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# Sub-Nyquist Sampling for TDR Sensors:

## Finite Rate of Innovation with Dithering

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# Who We are

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# Presentation Outline

- Introduction – TDR Sensor
- Problem Formulation
- FRI and the Proposed Approach
- Description of the System
- Simulations
- Conclusion

# Time Domain Reflectometry Sensor (Guided Wave Radar Level Sensor)

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**Aim: to measure liquid level in an industrial container by measuring ToF.**

Reflection coefficient:

$$R = \frac{Z_1 - Z_0}{Z_1 + Z_0}$$

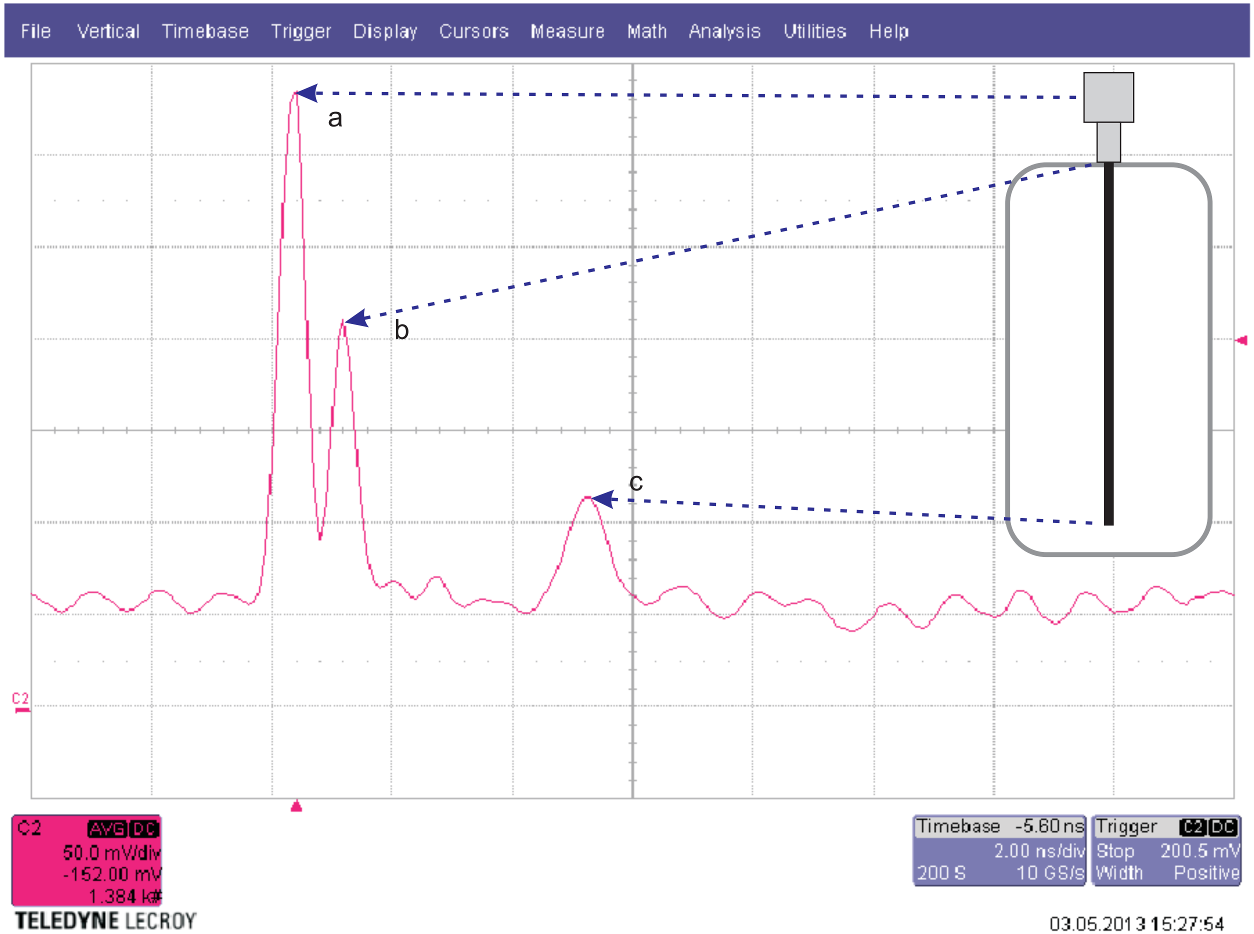
The processed signal ($K$ pulses):

$$x(t) = \sum_{i=0}^{K-1} a_i p(t - t_i)$$

$a_i$: amplitude of the reflected pulse.

$t_i$: location of the reflected pulse.

Gaussian pulses are typically used with given $\sigma$ values.



# TDR: An Example

**Sensing requirements:**

| Requirement | Value |
|---|---|
| Measuring Range | 5 cm ... 10 m |
| Inaccuracy | < 5mm |
| Resolution | < 0.5 mm |
| Response Time | < 100 ms |

➔ Maximum tolerated relative ToF measurement error is:

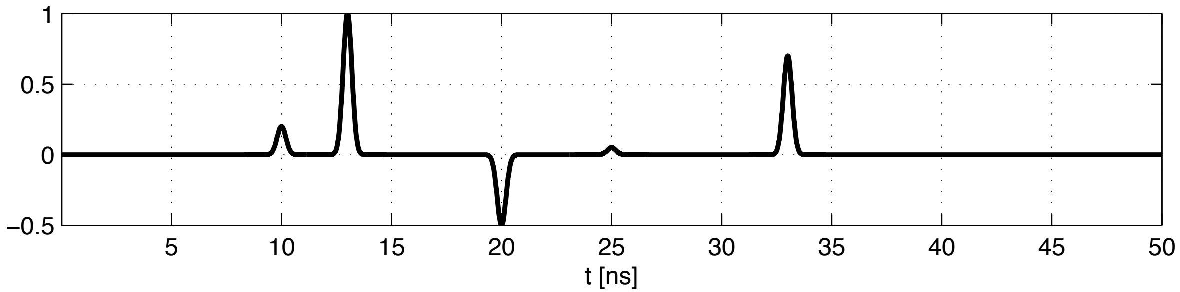
$$t_{\text{error}} = \frac{s}{c} = 33 \text{ ps}$$

TDR-Level Sensor
LFP Cubic; SICK AG

# Problem Formulation and Proposed Approach

Classical Nyquist sampling demands collecting several Giga samples per second.

- Infeasible due to practical SWPaC limitations of miniature TDR sensors.




Alternative sub-Nyquist techniques:

- **Equivalent Time Sampling**: Bulky sensitive circuits (PLL) and long signal acquisition times.
- **Compressed Sensing**: Infinite time resolution and high SWPaC implementation.
- **Finite Rate of Innovation:** Can be easily integrated into existing TDR sensor architecture.

