

Tobias Wulf

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# Bachelorarbeit

Winkelmessung durch magnetische Sensor-Arrays und  
Toleranzkompensation mittels Gauß-Prozess

Fakultät Technik und Informatik  
Department Informations- und Elektrotechnik

Faculty of Computer Science and Engineering  
Department of Information and Electrical Engineering

# Übersicht

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- Applikation
- Kennfelder
- Datenadaption
- Gauß-Prozesse

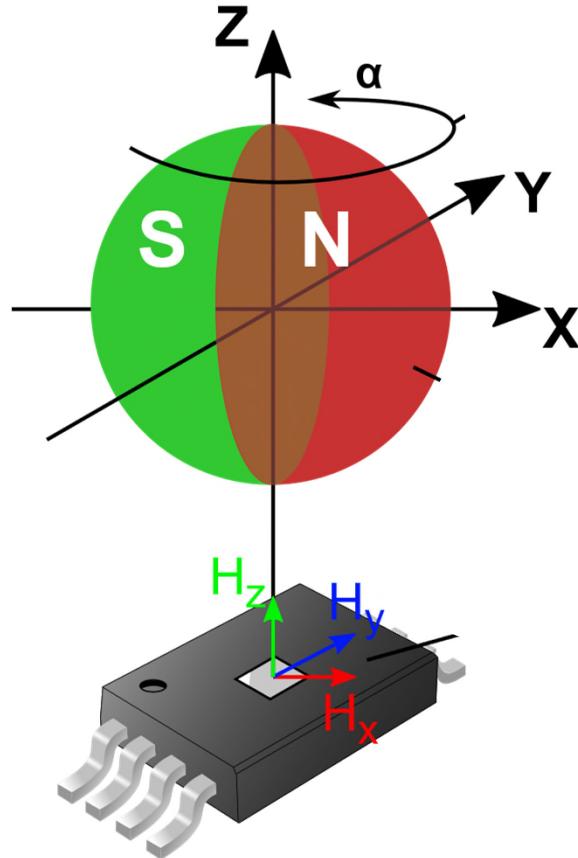
# Übersicht

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- Applikation
- Kennfelder
- Datenadaption
- Gauß-Prozesse
- Software-Aufbau
- Simulation – Sensor-Array
- Simulation – Gauß-Prozesse
- Erprobungsexperimente
- Zusammenfassung

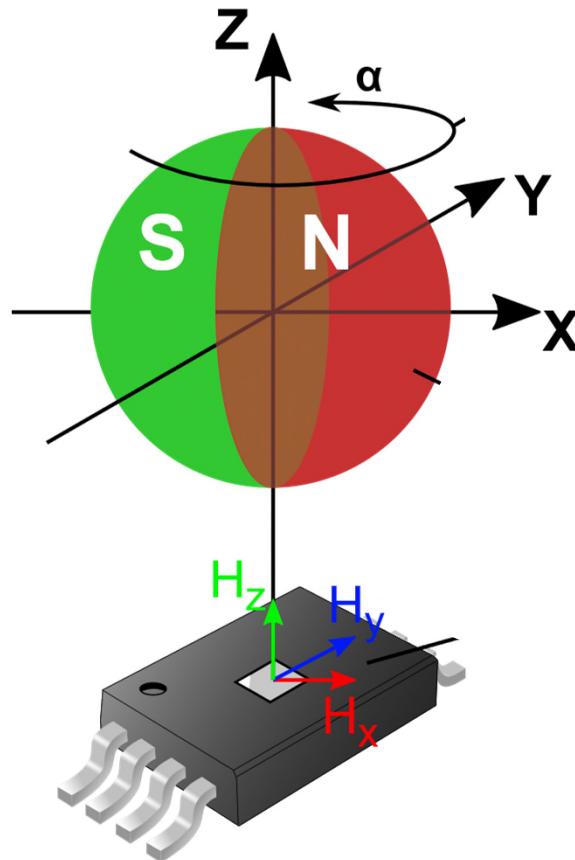
# Applikation

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# Applikation

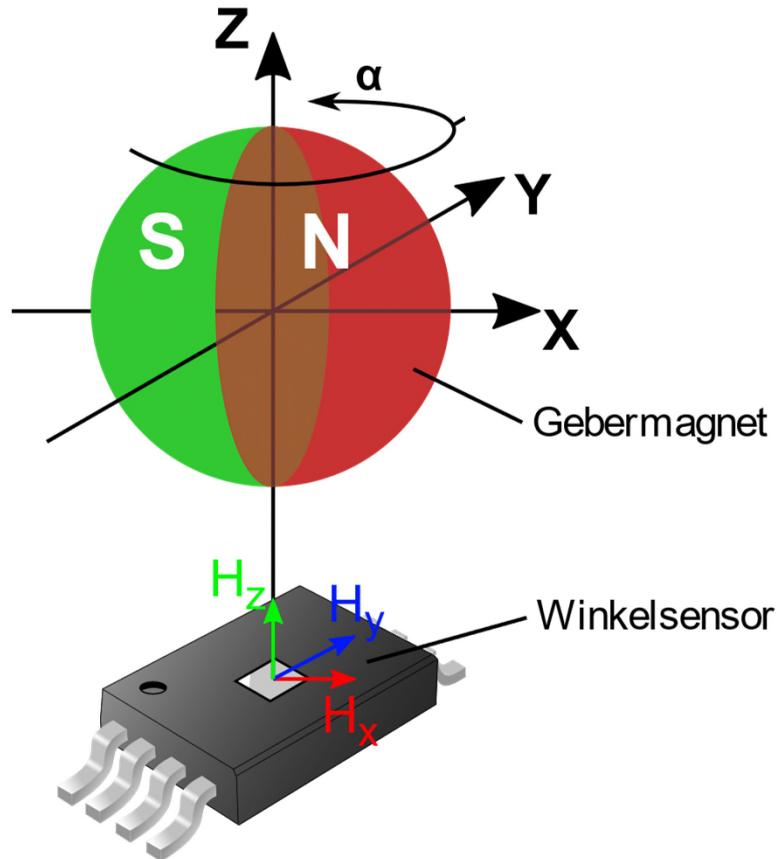
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- Kontaktlose Winkelmessung

# Applikation

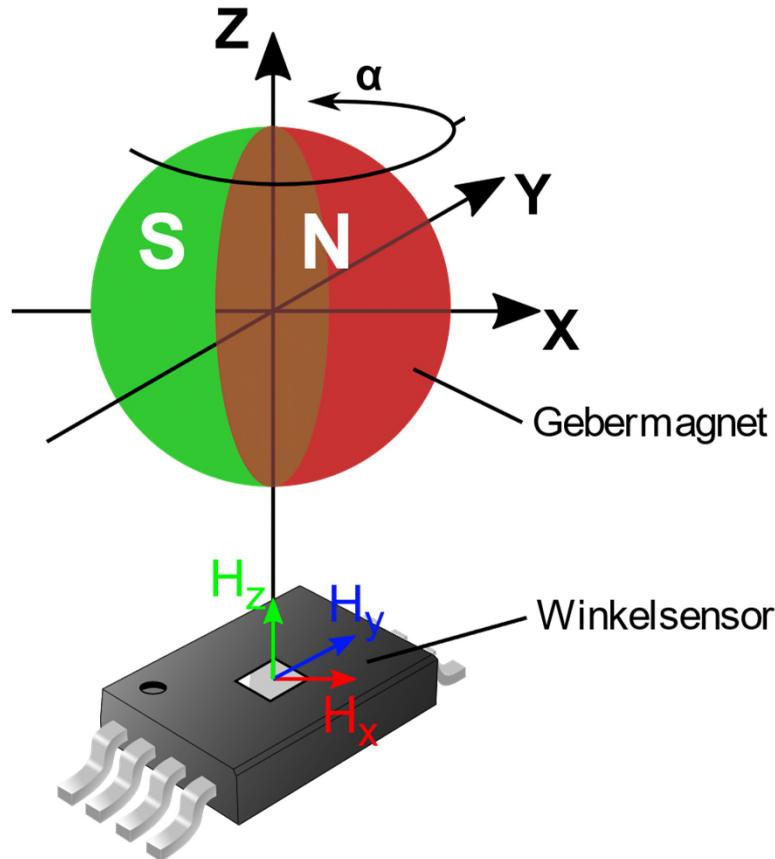
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- Kontaktlose Winkelmessung
- Winkel encodiert durch Magnetfeld

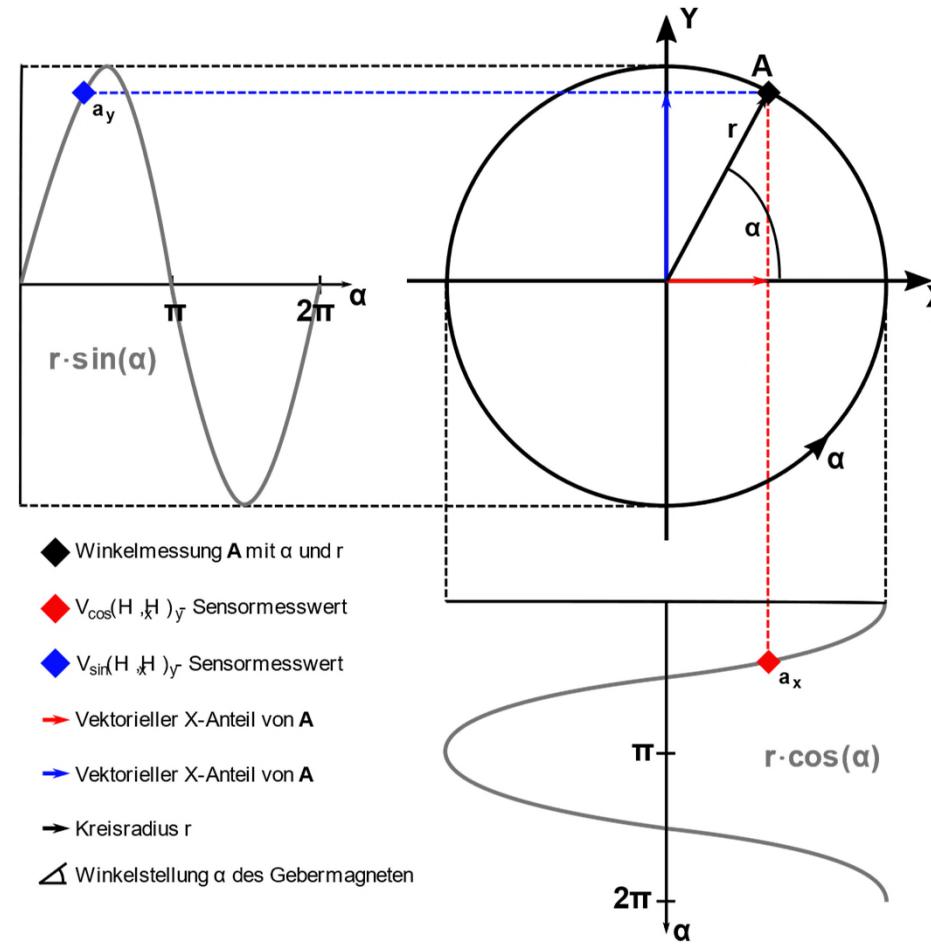
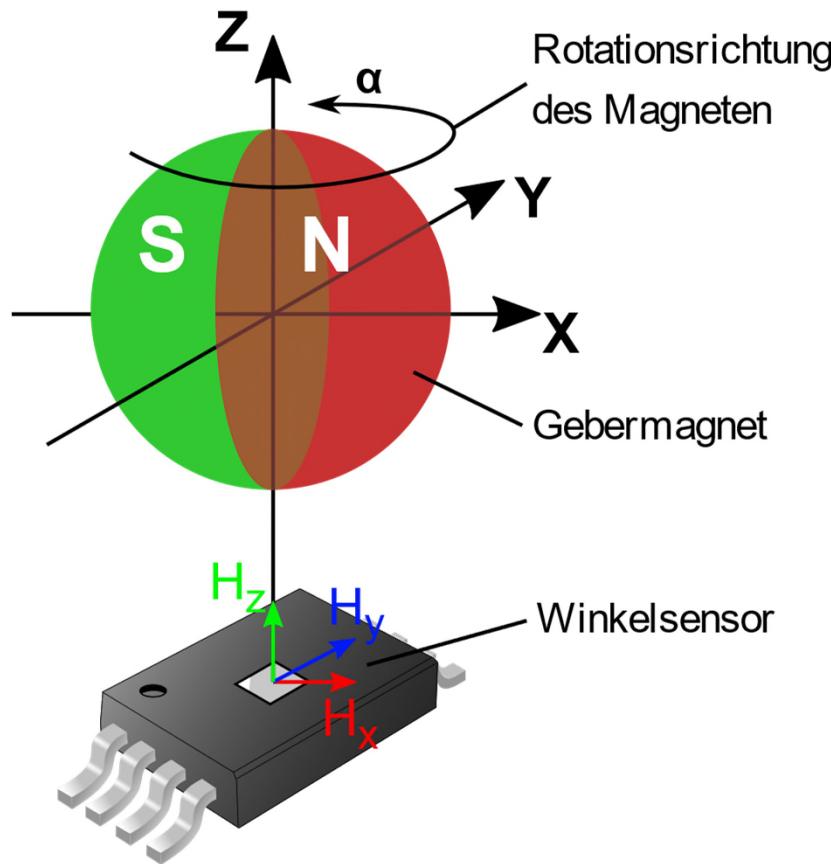
# Applikation

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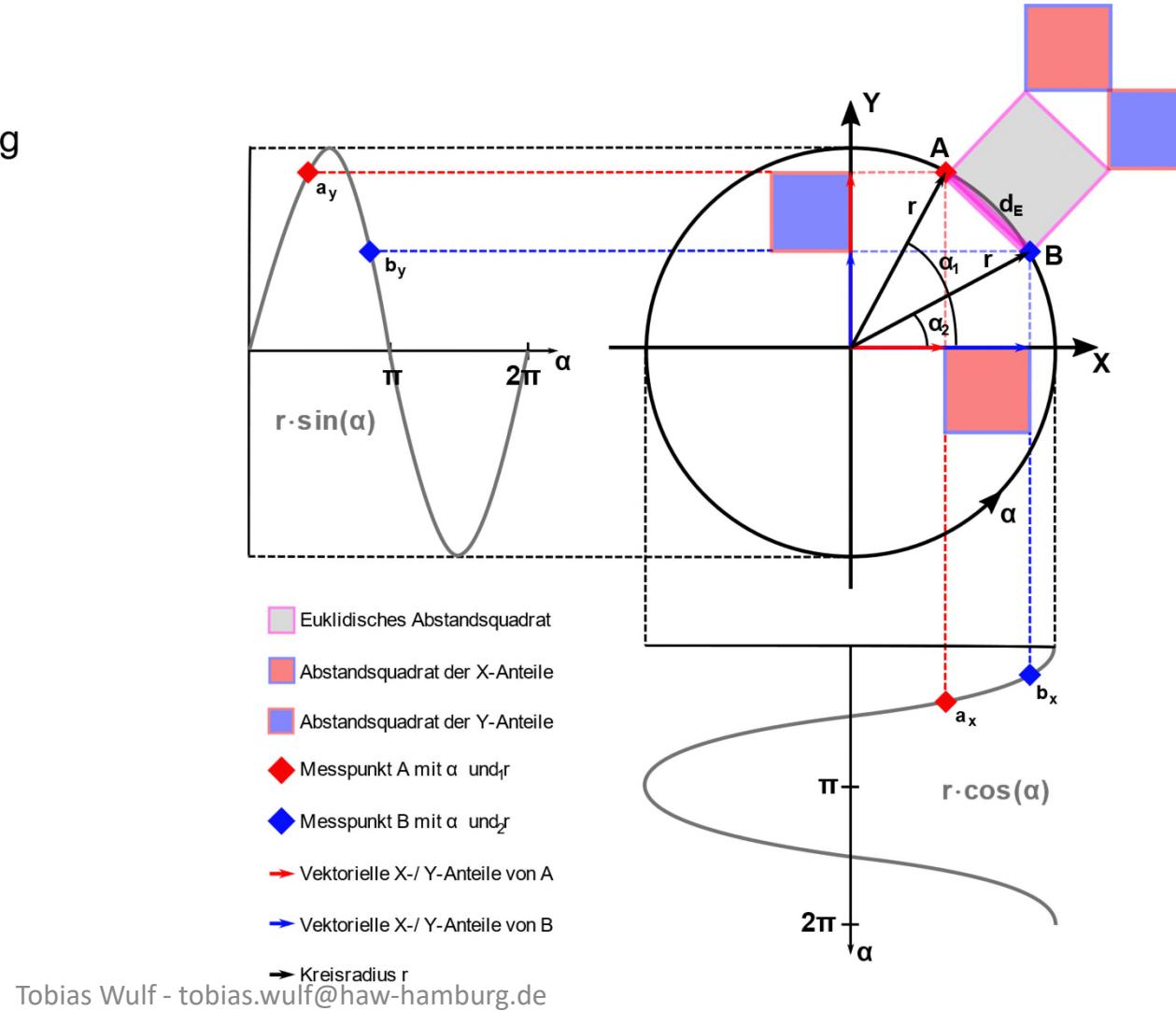
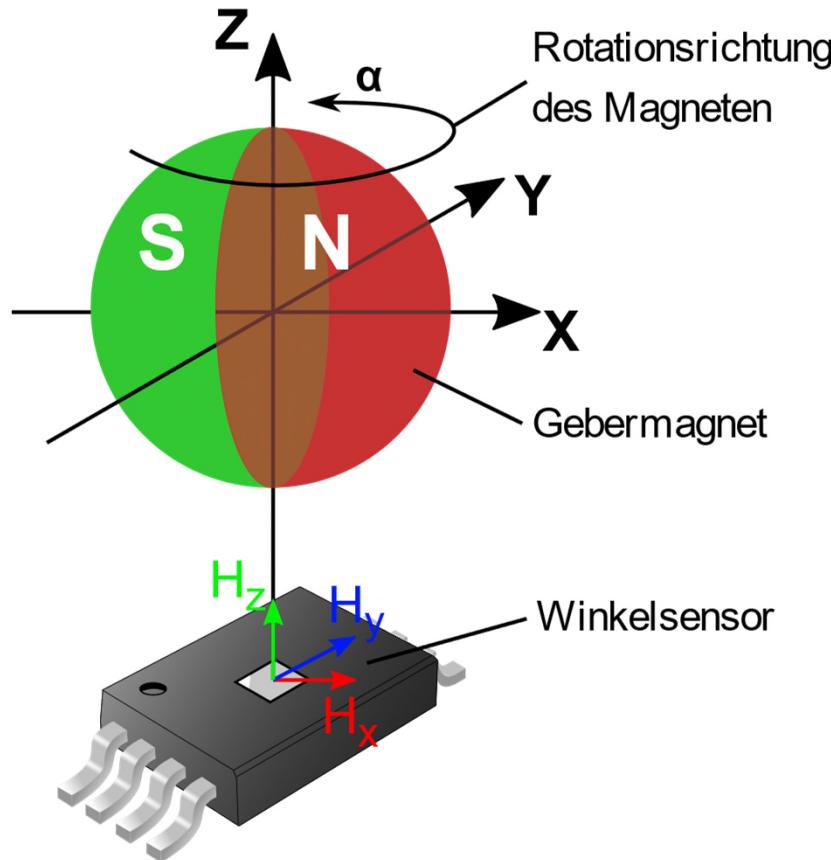


- Kontaktlose Winkelmessung
- Winkel encodiert durch Magnetfeld
- Feldstärkenmessung in X-/ Y-Richtung

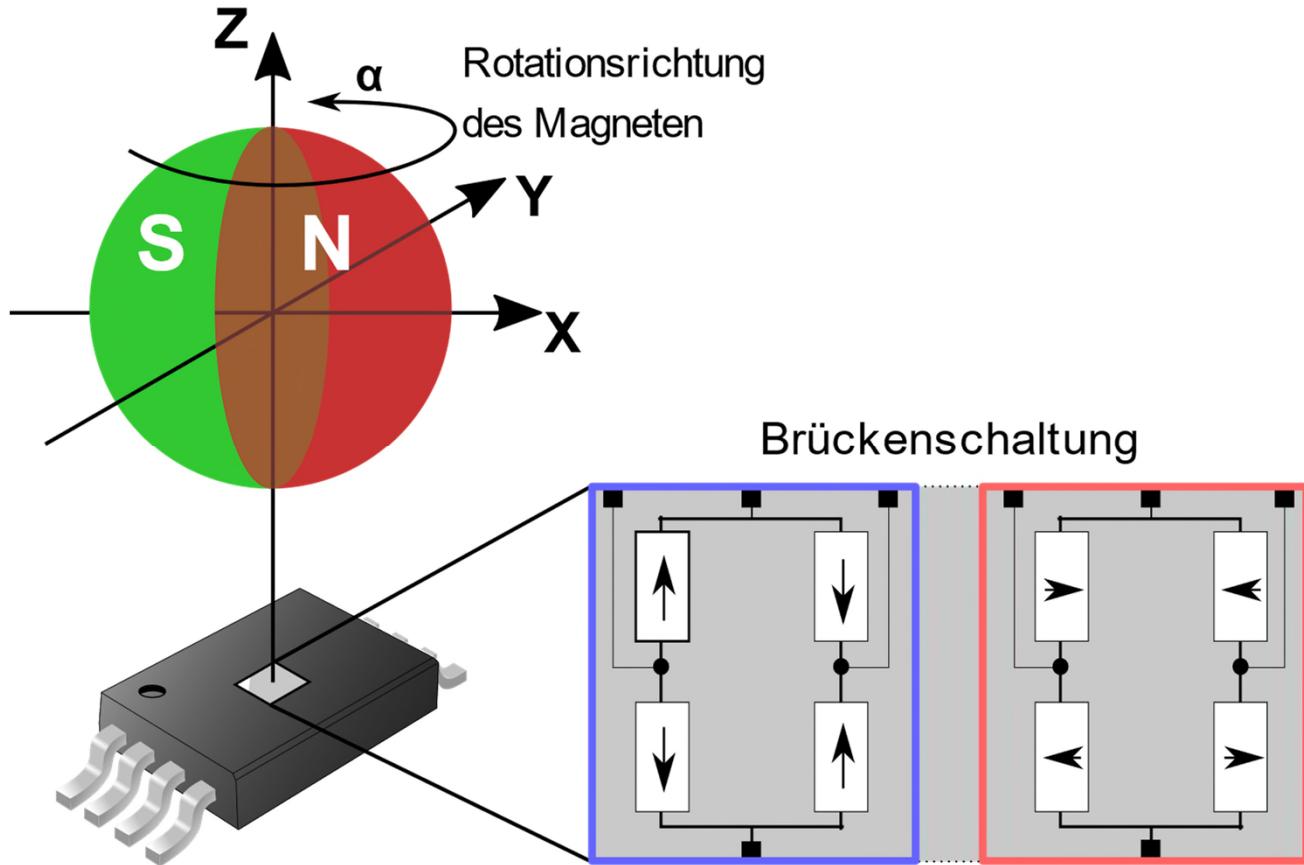
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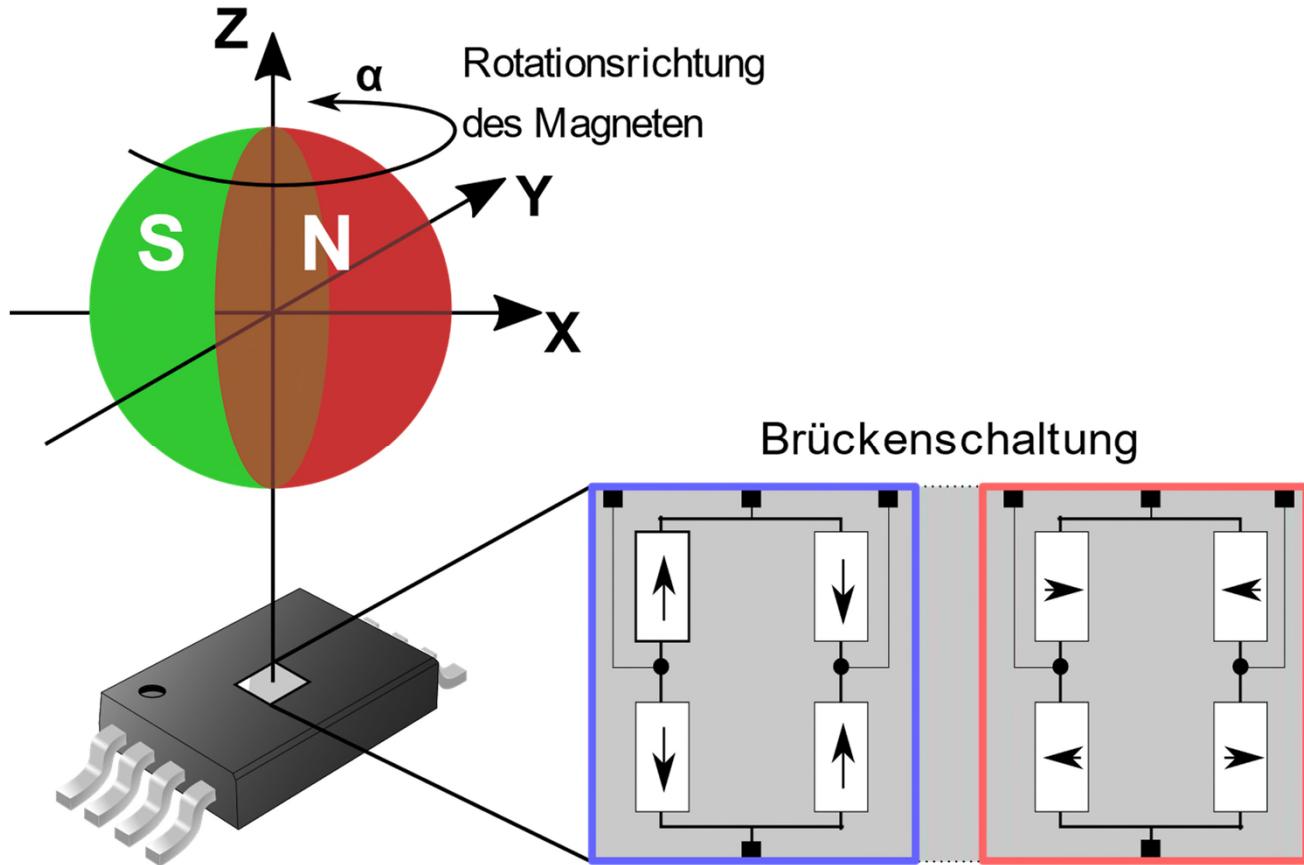
# Applikation



# Applikation

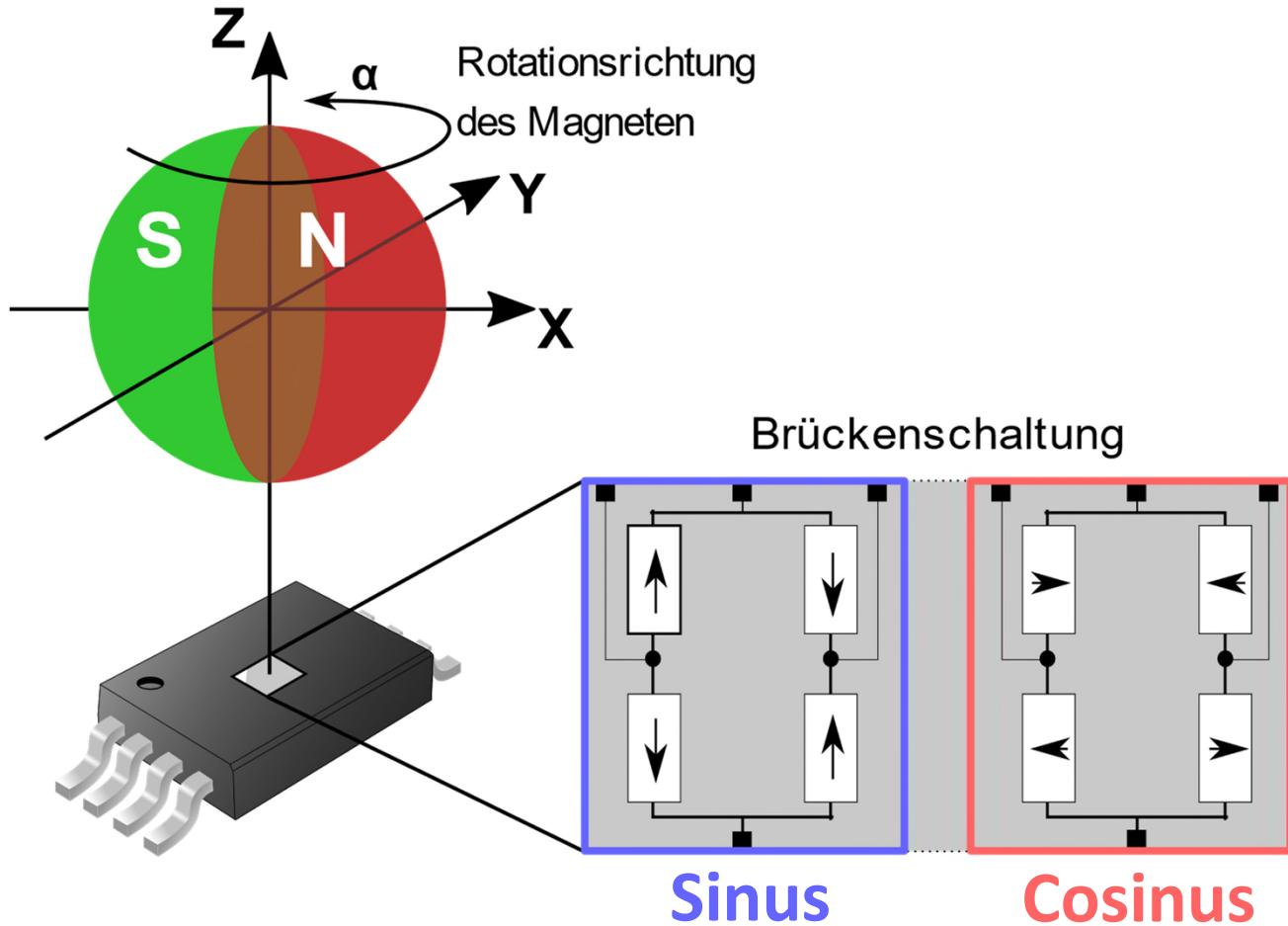


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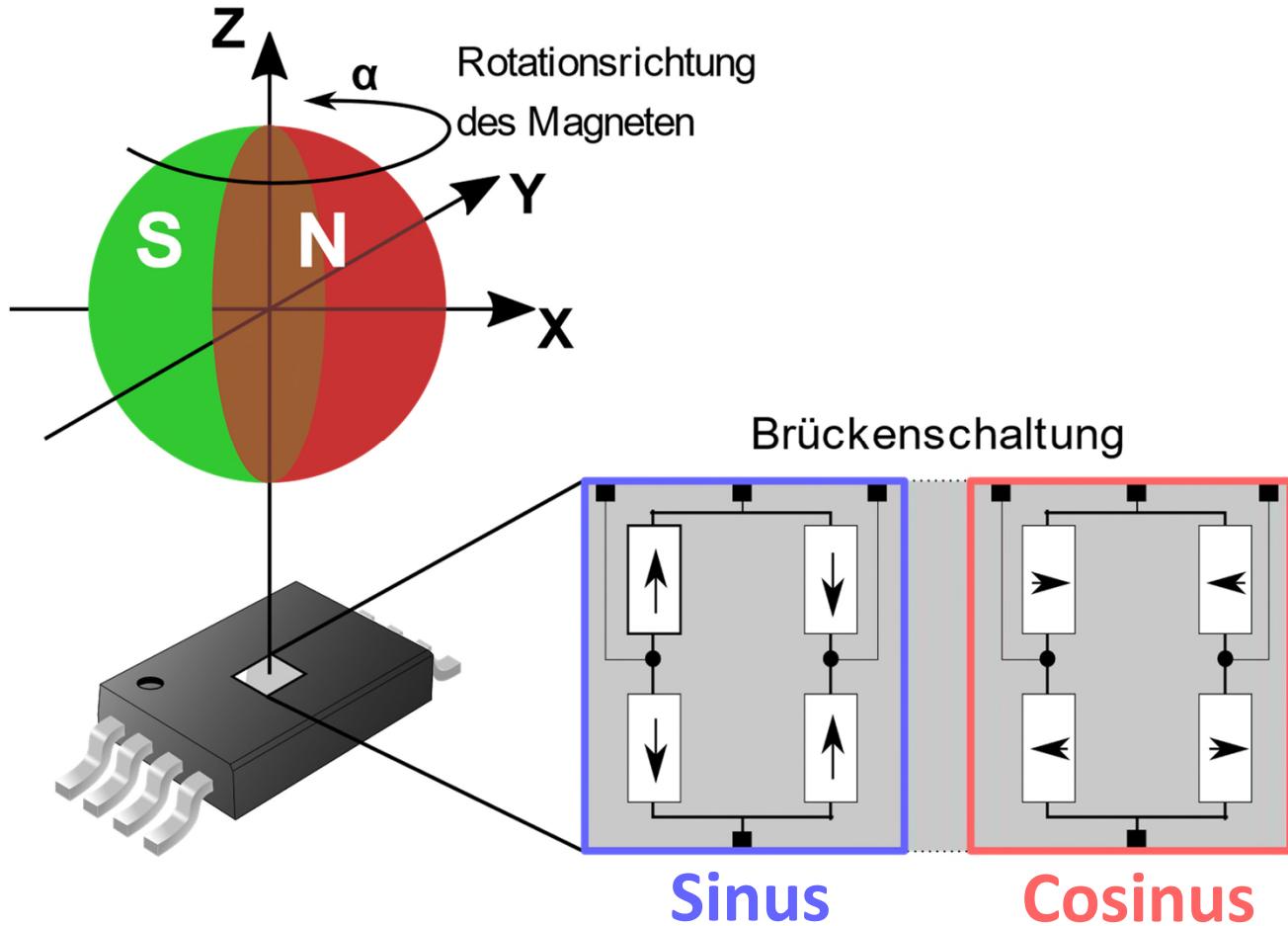
- TMR-Sensor

# Applikation



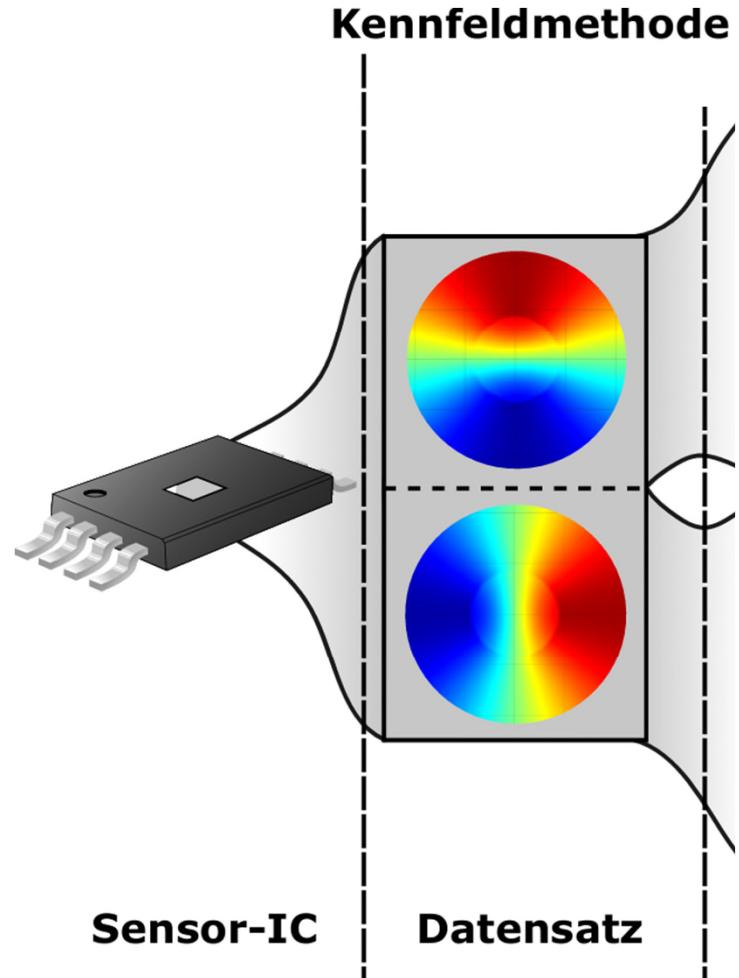
- TMR-Sensor
- Wheatstone'sche Messbrücken

# Applikation



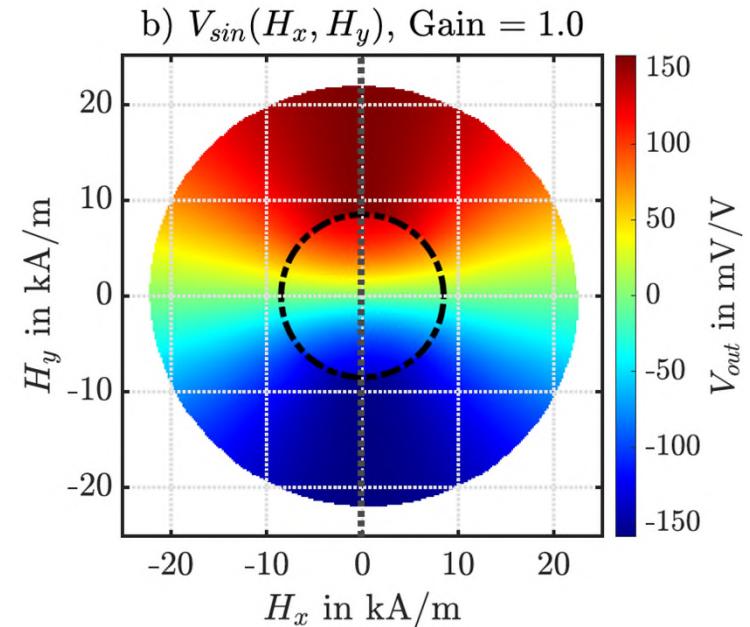
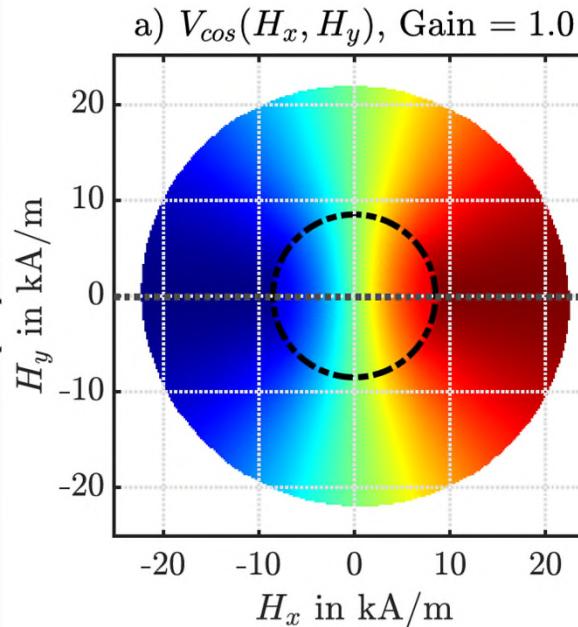
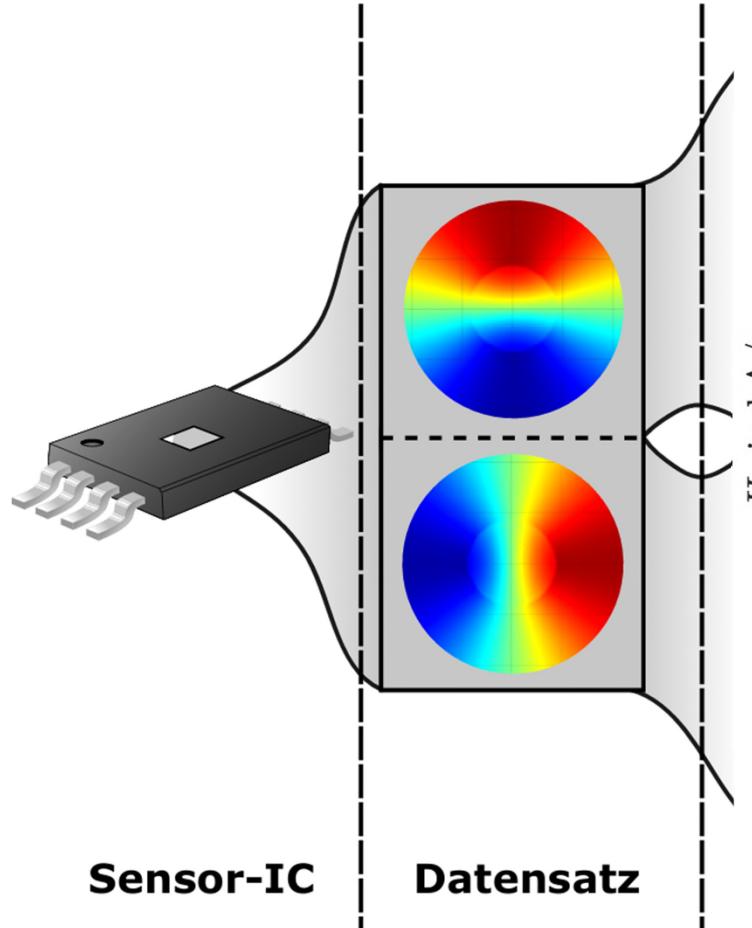
- TMR-Sensor
- Wheatstone'sche Messbrücken
- 90° verdreht zueinander
- 360° Periodizität

# Kennfelder



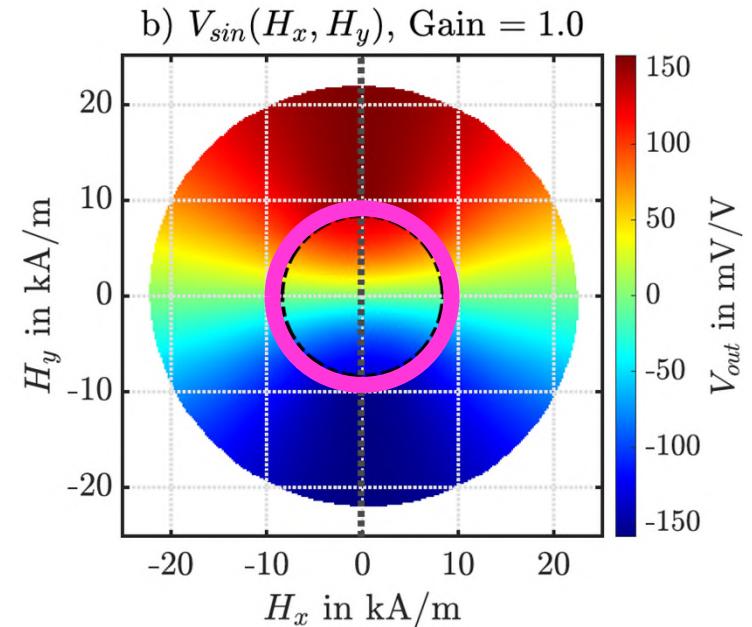
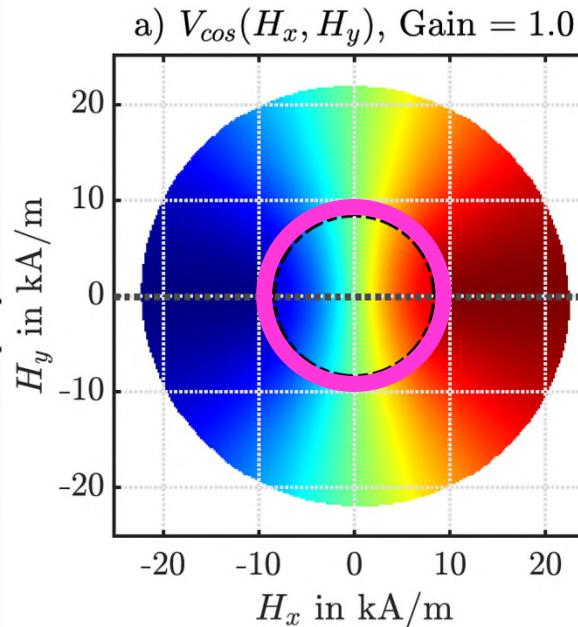
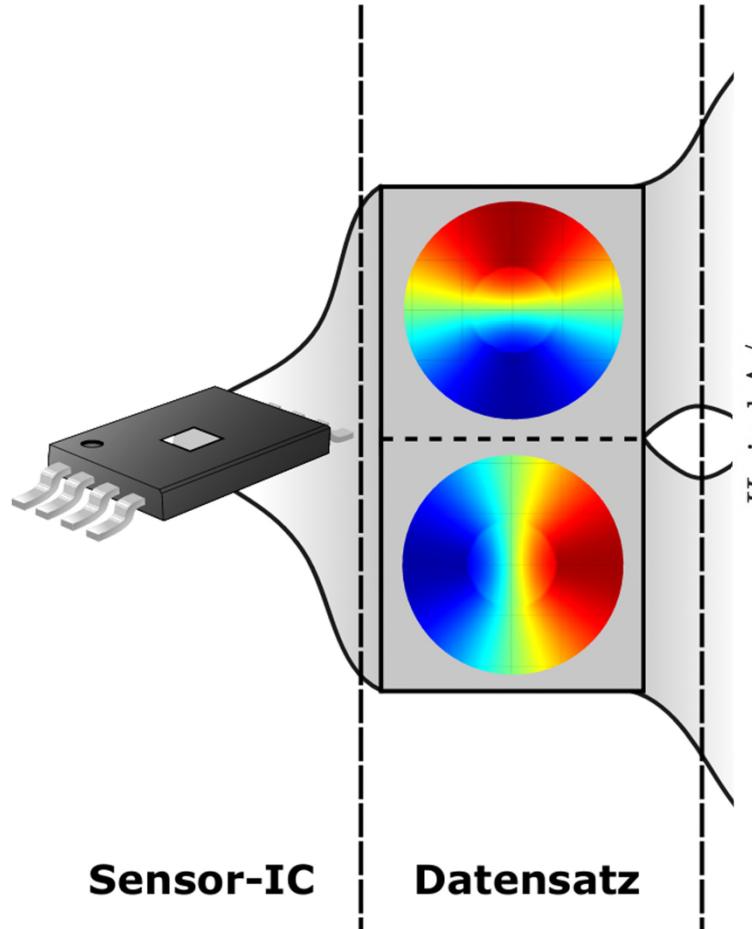
# Kennfelder

## Kennfeldmethode



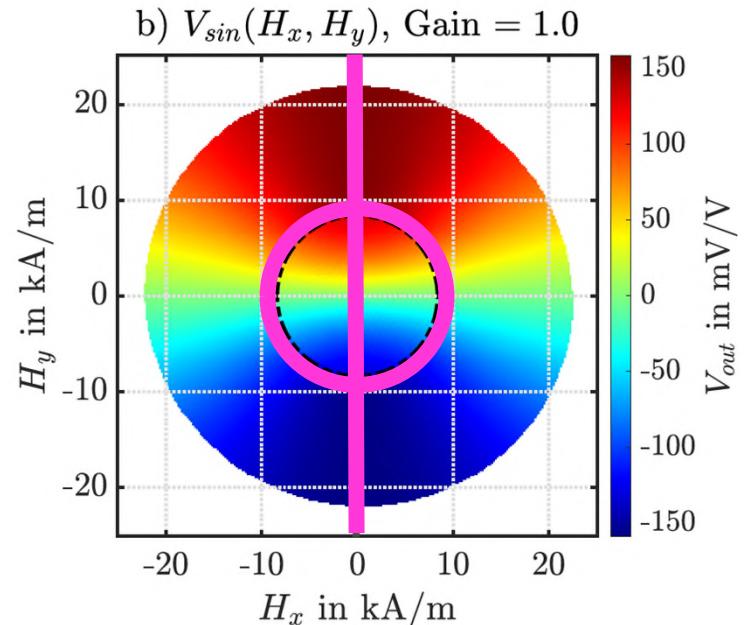
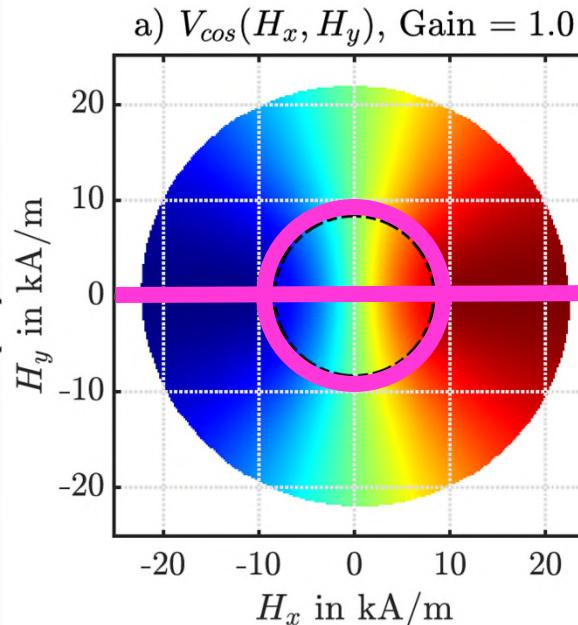
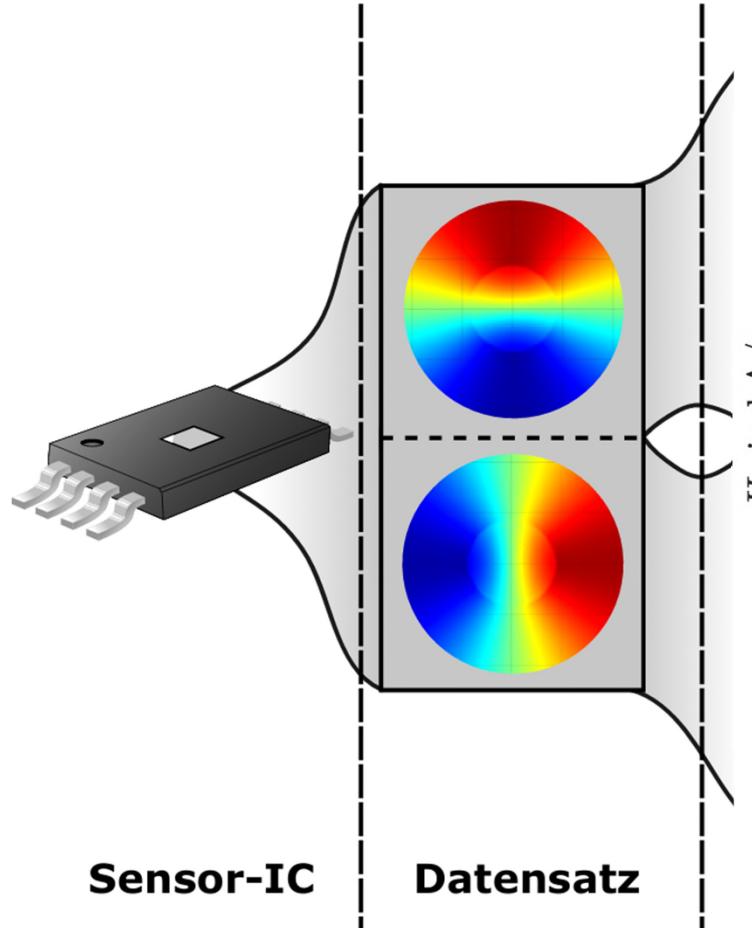
# Kennfelder

## Kennfeldmethode



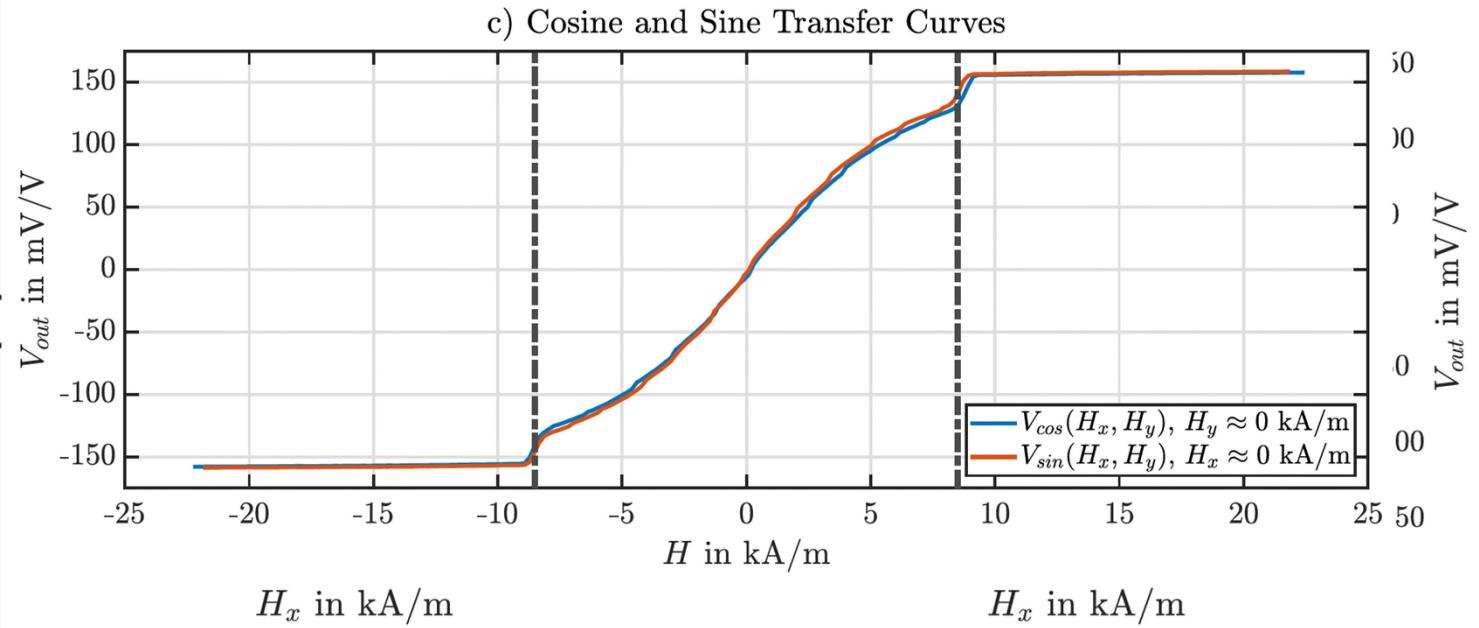
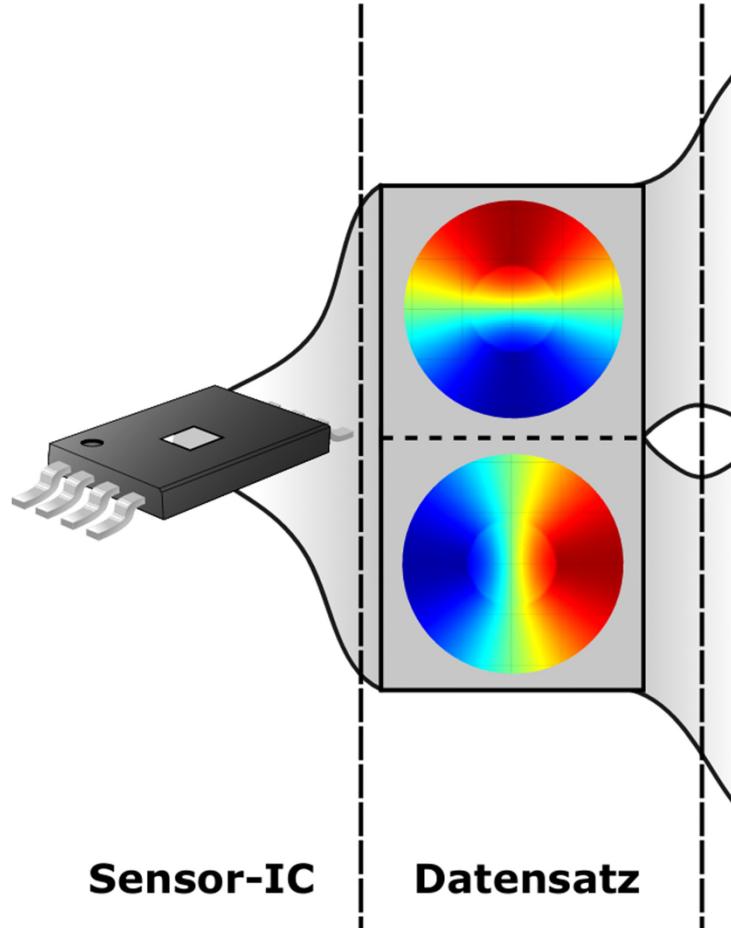
# Kennfelder

## Kennfeldmethode



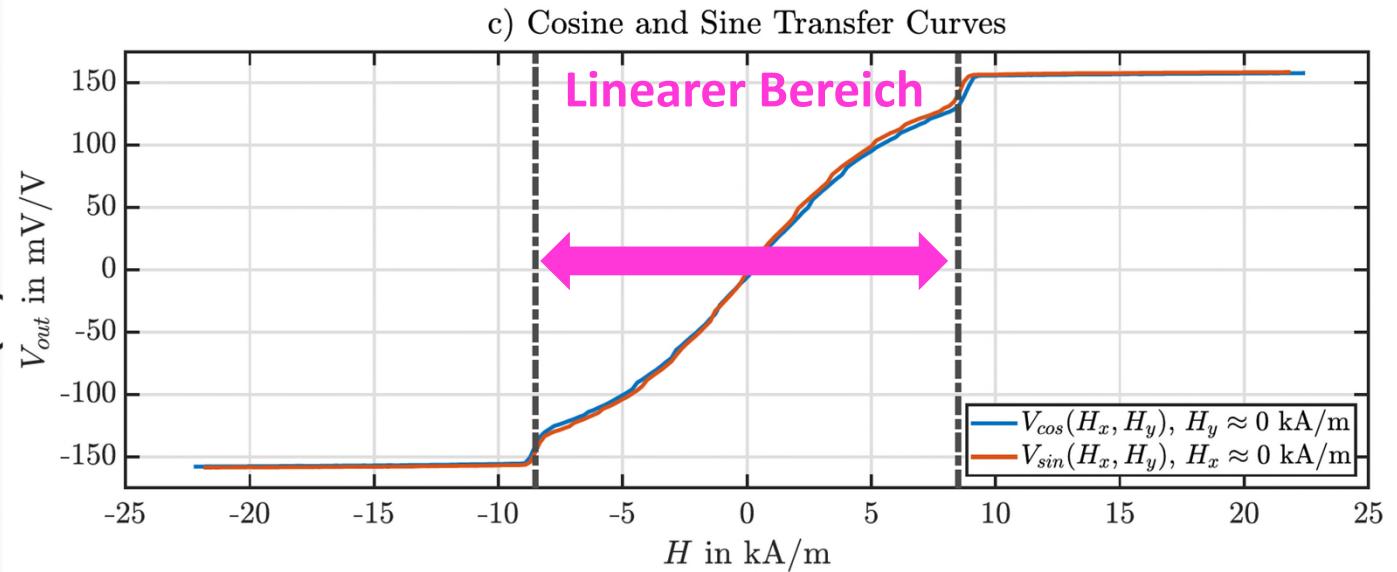
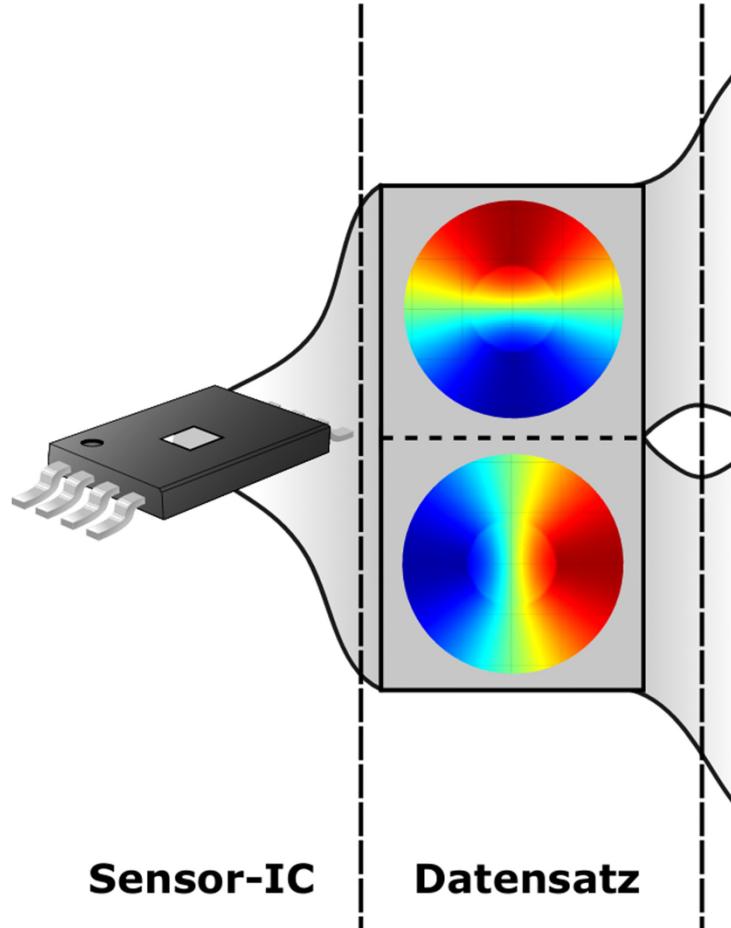
# Kennfelder

## Kennfeldmethode

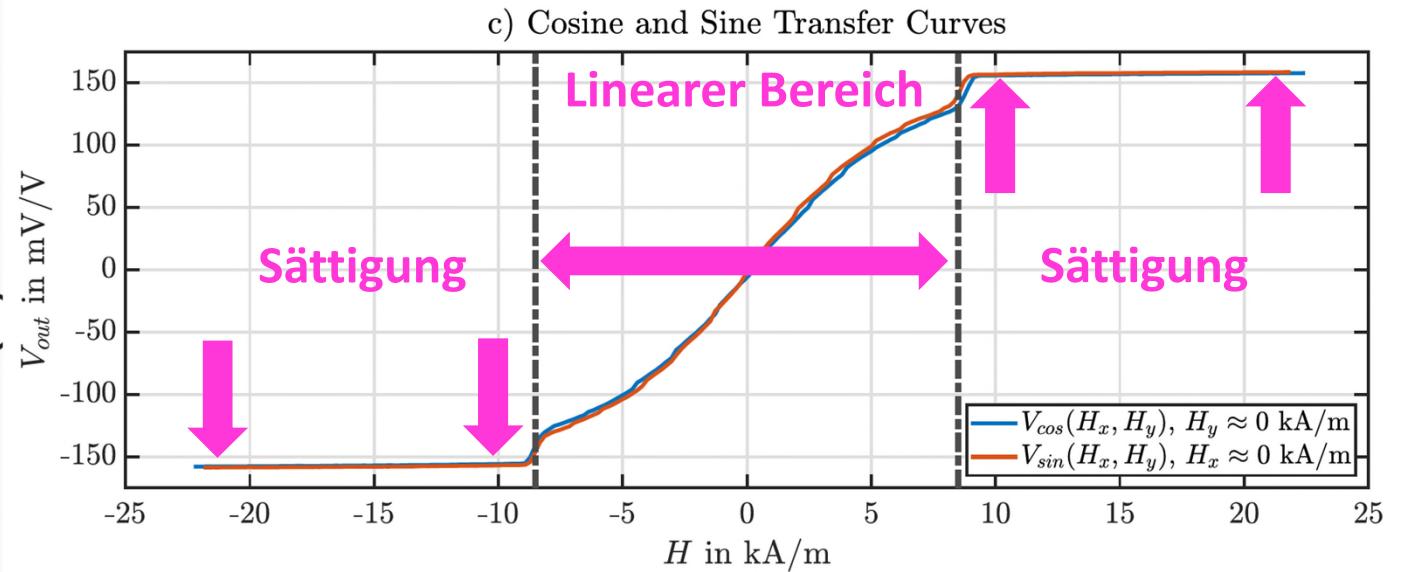
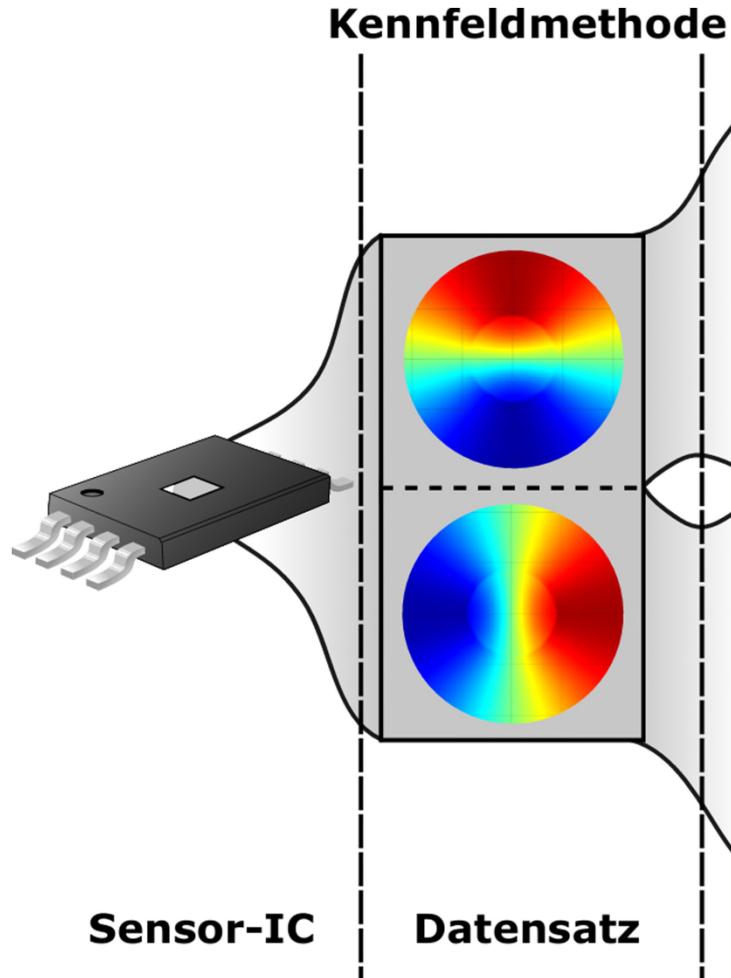


# Kennfelder

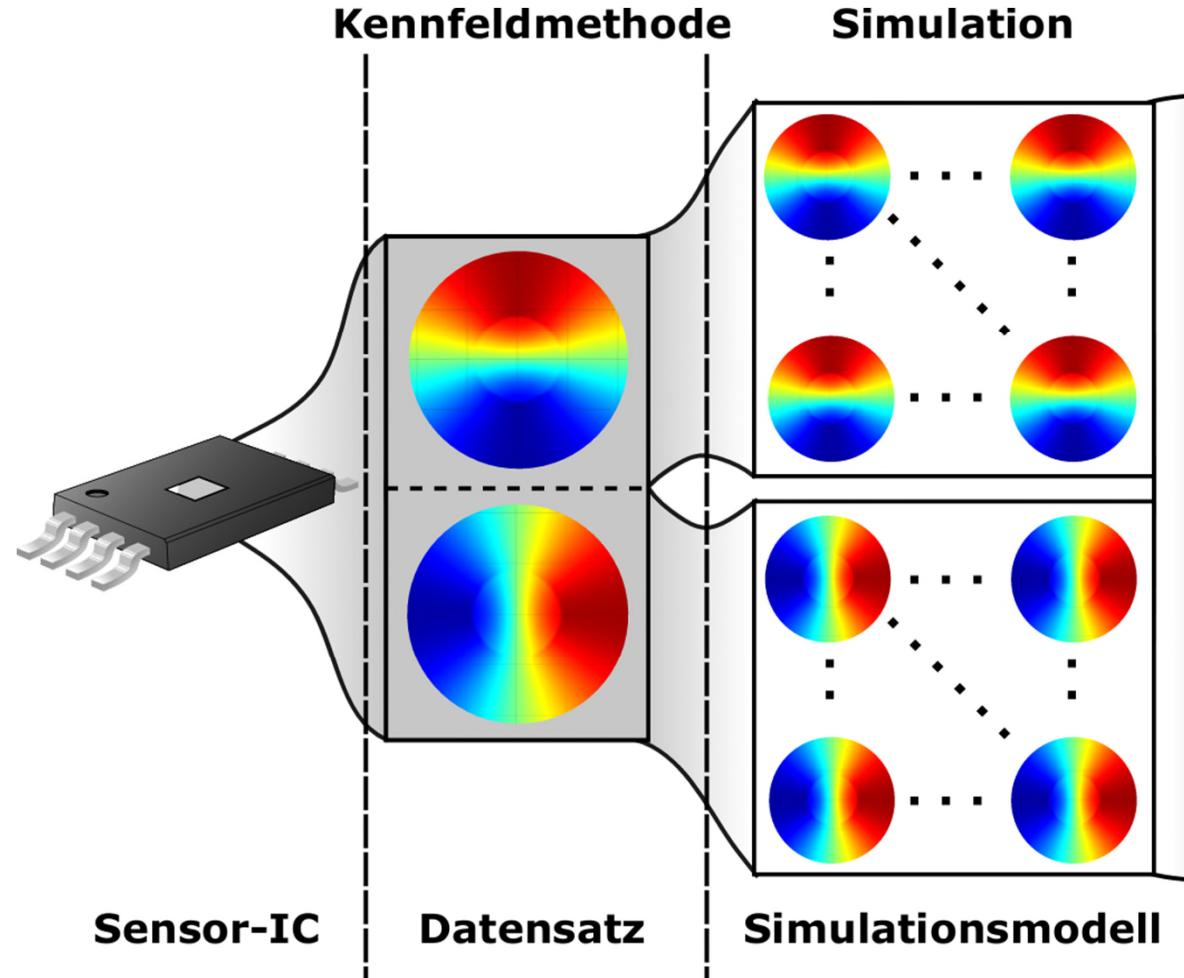
## Kennfeldmethode



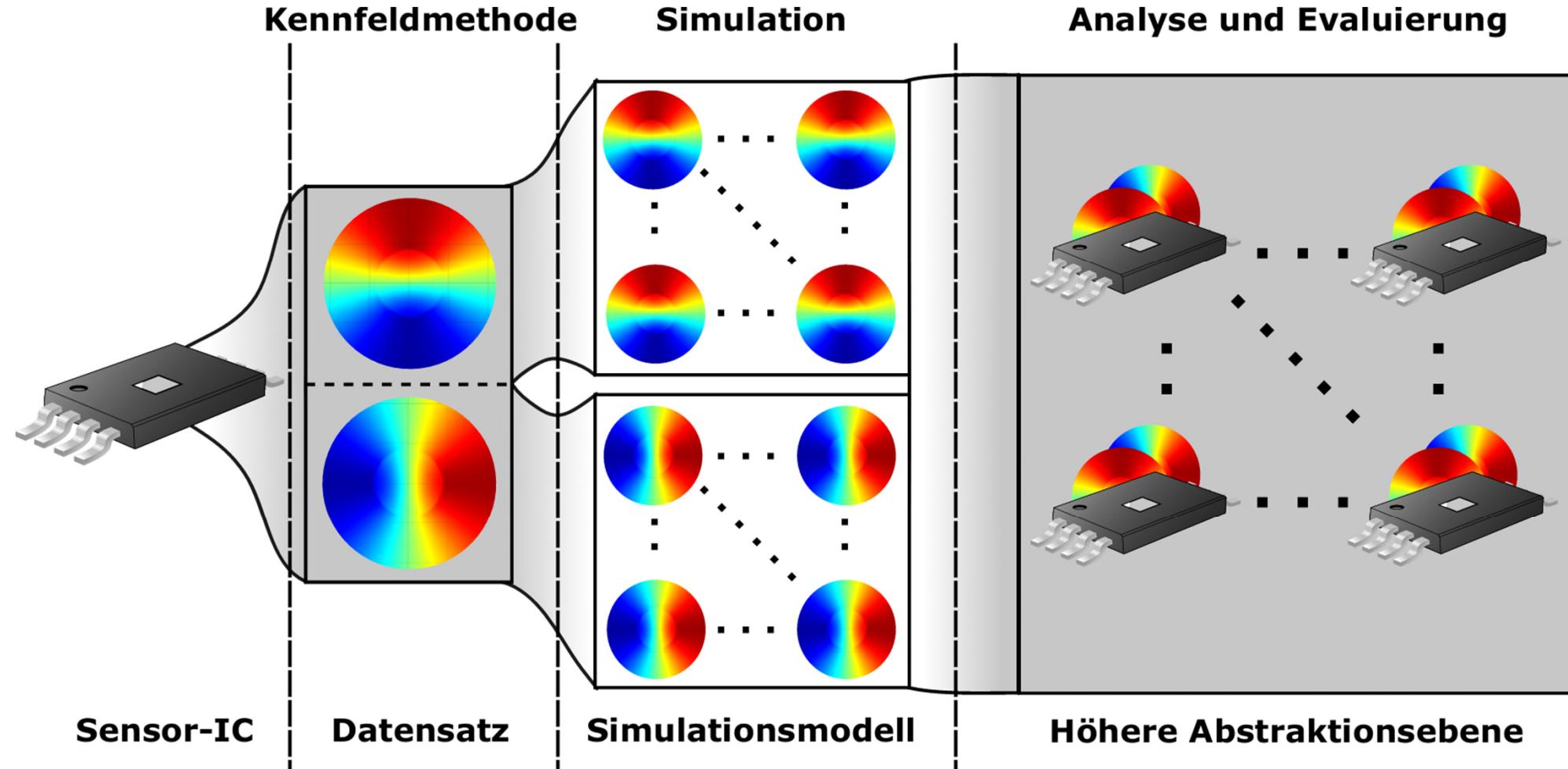
# Kennfelder



# Kennfelder

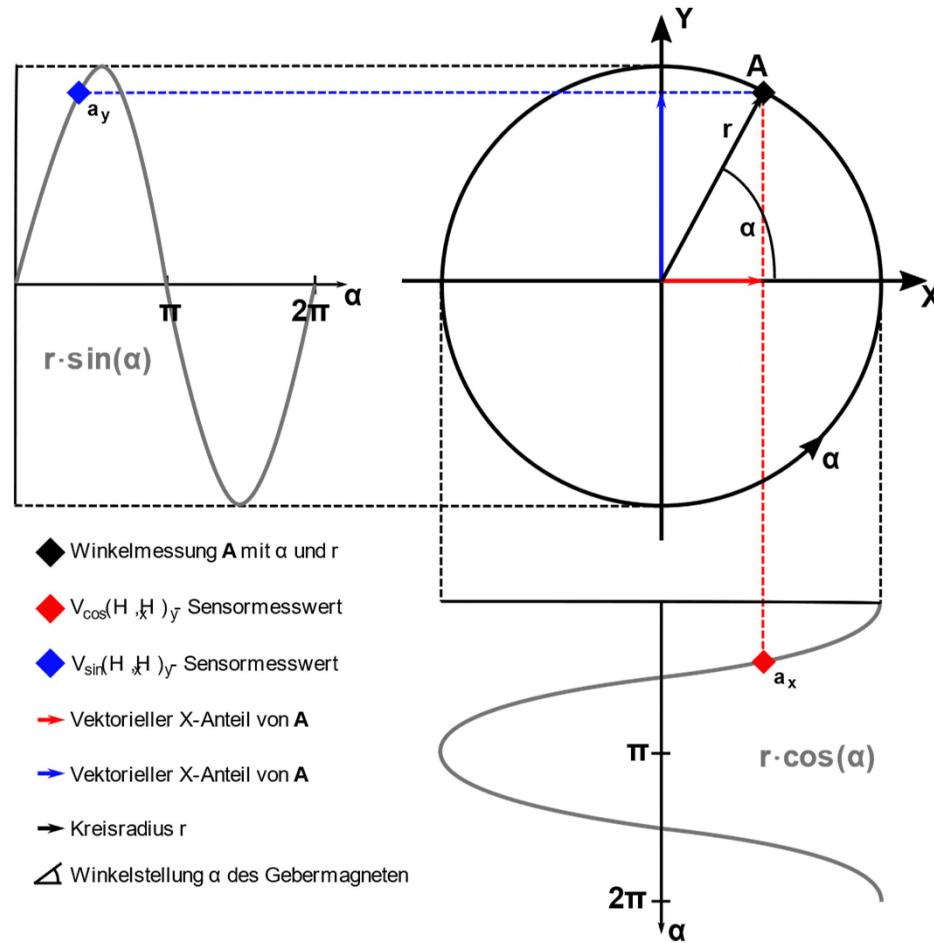


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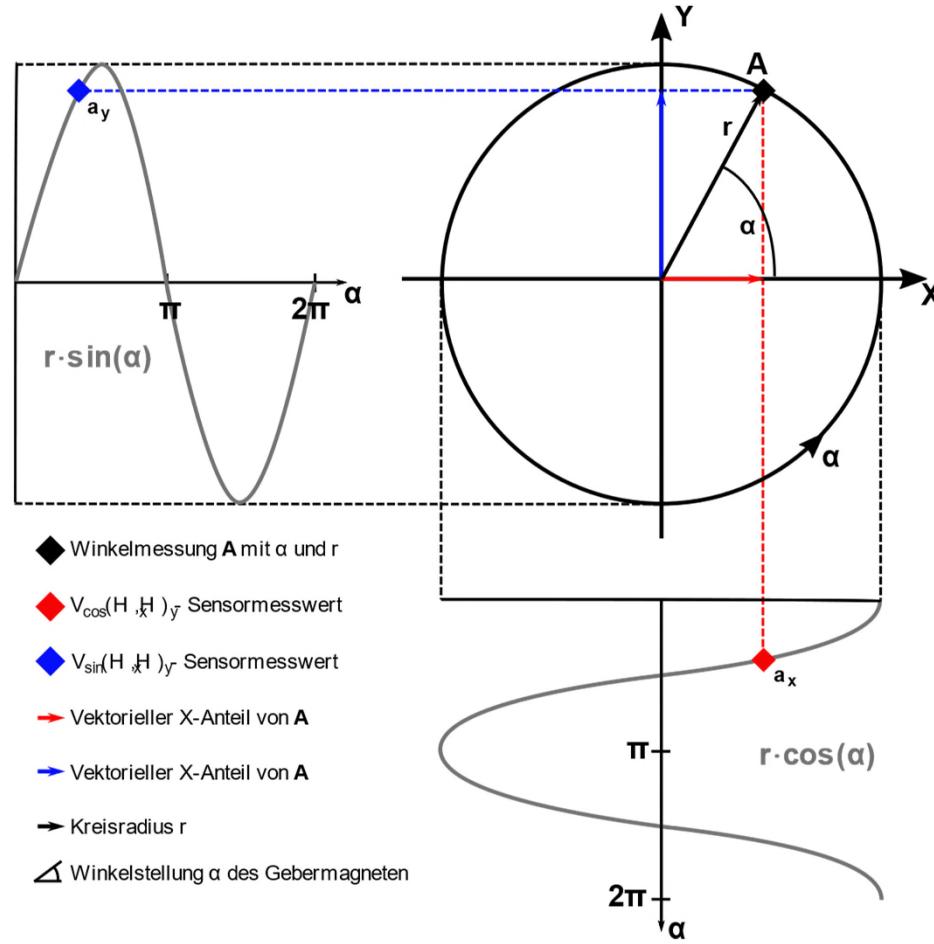
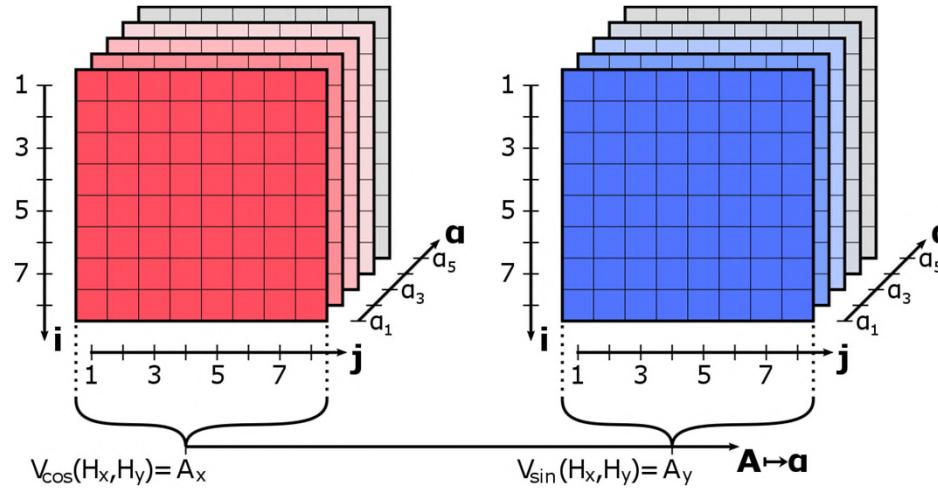


