Identifizierung von Fehlereinflüssen auf die SAFT-Rekonstruktion händisch aufgenommener Ultraschallmessdaten

Jan.29.2019

Sayako Kodera
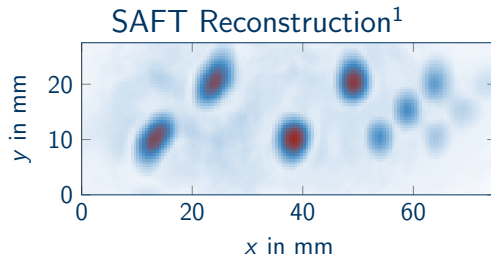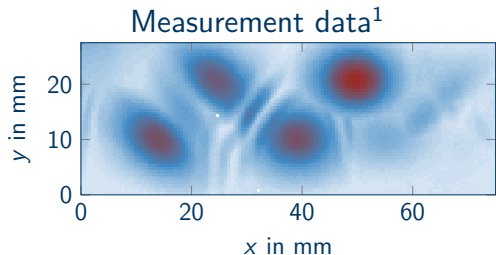Technische Universität Ilmenau

Background
●○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○○

Summary
○○

Ultrasonic Testing

Source: Quality Magazine

Motivation: Image Quality Improvement
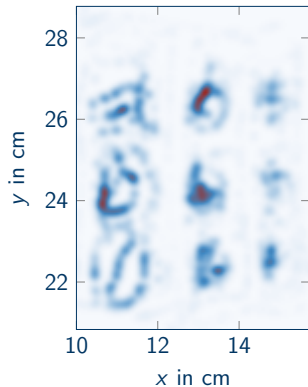
Automatic measurement

Measurement data[1]

SAFT Reconstruction[1]

---

[1]F. Krieg et al., SAFT processing for manually acquired ultrasonic measurement data with 3D SmartInspect, *SHM-NDT*, 2018

Background
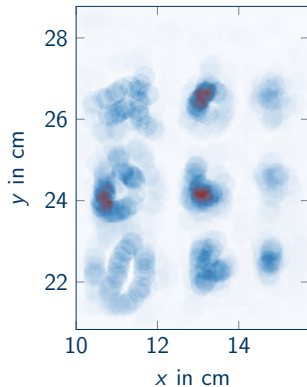○●○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○○

Summary
○○

Motivation: Image Quality Improvement

Manual measurement

Measurement data[1]

SAFT Reconstruction[1]

Background
○○●○○

Error Sources
○○

Simulation
○○○○○

Results
○○○○

Summary
○○

Objectives and Contribution

Problem

- Degraded image quality when manual data is reconstructed
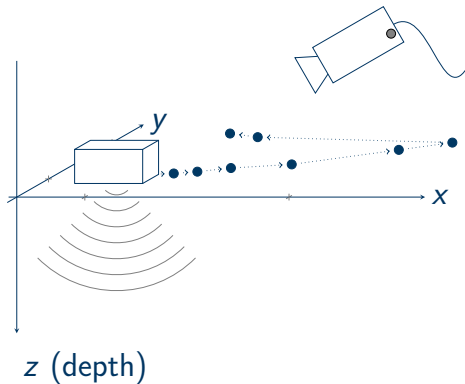
Objectives

- Identification of possible error sources
- Evaluation of their impact
- Determination of the error tolerance

Contribution

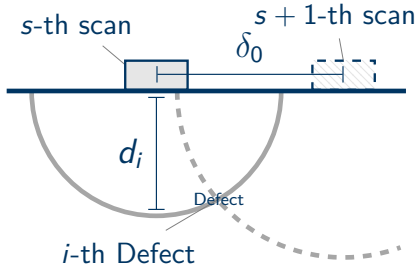- Provide indicators for developing measurement assistance systems

Simulation Scenario

y

x

z (depth)

Assumptions

- Handheld transducer
- Contact testing
- Scan positions recognized by a camera
- Simultaneous reconstruction during the measurement

Background
○○○○●

Error Sources
○○

Simulation
○○○○○

Results
○○○○

Summary
○○

Reconstruction Method

Synthetic Aperture Focusing Technique (SAFT)

s-th scan

$s + 1$-th scan

δ_0

d_i

Defect

i-th Defect

- Superposition according to propagation time delay
- Undersampling should be avoided
  $\rightarrow$ Spatial sampling interval
  $\leq 0.5\lambda$

Background
○○○○●

Error Sources
○○

Simulation
○○○○○

Results
○○○○

Summary
○○

Reconstruction Method

Synthetic Aperture Focusing Technique (SAFT)

- Superposition according to propagation time delay
- Undersampling should be avoided
  → Spatial sampling interval
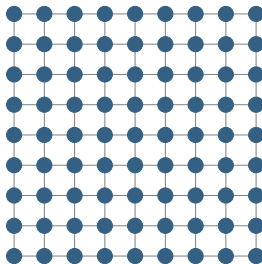 $\leq 0.5\lambda$

Background
○○○○○

Error Sources
●○

Simulation
○○○○○

Results
○○○○

Summary
○○
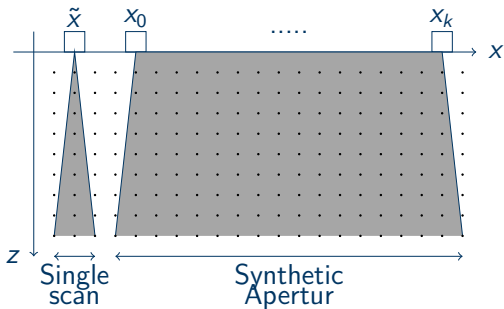
Identification of Error Sources

Path selection
- Unequal scan distribution
- Larger sampling interval
- Incomplete spatial coverage

System inaccuracy
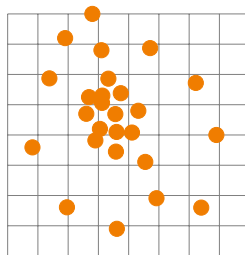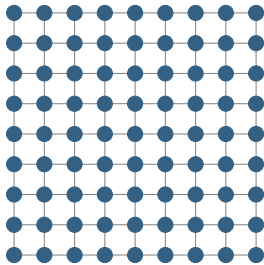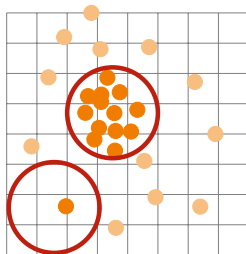- Positional inaccuracy
- Propagation time change

Example scan positions

Automatic

Manual

Background
○○○○○

Error Sources
●○

Simulation
○○○○○
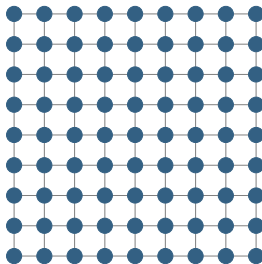
Results
○○○○

Summary
○○

Identification of Error Sources

Path selection

- Unequal scan distribution
- Larger sampling interval
- Incomplete spatial coverage

System inaccuracy

- Positional inaccuracy
- Propagation time change

Scan distribution

Equal

Unequal

Background
○○○○○

Error Sources
●○

Simulation
○○○○○

Results
○○○○

Summary
○○

Identification of Error Sources

Path selection

- Unequal scan distribution
- Larger sampling interval
- Incomplete spatial coverage

