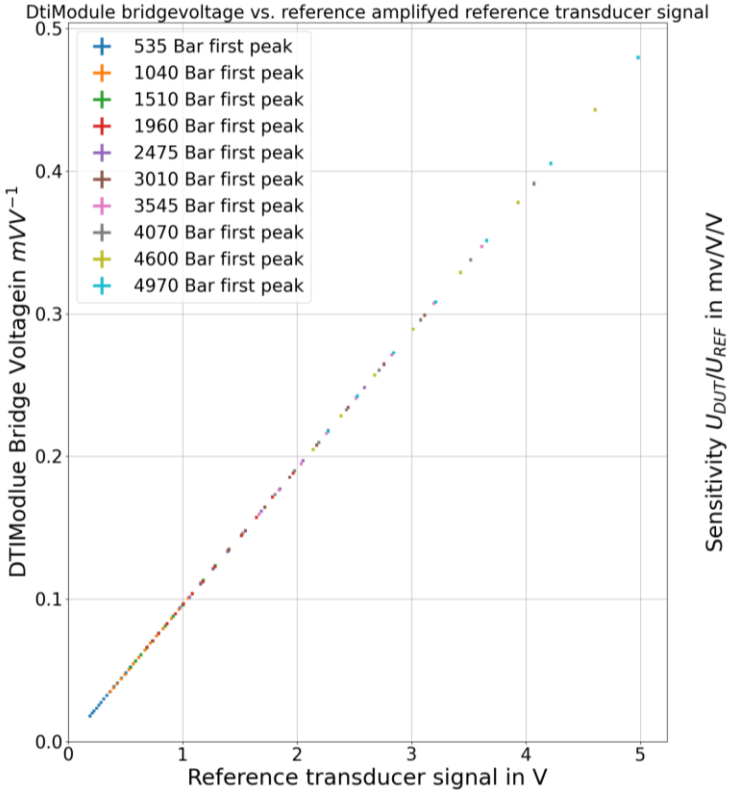


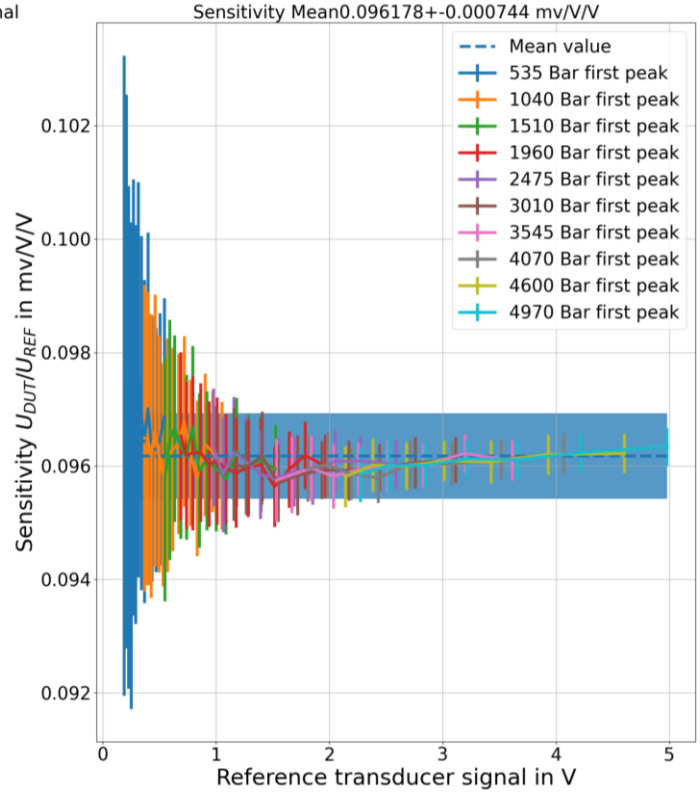
Top 20 % 4970 bar first pulse





Results


DtiModule bridgevoltage vs. reference amplifyed reference transducer signal
535 Bar first peak
1040 Bar first peak
1510 Bar first peak
1960 Bar first peak
2475 Bar first peak
3010 Bar first peak
3545 Bar first peak
4070 Bar first peak
4600 Bar first peak
4970 Bar first peak
DTIModlue Bridge Voltagein mVV^{-1}
Reference transducer signal in V