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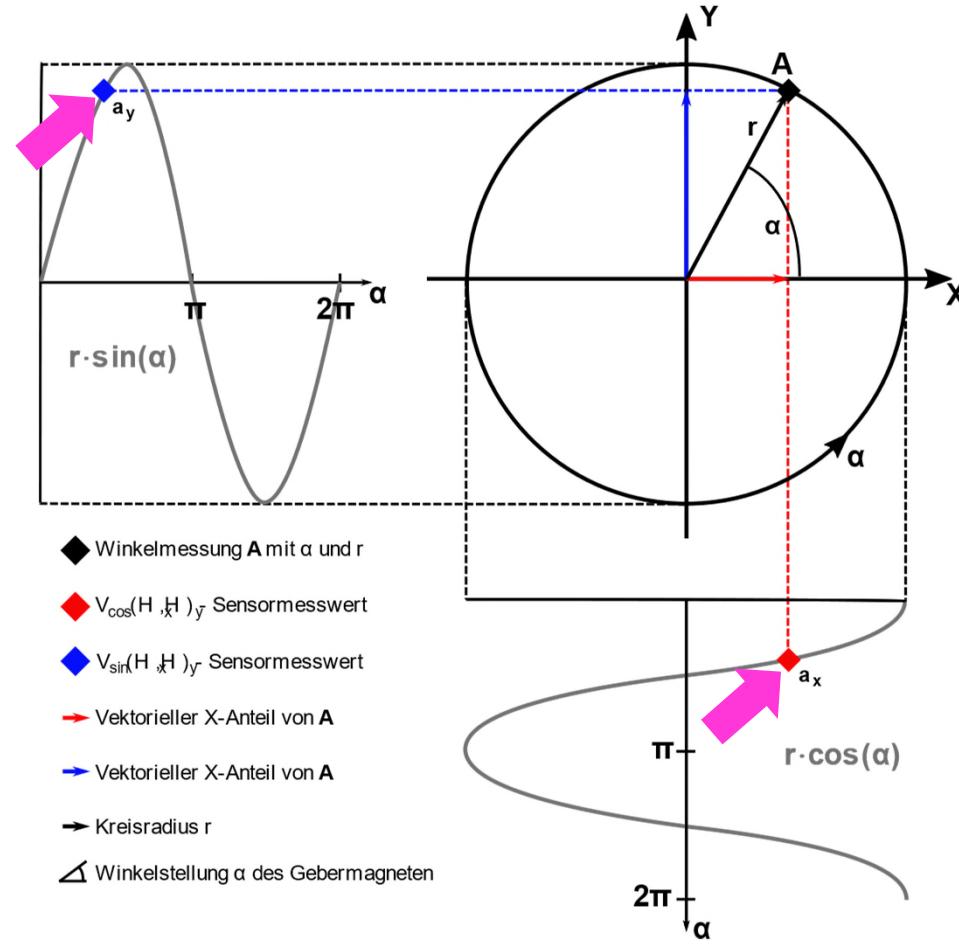
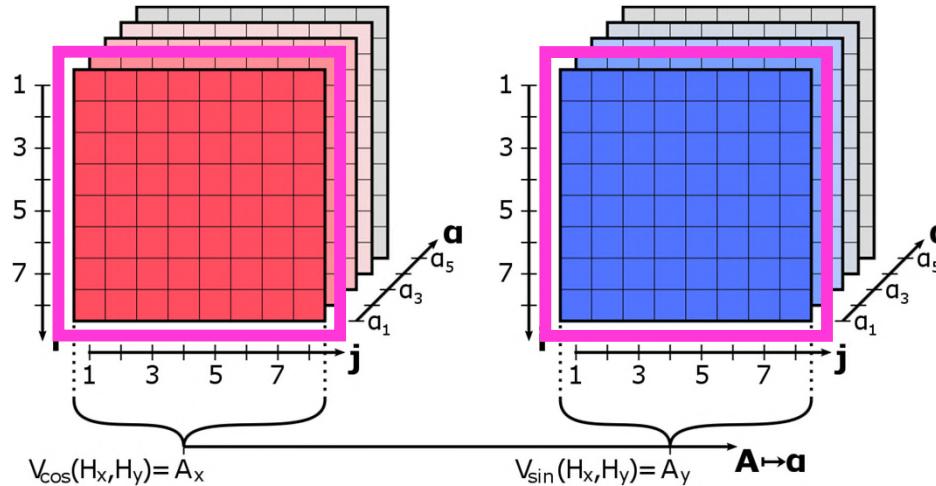
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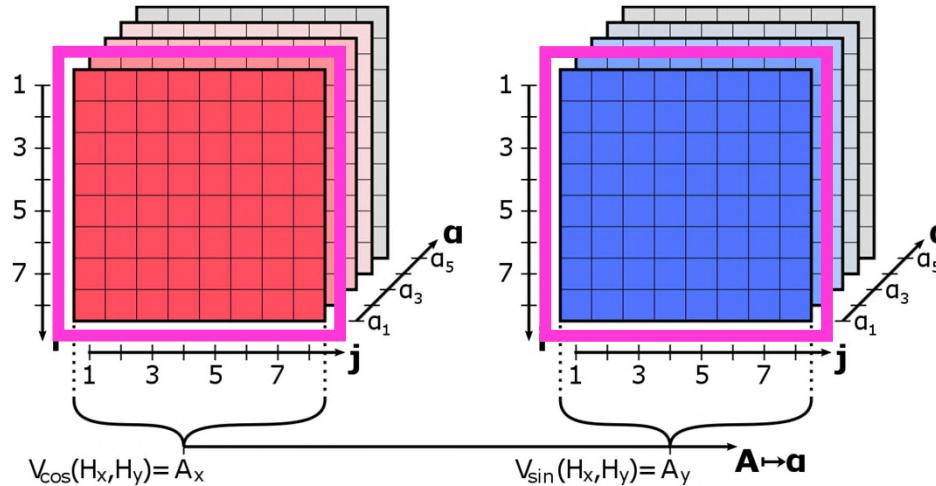
# Datenadaption



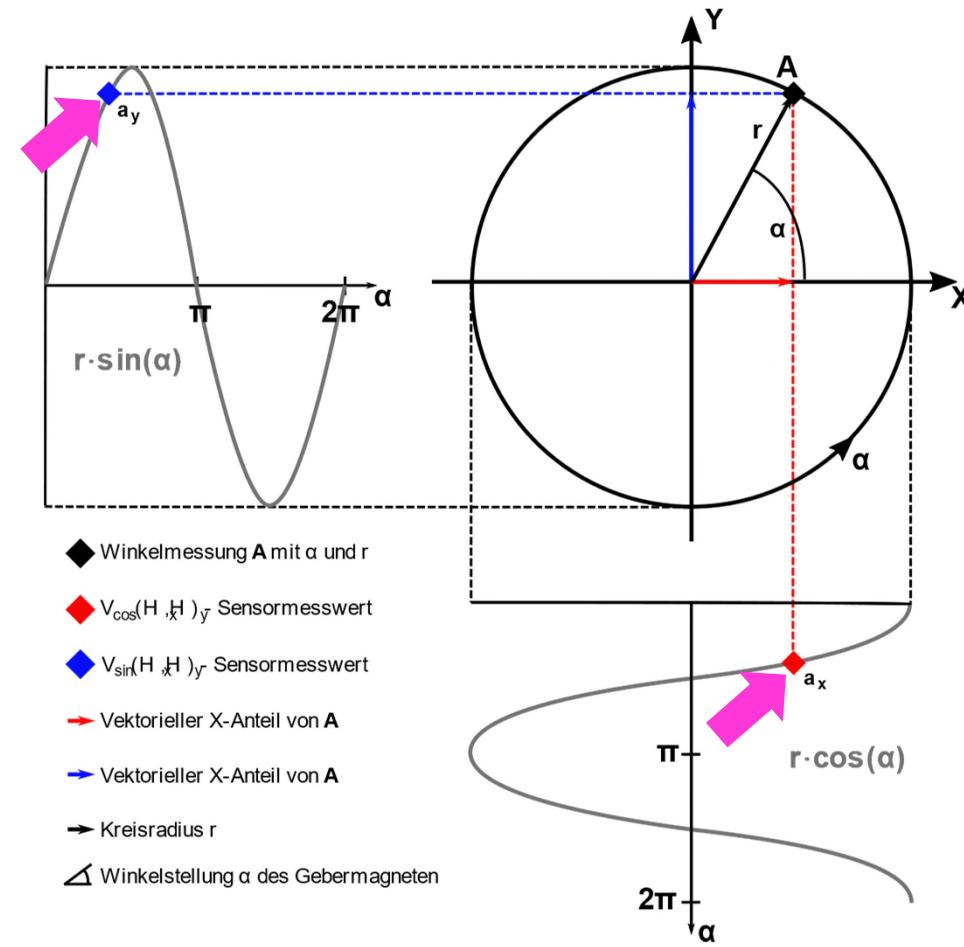
# Datenadaption



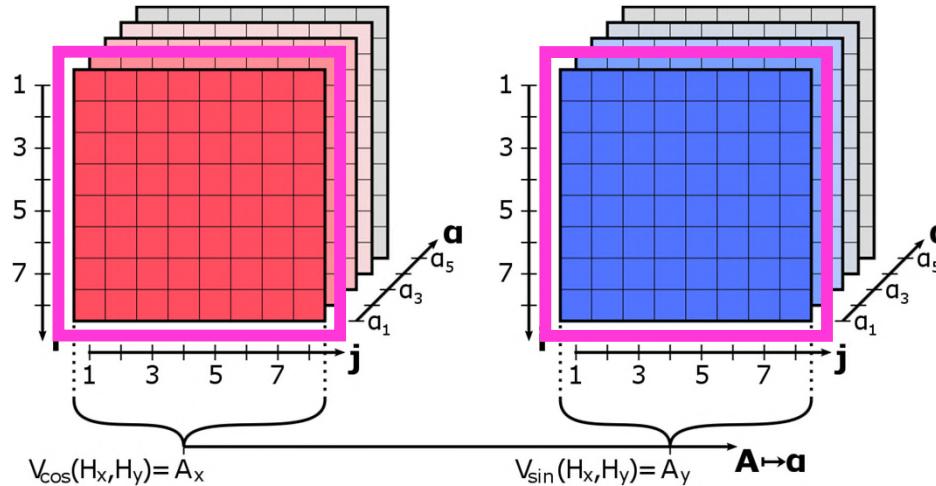
# Datenadaption



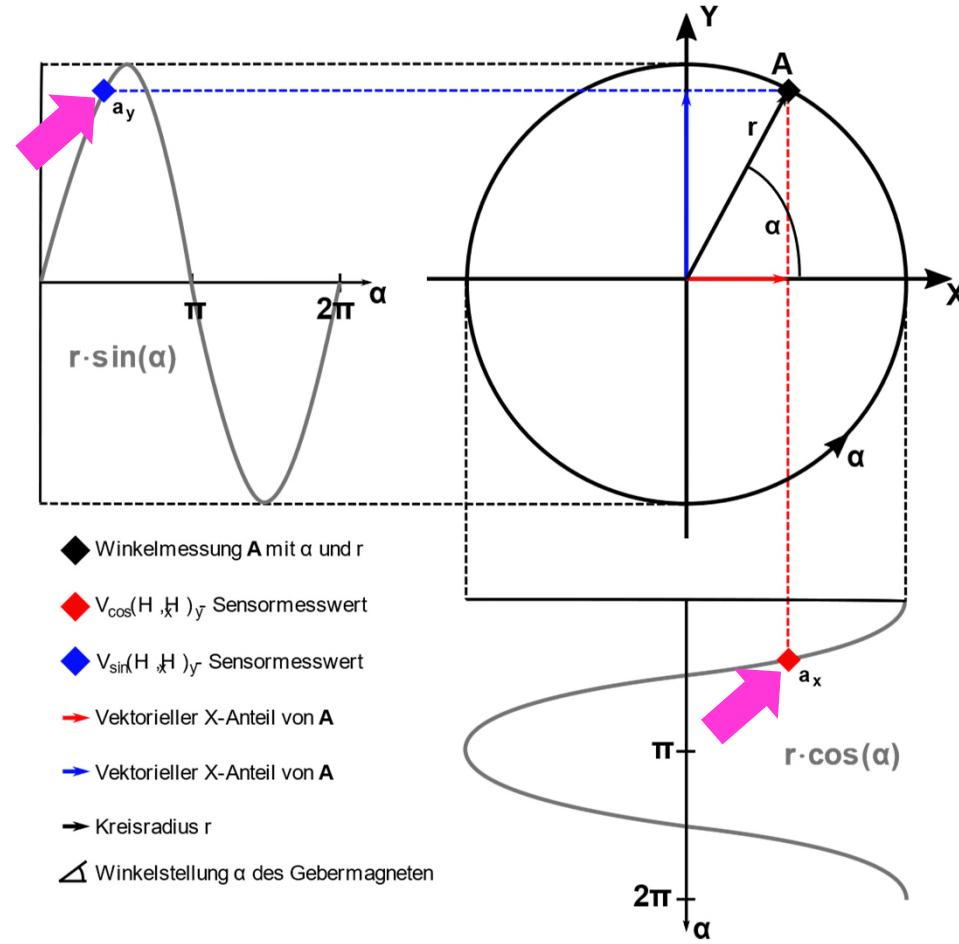
- Arrays als lange Vektoren



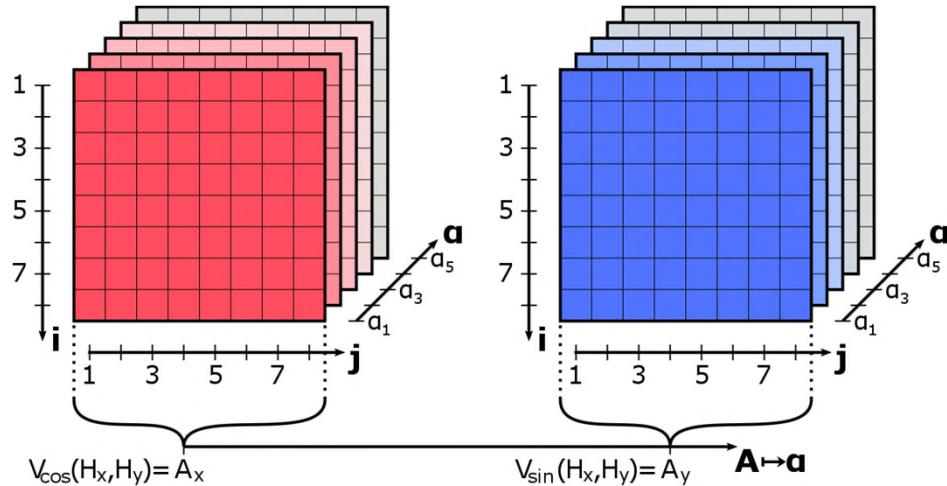
# Datenadaption



- Arrays als lange Vektoren
- Frobenius-Norm

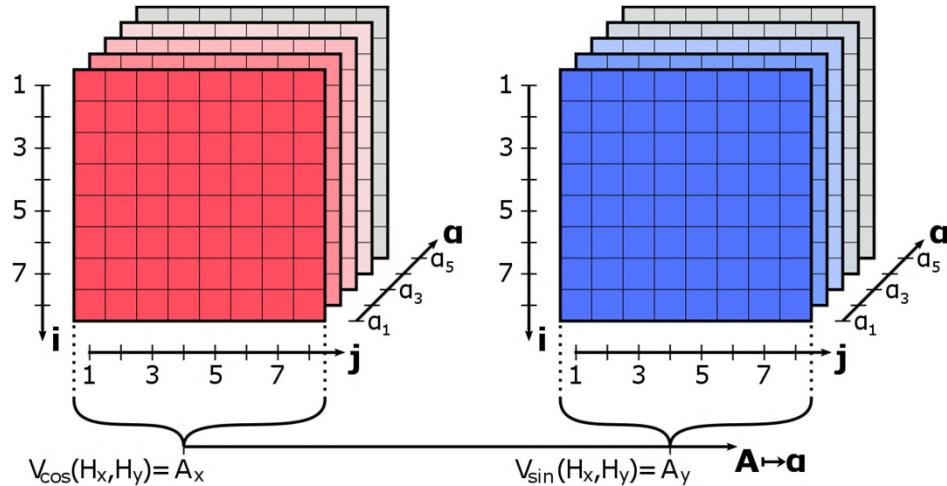


# Gauß-Prozesse



# Gauß-Prozesse

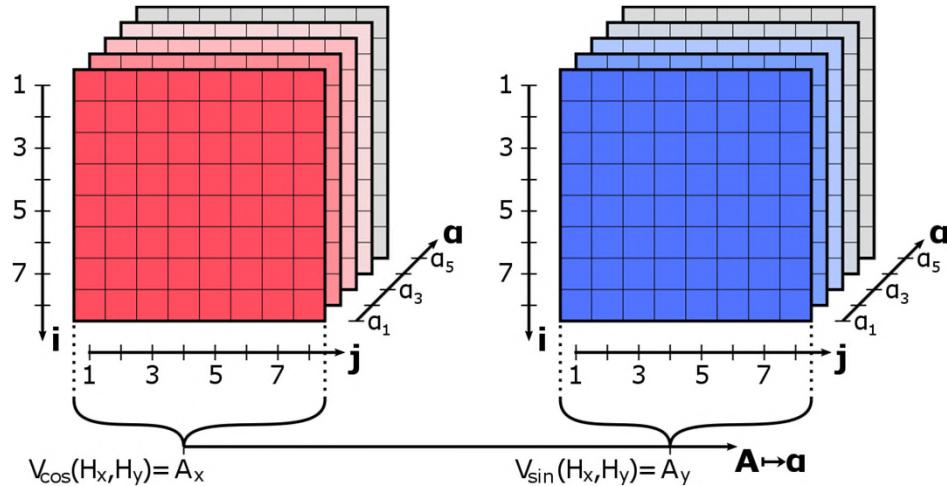
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- Lernen über Trainingsdaten

# Gauß-Prozesse

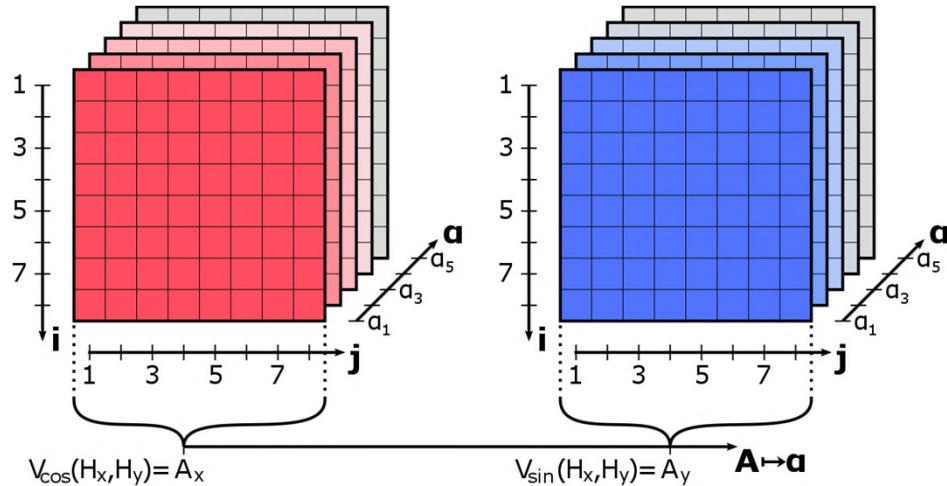
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- Lernen über Trainingsdaten
- Anpassung über Testdaten
- Optimieren über Parameter

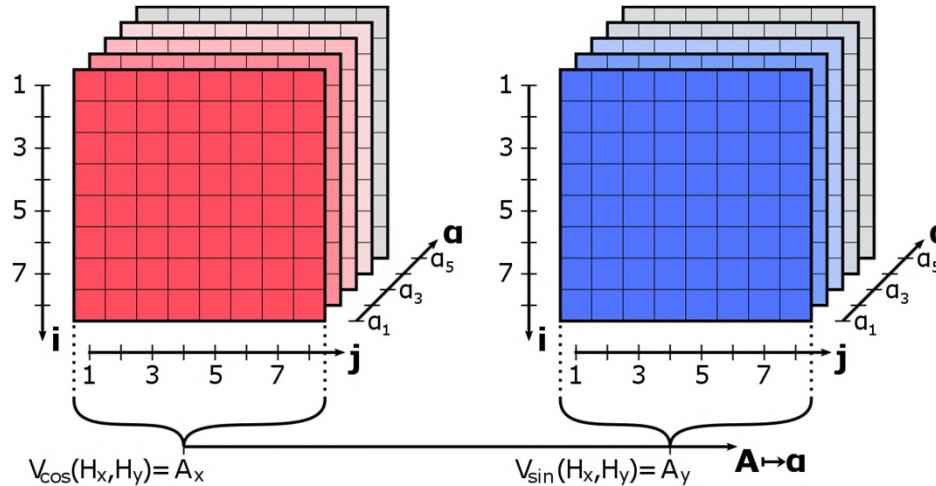
# Gauß-Prozesse

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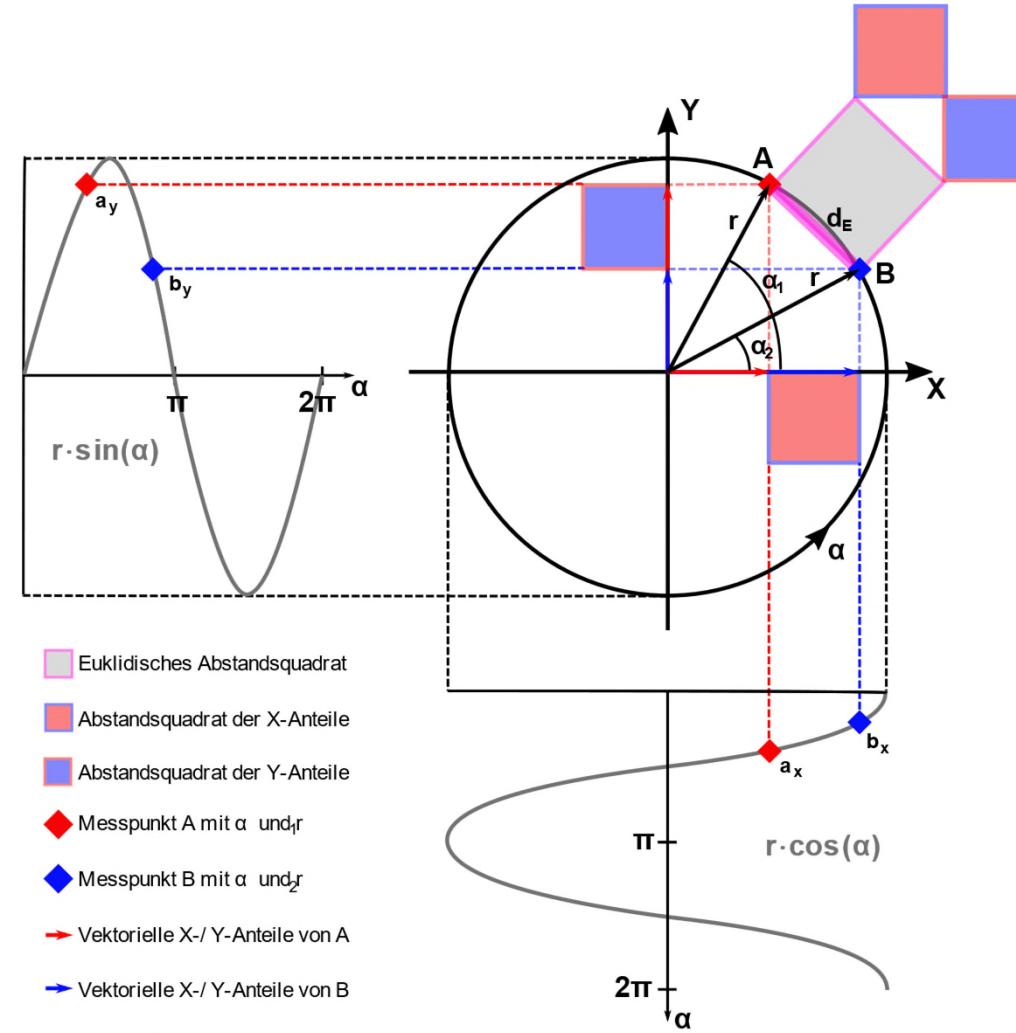


- Lernen über Trainingsdaten
- Anpassung über Testdaten
- Optimieren über Parameter
- Vorhersage durch Stützwerte

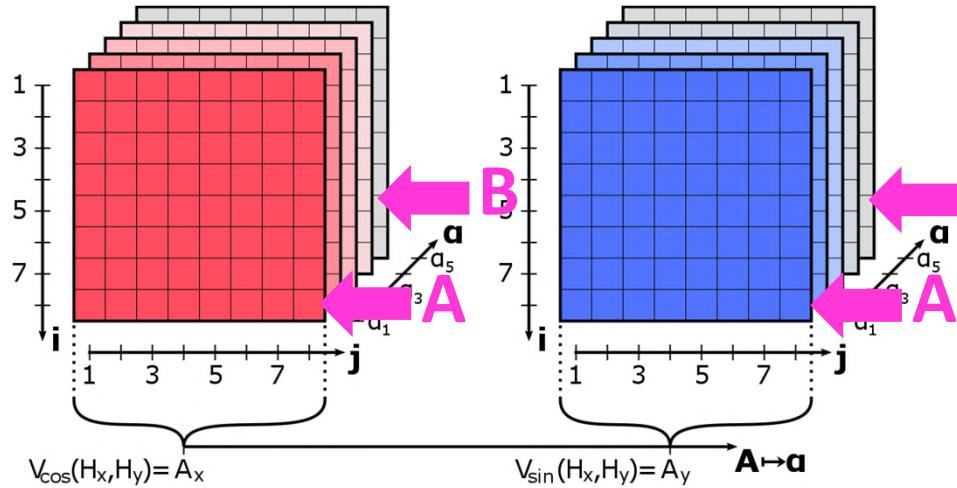
# Gauß-Prozesse



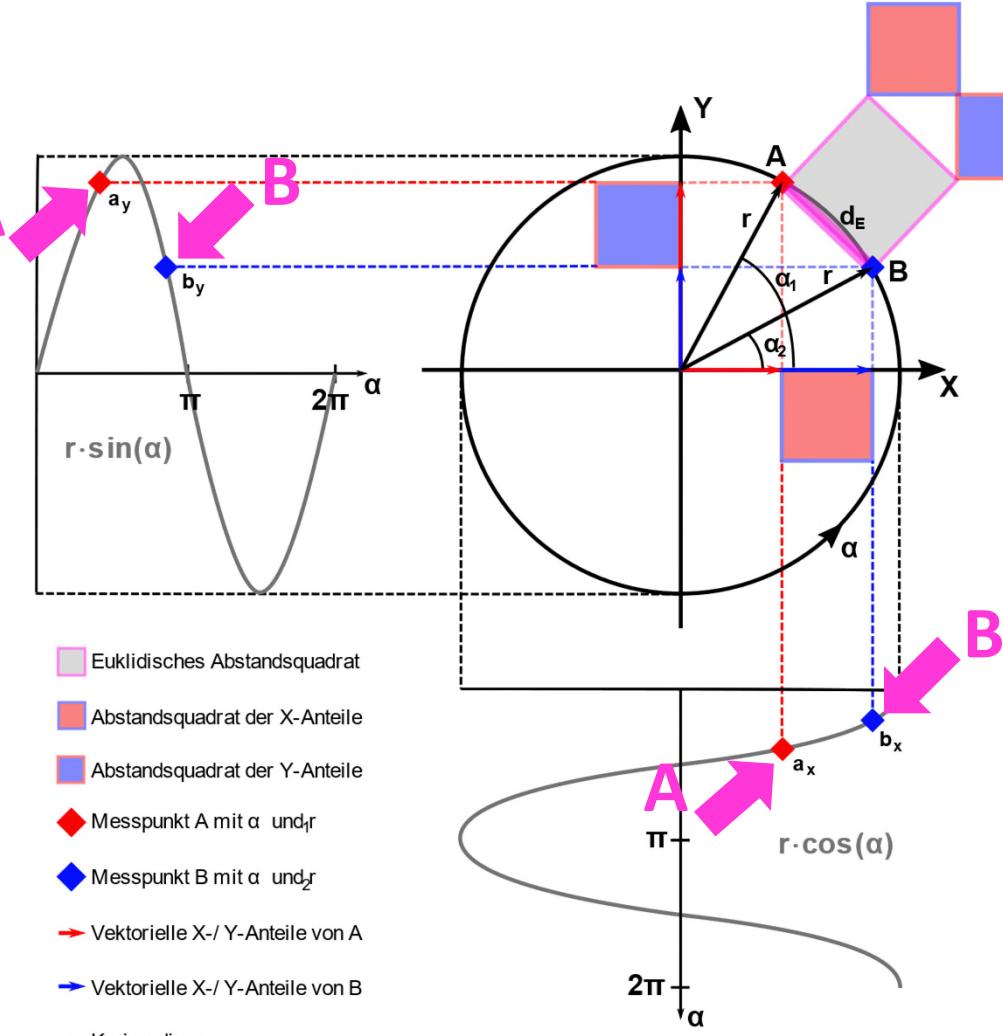
$$d_x^2 \langle A, B \rangle$$



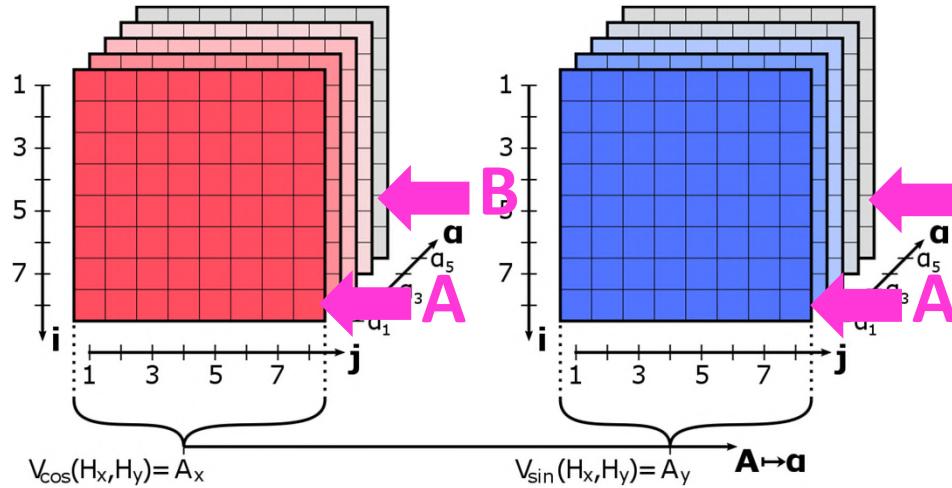
# Gauß-Prozesse



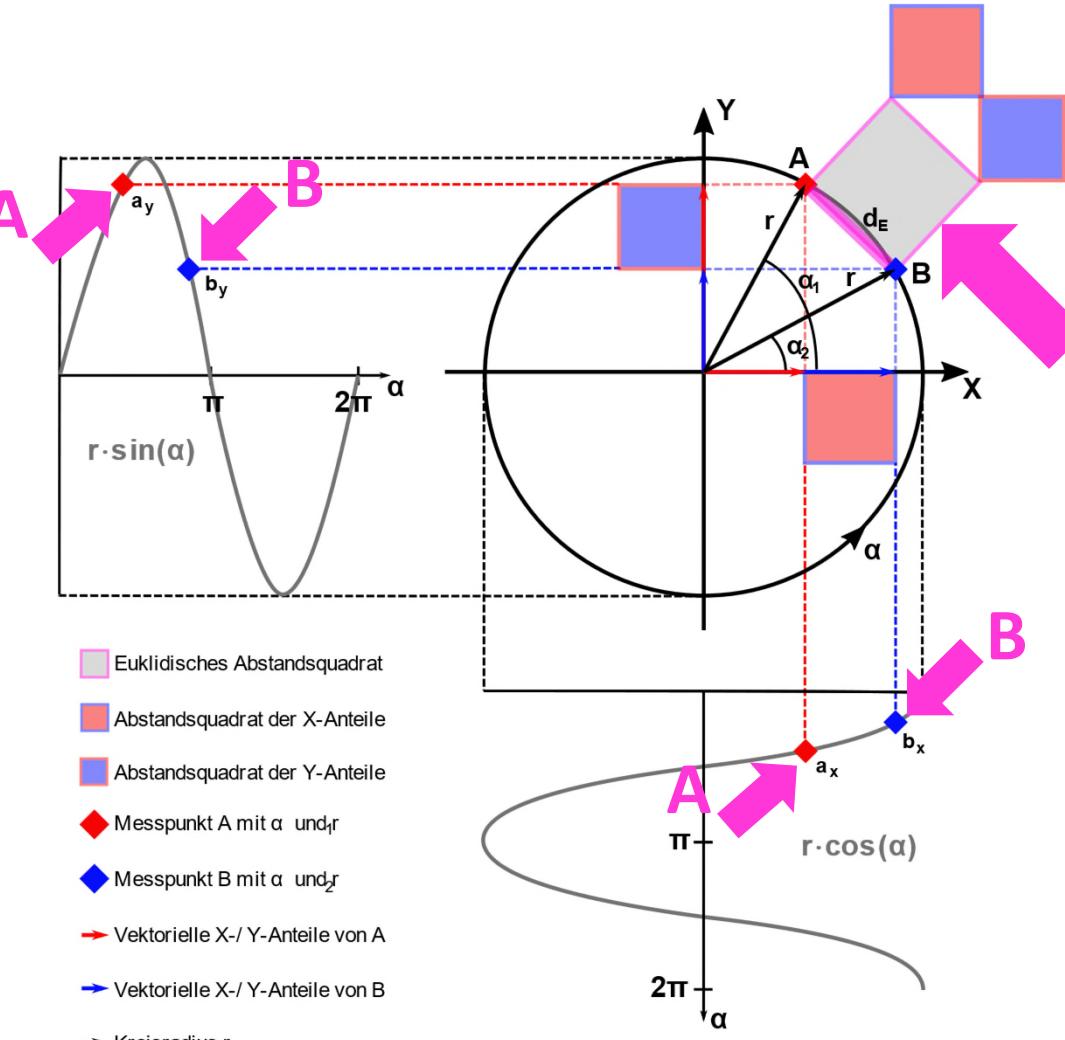
$$d_x^2 \langle A, B \rangle$$



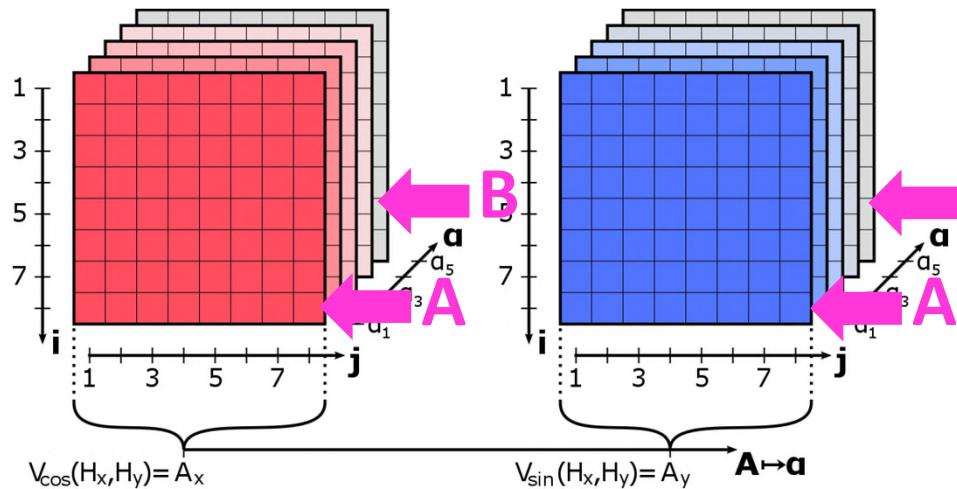
# Gauß-Prozesse



$$d_x^2 \langle A, B \rangle$$

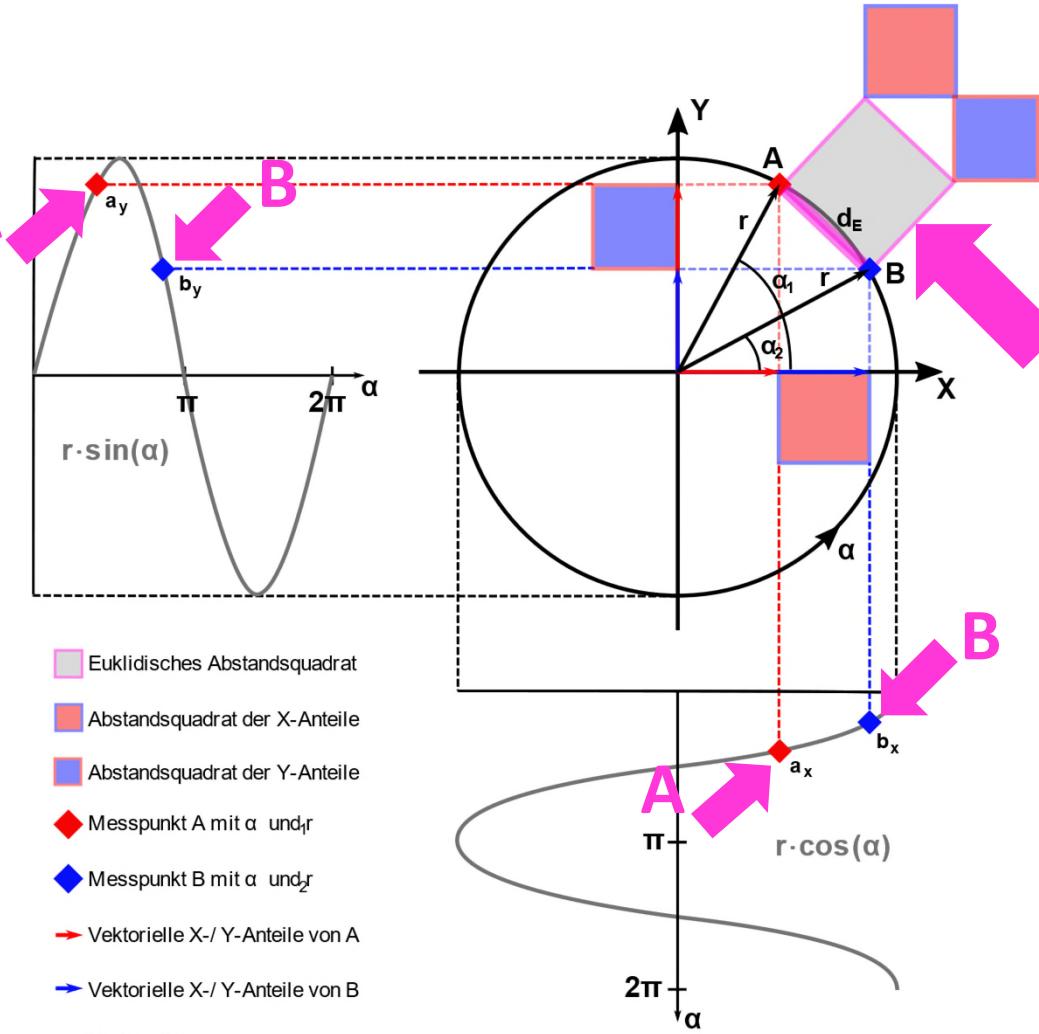


# Gauß-Prozesse

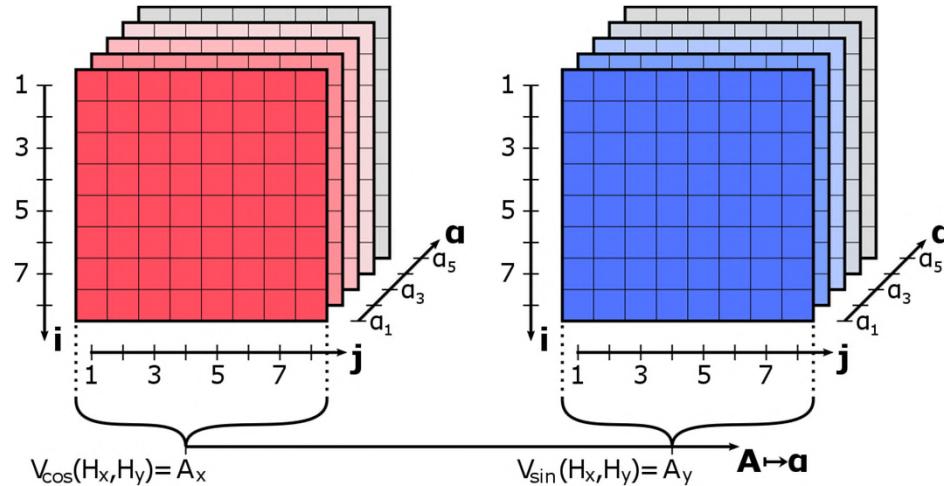


## Fractional Kernel

$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$

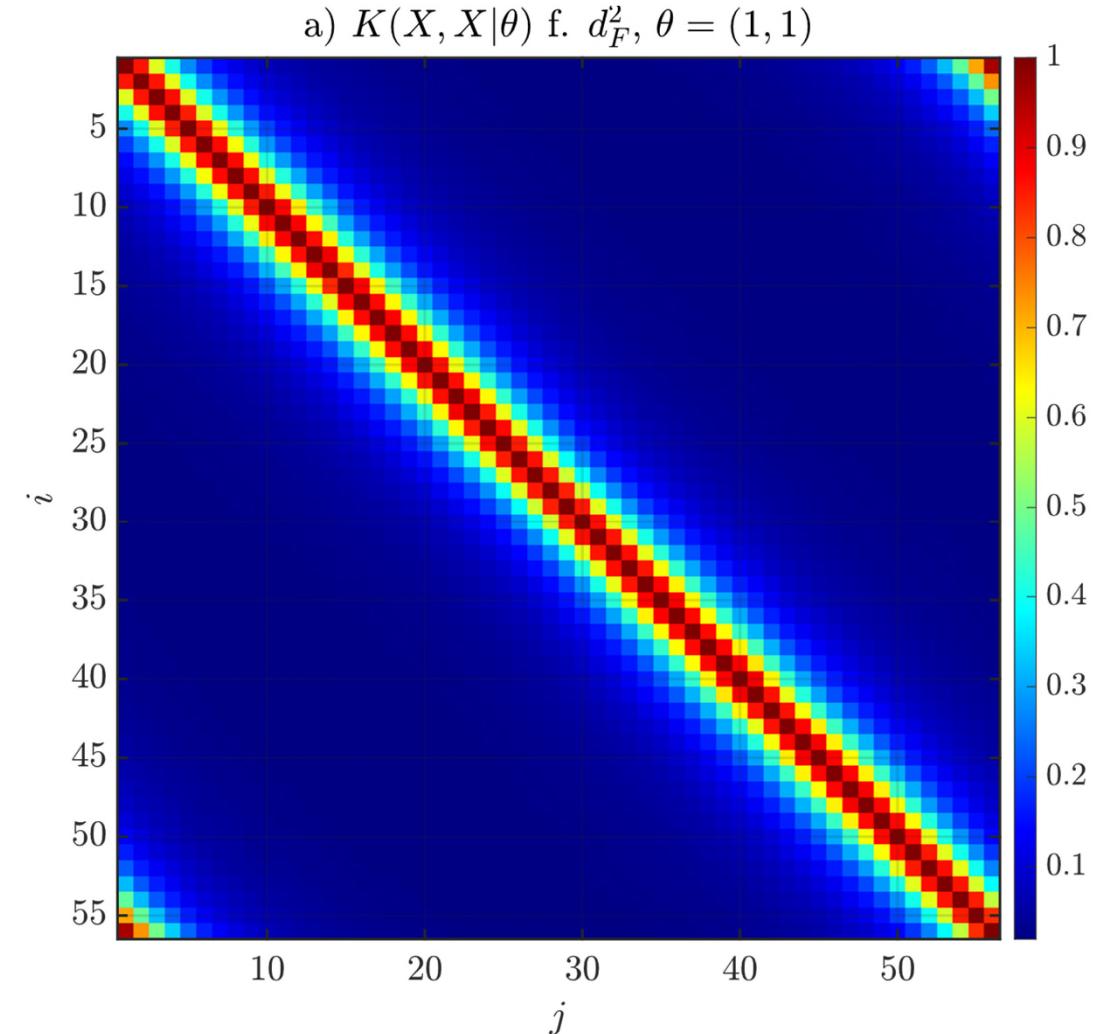


# Gauß-Prozesse

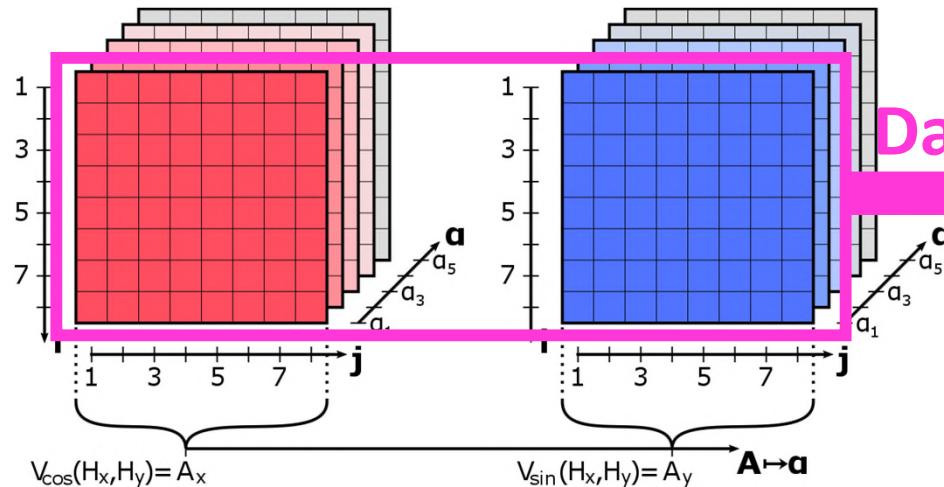


Fractional Kernel

$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$

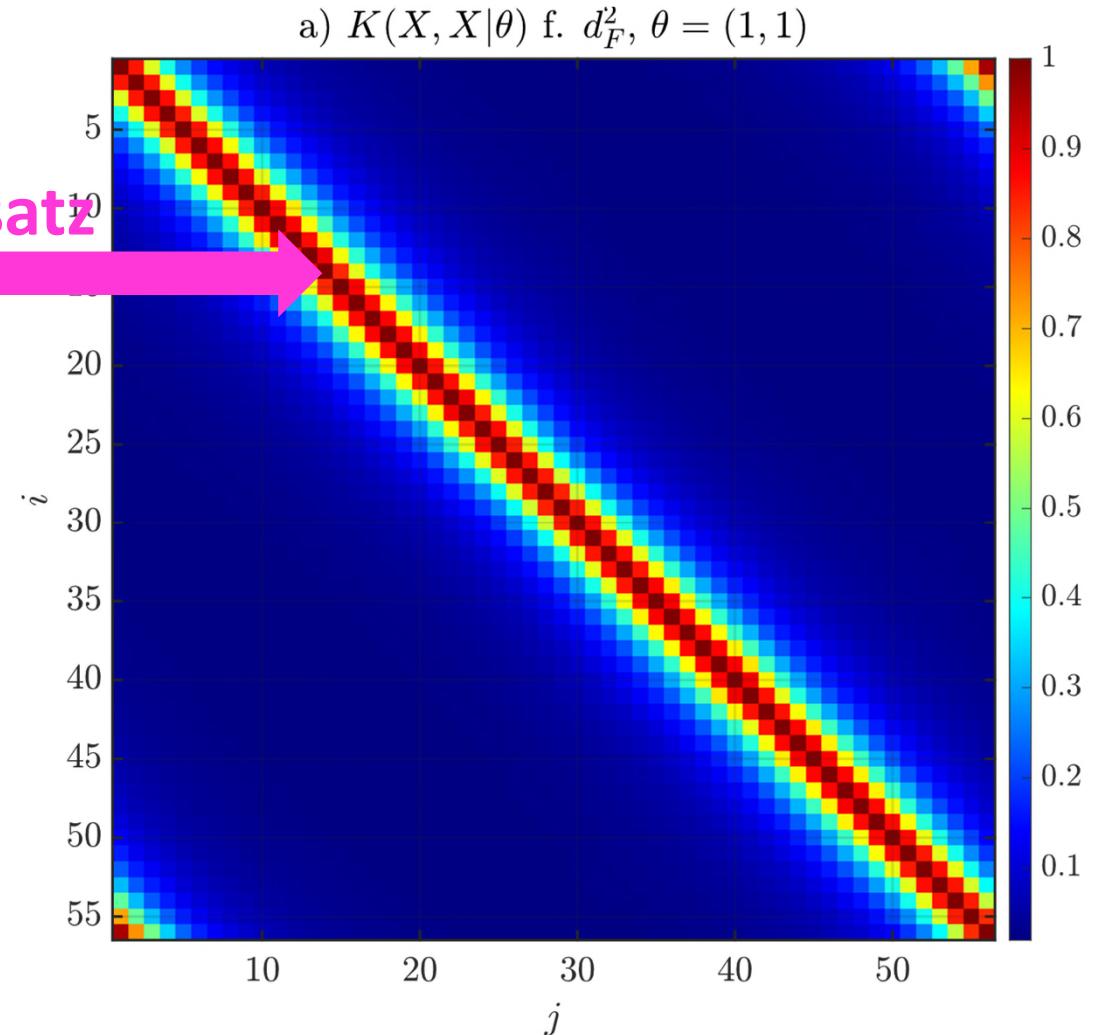


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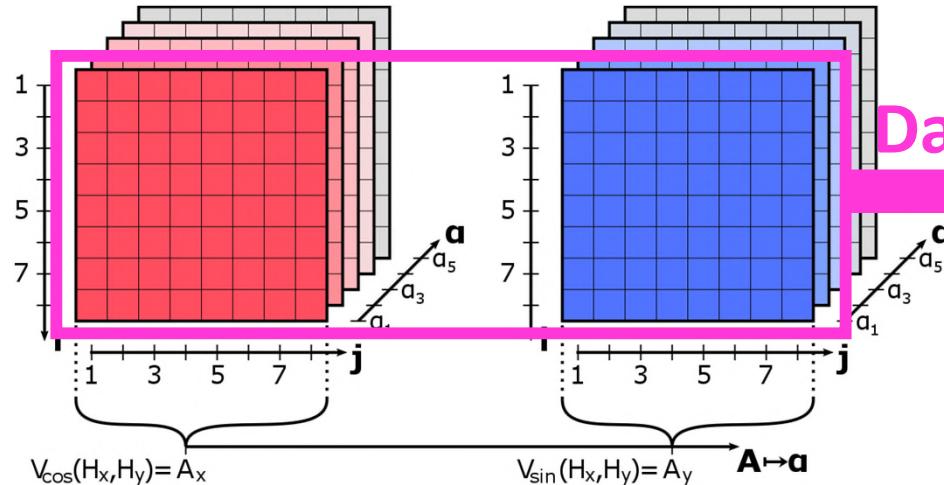


Fractional Kernel

$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$

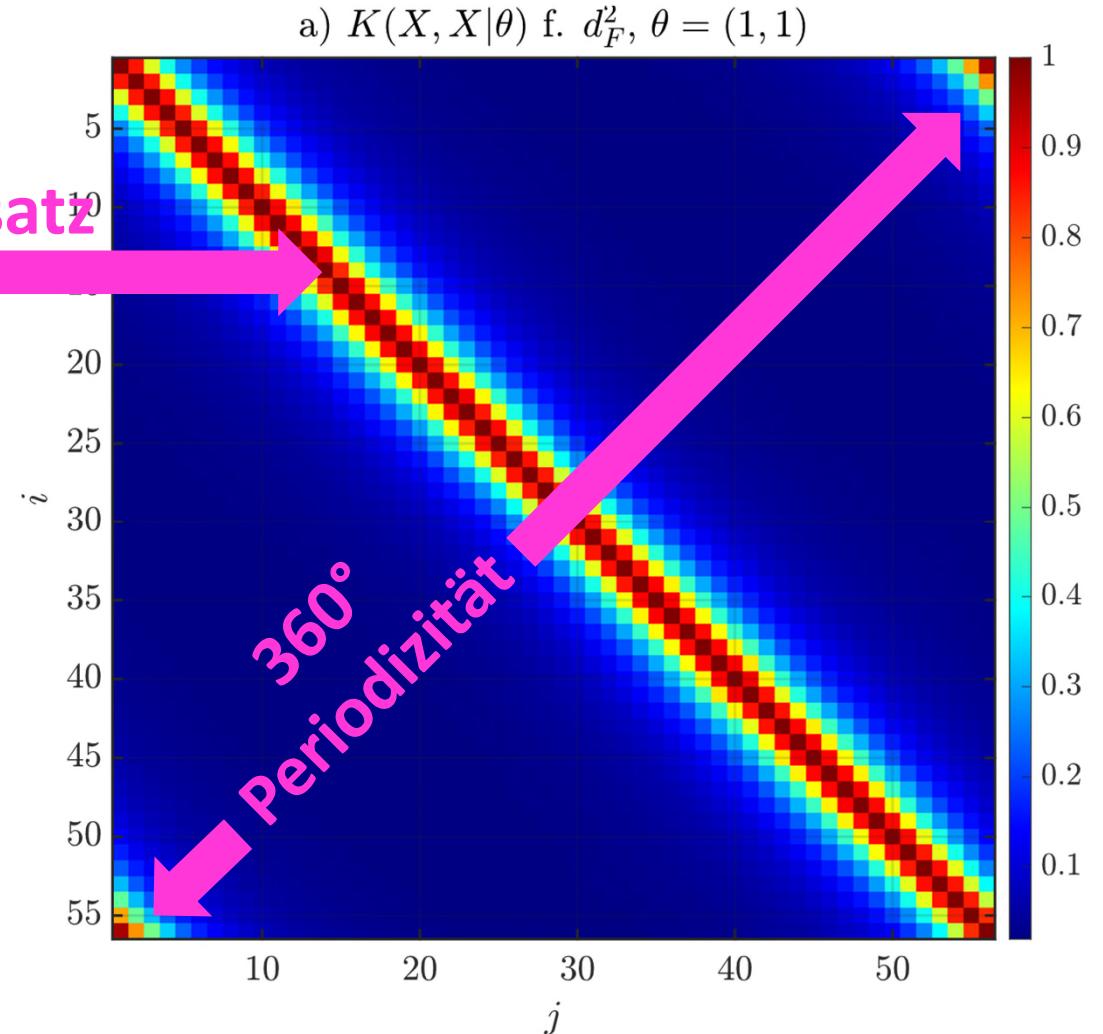


# Gauß-Prozesse



Fractional Kernel

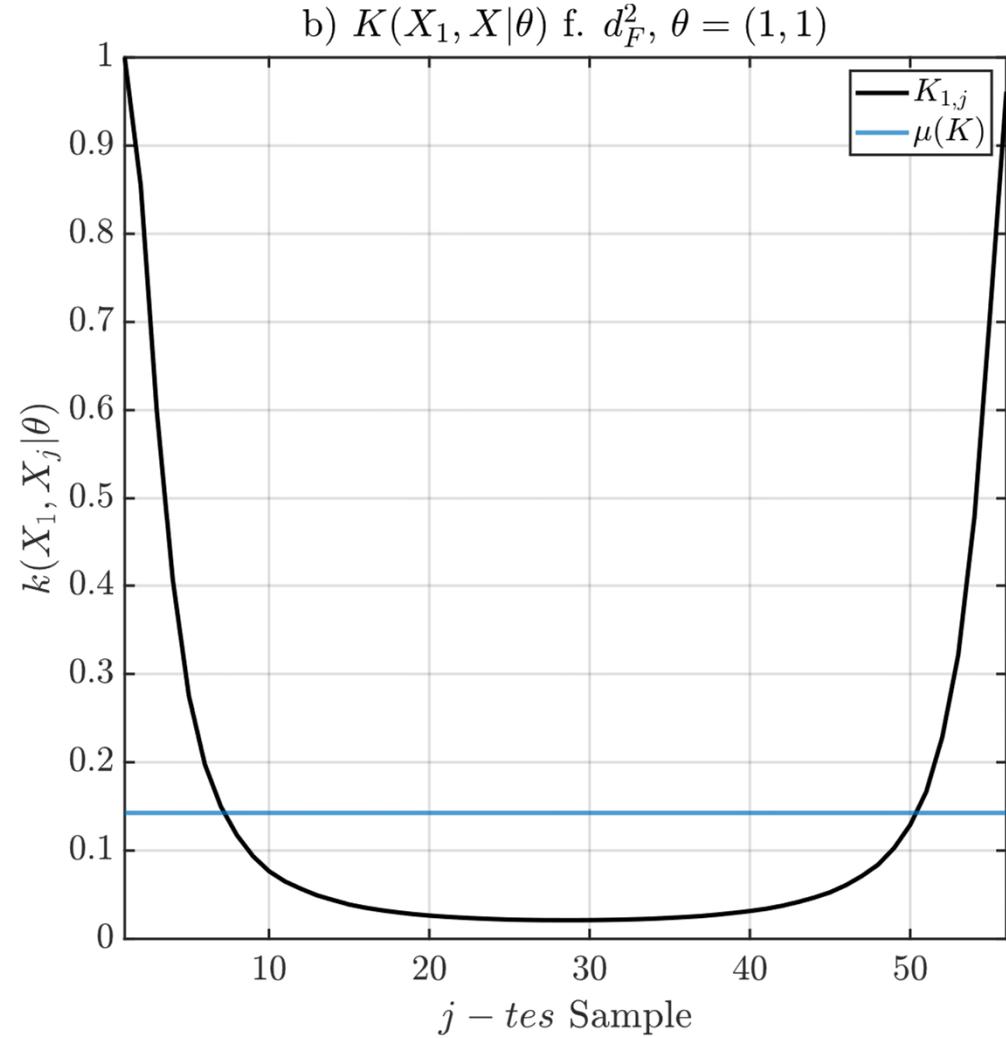
$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$



# Gauß-Prozesse

Fractional Kernel

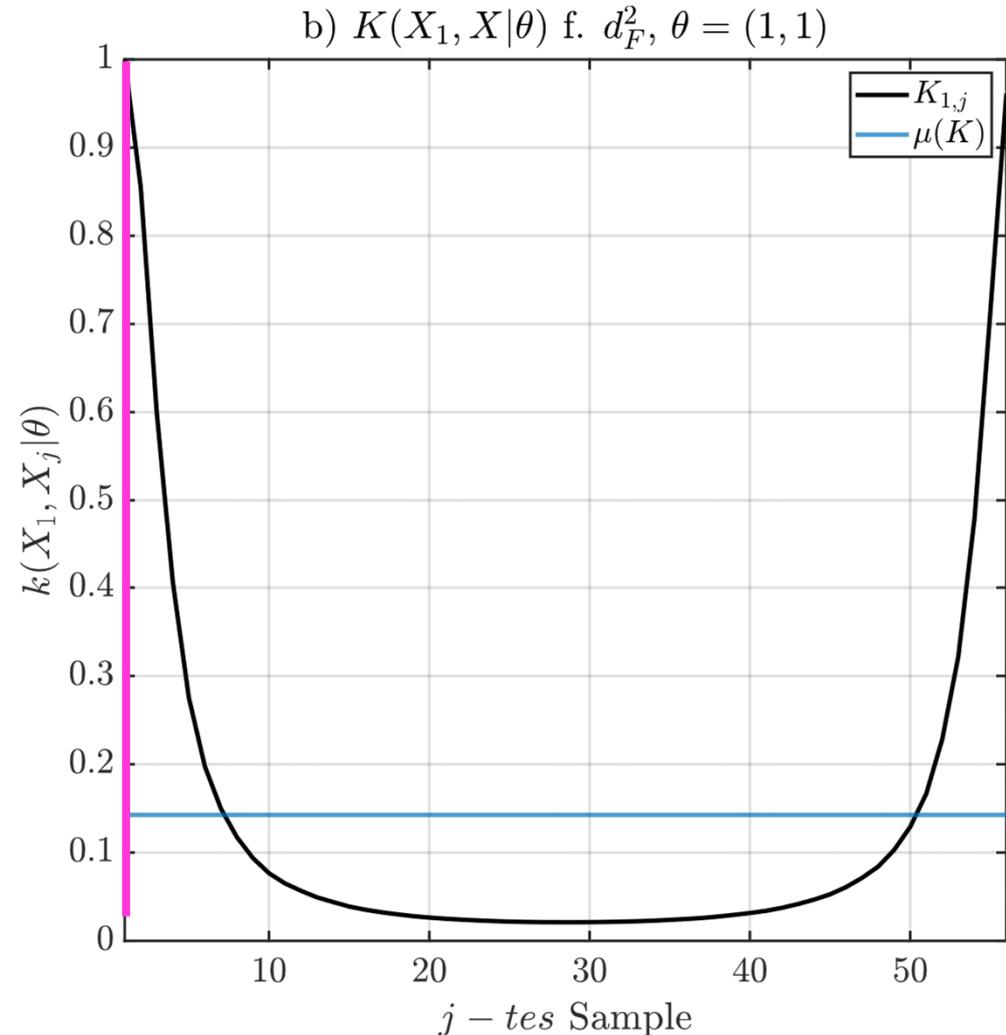
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# Gauß-Prozesse

## Fractional Kernel

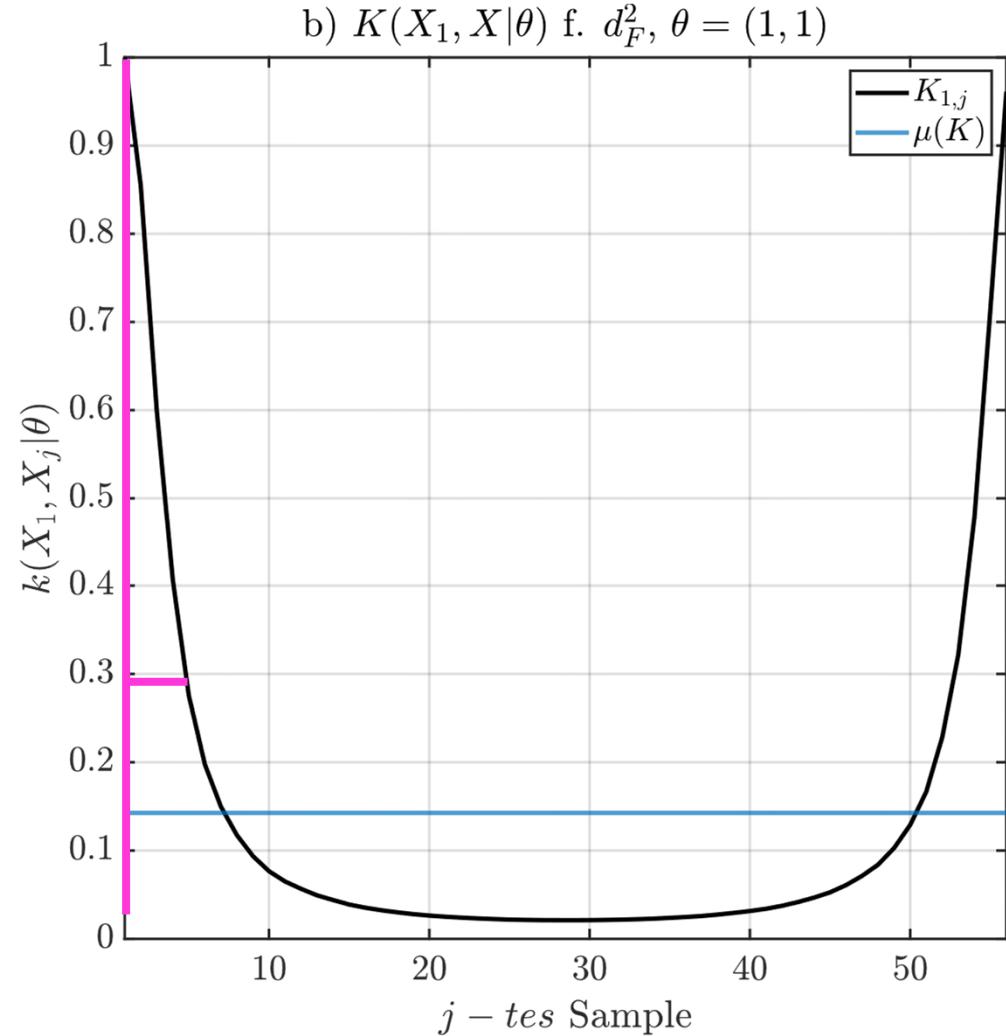
$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$



# Gauß-Prozesse

## Fractional Kernel

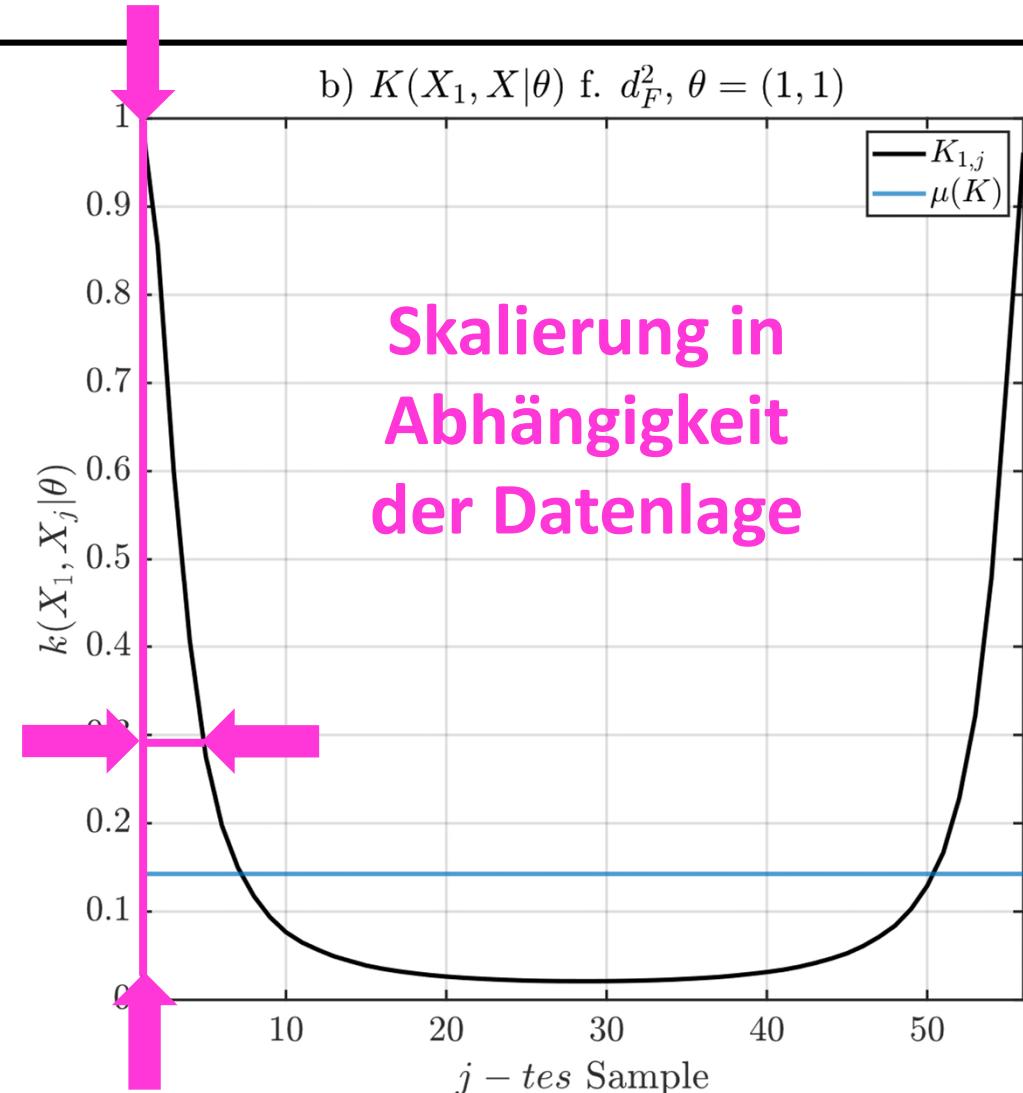
$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$



