Modellierung und Korrektur dynamischer elektrischer Wellenformen

23NRM01 SBS Uncert

Support for standardization of sample-by-sample waveform uncertainty calculation

333. PTB Seminar, 06.05.2026

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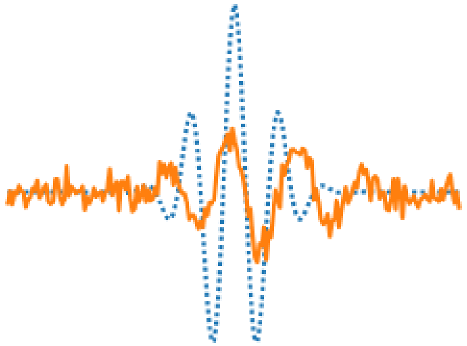
Outline

- Motivation
- Digital Sampling Oscilloscopes
- Digital Real-Time Oscilloscopes

Motivation

- Knowledge of exact waveform of growing importance
  - High-bandwidth communication technology
  - Electrical power grid stability

- Significant influence of measurement system
  - Device impairments need to be characterized
  - Measured waveforms need to be corrected



- Adaption of existing knowledge (GUM, ...) not always straight-forward
  - Sample-by-sample uncertainty computation

IEC: Sample-by-sample waveform uncertainty computation

SBS uncert

Support the writing of a new IEC standard

- IEC Working title
  Electrical Waveform Uncertainties

- Complements existing standard IEC 62754
  Computation of waveform ***parameter*** *uncertainties*

- New standard: **waveform metrology**
  - waveform reconstruction and processing methods
  - uncertainty analysis/propagation methods

IEC

IEC 62754

Edition 1.0 2017-05

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Computation of waveform parameter uncertainties

Calcul des incertitudes des paramètres des formes d'onde

https://webstore.iec.ch/en/publication/29773

IEC: Sample-by-sample waveform uncertainty computation

IEC 62754:

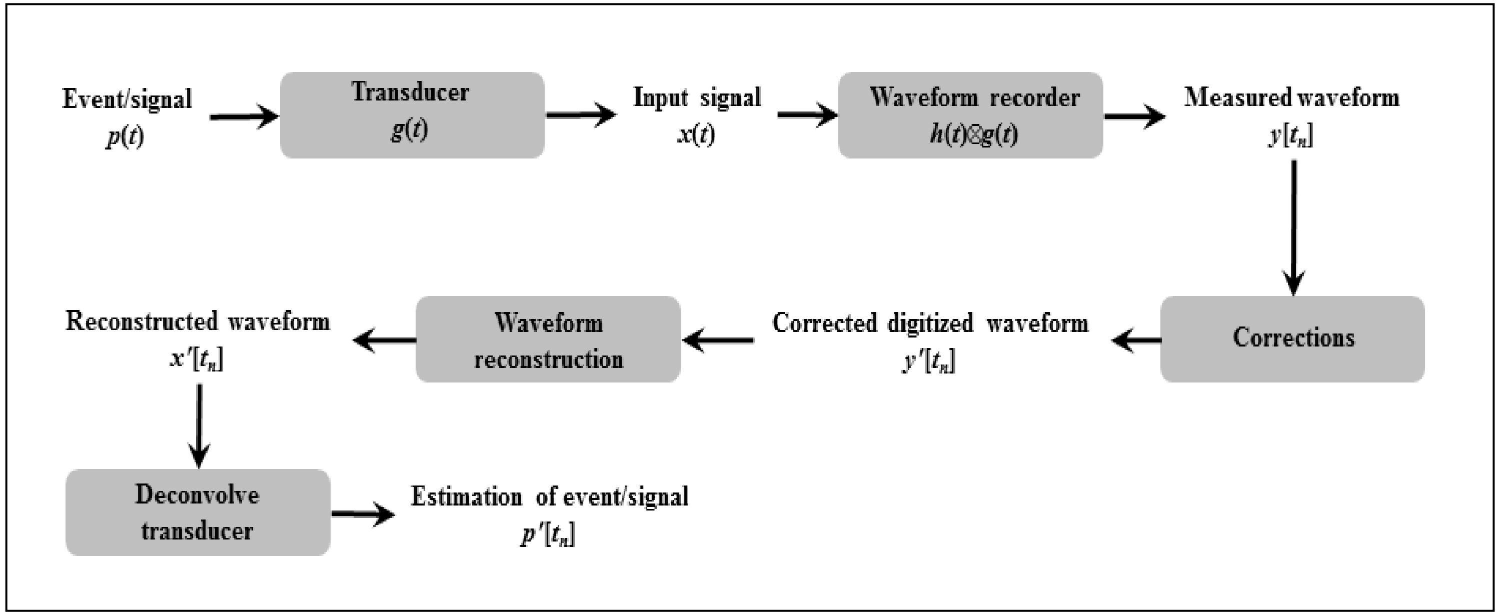
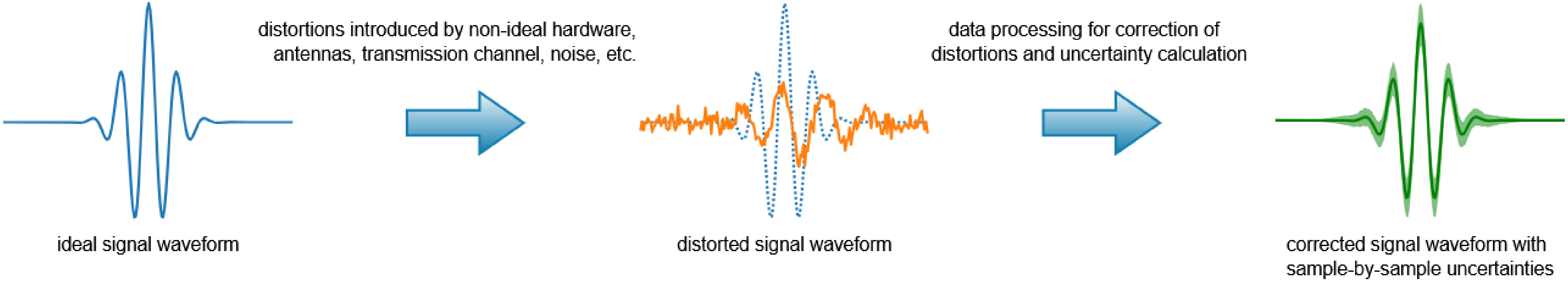


Figure 3 – Creation of measured, corrected, and reconstructed waveforms and the final estimate of the input signal

5.3.2 Sample-by-sample correction

Sample-by-sample waveform corrections and their resultant contribution to both sample-by-sample waveform uncertainties and waveform parameter uncertainties will be the subject of a different documentary standard but a brief mention is provided in 5.3.2.