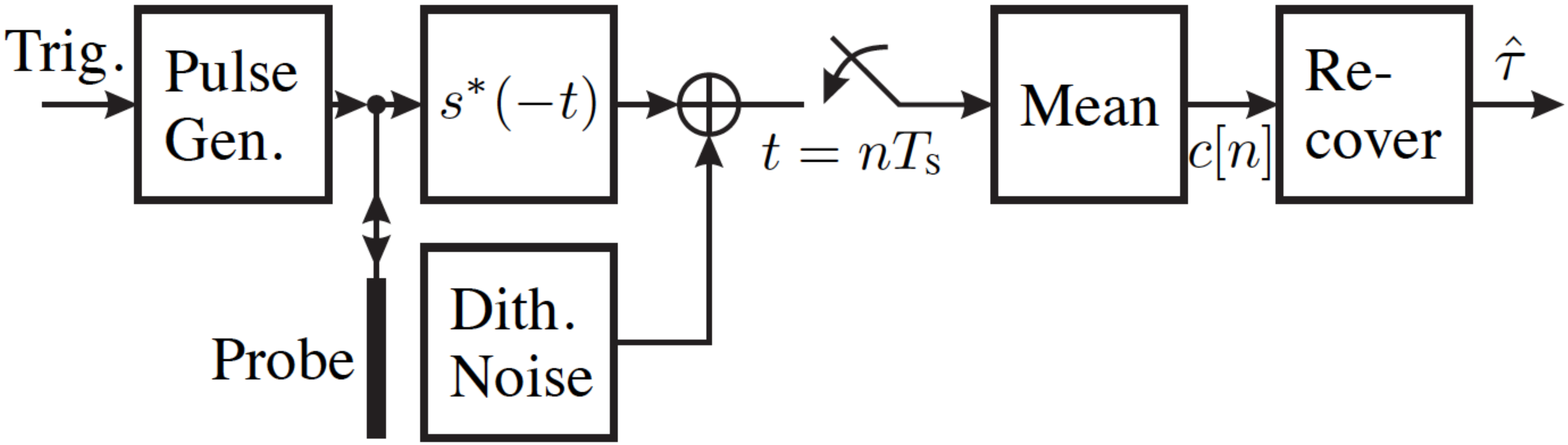
**FRI is an effective solution to the data acquisition problem in TDR sensors.**

**FRI Limitation:** Very sensitive to quantisation noise and high resolution ADCs cannot be used, e.g. due to TDR sensor practical limitations.

**Proposed Approach:** FRI with dithering and averaging to combat quantisation noise.

# System Description: Proposed Approach

## Implementation using FRI with Dithering and Averaging




- Ensemble averaging of consecutive sequences shall improve the ADC resolution.
- Averaging may lead to a slightly increased response time.

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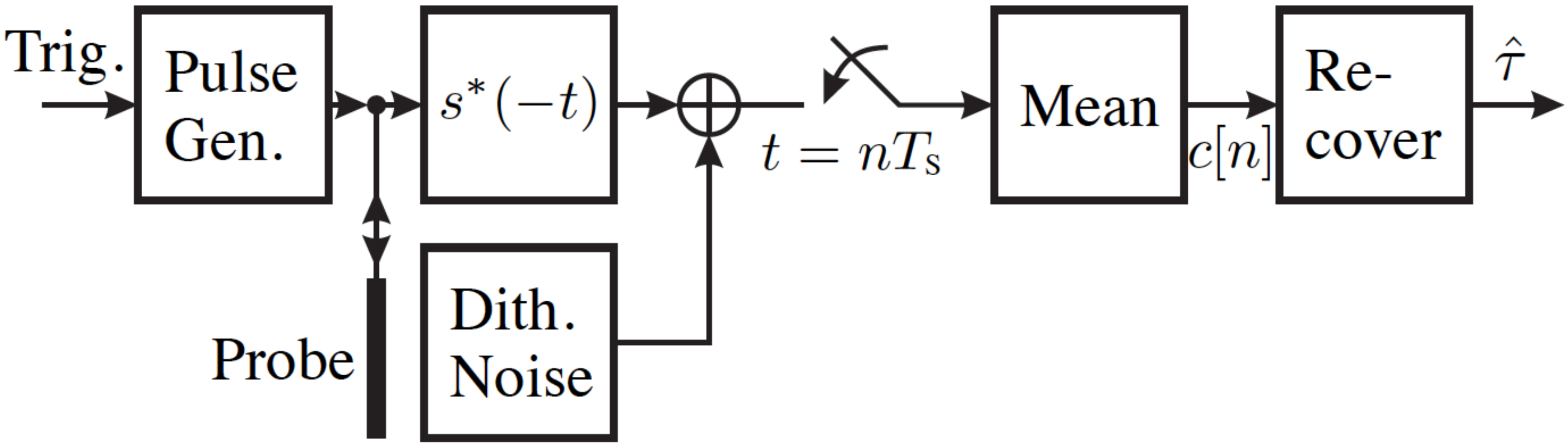
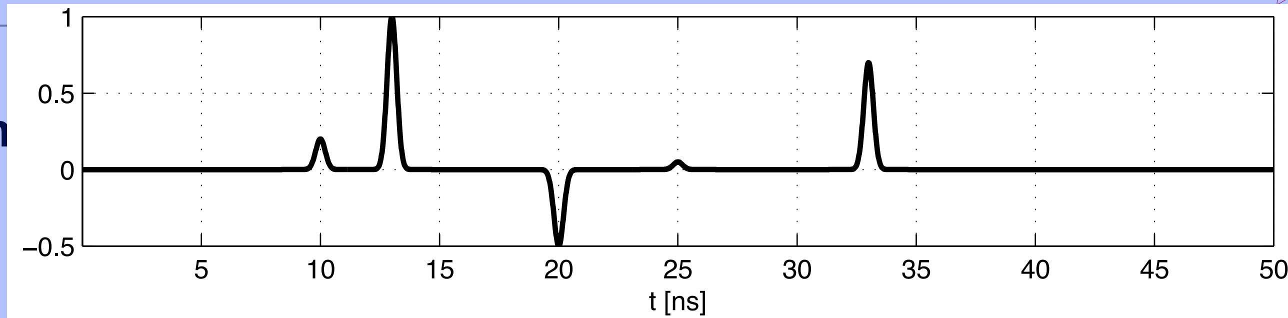
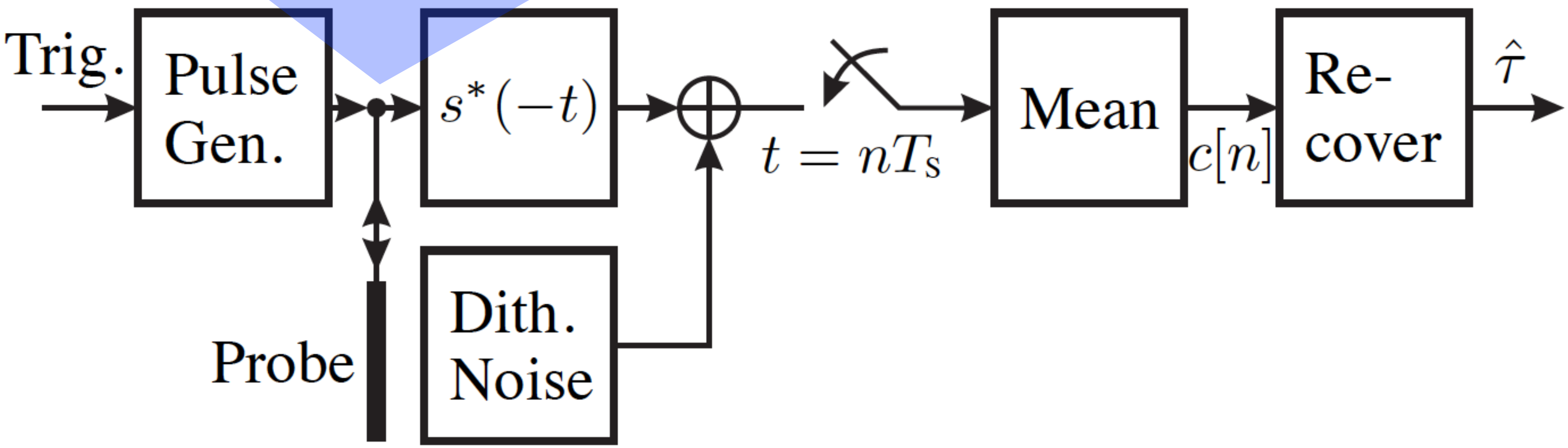
**Signals along the path**