# Gauß-Prozesse

## Fractional Kernel

$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$

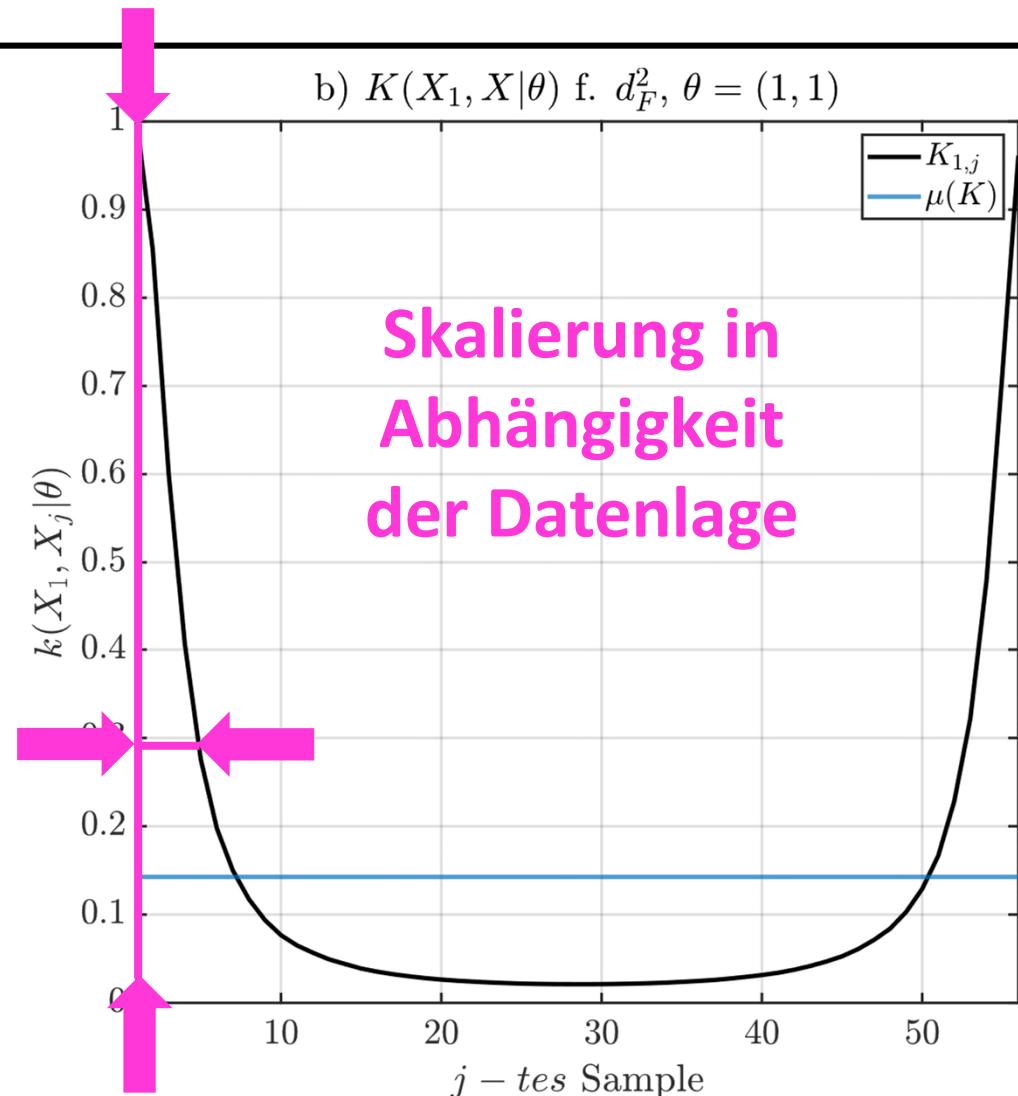


# Gauß-Prozesse

- Kontrolle über Einflussnahme

## Fractional Kernel

$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$

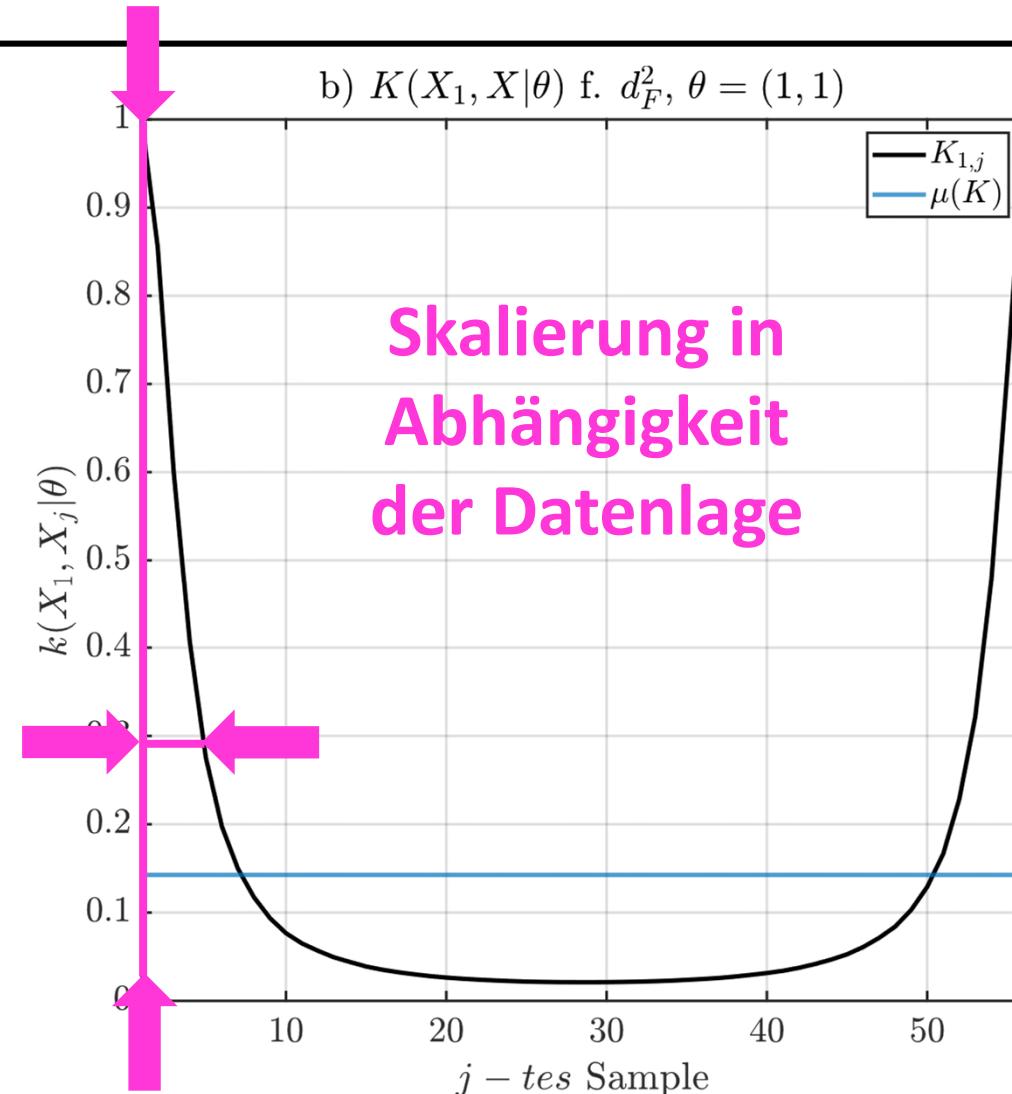


# Gauß-Prozesse

- Kontrolle über Einflussnahme
- Fit über Plausibilitäten
- Generalisierung über Verluste

## Fractional Kernel

$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$



# Software-Aufbau

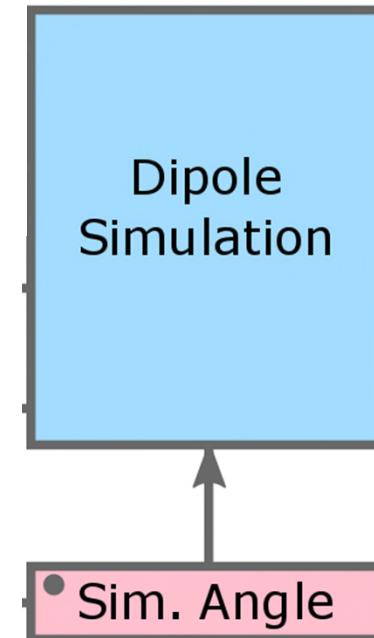
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# Software-Aufbau

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**Sensor Array**  
Generate Data

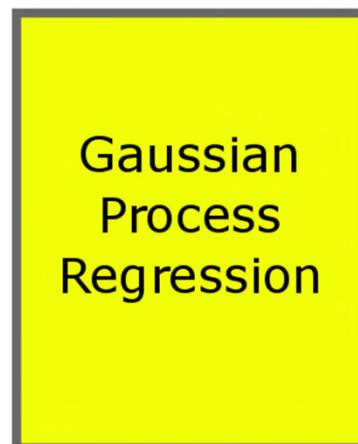


Physical  
Simulation

# Software-Aufbau

## ASIC Model

Analyze Data

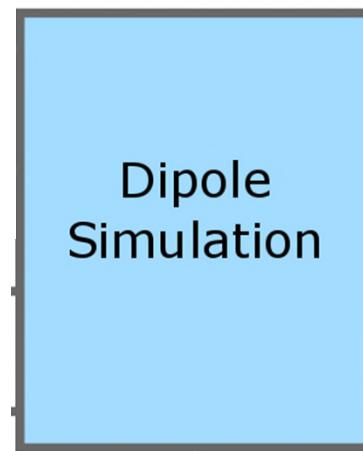


Pred. Angle

Mathematical Simulation

## Sensor Array

Generate Data



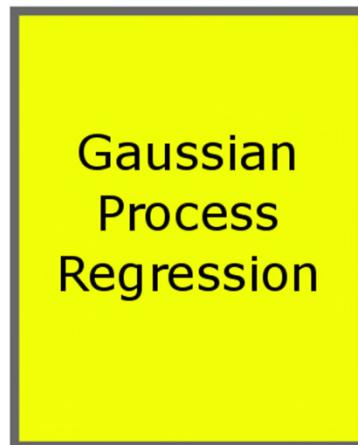
Sim. Angle

Physical Simulation

# Software-Aufbau

## ASIC Model

Analyze Data

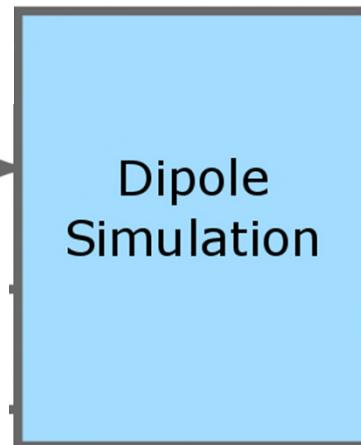


Pred. Angle

Mathematical Simulation

## Sensor Array

Generate Data



Sim. Angle

Physical Simulation

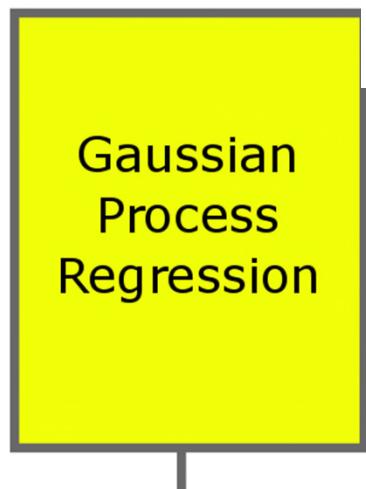
Characterization DS



# Software-Aufbau

## ASIC Model

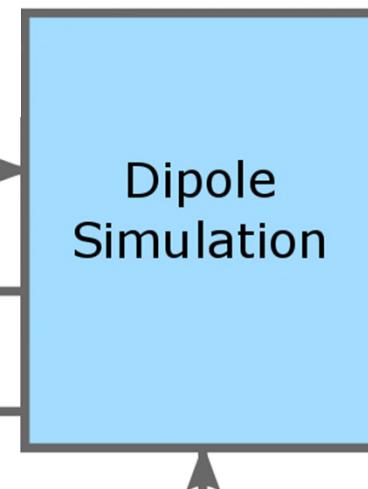
Analyze Data



Mathematical  
Simulation

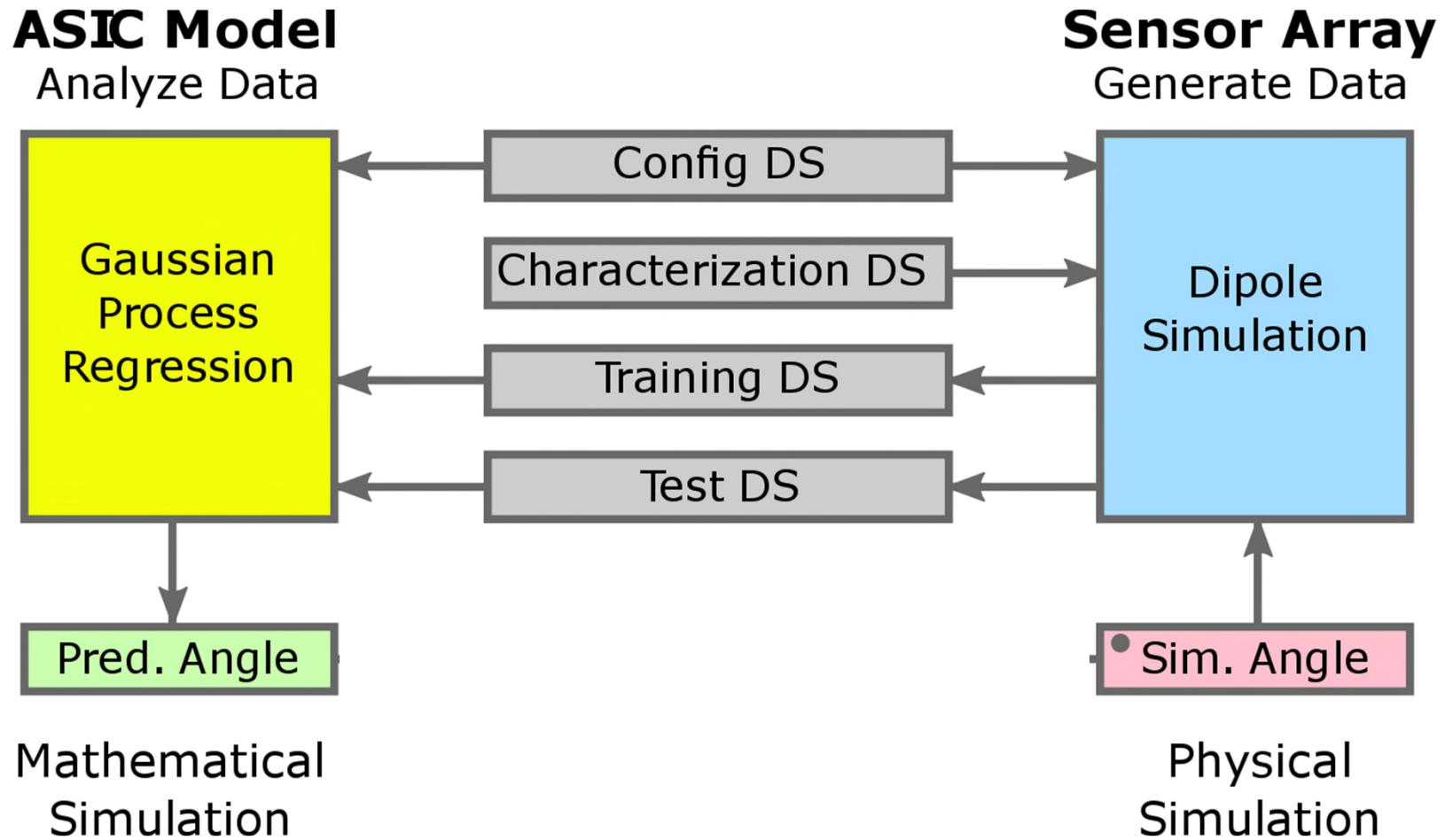
## Sensor Array

Generate Data

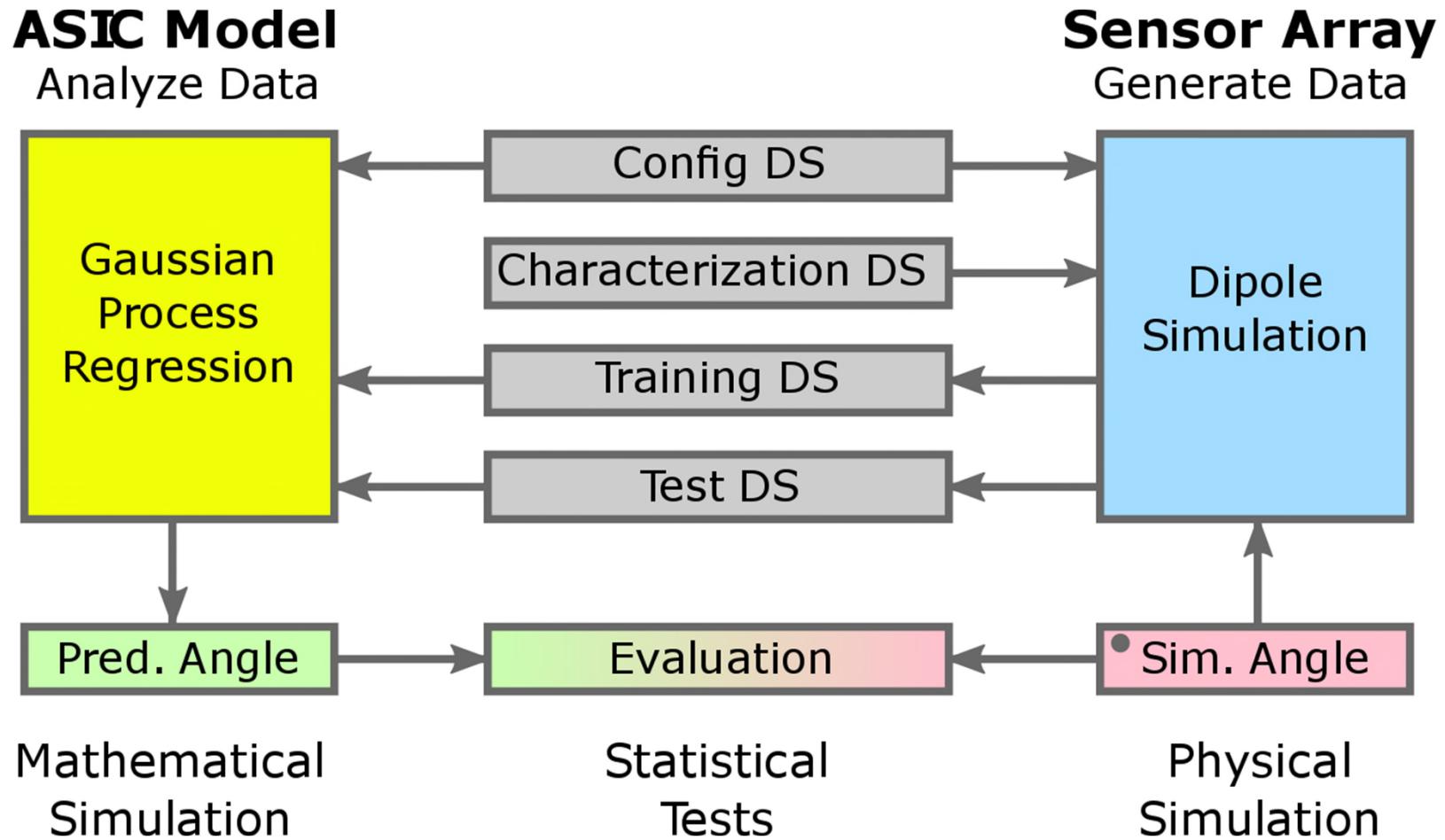


Physical  
Simulation

# Software-Aufbau

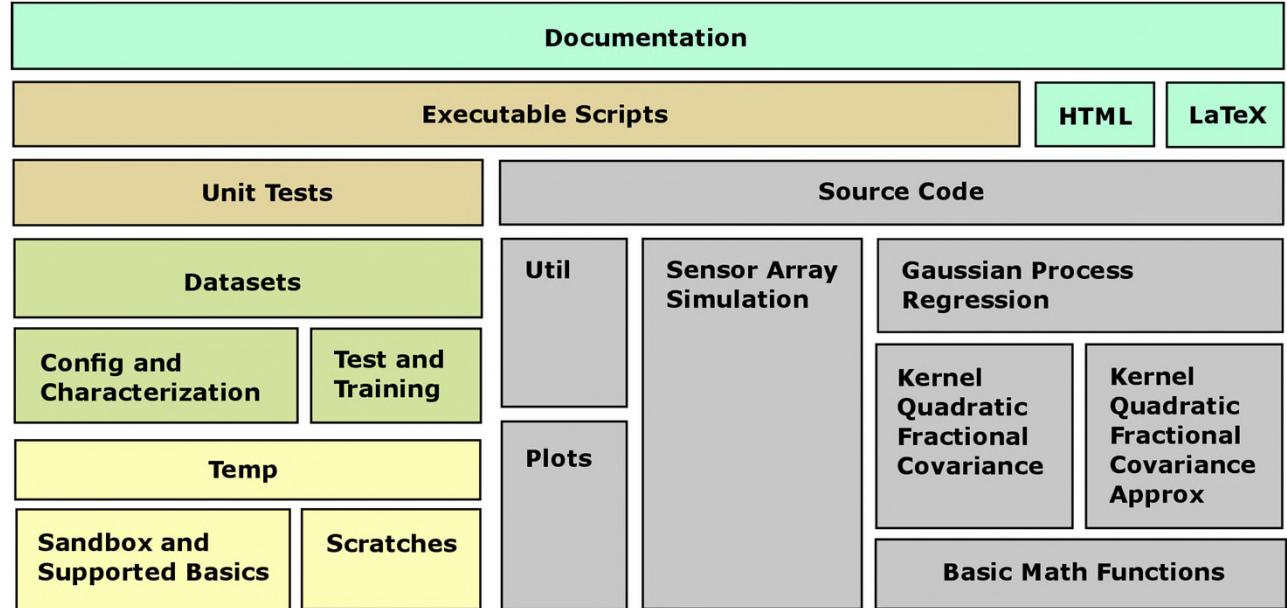


# Software-Aufbau



# Software-Aufbau

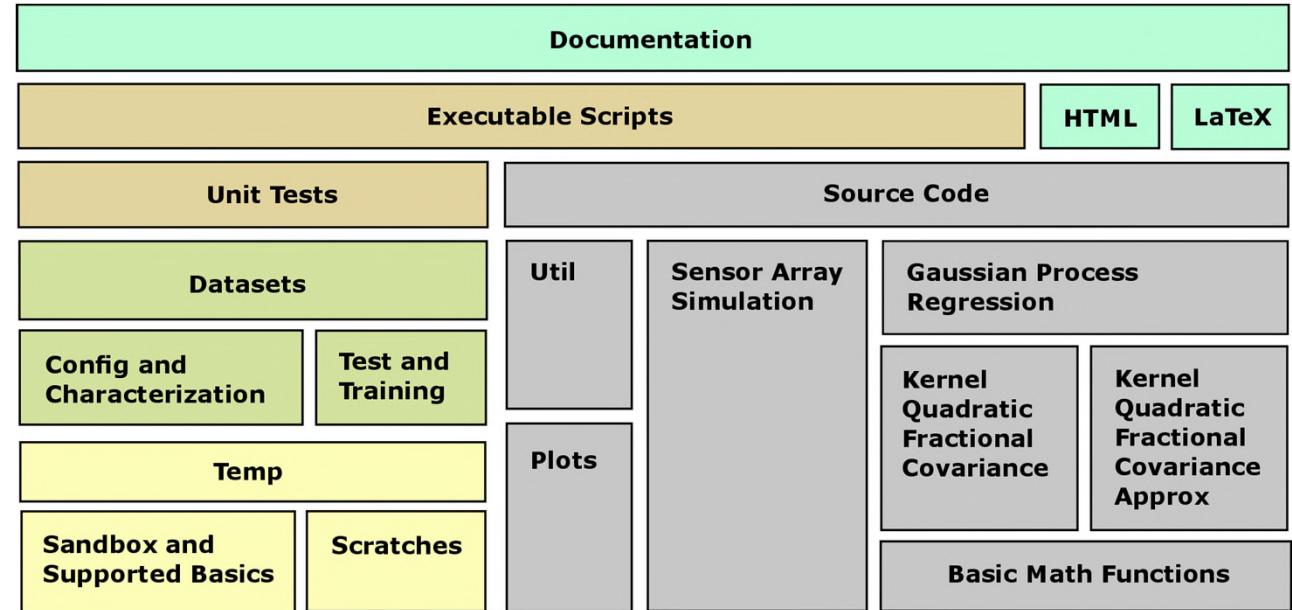
- Modularer Aufbau



# Software-Aufbau

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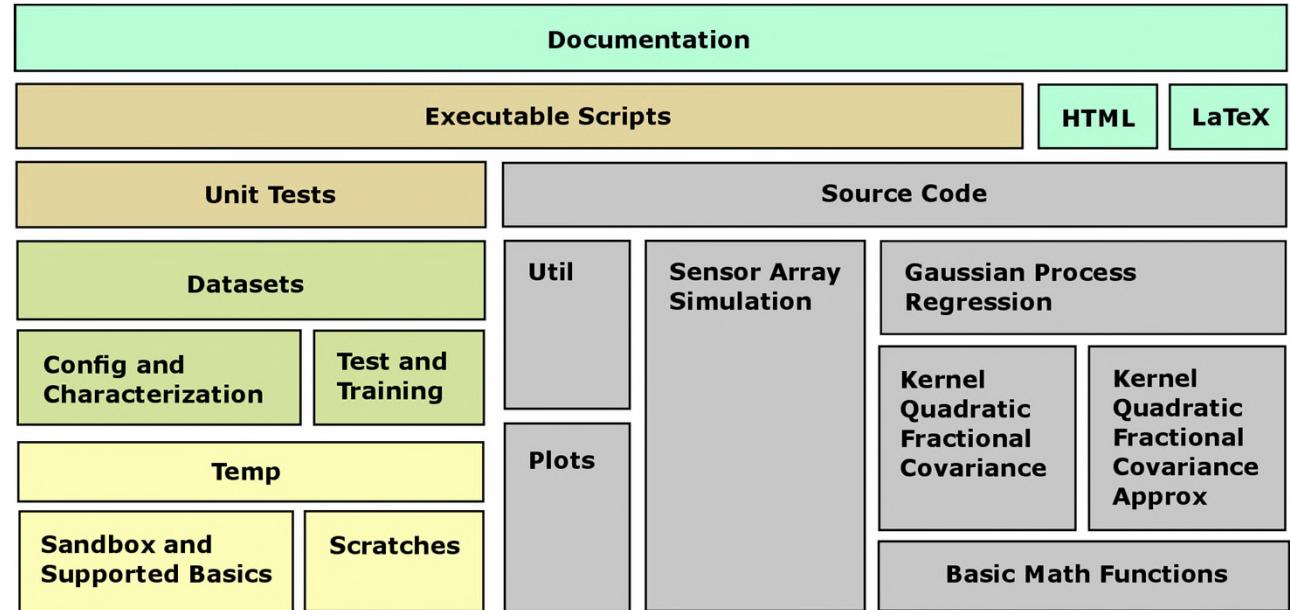
- Modularer Aufbau
- Wiederverwendbarkeit
- Erweiterbarkeit



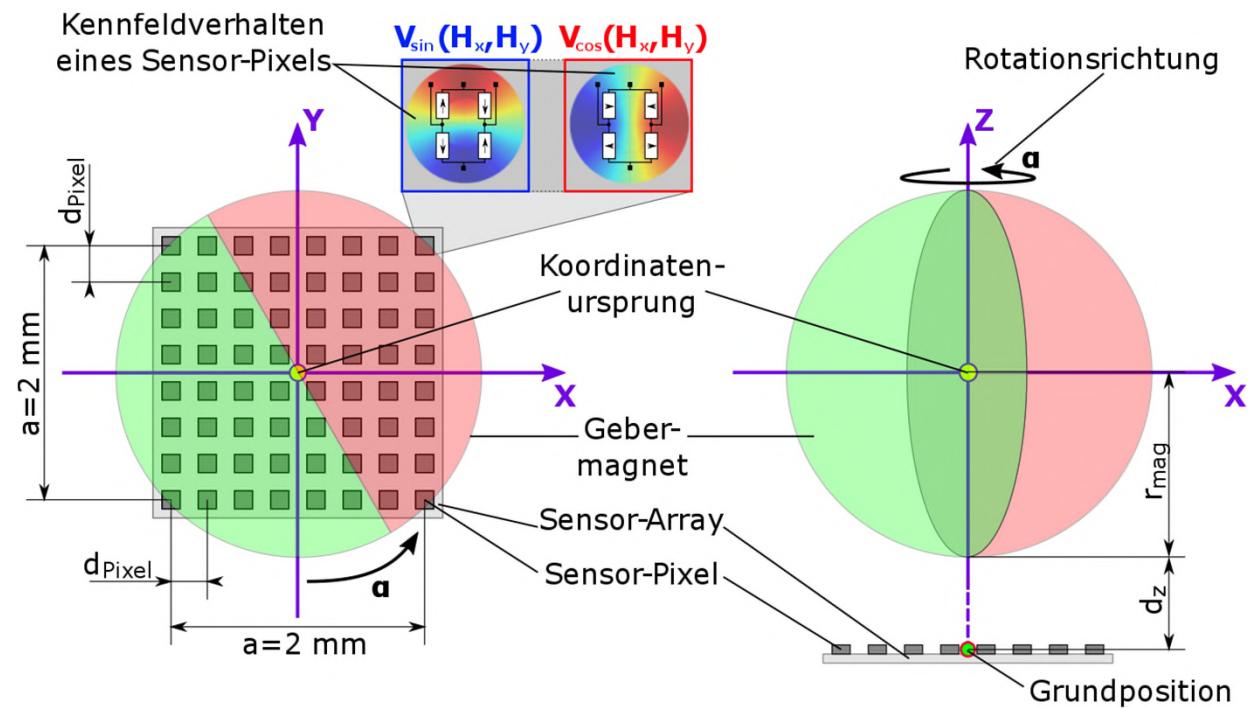
# Software-Aufbau

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- Modularer Aufbau
- Wiederverwendbarkeit
- Erweiterbarkeit
- Integration
- Dokumentation

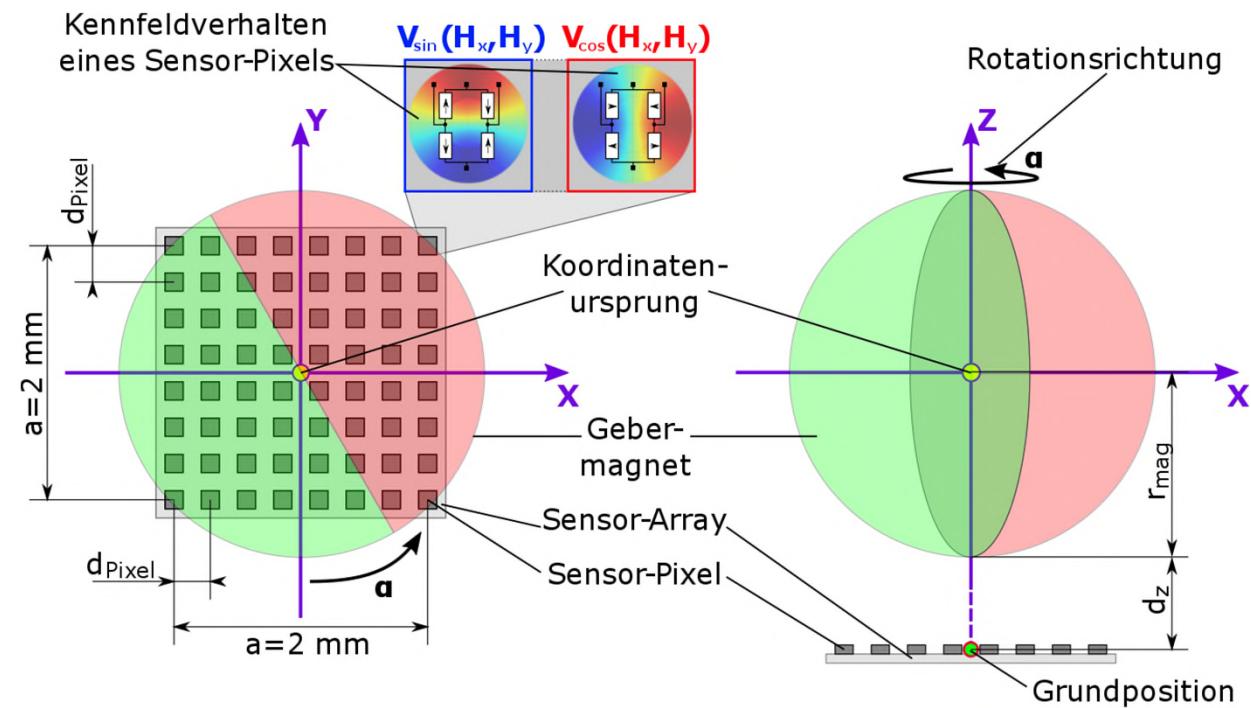


# Simulation – Sensor-Array



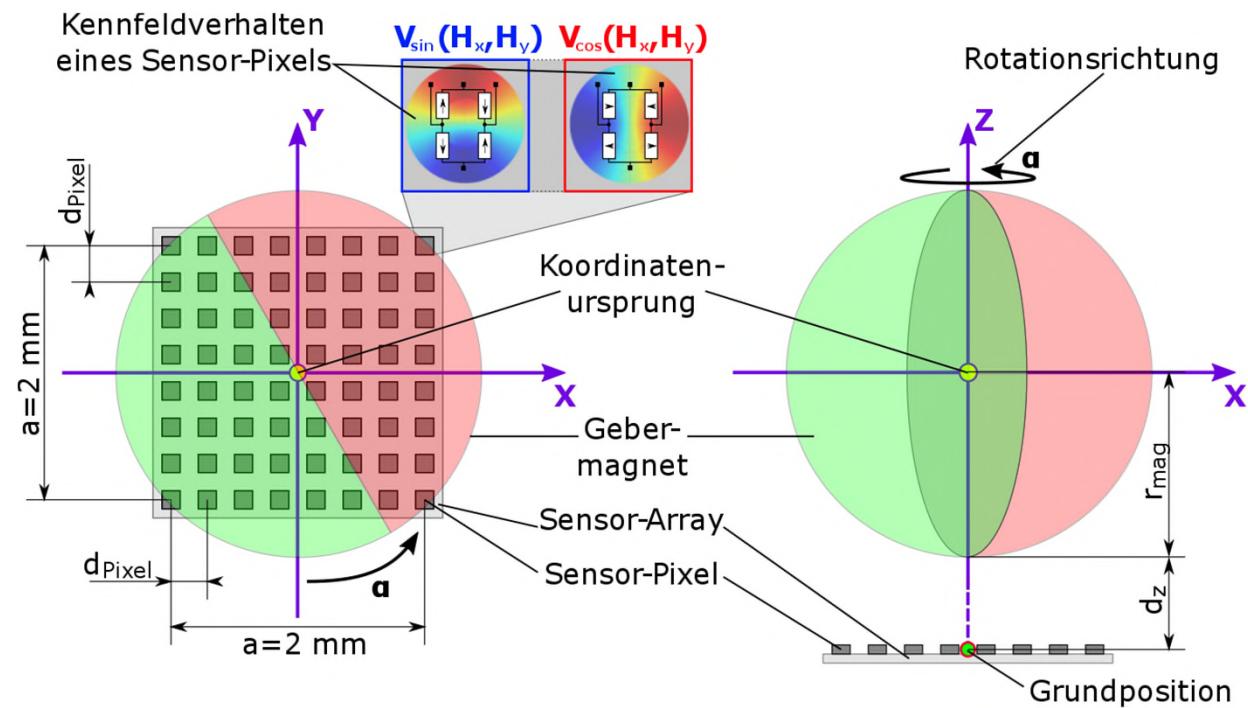
# Simulation – Sensor-Array

- Konfiguration von Abmaße,  
Position, Anordnung und  
Spannungsversorgung

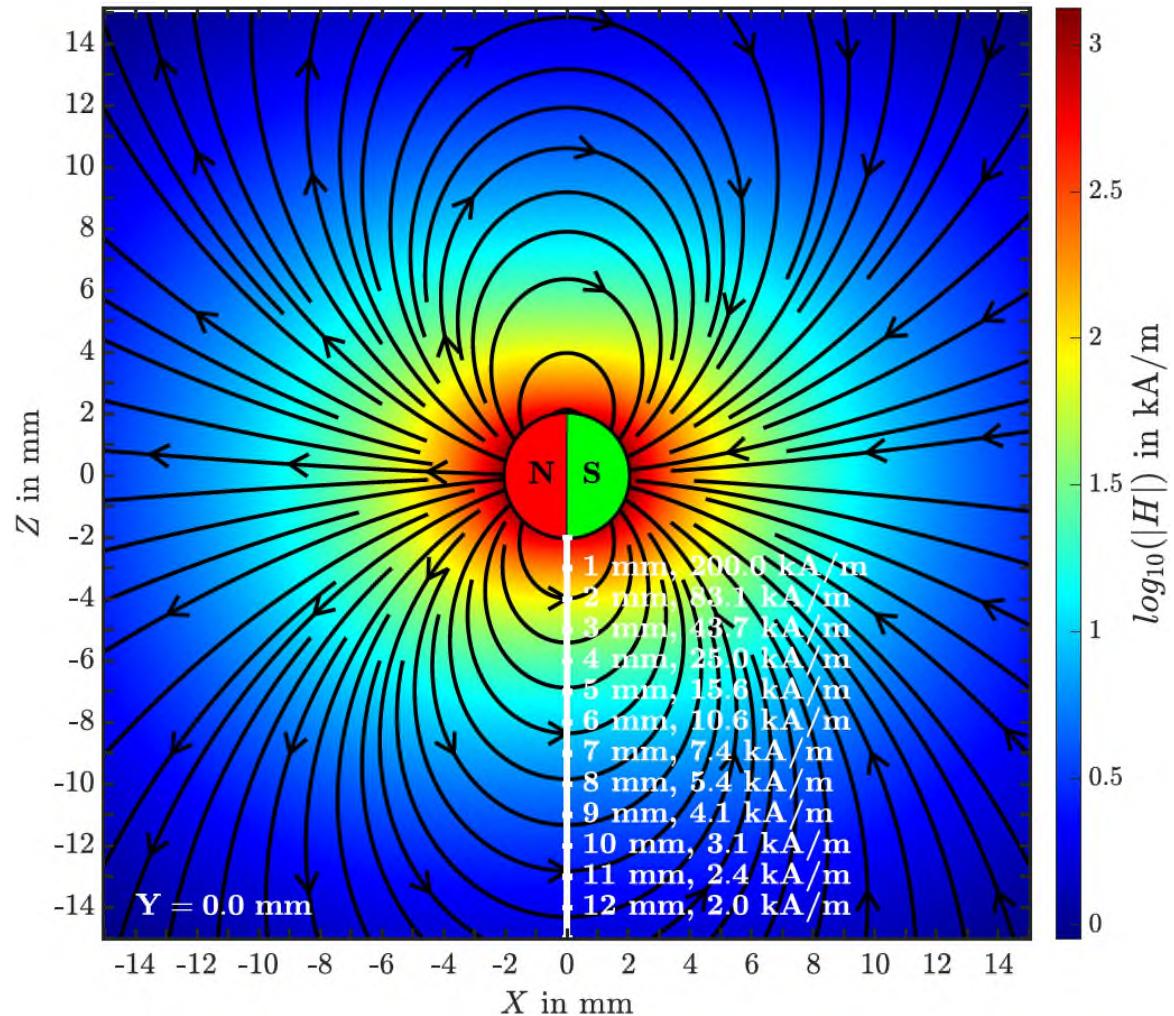


# Simulation – Sensor-Array

- Konfiguration von Abmaße,  
Position, Anordnung und  
Spannungsversorgung
- Festlegen des Startpunktes  
bzw. Ruhelage

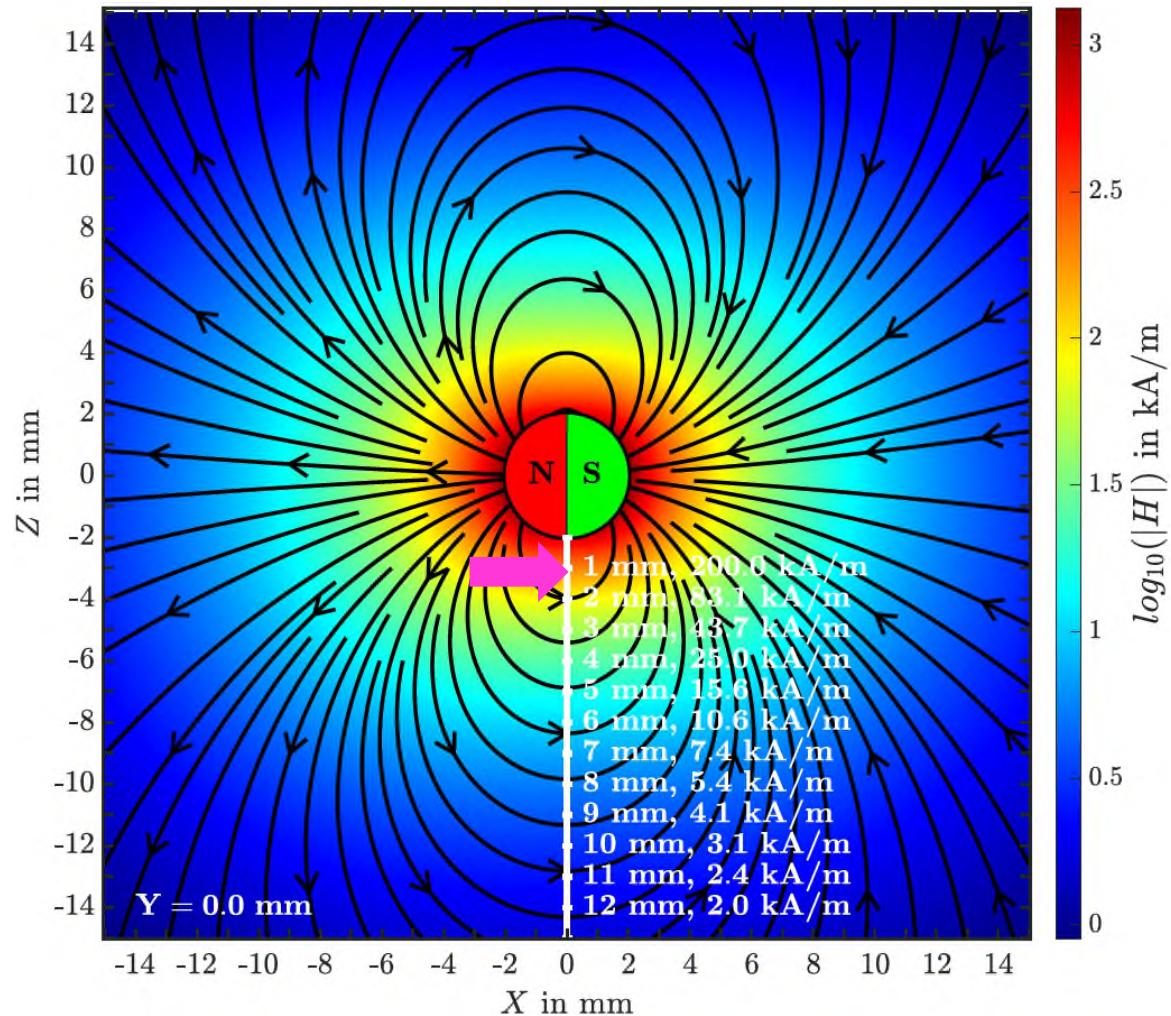


# Simulation – Sensor-Array



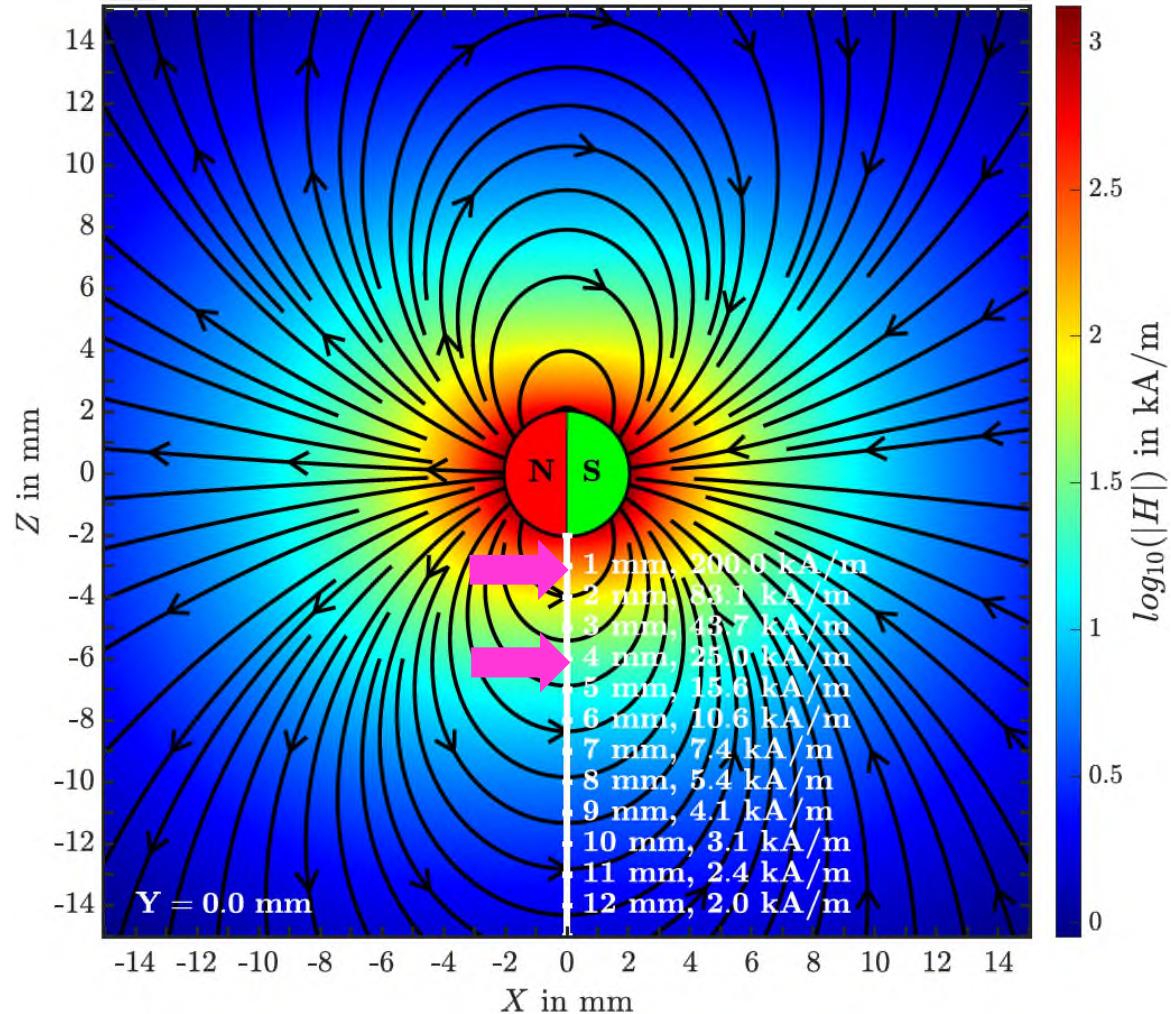
# Simulation – Sensor-Array

- Konfigurierung der Prägung  
bei 1 mm und 200 kA/m



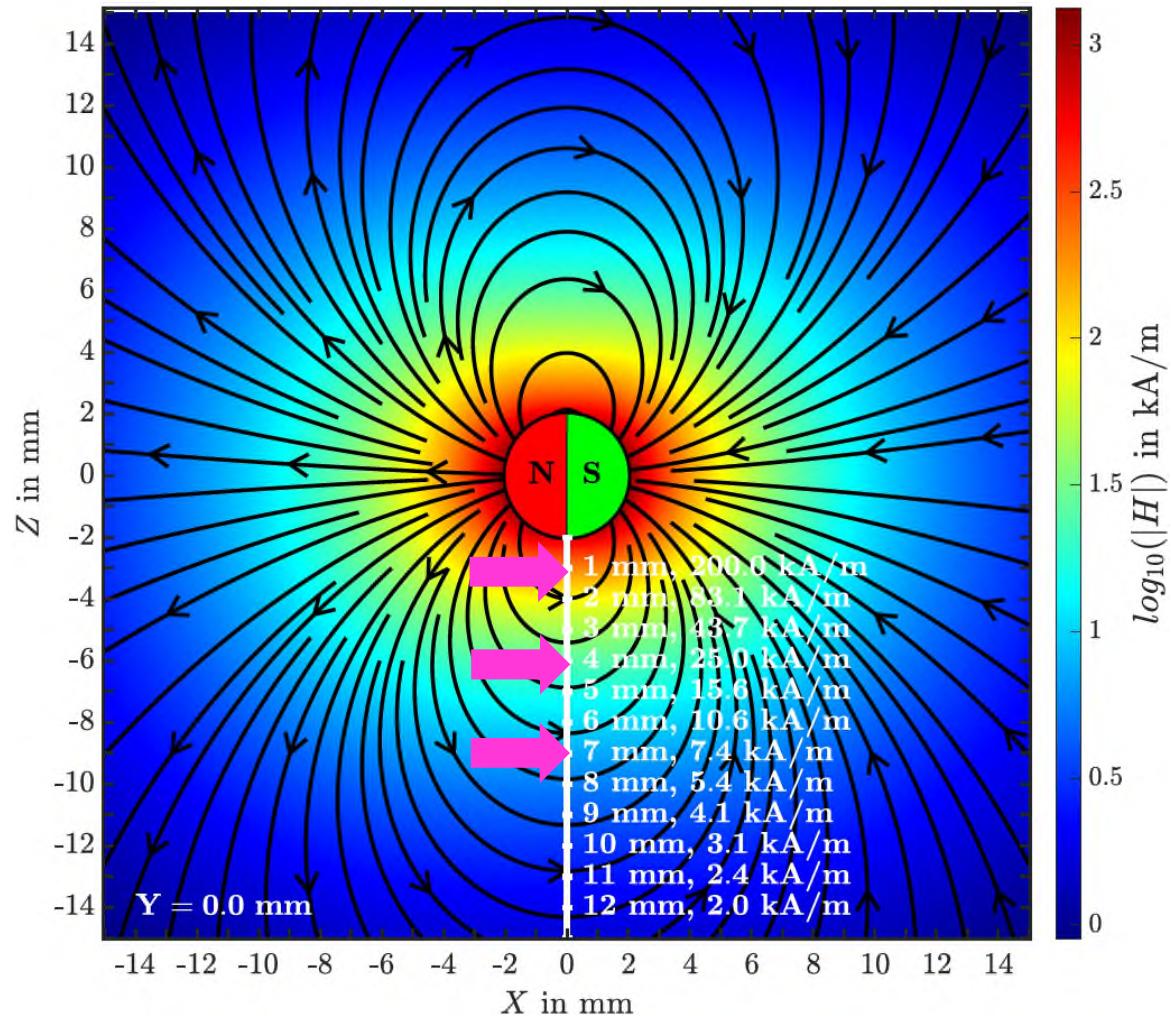
# Simulation – Sensor-Array

- Konfigurierung der Prägung bei 1 mm und 200 kA/m
- Mindestabstand bei 4 mm und 25 kA/m

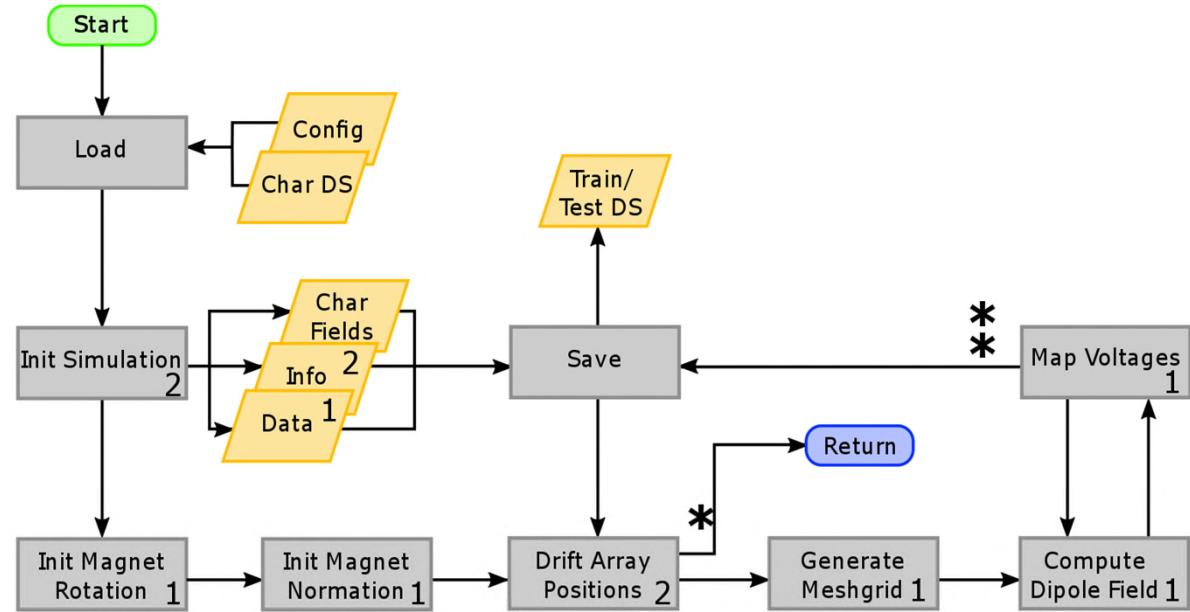


# Simulation – Sensor-Array

- Konfigurierung der Prägung bei 1 mm und 200 kA/m
- Mindestabstand bei 4 mm und 25 kA/m
- Linearer Bereich bei 7 mm und 7,4 kA/m



# Simulation – Sensor-Array

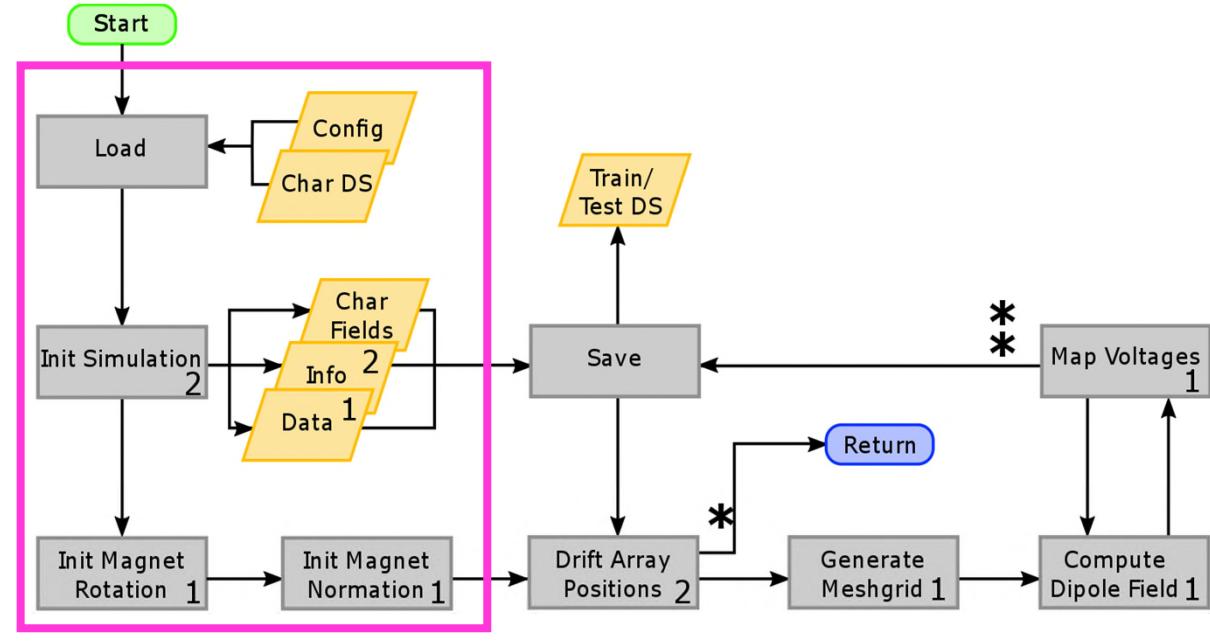


## Legende

[Green rounded rectangle]	Prozessstart	[Yellow rounded rectangle]	Datensatz, Datenstruktur
[Blue rounded rectangle]	Prozessende	[Grey rounded rectangle]	Prozessschritt
*	Alle Positionen	1	Schreibt in Data-Container
**	Alle Winkel	2	Schreibt in Info-Container

# Simulation – Sensor-Array

- Laden und initiieren der Simulationsparametern

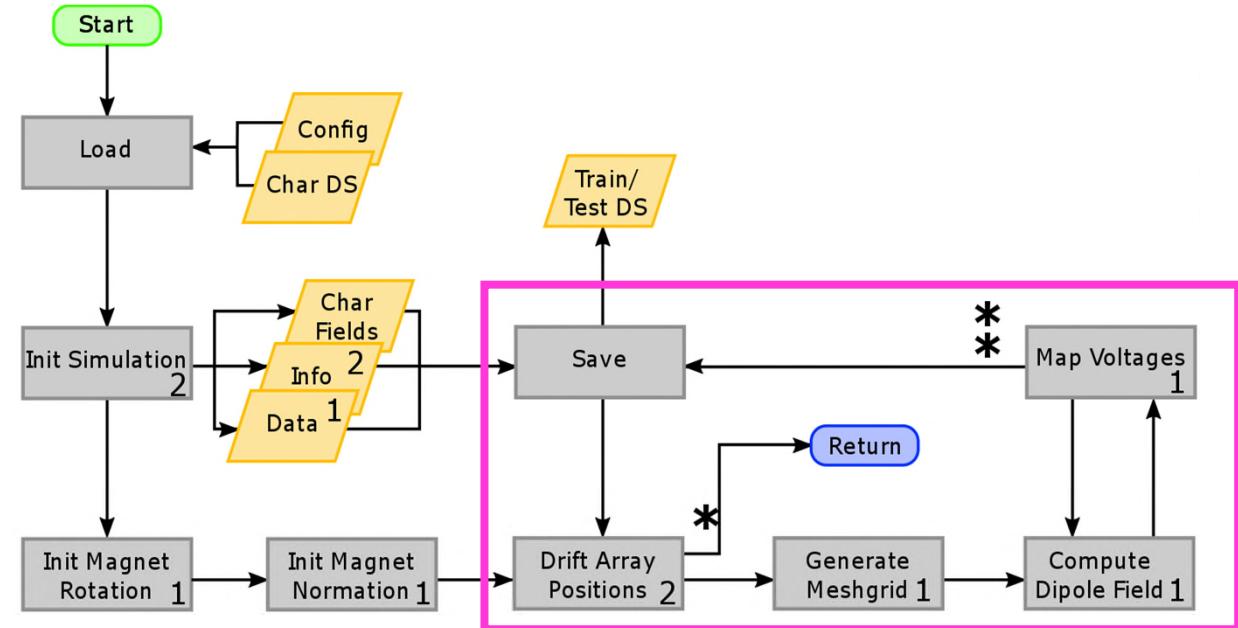


Legende

[Green rounded rectangle]	Prozessstart	[Yellow rounded rectangle]	Datensatz, Datenstruktur
[Blue rounded rectangle]	Prozessende	[Grey rounded rectangle]	Prozessschritt
*	Alle Positionen	1	Schreibt in Data-Container
**	Alle Winkel	2	Schreibt in Info-Container

# Simulation – Sensor-Array

- Laden und initiieren der Simulationsparametern
- Durchführung in For-Schleifen

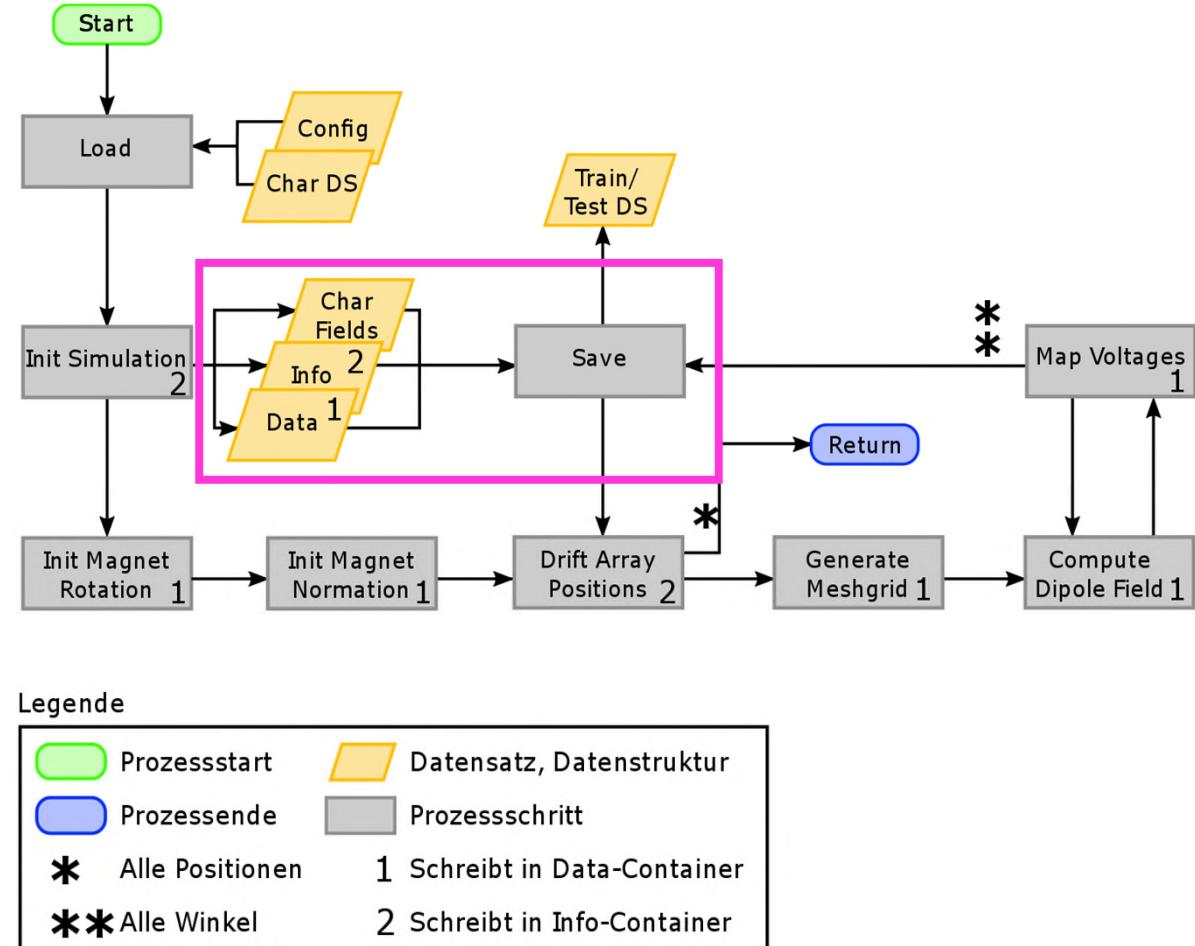


Legende

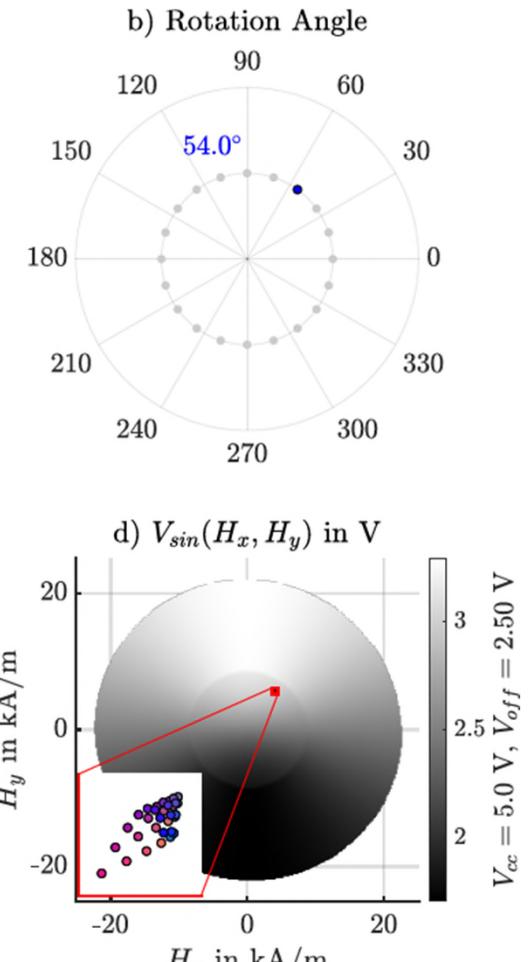
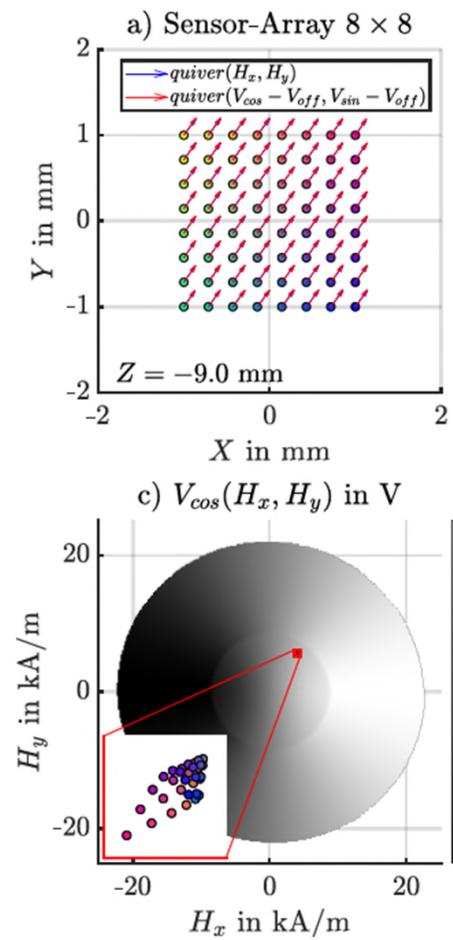
[Green rounded rectangle]	Prozessstart	[Yellow rounded rectangle]	Datensatz, Datenstruktur
[Blue rounded rectangle]	Prozessende	[Grey rounded rectangle]	Prozessschritt
*	Alle Positionen	1	Schreibt in Data-Container
**	Alle Winkel	2	Schreibt in Info-Container

# Simulation – Sensor-Array

- Laden und initiieren der Simulationsparametern
- Durchführung in For-Schleifen
- Speichern der Datencontainer

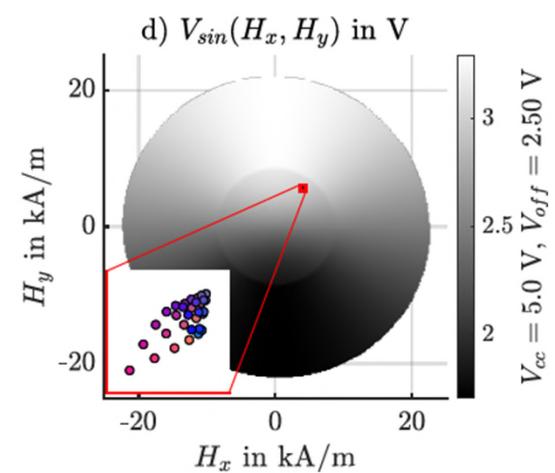
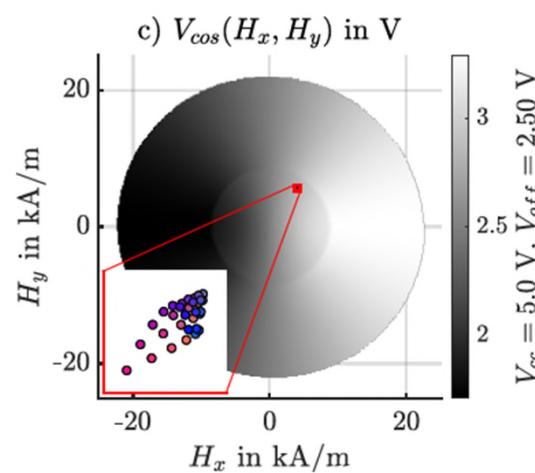
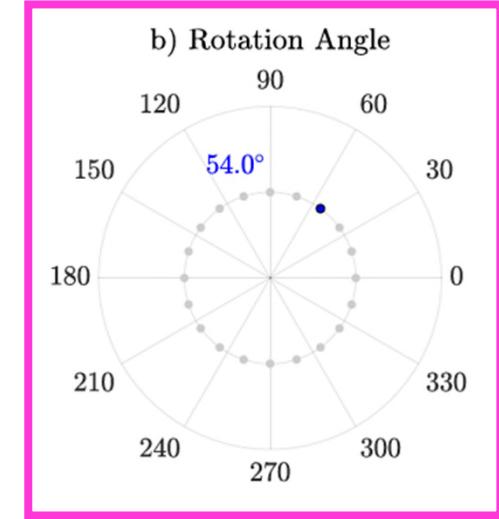
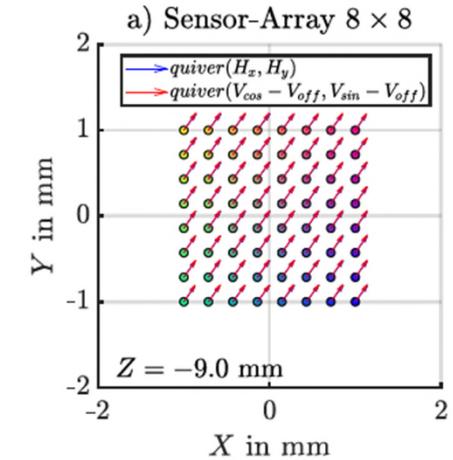


# Simulation – Sensor-Array



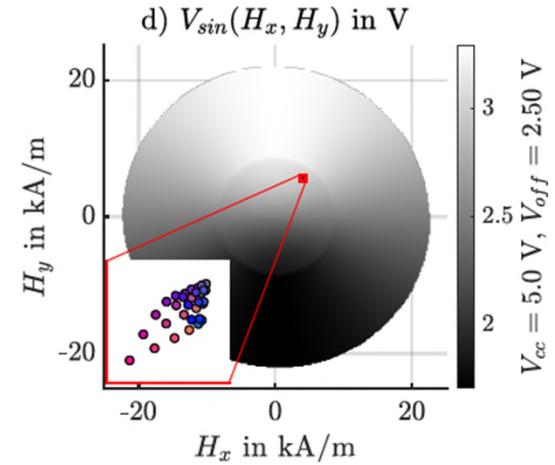
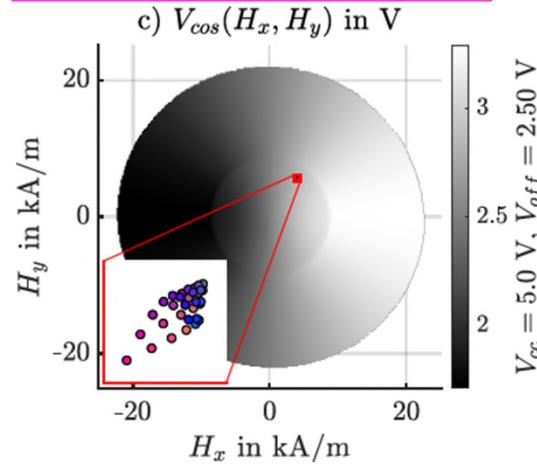
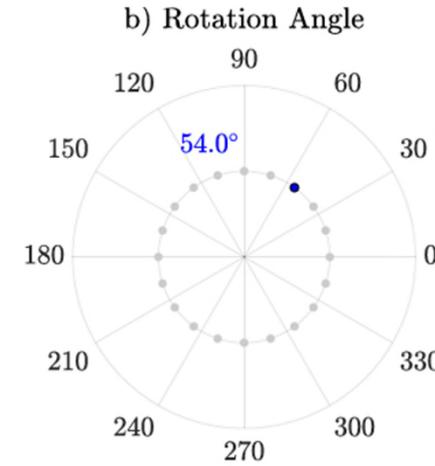
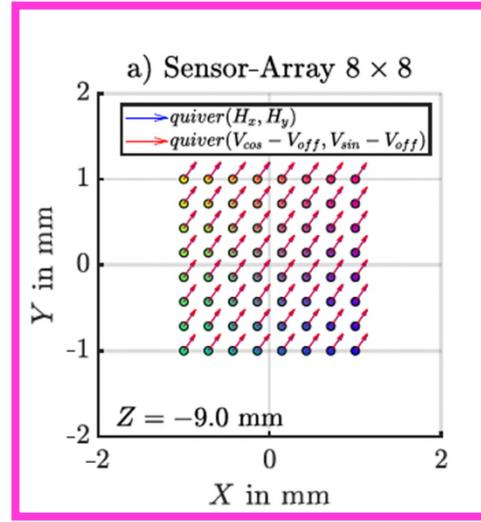
# Simulation – Sensor-Array