EURAMET 23NRM01: SBS Uncert



Selected instruments

- sampling oscilloscopes
- real-time digital oscilloscopes
- ~~ADC~~s

not today

Tasks

1. system modelling
2. characterization of impairments
3. waveform correction / reconstruction
4. uncertainty propagation

Outline

- Motivation
- Digital Sampling Oscilloscopes
- Digital Real-Time Oscilloscopes

Digital Sampling Oscilloscopes

- High bandwidth (up to 110 GHz bandwidth)
- Cost efficient per GHz: fraction of price of real-time oscilloscopes
- Use cases:
  - Analysis of high-speed data transmission signals
  - Compliance testing, TDR measurements
- Advantages:
  - High resolution, low noise, minimal jitter
  - Established technique (characterization, data correction)
- Limits:
  - Repetitive signals only
  - Trigger dependency
  - Distortions due to hardware imperfections

DSO: Model

- Time gating (sample-and-hold)
- Low-pass filter
- White-noise jitter
- Connector losses, mismatch

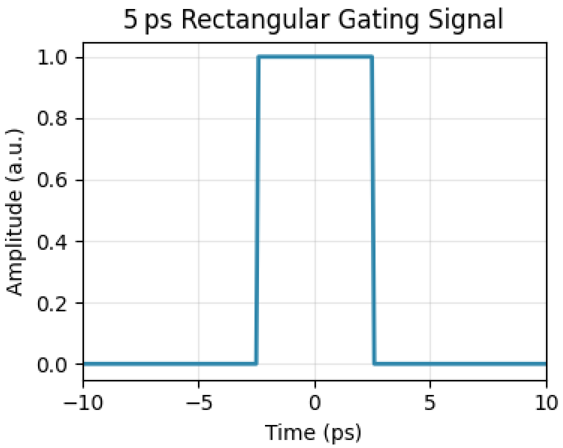
front end

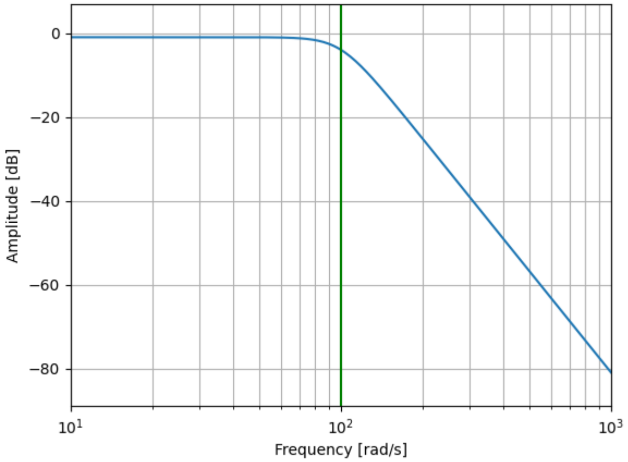
- Systematic time base distortion
- Interpolate sampling instants
- Quantisation errors

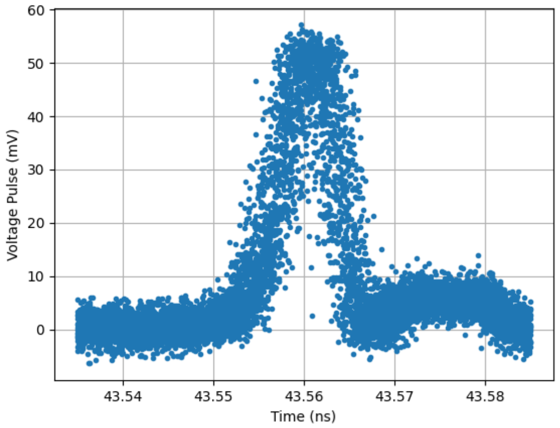
ADC

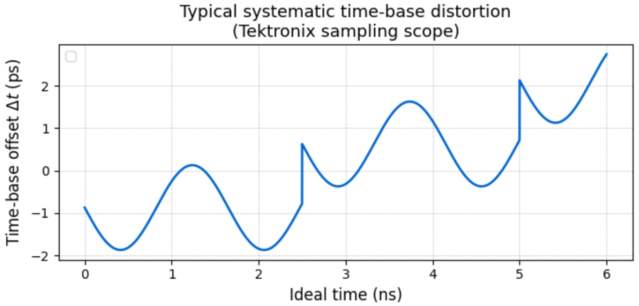
→ Set up transfer function H(f)