System inaccuracy
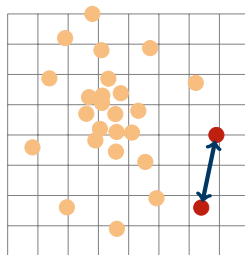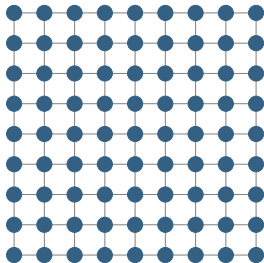
- Positional inaccuracy
- Propagation time change

Sampling interval

Small

Large

Background
○○○○○

Error Sources
●○

Simulation
○○○○○

Results
○○○○

Summary
○○

Identification of Error Sources

Path selection

- Unequal scan distribution
- Larger sampling interval
- Incomplete spatial coverage

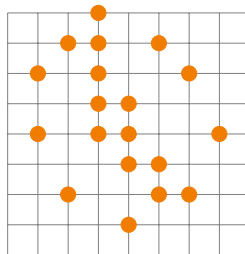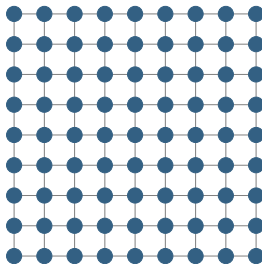System inaccuracy

- Positional inaccuracy
- Propagation time change

Spatial coverage

Full

Incomplete

Background
○○○○○

Error Sources
●○

Simulation
○○○○○

Results
○○○○

Summary
○○

Identification of Error Sources

Path selection

- Unequal scan distribution
- Larger sampling interval
- Incomplete spatial coverage

System inaccuracy
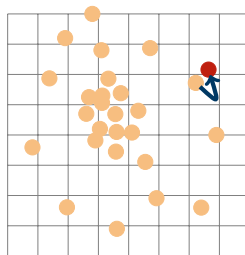
- Positional inaccuracy
- Propagation time change

Positional inaccuracy

Accurate

Inaccurate

Background
○○○○○

Error Sources
●○

Simulation
○○○○○
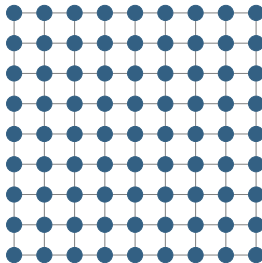
Results
○○○○

Summary
○○

Identification of Error Sources

Path selection
- Unequal scan distribution
- Larger sampling interval
- Incomplete spatial coverage

System inaccuracy
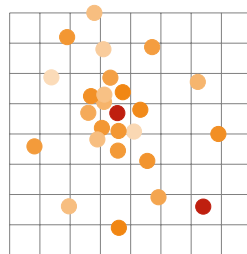- Positional inaccuracy
- Propagation time change

Contact pressure

Constant

Inconsistent

Background
○○○○○

Error Sources
●○

Simulation
○○○○○
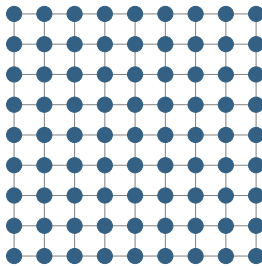
Results
○○○○

Summary
○○

Identification of Error Sources

Path selection

- Unequal scan distribution
- Larger sampling interval
- Incomplete spatial coverage

System inaccuracy
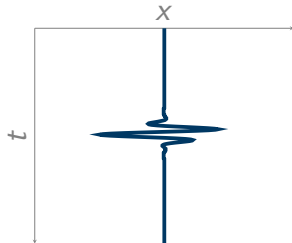
- Positional inaccuracy
- Propagation time change

$\rightarrow$ Propagation time change

Constant

Inconsistent

Background
○○○○○

Error Sources
●○

Simulation
○○○○○
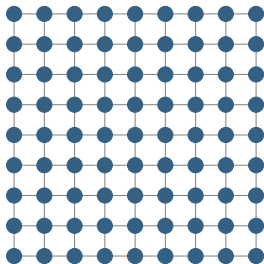
Results
○○○○

Summary
○○

Identification of Error Sources

Path selection

- Unequal scan distribution
- Larger sampling interval
- Incomplete spatial coverage

System inaccuracy
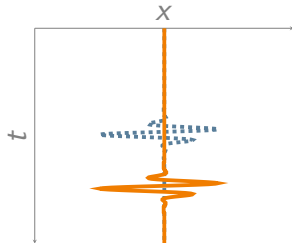
- Positional inaccuracy
- Propagation time change

$\rightarrow$ Propagation time change

Constant

Inconsistent

Background
○○○○○

Error Sources
○●

Simulation
○○○○○

Results
○○○○

Summary
○○

Error Sources and Simulations

Path selection

- Unequal scan distribution [2]
- Larger sampling interval [3]
- Incomplete spatial coverage

System inaccuracy

- Positional inaccuracy
- Propagation time change

---

[2] K. Mayer et al., *19th World Conference on Non-Destructive Testing*, 2016
[3] H. Mooshofer et al., *19th World Conference on Non-Destructive Testing*, 2016

Error Sources and Simulations

Path selection

- Unequal scan distribution [2]
- Larger sampling interval [3]
- Incomplete spatial coverage

System inaccuracy

- Positional inaccuracy
- Propagation time change

---

[2]K. Mayer et al., *19th World Conference on Non-Destructive Testing*, 2016
[3]H. Mooshofer et al., *19th World Conference on Non-Destructive Testing*, 2016

Error Sources and Simulations

Path selection

- Unequal scan distribution [2]
- Larger sampling interval [3]
- Incomplete spatial coverage

System inaccuracy

- Positional inaccuracy
- Propagation time change

$\rightarrow$ 2 Simulation studies, 3 factors

(1) Positional inaccuracy with different spatial coverage

(2) Propagation time change

---

[2] K. Mayer et al., *19th World Conference on Non-Destructive Testing*, 2016
[3] H. Mooshofer et al., *19th World Conference on Non-Destructive Testing*, 2016

Background
○○○○○

Error Sources
○●

Simulation
○○○○○

Results
○○○○

Summary
○○

Error Sources and Simulations

Path selection

- Unequal scan distribution [2]
- Larger sampling interval [3]
- Incomplete spatial coverage

System inaccuracy

- Positional inaccuracy
- Propagation time change

$\rightarrow$ 2 Simulation studies, 3 factors

(1) Positional inaccuracy with different spatial coverage

(2) Propagation time change

---

[2]K. Mayer et al., *19th World Conference on Non-Destructive Testing*, 2016
[3]H. Mooshofer et al., *19th World Conference on Non-Destructive Testing*, 2016