- Eingabe – Simulationswinkel



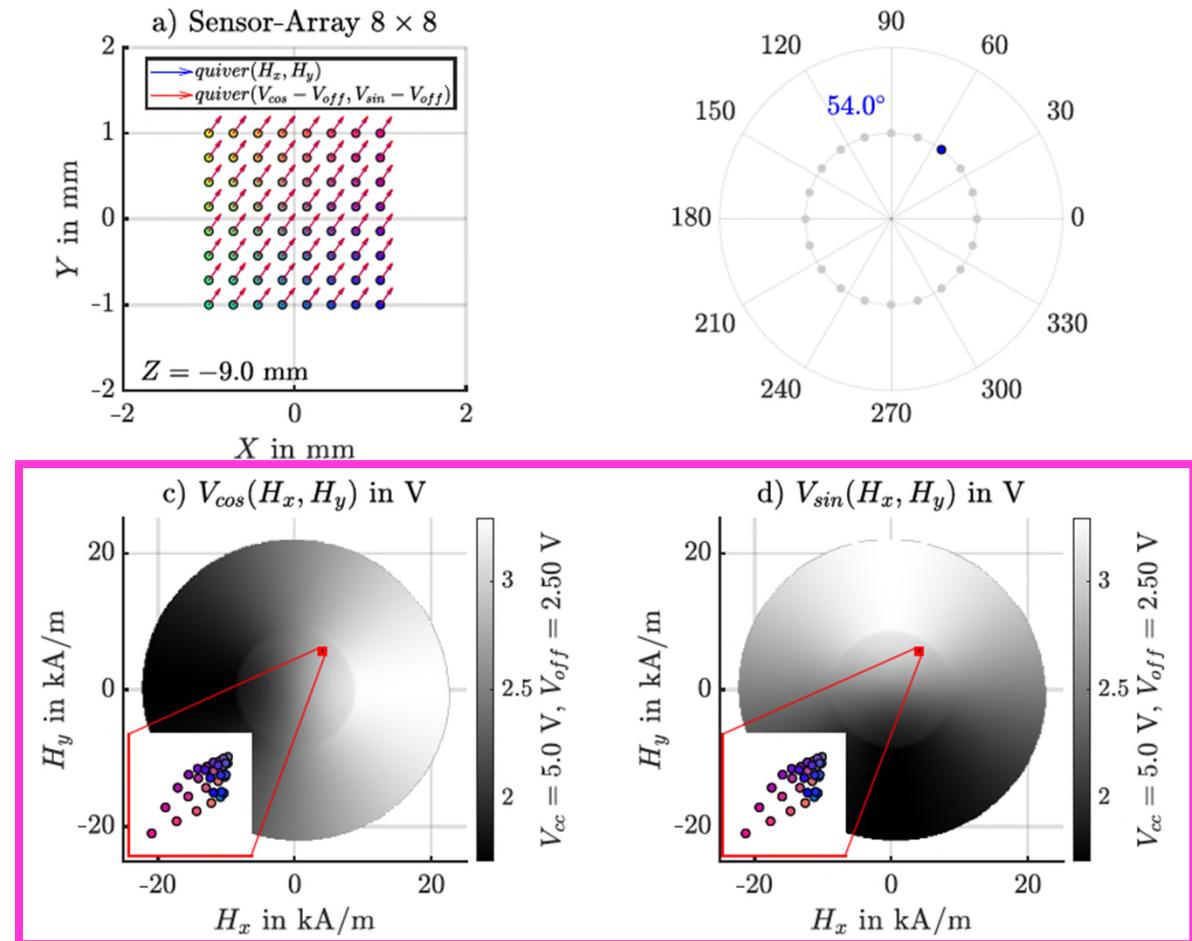
# Simulation – Sensor-Array

- Eingabe – Simulationswinkel
- Meshgrid – Berechnungen  
an Sensor-Pixel



# Simulation – Sensor-Array

- Eingabe – Simulationswinkel
- Meshgrid – Berechnungen an Sensor-Pixel
- Mapping – Entnahme von Referenzspannungen



# Simulation – Gauß-Prozesse

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- Koniguration

MSLL – Mean-Standardized-Logarithmic-Loss

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Generalisierung

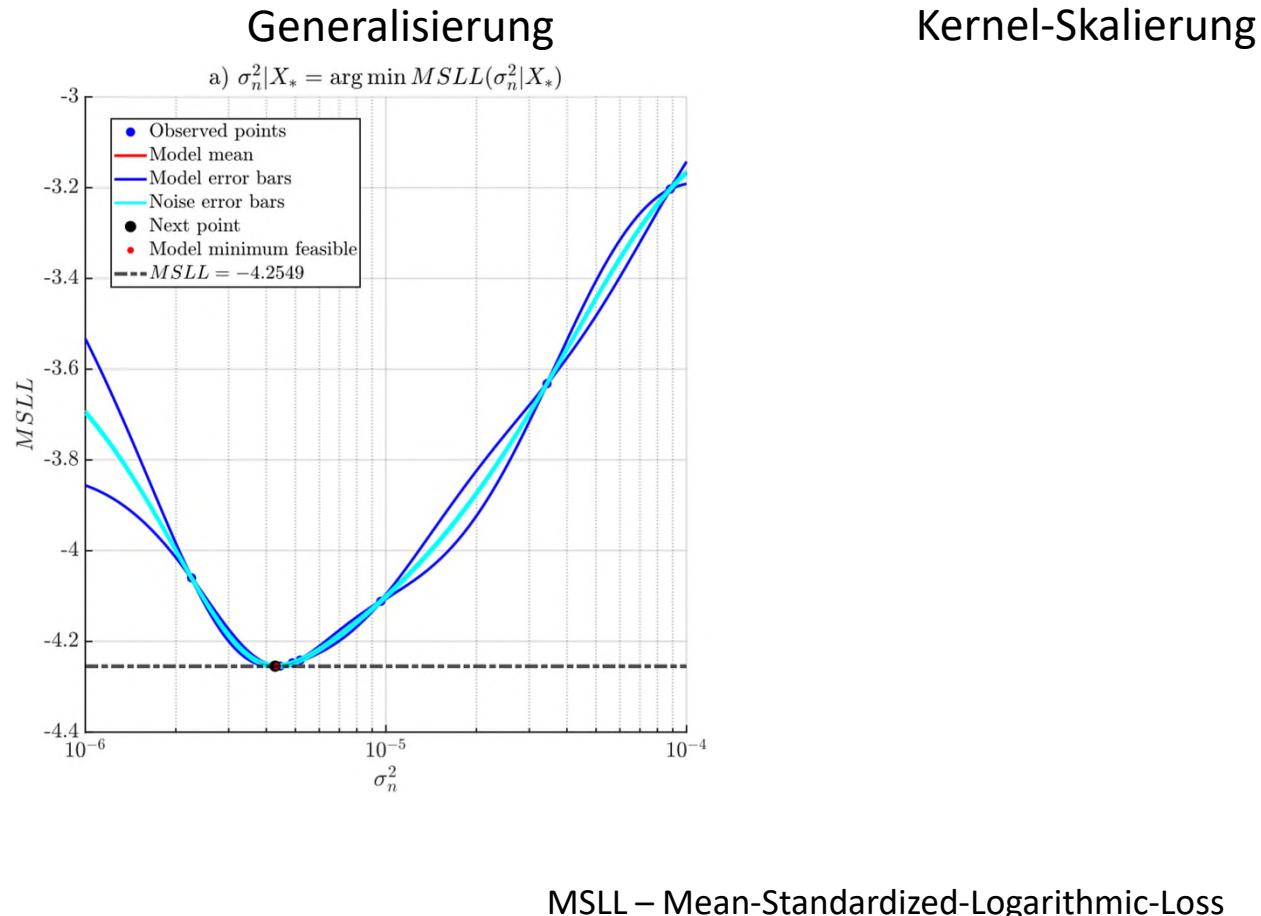
Kernel-Skalierung

- Konfiguration
  - Kernel-Modul
  - Mittelwertbildung

MSLL – Mean-Standardized-Logarithmic-Loss

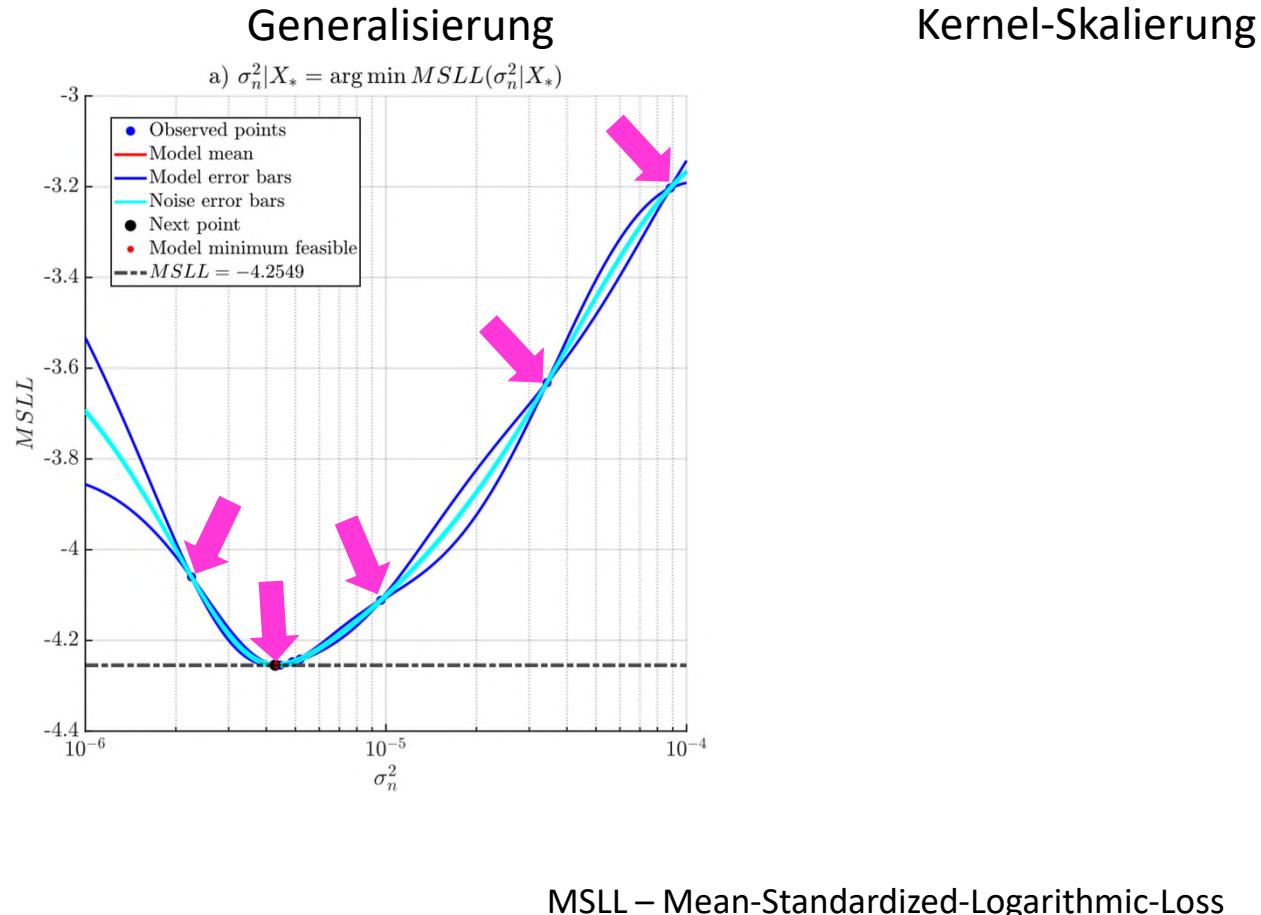
# Simulation – Gauß-Prozesse

- Konfiguration
  - Kernel-Modul
  - Mittelwertbildung
  - Verlustberechnung



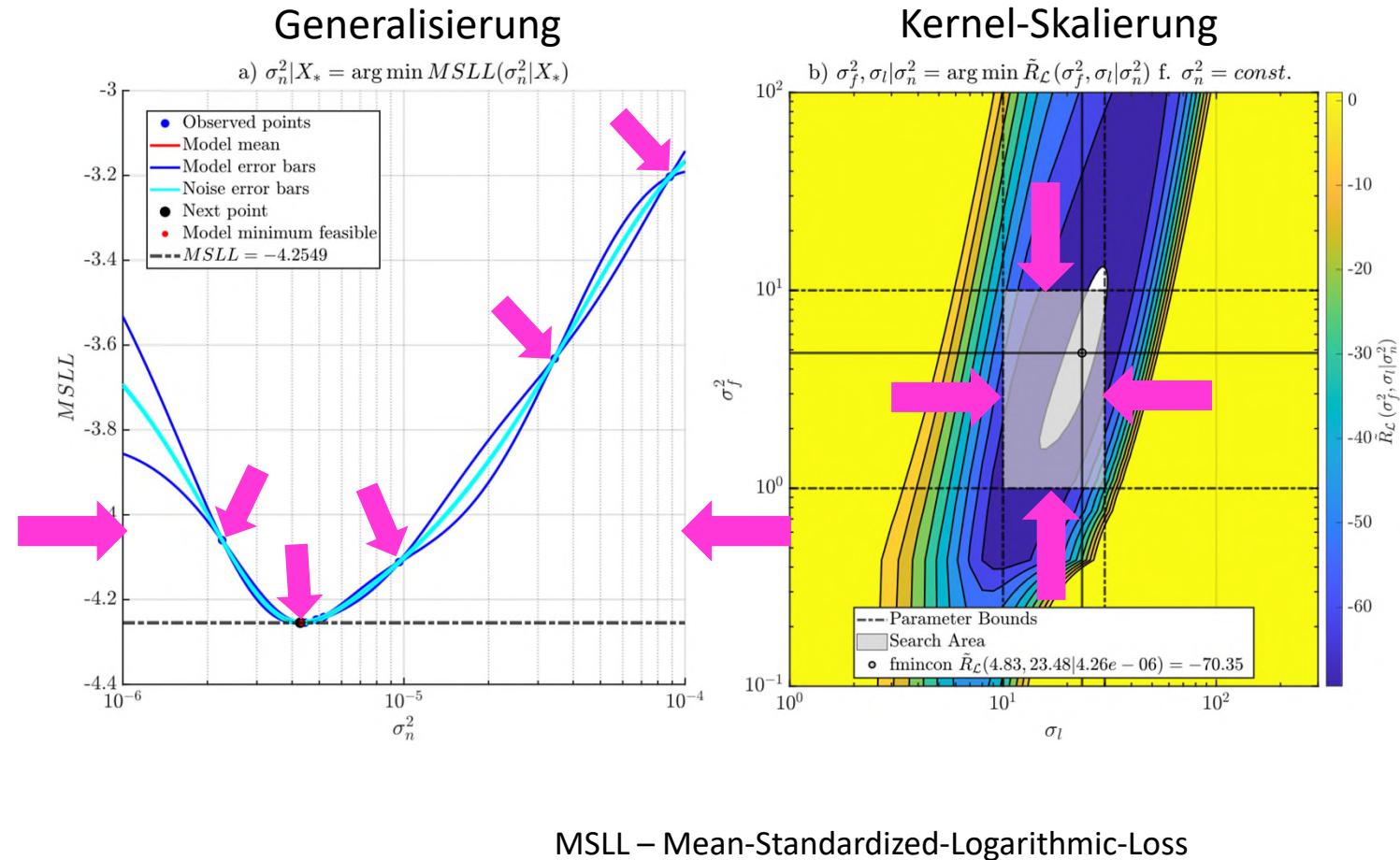
# Simulation – Gauß-Prozesse

- Konfiguration
  - Kernel-Modul
  - Mittelwertbildung
  - Verlustberechnung
  - Durchlaufanzahl



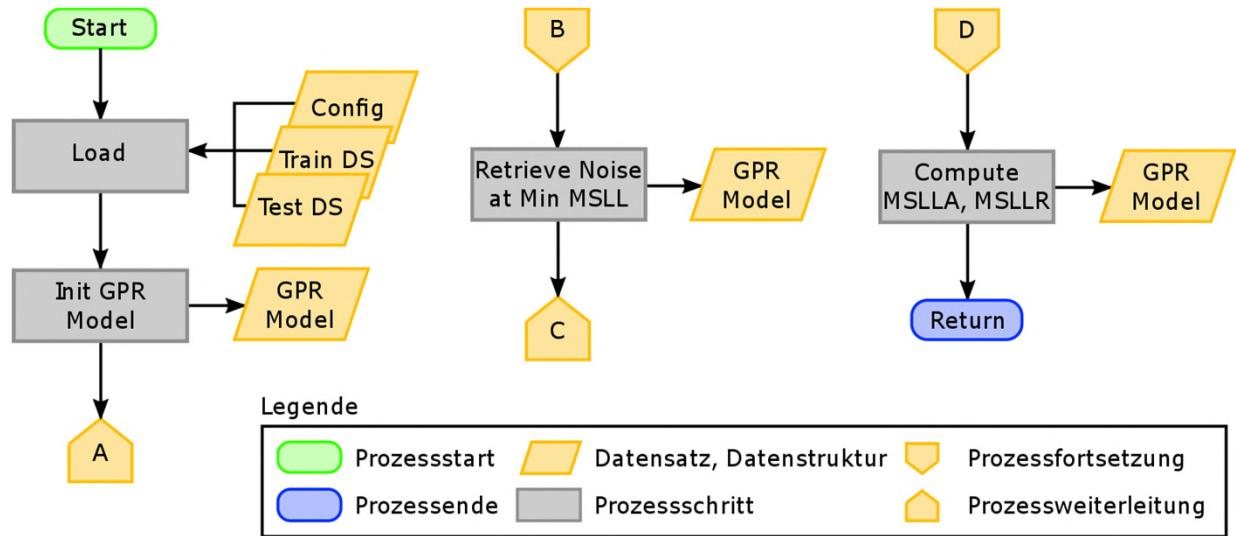
# Simulation – Gauß-Prozesse

- Konfiguration
  - Kernel-Modul
  - Mittelwertbildung
  - Verlustberechnung
  - Durchlaufanzahl
  - Parametergrenzen



# Simulation – Gauß-Prozesse

- Trainingsphase



GPR – Gaussian Processes for Regression

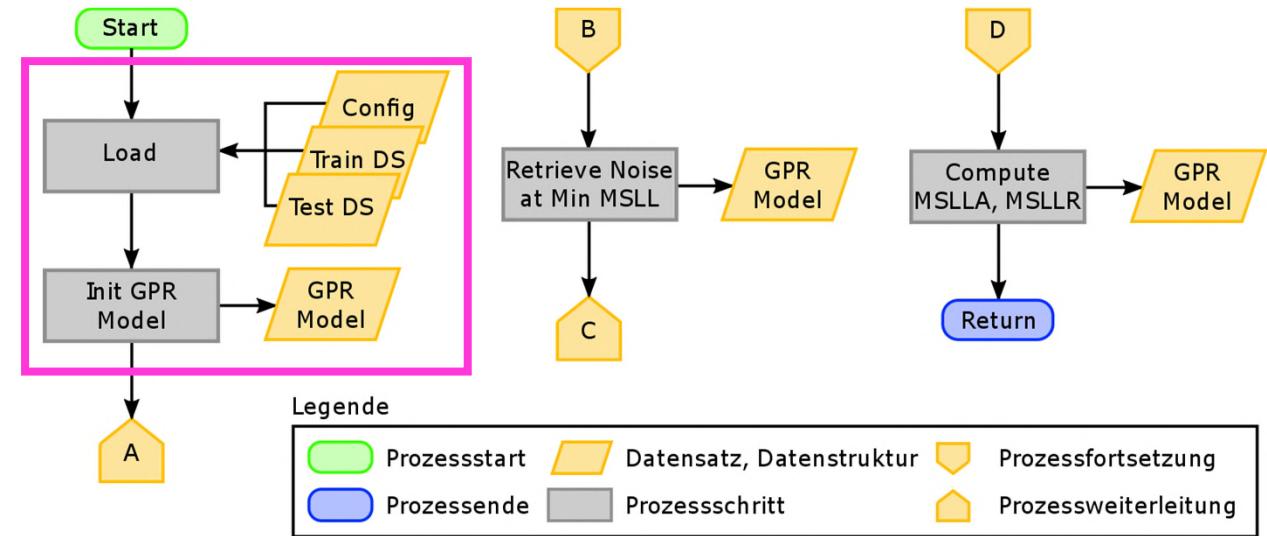
MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

# Simulation – Gauß-Prozesse

- Trainingsphase
  - Laden und Initialisierung



GPR – Gaussian Processes for Regression

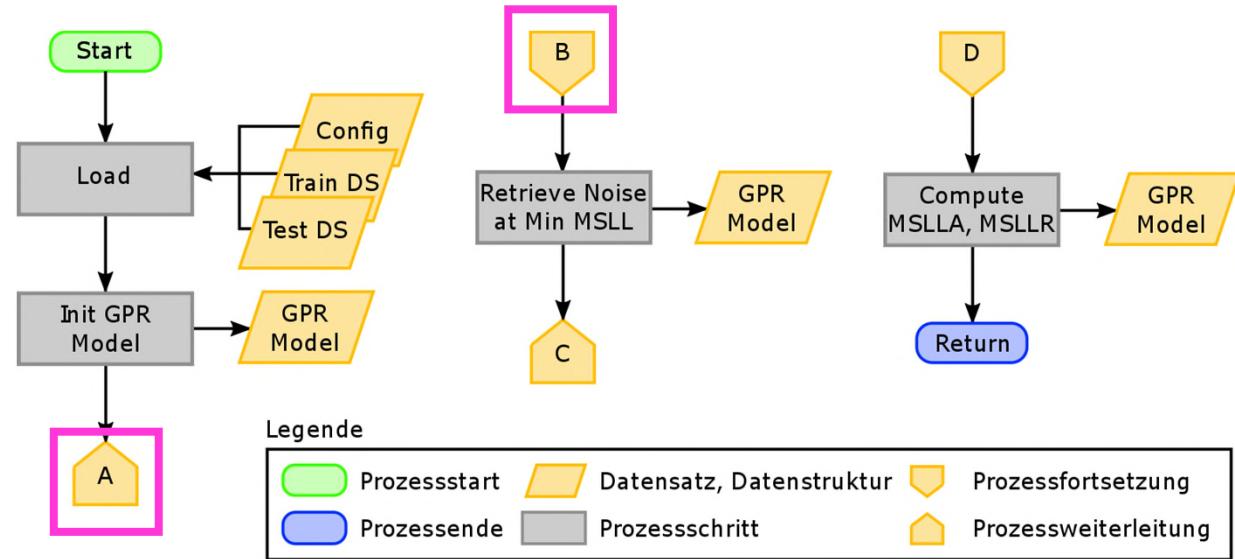
MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

# Simulation – Gauß-Prozesse

- Trainingsphase
  - Laden und Initialisierung
  - Generalisierung mit eingebetteter Skalierung



GPR – Gaussian Processes for Regression

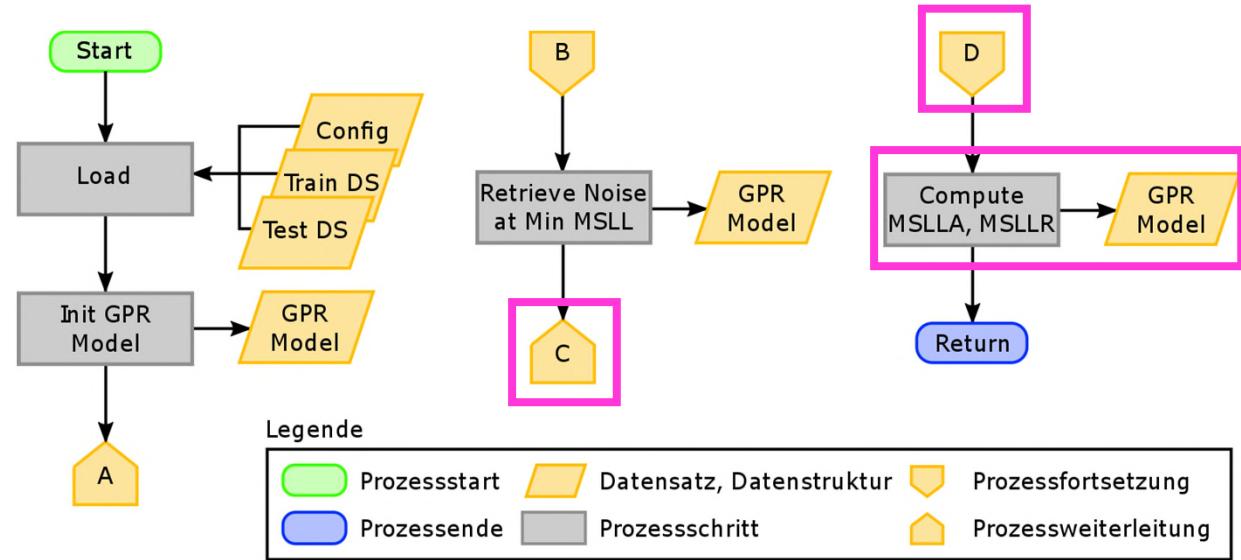
MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

# Simulation – Gauß-Prozesse

- Trainingsphase
  - Laden und Initialisierung
  - Generalisierung mit eingebetteter Skalierung
  - Finale Skalierung und Bewertung



GPR – Gaussian Processes for Regression

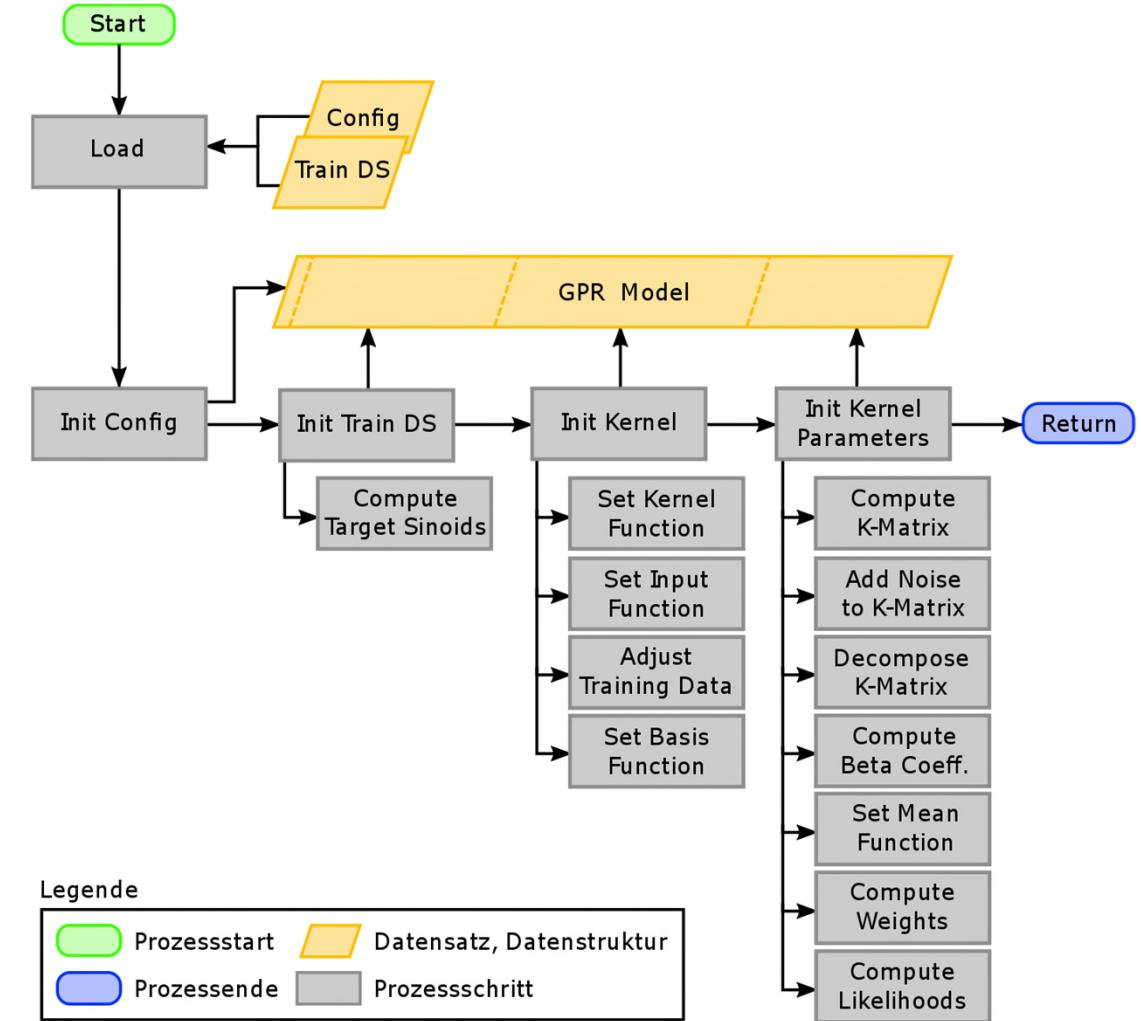
MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

# Simulation – Gauß-Prozesse

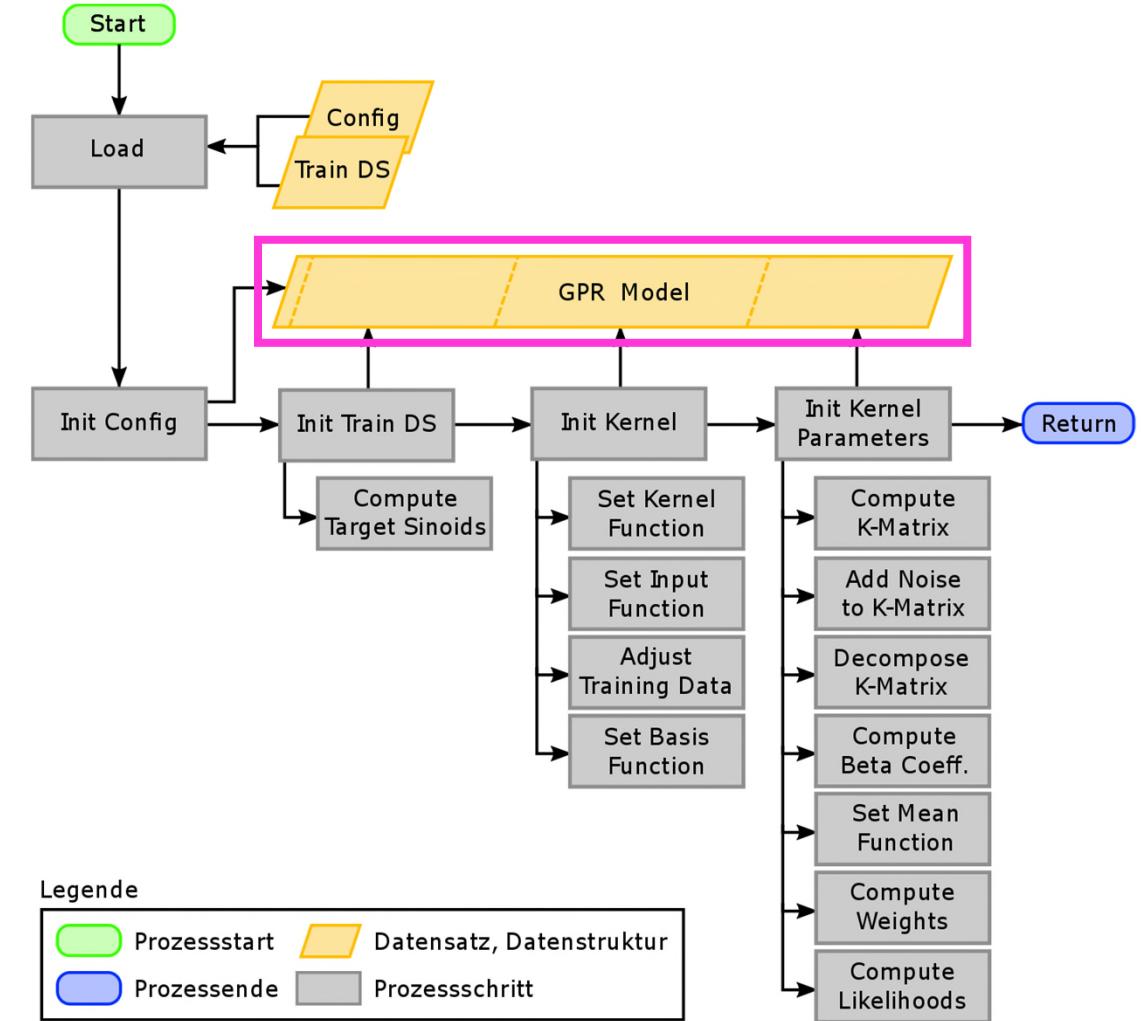
- Sequenzielle Initialisierung



GPR – Gaussian Processes for Regression  
DS – Dataset

# Simulation – Gauß-Prozesse

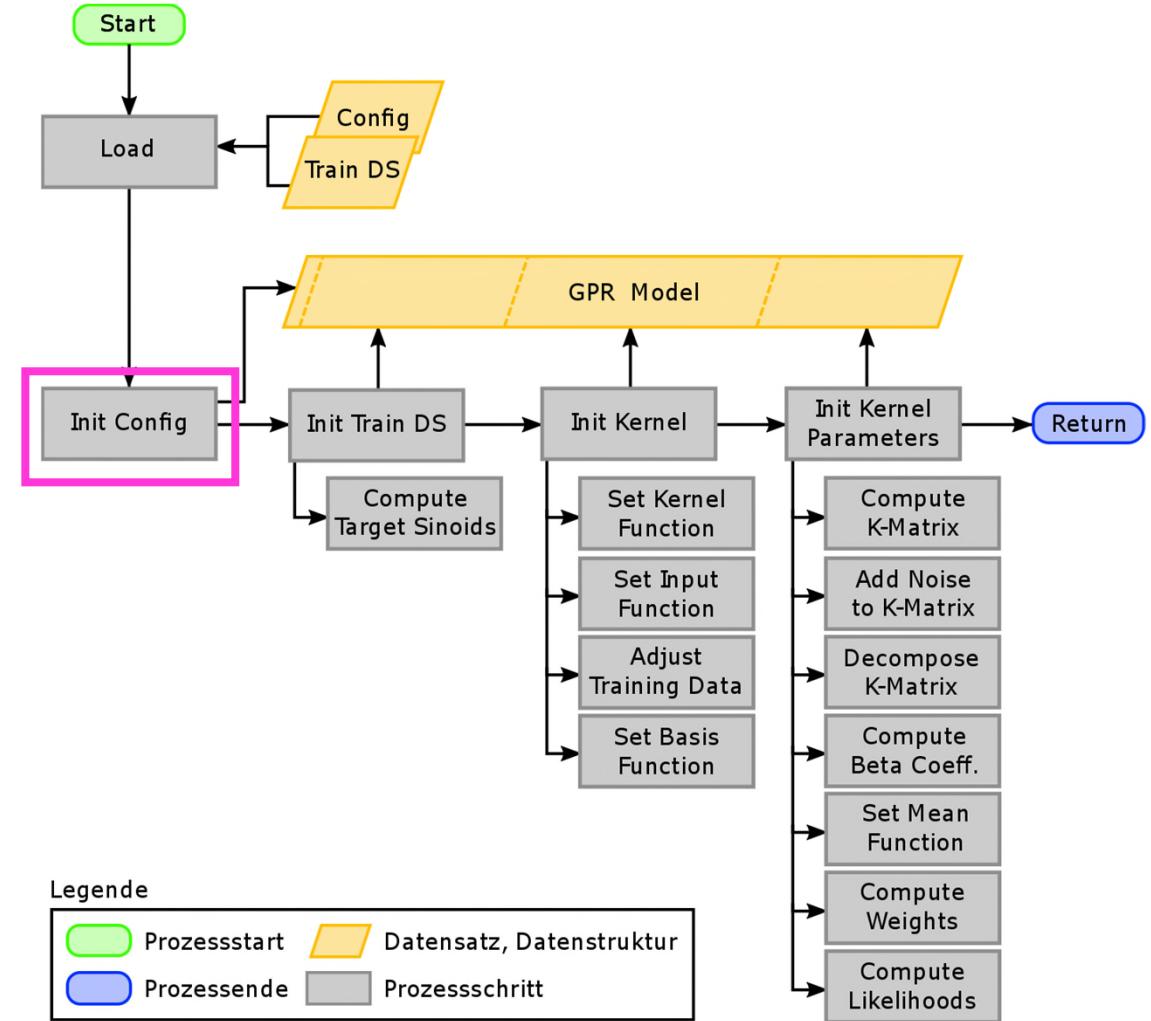
- Sequenzielle Initialisierung
  - Struct-basiertes Modell



GPR – Gaussian Processes for Regression  
DS – Dataset

# Simulation – Gauß-Prozesse

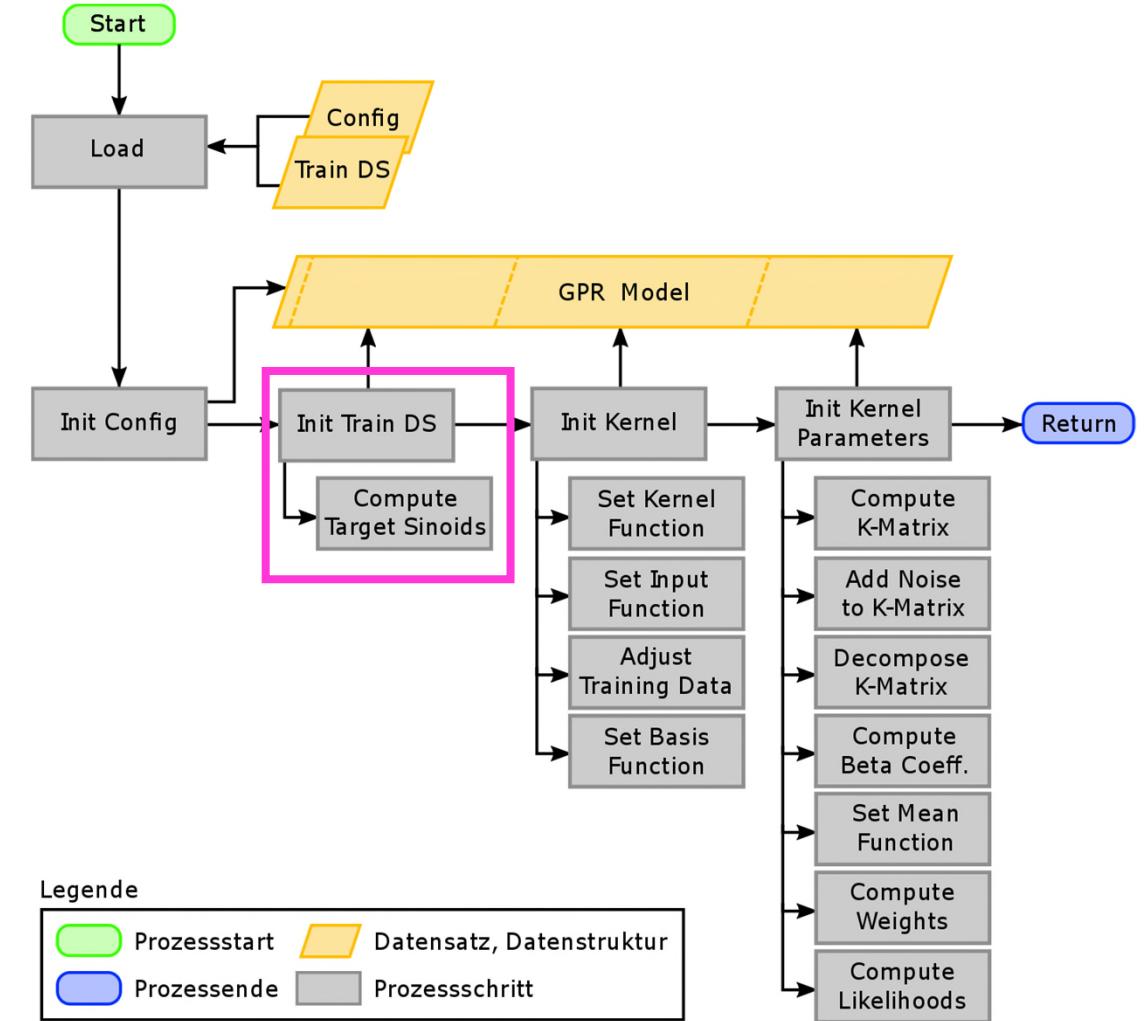
- Sequenzielle Initialisierung
  - Struct-basiertes Modell
  - Konfigurierung Framework



GPR – Gaussian Processes for Regression  
DS – Dataset

# Simulation – Gauß-Prozesse

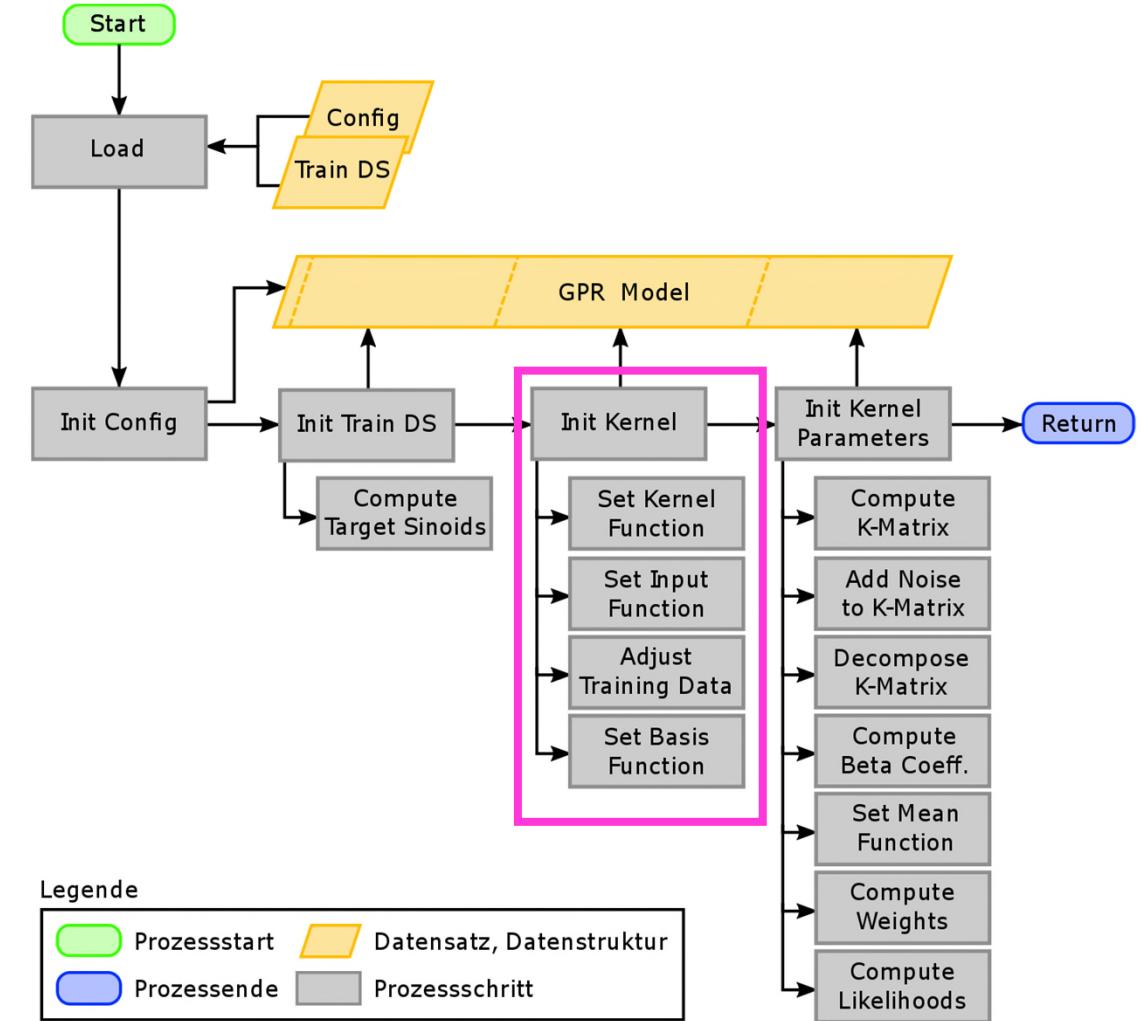
- Sequenzielle Initialisierung
  - Struct-basiertes Modell
  - Konfigurierung Framework
  - Anlegen von Referenzen



GPR – Gaussian Processes for Regression  
DS – Dataset

# Simulation – Gauß-Prozesse

- Sequenzielle Initialisierung
  - Struct-basiertes Modell
  - Konfigurierung Framework
  - Anlegen von Referenzen
  - Laden der Funktionalität

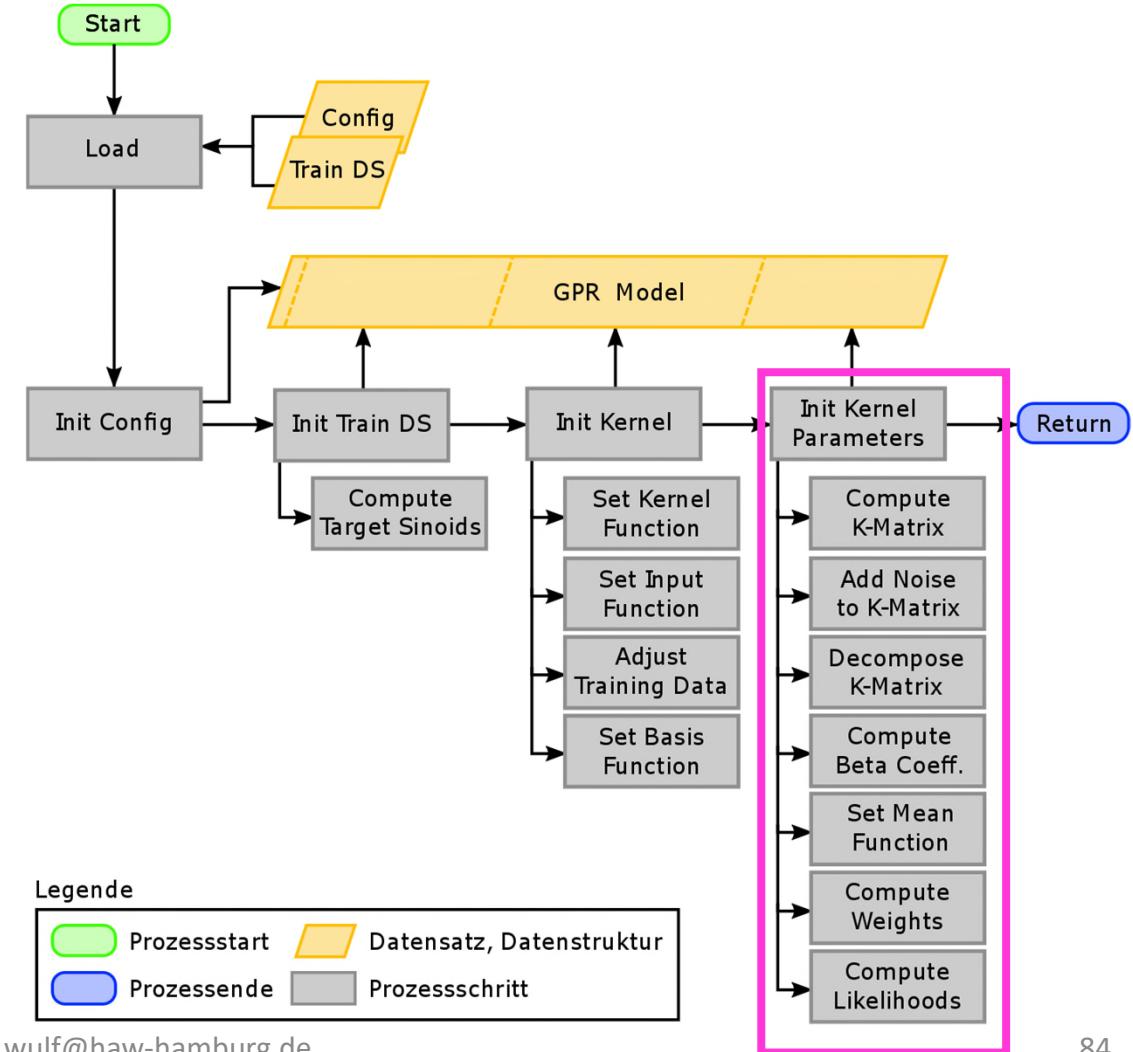


GPR – Gaussian Processes for Regression  
DS – Dataset

# Simulation – Gauß-Prozesse

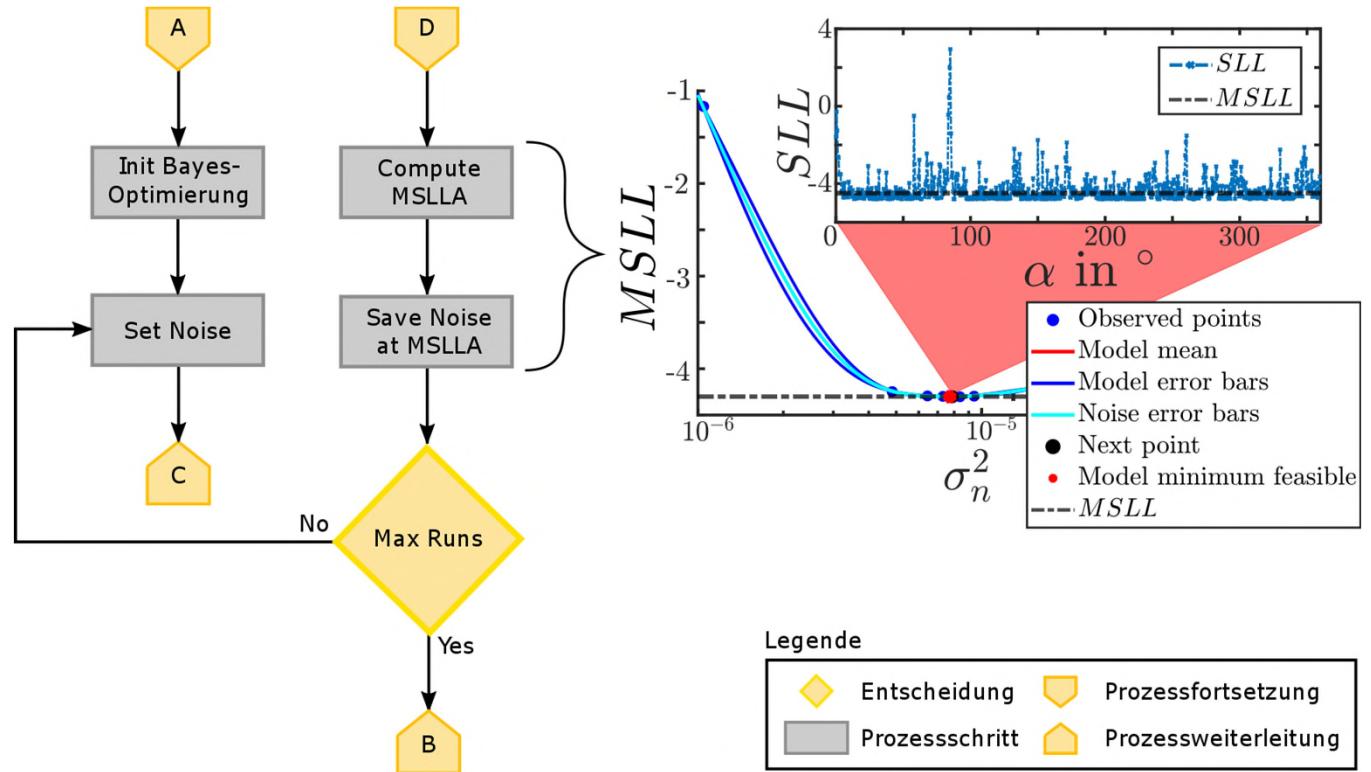
- Sequenzielle Initialisierung
  - Struct-basiertes Modell
  - Konfigurierung Framework
  - Anlegen von Referenzen
  - Laden der Funktionalität
  - Modellparametrierung

GPR – Gaussian Processes for Regression  
DS – Dataset



# Simulation – Gauß-Prozesse

- Generalisierung



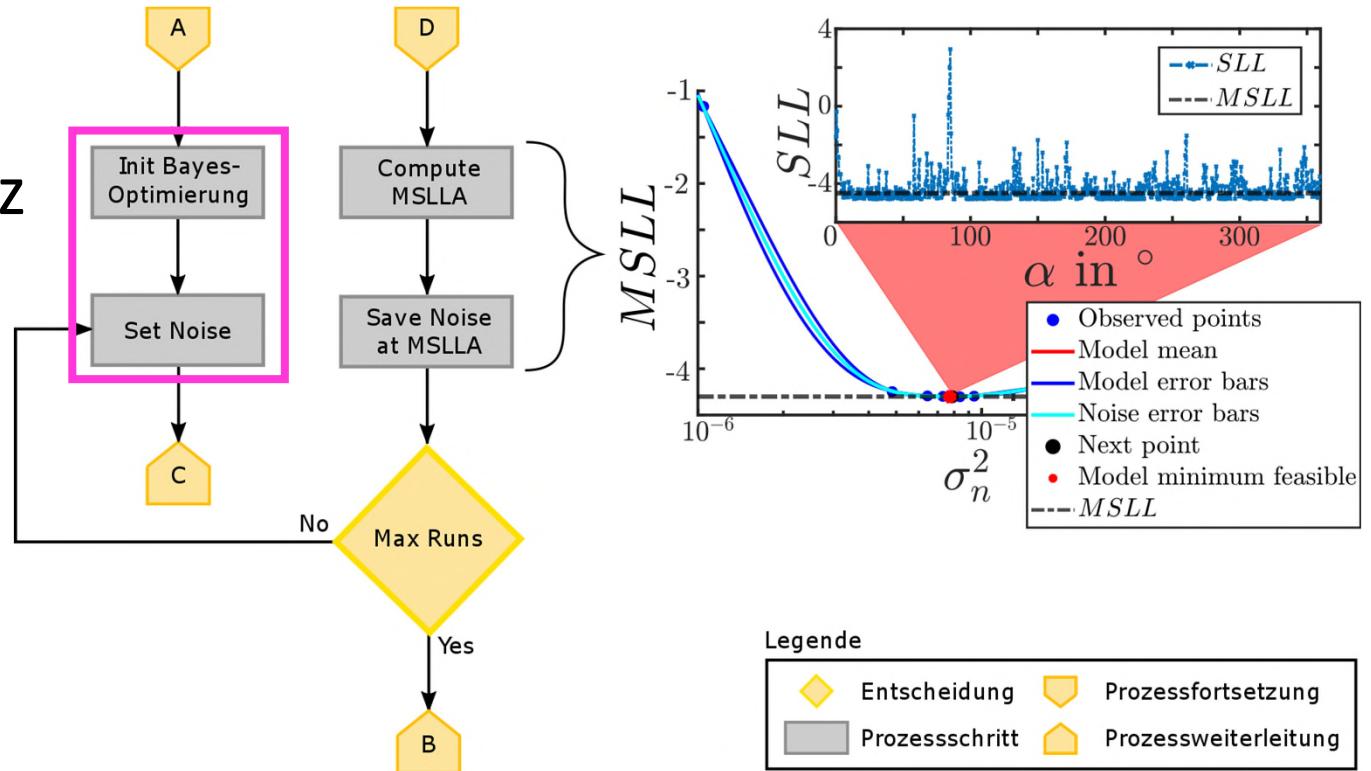
SLL – Standardized-Logarithmic-Loss

MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

# Simulation – Gauß-Prozesse

- Generalisierung
  - Setzen der Noise-Varianz



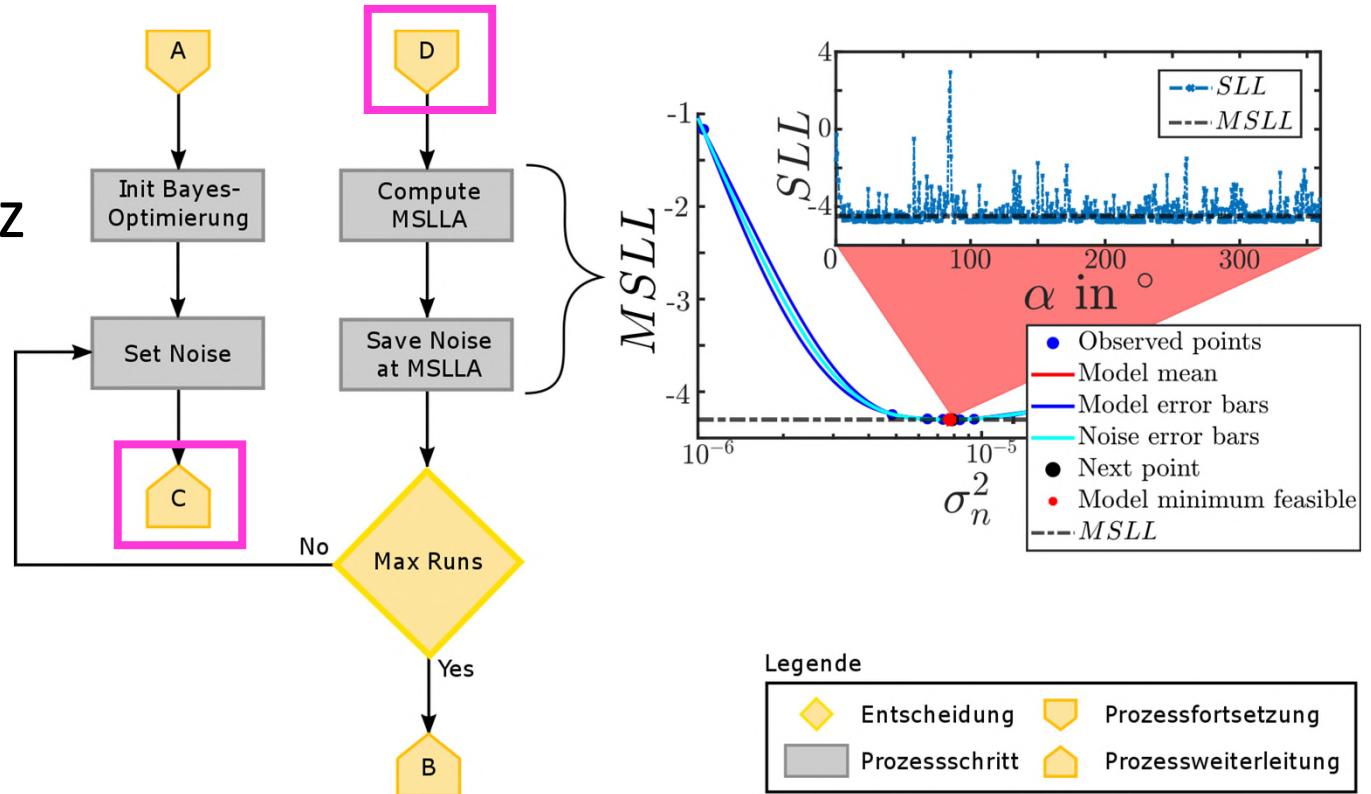
SLL – Standardized-Logarithmic-Loss

MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

# Simulation – Gauß-Prozesse

- Generalisierung
  - Setzen der Noise-Varianz
  - Kernel-Skalierung



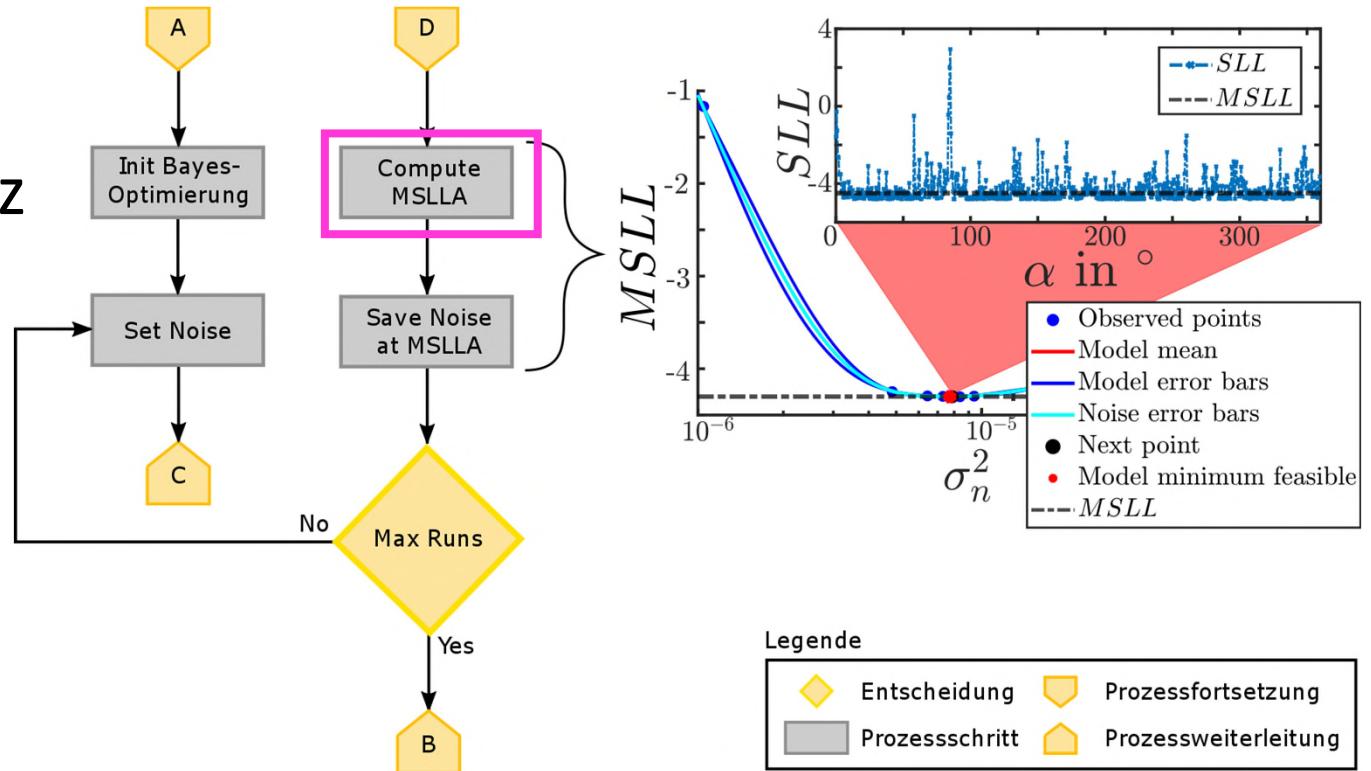
SLL – Standardized-Logarithmic-Loss

MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

# Simulation – Gauß-Prozesse

- Generalisierung
  - Setzen der Noise-Varianz
  - Kernel-Skalierung
  - Verlustberechnung



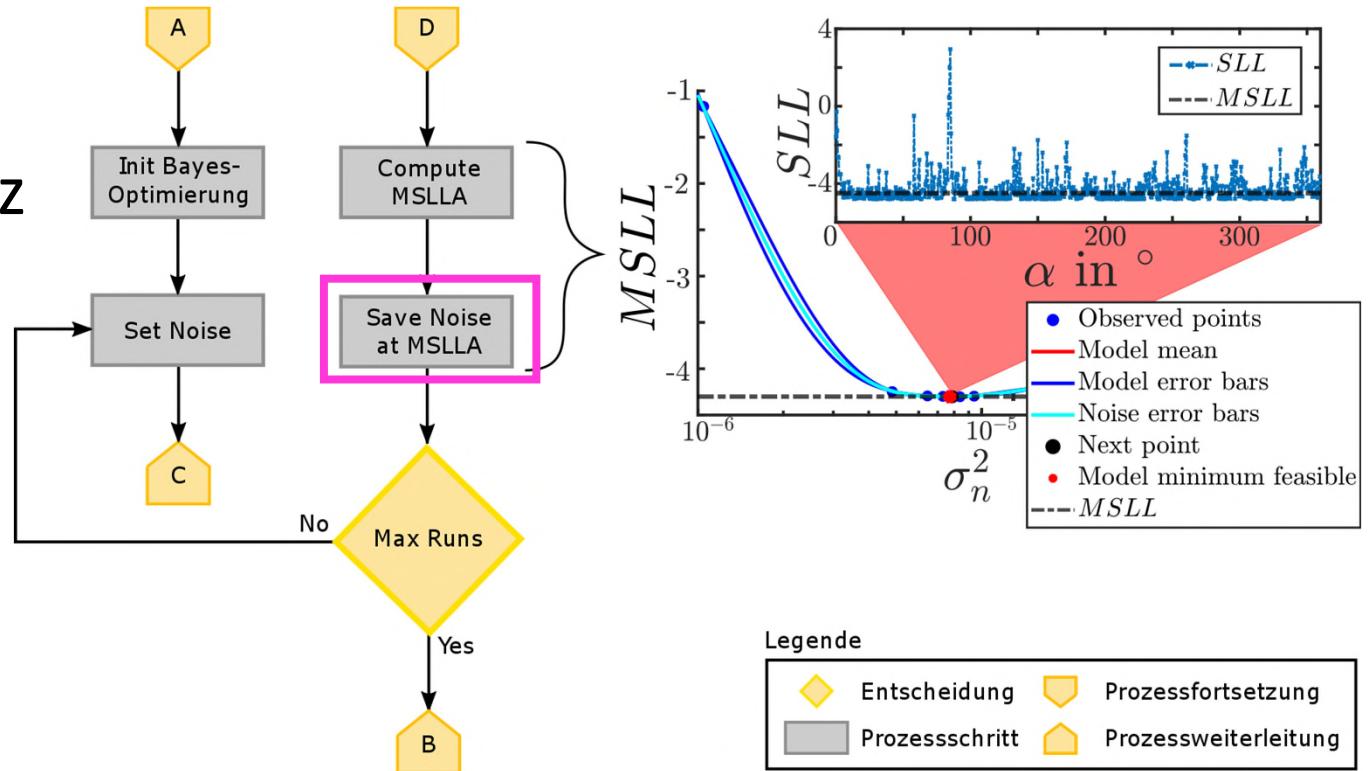
SLL – Standardized-Logarithmic-Loss

MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

# Simulation – Gauß-Prozesse

- Generalisierung
  - Setzen der Noise-Varianz
  - Kernel-Skalierung
  - Verlustberechnung
  - Speichern



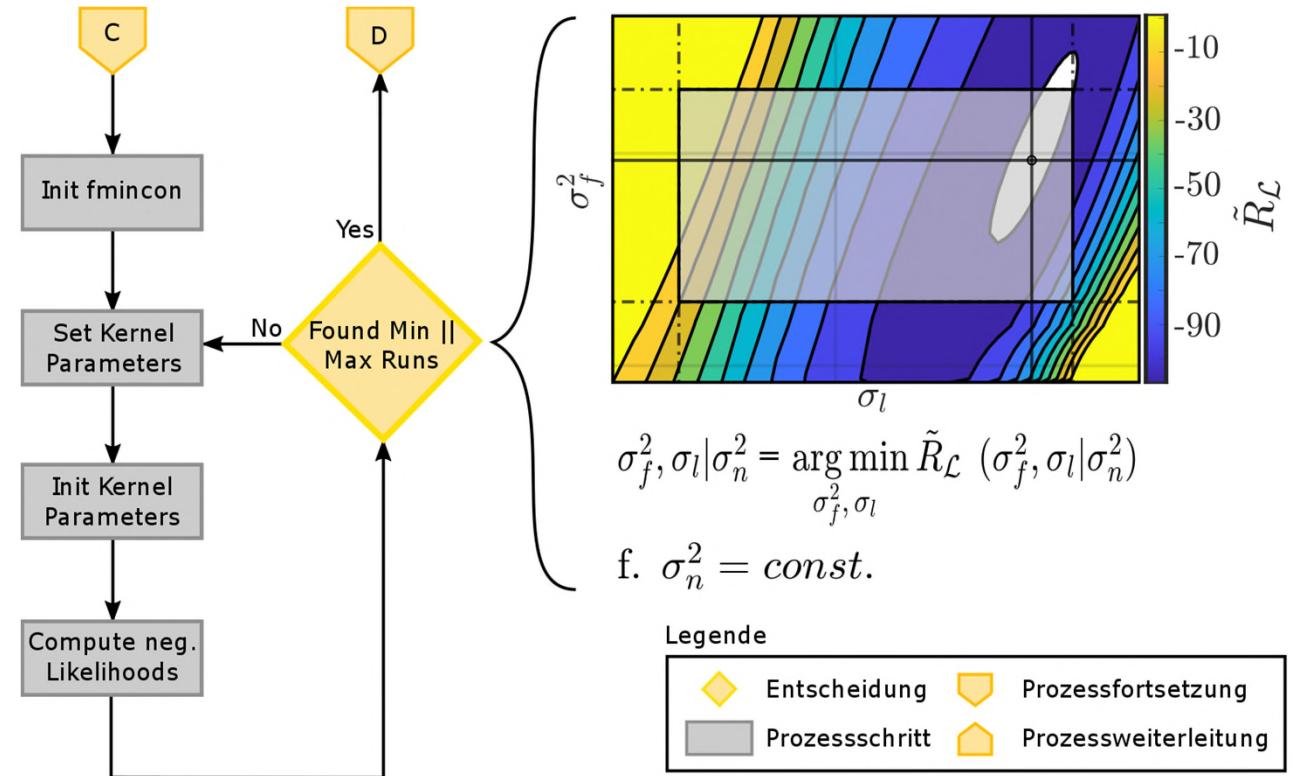
SLL – Standardized-Logarithmic-Loss

MSLL – Mean-Standardized-Logarithmic-Loss

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

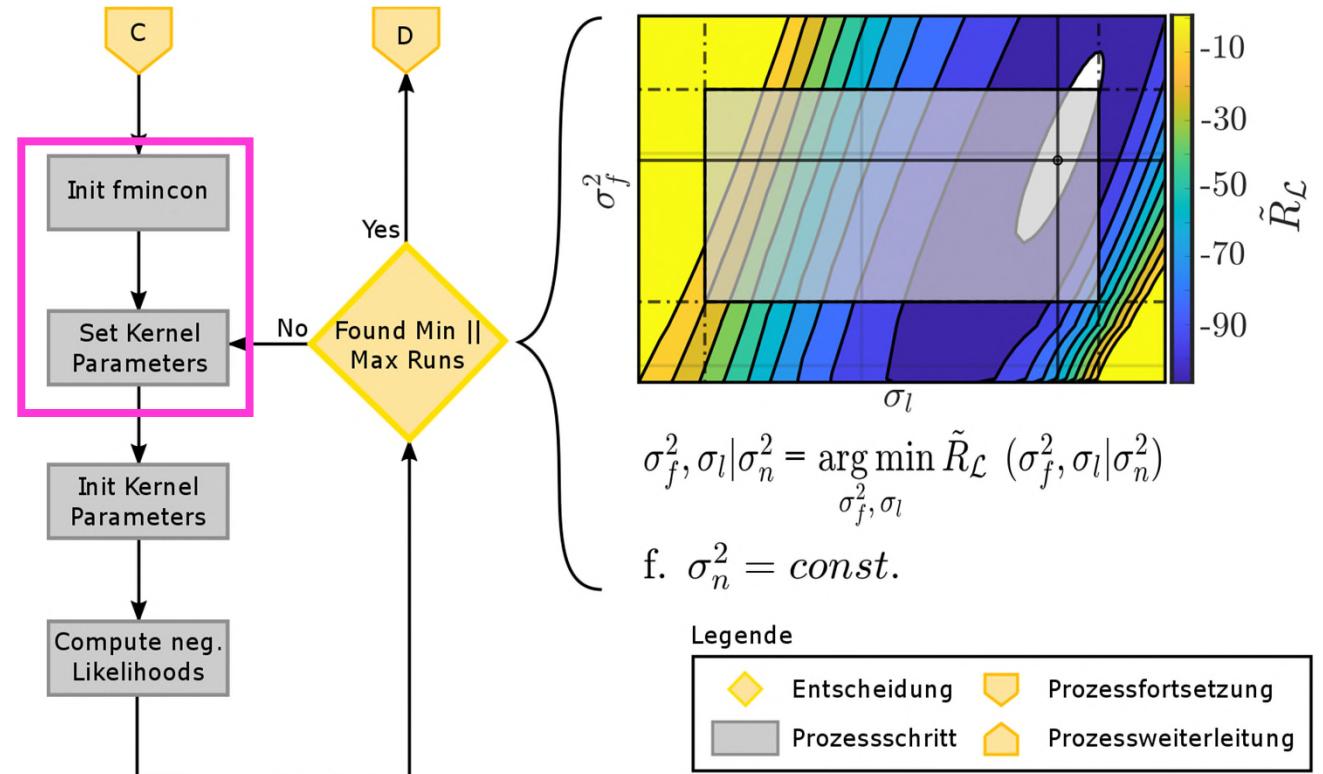
# Simulation – Gauß-Prozesse

- Kernel-Skalierung



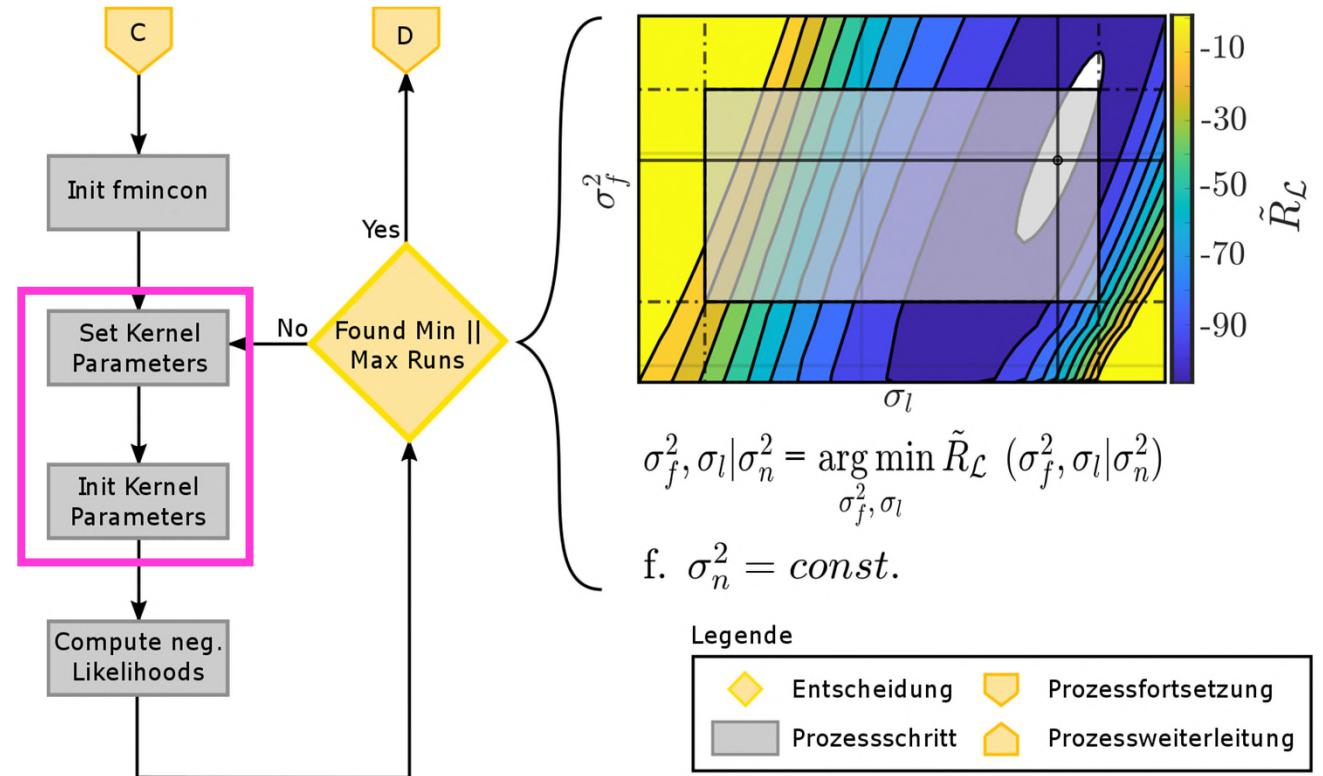
# Simulation – Gauß-Prozesse

- Kernel-Skalierung
  - Setzen der Parameter



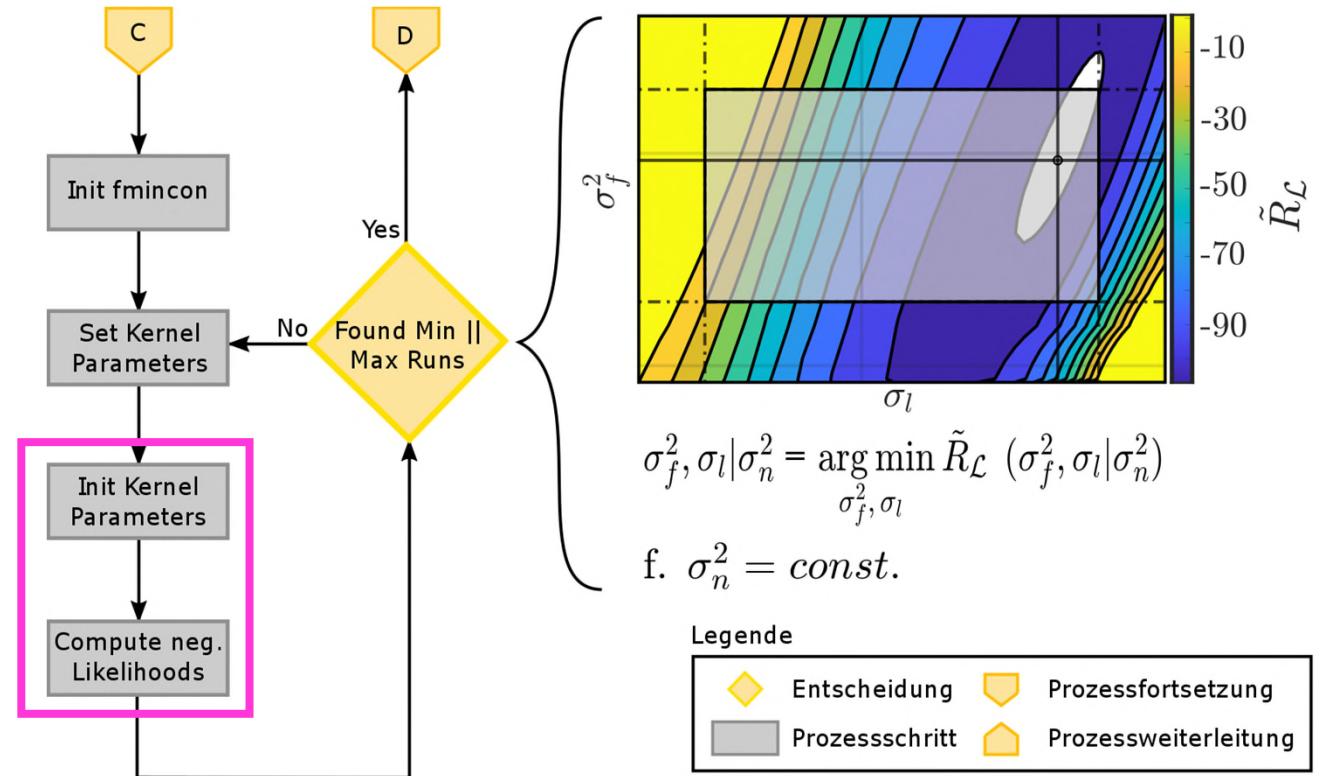
# Simulation – Gauß-Prozesse

- Kernel-Skalierung
  - Setzen der Parameter
  - Teilreinitialisierung



# Simulation – Gauß-Prozesse

- Kernel-Skalierung
  - Setzen der Parameter
  - Teilreinitialisierung
  - Plausibilitätsberechnung