→ Apply to data $H(f) \cdot X(f) = Y(f)$

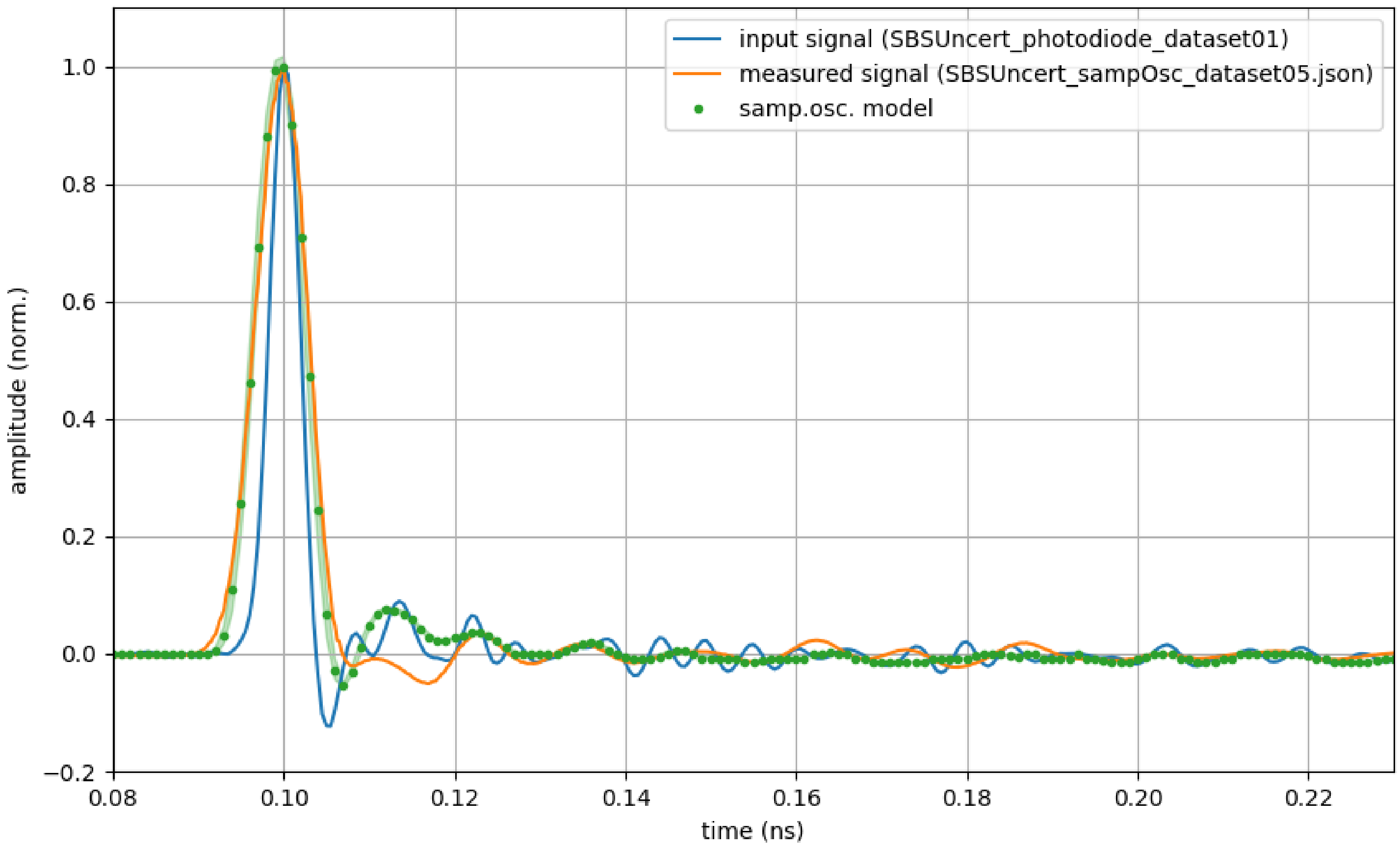


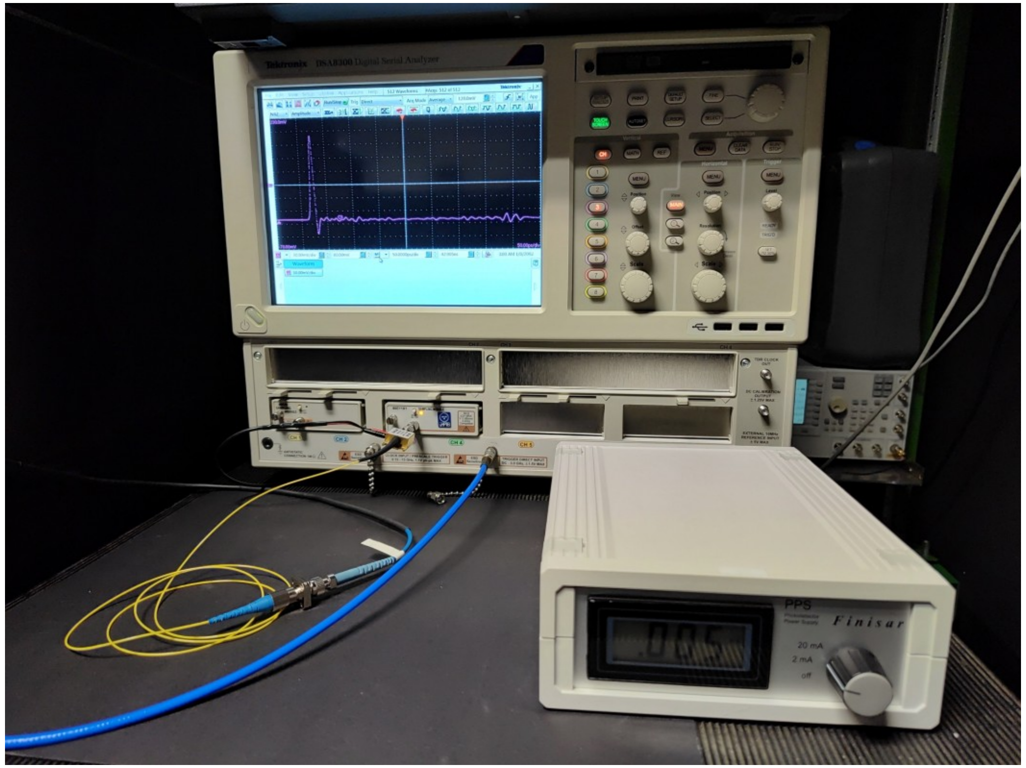






DSO: Model vs. Measurements





DSO: Waveform correction

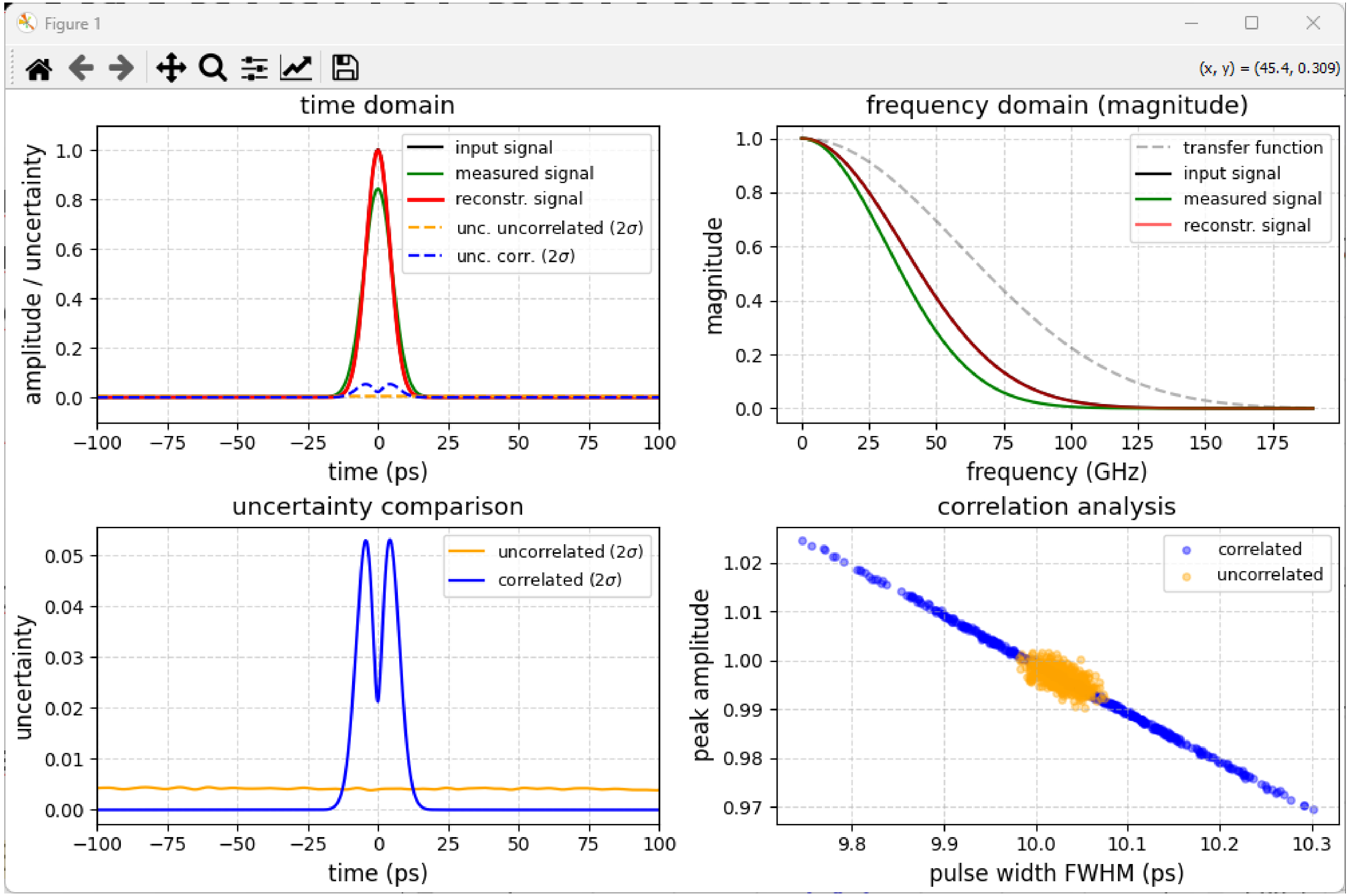
Recipe

1. model a transfer function H(f)
2. model an input signal x(t)
3. ‚measure' by applying H:
   H(f) · X(f) = Y(f) → y(t)
4. Reconstruct via deconvolution
   $X_{recon}(f) = Y(f) / H(f)$ → $x_{recon}(t)$

→ What about the uncertainty?
→ **Correlation is key!**

```
Mean and standard deviation
amplitude: 0.9966 V ± 0.0039 V (k=2)
FWHM: 10.03 ps ± 0.03 ps (k=2)

Mean and covariance matrix
amplitude: 0.9957 V ± 0.0211 V (k=2)