Background
○○○○○

Error Sources
○○

Simulation
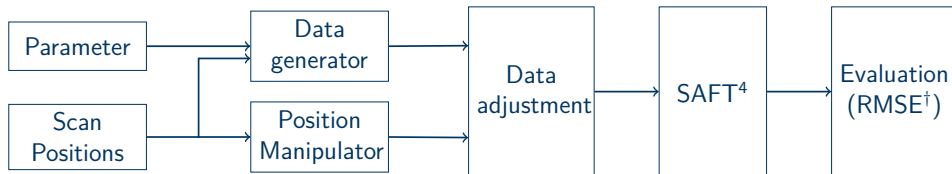●○○○○

Results
○○○○

Summary
○○

Simulation Setup

Defect positions (part of a large object)
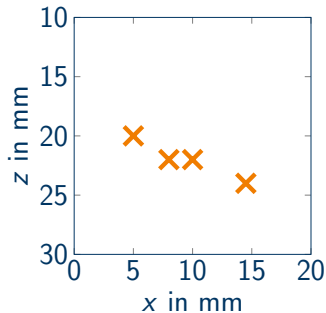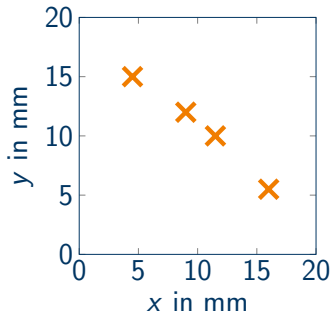
Assumptions

- Pulse-echo setup
- Single transducer
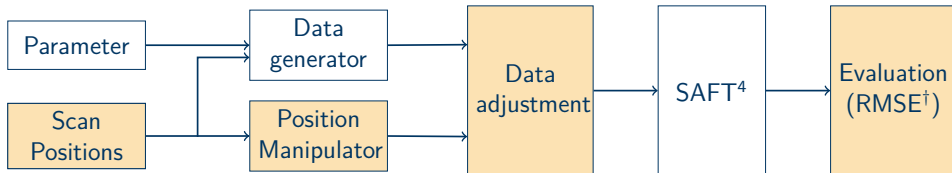- Aluminium
- Planar surface
- Point scatterers
- Noise free

Background
○○○○○

Error Sources
○○

Simulation
○●○○○

Results
○○○○

Summary
○○

Simulation Flow

---

[4]F. Krieg et al., *Progressive online 3-D SAFT processing by matrix structure exploitation*, *IEEE IUS*, 2018

Background
○○○○○

Error Sources
○○

Simulation
○●○○○

Results
○○○○

Summary
○○

Simulation Flow

- How many scans should be taken?
  $\rightarrow$ Variation of number of scans N_{point}
- How big can the distance error be?
  $\rightarrow$ Variation of position error $\hat{=}\sigma$

Background
○○○○○

Error Sources
○○

Simulation
○○●○○

Results
○○○○

Summary
○○

Scan Position Selection
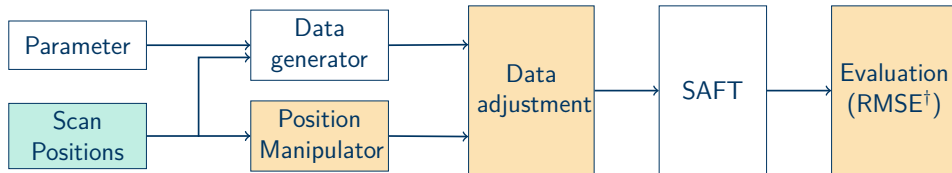
$\rightarrow$ number of scans N_{point} variation

Background
○○○○○

Error Sources
○○

Simulation
○○●○○

Results
○○○○

Summary
○○

Scan Position Selection
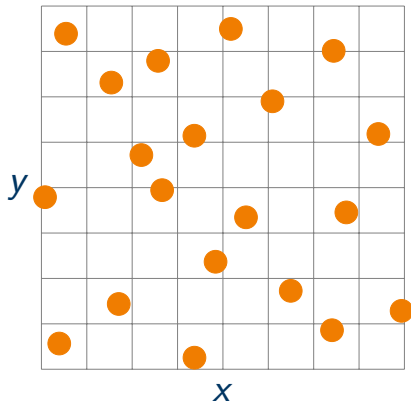
Scan position selection:

- Set the number of total scans N_{point}
- Select N_{point} random positions
- N_{point} = variable

Background
○○○○○

Error Sources
○○

Simulation
○○○●○

Results
○○○○

Summary
○○

Position Manipulation
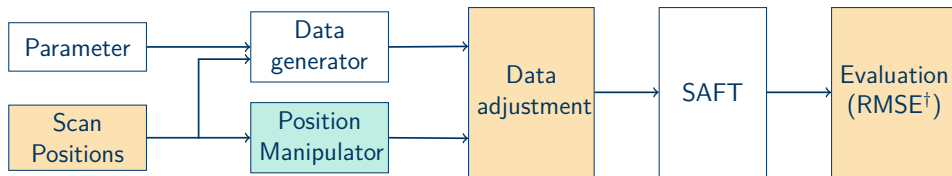
Equivalent to the recognition error
$\rightarrow \sigma$ variation

Background
○○○○○

Error Sources
○○

Simulation
○○○●○

Results
○○○○

Summary
○○

Position Manipulation
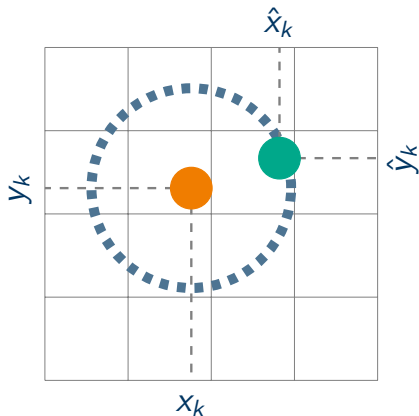
$$\hat{x}_k \quad = r \cdot \cos(\theta)+ \quad x_k$$
$$\hat{y}_k \quad = r \cdot \sin(\theta)+ \quad y_k$$

θ: uniform distribution
r: normal distribution (σ)
$\rightarrow \sigma =$ variable
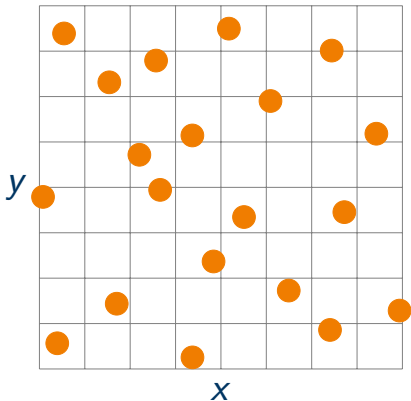
Background
○○○○○

Error Sources
○○

Simulation
○○○●○

Results
○○○○

Summary
○○

Position Manipulation

Position manipulation

- Using the polar coordinate
- Radius variation with σ
- σ = variable

Background
○○○○○

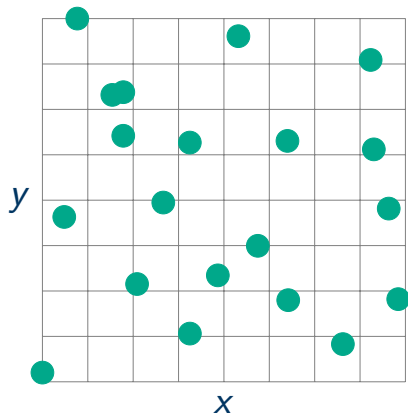Error Sources
○○

Simulation
○○○●○

Results
○○○○

Summary
○○

Position Manipulation

Position manipulation
- Using the polar coordinate
- Radius variation with σ
- $\sigma =$ variable