- Arbeitsphase

- Arbeitsphase
  - Ausrichtung des Modells wird von Innen nach Außen umgelegt

- Arbeitsphase
  - Ausrichtung des Modells wird von Innen nach Außen umgelegt
  - Minimale Parametrierung und funktionaler Aufbau der Vorhersage

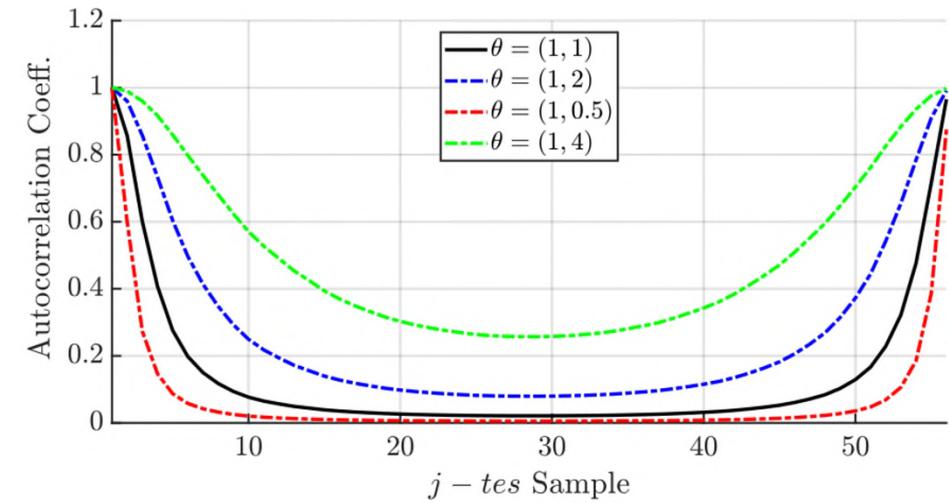
- Arbeitsphase
  - Ausrichtung des Modells wird von Innen nach Außen umgelegt
  - Minimale Parametrierung und funktionaler Aufbau der Vorhersage
  - Vorhersage ausgeführt Frame für Frame oder blockweise

- Arbeitsphase
  - Ausrichtung des Modells wird von Innen nach Außen umgelegt
  - Minimale Parametrierung und funktionaler Aufbau der Vorhersage
  - Vorhersage ausgeführt Frame für Frame oder blockweise
  - Ergebnisse, Derivate und Qualitätskriterien als Vektoren ausgegeben

# Erprobungsexperimente

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- Skalierung der Kovarianzfunktion



— SLLA	- - SLLR	— MSLLA	- - MSLLR
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SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

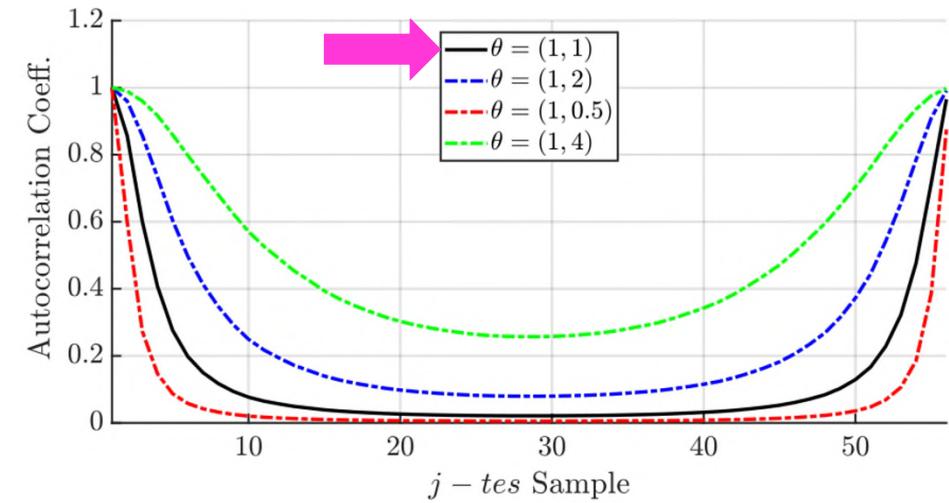
MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

# Erprobungsexperimente

---

- Skalierung der Kovarianzfunktion
  - Empirisch ohne Optimierung
  - Bewertung der Generalisierung



— SLLA	- - - SLLR	— MSLLA	- - - MSLLR
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SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

# Erprobungsexperimente

- Skalierung der Kovarianzfunktion
  - Empirisch ohne Optimierung
  - Bewertung der Generalisierung

**Ausgeschaltet**



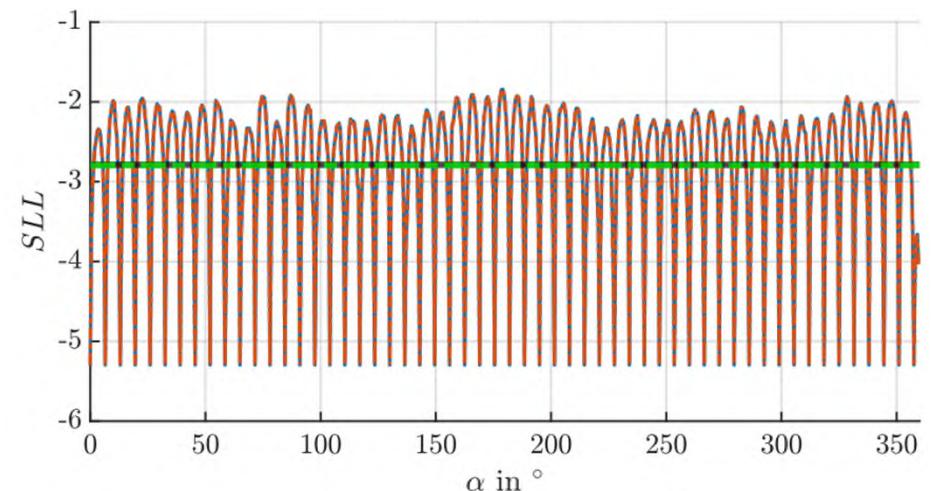
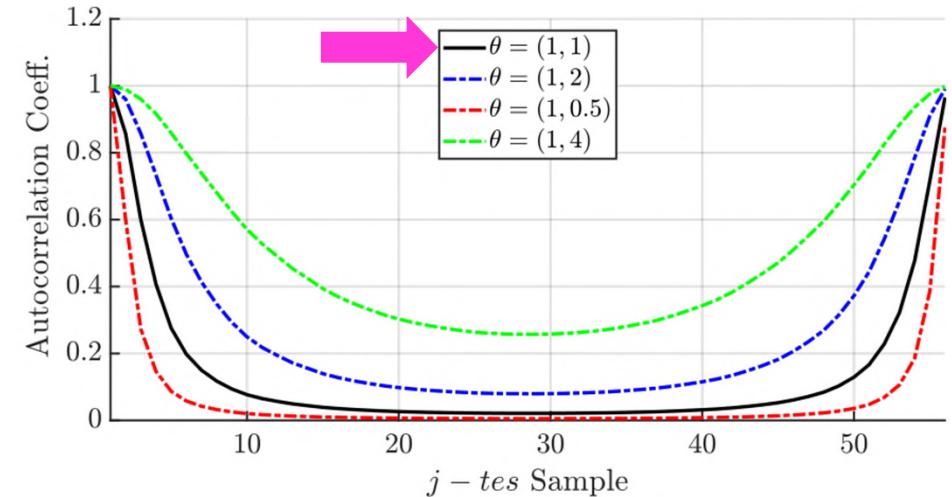
SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

02.07.2021



# Erprobungsexperimente

- Skalierung der Kovarianzfunktion
  - Empirisch ohne Optimierung
  - Bewertung der Generalisierung

Ausgeschaltet



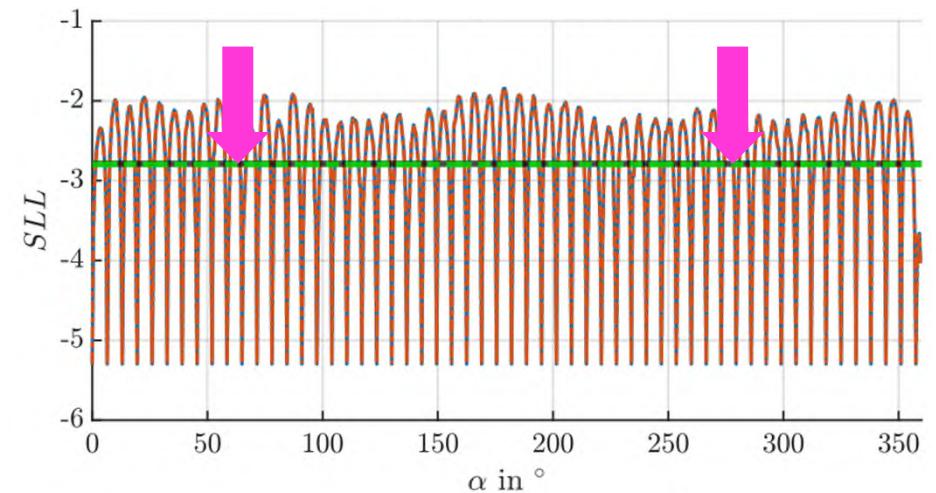
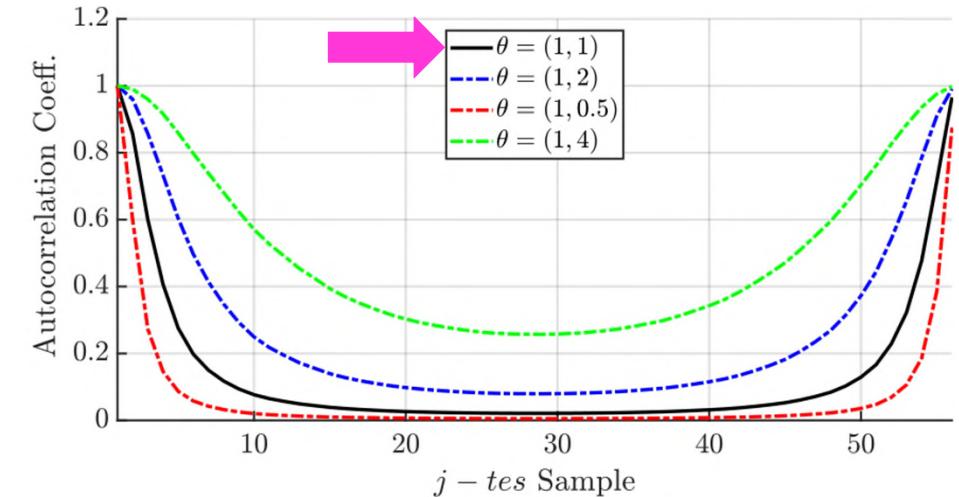
SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

02.07.2021



# Erprobungsexperimente

- Skalierung der Kovarianzfunktion
  - Empirisch ohne Optimierung
  - Bewertung der Generalisierung

**Verschlechtert**

SLLA	SLLR	MSLLA	MSLLR
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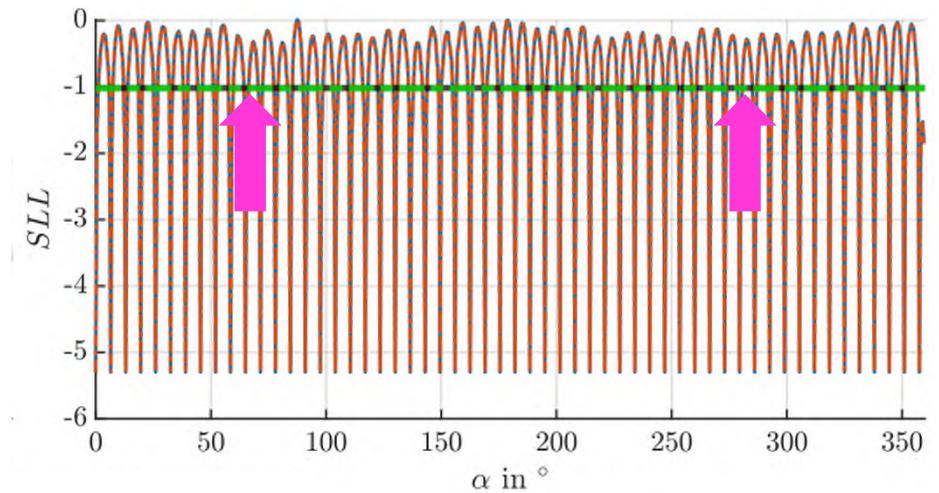
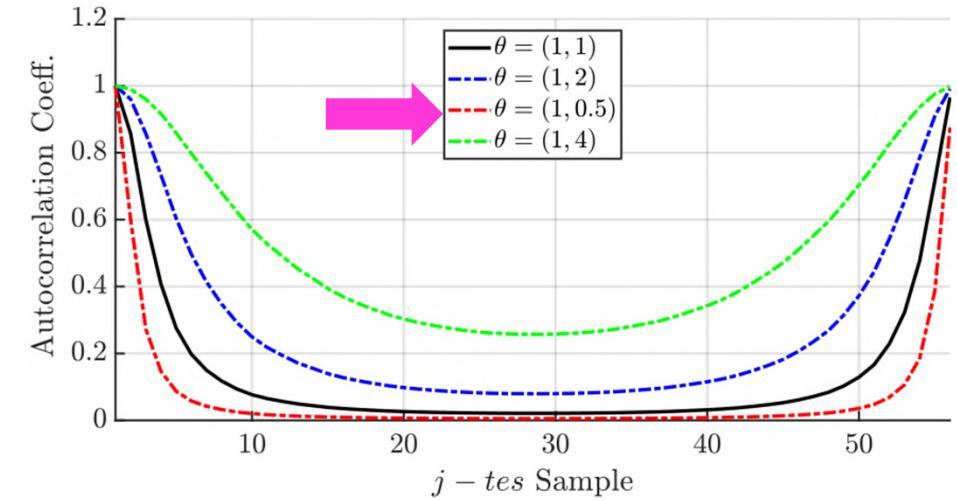
SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

02.07.2021



# Erprobungsexperimente

- Skalierung der Kovarianzfunktion
  - Empirisch ohne Optimierung
  - Bewertung der Generalisierung

**Verbessert**



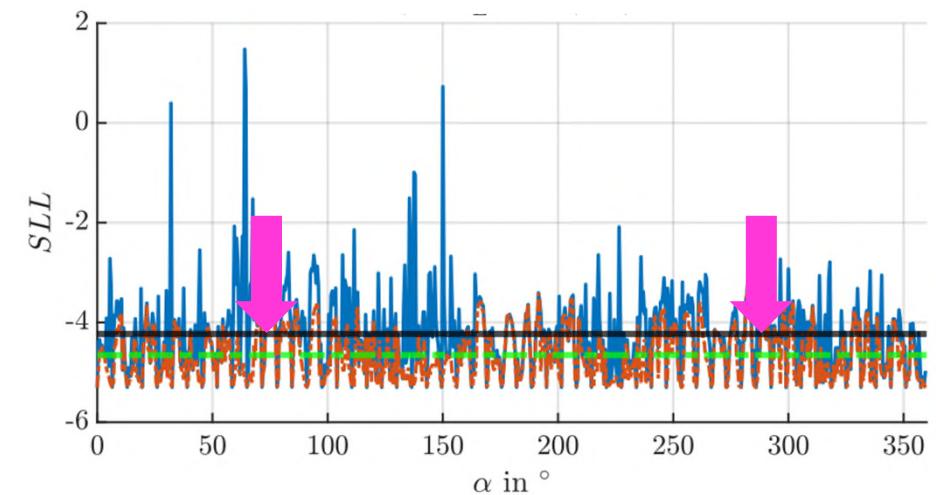
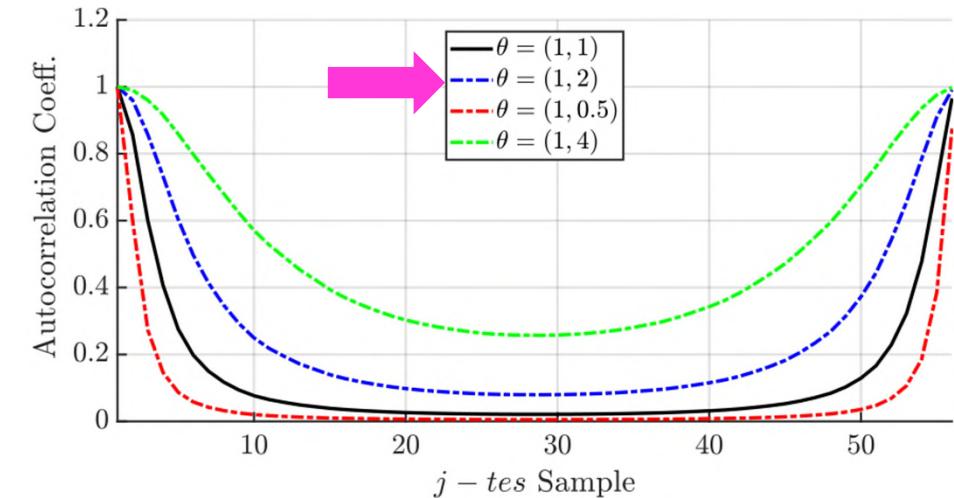
SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

02.07.2021



# Erprobungsexperimente

- Skalierung der Kovarianzfunktion
  - Empirisch ohne Optimierung
  - Bewertung der Generalisierung

**Verbessert**



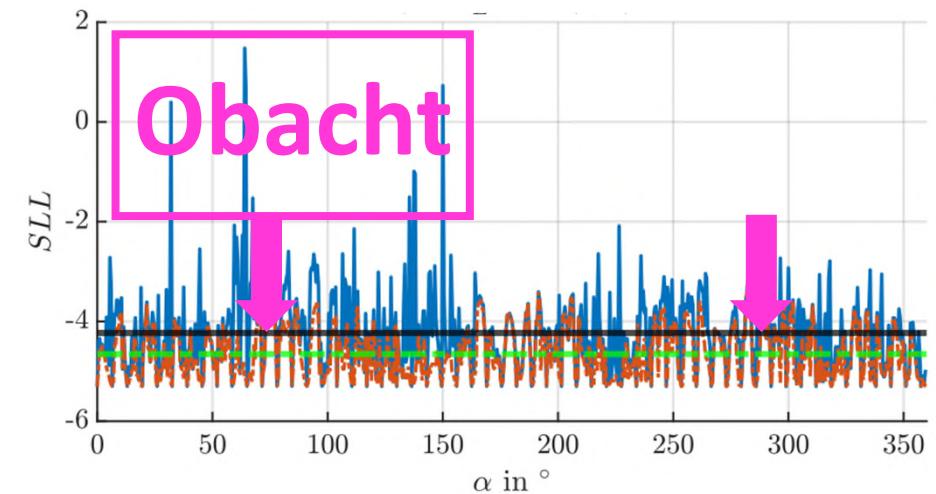
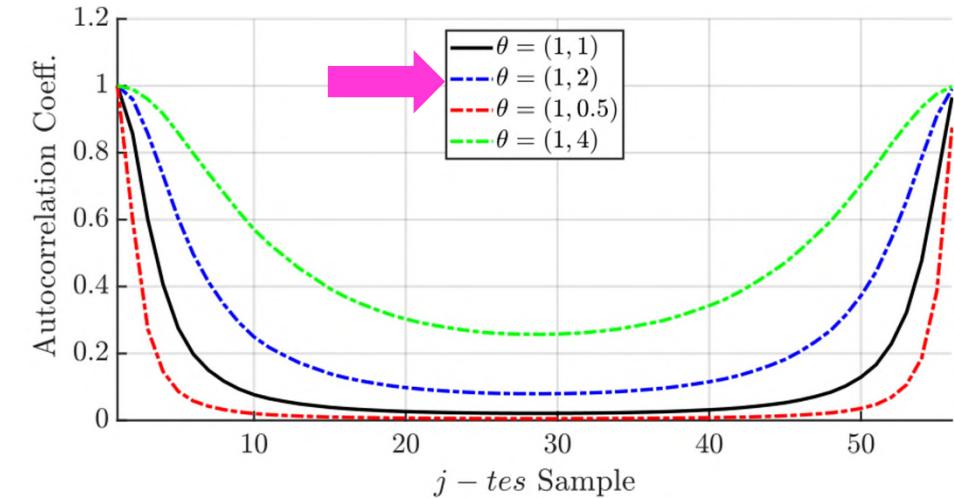
SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

02.07.2021



# Erprobungsexperimente

- Skalierung der Kovarianzfunktion
  - Empirisch ohne Optimierung
  - Bewertung der Generalisierung

**Optimierbar**



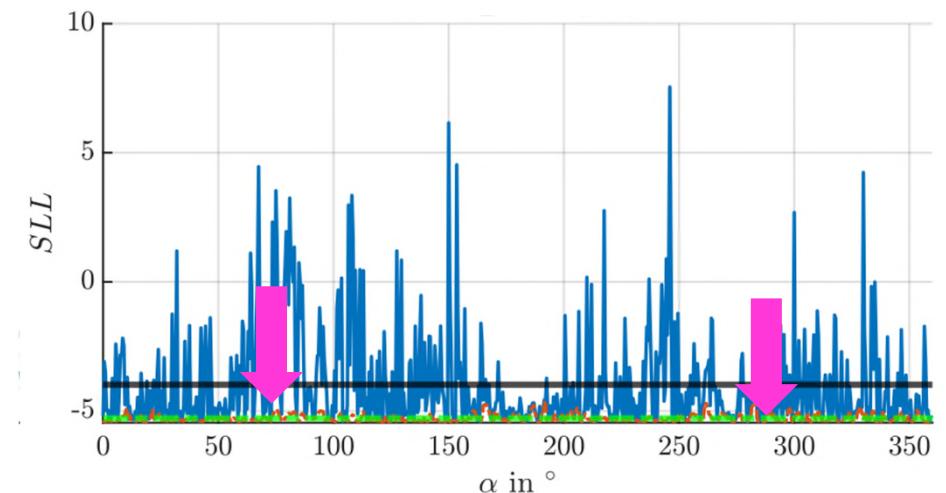
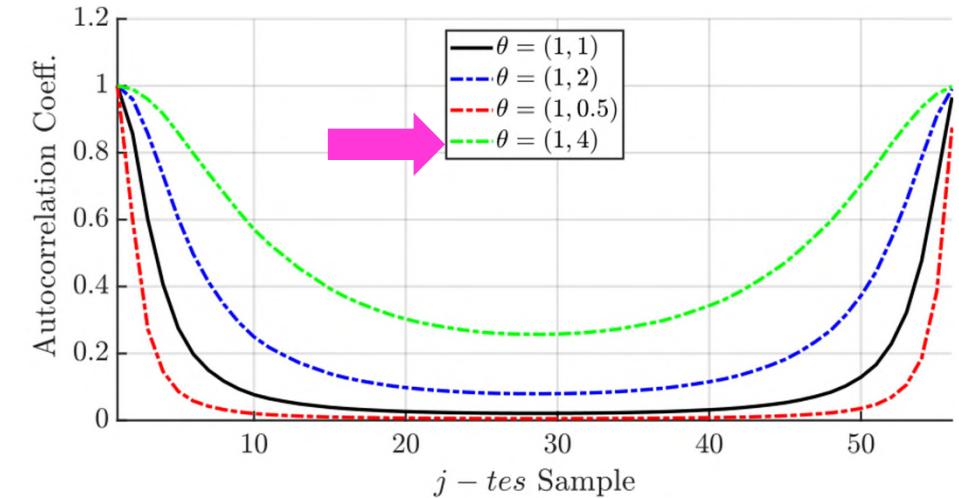
SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

02.07.2021



# Erprobungsexperimente

- Skalierung der Kovarianzfunktion
  - Empirisch ohne Optimierung
  - Bewertung der Generalisierung

**Optimierbar**



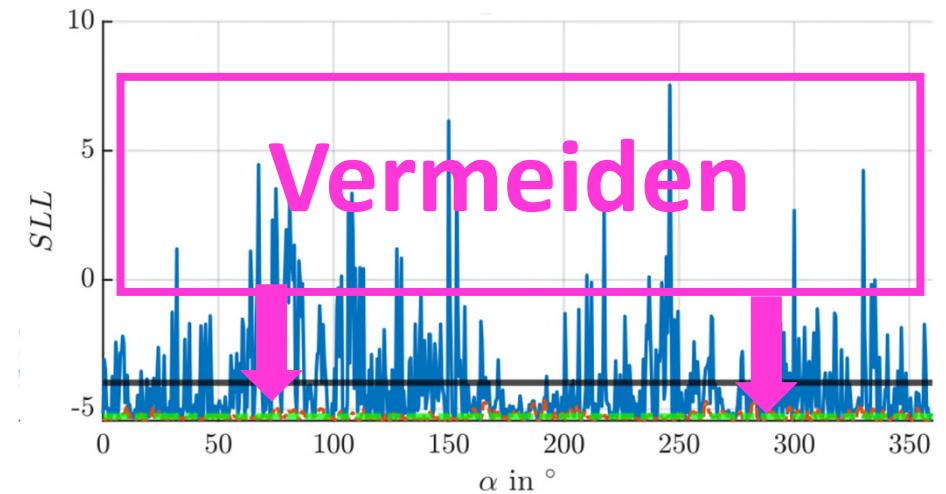
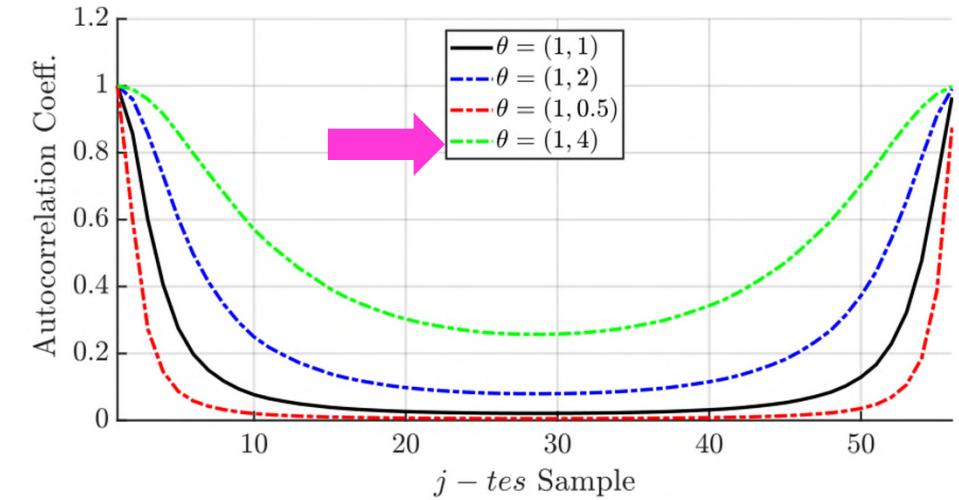
SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

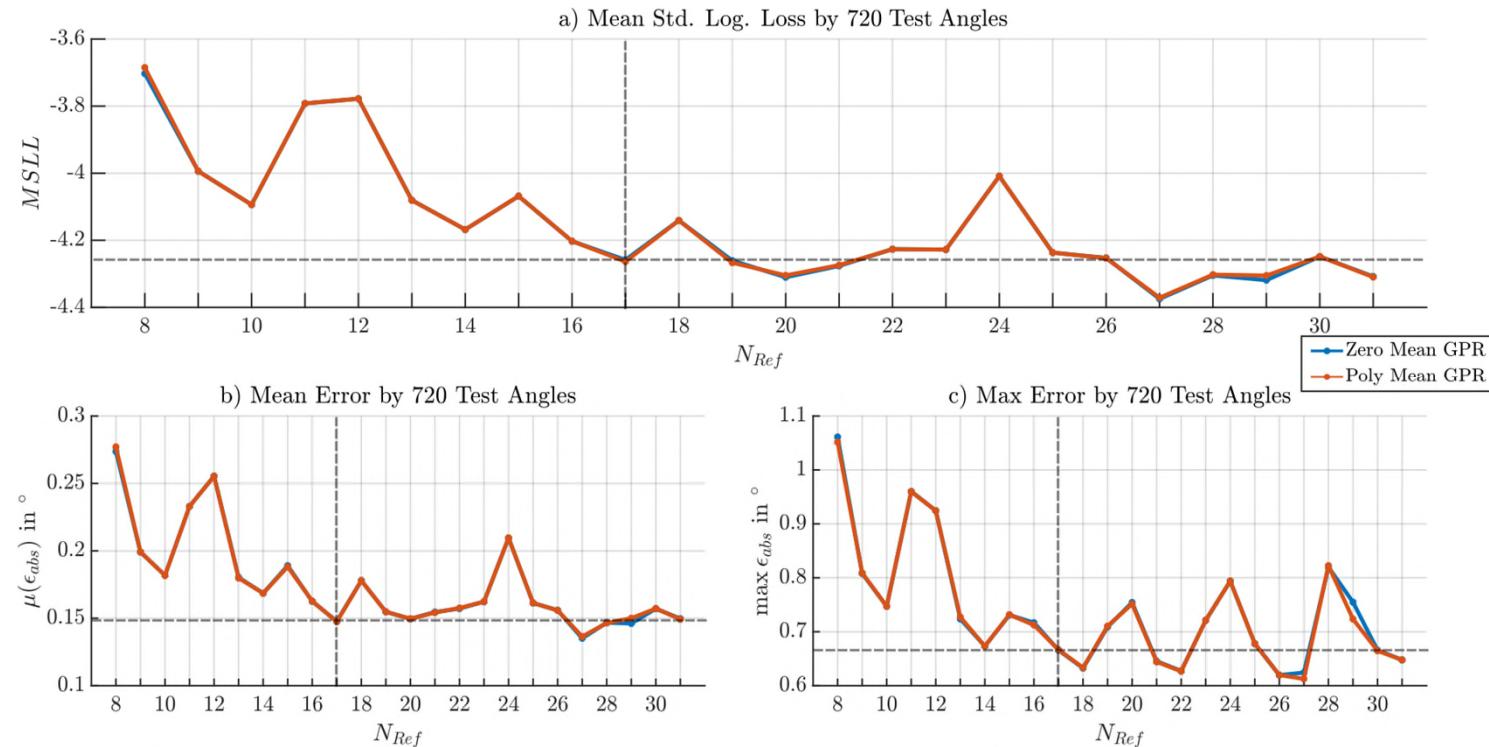
02.07.2021



# Erprobungsexperimente

---

- Kompromissbildung

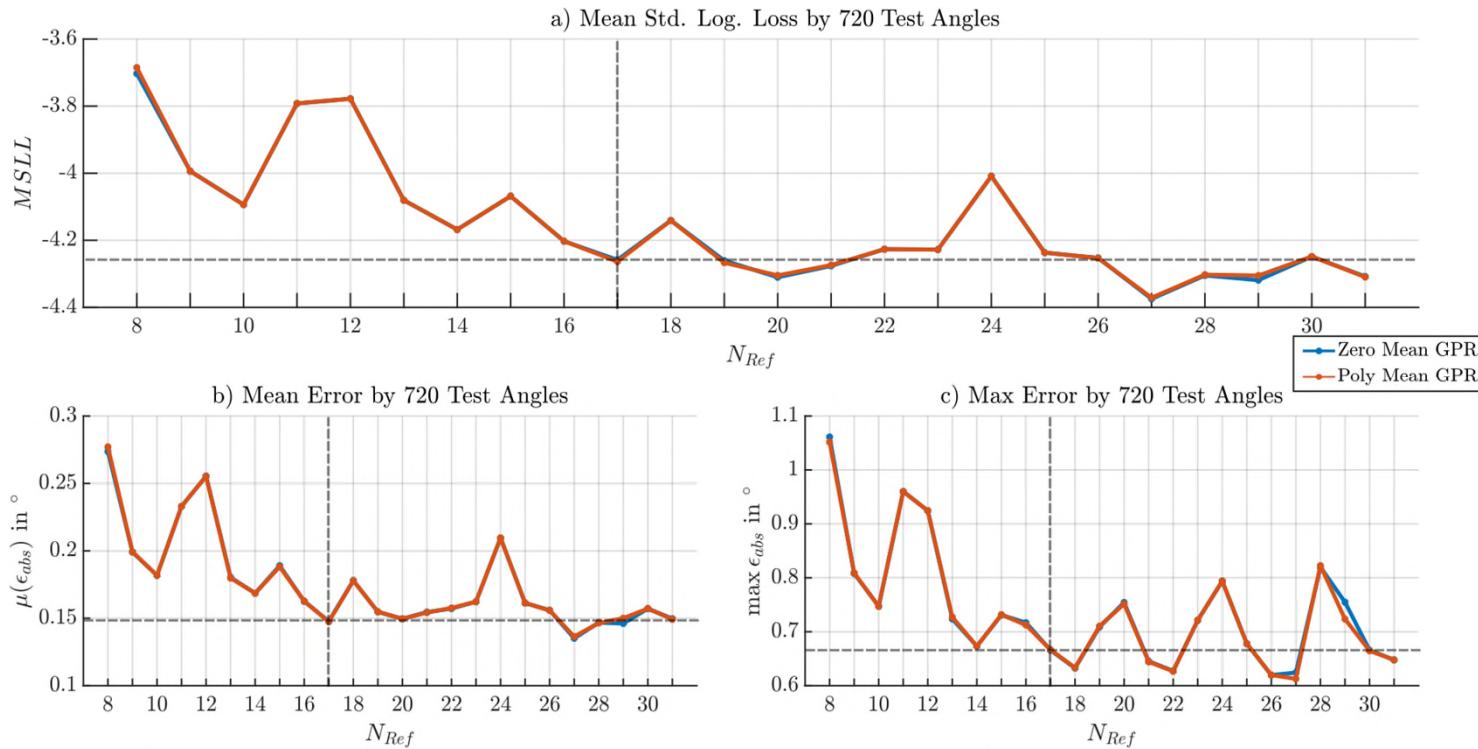


MSLL – Mean-Standardized-Logarithmic-Loss

# Erprobungsexperimente

---

- Kompormissbildung
  - Optimierung zusschalten

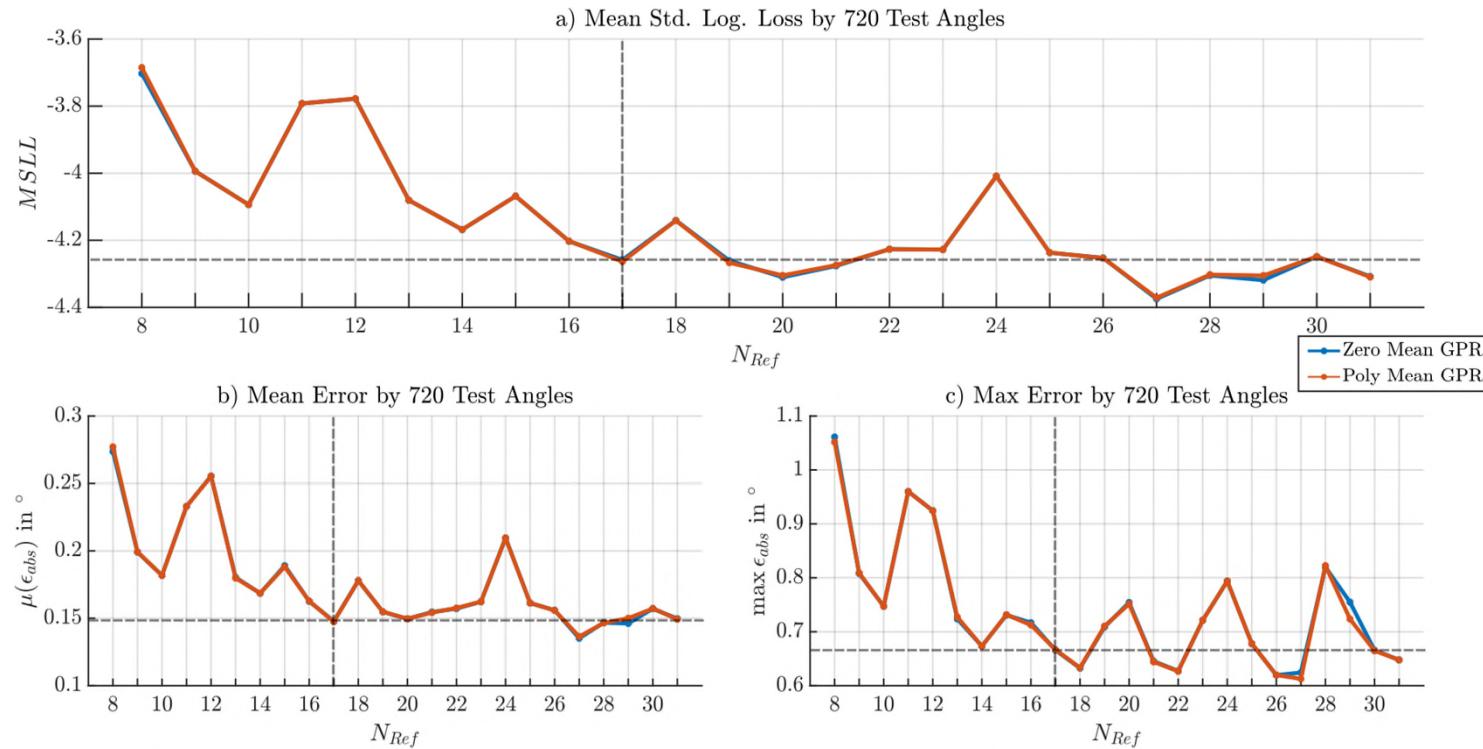


MSLL – Mean-Standardized-Logarithmic-Loss

# Erprobungsexperimente

---

- Kompromissbildung
  - Optimierung zusschalten
  - Ressourceneinsparung

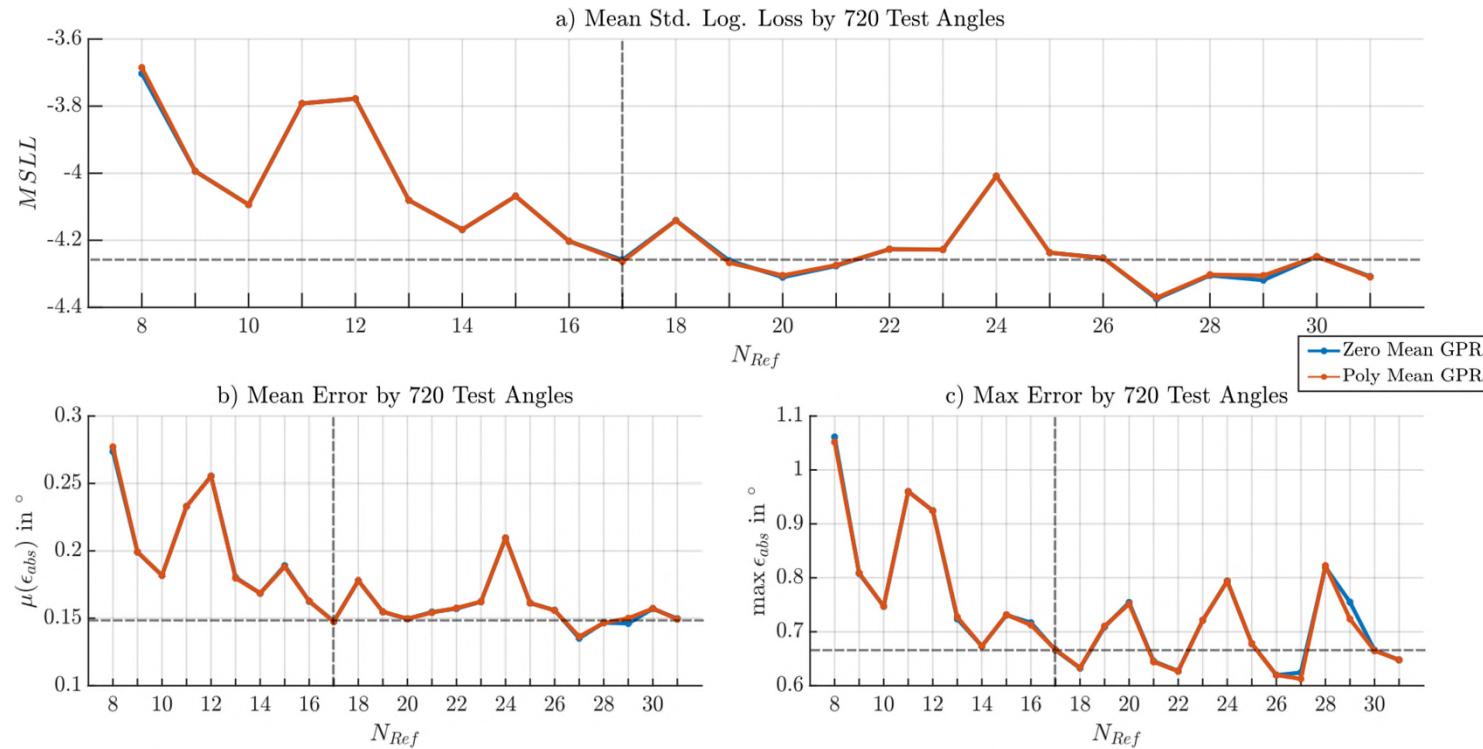


MSLL – Mean-Standardized-Logarithmic-Loss

# Erprobungsexperimente

---

- Kompromissbildung
  - Optimierung zusschalten
  - Ressourceneinsparung
  - Aufwandabschätzung

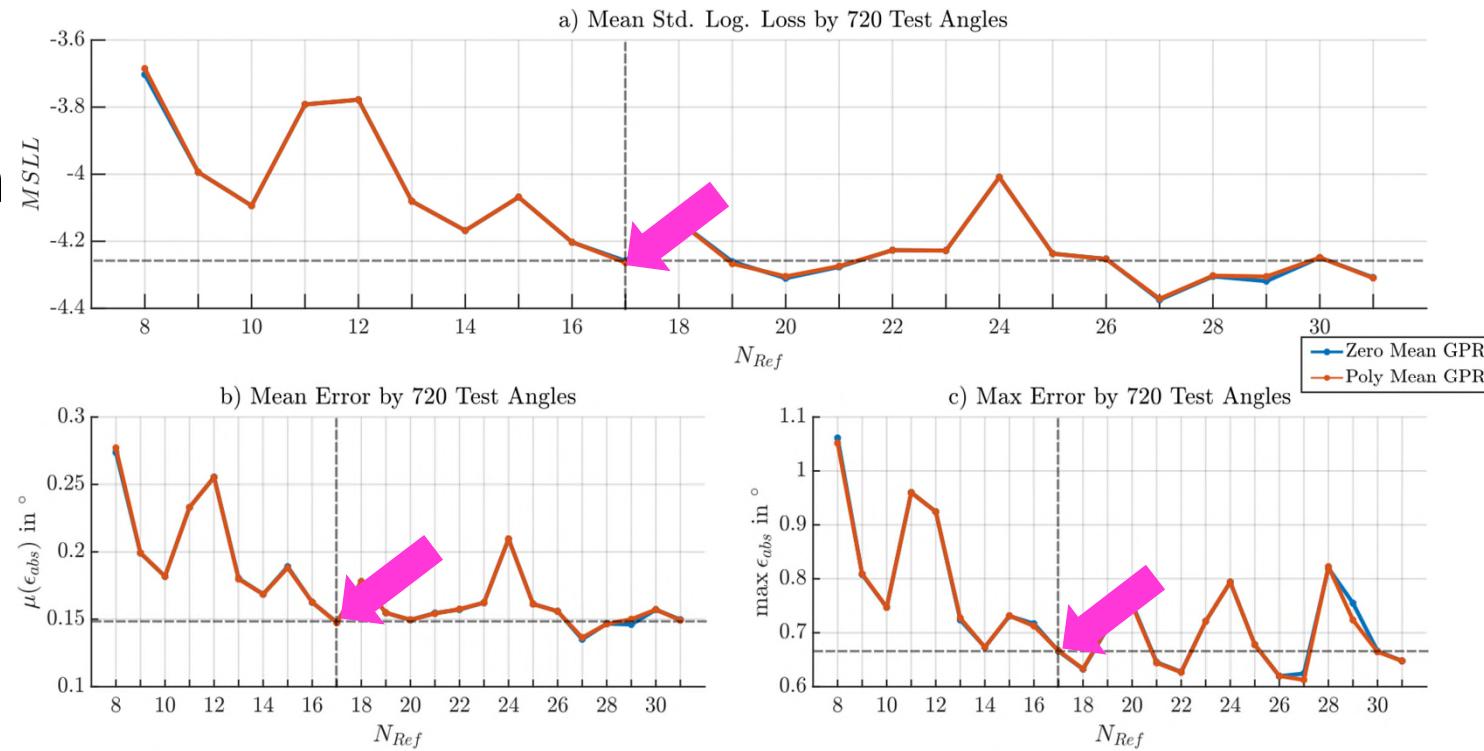


MSLL – Mean-Standardized-Logarithmic-Loss

# Erprobungsexperimente

---

- Kompromissbildung
  - Optimierung zusschalten
  - Ressourceneinsparung
  - Aufwandabschätzung
  - Gleichgewicht zwischen Fehlern und Verlusten

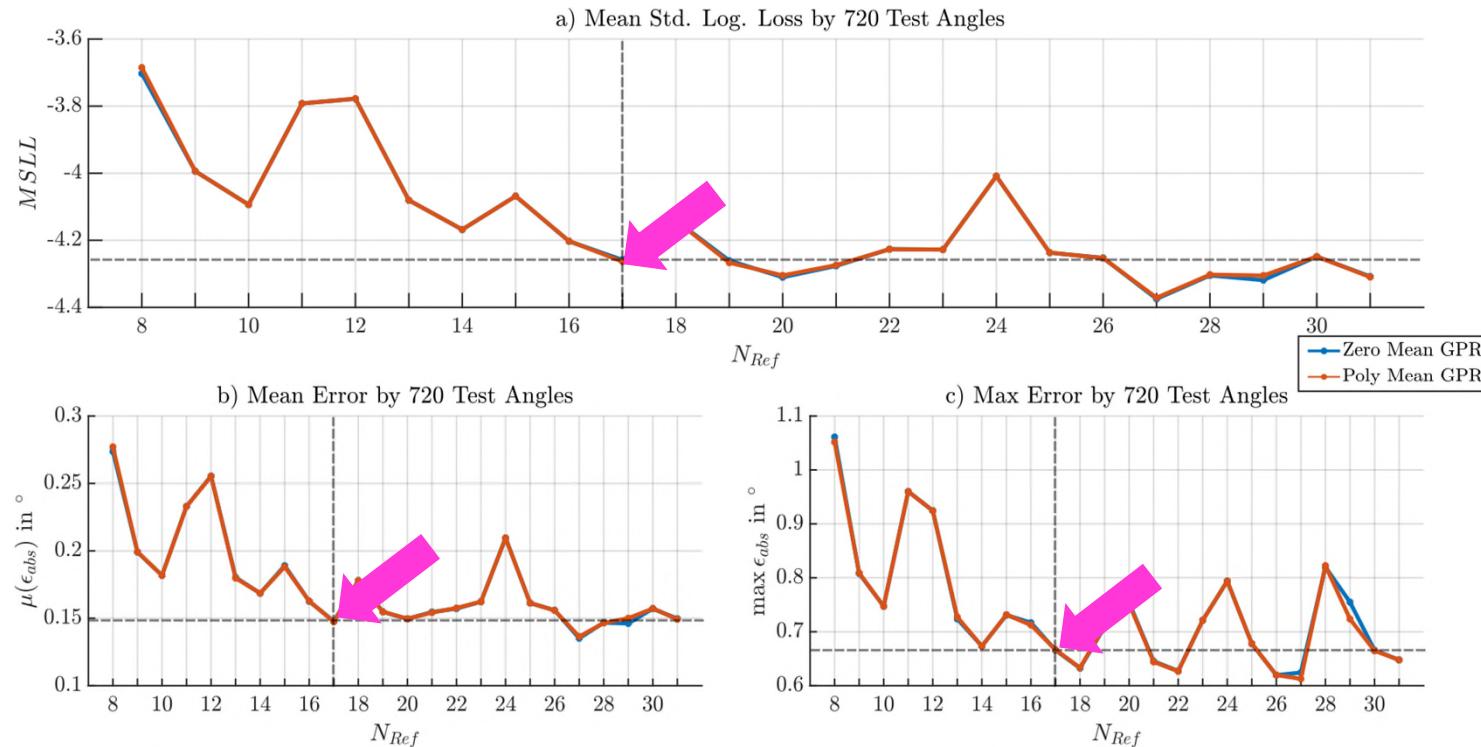


MSLL – Mean-Standardized-Logarithmic-Loss

# Erprobungsexperimente

## 17 Referenzwinkel

- Kompromissbildung
  - Optimierung zusschalten
  - Ressourceneinsparung
  - Aufwandabschätzung
  - Gleichgewicht zwischen Fehlern und Verlusten



MSLL – Mean-Standardized-Logarithmic-Loss

# Erprobungsexperimente

---

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



# Erprobungsexperimente

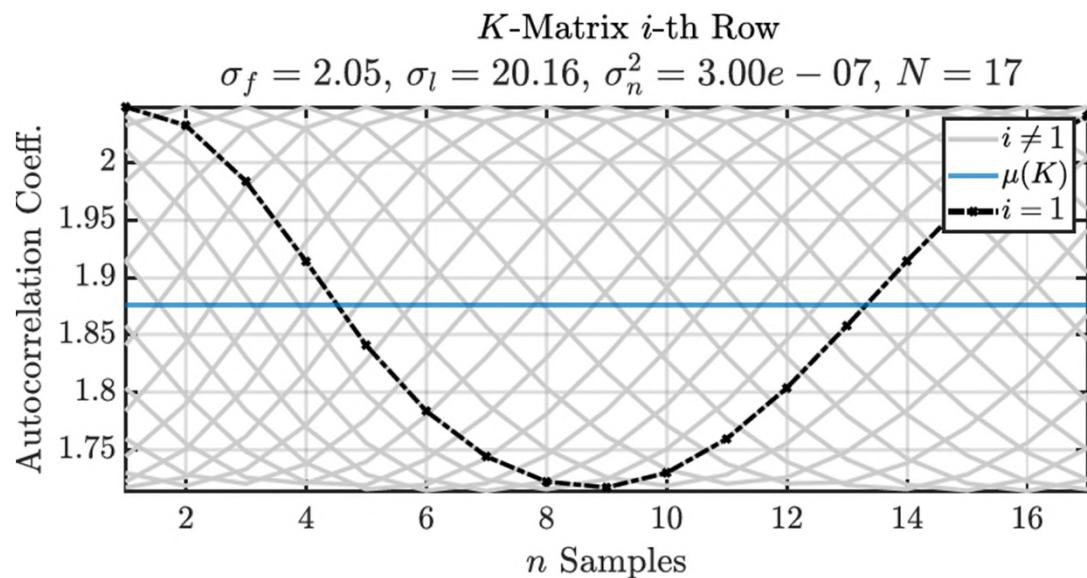
---

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt: 11.0°

- Verschoben in X-/ Y-Richtung
- Abstand verringert
- Magnet verkippt

# Erprobungsexperimente

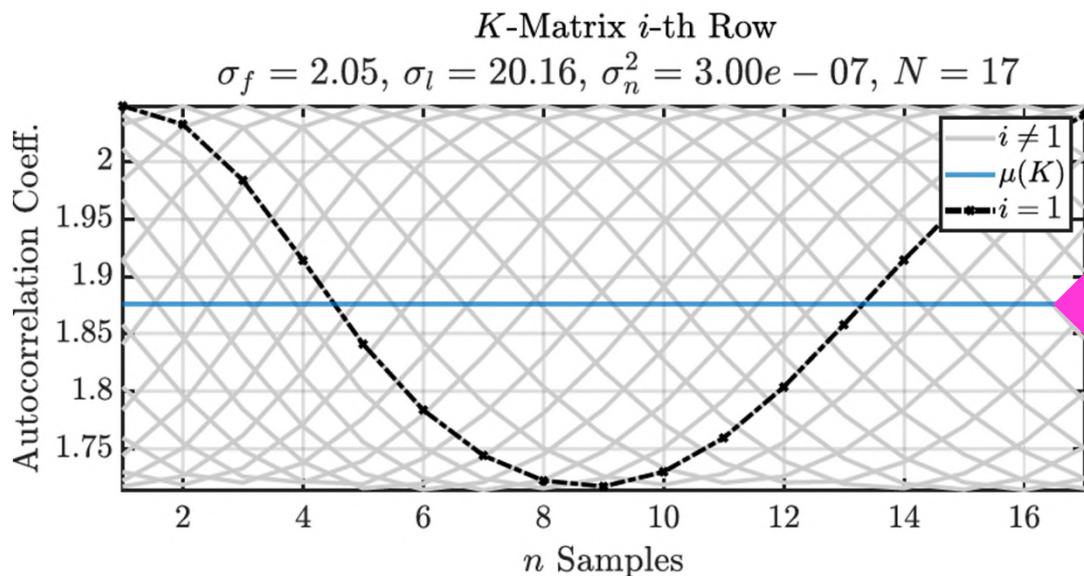
Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



- Verschoben in X-/ Y-Richtung
- Abstand verringert
- Magnet verkippt

# Erprobungsexperimente

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



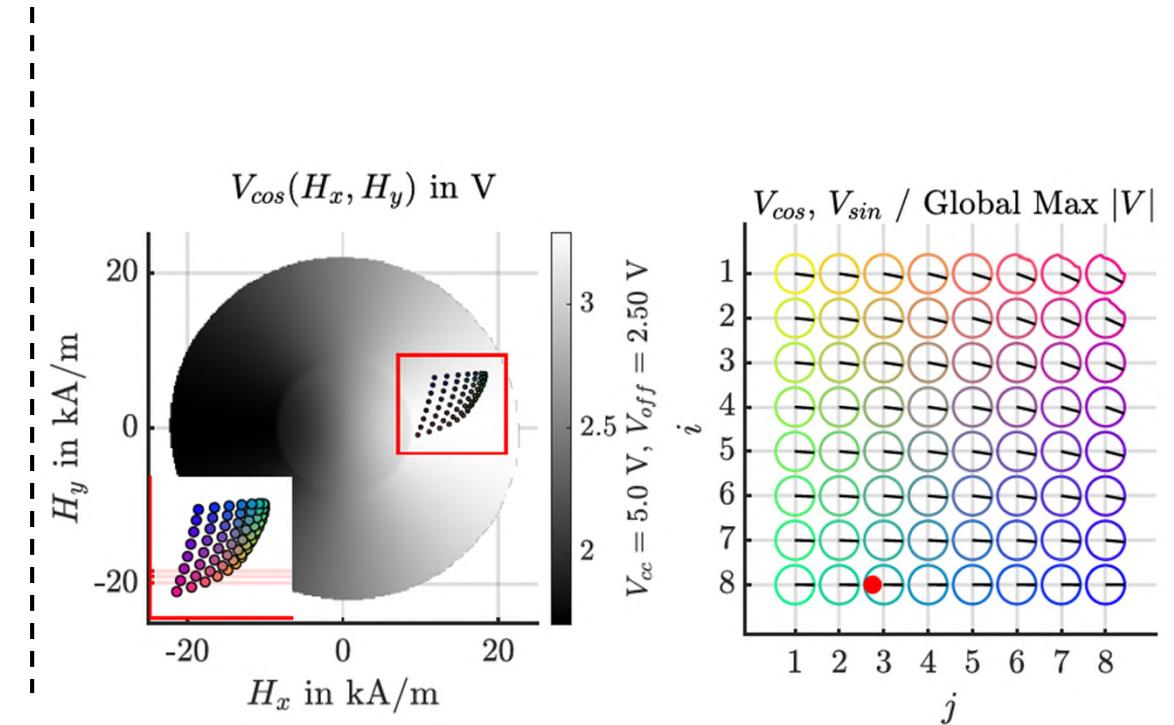
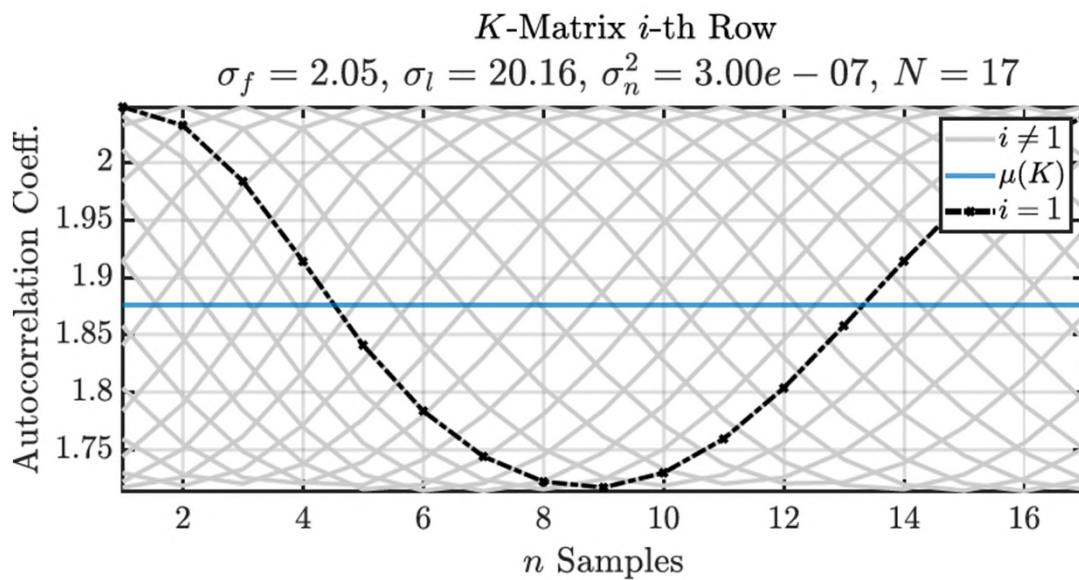
- Verschoben in X-/ Y-Richtung
- Abstand verringert
- Magnet verkippt
- Ausgleich zwischen Referenzen
- Abdeckung in der Einflussnahme

Gute Voraussetzungen

# Erprobungsexperimente

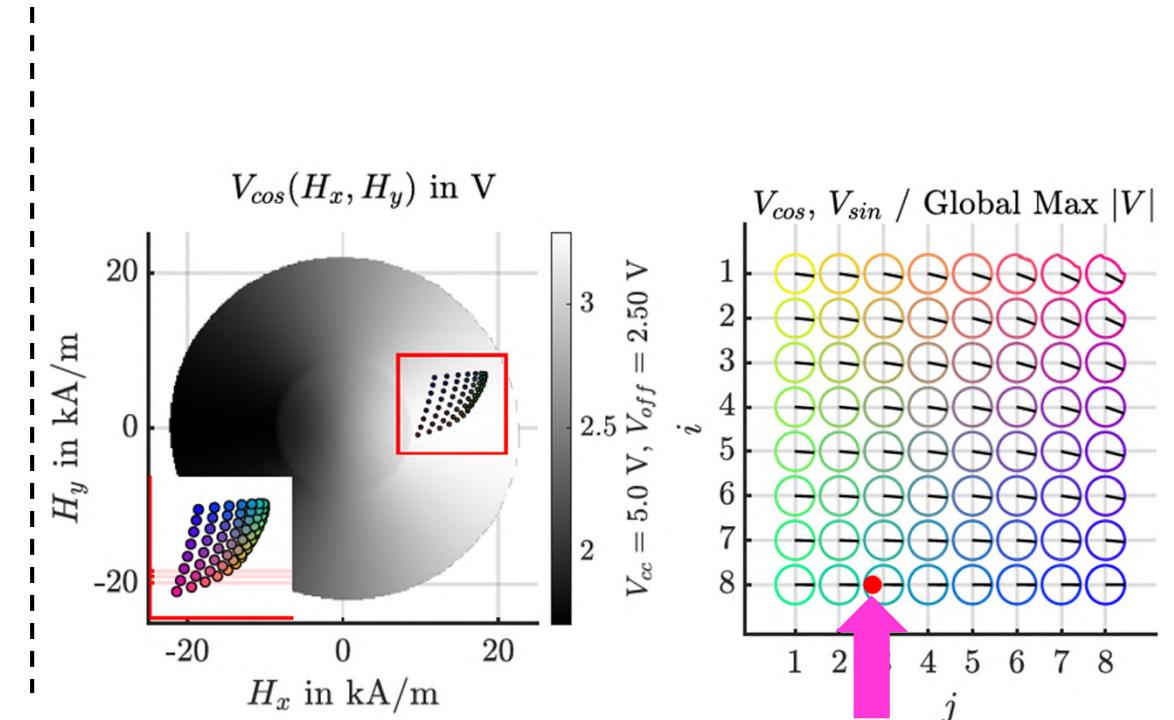
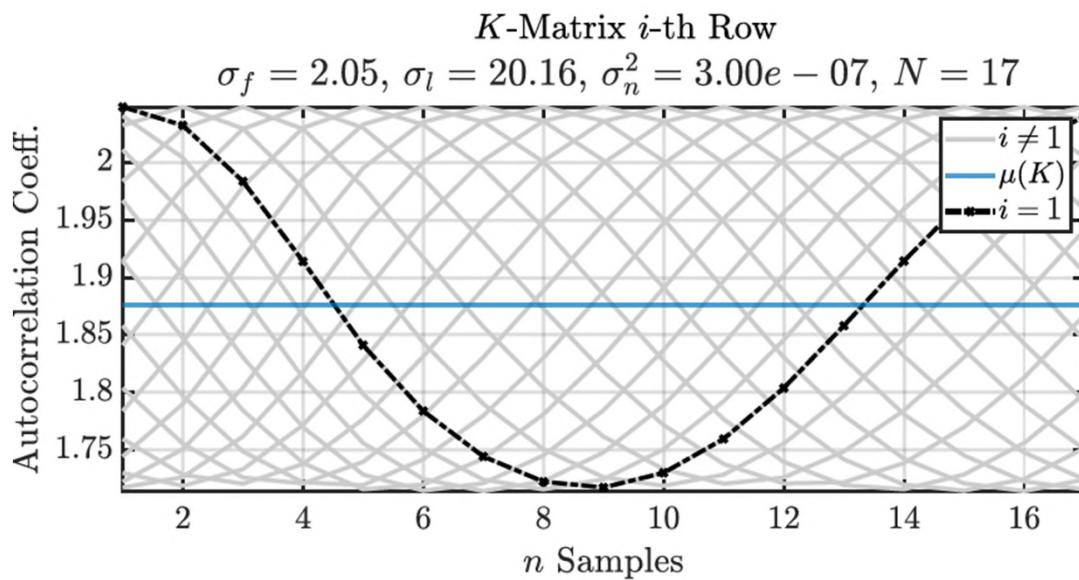
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Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



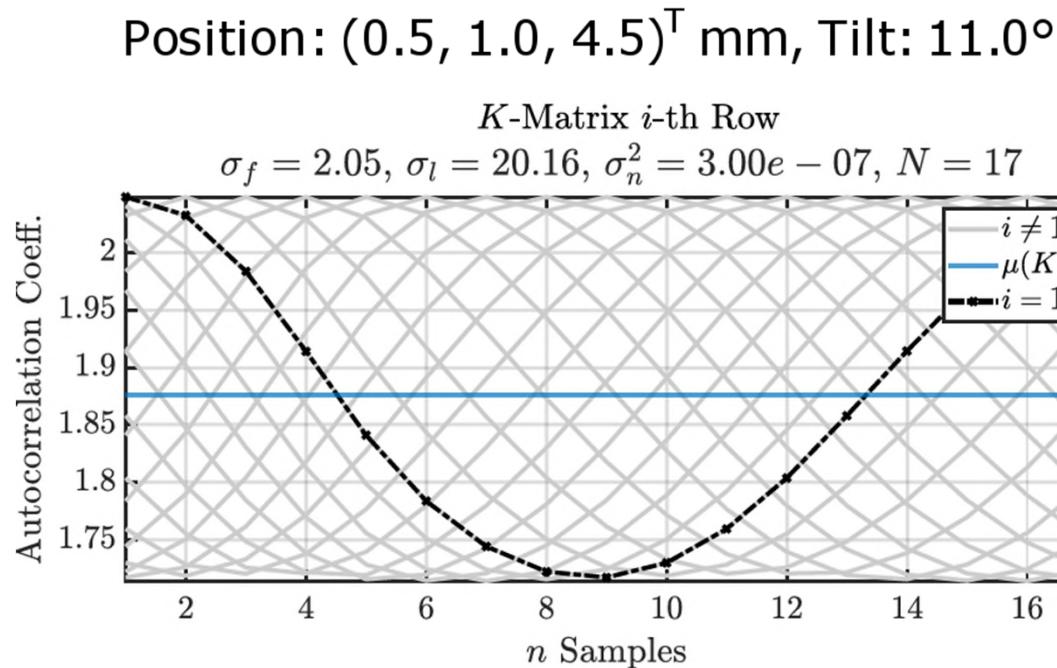
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Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



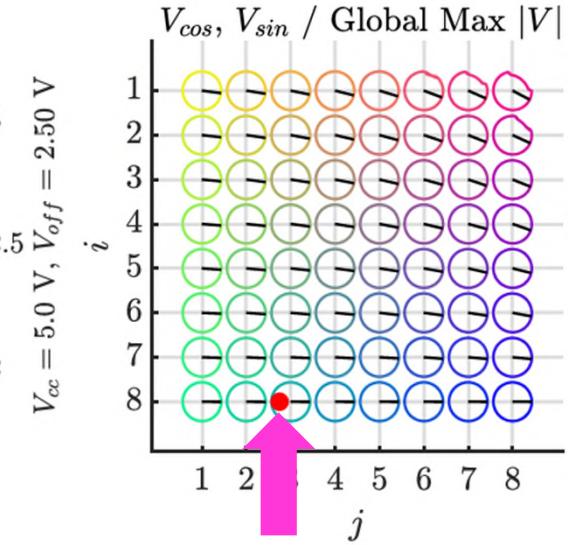
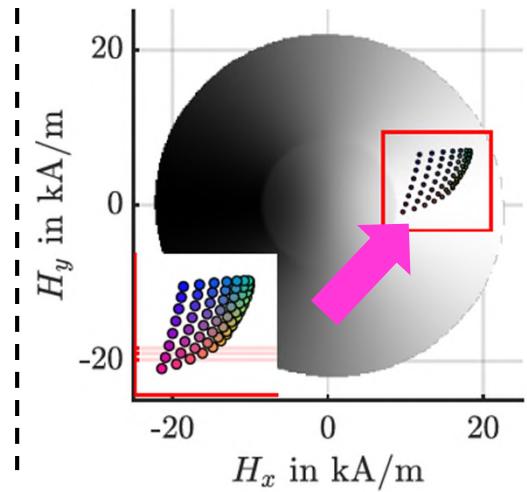
Magnet in Randlag  
zum Array

