Online Identification of key-parameters for Synthetic-Based Calibration with Pyramid WFS

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WAVEFRONT SENSING IN THE VLT/ELT ERA
4TH EDITON

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ESO

Introduction - AO Calibration

Interaction Matrix D

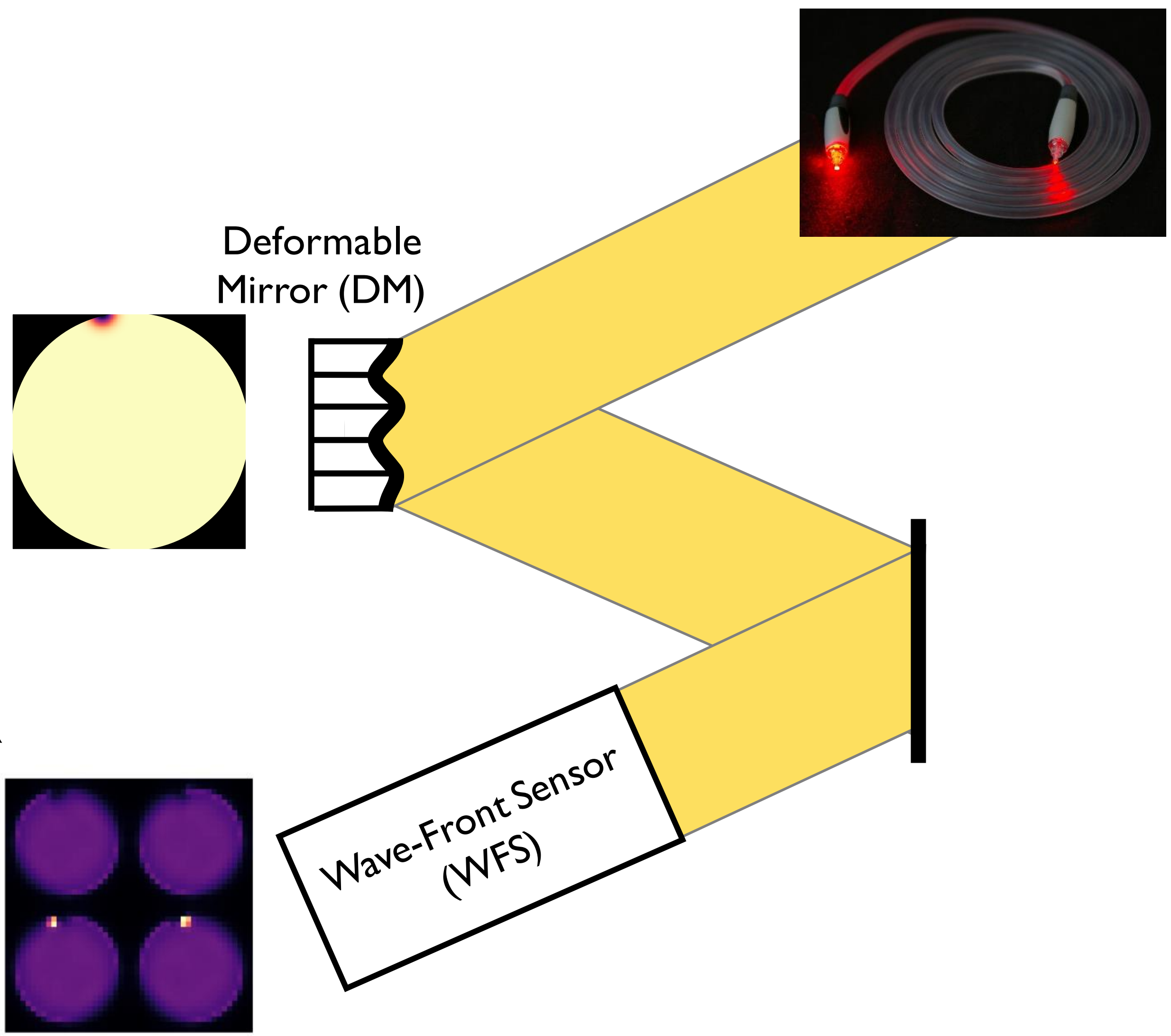
=

How the DM Surface is seen by the WFS

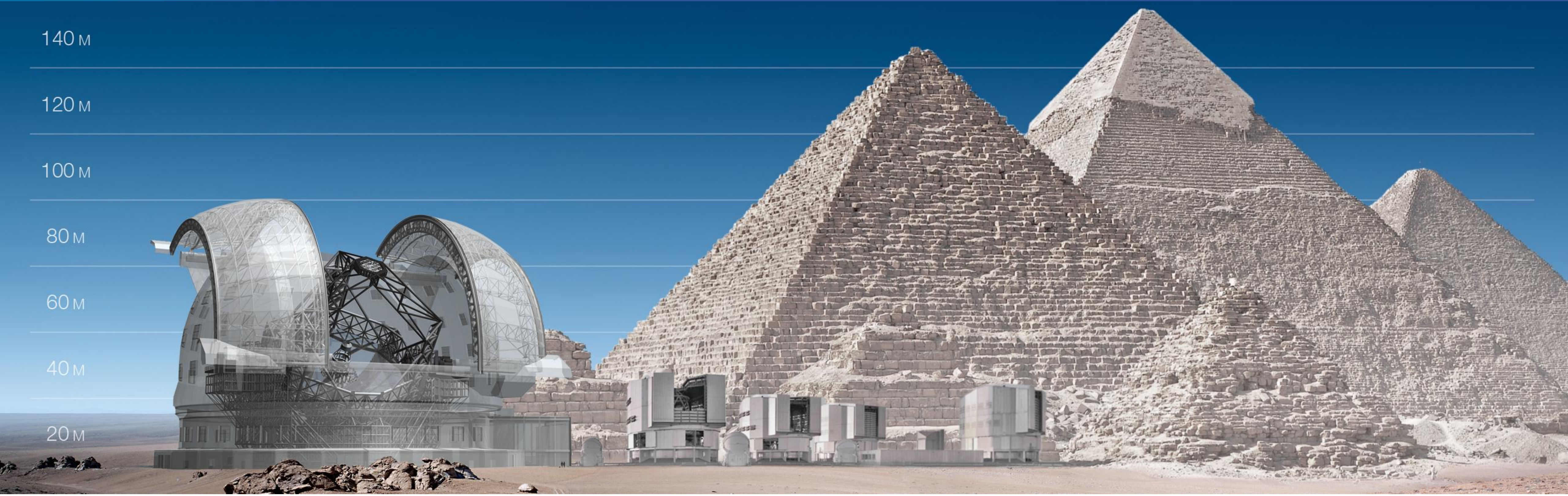