Background
○○○○○

Error Sources
○○

Simulation
○○○○●

Results
○○○○

Summary
○○
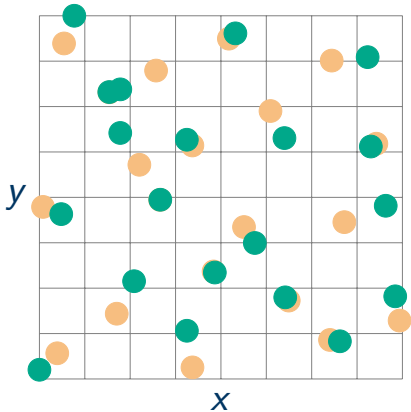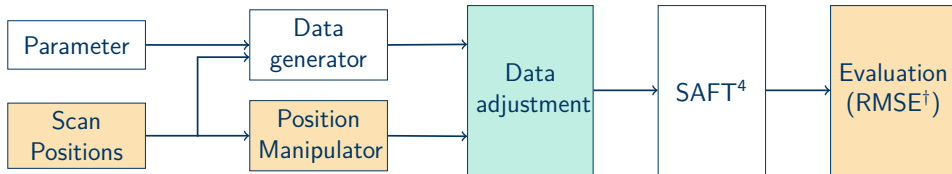
Data Adjustment

Adjustment to the required format
$\rightarrow$ Scan positions on the reconstruction grid

---

[4]F. Krieg et al., Progressive online 3-D SAFT processing by matrix structure exploitation, *IEEE IUS*, 2018

Background
○○○○○

Error Sources
○○

Simulation
○○○○●

Results
○○○○

Summary
○○

Data Adjustment

Data adjustment

- Quantize scan positions
- Avoid overemphasis
  $\rightarrow$ Take only the first A-Scan [1]

Background
○○○○○

Error Sources
○○

Simulation
○○○○○●

Results
○○○○

Summary
○○

Data Adjustment

Data adjustment

- Quantize scan positions
- Avoid overemphasis
  $\rightarrow$ Take only the first A-Scan [1]

Background
○○○○○

Error Sources
○○

Simulation
○○○○●

Results
○○○○

Summary
○○
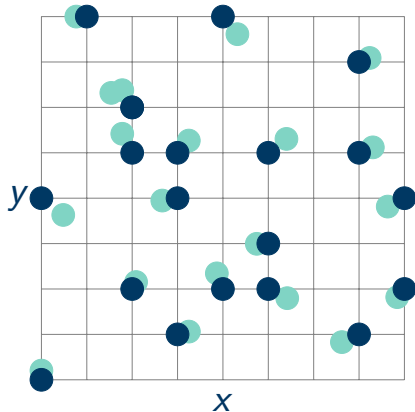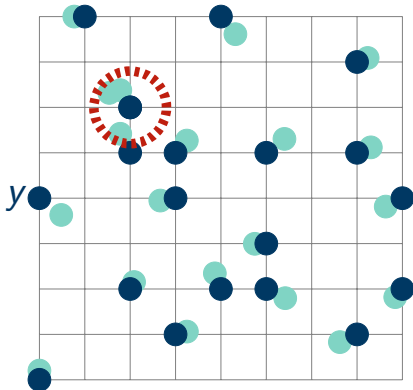
Data Adjustment

Data adjustment

- Quantize scan positions
- Avoid overemphasis
  $\rightarrow$ Take only the first A-Scan [1]

---

[1]F. Krieg et al., SAFT processing for manually acquired ultrasonic measurement data with 3D SmartInspect, *SHM-NDT*, 2018

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
●○○○

Summary
○○

Visual Results and Evaluation
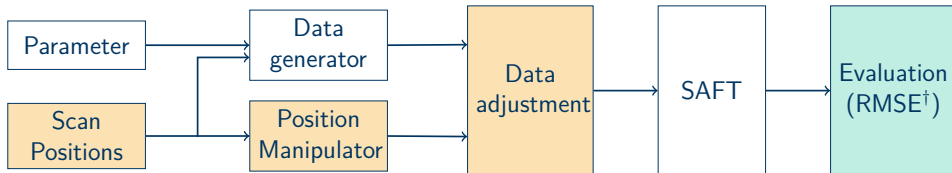
RMSE†-Evaluation
Corresponding visual results

$$\text{RMSE}^{\dagger} = \frac{\left\| \alpha \cdot \hat{\boldsymbol{C}} - \boldsymbol{C} \right\|_F}{\left\| \boldsymbol{C} \right\|_F} \qquad \begin{array}{l} \boldsymbol{C} = \text{reference} \\ \hat{\boldsymbol{C}} = \text{obtained result} \end{array}$$

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
●○○○

Summary
○○

Visual Results and Evaluation

Reference (C-Scan)
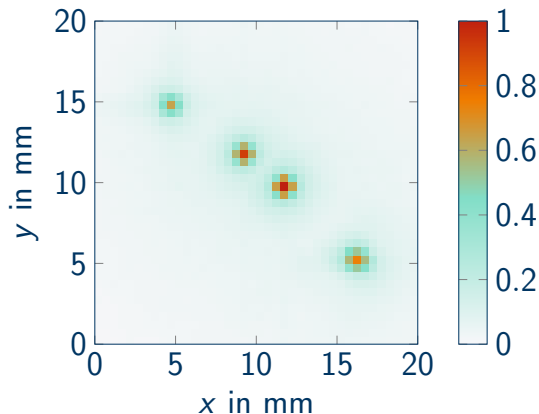
SAFT reconstruction of a simulated
automatic measurement data

- Scan positions on fine grid
- 100% coverage (1600 grid
  points)
- No positional error