# Description of the System

**Signals alon**

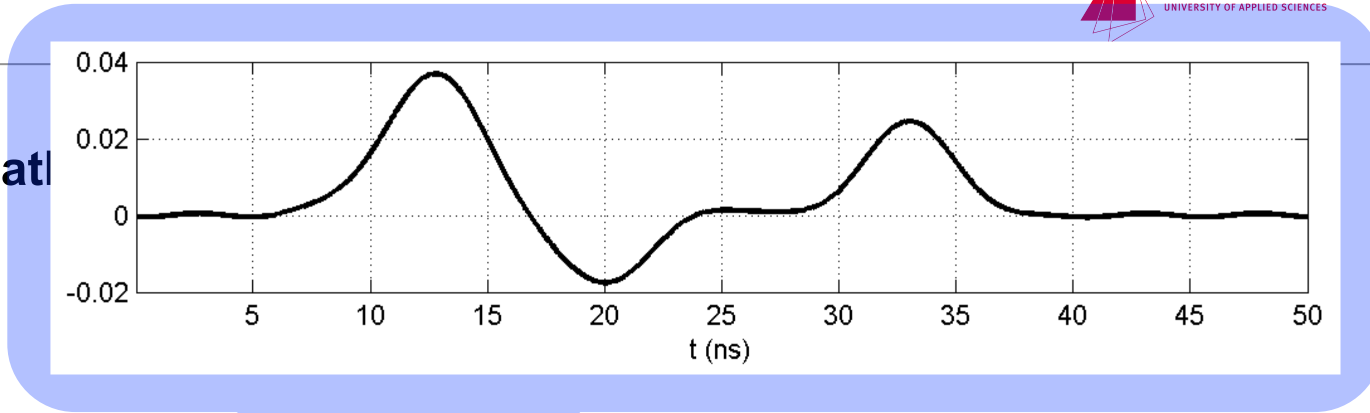


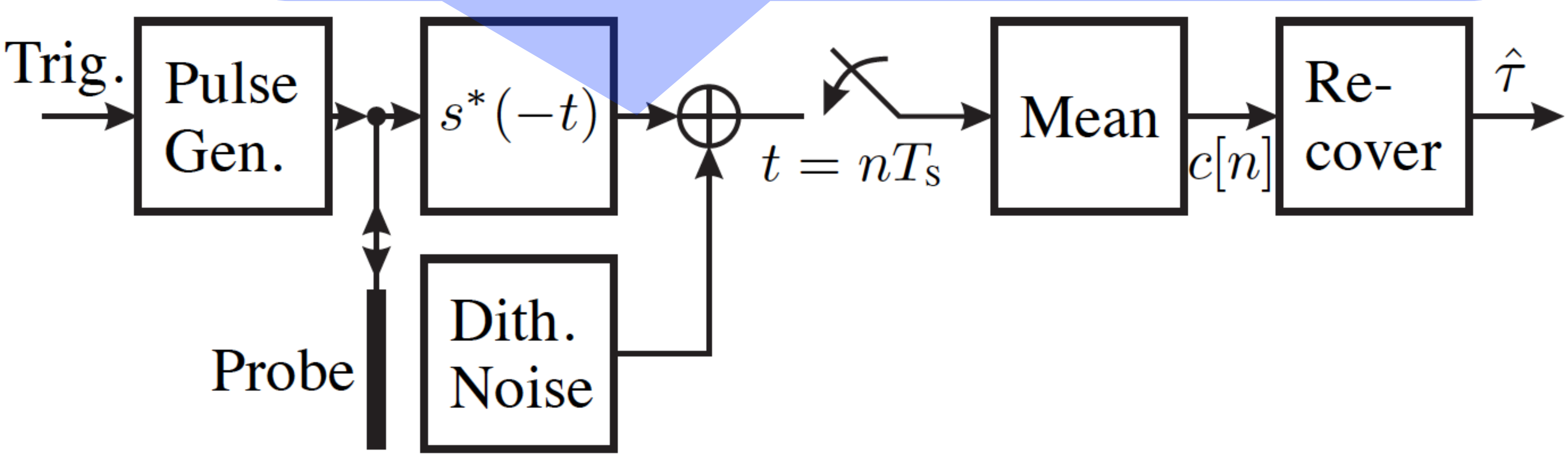



# Description of the System



**Signals along the path**