WFS Measurement Model

$$\mathbf{D} = \mathbf{M}_{\mathbf{WFS}} \cdot \mathbf{M}_{\mathbf{DM}}$$

DM Influence Functions



AO Calibration in the ELT Context

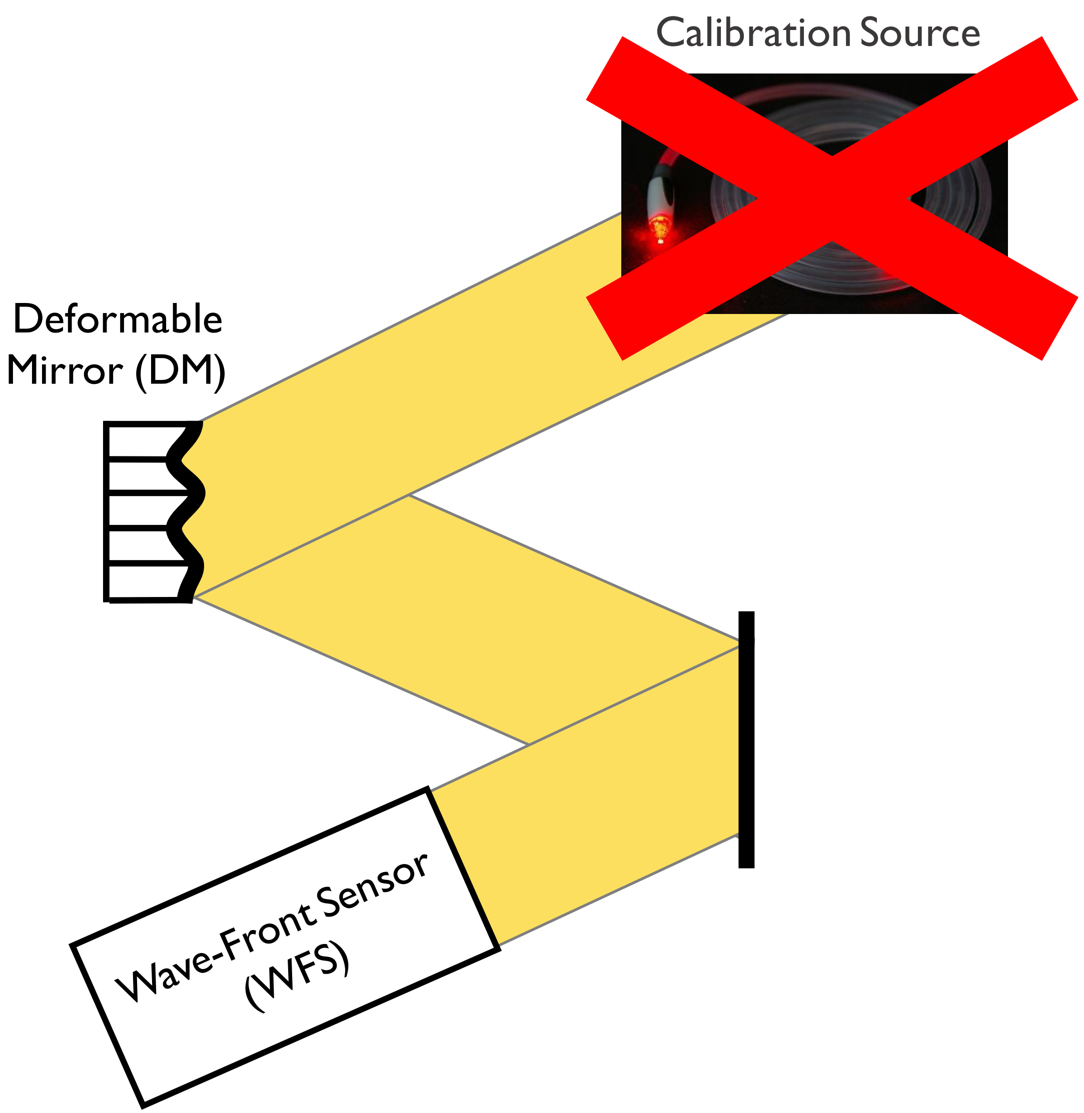


The Future Generation of Telescopes: **The Extremely Large Telescopes**

Extremely Large Telescope – 39 m diameter
Giant Magellan Telescope – 24.5 m diameter
Thirty Meter Telescope – 30 m diameter