FWHM: 10.03 ps ± 0.21 ps (k=2)
r(A, FWHM): -0.9997
```



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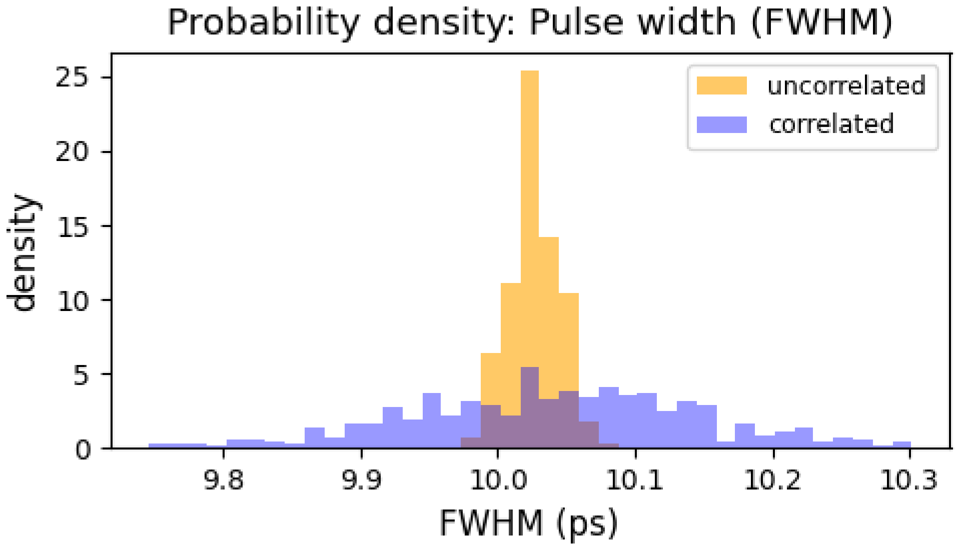


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```

Waveform correction w/o covariance matrix

- Underestimates the uncertainty
- Hides correlations
- May introduce statistical bias

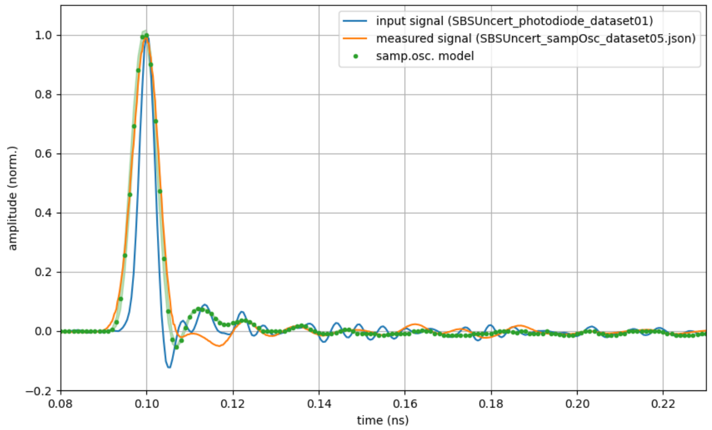
DSO: Summary

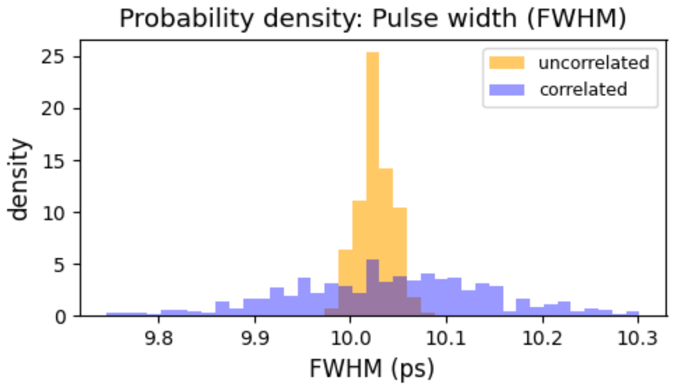
DSO Model

- Impairments due to front end + ADC
    - Parameter tuning to match different oscilloscopes
- Input signal via
    - measurement data
    - source models (photodiode, electrical pulse generator)
- model output matches measurements