# Erprobungsexperimente



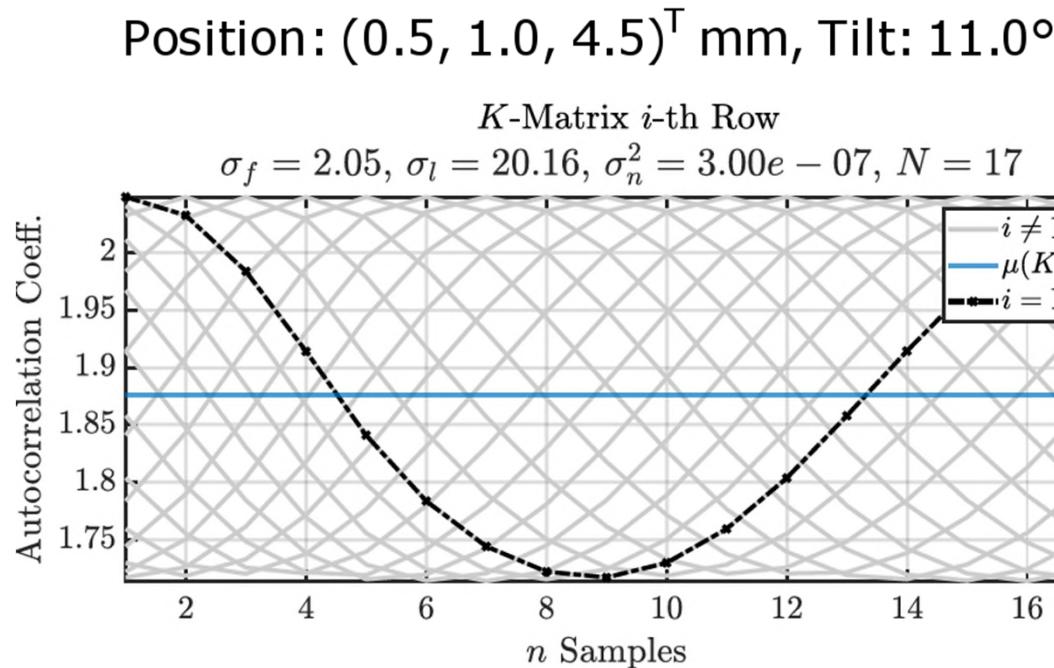
Sättigung +  
Streuung

$V_{cos}(H_x, H_y)$  in V



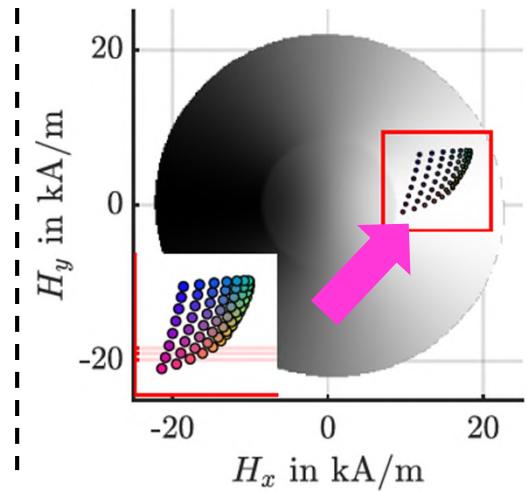
Magnet in Randlag  
zum Array

# Erprobungsexperimente

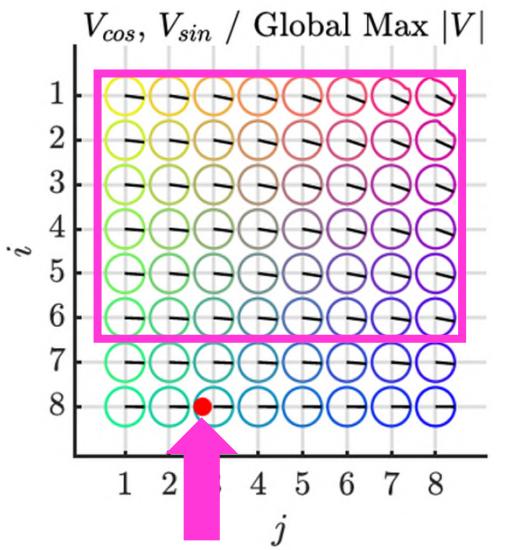


Sättigung +  
Streuung

$V_{cos}(H_x, H_y)$  in V

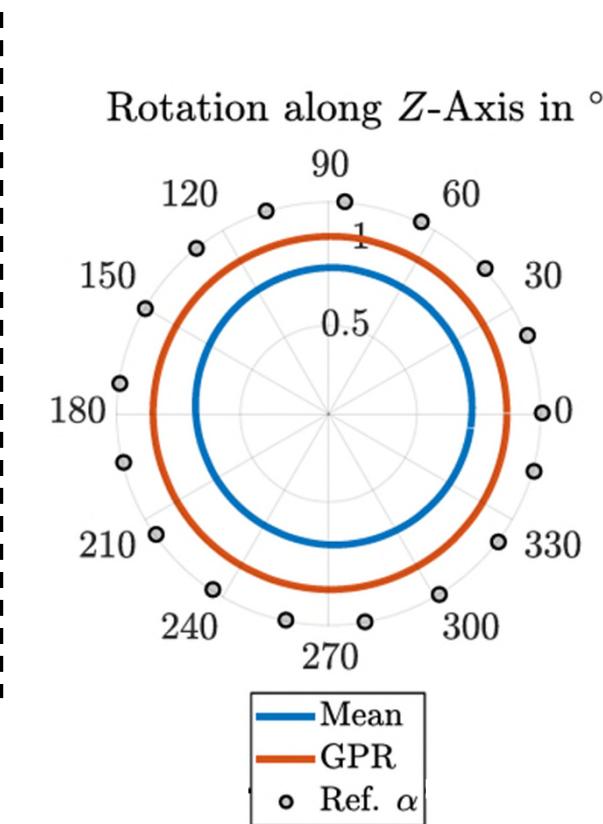
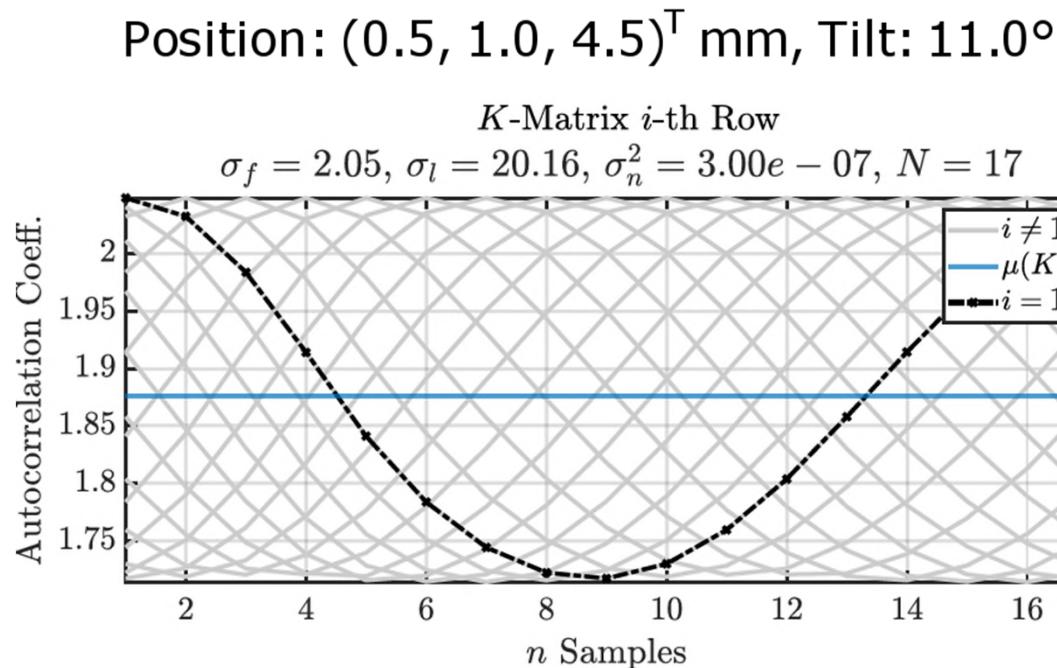


Verfälschte Winkel

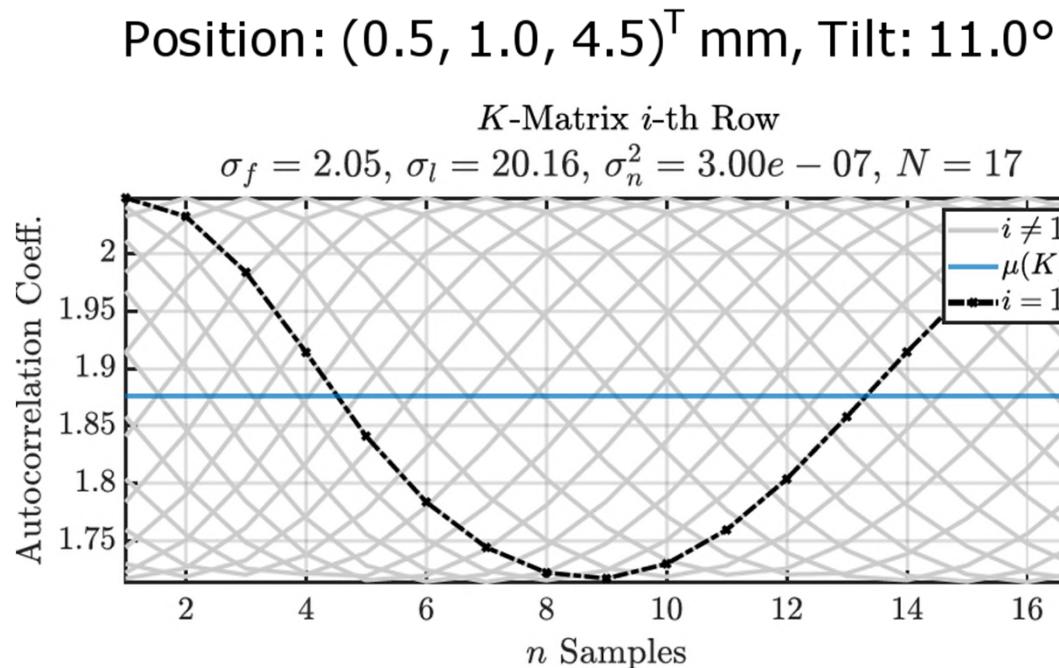


Magnet in Randlag  
zum Array

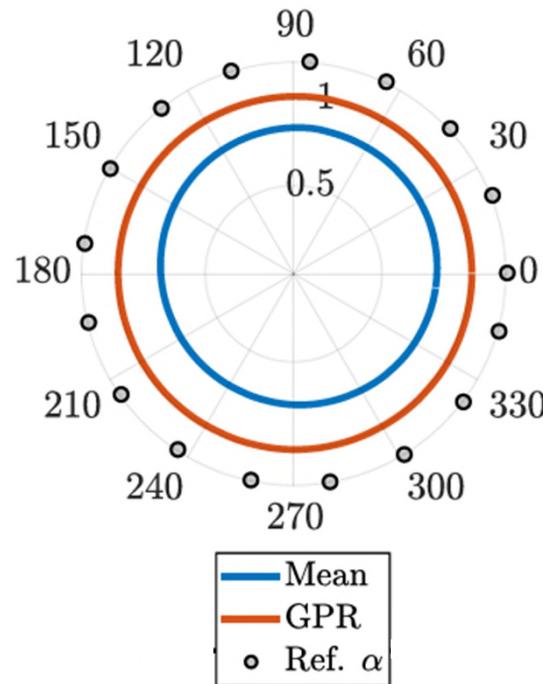
# Erprobungsexperimente



# Erprobungsexperimente

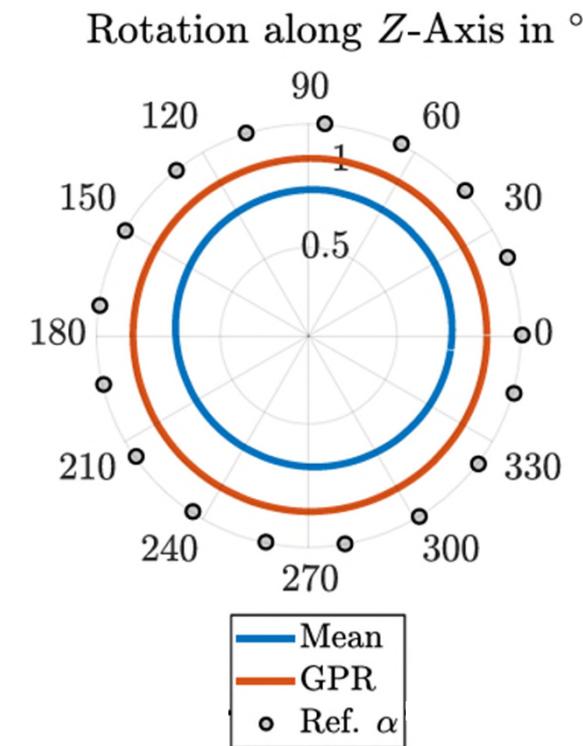
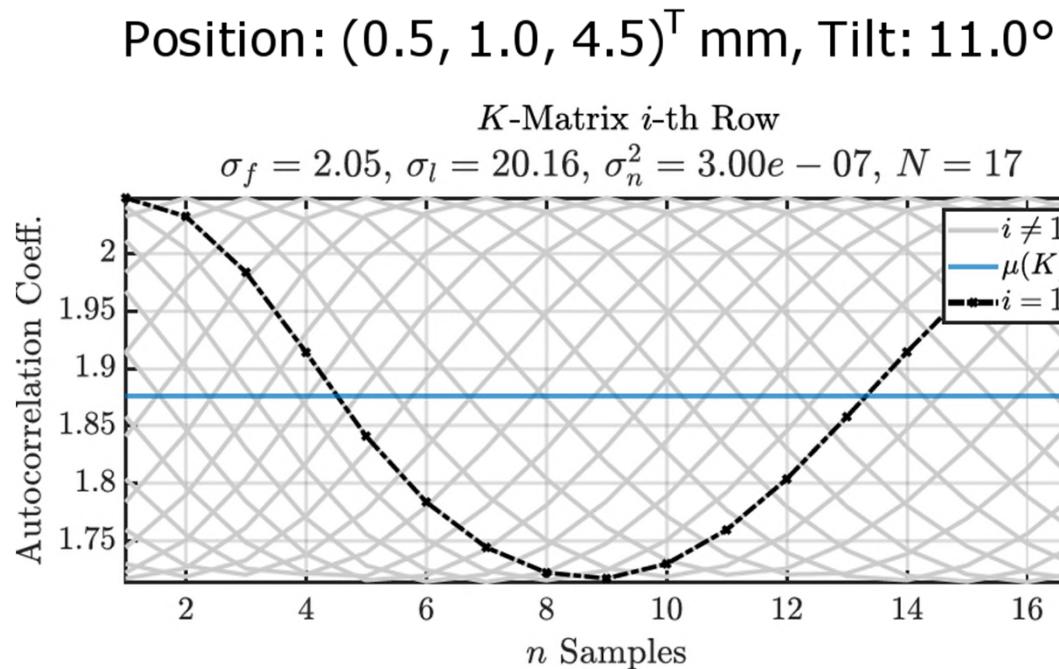


Rotation along Z-Axis in  $^\circ$



- Einfacher Mittelwert verschoben

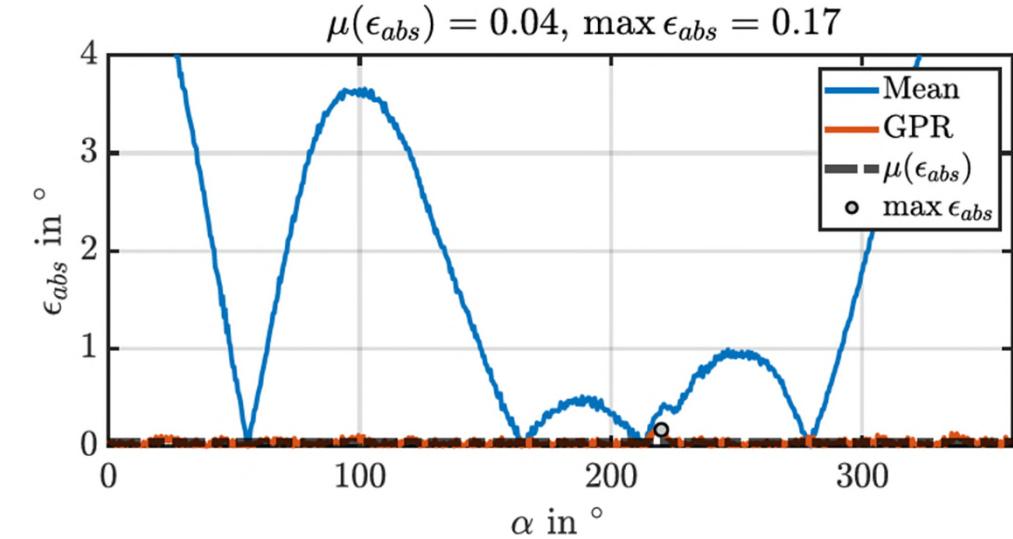
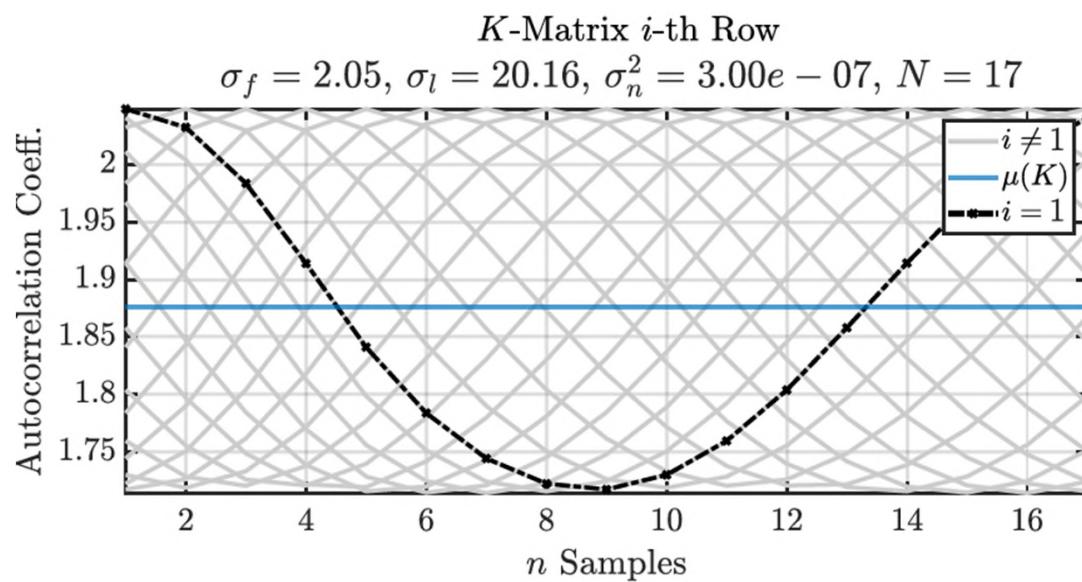
# Erprobungsexperimente



- Einfacher Mittelwert verschoben
- Regression schafft den Ausgleich

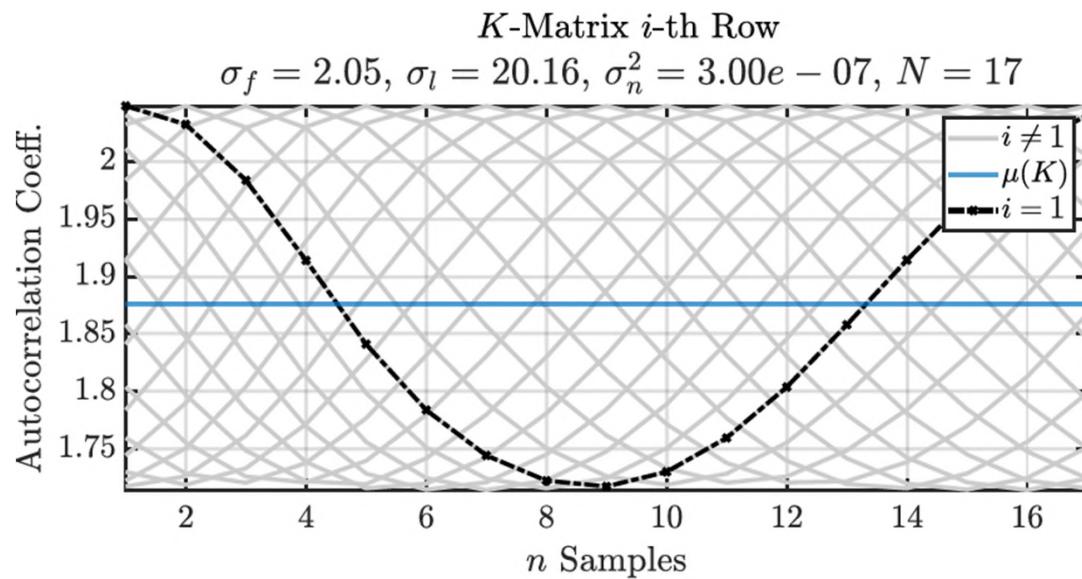
# Erprobungsexperimente

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$

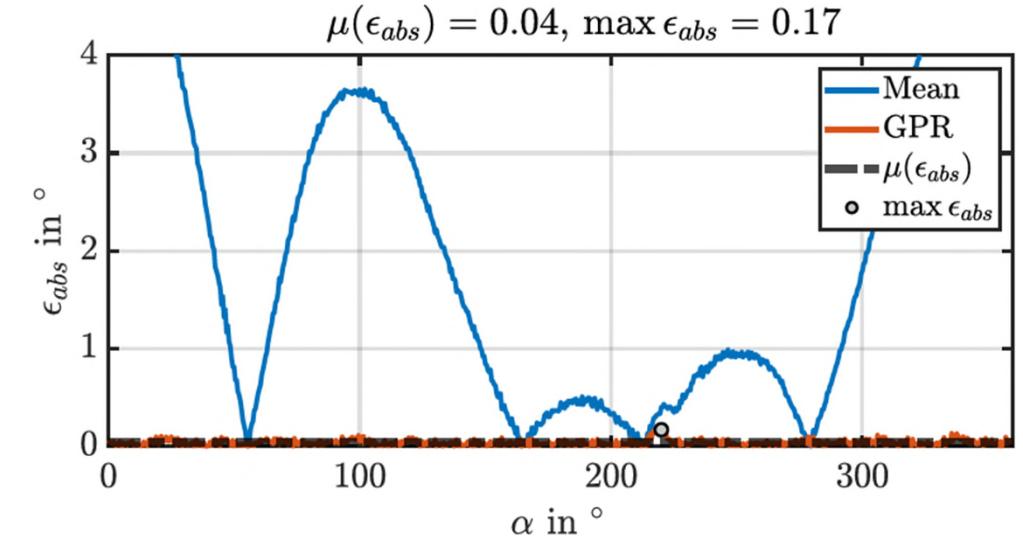


# Erprobungsexperimente

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$

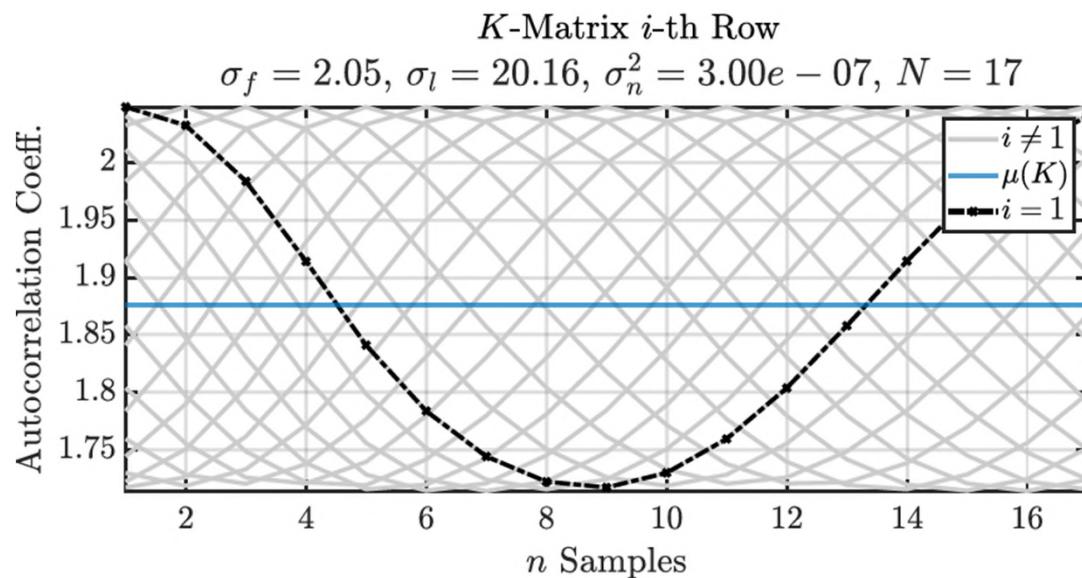


Geringe Winkelfehler über volle Rotation

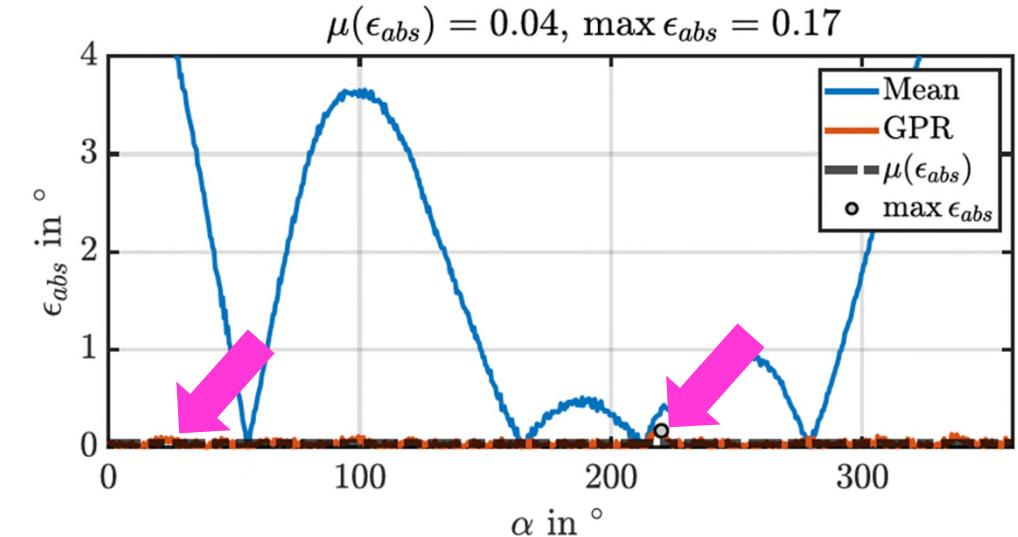


# Erprobungsexperimente

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



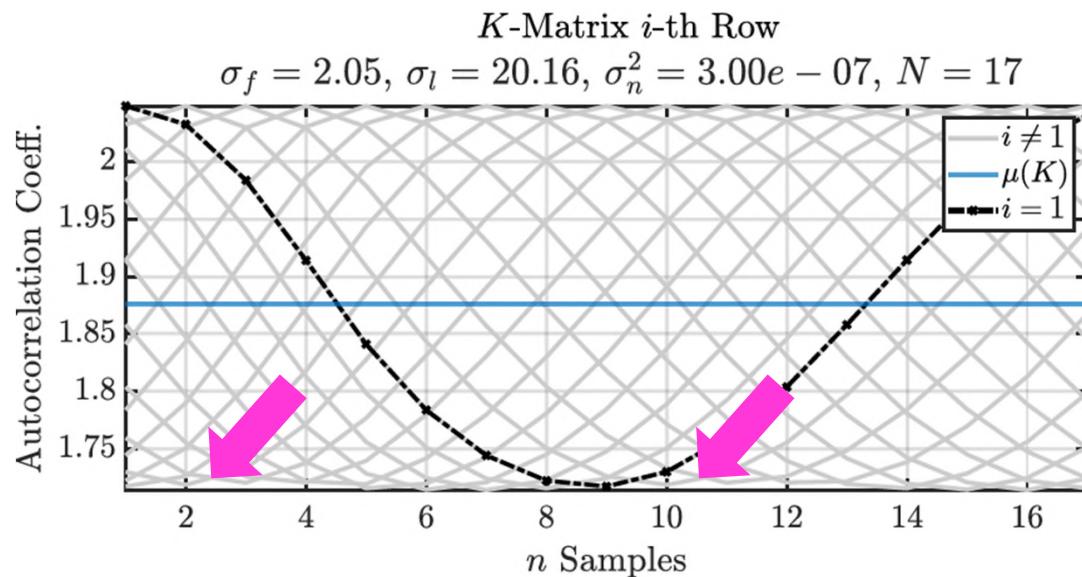
Geringe Winkelfehler über volle Rotation



Leichte Schwankungen

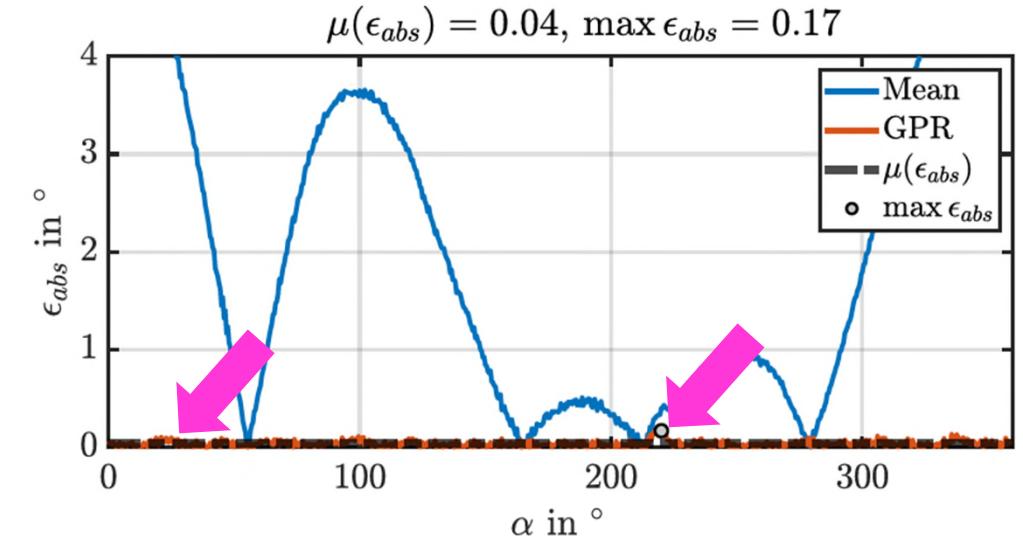
# Erprobungsexperimente

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



Leichte Anhebung, Lücke in Abdeckung

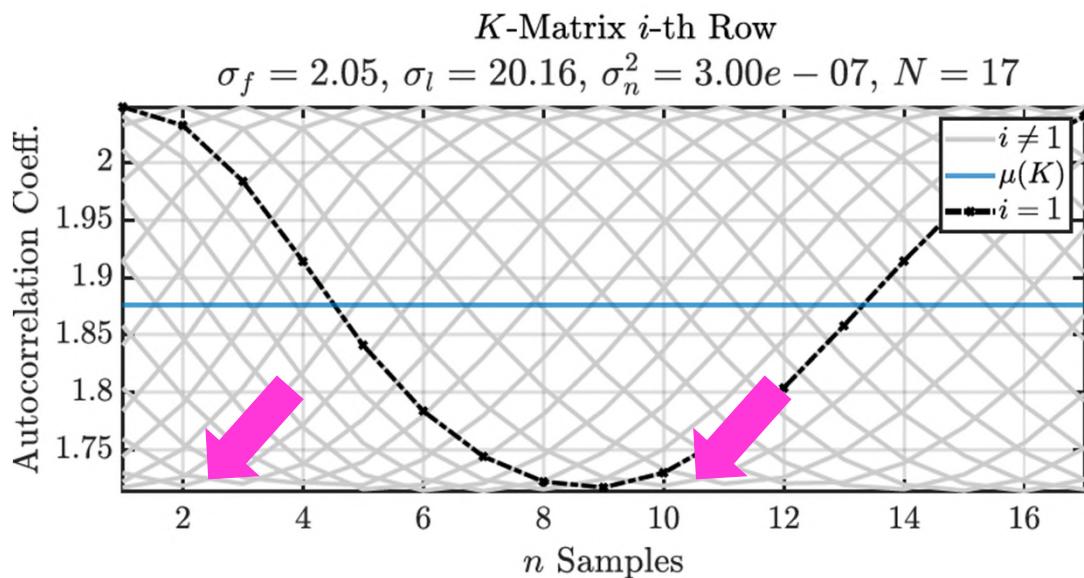
Geringe Winkelfehler über volle Rotation



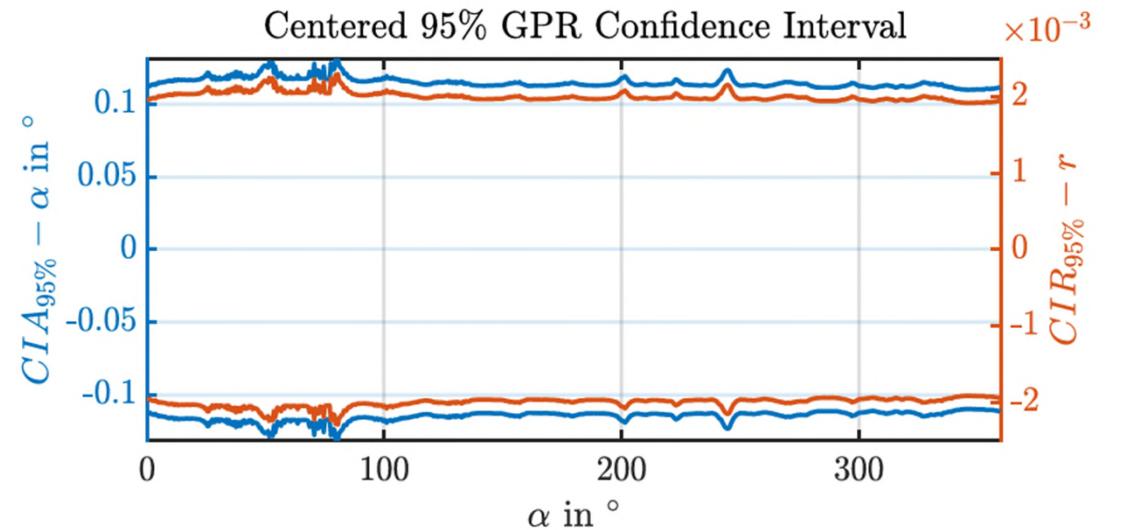
Leichte Schwankungen

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Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



Leichte Anhebung, Lücke in Abdeckung

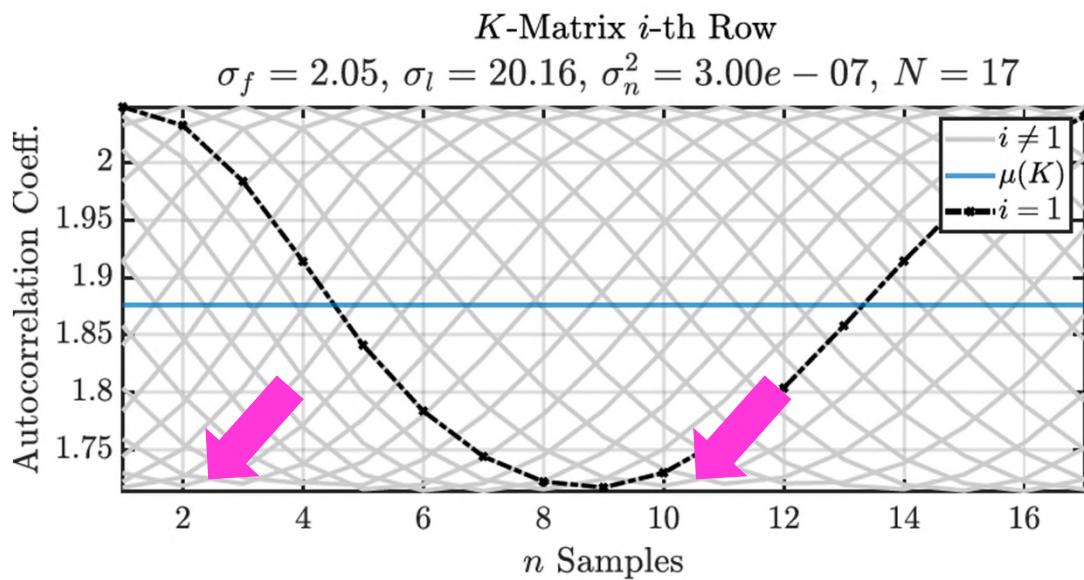


Hohes Vertrauen, enge Intervalle

CIA – Confidence-Interval-Angle  
CIR – Confidence-Interval-Radius

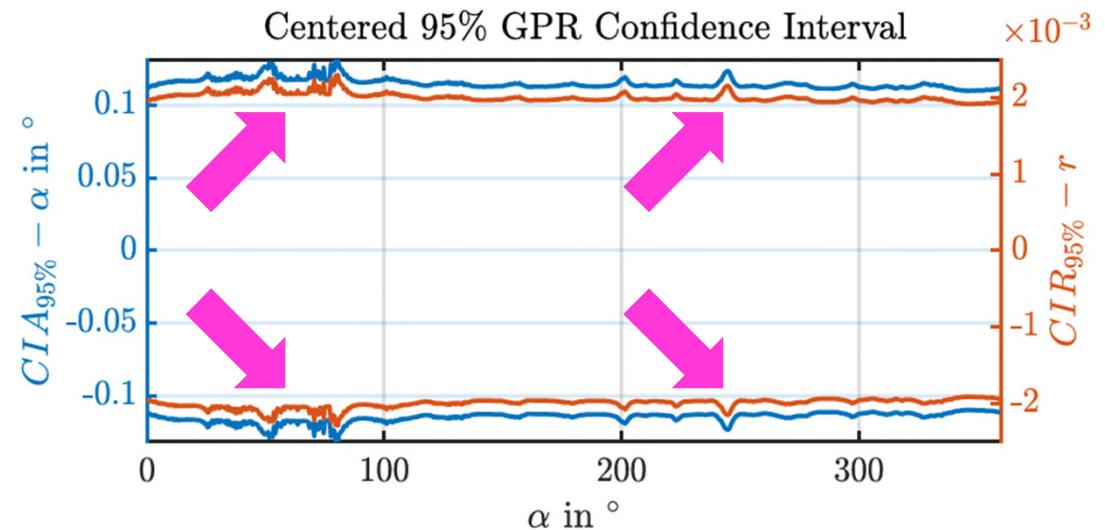
# Erprobungsexperimente

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



Leichte Anhebung, Lücke in Abdeckung

Anzeige der Abdeckungslücke

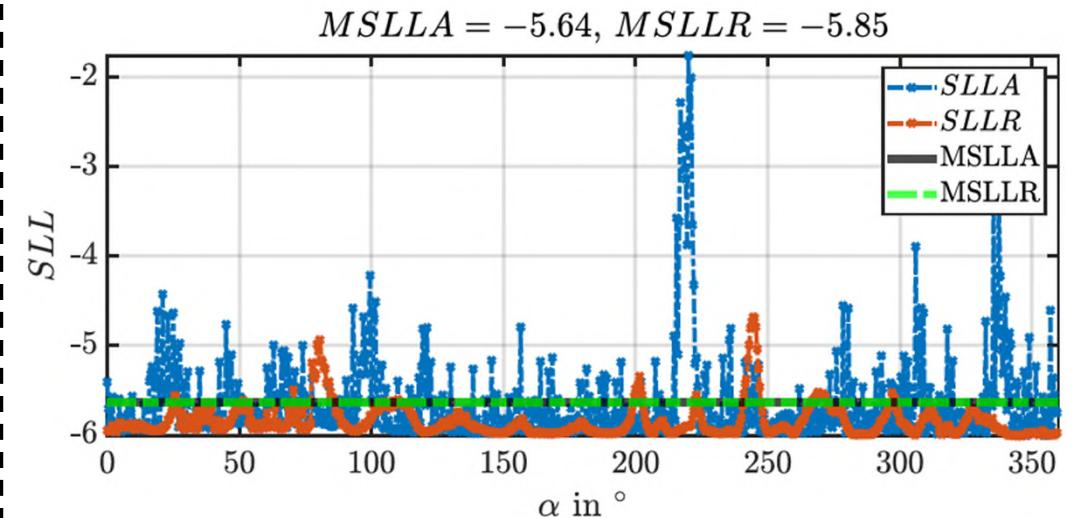
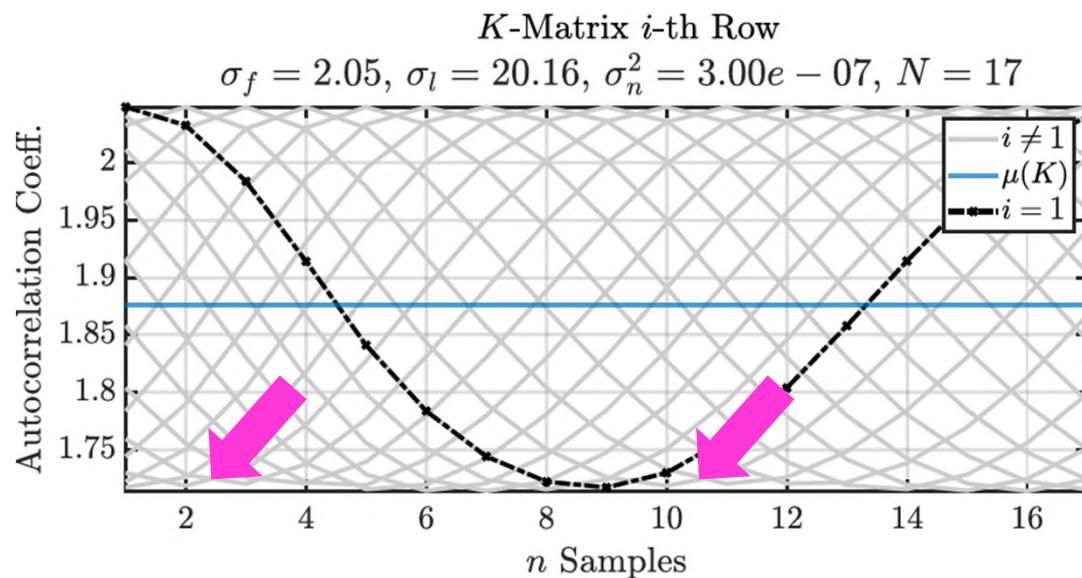


Hohes Vertrauen, enge Intervalle

CIA – Confidence-Interval-Angle  
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Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$

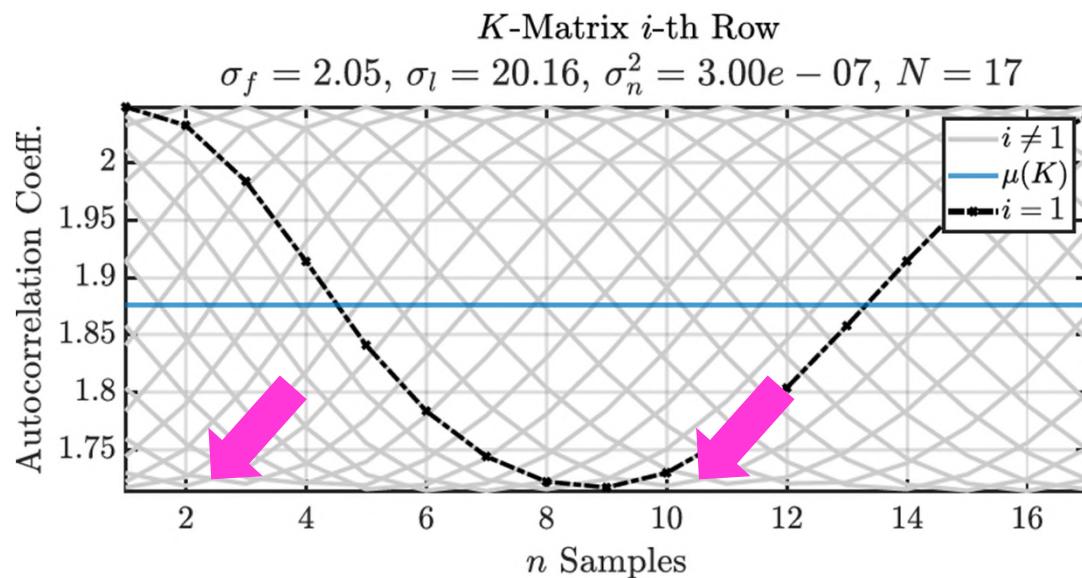


Leichte Anhebung, Lücke in Abdeckung

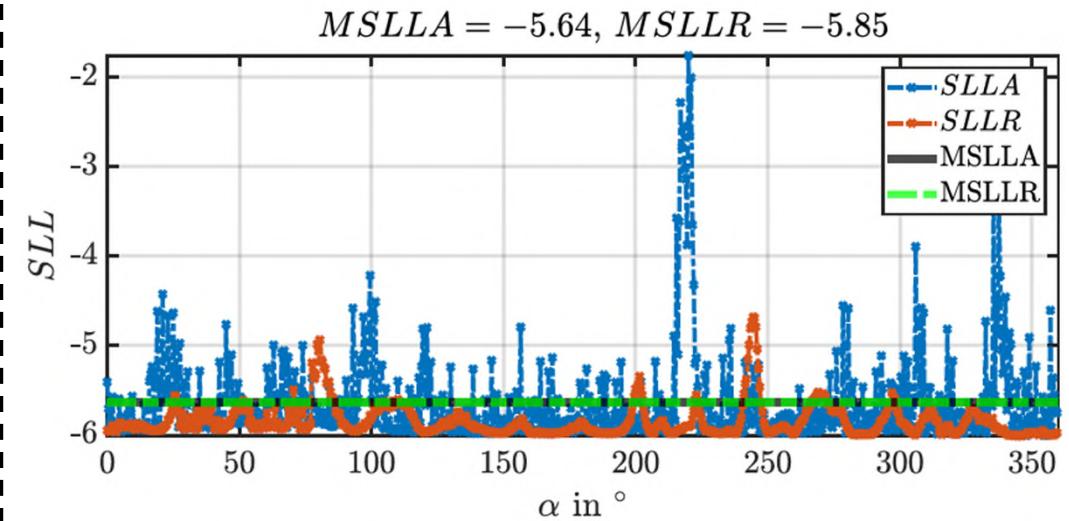
SLLA – Standardized-Logarithmic-Loss-Angle  
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 MSLLA – Mean-Standardized-Logarithmic-Loss-Angle  
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# Erprobungsexperimente

Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



Leichte Anhebung, Lücke in Abdeckung



Starke Generalisierung

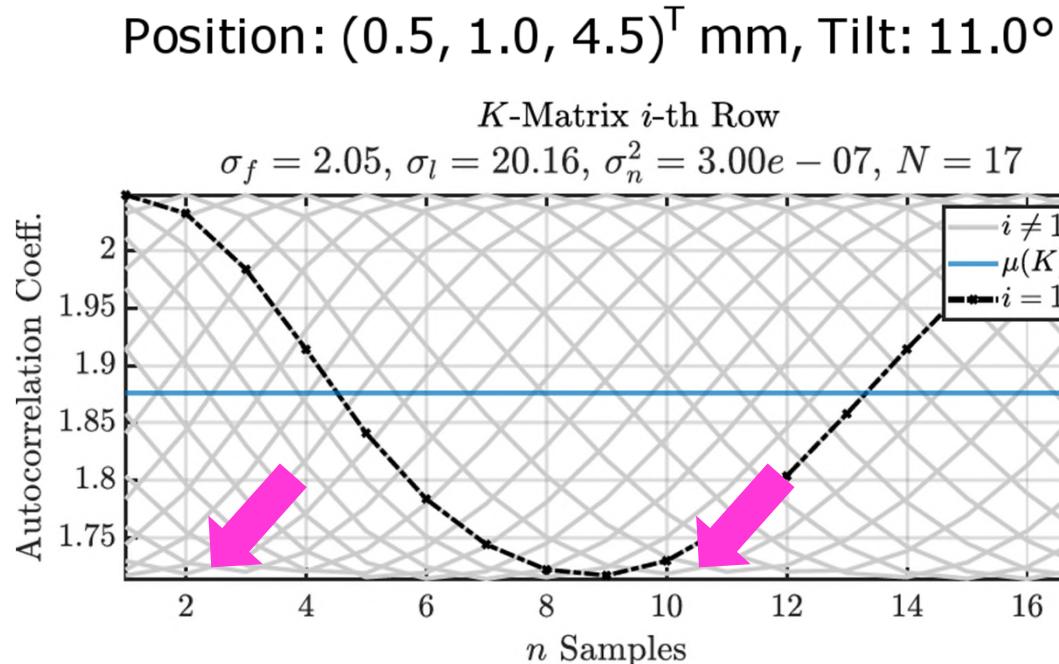
SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

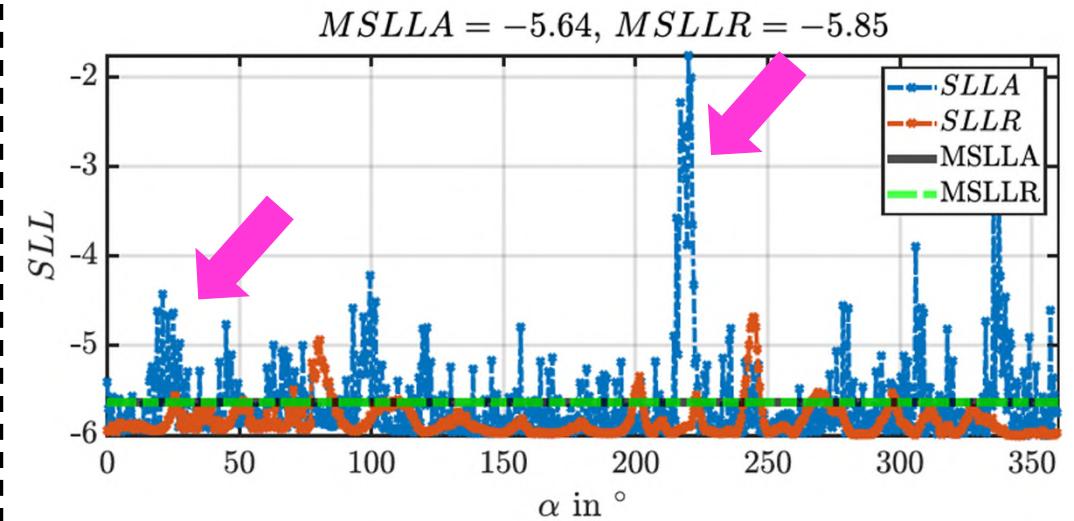
MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

# Erprobungsexperimente



**Leichte Anhebung, Lücke in Abdeckung**

**Abdeckungslücke schwächt Generalisierung**



**Starke Generalisierung**

SLLA – Standardized-Logarithmic-Loss-Angle

SLLR – Standardized-Logarithmic-Loss-Radius

MSLLA – Mean-Standardized-Logarithmic-Loss-Angle

MSLLR – Mean-Standardized-Logarithmic-Loss-Radius

# Zusammenfassung

---



- Erreichtes
- Offene Punkte

# Zusammenfassung

---

- **Erreichtes**
  - Simulations-Framework
  - Erweiterbarkeit
- **Offene Punkte**

# Zusammenfassung

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- **Erreichtes**
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# Zusammenfassung

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- **Erreichtes**
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  - Toleranzkompenstation
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# Zusammenfassung

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  - Verfahrensminimierung
  - Hardwarenahe Bibliotheken

# Zusammenfassung

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- **Erreichtes**
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  - Anbindung an Realdaten
  - Große Charakterisierung

# Zusammenfassung

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- **Erreichtes**
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  - Erweiterbarkeit
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  - Verfahrensminimierung
  - Hardwarenahe Bibliotheken
  - Anbindung an Realdaten
  - Große Charakterisierung
  - Zirkuläre Statistik

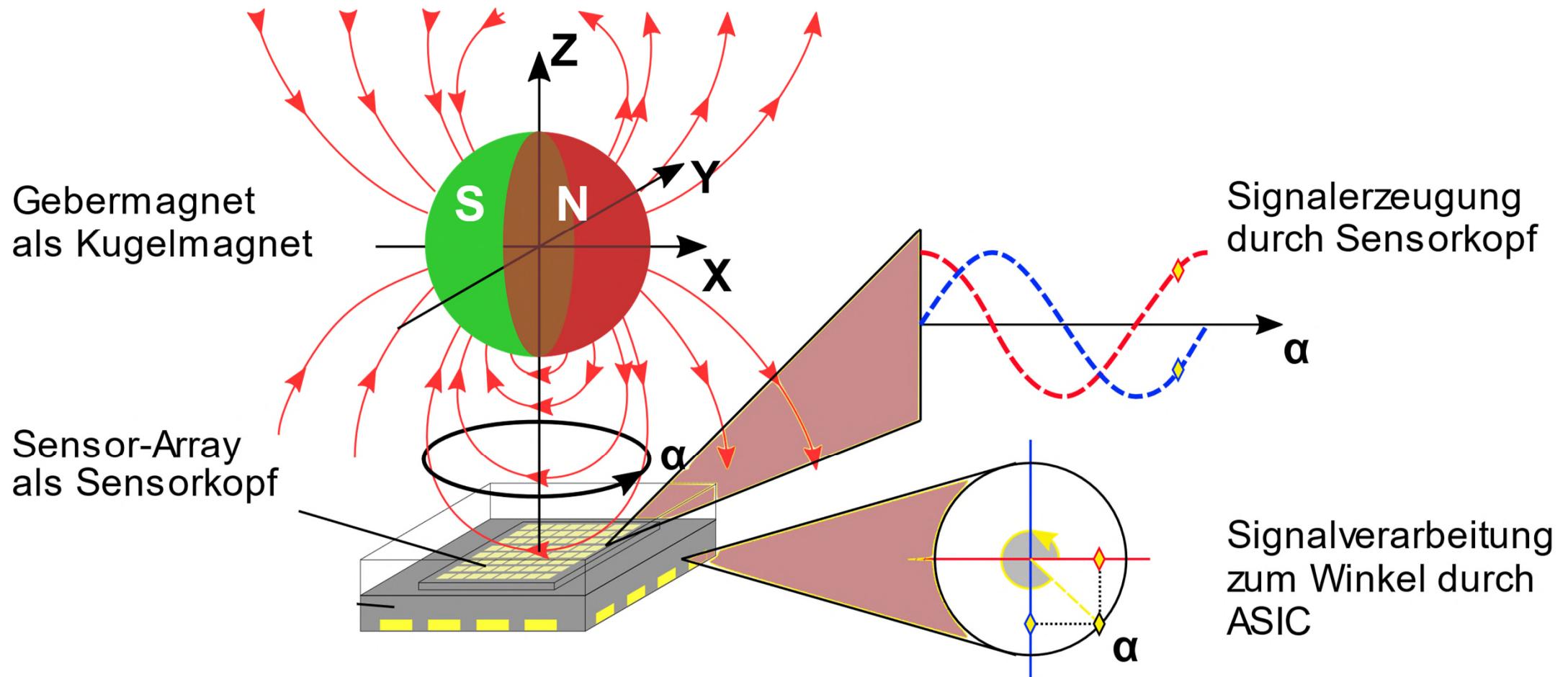
Ende

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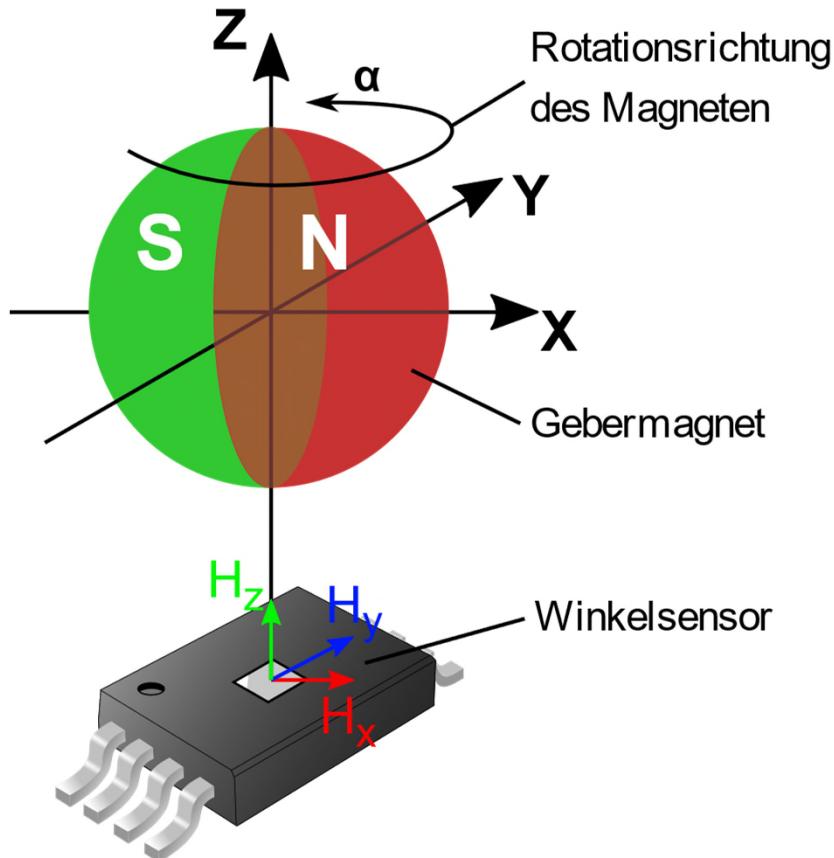


Vielen Dank!

# Applikation



# Applikation



## Winkelmessung

$$\underbrace{\begin{pmatrix} H_x(\alpha) \\ H_y(\alpha) \end{pmatrix}}_{\text{Gebermagnetfeld}} \Rightarrow \underbrace{\begin{pmatrix} V_{\cos}(H_x, H_y) \\ V_{\sin}(H_x, H_y) \end{pmatrix}}_{\text{Winkelsensormesswerte}} = \underbrace{\begin{pmatrix} r \cdot \cos(\alpha) \\ r \cdot \sin(\alpha) \end{pmatrix}}_{\text{Kreisdarstellung}} = \begin{pmatrix} a_x \\ a_y \end{pmatrix} = \underbrace{\mathbf{A}(\alpha)}_{\text{Winkelmessung}}$$

## Orthogonalität der Messwerte

$$V_{\cos}(H_x, H_y) \perp V_{\sin}(H_x, H_y) \Leftrightarrow \mathbf{A} \mapsto \alpha$$

# Applikation

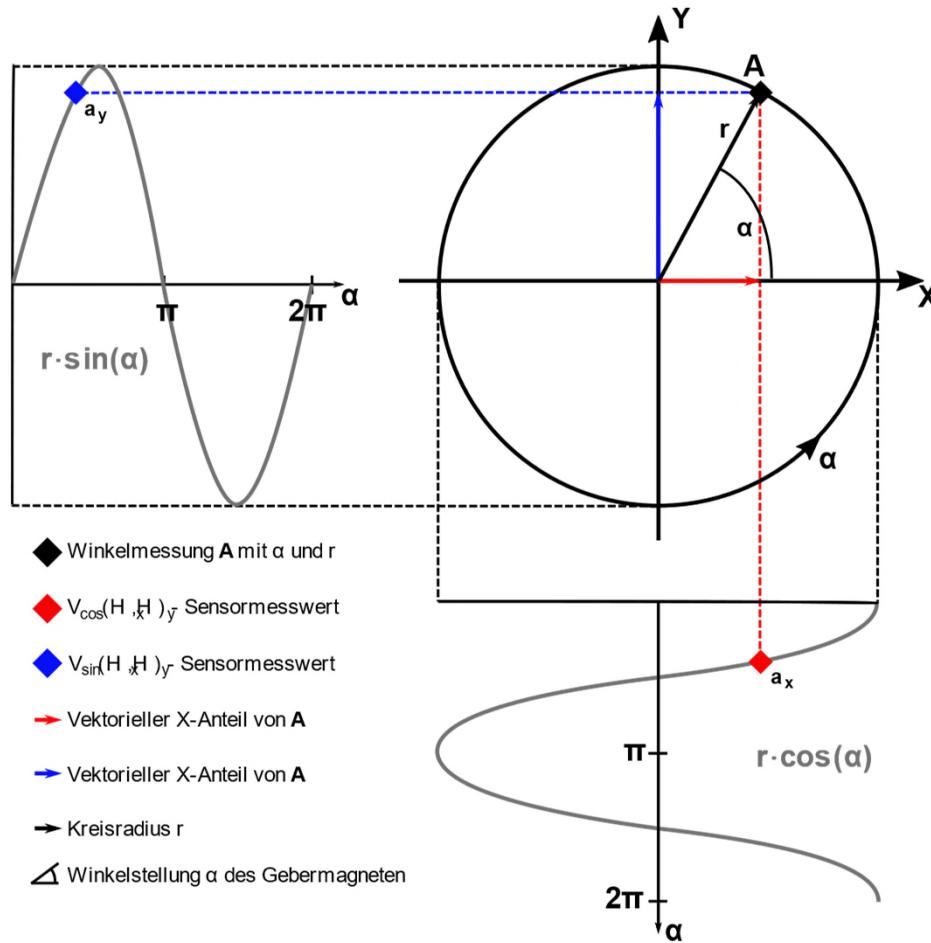
---

Radius

$$r = |\mathbf{A}| = \sqrt{a_x^2 + a_y^2}$$

Winkel

$$\alpha = \begin{cases} \arctan2(a_y, a_x) & \text{f. } a_y > 0 \\ \pi & \text{f. } a_y = 0 \\ \arctan2(a_y, a_x) + 2\pi & \text{f. } a_y < 0 \end{cases}$$



# Applikation

## Winkelmessungen

$$\mathbf{A} \mapsto \alpha_1 \quad \mathbf{B} \mapsto \alpha_2$$

## Radius

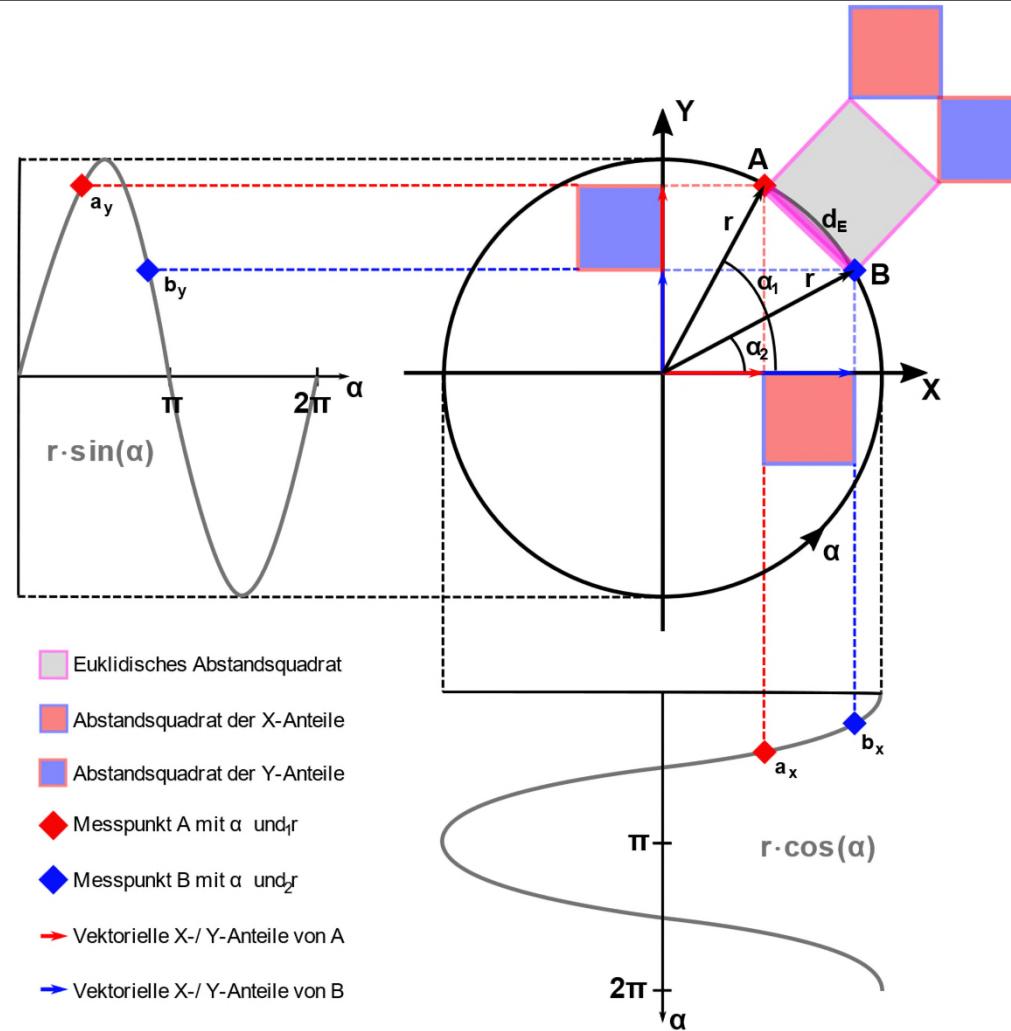
$$r = |\mathbf{A}| = |\mathbf{B}| = \text{konst.}$$

## Euklidischer Abstand

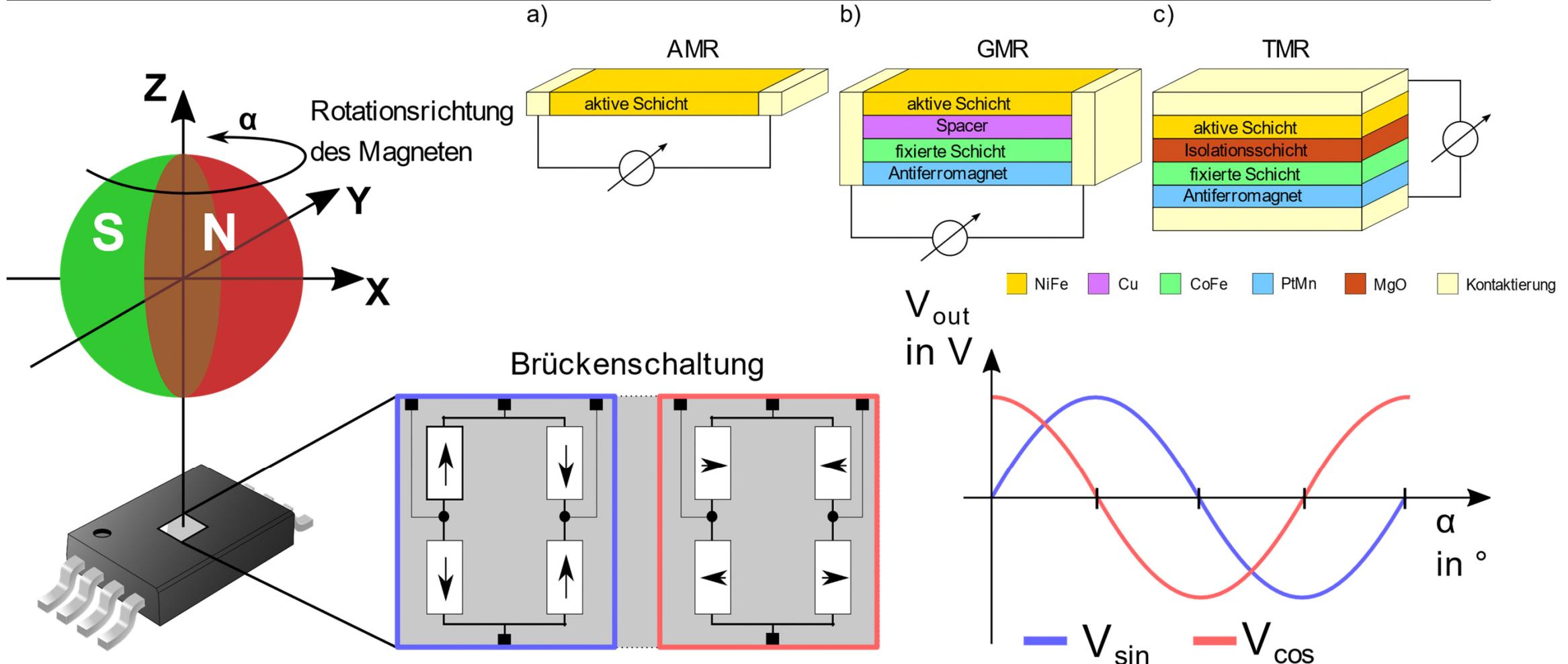
$$d_E(\mathbf{A}, \mathbf{B}) = \sqrt{(a_x - b_x)^2 + (a_y - b_y)^2}$$

## Abstandsquadrat

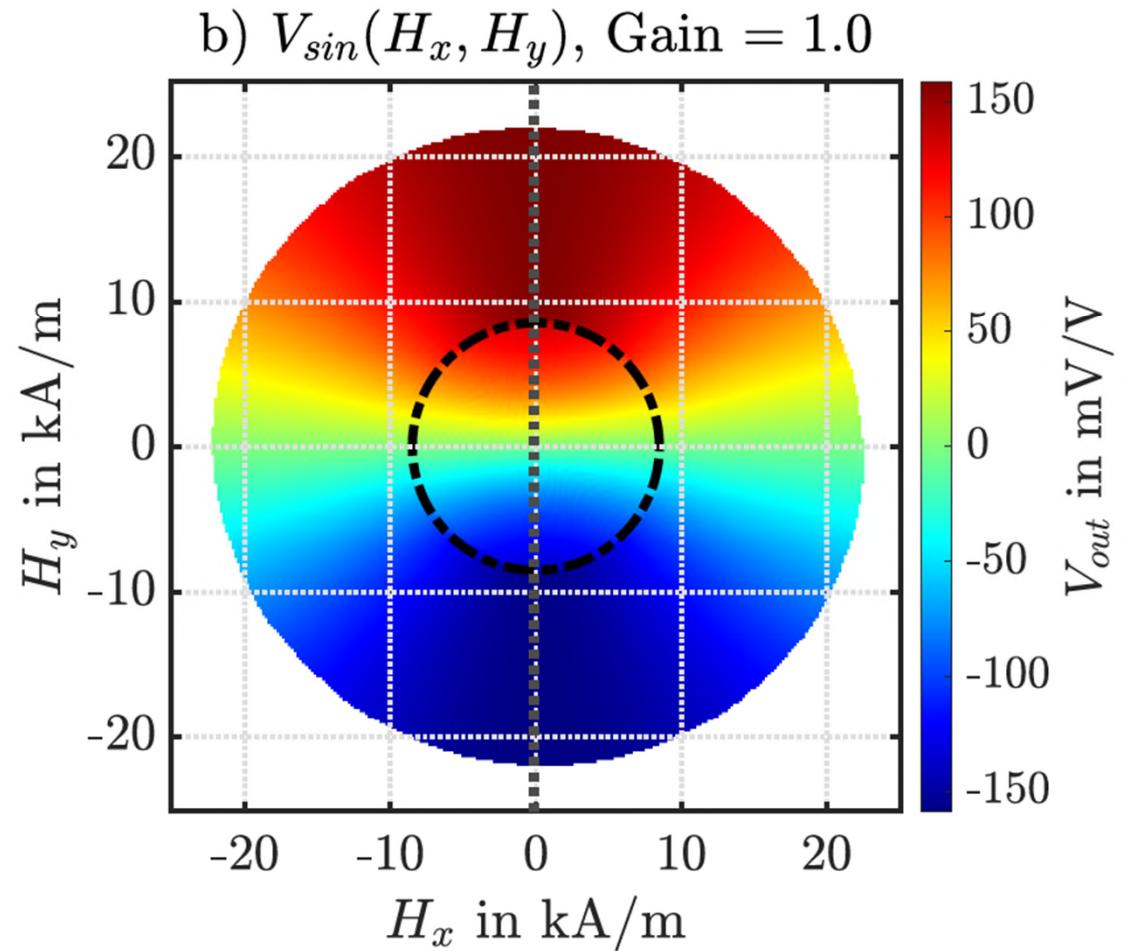
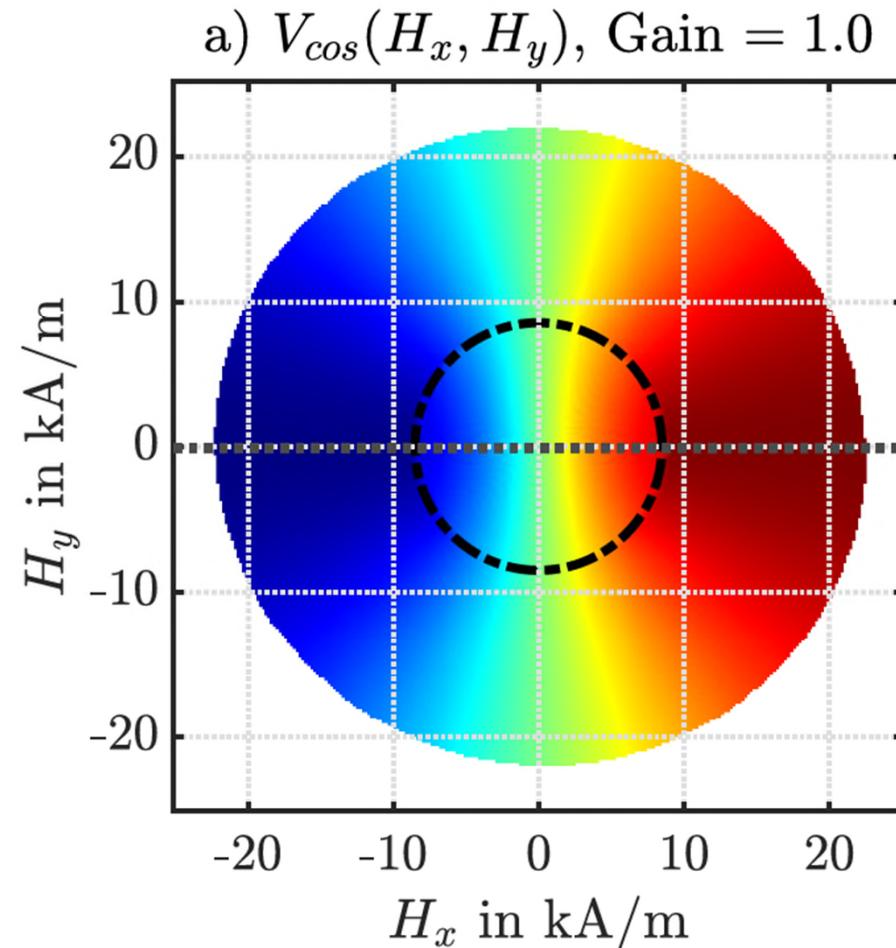
$$d_E^2(\mathbf{A}, \mathbf{B}) = (a_x - b_x)^2 + (a_y - b_y)^2$$