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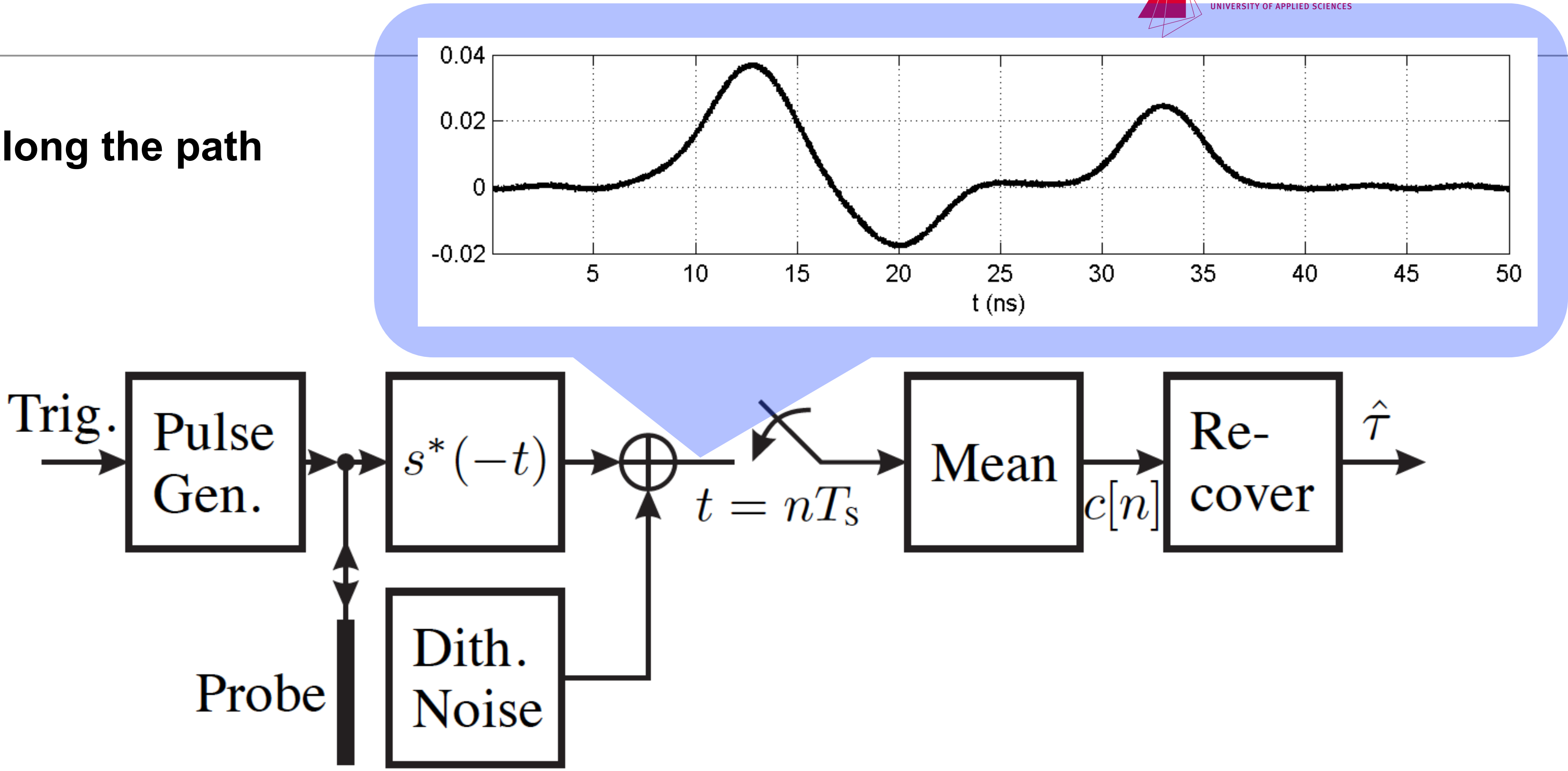

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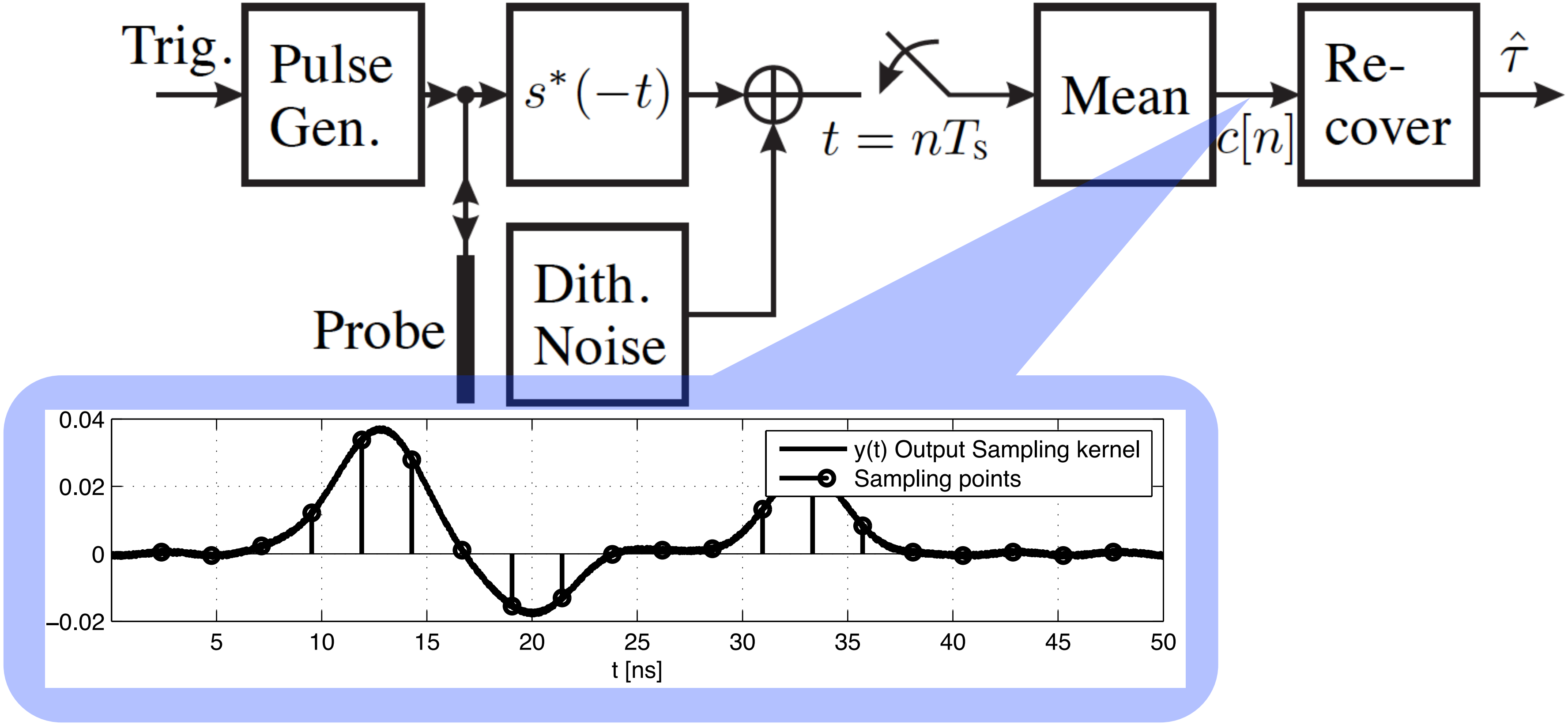