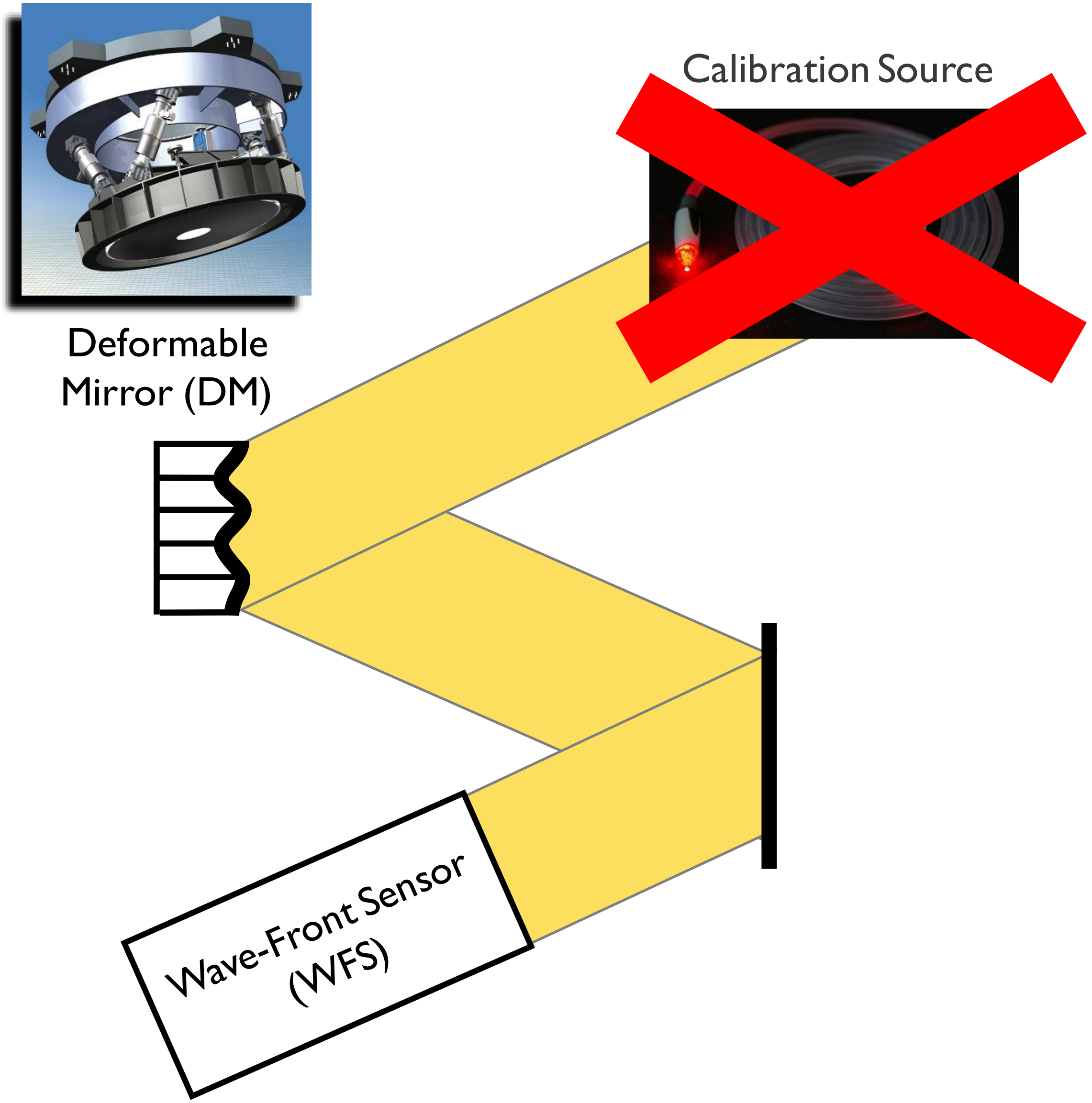
AO Calibration in the ELT Context

- No External Calibration Source
- …



AO Calibration in the ELT Context

- No External Calibration Source
- ~ 5000 Actuators DM
- …



AO Calibration in the ELT Context

- No External Calibration Source
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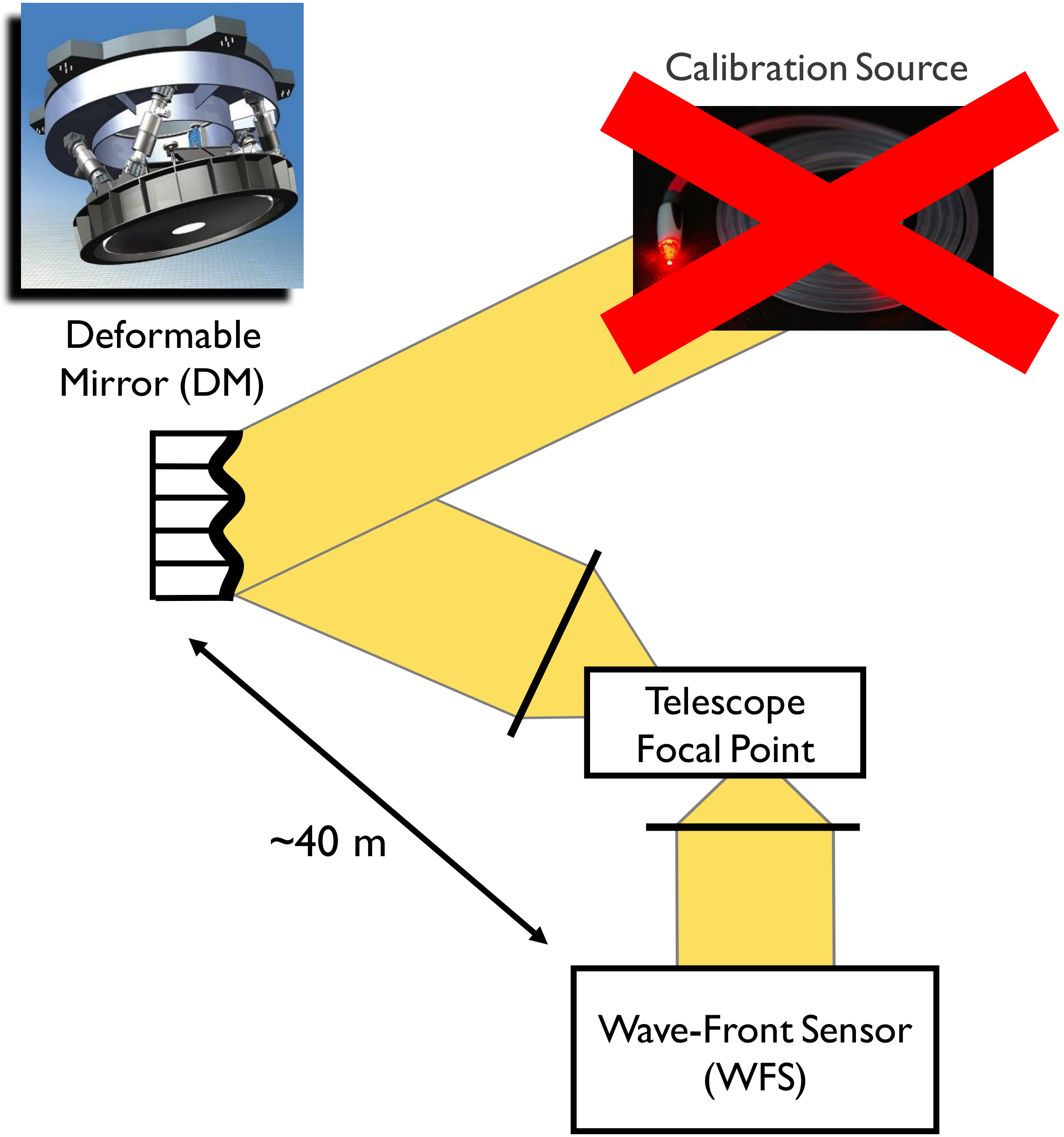
- DM located inside the telescope
- …