Waveform Correction

- Based on model transfer function
- Includes sample-by-sample waveform uncertainty computation
- Highlights relevance of covariance matrix for signal reconstruction





DSO: Next steps

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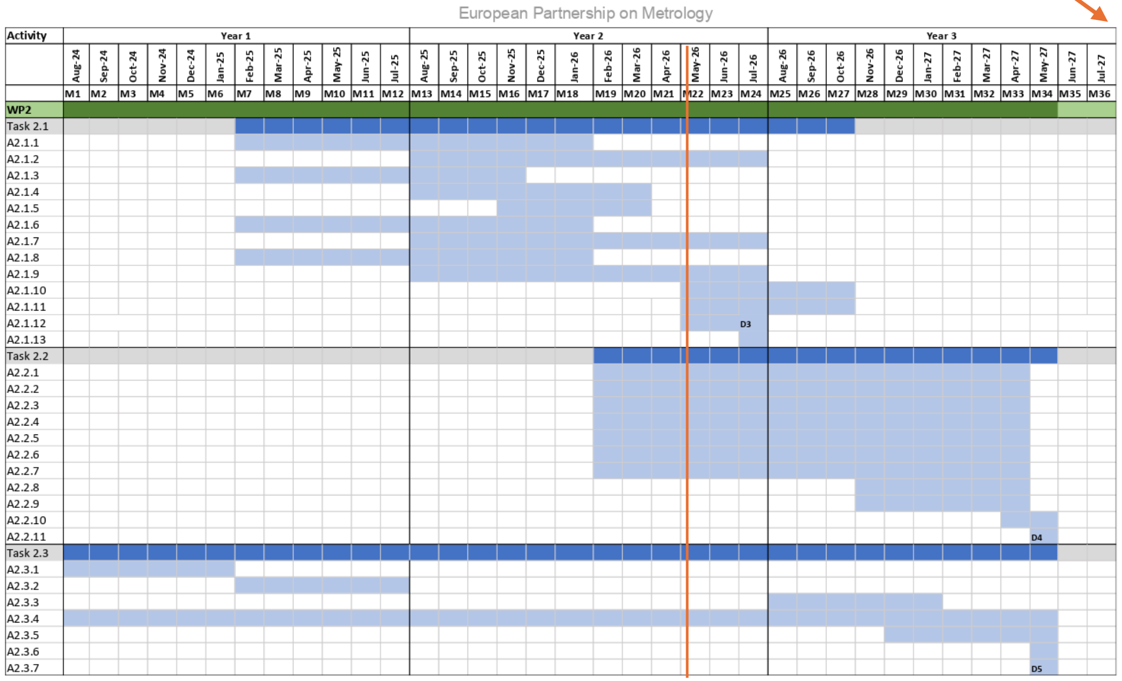
- Model validation / improvement
  - Different architectures, input sources
- Implement efficient calculation methods
  - Advanced Monte Carlo Methods
  - Principle Component Analysis
- Contribute to IEC standard
- Online-services for easy-access to model and reconstruction routines
  - International Data Spaces (‚QI-Digital')
  - „correct your data online" (DCC, ...)

08/2027



Outline

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- Digital Real-Time Oscilloscopes

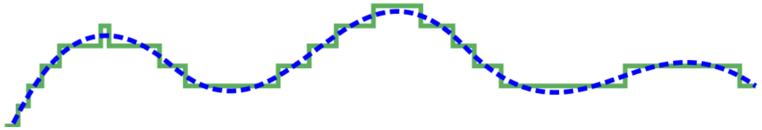
Digital Real-Time Oscilloscopes

- Broadband instruments (up to 110 GHz bandwidth, 256 GS/s)
- Relatively cost efficient
- Use cases:
  - Demodulation of optical communication signals
  - Broadband signal integrity measurement
- Advantages:
  - Sophisticated signal post-processing available
  - Real-time measurement
- Limits:
  - Fast ADC architecture limits vertical resolution
  - Low dynamic range
  - Distortions due to hardware imperfections