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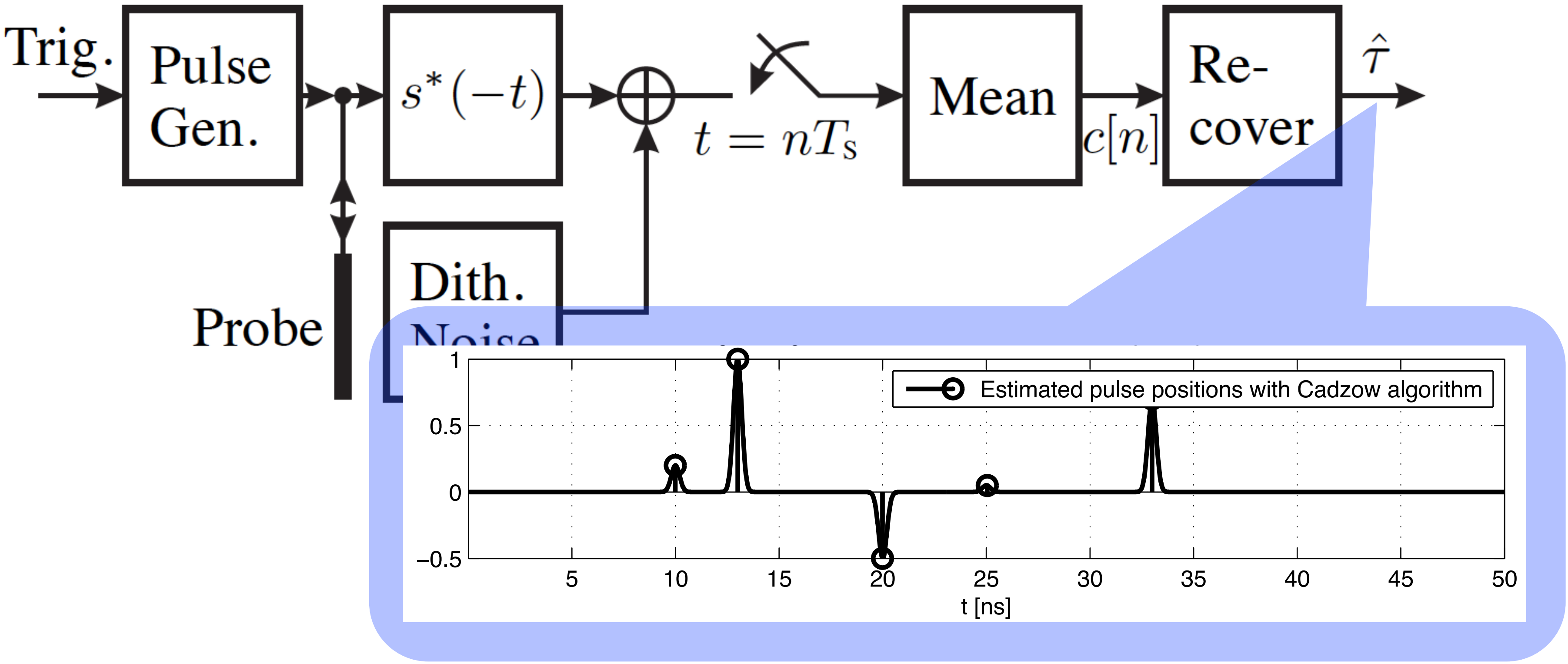
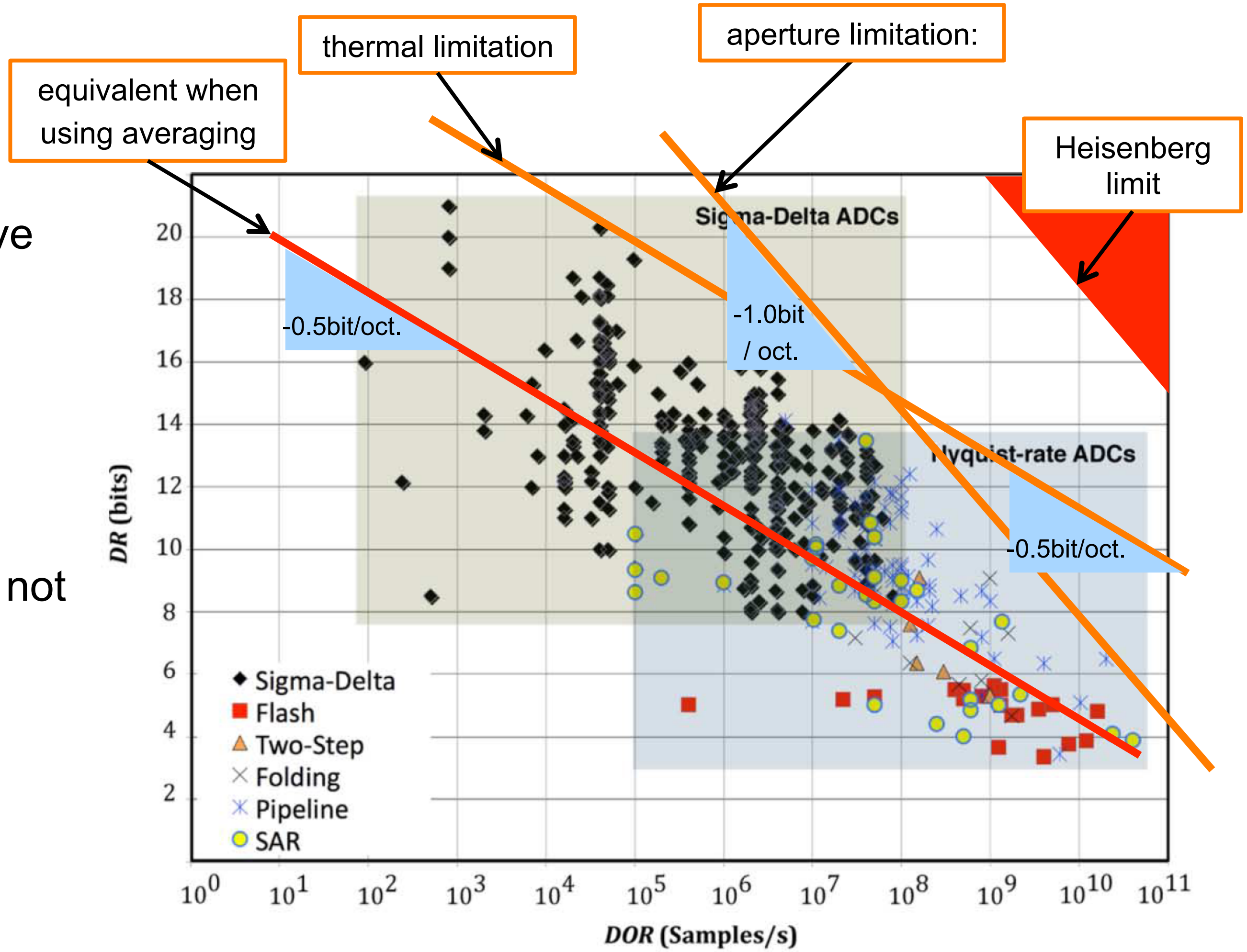
## Signals along the path



# Data Acquisition Device

## ADC selection

- Resolutions > 8bit are expensive for $f_s$ < 1ns.
- High-speed ADCs are mainly limited by the aperture jitter.
- Averaging adjacent samples is not efficient; ensemble averaging however is.