AO Calibration in the ELT Context

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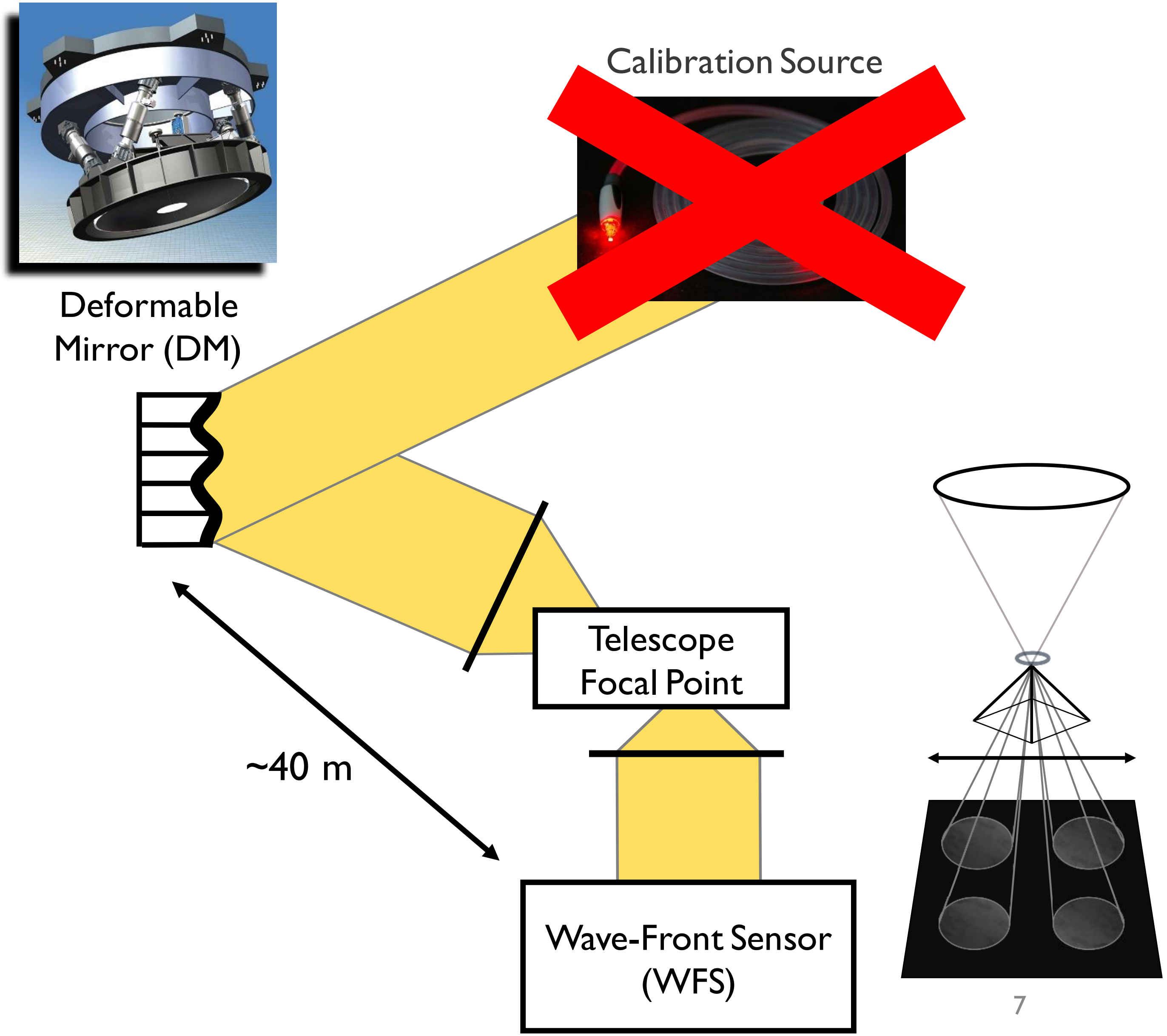
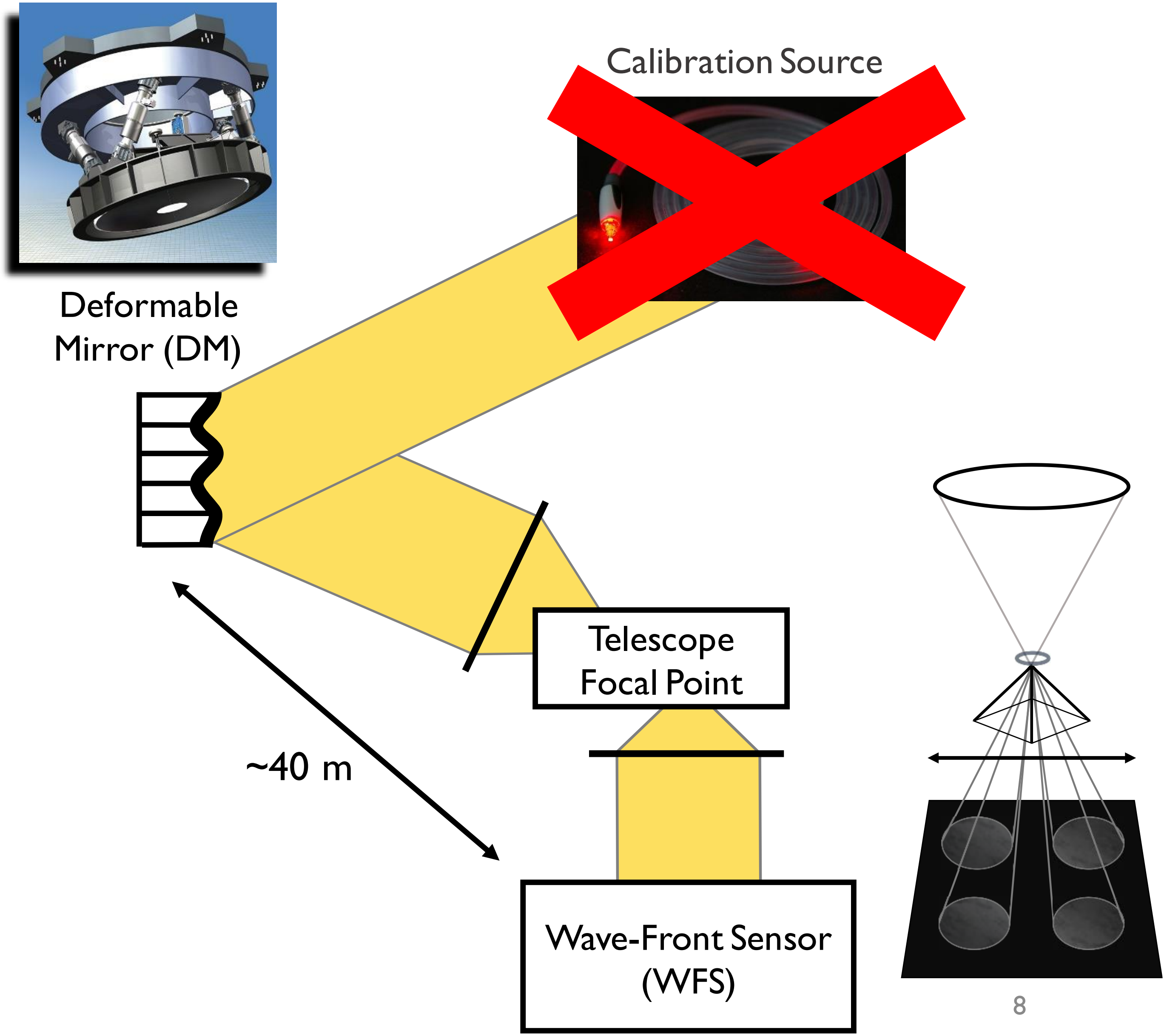
- Pyramid WFS Specifities
- …