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
●○○○

Summary
○○

Visual Results and Evaluation

Result (1) Coverage

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○●○○

Summary
○○

Result (1) Coverage

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○●○○

Summary
○○

Result (1) Coverage

$N_{point} = 160,\ \sigma = 0$

$N_{point} = 1600,\ \sigma = 0$

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○●○

Summary
○○

Result (2) 0.1λ Error

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○●○

Summary
○○

Result (2) 0.1λ Error

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○●○

Summary
○○

Result (2) 0.1λ Error

$N_{\text{point}} = 160$

$\sigma = 0$, RMSE$^\dagger = 0.43$
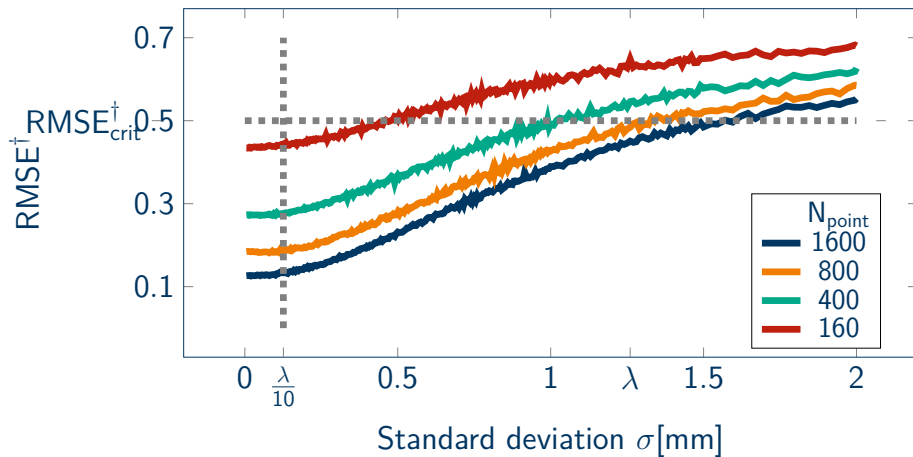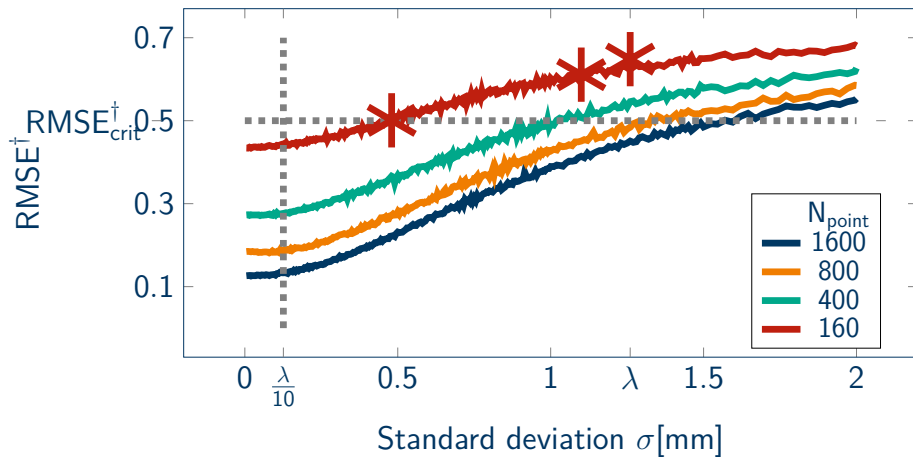

$\sigma = 0.1\lambda$, RMSE$^\dagger = 0.44$

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○●○

Summary
○○

Result (2) 0.1λ Error

Difference between $\sigma = 0$ and 0.1λ

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○●○

Summary
○○

Result (2) 0.1λ Error

$N_{\text{point}} = 160$

$\sigma = 0$, RMSE$^\dagger = 0.43$

$\sigma = 0.1\lambda$, RMSE$^\dagger = 0.44$

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○●

Summary
○○

Result (3) RMSE$_{\text{crit}}^{\dagger}$

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○●

Summary
○○

Result (3) RMSE$^{\dagger}_{\text{crit}}$

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○●

Summary
○○

Result (3) RMSE$_{\text{crit}}^{\dagger}$

$$N_{\text{point}} = 160$$

$\sigma = 0.5\,\text{mm}, \text{RMSE}^{\dagger} = 0.5$

$\sigma = 1.1\,\text{mm}, \text{RMSE}^{\dagger} = 0.61$

Result (3) RMSE$^{\dagger}_{\text{crit}}$

$N_{\text{point}} = 160$

$\sigma = 0.5\,\text{mm}$, RMSE$^{\dagger} = 0.5$

$\sigma = 1.26\,\text{mm}(\lambda)$, RMSE$^{\dagger} = 0.65$

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○●

Summary
○○

Result (3) RMSE$^\dagger_{crit}$

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○○

Summary
●○

Conclusion

Identified 5 factors as error sources, 3 were investigated

Factor	Negligible	Note
Spatial coverage	-	Still satisfying results with 10% coverage
Position inaccuracy	$\leq 0.1\lambda$	Larger error can be tolerated with higher coverage
Propagation time change	$\leq 0.06\lambda$	Stronger artifact formation

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○○

Summary
○●

Future Work

- Measurement of the system error
- Other evaluation methods
- Development of measurement assistance systems

Background
○○○○○

Error Sources
○○

Simulation
○○○○○

Results
○○○○

Summary
○●

Future Work

- Measurement of the system error
- Other evaluation methods
- Development of measurement assistance systems

ⒸUwe Bellhäuser

Appendix

Parameters w.r.t. Test Object

Parameter	Value
Material	Aluminium
Dimension (L $\times$ B $\times$ H)	20 mm $\times$ 20 mm $\times$ 35 mm
$N_x \times N_y \times N_z$	40 $\times$ 40 $\times$ 880
Speed of sound c_0	6300 m s^{-1}
Sampling frequency f_S	80 MHz
dt $= \frac{1}{f_s}$	12.5 ns
Sampling distance, surface (dx, dy)	0.5 mm
Sampling distance, depth (dz)	39.375 µm
Position of point scatters	[9, 29, 520] = [4.5 mm, 14.5 mm, 20.67 mm], [18, 23, 554] = [9 mm, 11.5 mm, 22.02 mm], [23, 19, 571] = [11.5 mm, 11.5 mm, 9.5 mm], [32, 10, 614] = [16 mm, 16 mm, 5 mm]

Parameters w.r.t. Pulse

Parameter	Value
Model	Gaussian (Gabor)
Carrier frequency f_c	5 MHz
Wavelength λ	1.26 mm
Relative bandwidth	0.5
Length of the pulse	$20 \cdot dt$
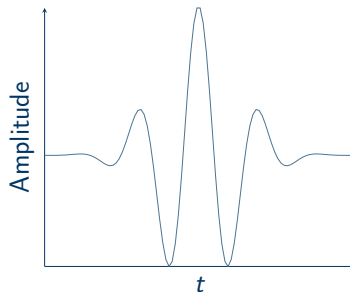
Parameters w.r.t. Simulation

	Parameter	Value
Constant	Scan positions	random, off the grid
	Opening angle	$20°$
	Number of simulations per σ	10
Variable	Position error (σ)	$0\dots2\,\text{mm}$
	Number of scan positions (N_{point})	160, 400, 800, 1600 (10%, 25%, 50%, 100%)

State of the Art

SAFT application to the manual measurement data

- Little investigated
    - Potential
    - Implementation
    - Challenges
- Application to concrete objects is proven [2]
    - Validity to metal objects is questionable

---

[1]K. Mayer, M. Ibrahim, M. Krause, M. Schubert, Requirements for a small size ultrasonic imaging system for inspection of concrete elements, *19th World Conference on Non-Destructive Testing*, 2016

Results of Literature Search (1)

Keywords (w.r.t. SAFT and manual scan)	Hits	Relevant
ultrasonic "NDT" "SAFT" "arbitrary scan"	7	-
ultrasonic "NDT" "SAFT" "random scan"	9	-
ultrasonic "NDT" "SAFT" "gridless"	14	-
ultrasonic "NDT" "SAFT" "manual scan"	23	-
ultrasonic "NDT" "SAFT" "manual measurement"	28	-
ultrasonic "NDT" "SAFT" "handheld device"	56	-
ultrasonic "synthetic aperture focusing technique" "freehand"	343	-
ultrasonic synthetic aperture focusing technique "arbitrary sampling"	348	-

Results of Literature Search (2)

Keywords (w.r.t. SAFT and error sources)	Hits	Relevant
ultrasonic NDT "SAFT" "minimum data size"	0	-
ultrasonic NDT "SAFT" "scan position error"	0	-
ultrasonic NDT "SAFT" "positional inaccuracy"	2	-
ultrasonic NDT "SAFT" "course surface"	6	-
ultrasonic NDT "SAFT" "inconsistent time"	6	-
ultrasonic NDT "SAFT" "positional error"	17	1
ultrasonic NDT "SAFT" "non planar surface"	24	1
ultrasonic "NDT" "SAFT" "grid size"	160	1
ultrasonic NDT "SAFT" "position error"	226	-
ultrasonic "NDT" "SAFT" "small size"	3300	1 (up to the first 100)