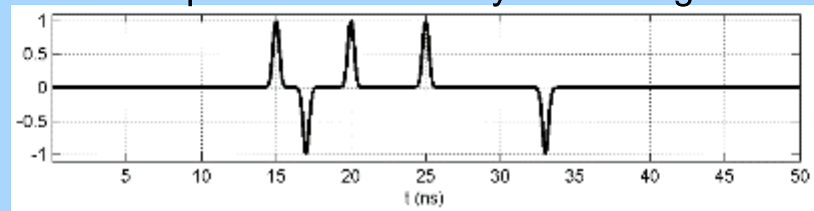

Graph taken from: "Sigma-Delta Modulators: Tutorial Overview, Design Guide, and State-of-the-Art Survey"; IEEE Trans. on Circuits and Systems, Vol. 58, No. 1, Jan. 2011
Limitations according: R. H. Walden: "ADC Survey and Analysis", IEEE Journal on Selected Areas in Communications, Vol. 17, No. 4, April 1999

# Monte Carlo Simulations – Set Up

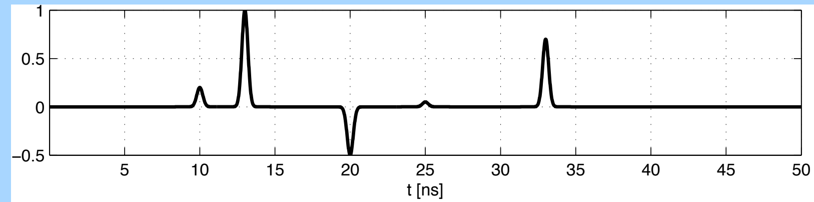
**Signal Model:**

- $K$ = 5 Gaussian Pulses with $\sigma$ = 200 ps, each.
- Period of the pulse sequence is 50 ns.
- Two dynamic ranges are examined: 0 dB and 26 dB.

Pulse sequence with 0 dB dynamic range:




Pulse sequence with 26 dB dynamic range:




**FRI:**

- Sum of Sincs (SoS) sampling kernel is used.
- Cadzow plus total least squares are applied.
- FRI minimum sampling rate is 220 MHz.

**Dithering:**

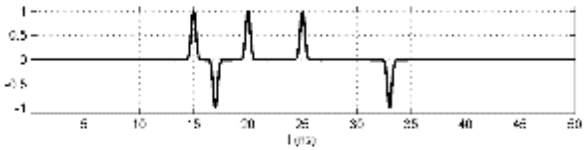
- Uniform distributed dither is used.
- Maximum dithering amplitude is $\pm Q/2$.

**Assessment:**

- Maximum error and RMS error are used to assess the results accuracy.
- In practise the maximum error is more important.

# Simulations

## Effect of ADC Resolution

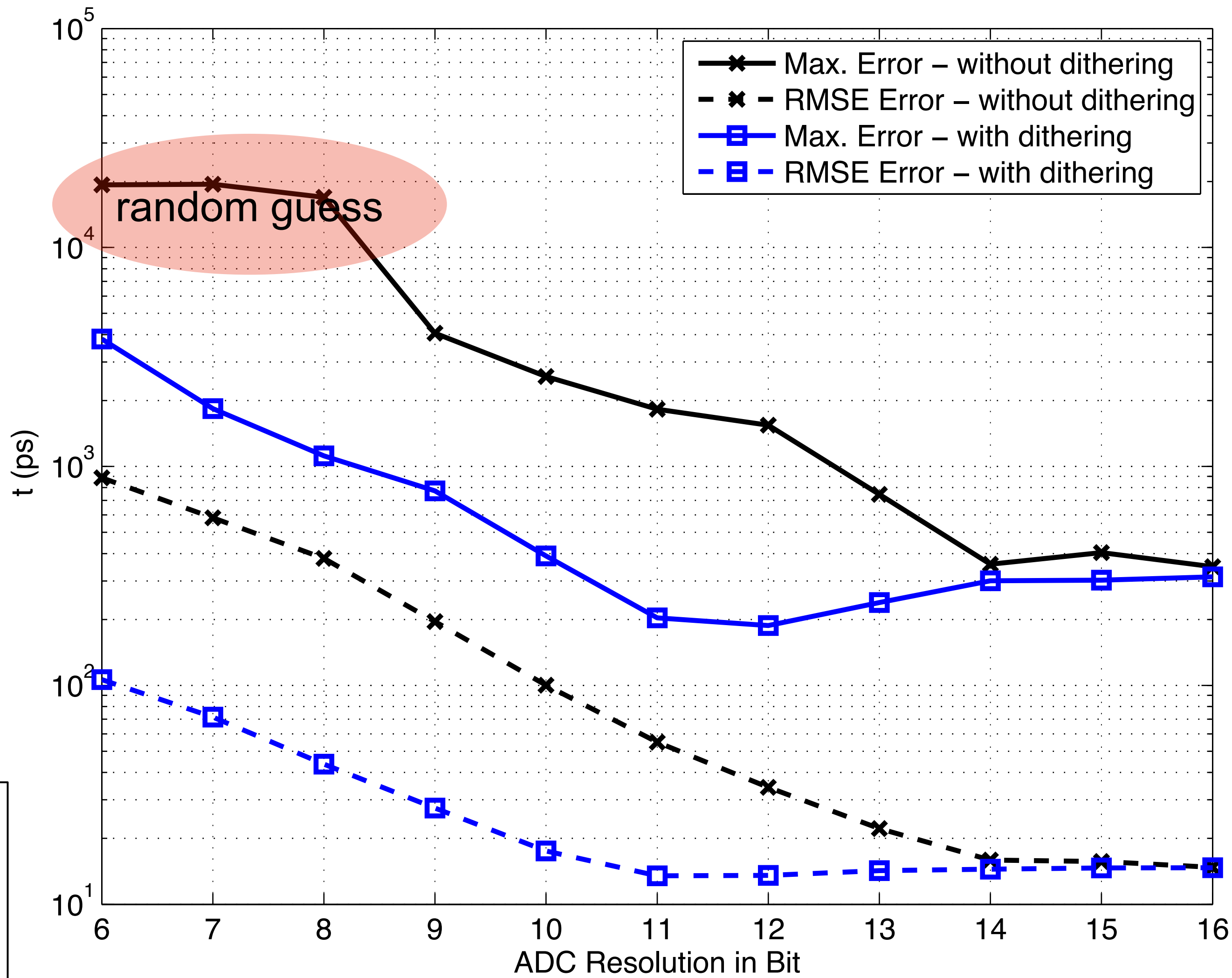


(0 dB dynamic range)

- Errors of more than 10 ns correspond to random guesses.
- ADC resolution of at least 10 bits is needed.