AO Calibration in the ELT Context

- No External Calibration Source
- ~ 5000 Actuators DM
- DM located inside the telescope
- Pyramid WFS Specifities
- **Minimize impact on Science**



AO Calibration in the ELT Context

Post Focal AO System

Deformable Mirror → Stable Optical Propagation → Wave-Front Sensor

AO Calibration in the ELT Context

Large Adaptive Telescope

Deformable Mirror → Dynamically evolving Optical Propagation → Wave-Front Sensor

AO Calibration in the ELT Context

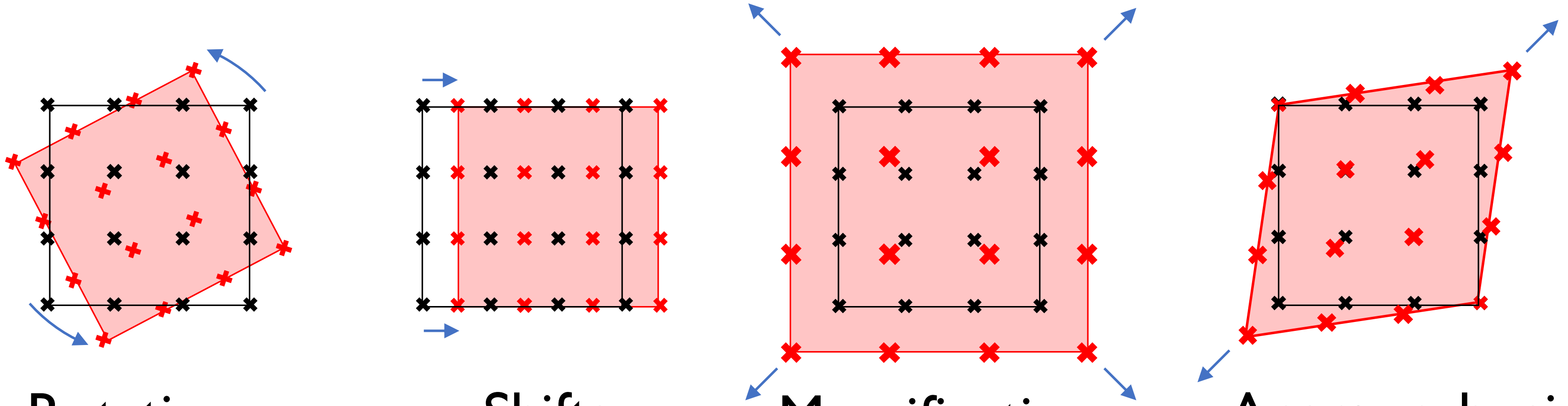
<u>Large Adaptive Telescope</u>

Deformable Mirror → **Dynamically evolving Optical Propagation** → Wave-Front Sensor

↓

Mis-Registrations

Evolution the DM Actuator grid image as seen by to the WFS.