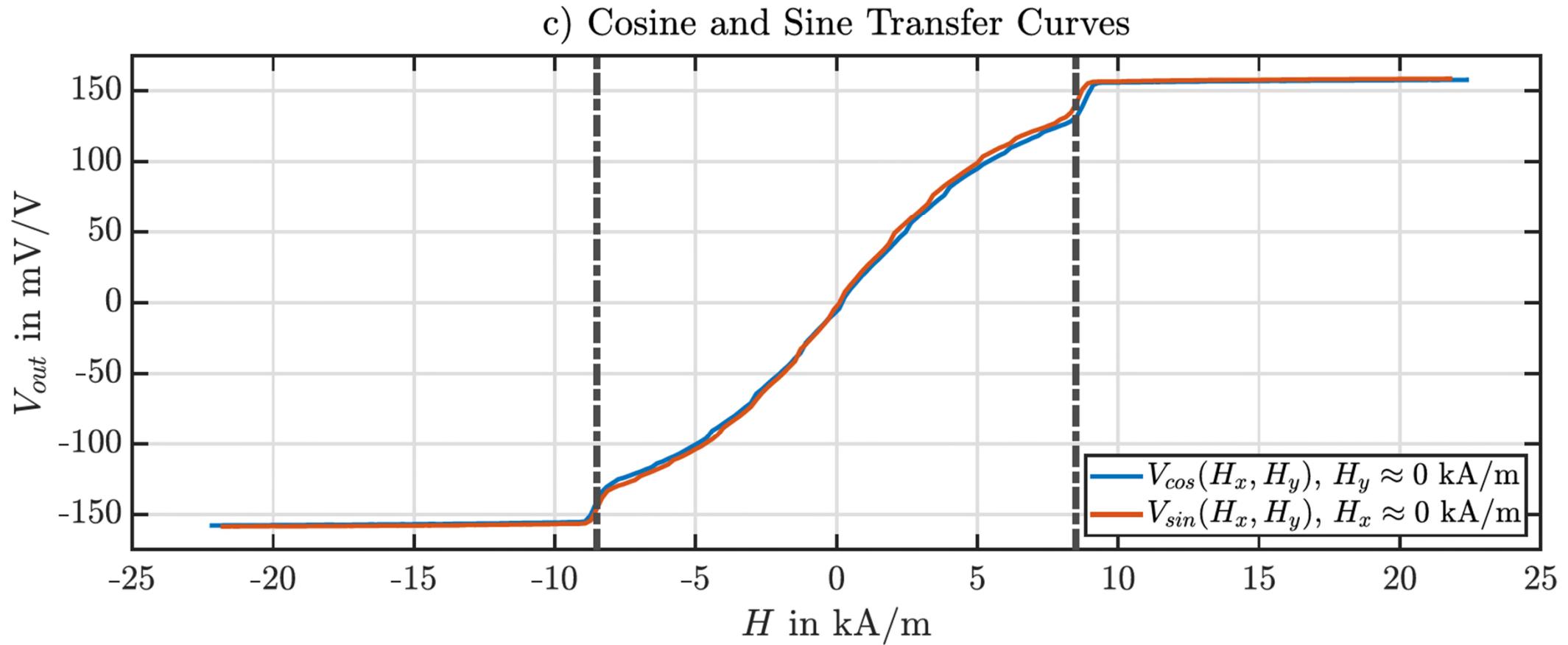
# Applikation



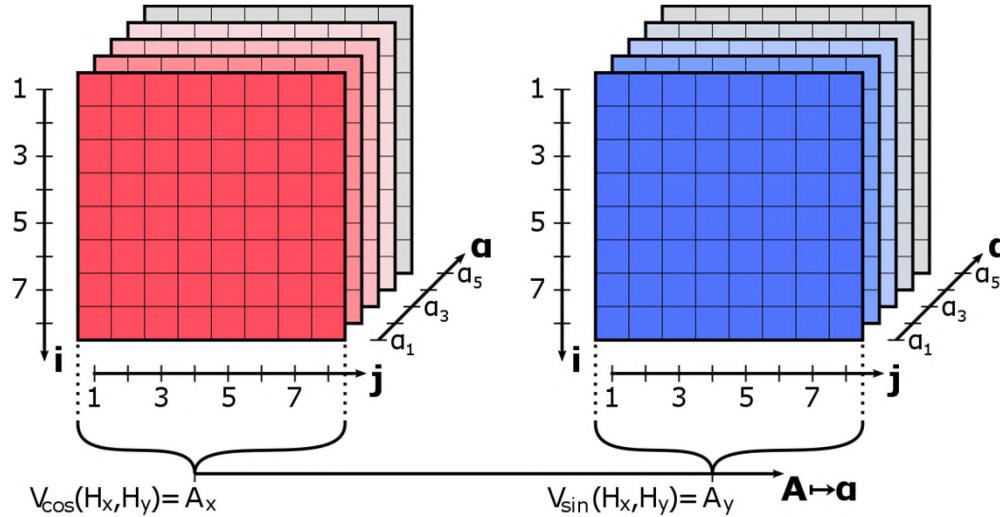
# Kennfelder



# Kennfelder

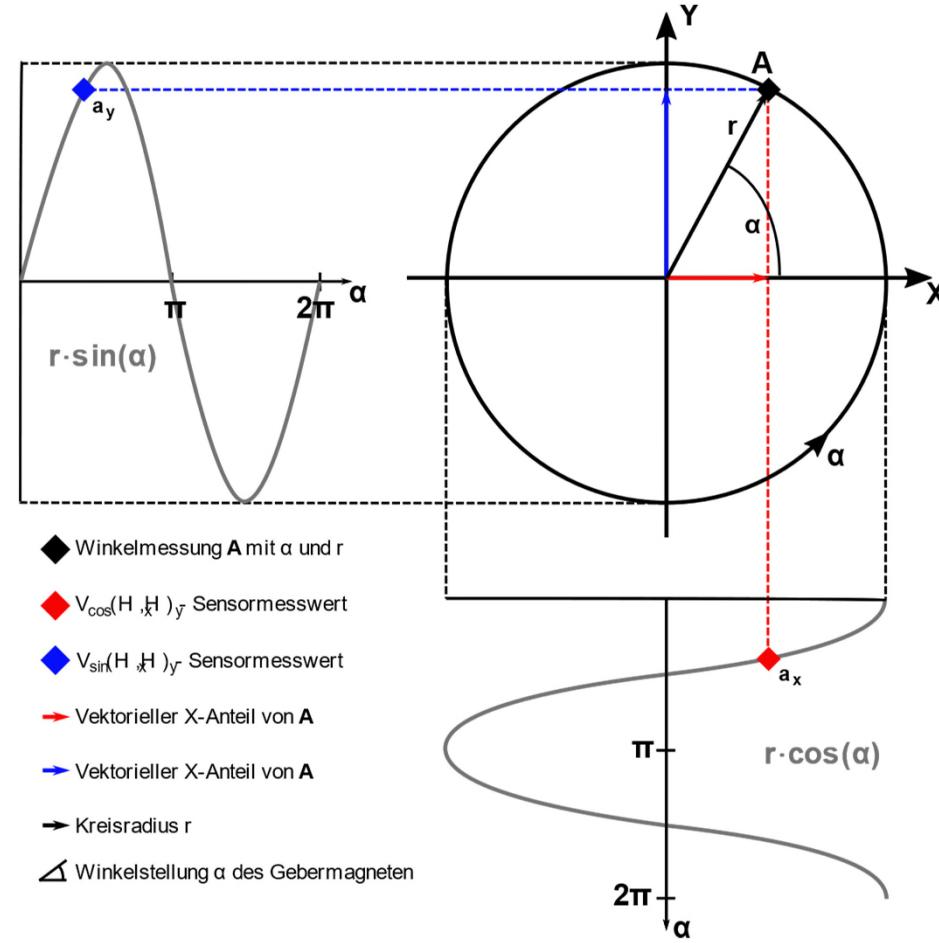


# Datenadaption

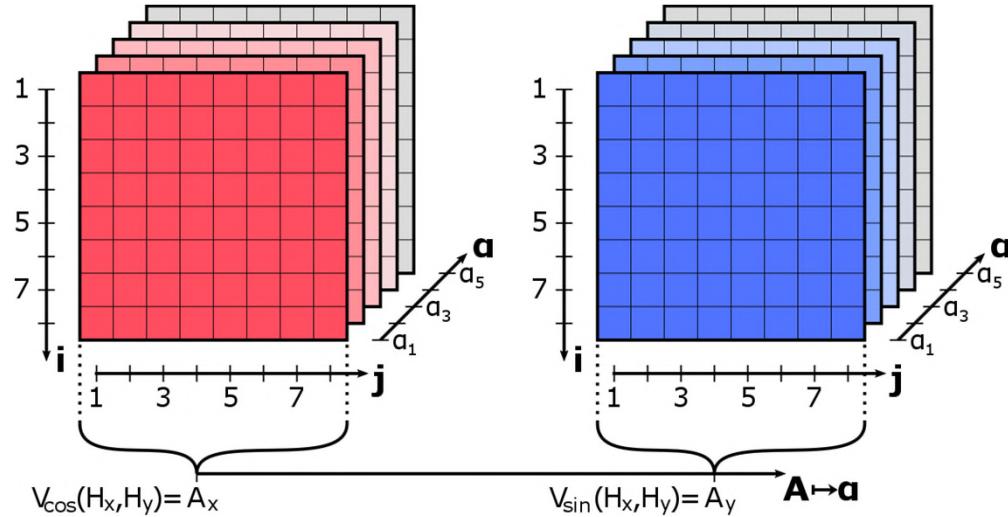


Vektor-2-Norm<sup>2</sup> f. j-te Spalte

$$\|\mathbf{A}_x\|_F = \sqrt{\sum_{j=1}^n \|A_{xj}\|_2^2}$$

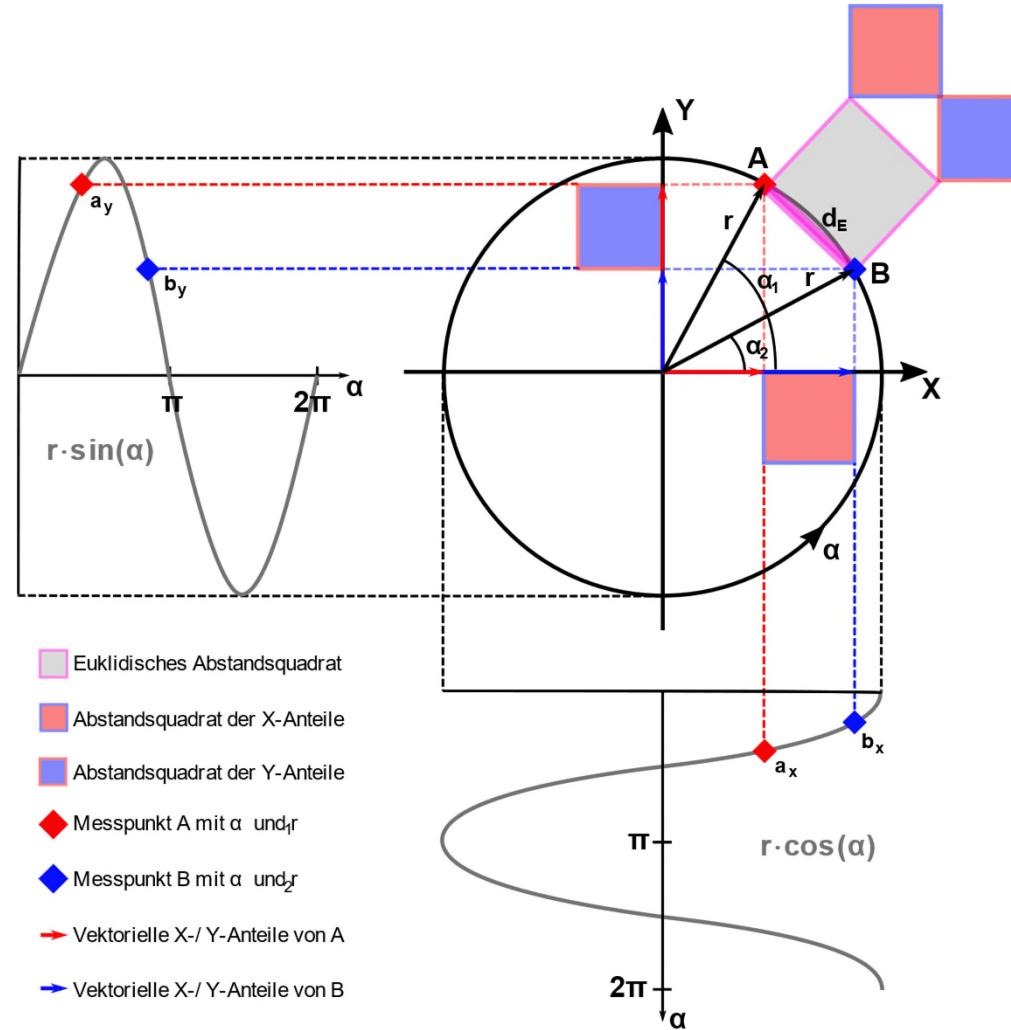


# Datenadaption



## Aufbau über euklidischen Abstand

$$\begin{aligned}
 d_E^2(\mathbf{A}, \mathbf{B}) &= (\|\mathbf{A}_x\|_F - \|\mathbf{B}_x\|_F)^2 + (\|\mathbf{A}_y\|_F - \|\mathbf{B}_y\|_F)^2 \\
 &\leq \\
 d_F^2(\mathbf{A}, \mathbf{B}) &= \|\mathbf{A}_x - \mathbf{B}_x\|_F^2 + \|\mathbf{A}_y - \mathbf{B}_y\|_F^2 = \|\mathbf{A} - \mathbf{B}\|_F^2
 \end{aligned}$$

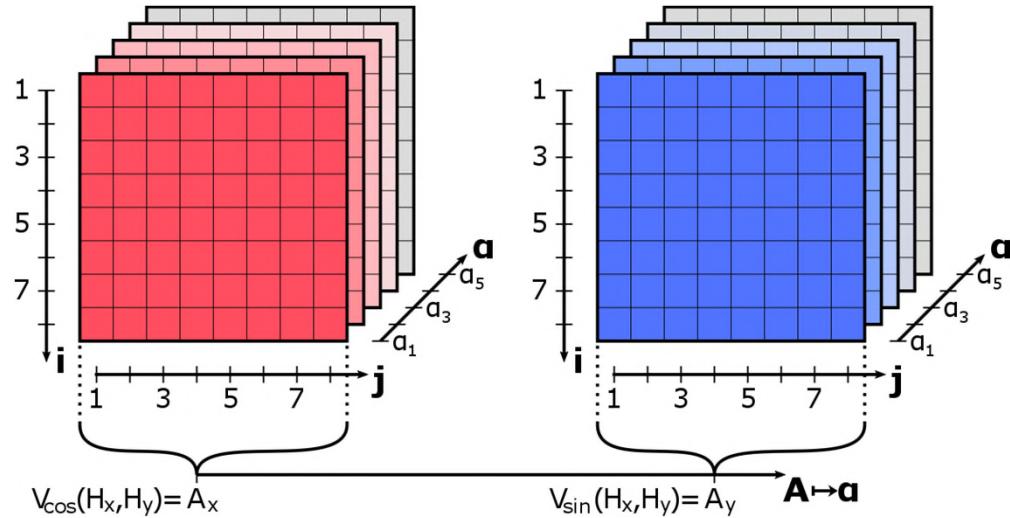


# Datenadaption

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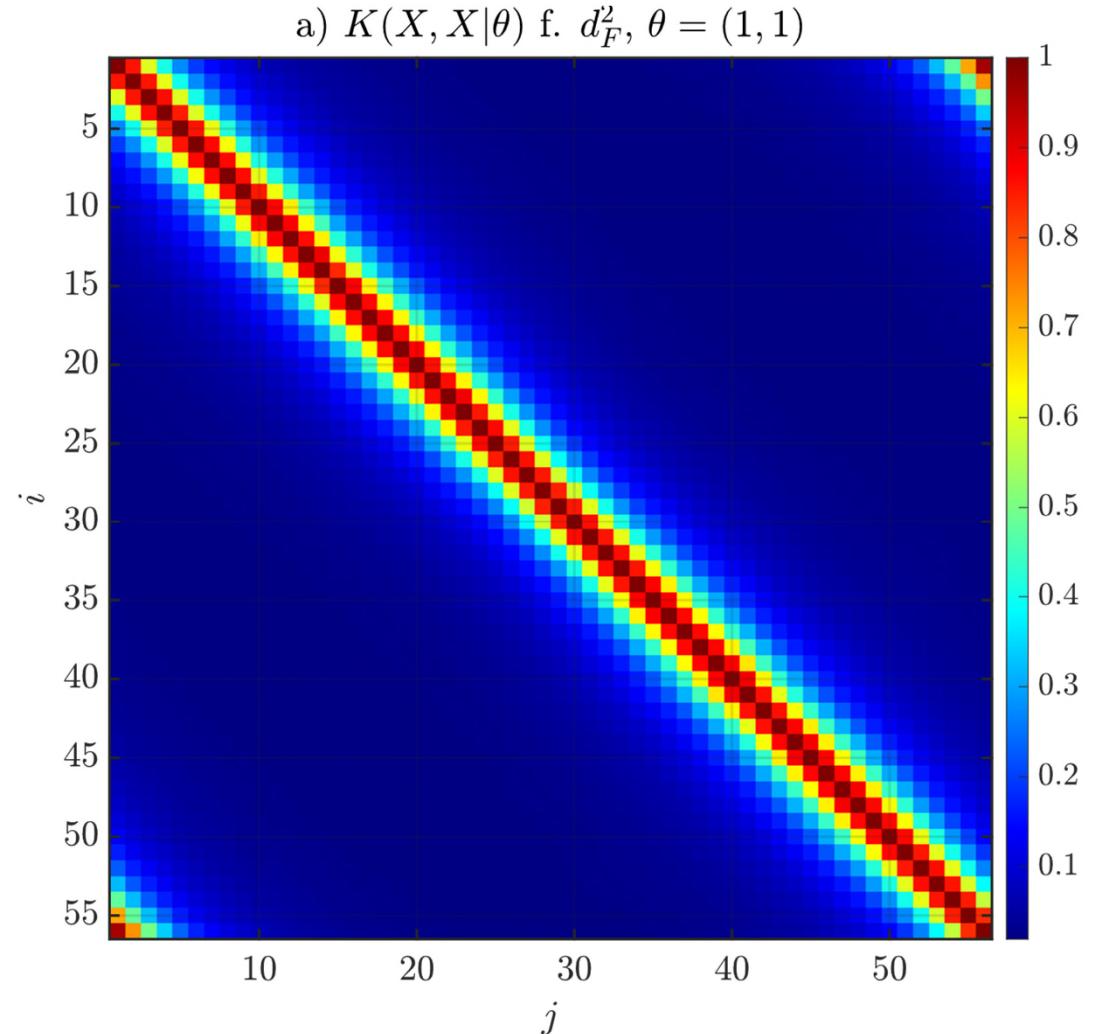
Vektor-2-Norm	$\Rightarrow$	Frobenius Norm
$\mathbf{A} = (a_x, a_y)$	$\Rightarrow$	$\mathbf{A} = [\mathbf{A}_x, \mathbf{A}_y]$
$\downarrow$		$\downarrow$
$\ \mathbf{A}\ _2 = \sqrt{\sum_{i=1}^n  A_i ^2}$	$\Rightarrow$	$\ \mathbf{A}_x\ _F = \sqrt{\sum_{j=1}^n \ \mathbf{A}_{xj}\ _2^2}$ f. j-te Spalte
$\downarrow$		$\downarrow$
$d_E^2(\mathbf{A}, \mathbf{B})$	$\Rightarrow$	$d_F^2(\mathbf{A}, \mathbf{B})$
$=$		$=$
$\ \mathbf{A} - \mathbf{B}\ _2^2$	$\Rightarrow$	$\ \mathbf{A} - \mathbf{B}\ _F^2$
$=$		$=$
$\vdots$		$\ \mathbf{A}_x - \mathbf{B}_x\ _F^2 + \ \mathbf{A}_y - \mathbf{B}_y\ _F^2$
$\vdots$		$\geq$
$(a_x - b_x)^2 + (a_y - b_y)^2$	$\Leftrightarrow$	$(\ \mathbf{A}_x\ _F - \ \mathbf{B}_x\ _F)^2 + (\ \mathbf{A}_y\ _F - \ \mathbf{B}_y\ _F)^2$
$\downarrow$		$\downarrow$
$r =  \mathbf{A}  = \sqrt{a_x^2 + a_y^2}$	$\Rightarrow$	$\ r\ _F =  \ \mathbf{A}\ _F  = \sqrt{\ \mathbf{A}_x\ _F^2 + \ \mathbf{A}_y\ _F^2}$

# Gauß-Prozesse

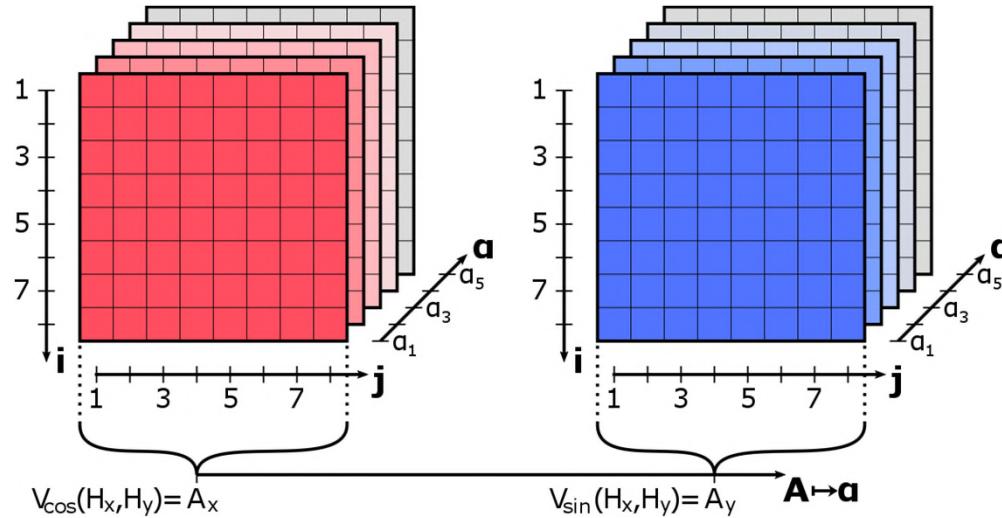


Fractional Kernel

$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$

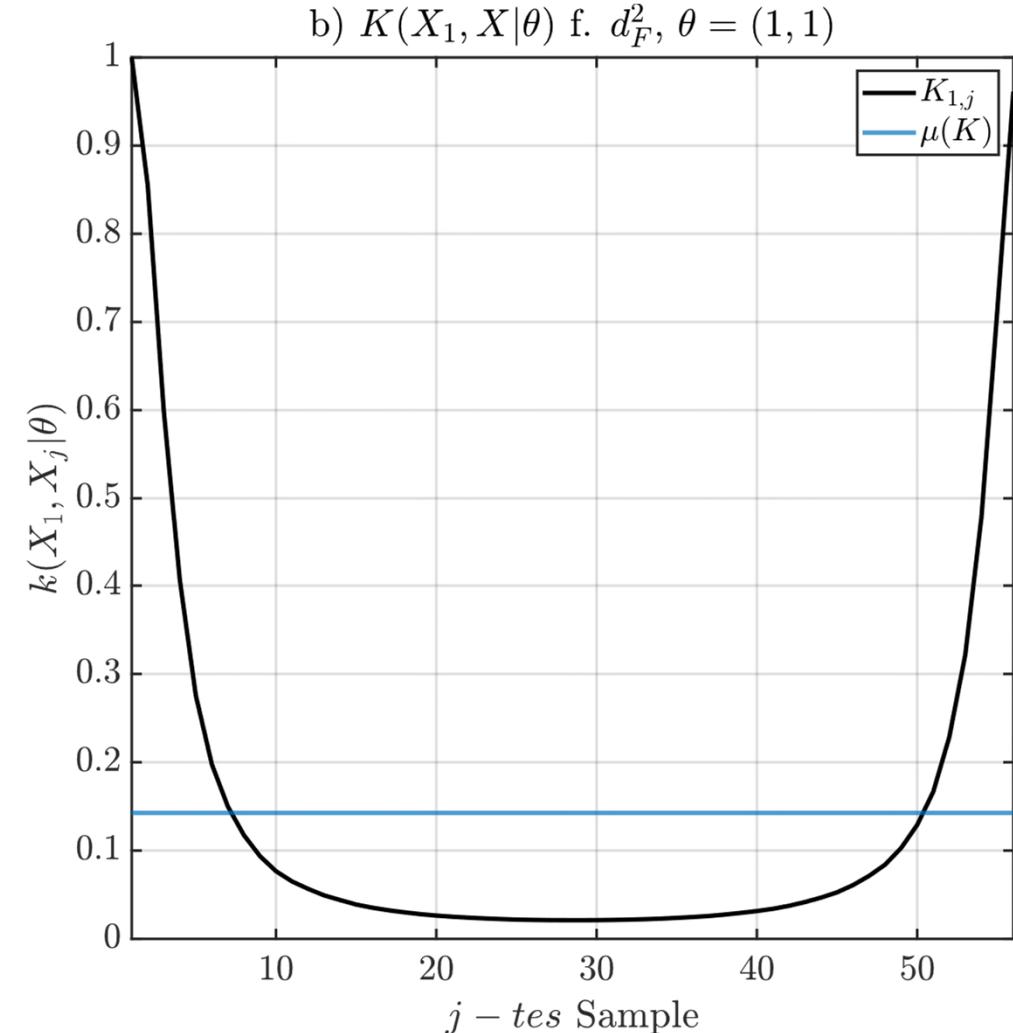


# Gauß-Prozesse

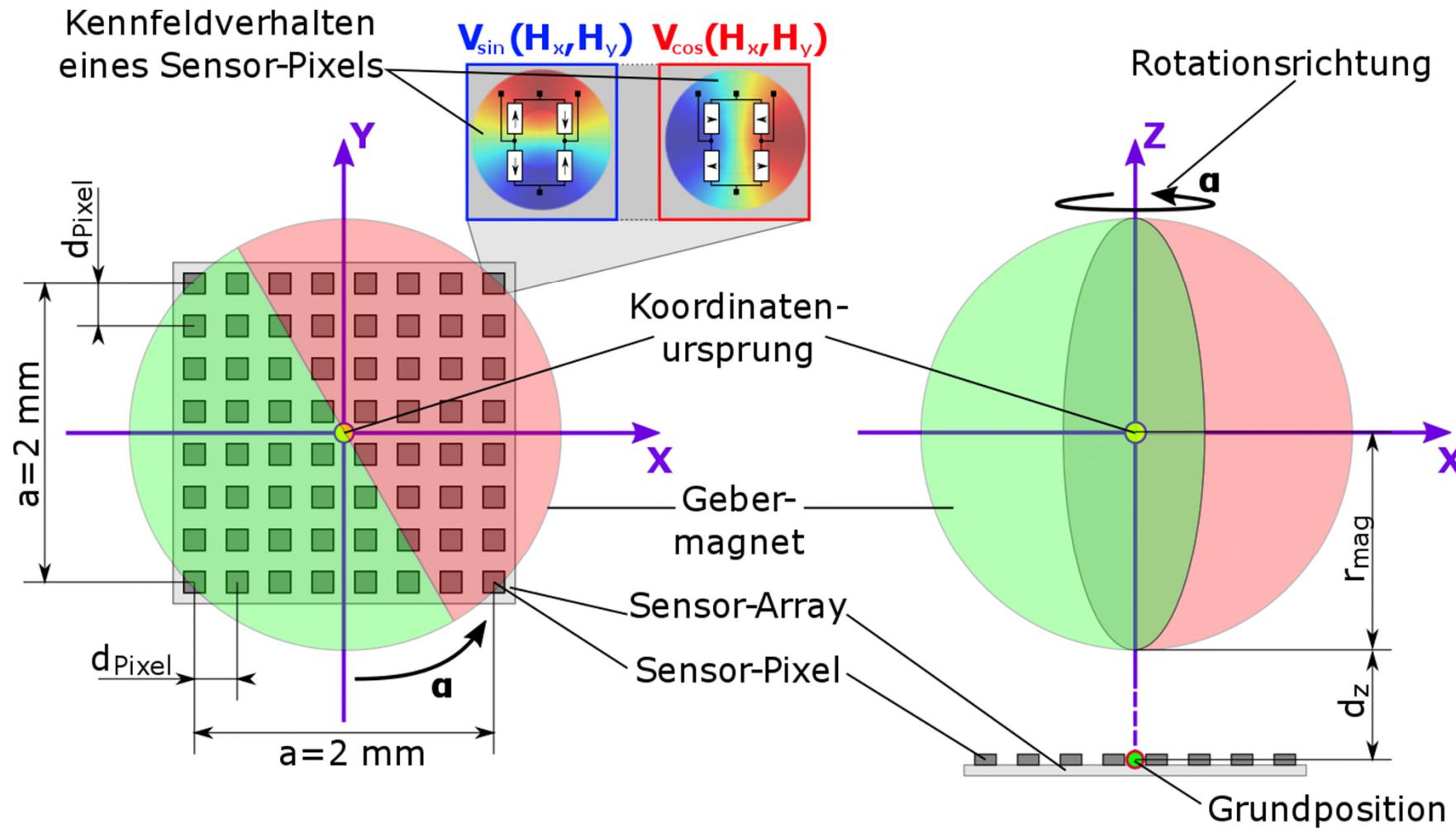


Fractional Kernel

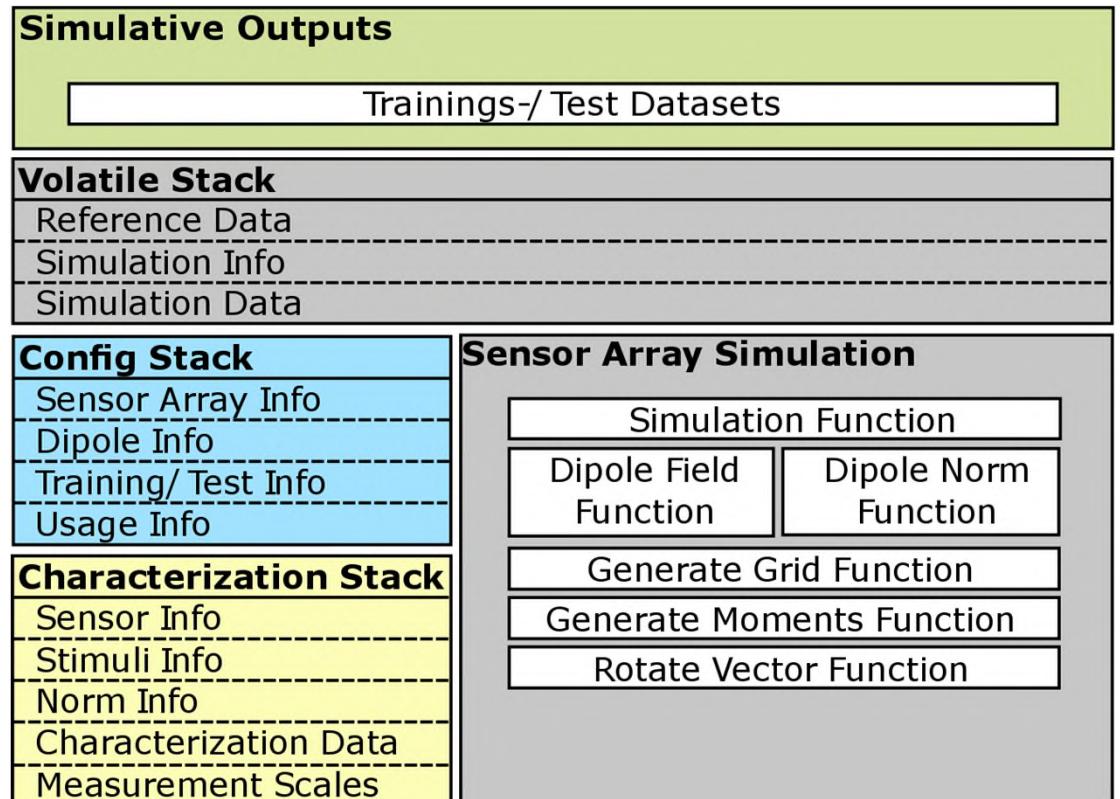
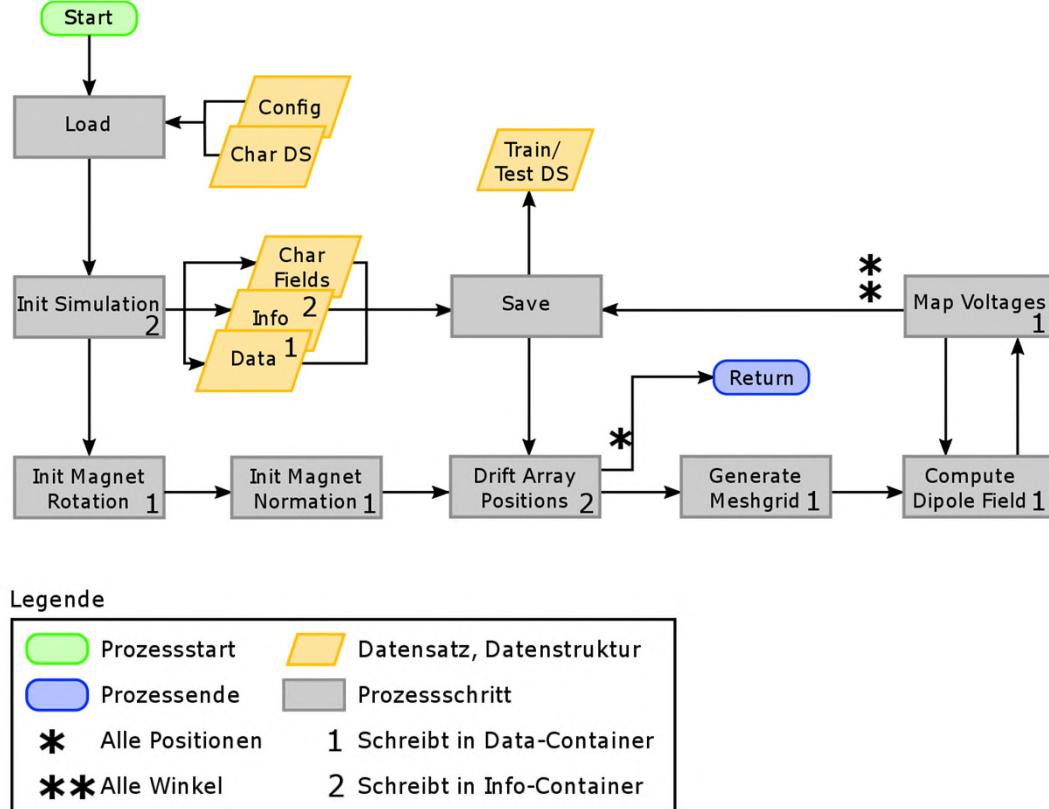
$$\frac{\sigma_f^2}{1 + \frac{d_x^2 \langle \mathbf{A}, \mathbf{B} \rangle}{2\sigma_I^2}}$$



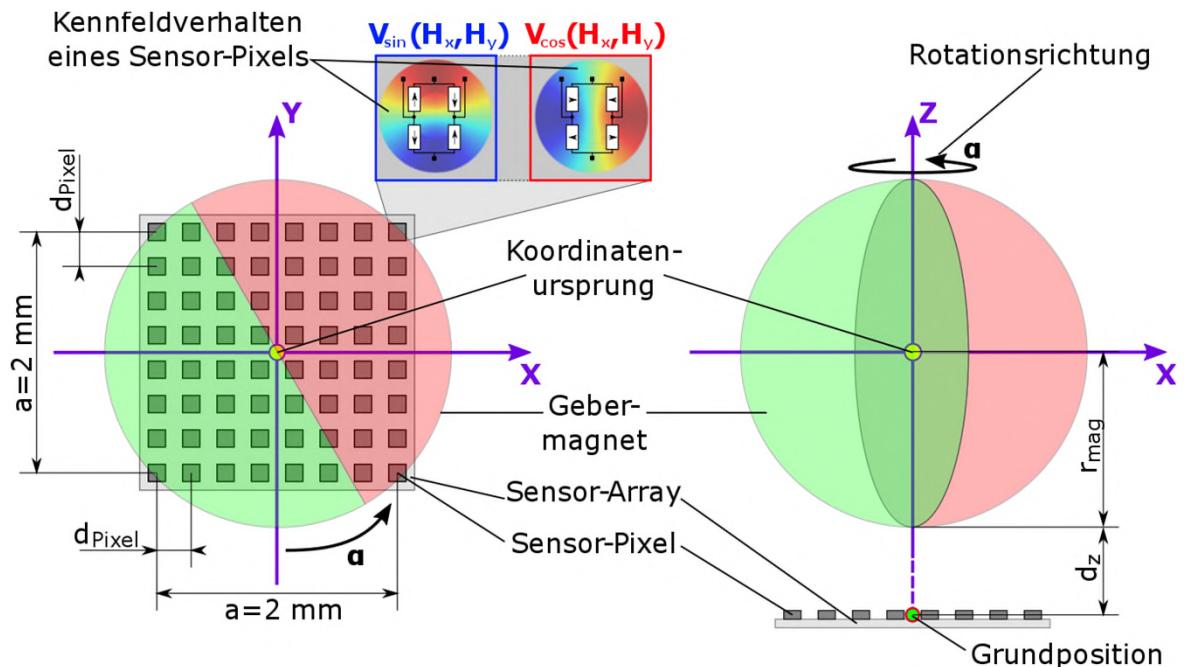
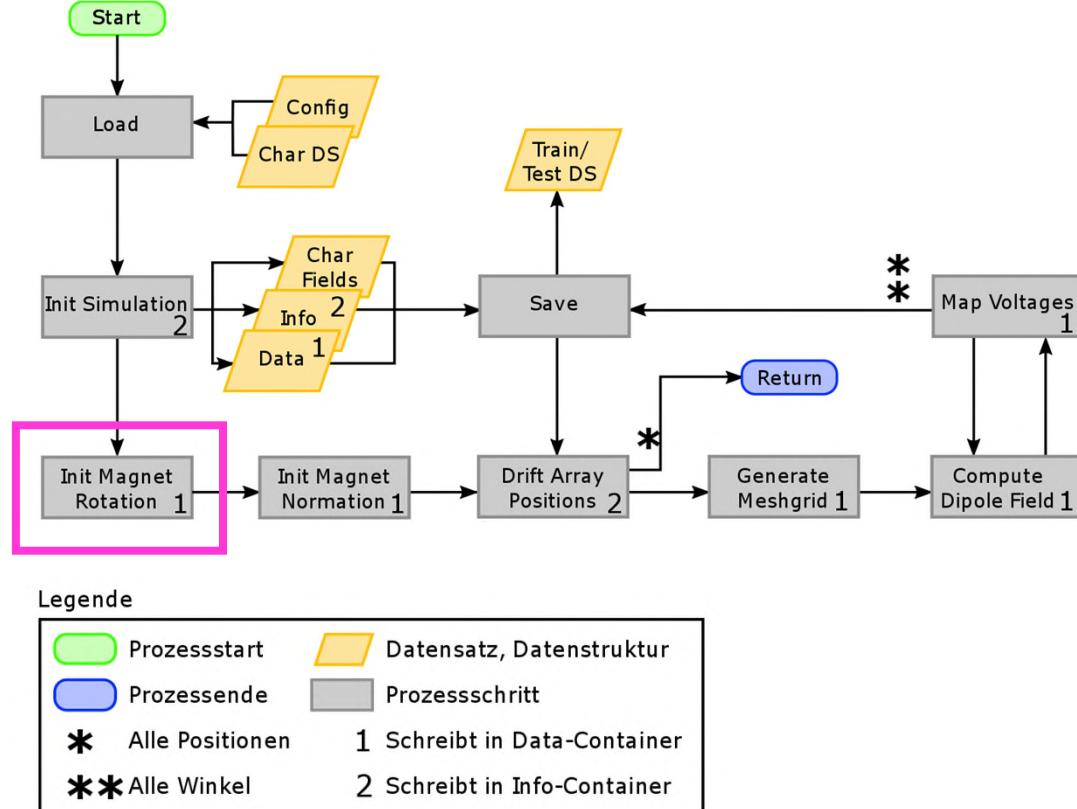
# Simulation – Sensor-Array



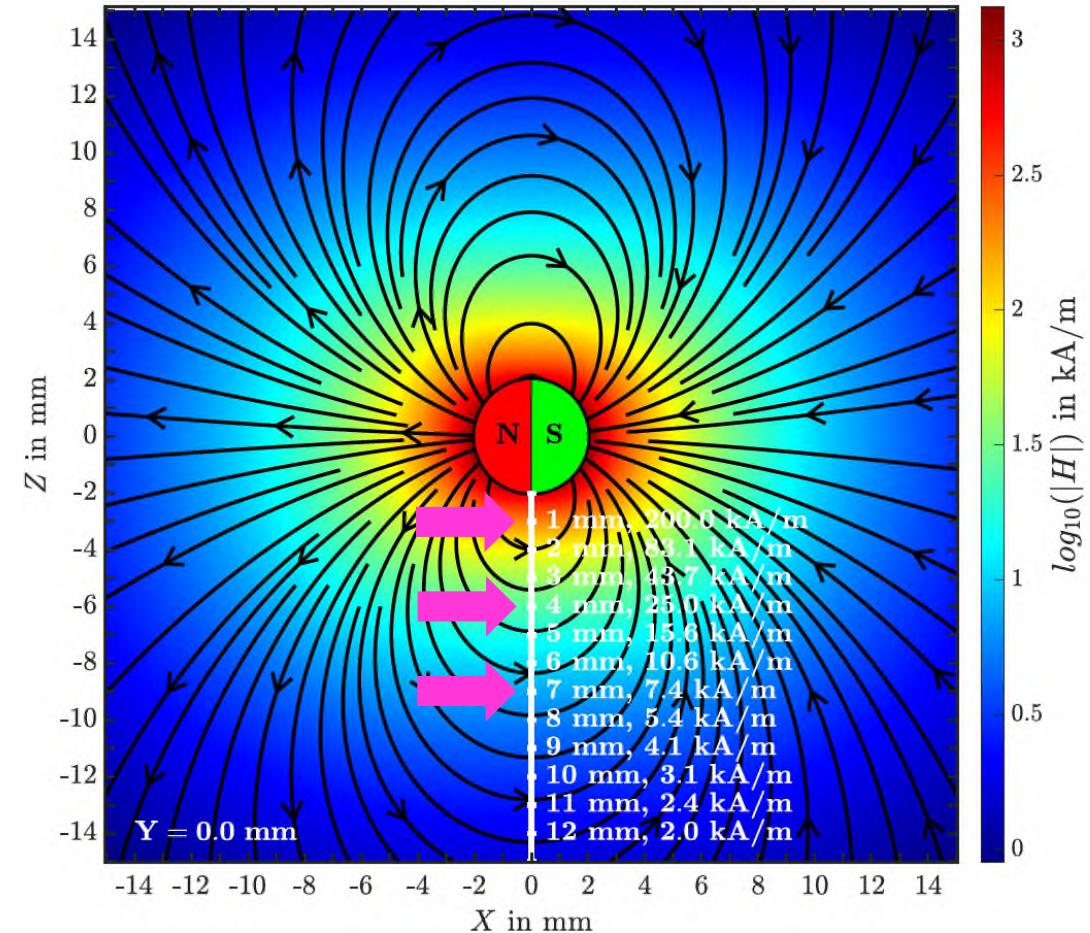
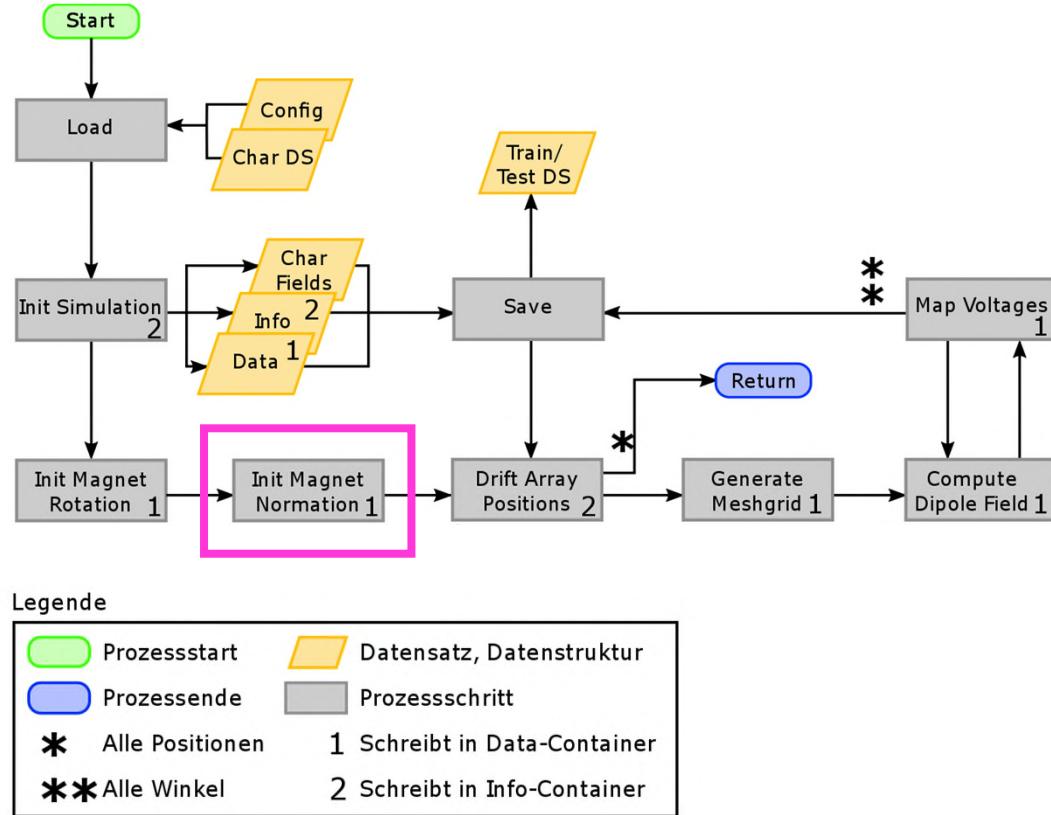
# Simulation – Sensor-Array



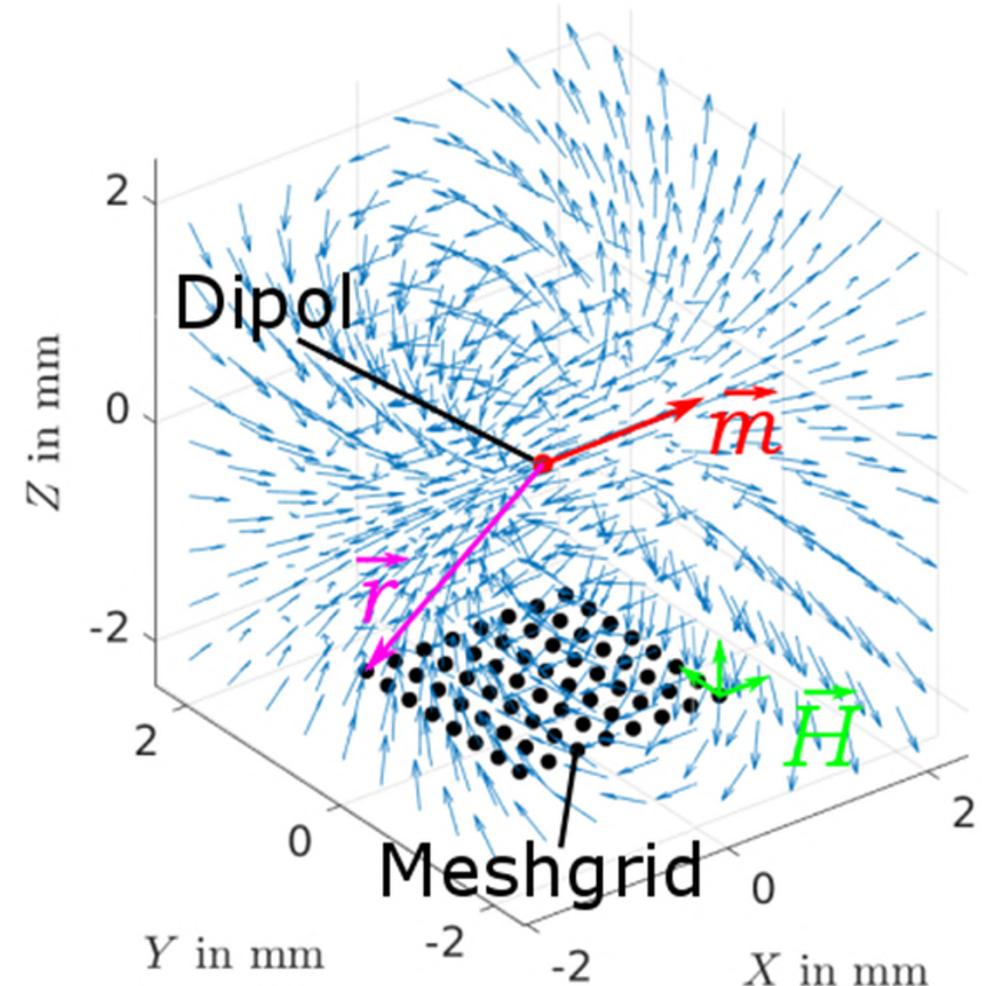
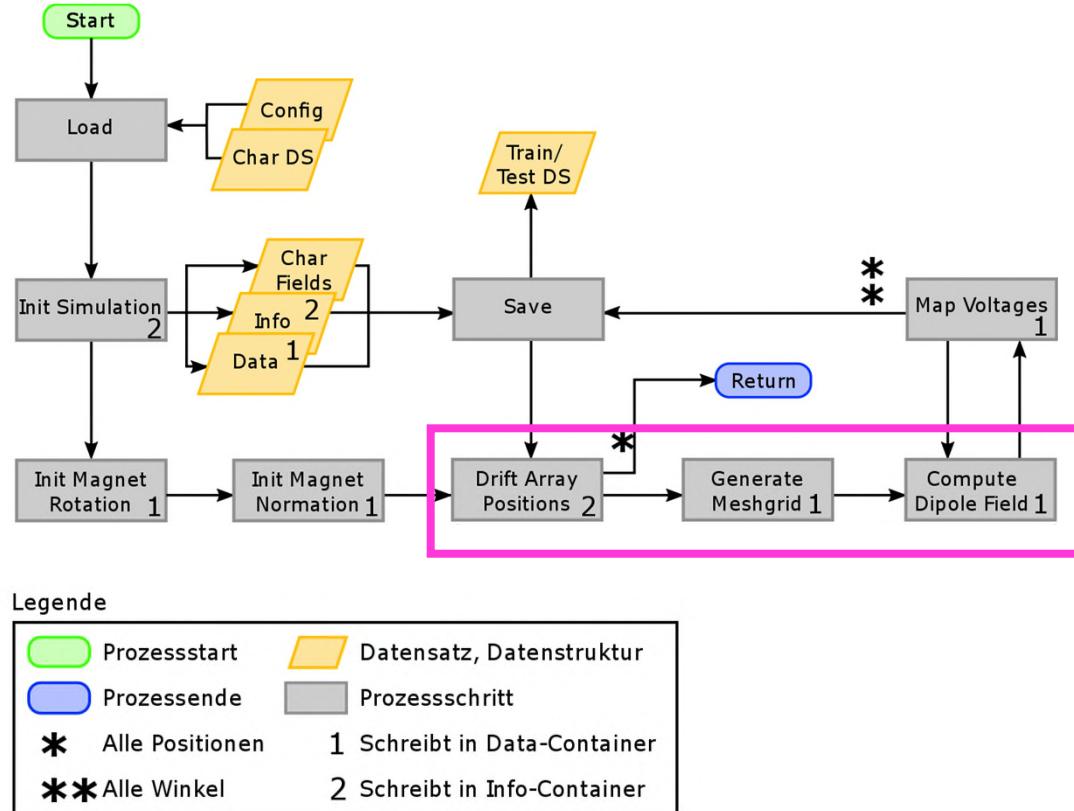
# Simulation – Sensor-Array



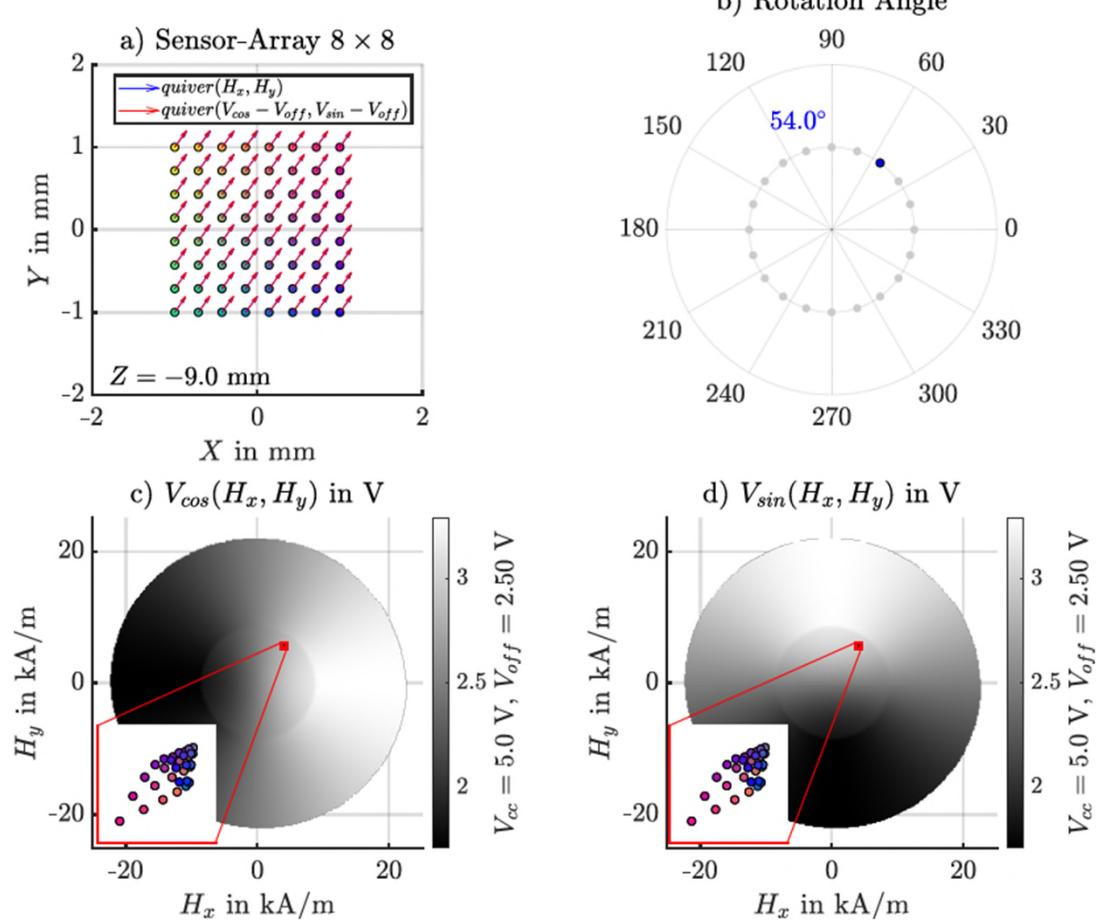
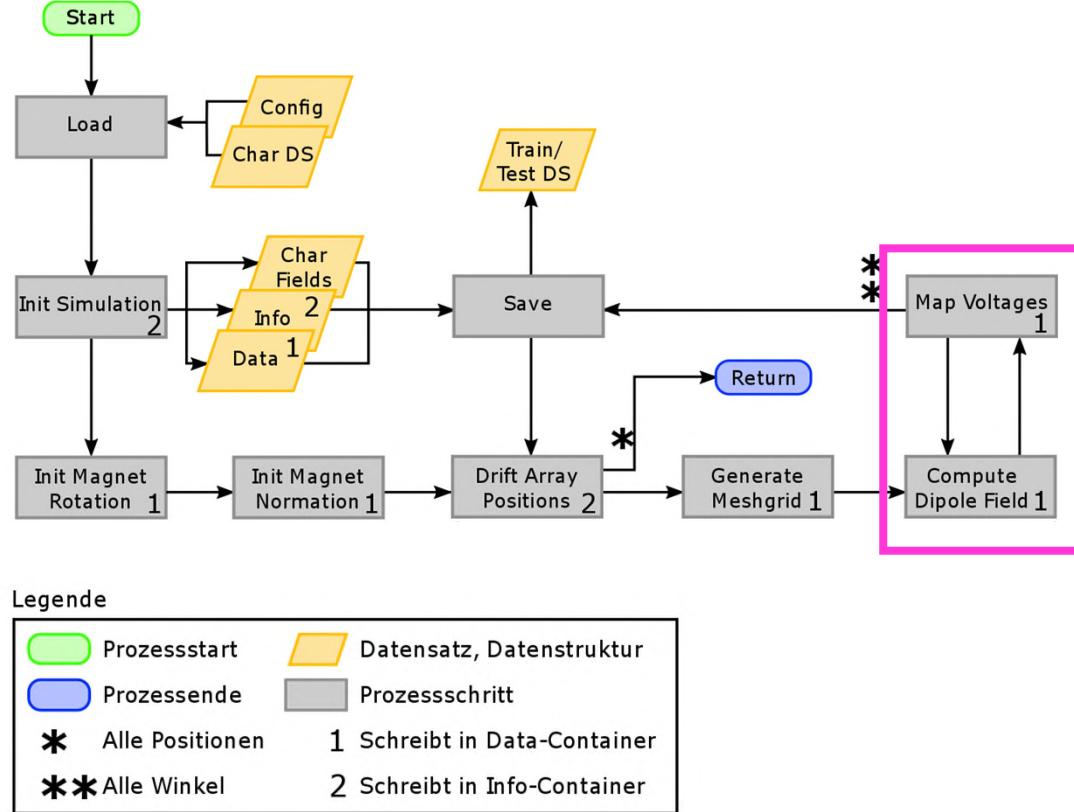
# Simulation – Sensor-Array



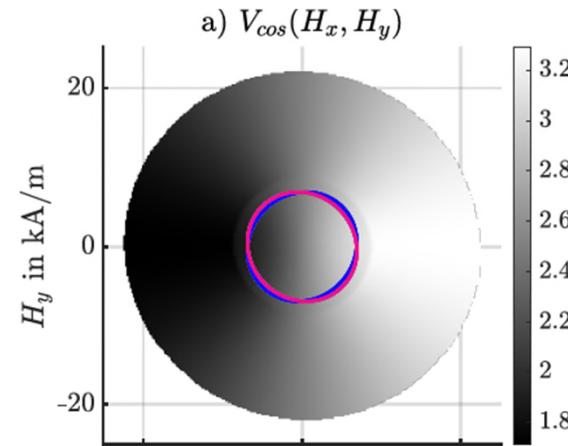
# Simulation – Sensor-Array



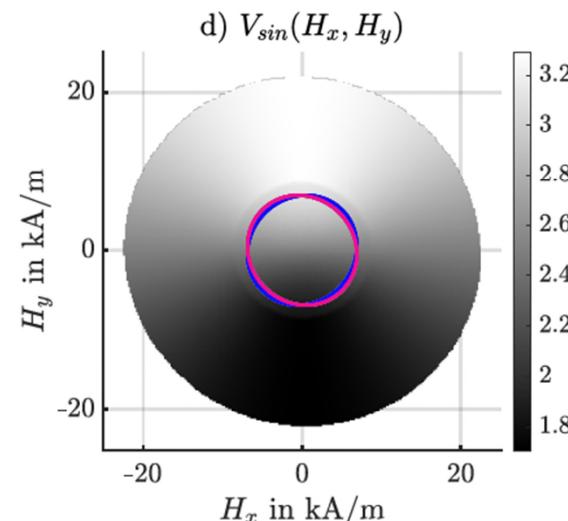
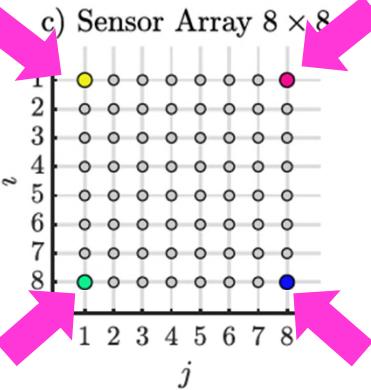
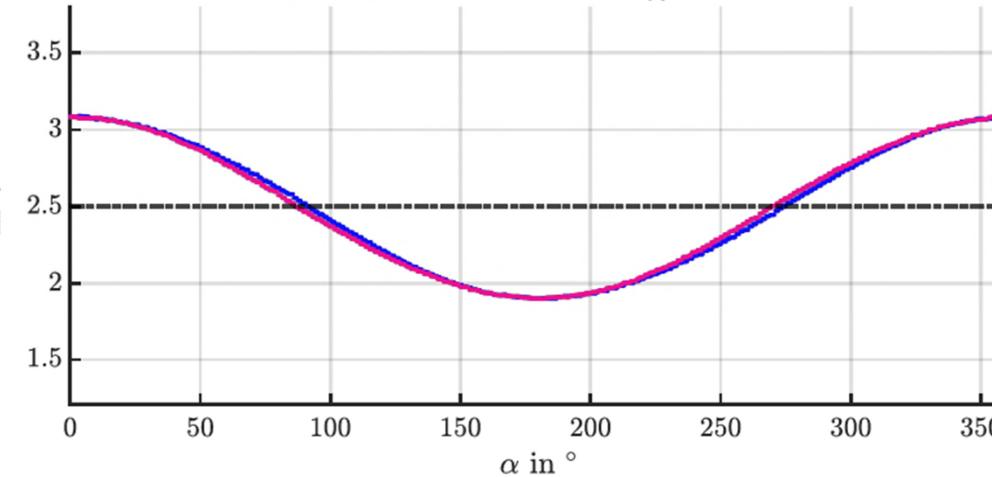
# Simulation – Sensor-Array



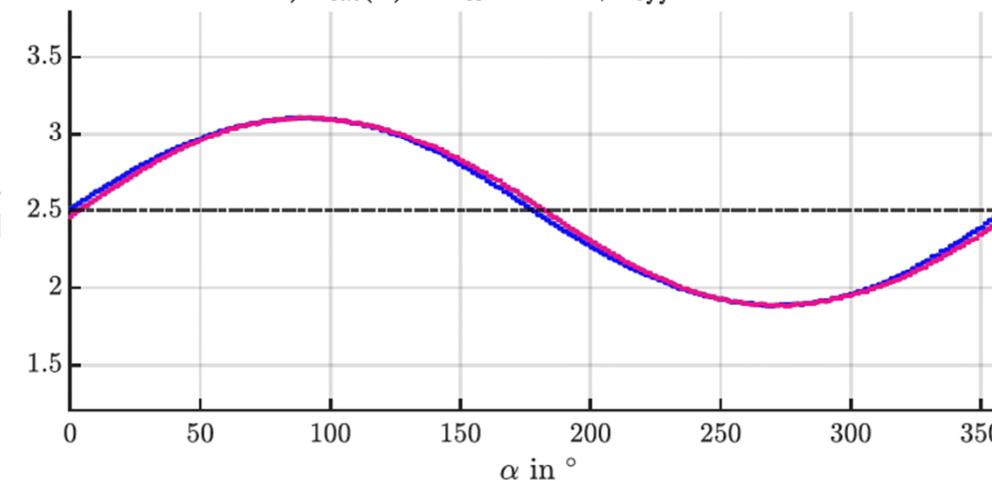
# Simulation – Sensor-Array



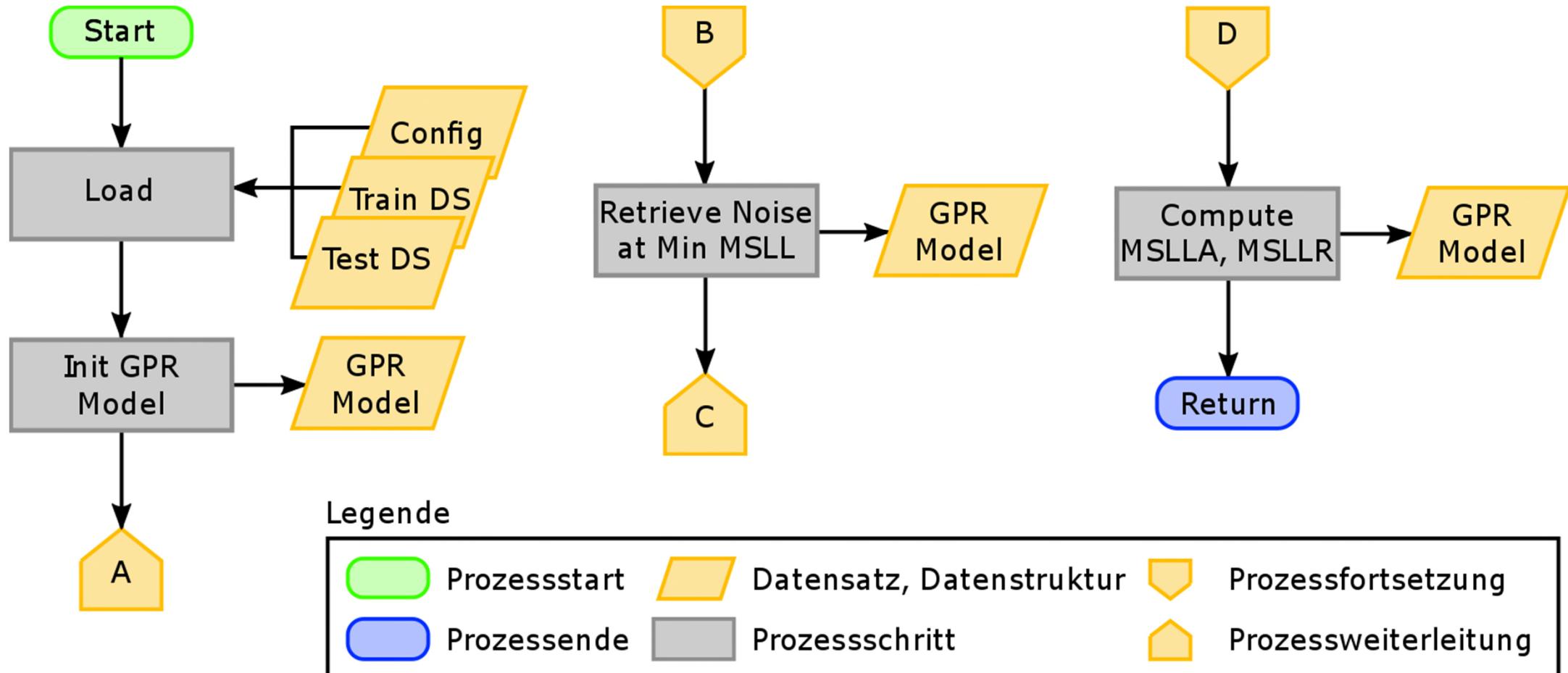
b)  $V_{cos}(\alpha)$  f.  $V_{cc} = 5.0$  V,  $V_{off} = 2.50$  V



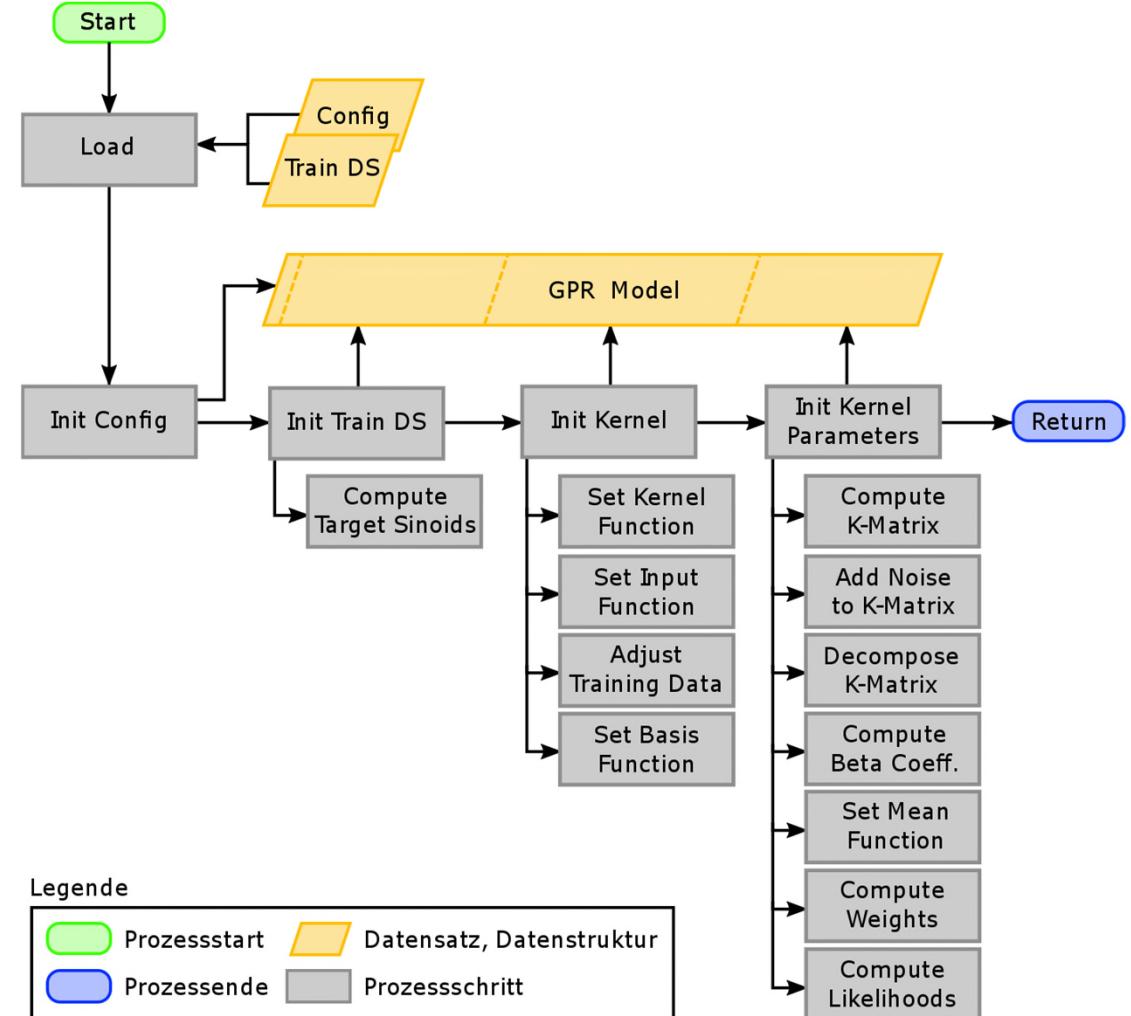
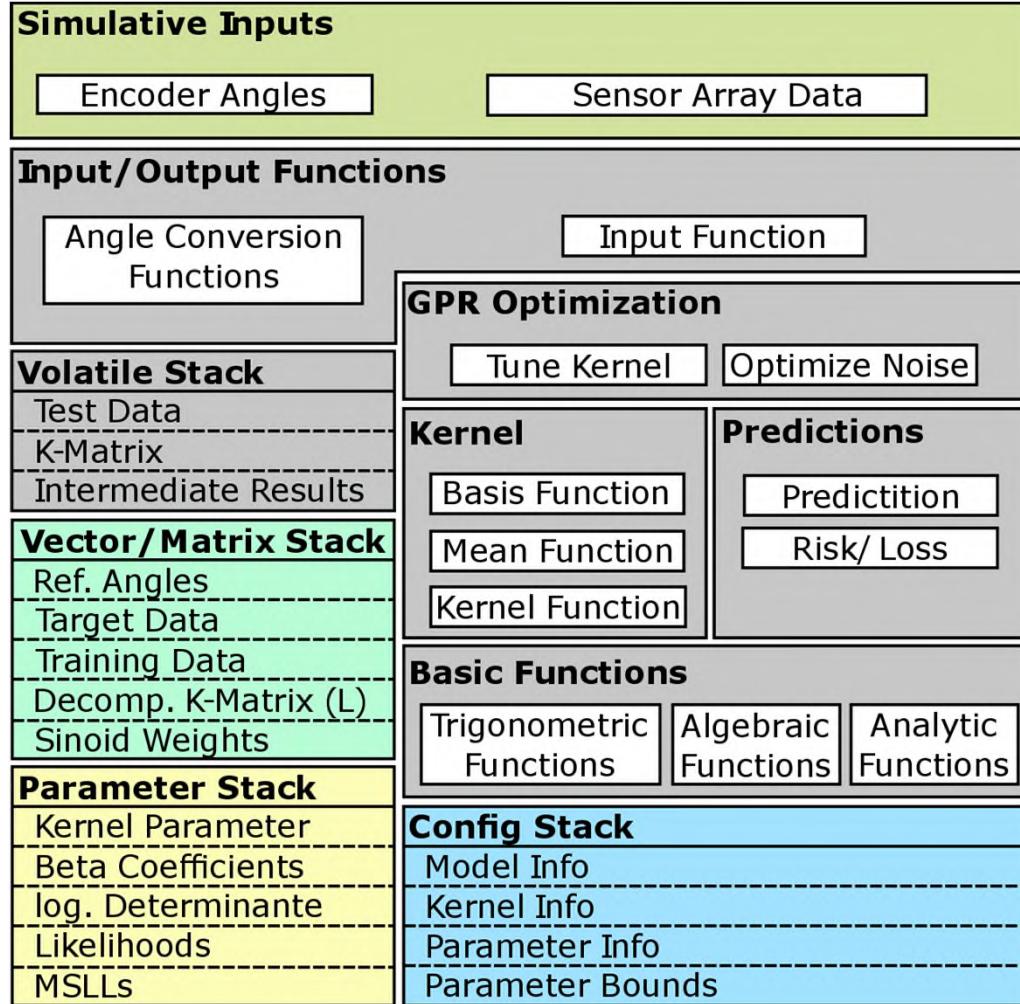
e)  $V_{sin}(\alpha)$  f.  $V_{cc} = 5.0$  V,  $V_{off} = 2.50$  V



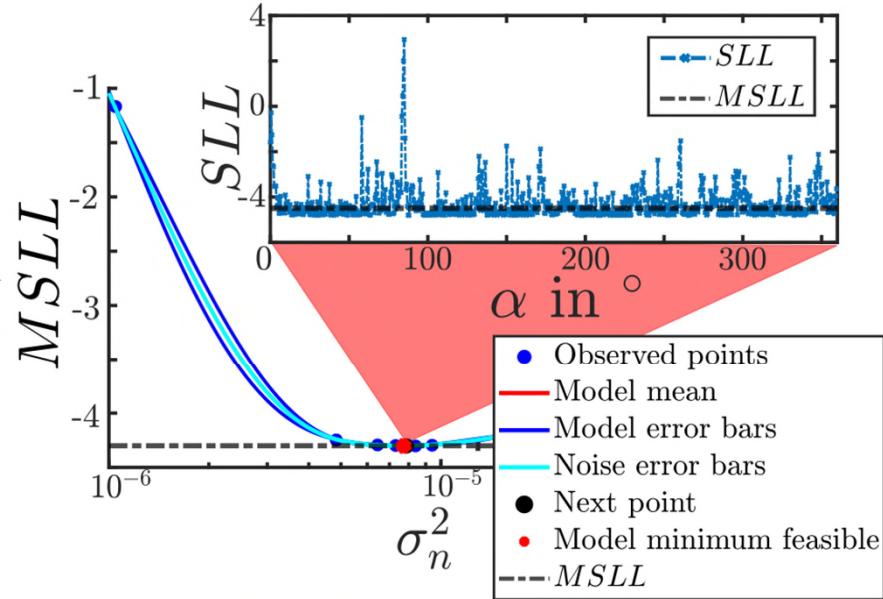
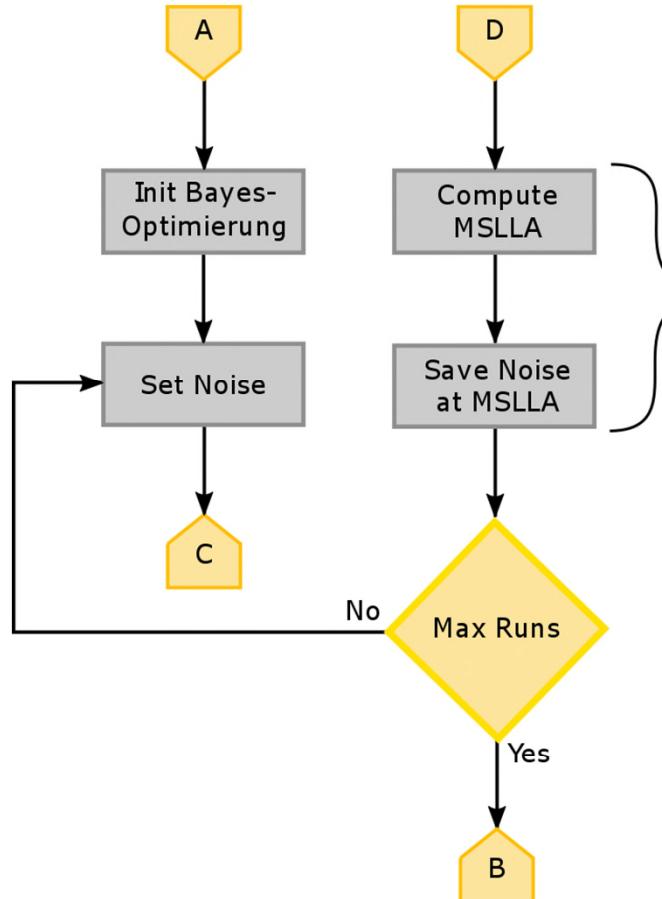
# Simulation – Gauß-Prozesse