Automatic vs Manual Data
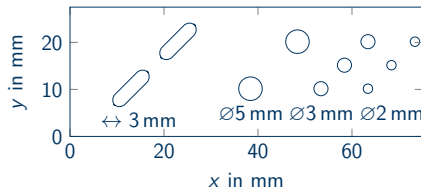
Test object[3]
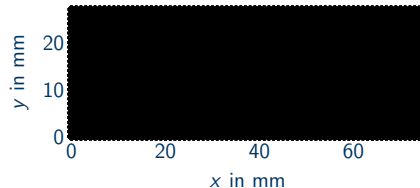
Scan positions[3]
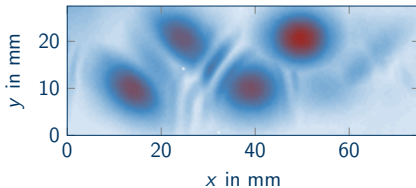
Measurement data[3]

SAFT Reconstruction[3]
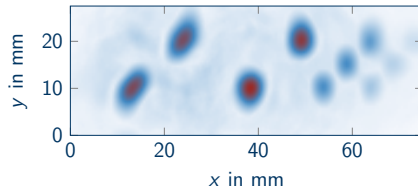
Automatic vs Manual Data
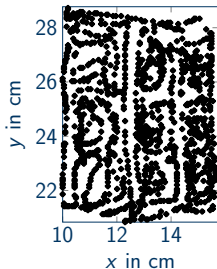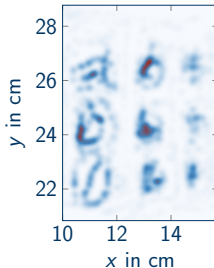
Test object[3]   Scan positions[3]   Measurement data[3]   SAFT Reconstruction[3]

---
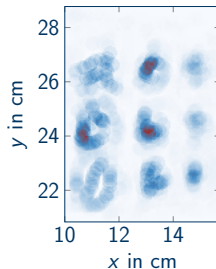
[1]F. Krieg et al., SAFT processing for manually acquired ultrasonic measurement data with 3D SmartInspect, *SHM-NDT*, 2018

Automatic vs Manual Data

Measurement data[3]
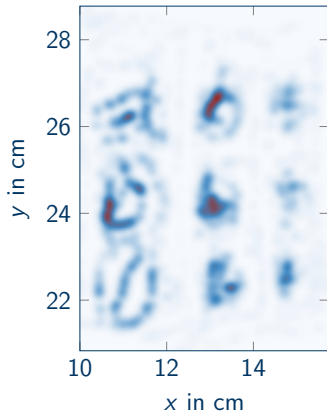
SAFT Reconstruction[3]
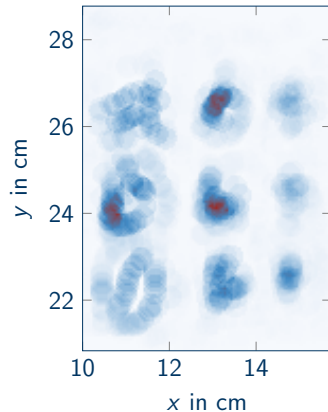
Position Manipulation
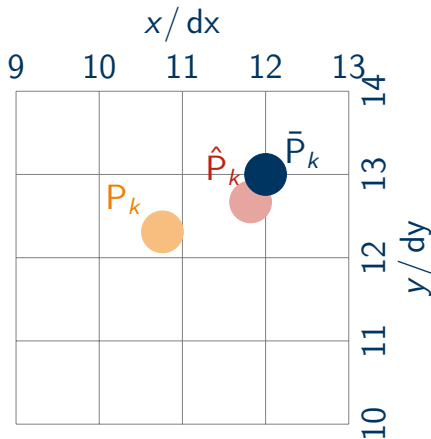
Scan Position P_k
$(10.76, 12.31)$

Recognized Position $\hat{P}_k$
$(11.82, 12.67)$

Rounded Position $\bar{P}_k$
$(12, 13)$

Recognition and Rounding Error

$$P_k = (x_k, y_k)$$

$$\hat{P}_k = (\hat{x}_k, \hat{y}_k)$$

$$= \begin{pmatrix} x_k + r \cdot \cos(\theta) \\ y_k + r \cdot \sin(\theta) \end{pmatrix}$$

Distribution of $\hat{P}_k$
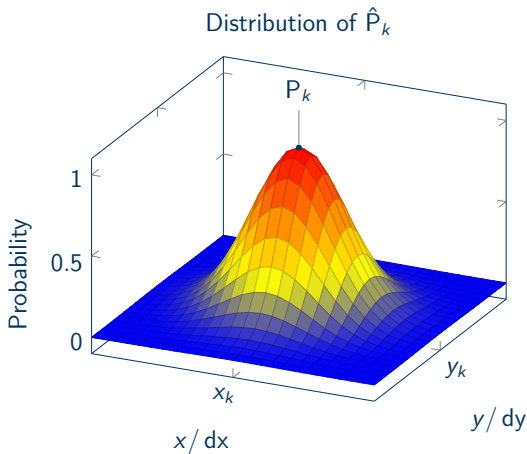
RMSE†

$$\text{RMSE}^{\dagger} = \frac{\left\| \alpha \cdot \hat{\boldsymbol{C}} - \boldsymbol{C} \right\|_F}{\left\| \boldsymbol{C} \right\|_F}$$

$$\alpha = \frac{\text{vec}(\boldsymbol{C})^{\mathsf{T}} \cdot \text{vec}(\hat{\boldsymbol{C}})}{\text{vec}(\hat{\boldsymbol{C}})^{\mathsf{T}} \cdot \text{vec}(\hat{\boldsymbol{C}})}.$$

where
$\boldsymbol{C} = $ reference data
$\hat{\boldsymbol{C}} = $ obtained results to compare

Effect of Rounding Methods

$N_{point} = 1600$ for both

Take only one and discard the others
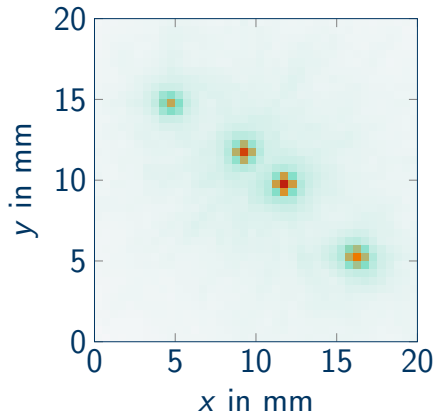
Take the average
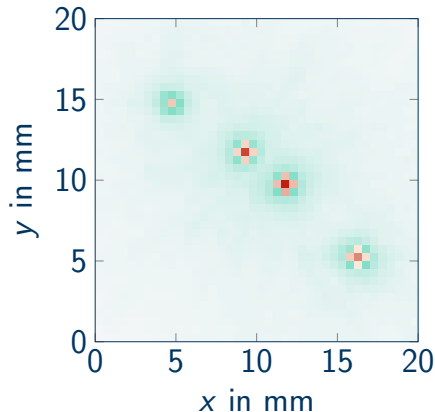
Scan Positions