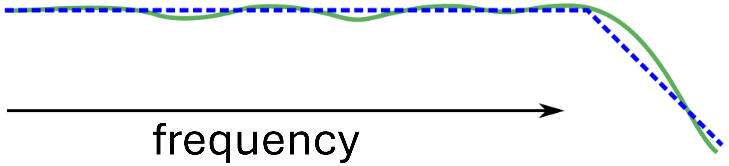
Impairments of fast DRTOs

- Noise

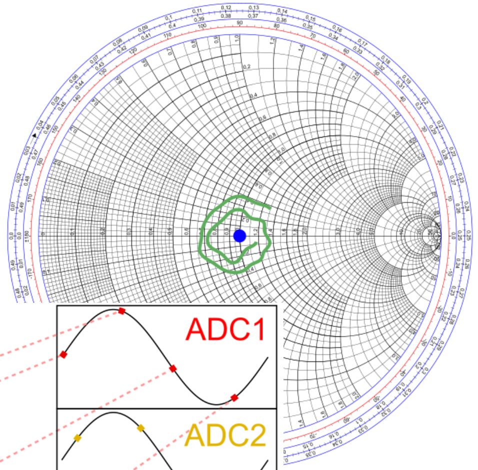
- Quantization



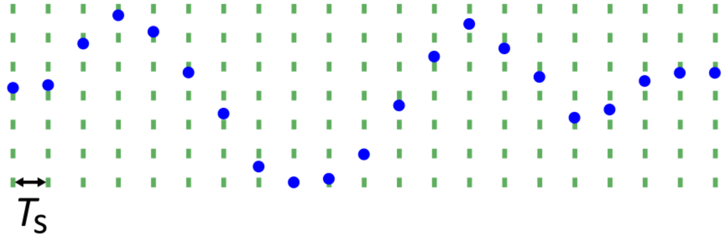
- Flatness / frequency response



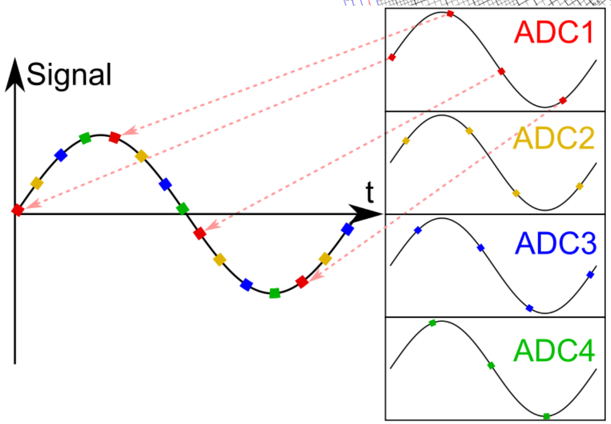
- Impedance mismatch



- Time-base stability



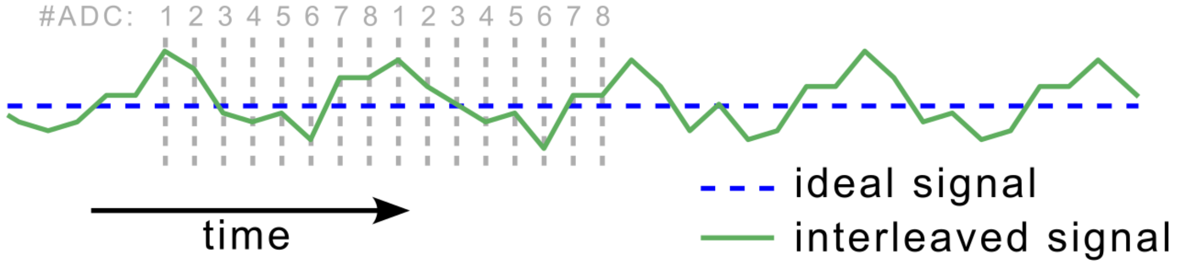
- Interleaving error



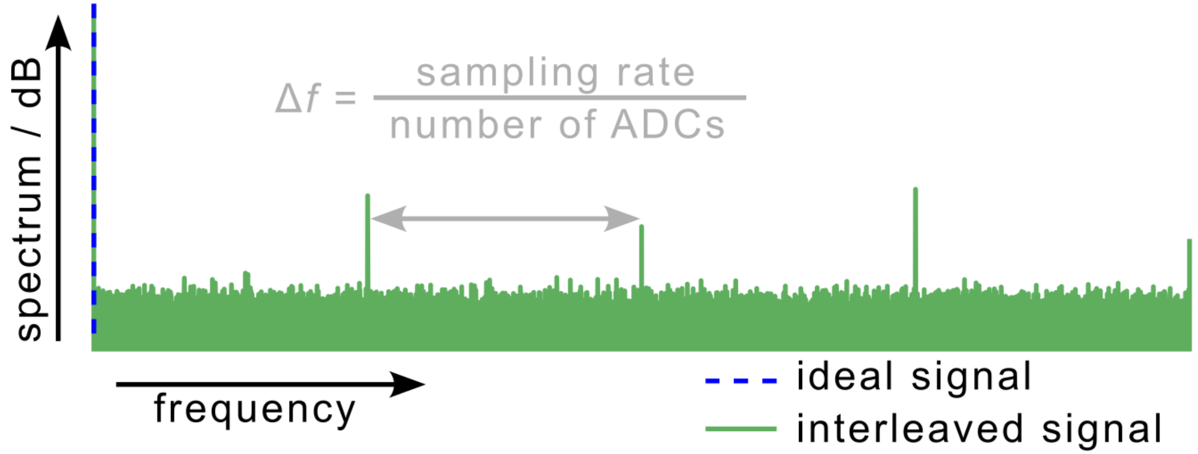
Interleaving Errors – why they matter

The synthesis of one fast signal from several sub-ADCs

- leads to a **repetitive pattern** in time domain.
  Example with 8 sub-ADCs:

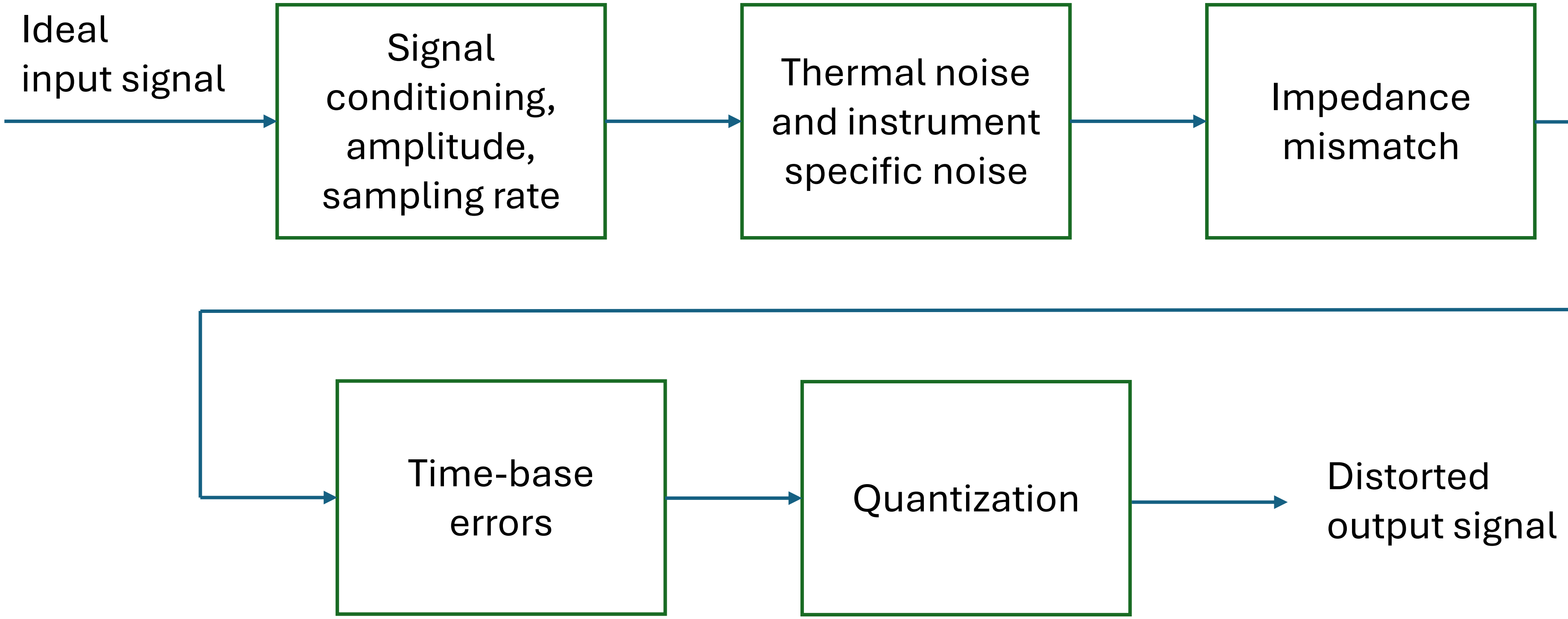


- corresponds to **sharp spurs** in frequency domain



Issue:
Some input signal signals are affected more than others!
Examples: Sine at Δf, broadband pulses