Sensitivity Mean0.096178+-0.000744 mv/V/V
Mean value
535 Bar first peak
1040 Bar first peak
1510 Bar first peak
1960 Bar first peak
2475 Bar first peak
3010 Bar first peak
3545 Bar first peak
4070 Bar first peak
4600 Bar first peak
4970 Bar first peak
Sensitivity U_{DUT}/U_{REF} in mv/V/V
Reference transducer signal in V

Summary

- With the Met4FoF Smartup unit + software, existing analog calibration systems can be extended for digital sensors.
  - no modification of the analog system required!
- Digital sensors must be treated like measuring chains.
- For evaluation in frequency domain, the sample frequency must be measured or provided externally.
  - if equidistant samples are required (e.g. FFT), interpolation must be performed
- Digital preasure transducers can be calibrated similar to ISO 16063-21 „Methods for the calibration of vibration and shock transducers“

Acknowledgement

https://github.com/met4FoF

https://circuitmaker.com/Projects/Details/Benedikt-Seeger-2/Met4FoF-Interface-Board

Contact: Benedikt Seeger
Benedikt.seeger@ptb.de

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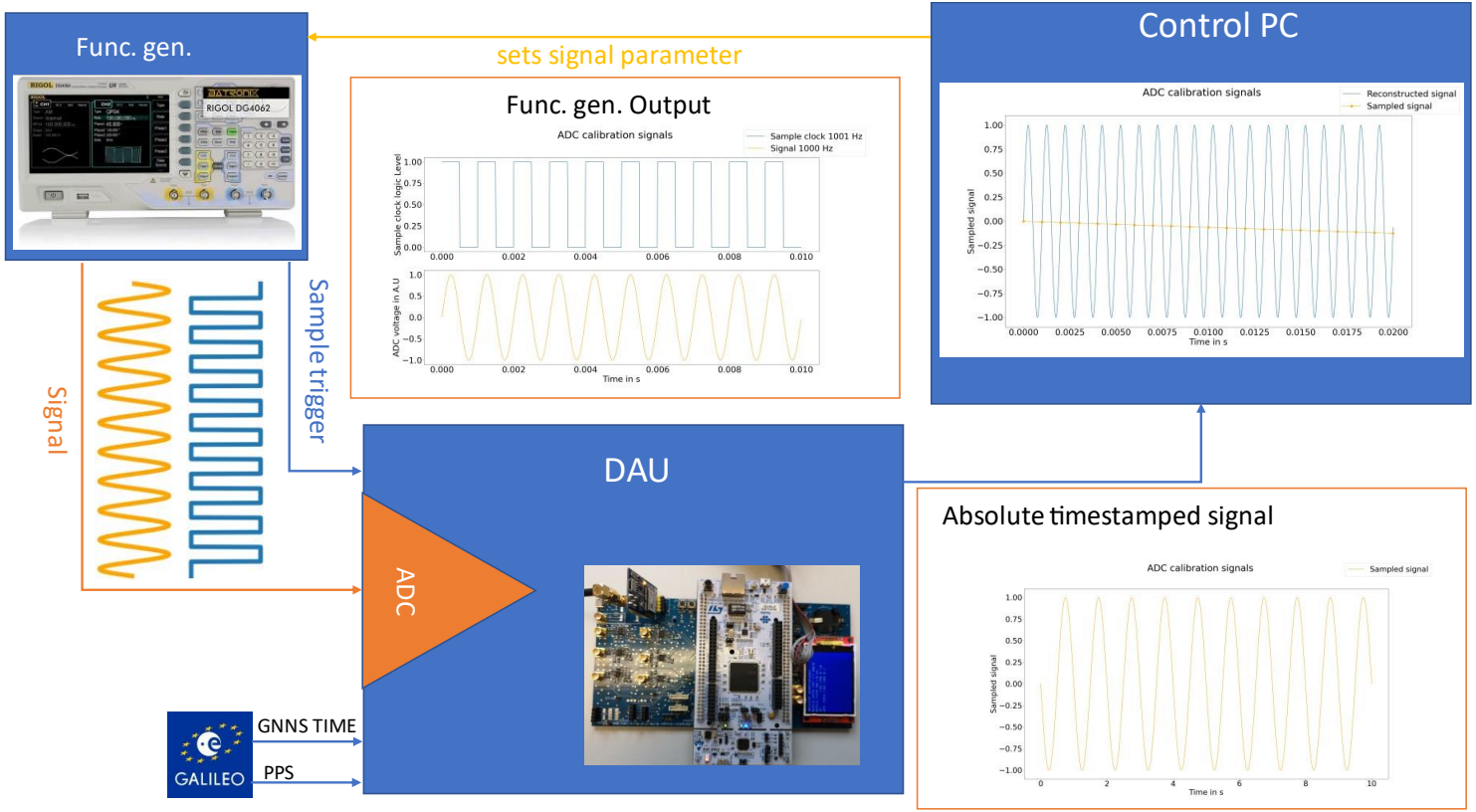
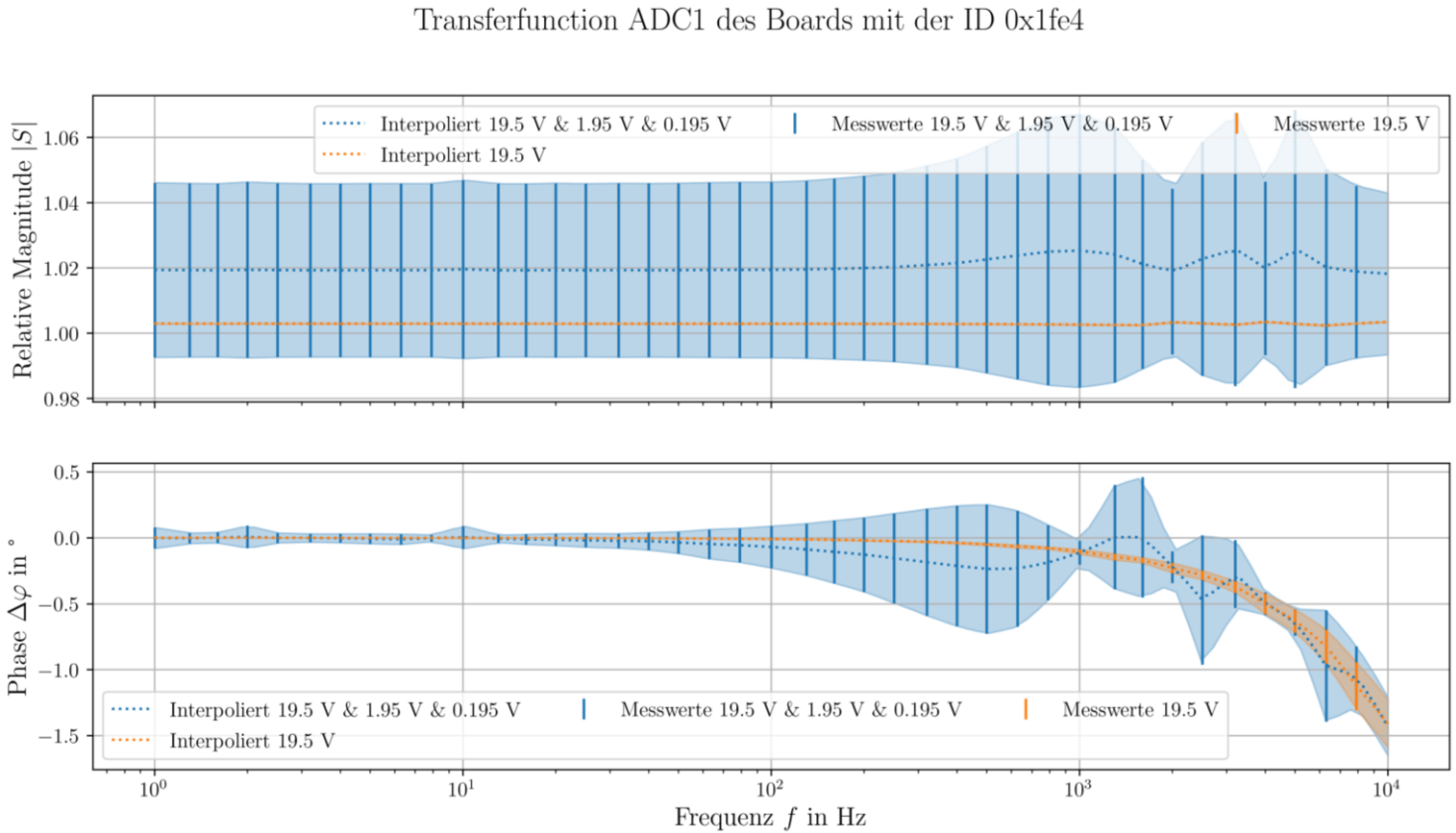
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

ADC Calibration



ADC transfer function



Calibration system in the AgentFramework