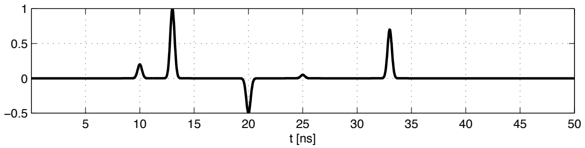
**Simulation parameters:**

sampling rate: $f_s$ = 440 MHz
oversampling: $\beta$ = 2
averaging: 250 times



# Simulations

## Effect of ADC Resolution




(26 dB dynamic range)

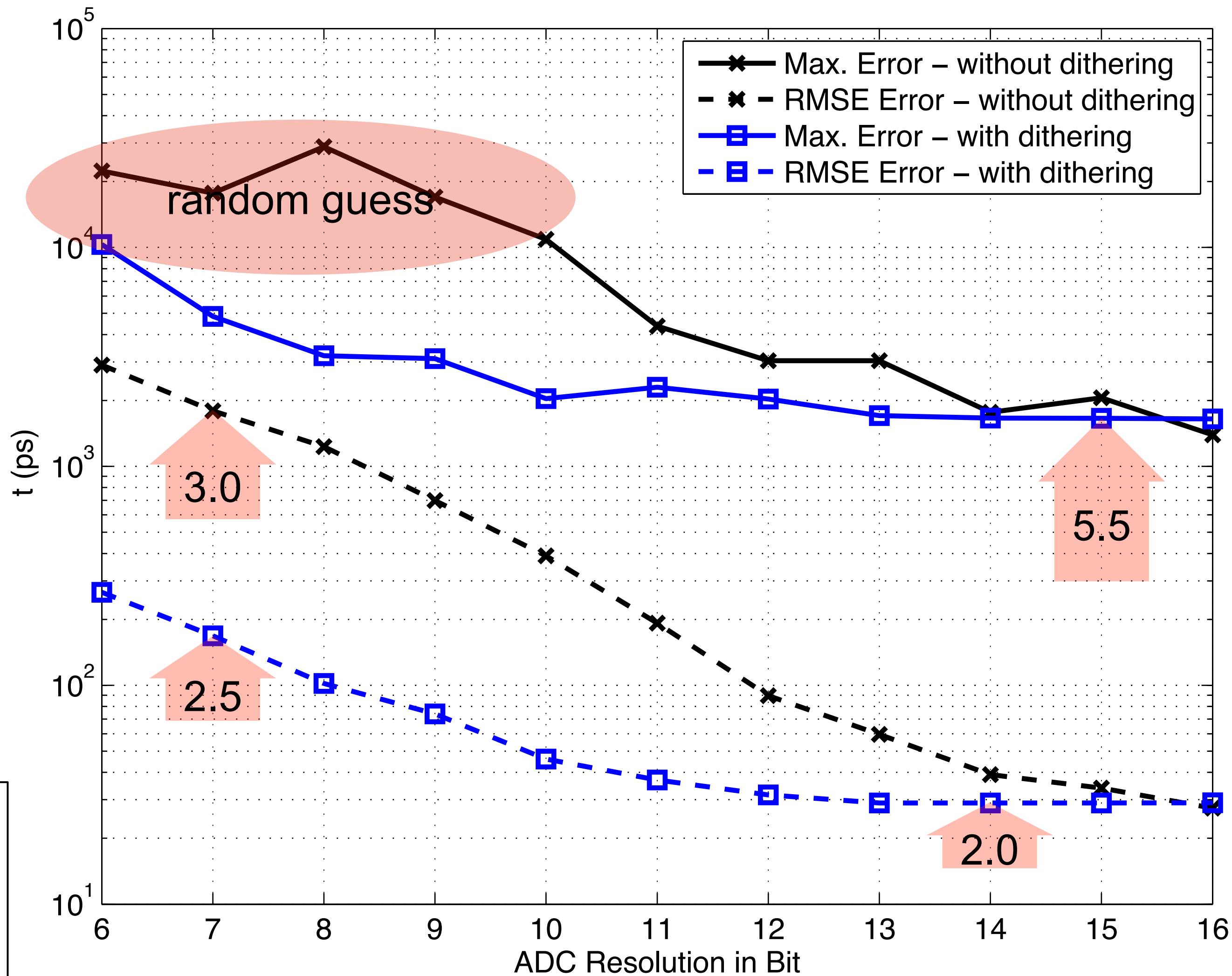
- 26 dB dynamic range causes the RMSE time resolution to decrease by a factor of 2 to 3.
- random guesses occur with ADC resolutions of up to 10 bits.
- maximum error notably increases by 5.5.