Modeling of DRTO Impairments



Characterization of Interleaving Error

Step 1:

- Finding the number of ADCs from noise measurement
  - Number of ADCs = sampling rate / Δf between spurs

Step 2:

- Characterizing the properties of sub-ADCs

Two published methods:

Relative difference between sub-ADCs[1]

- Can remove interleaving spurs
- Simple measurement setup

Absolute transfer function of sub-ADCs[2]

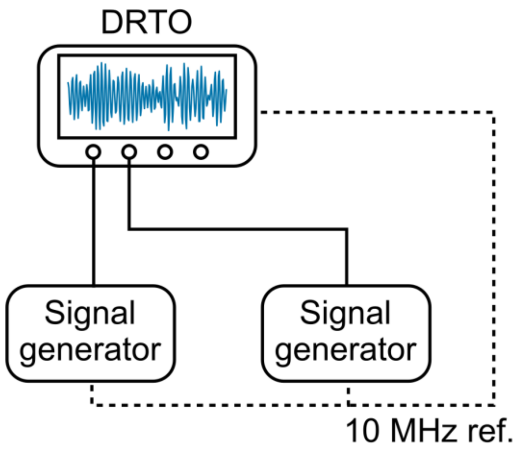
- Remove interleaving spurs
- Complex measurement setup

[1] C. Cho et al., "Calibration of Time-Interleaved Errors in Digital Real-Time Oscilloscopes," IEEE Trans. Microw. Theory Techn., vol. 64, no. 11, 2016.

[2] D. Kim et al., "Traceable calibration for a digital real-time oscilloscope with time interleaving architecture," Measurement Science and Technology, vol. 29, no. 1, 2018.

Relative Transfer Functions

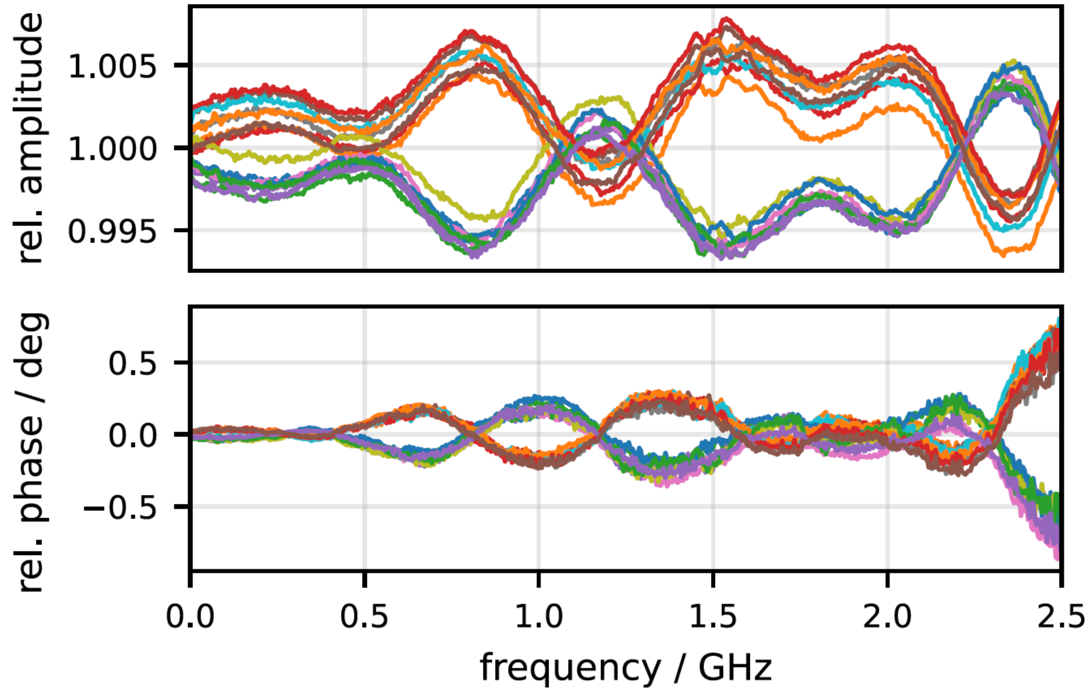
Setup



Main steps

- Port 1: swept sine, Port 3: reference sine
- Separate data by sub-ADCs
- Perform least-squares fit for each sub-ADC to find relative transfer function
- Assemble frequency dependent, relative transfer functions

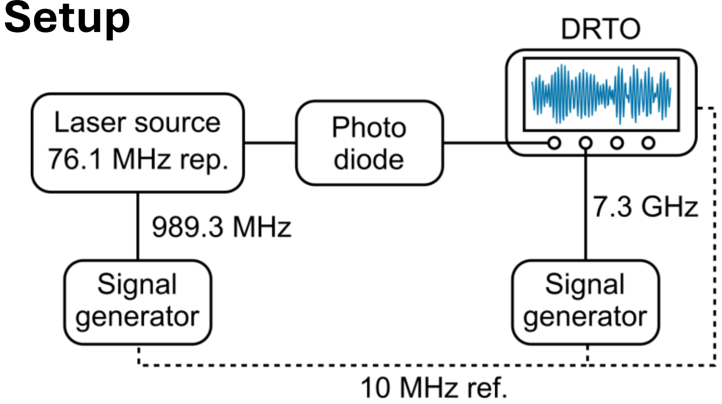
Exemplary results:



Relative transfer functions of 16 sub-ADCs from a DRTO with 2.5 GHz Bandwidth, 20 GS/s sampling rate