$N_{point} = 1600$
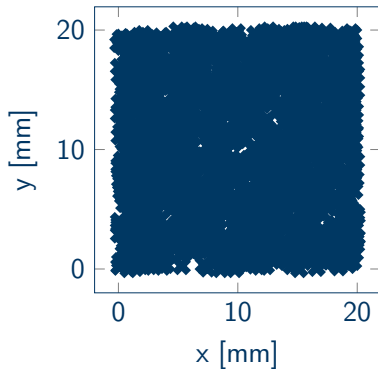
$N_{point} = 160$
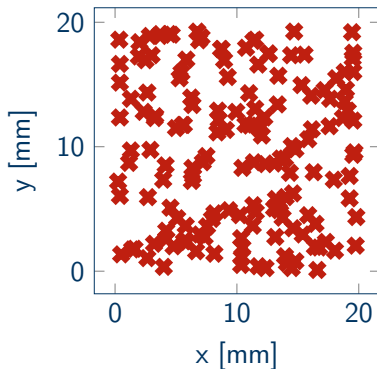
Coverage Change with Number of Scans
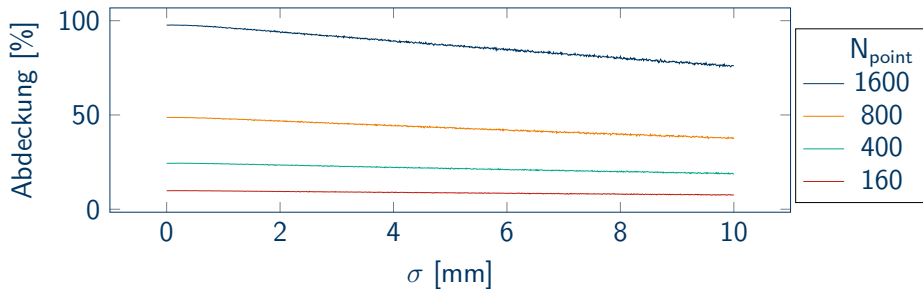
Note: spatial coverage (%) decreases with increasing σ by approx. 2% per mm relative to the number of scan positions (N_{point})
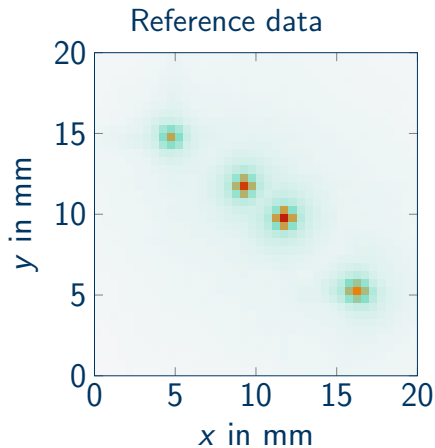
Effect of Varying Coverage

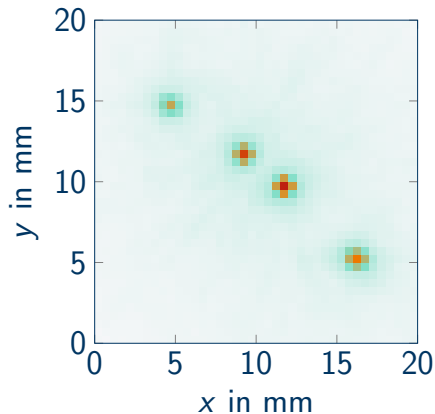Reference data

Effect of Varying Coverage

Reference data

1600 scan positions

Effect of Varying Coverage

Reference data
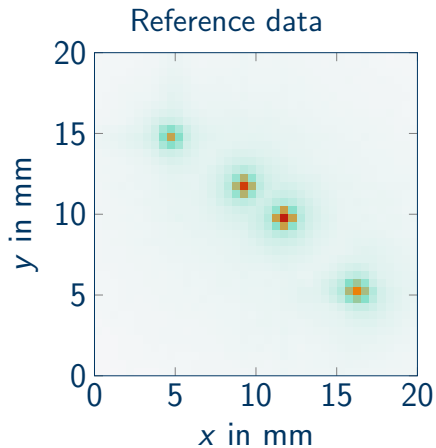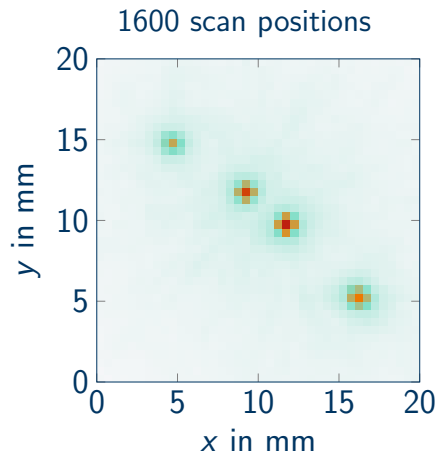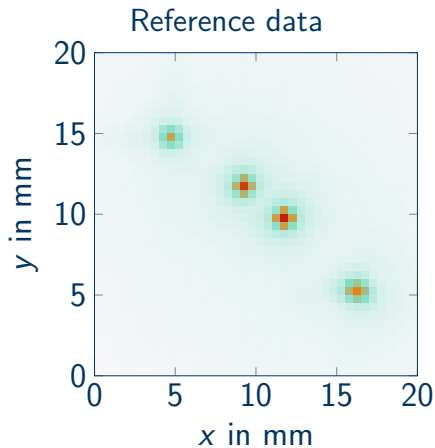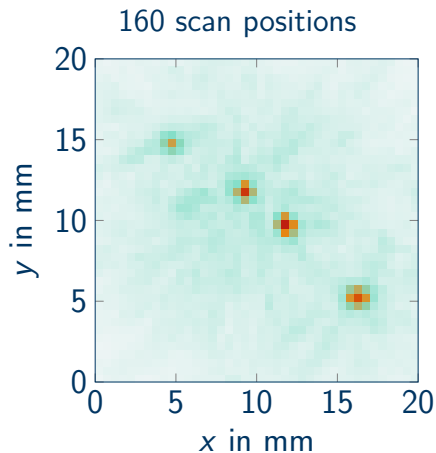
160 scan positions

Results in C-Scan Presentation
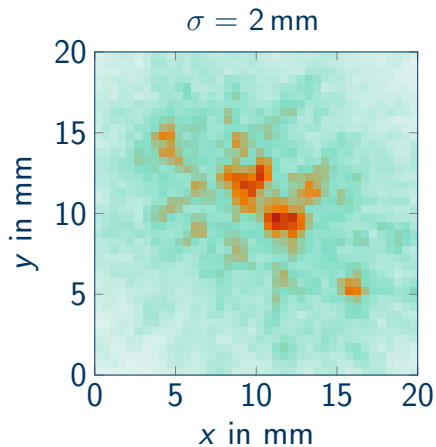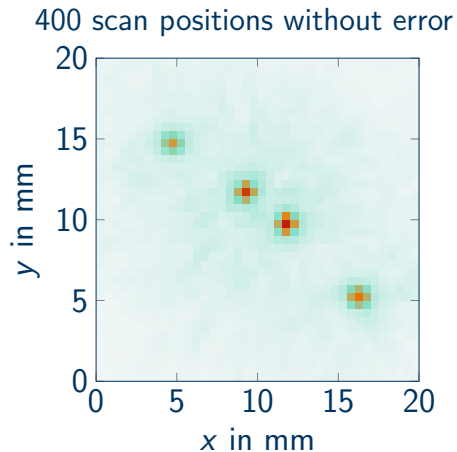