Rotation | Shifts | Magnification | Anamorphosis

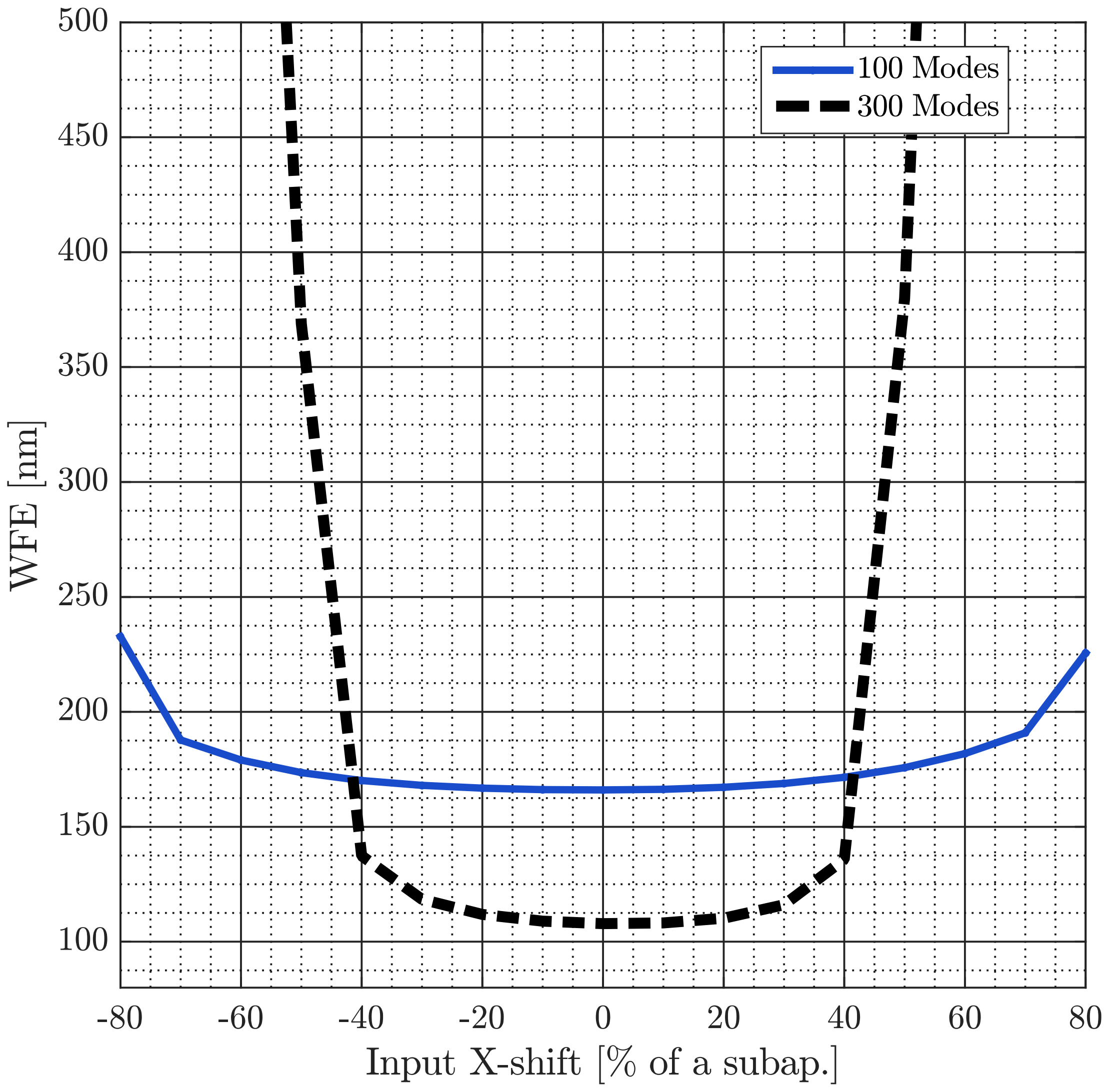
1 - Impact of a Mis-Registration

⇒ Dramatic impact on the AO Correction

⇒ Loss of Performance

⇒ Loop instability

Monitoring and Compensation of the Mis-Registrations is **necessary**!