**Simulation parameters:**

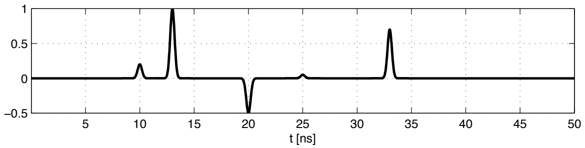
sampling rate: $f_s$ = 440 MHz

oversampling: $\beta$ = 2

averaging: 250 times



## Effect of Averaging



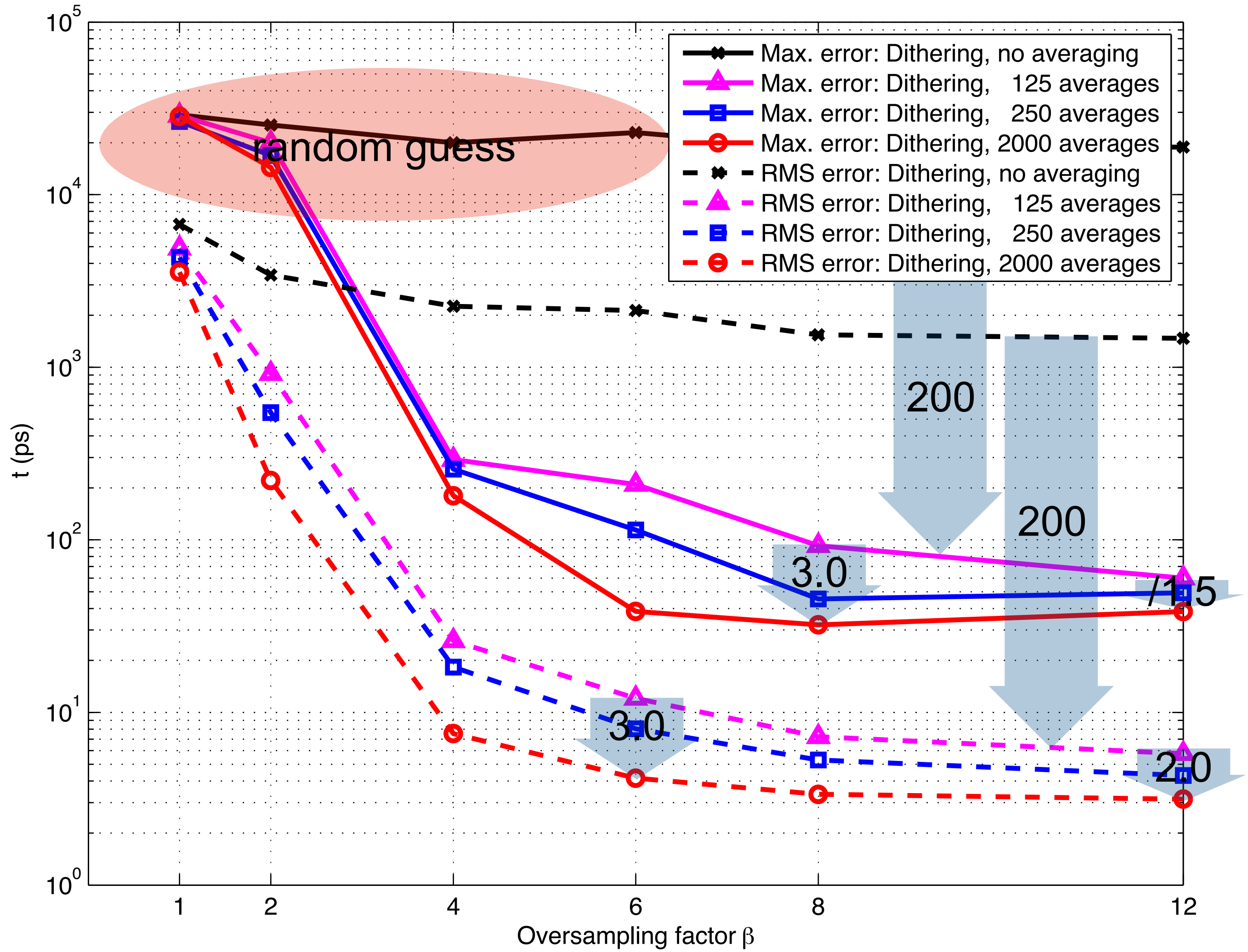

- Averaging 125 estimates enhances the RMSE time resolution by factor of 200.
- A further increase of the number of averages to 2000 enhances the RMSE time resolution again by at least a factor of 2.

**Simulation parameters:**

sampling rate: $f_s$ = 440 MHz

dynamic range: 26 dB

ADC resolution: 6 bits



# Simulations

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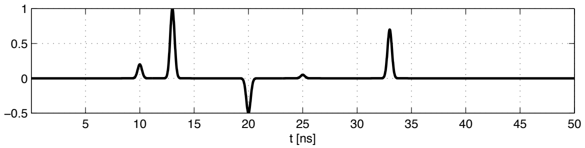
## Effect of Oversampling



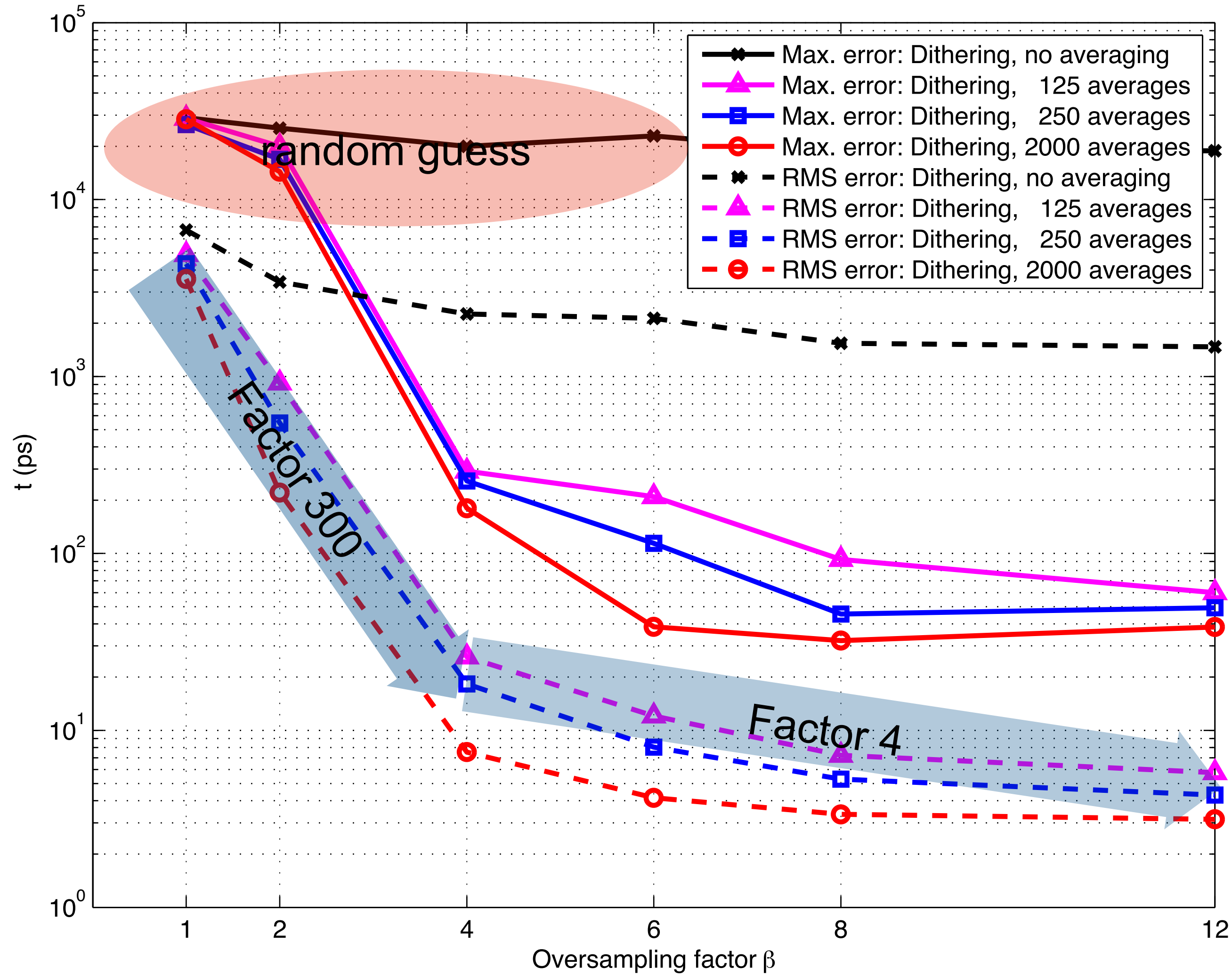

- Oversampling by a factor of 4 enhances the RMSE time resolution by factor of 300.
- An oversampling factor exceeding 12 gives a further improvement by a factor of 4.

**Simulation parameters:**

sampling rate: $f_s$ = 440 MHz

dynamic range: 26 dB

ADC resolution: 6 bits



# Conclusion and Outlook

**Conclusions:**

- TDR using FRI is a promising method in respect to efficient hardware implementation.
- However: TDR using FRI is very sensitive to quantisation noise.
- Dithering and Averaging leads to significant performance improvements.
- Improvements are not yet sufficient for highly demanding TDR requirements (<33 ps error).

**Outlook:**

- Further reduction of the ToF estimation error is needed.
- Evaluation of the minimum ToF estimation error bound (Cramer-Rao bound) pending.

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Thank you for your attention.