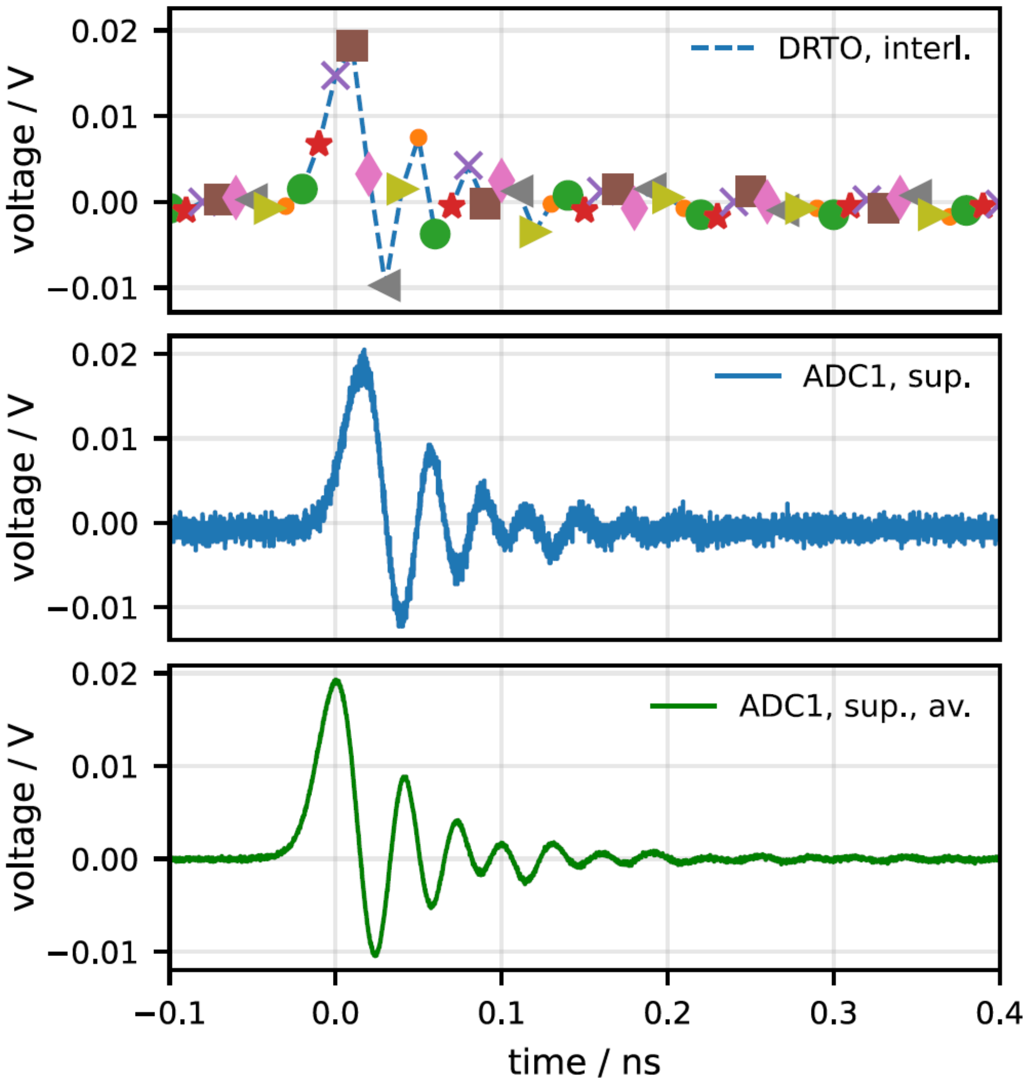
Absolute Transfer Functions

Setup



Main steps

- Port 1: fast pulse
  Port 3: reference sine
- Separate data by sub-ADCs
- Superimpose and average data for each sub-ADC
- Calculate complex transfer functions using reference pulse data



Challenges:

- Pulse amplitude is very low
- Small dynamic range, high noise floor
- Align calibration data from photodiode to DRTO data

Sequence Matching

Why do we need the reference signal?

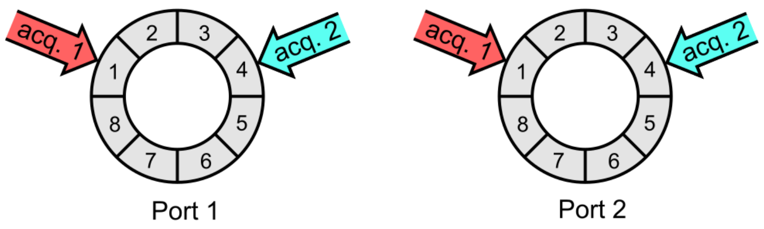
Problem:

- Each DRTO acquisition starts with a random sub-ADC
- How to apply the (relative) transfer functions to correct the signal?

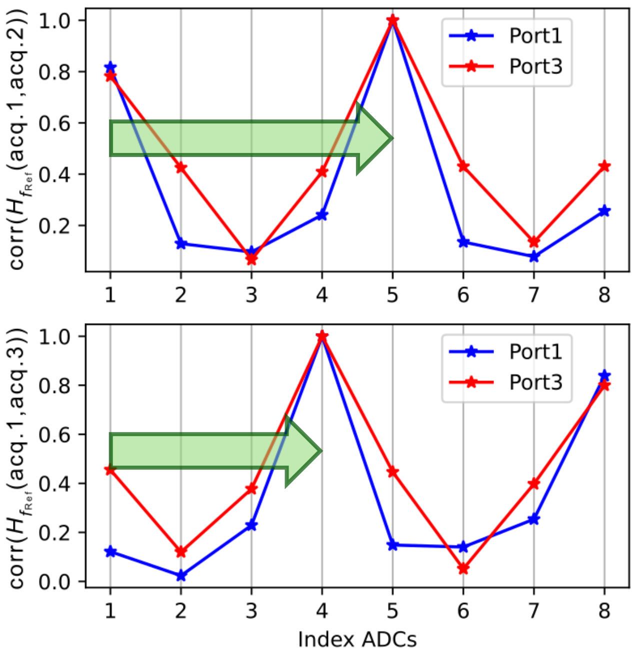
Solution:

- Use reference signal at second port
- Evaluate relative transfer functions at f_{Ref}
- Correlate transfer functions to find shift
- Assumption: shift between ports remains constant between measurements

Example: cyclic use of 8 sub-ADCs, random starting ADC



Test / calibration signal   Reference signal



Observation:
- ➢ Equal shift for both ports
- ➢ Reference signal can be used to find starting ADC of test signal

Result:

acq.2 starts with ADC 5
acq.3 starts with ADC 4

DRTO Next Steps

- Investigate **combination** of methods: relative and absolute transfer functions
- Use **DRTO model** to validate waveform correction and reconstruction algorithms for different instruments and signals
- Provide model and use cases in **online platform** to enable uptake

Acknkowledgement

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Questions?

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