I - Impact of a Mis-Registration

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⇒ Loop instability

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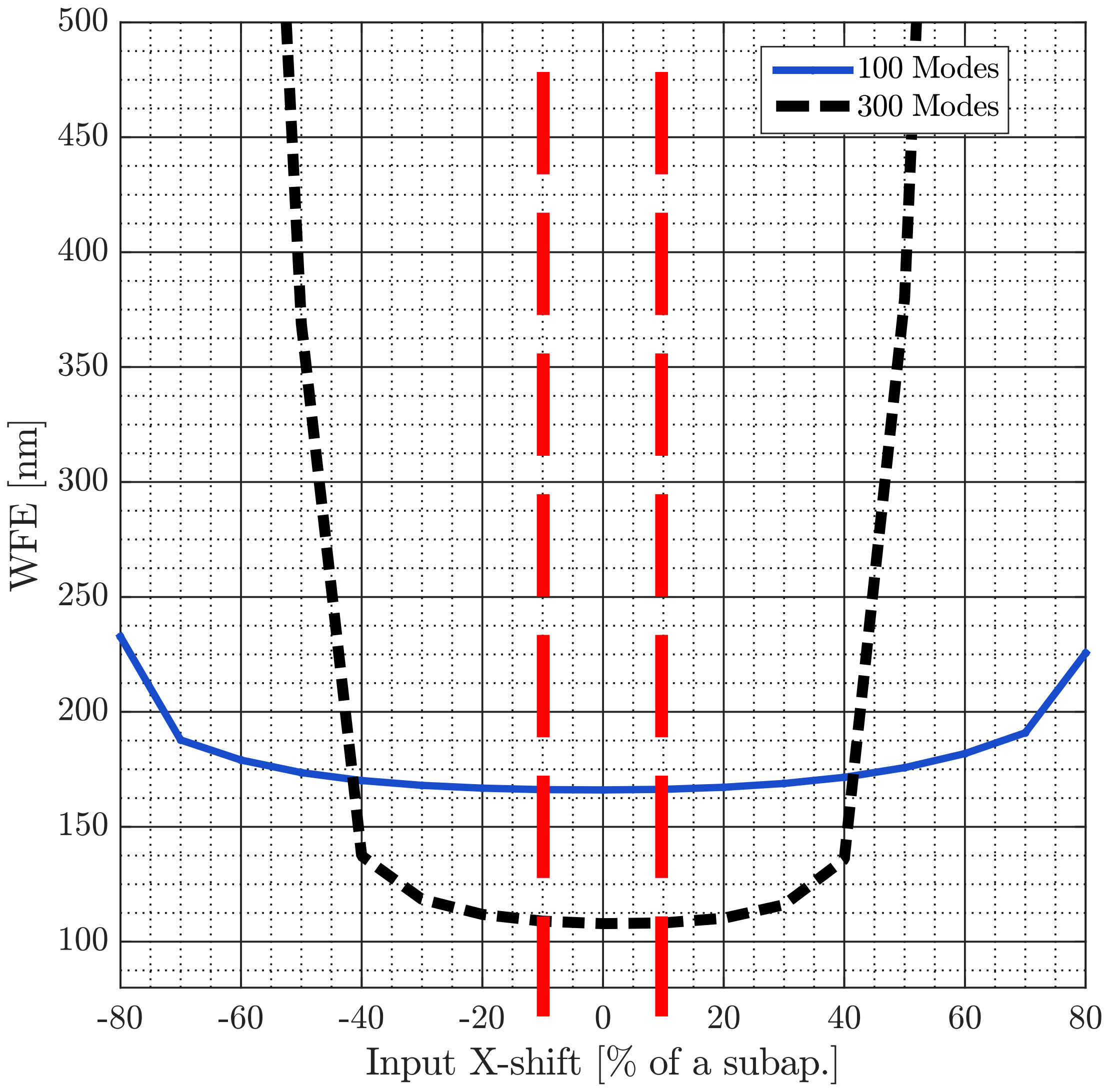
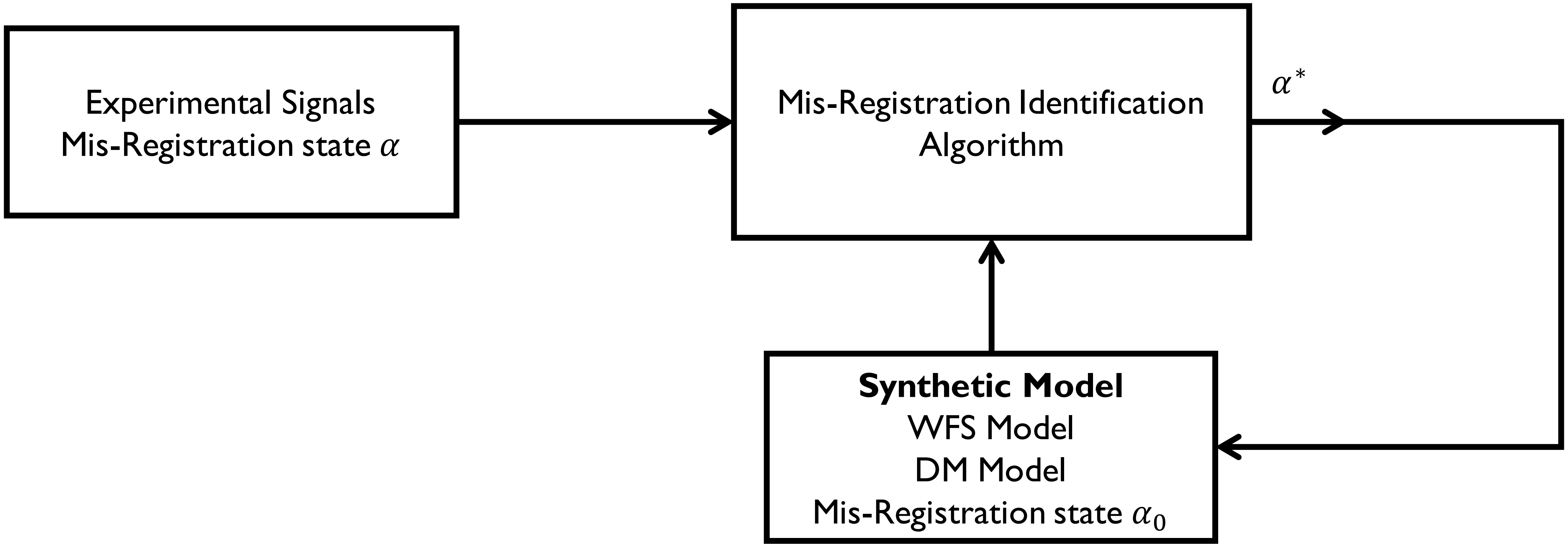
Typically:

Accuracy < 10% of a subaperture (System dependent)