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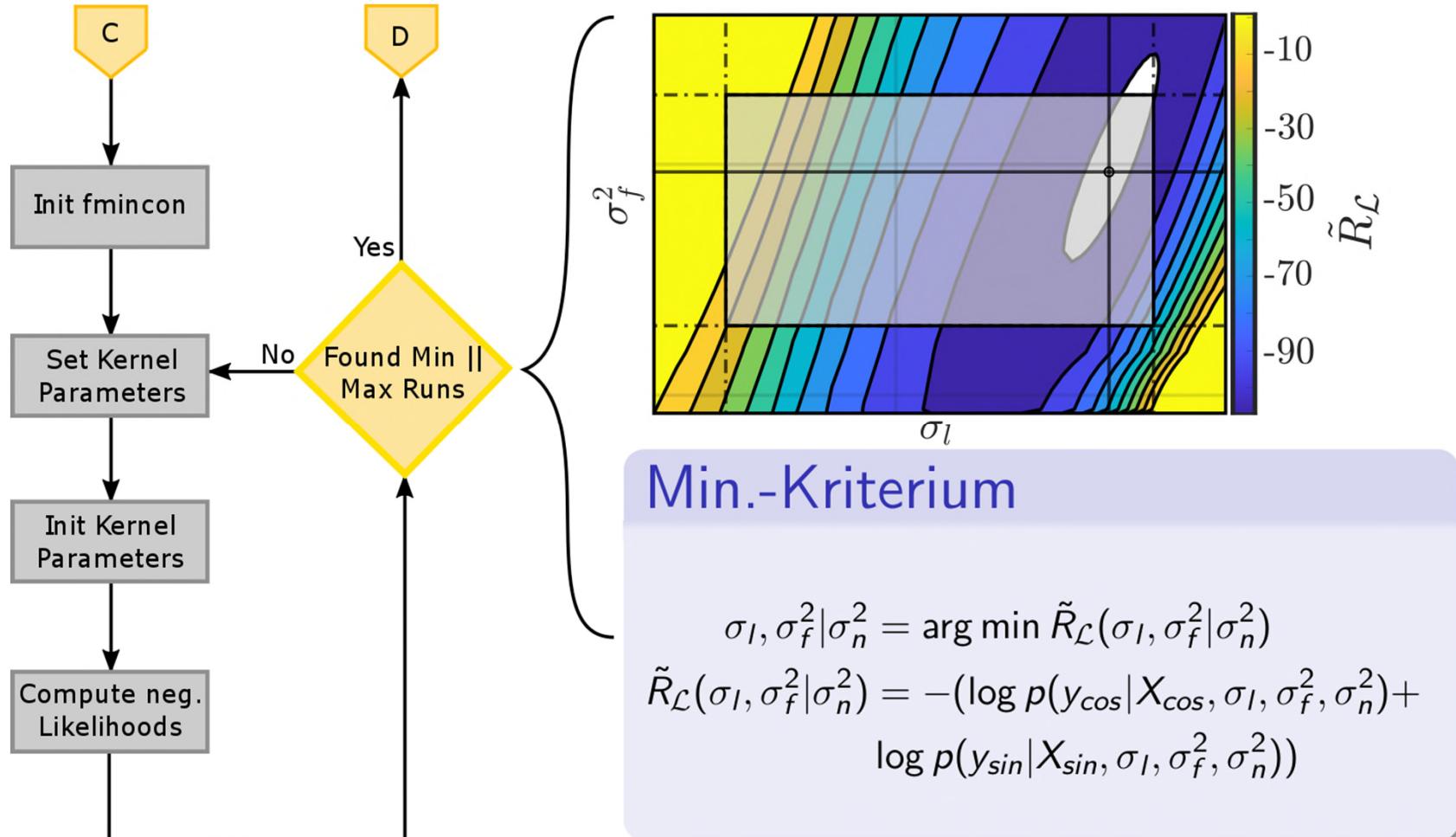
## Min.-Kriterium

$$\sigma_n^2 | \mathcal{D}, \alpha_* = \arg \min MSLLA(\sigma_n^2 | \mathcal{D}, \alpha_*)$$

$$SLLA = 0,5 \cdot \left( \log(2\pi\sigma_*^2) + \frac{(\alpha - \alpha_*)^2}{\sigma_*^2} \right)$$

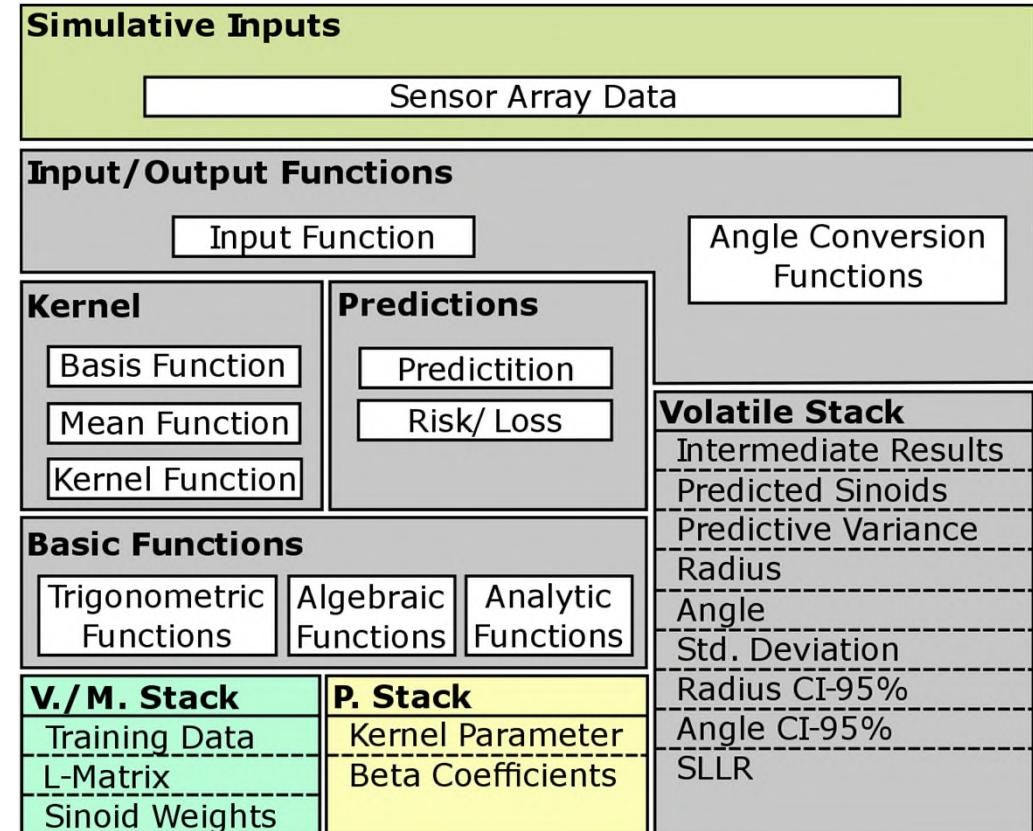
$$\sigma_*^2 = \sigma_n^2 + V_*$$

# Simulation – Gauß-Prozesse

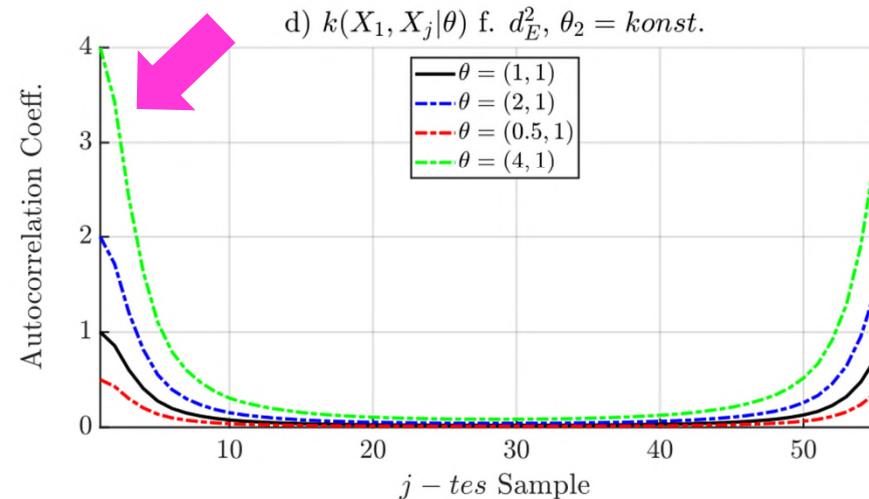
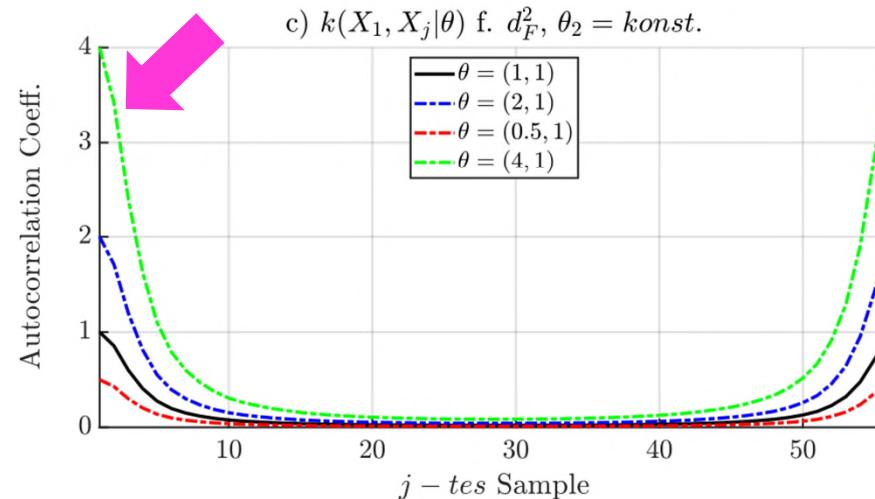
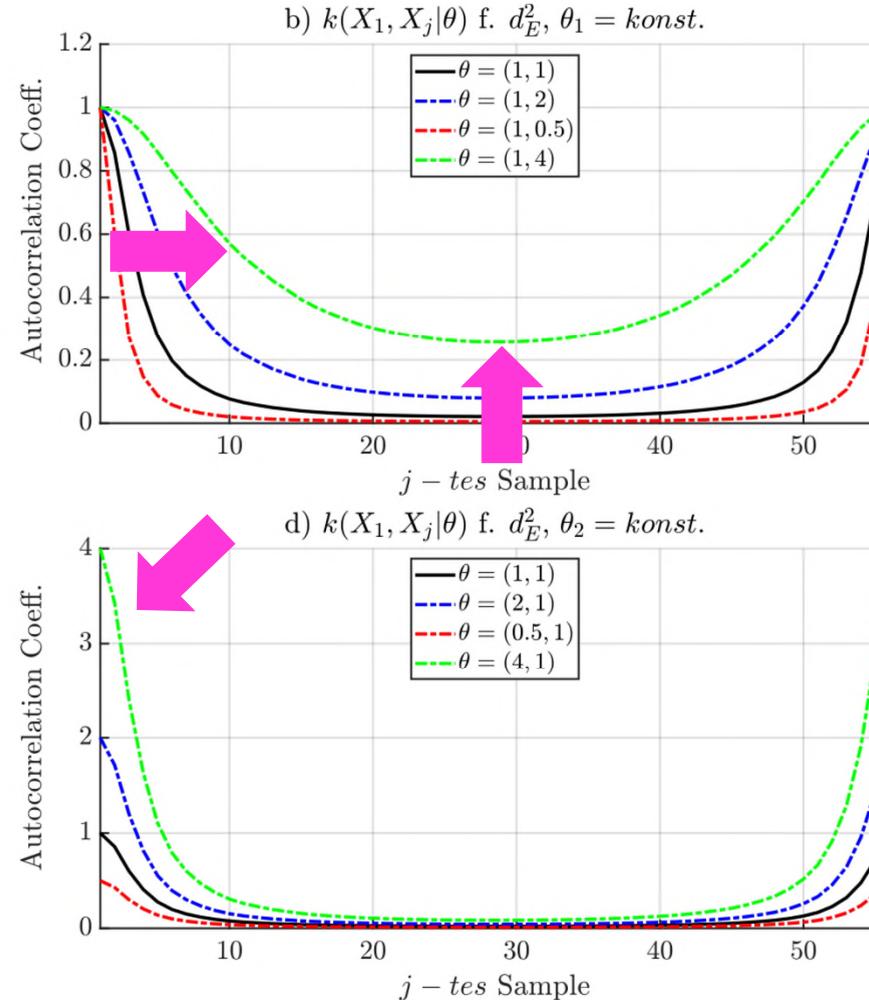
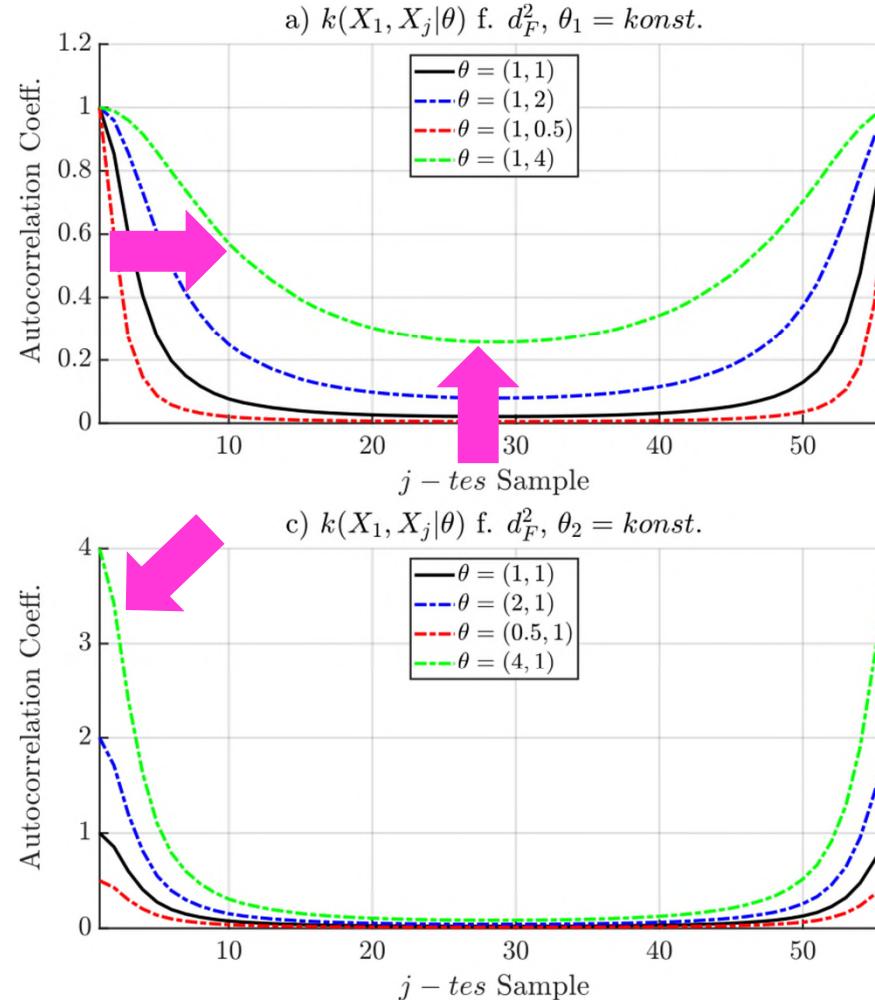


# Simulation – Gauß-Prozesse

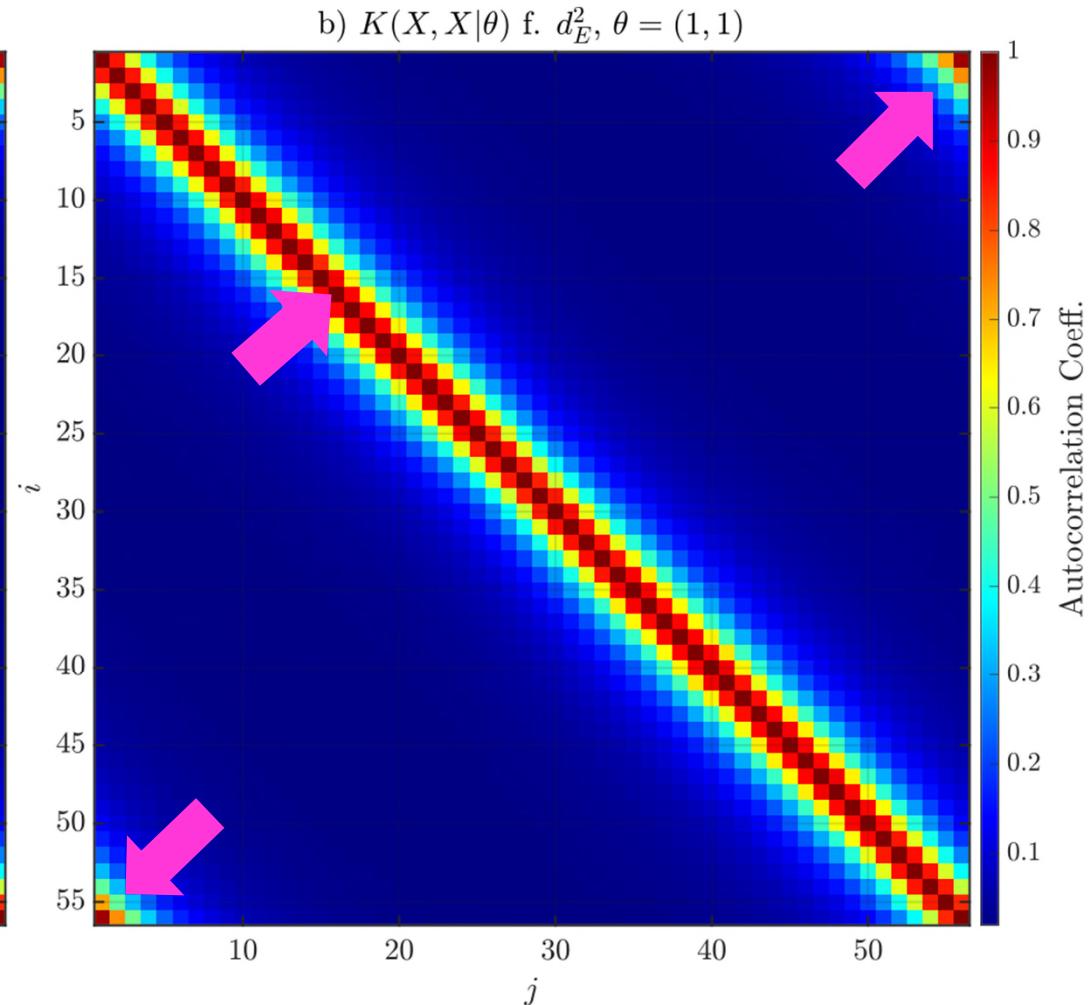
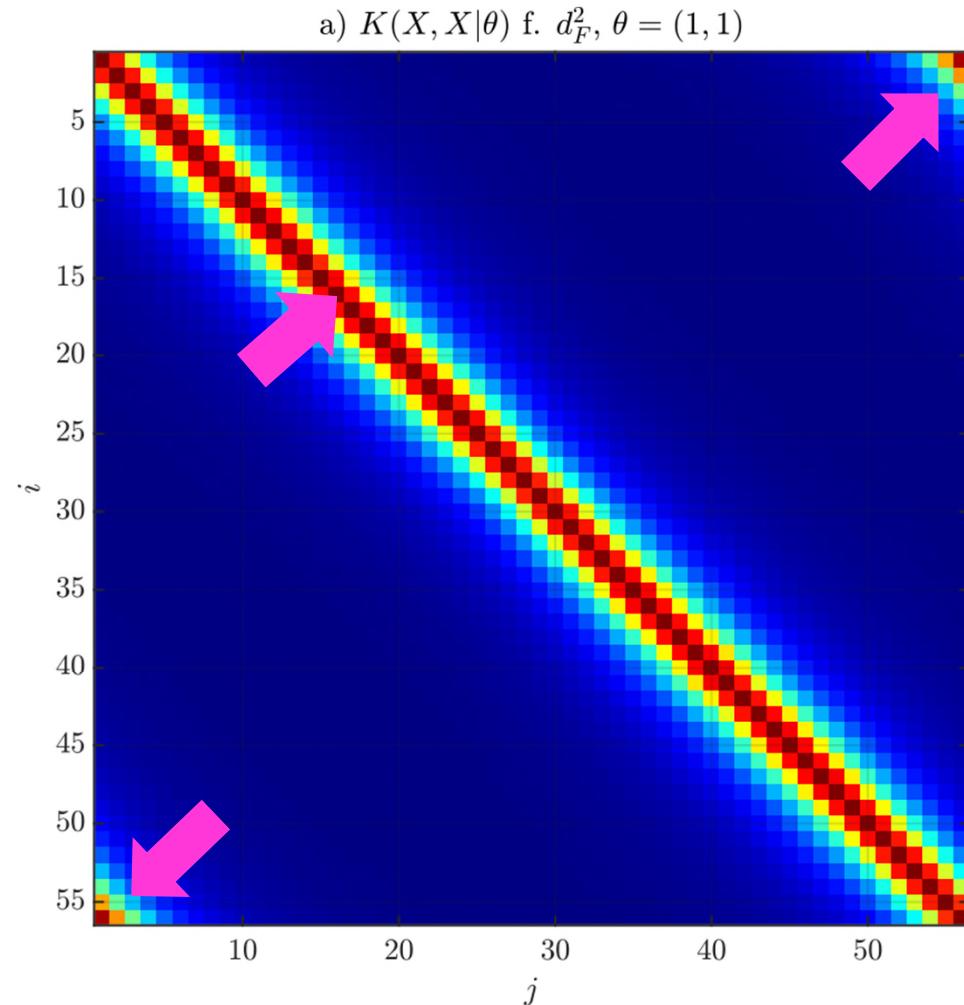
- Ausrichtung umgelegt
- Minimale Parametrierung
- Funktionaler Aufbau
- Vorhersage und Derivate
- Qualitätskriterien



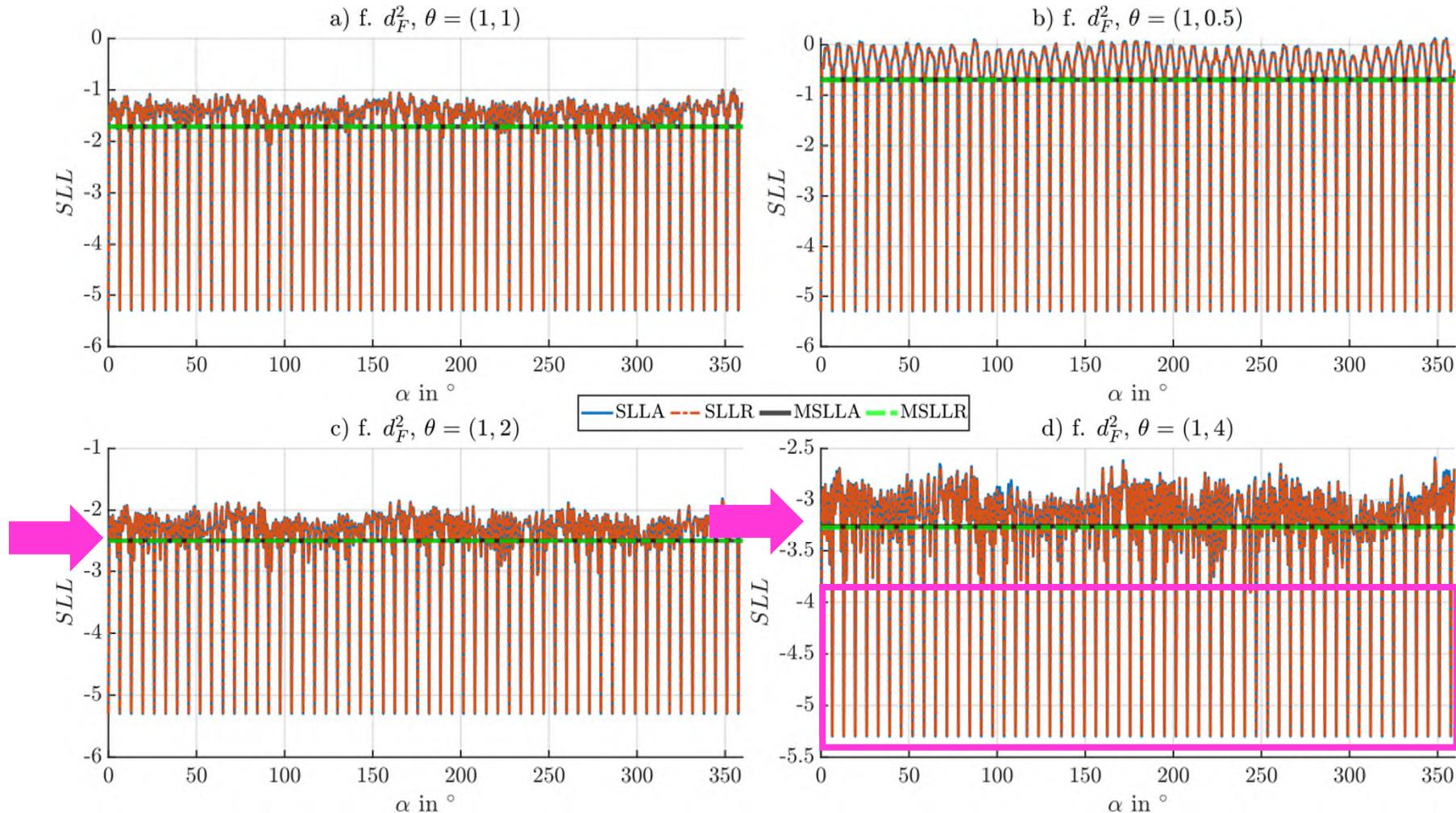
# Kernel-Vergleich



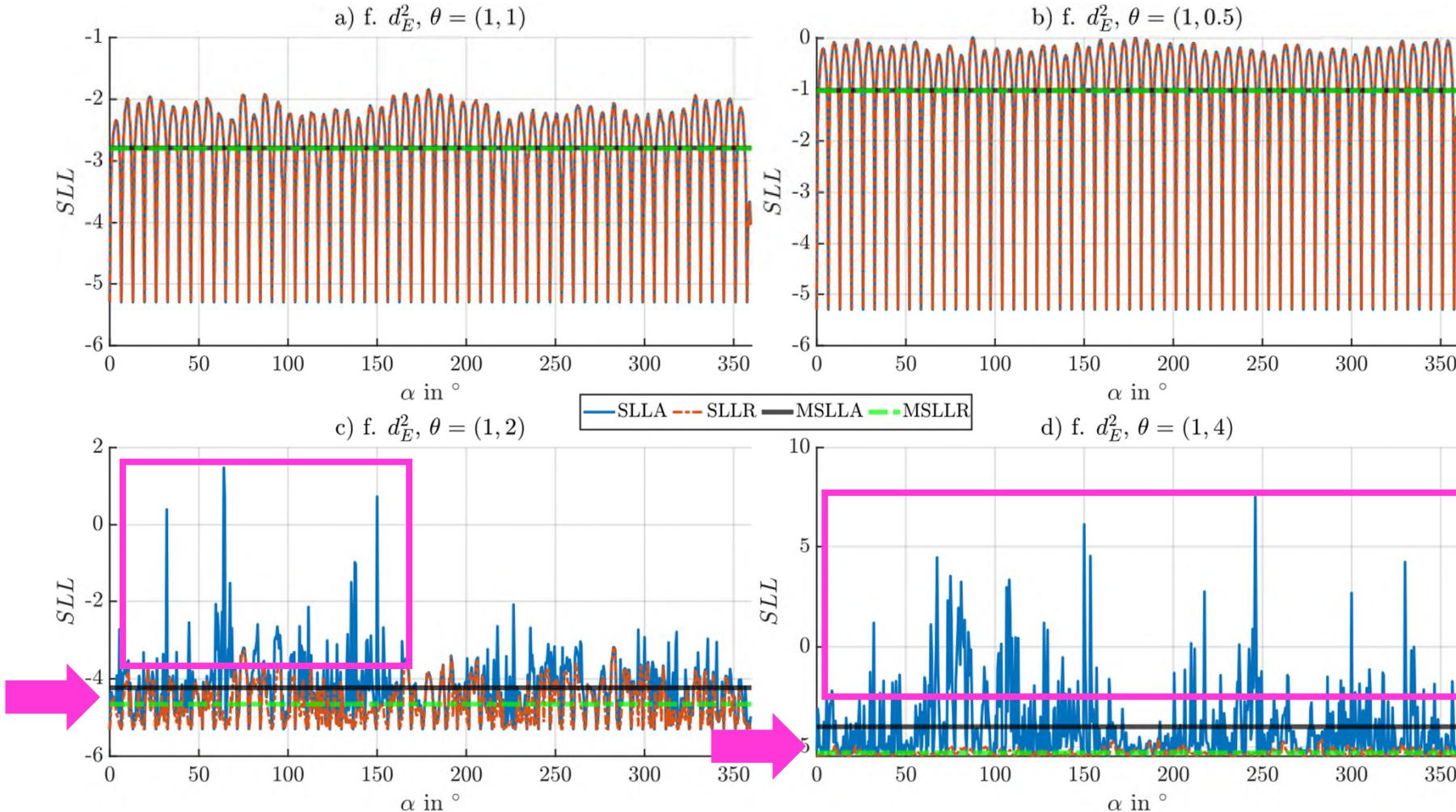
# Kernel-Vergleich



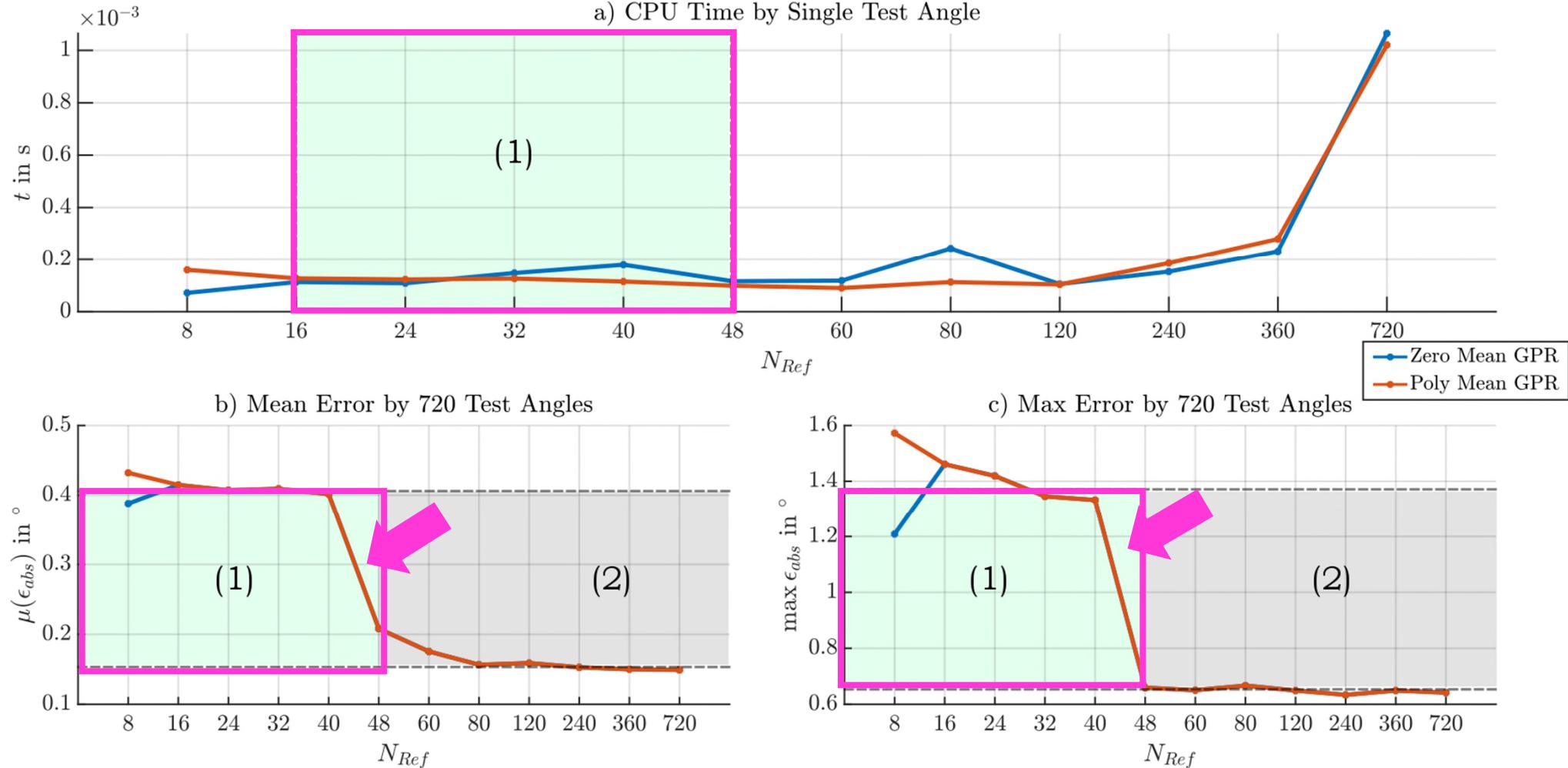
# Kernel-Vergleich



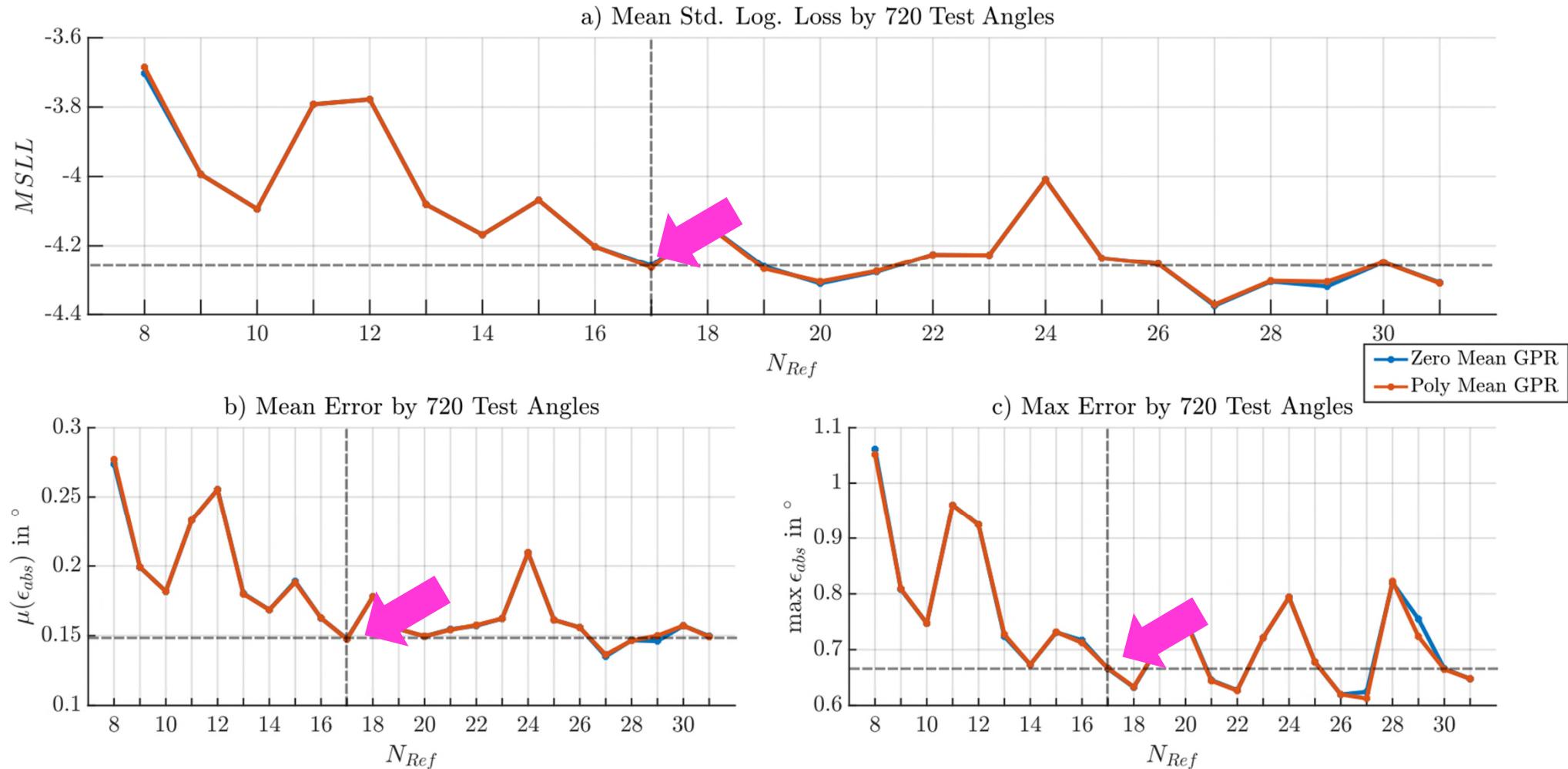
# Kernel-Vergleich



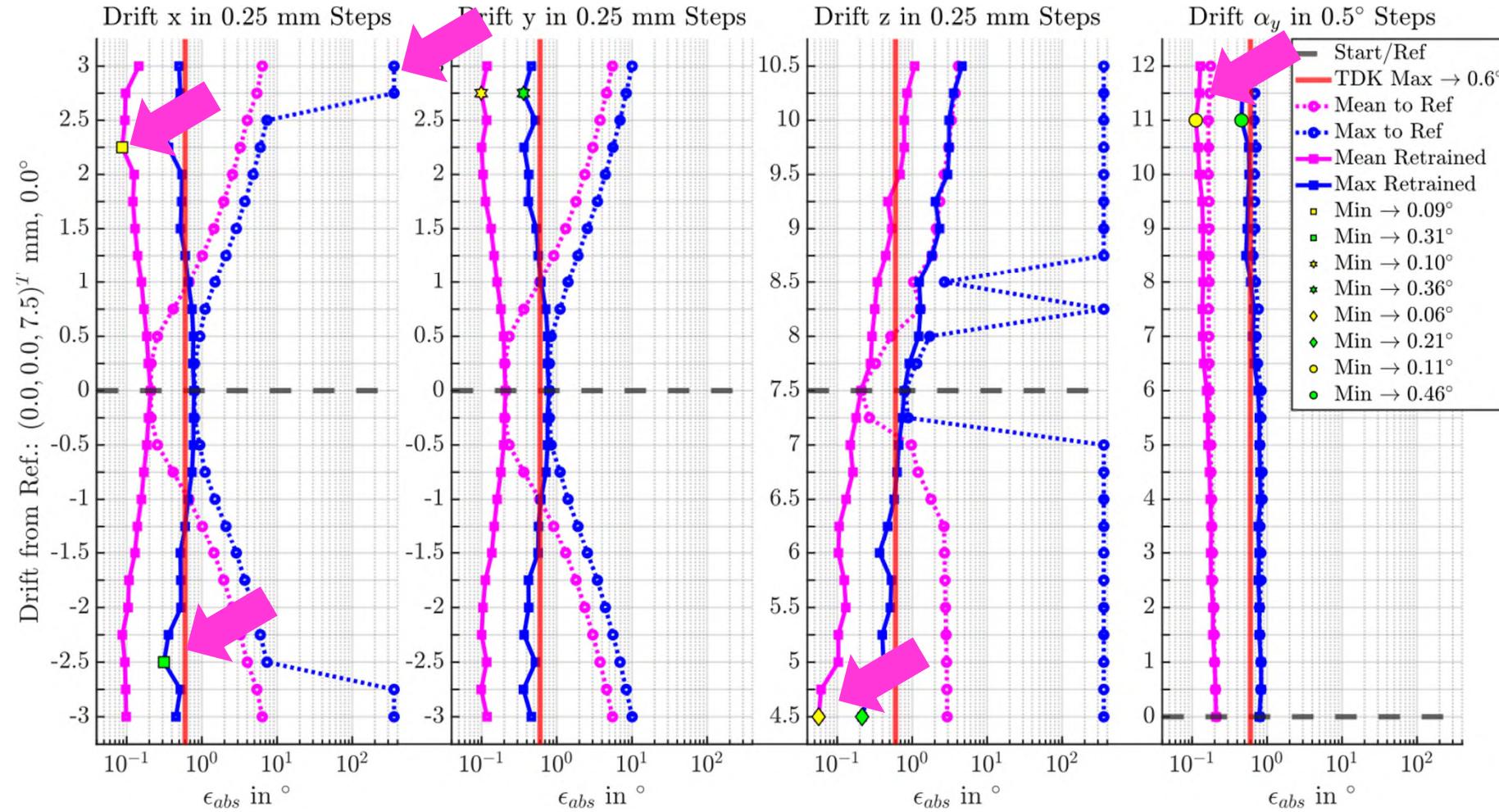
# Kompromissbildung



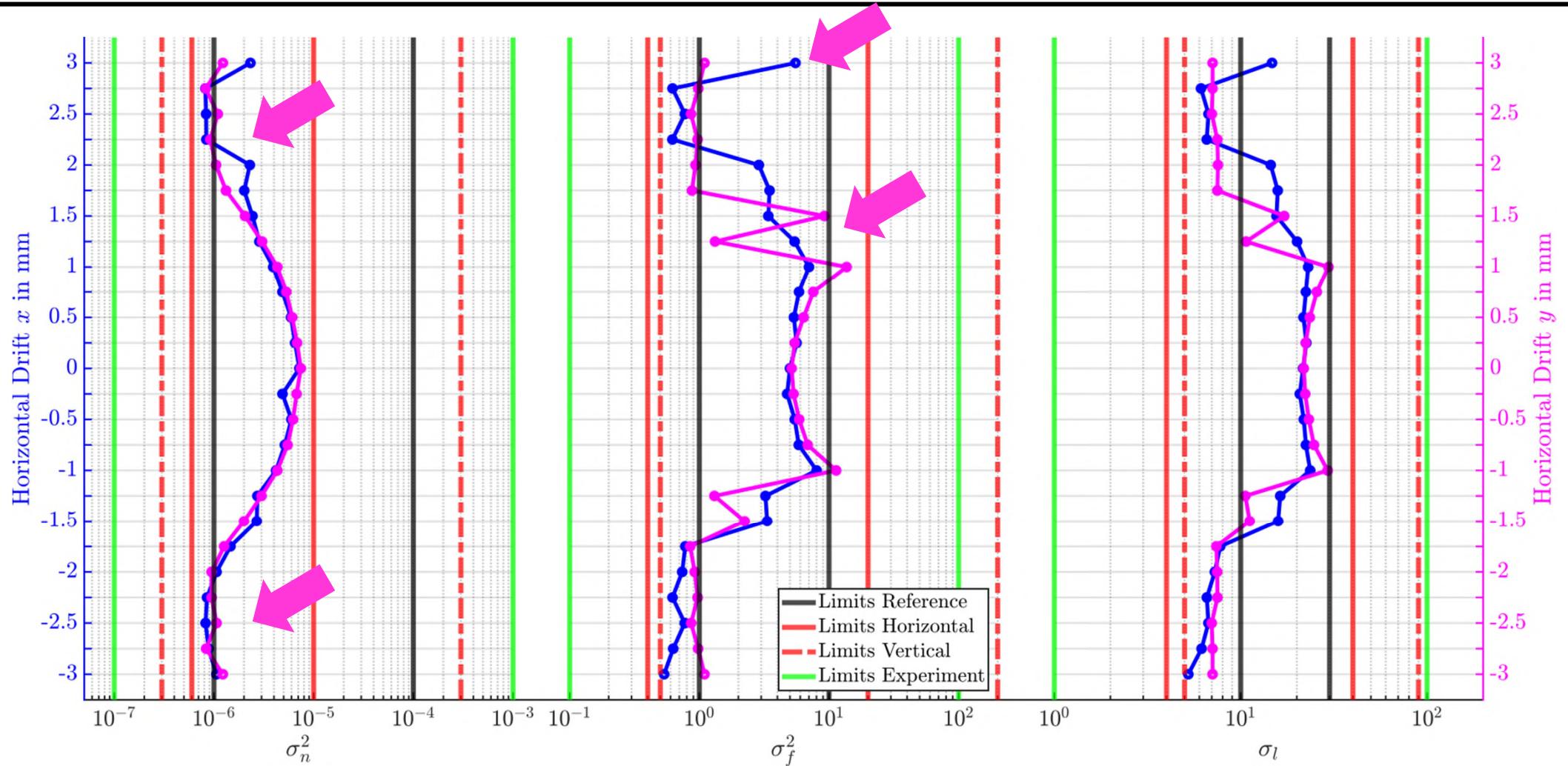
# Kompromissbildung



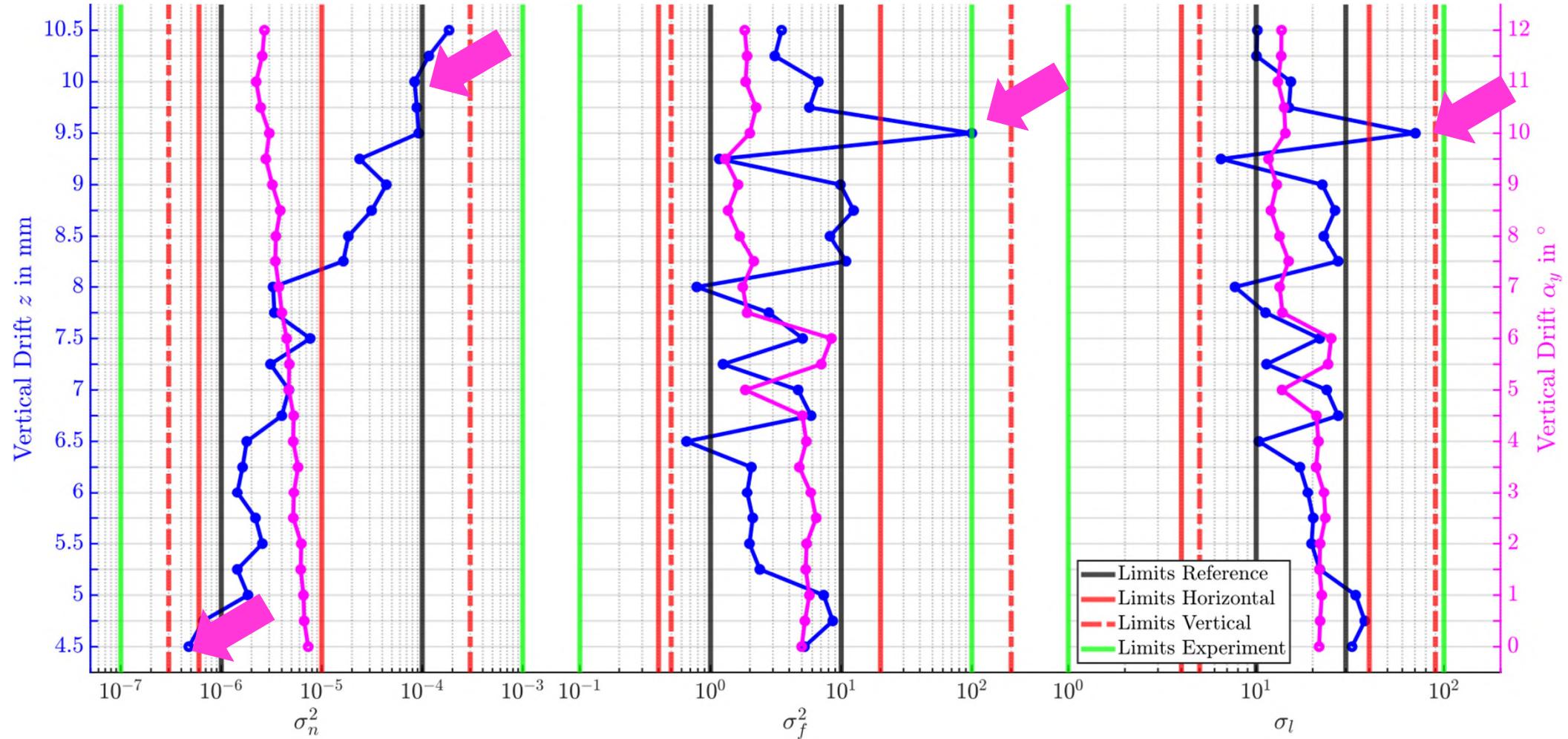
# Einfache Driftexperimente



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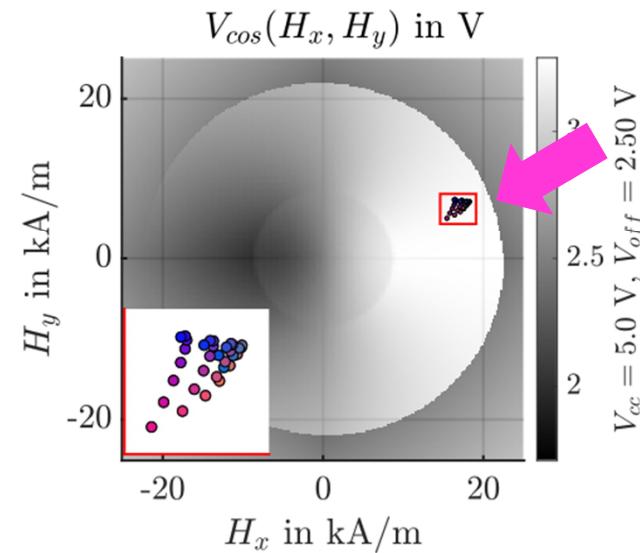


# Einfache Driftexperimente

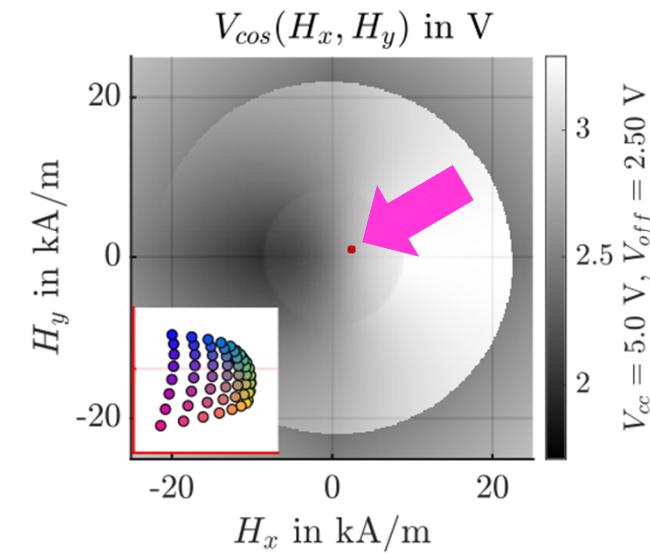


# Einfache Driftexperimente

a) Drift in z 4.5 mm

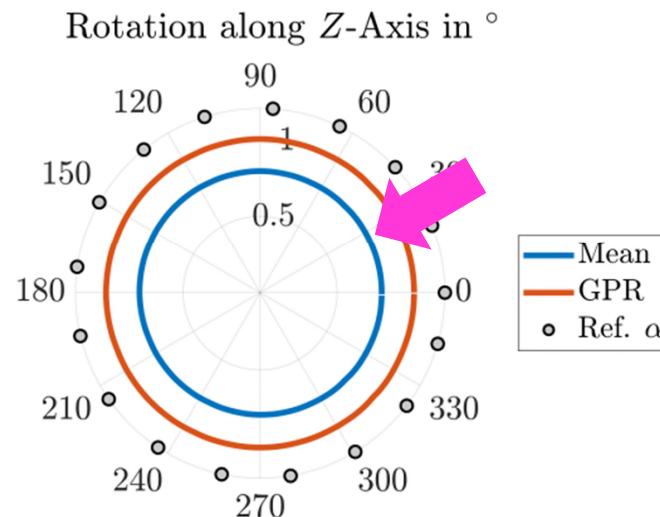


b) Drift in z 10.5 mm



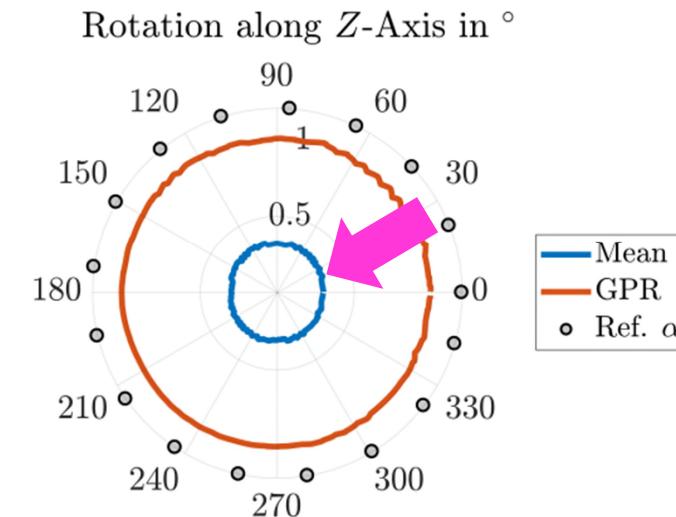
# Einfache Driftexperimente

a) Drift in z 4.5 mm



$$\mu(\epsilon_{abs}) = 0.06, \max \epsilon_{abs} = 0.21$$

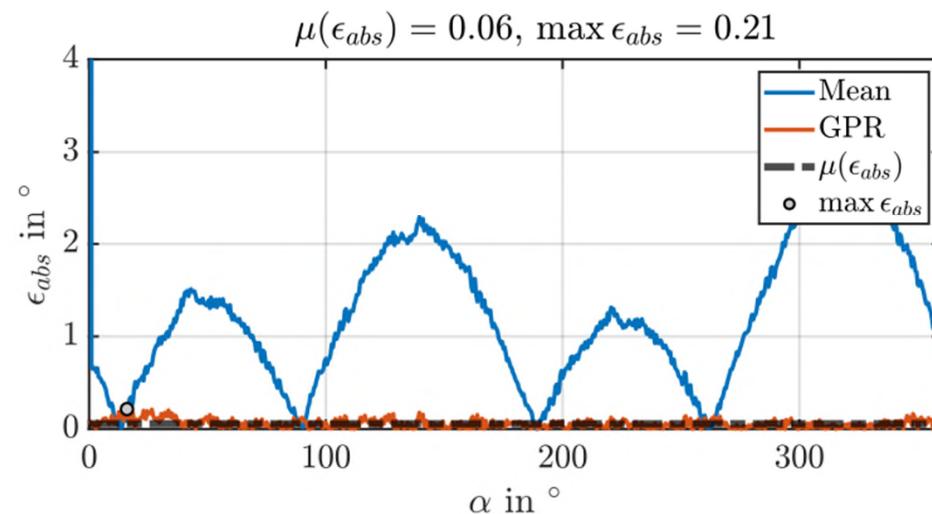
b) Drift in z 10.5 mm



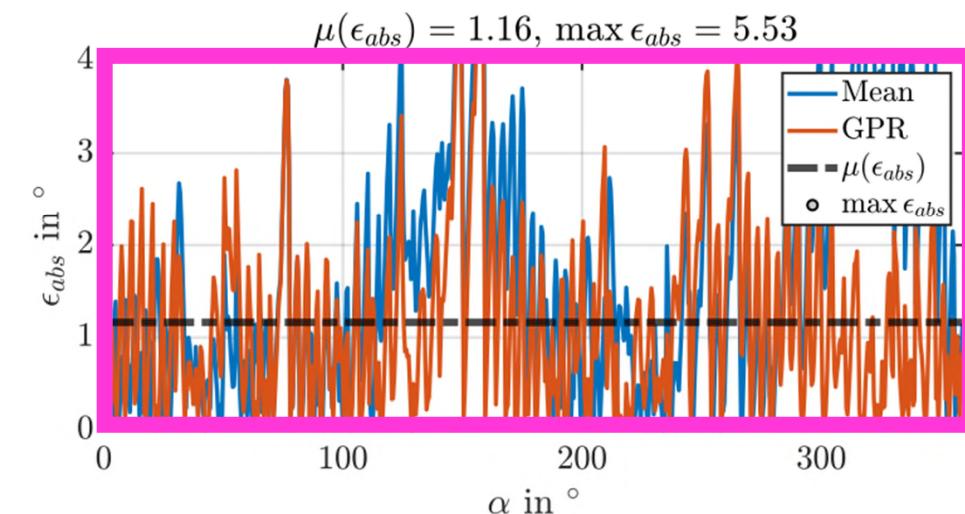
$$\mu(\epsilon_{abs}) = 1.16, \max \epsilon_{abs} = 5.53$$

# Einfache Driftexperimente

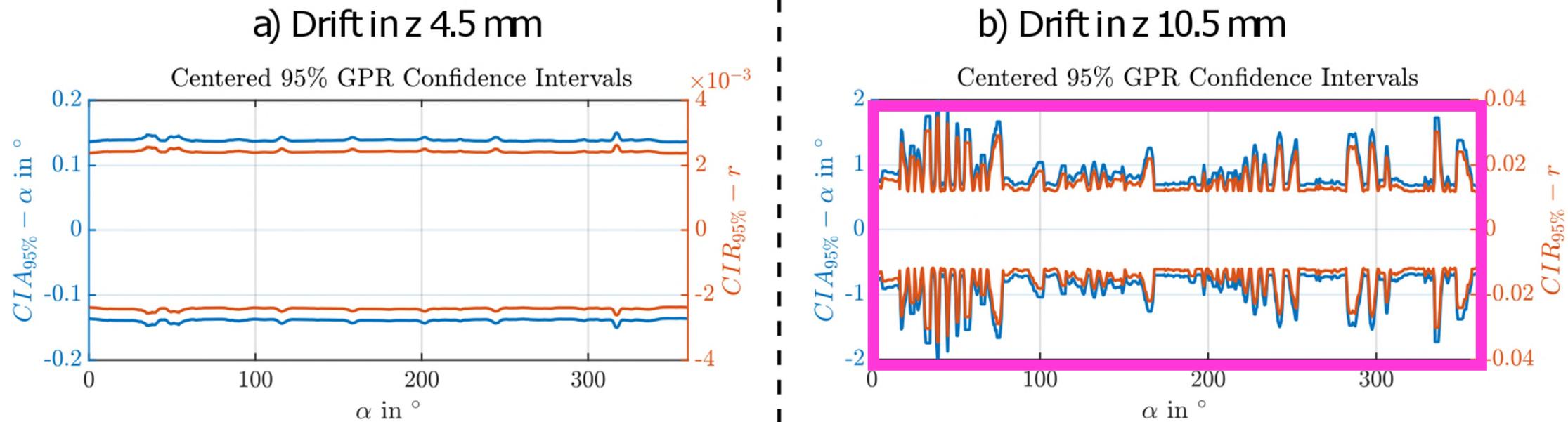
a) Drift in z 4.5 mm



b) Drift in z 10.5 mm

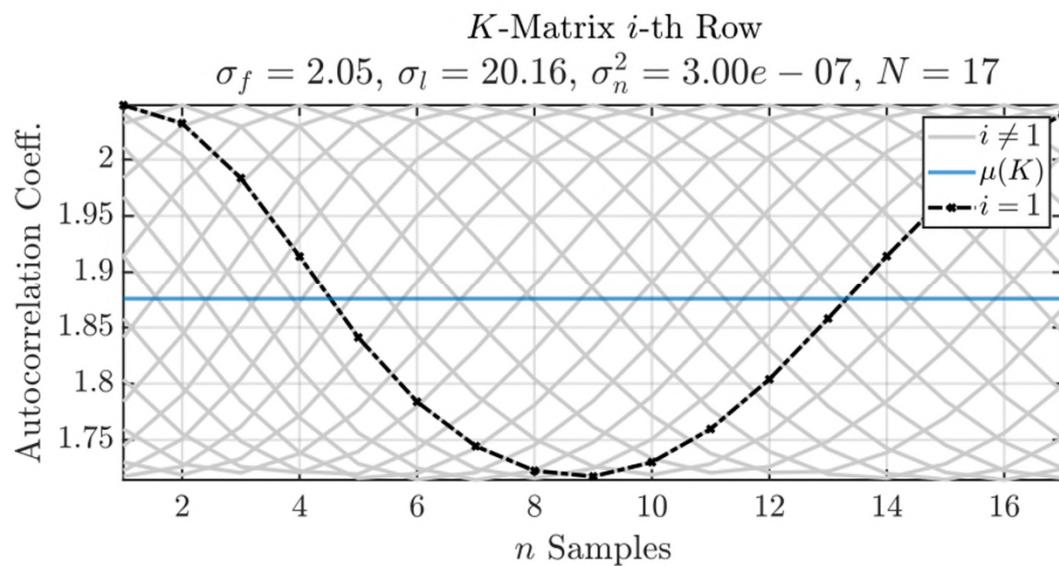


# Einfache Driftexperimente

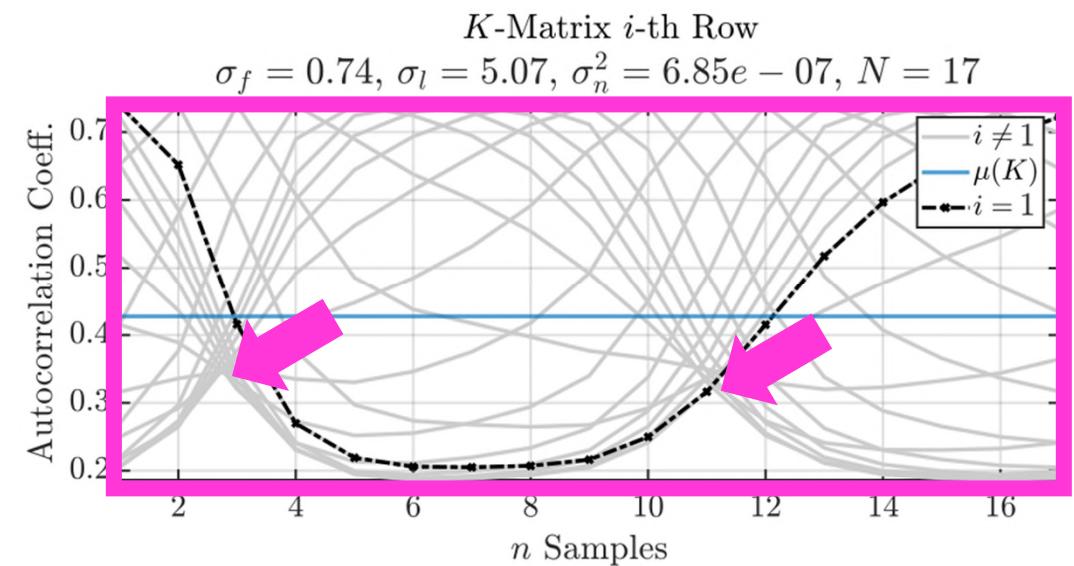


# Kombinierte Fehllage

a) Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$

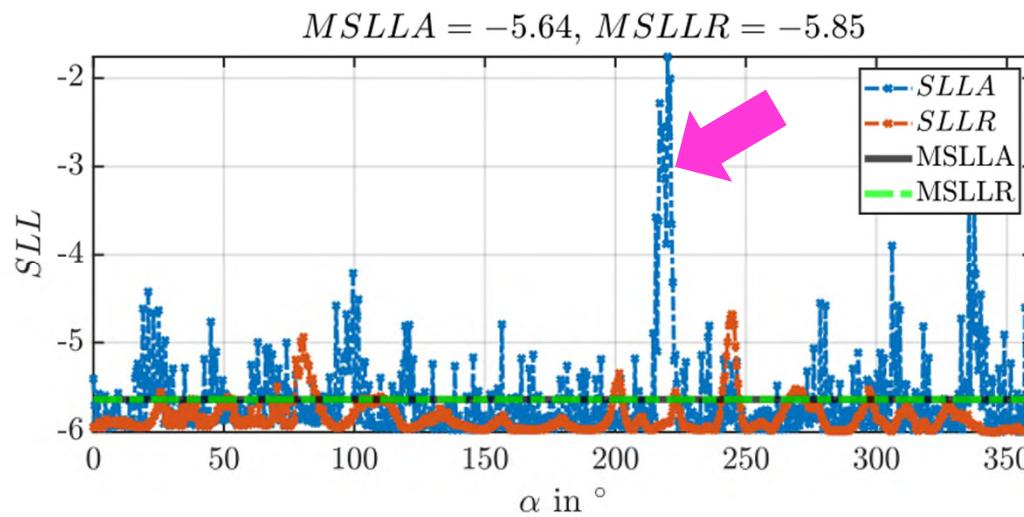


b) Position:  $(2.5, 2.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$

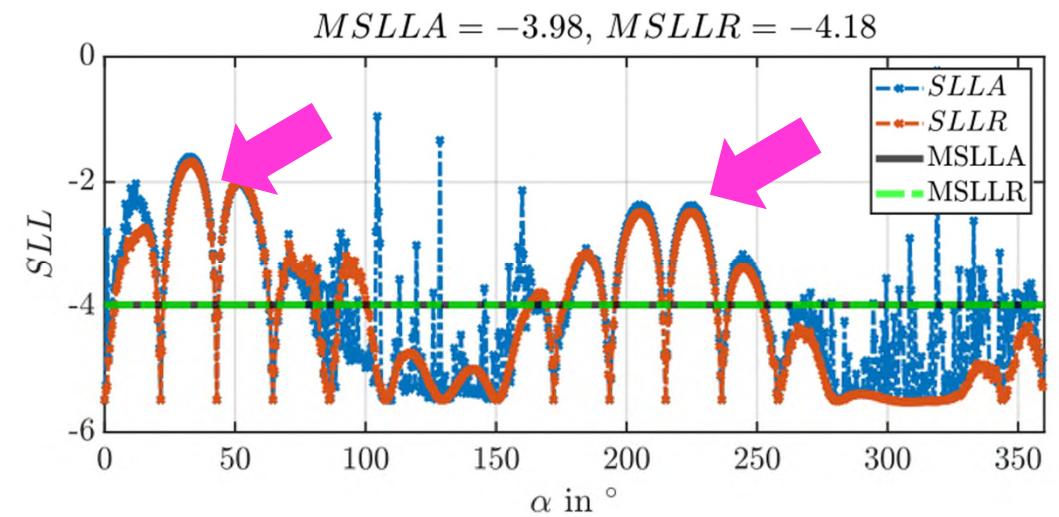


# Kombinierte Fehllage

a) Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



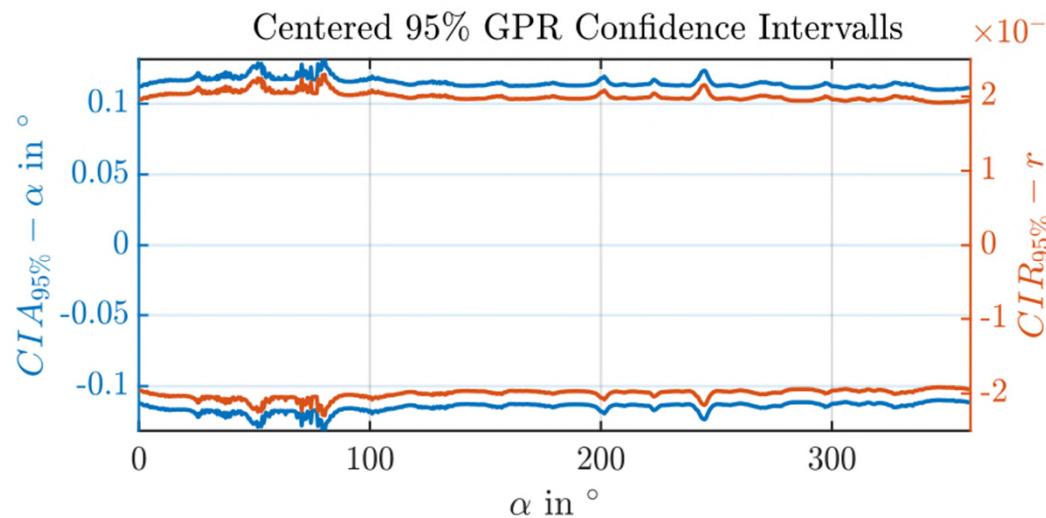
b) Position:  $(2.5, 2.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



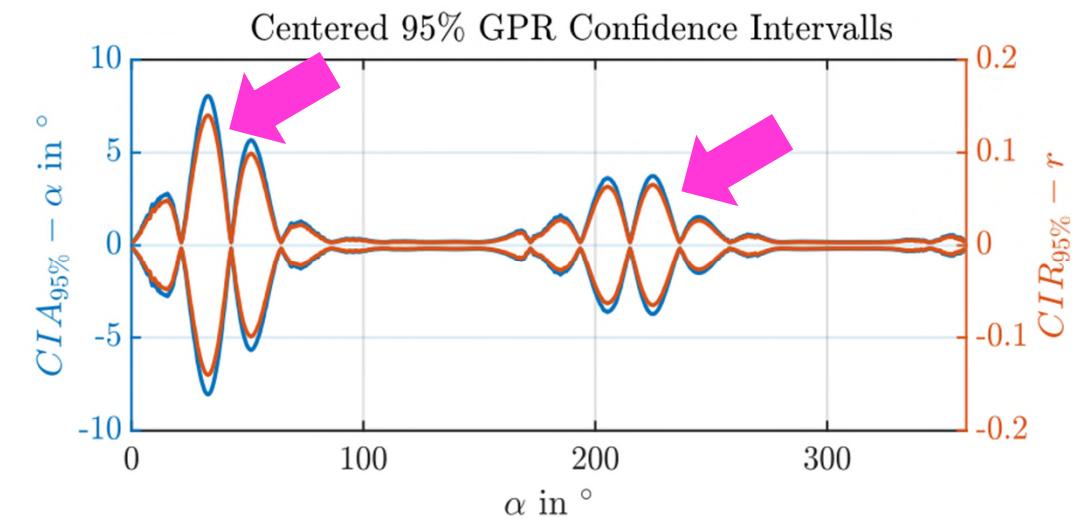
# Kombinierte Fehllage

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a) Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



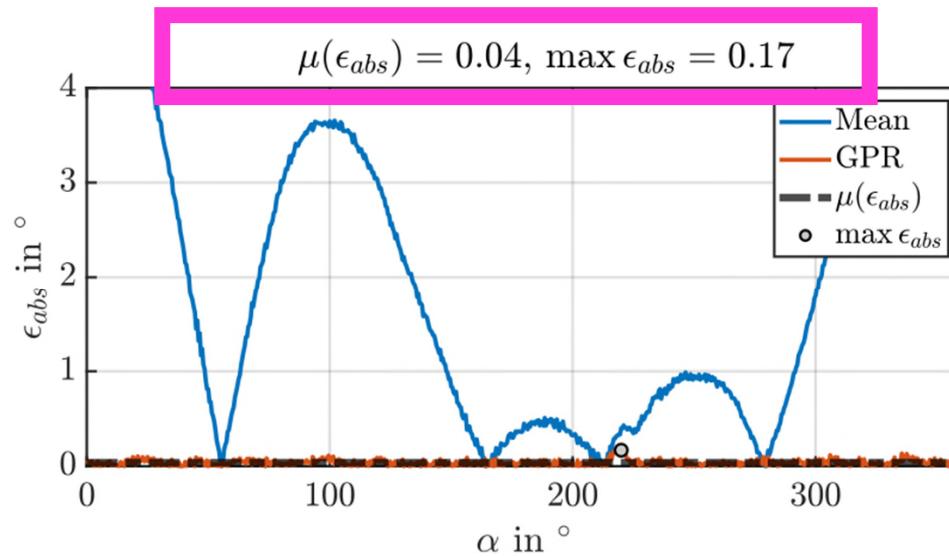
b) Position:  $(2.5, 2.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



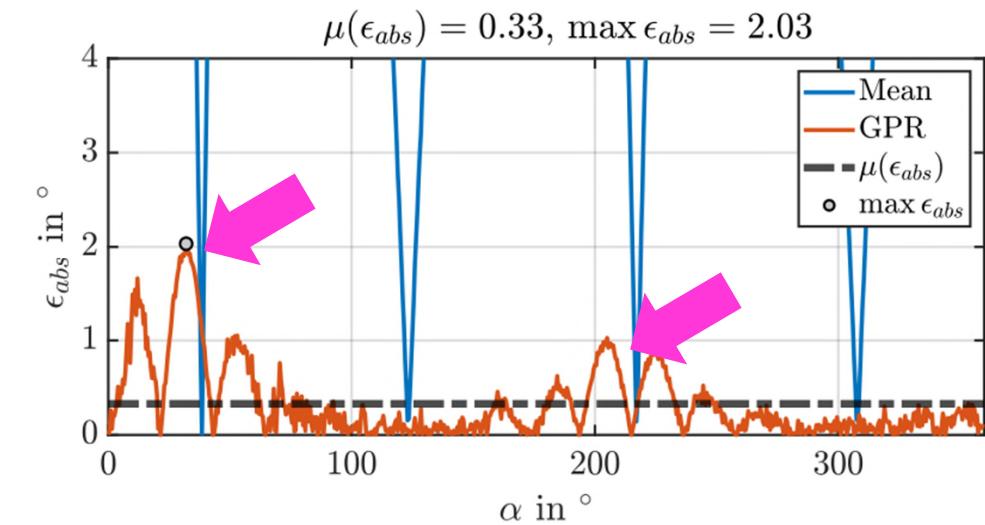
# Kombinierte Fehllage

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a) Position:  $(0.5, 1.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



b) Position:  $(2.5, 2.0, 4.5)^T$  mm, Tilt:  $11.0^\circ$



# Kombinierte Fehllage