1600 scan positions without error
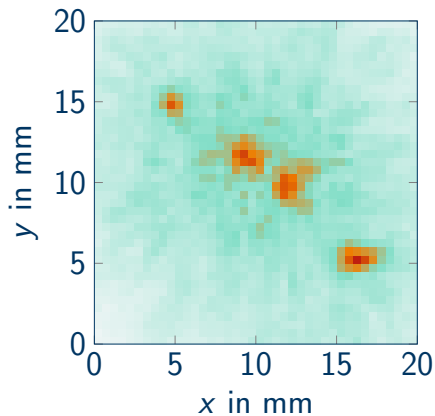
$\sigma = 2\,\mathrm{mm}$

Results in C-Scan Presentation

800 scan positions without error

$\sigma = 2\,\text{mm}$

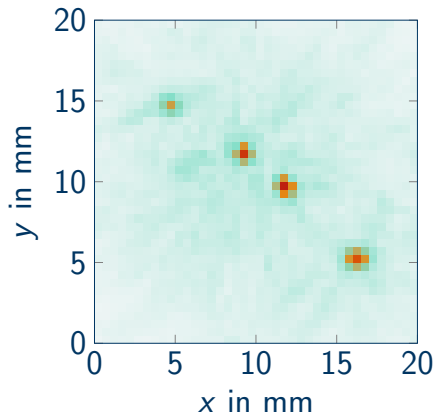# Results in C-Scan Presentation

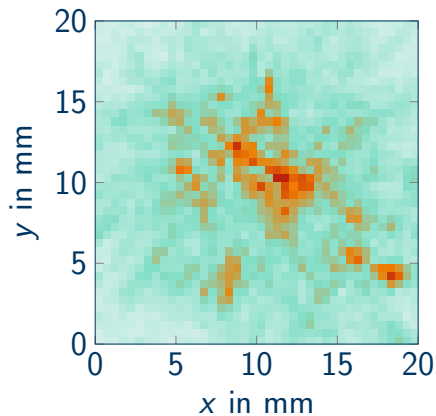400 scan positions without error

$\sigma = 2\,\mathrm{mm}$
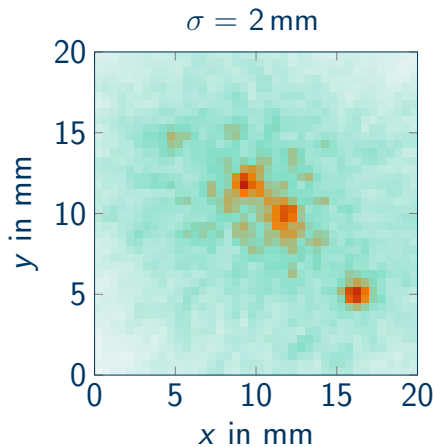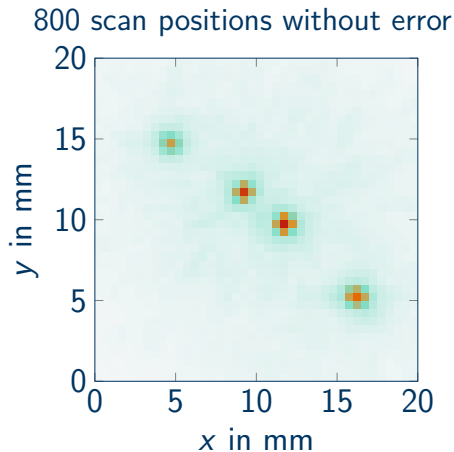
Results in C-Scan Presentation

160 scan positions without error

$\sigma = 2\,mm$

Simulation 2 Setups and Parameters

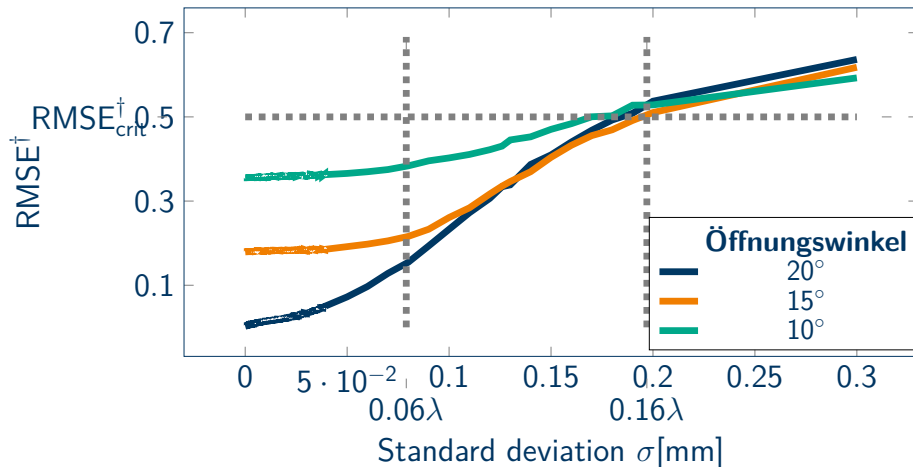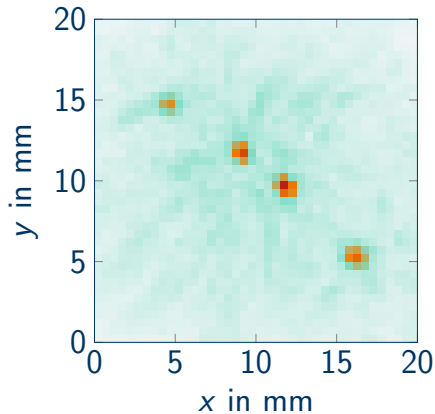|	Parameter	Value
Constant	Scan positions	on fine grid
	dx	0.5 mm
	$N_x = N_y$	40
	Number of simulations	10
	per σ	
Variable	Vertical distance change (σ)	0...0.3 mm
	Opening angle	20°, 15°, 10°

Simulation 2 Flow

Simulation flow
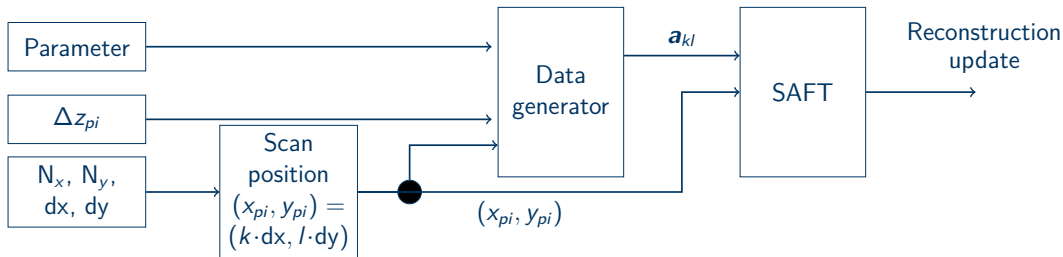
Simulation 2 RMSE† Results

Simulation 2 RMSE$_{\text{crit}}^{\dagger}$

Simulation 1: $N_{\text{point}} = 160$, RMSE$_{\text{crit}}^{\dagger}$

Simulation 2: Angle $= 10°$, RMSE$_{\text{crit}}^{\dagger}$