Pseudo Synthetic Interaction Matrix



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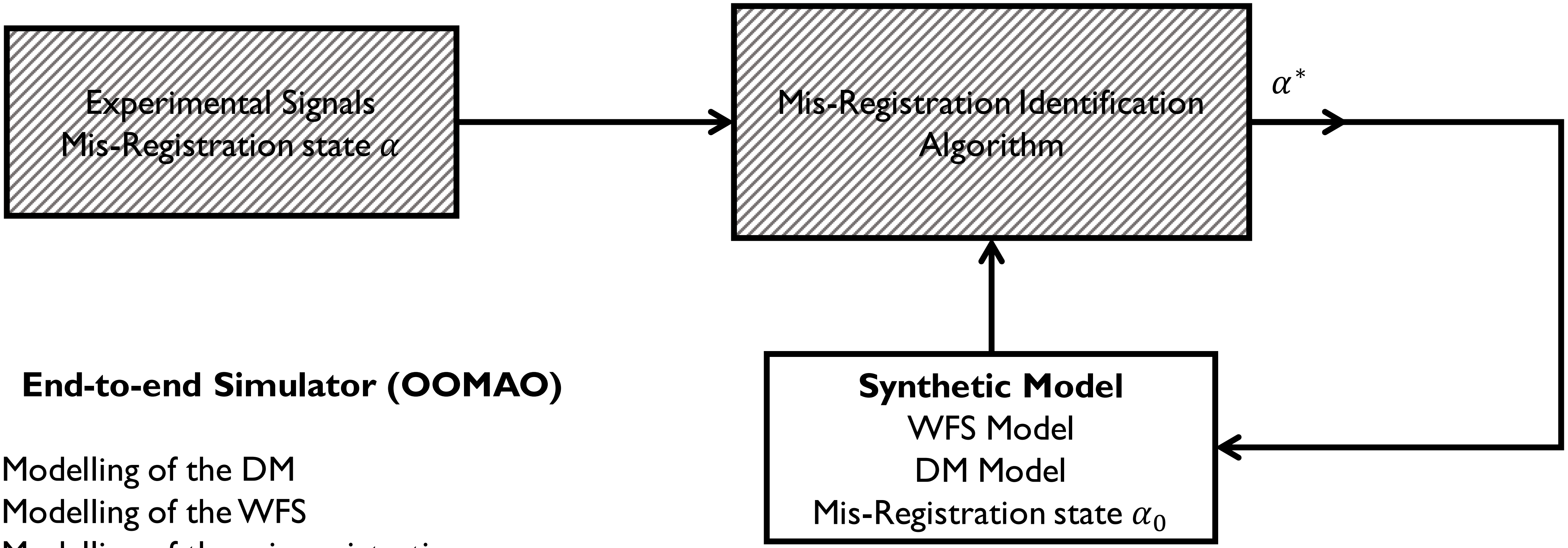
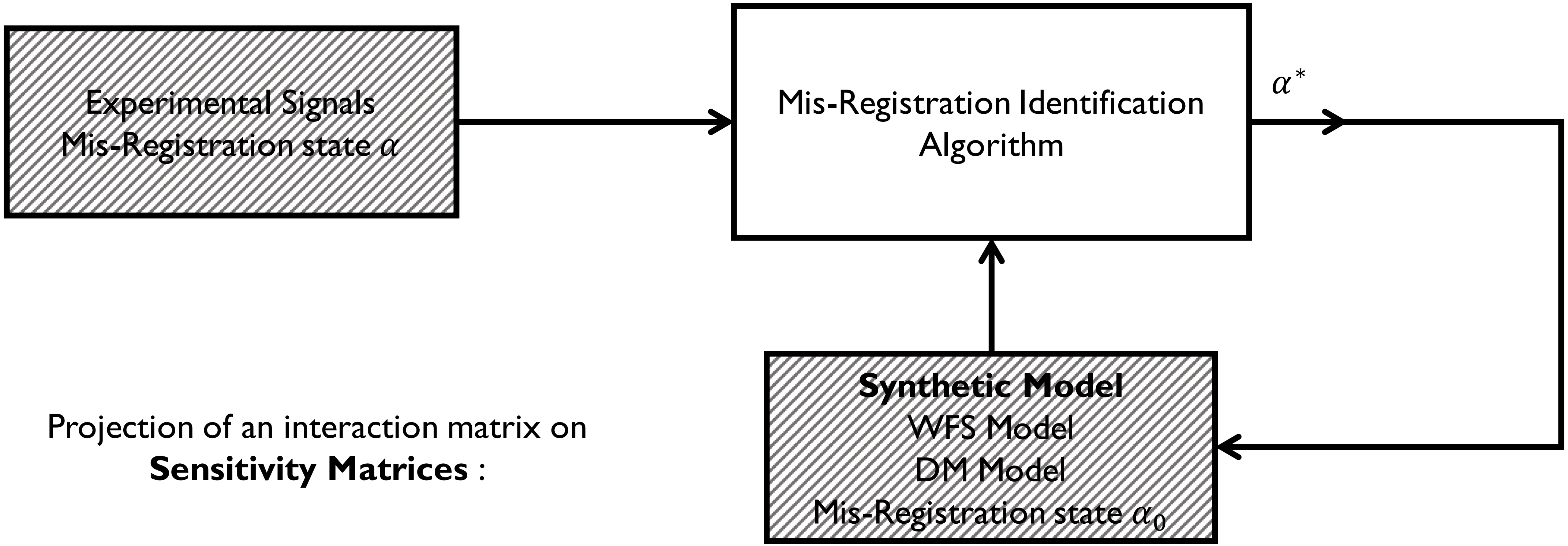


End-to-end Simulator (OOMAO)

- Modelling of the DM
- Modelling of the WFS
- Modelling of the mis-registrations α

Pseudo Synthetic Interaction Matrix

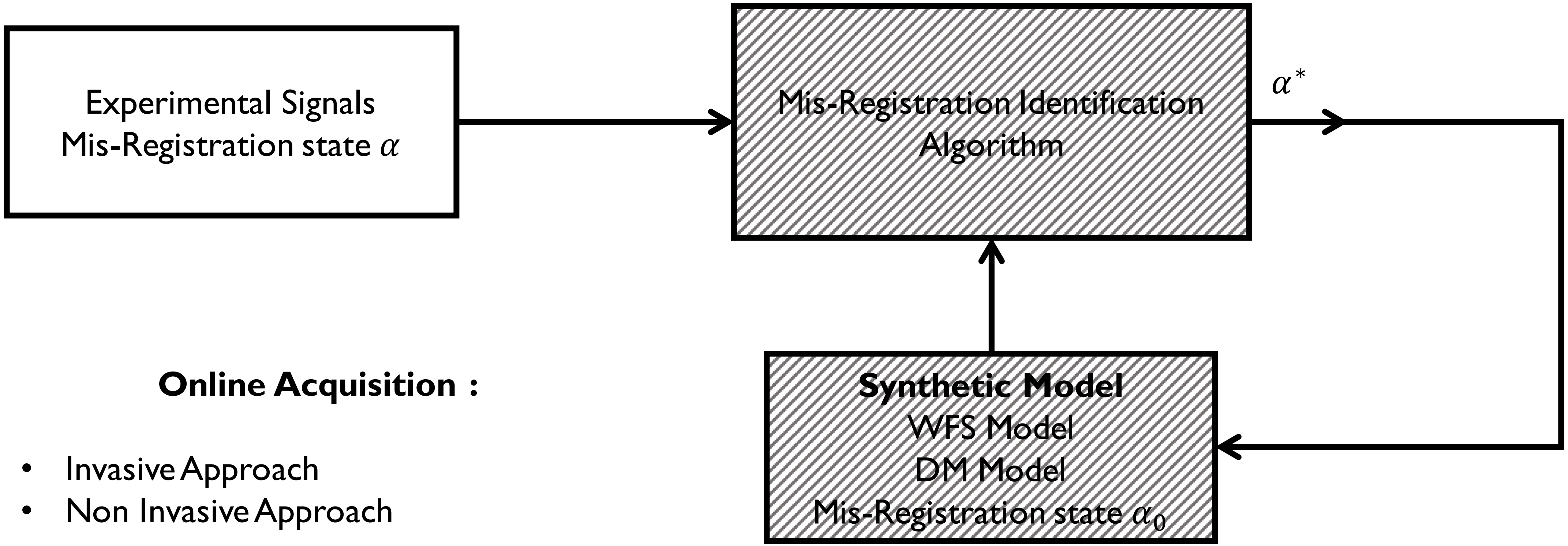


Projection of an interaction matrix on **Sensitivity Matrices** :

$$\boldsymbol{\delta}\mathbf{D}_{\boldsymbol{\alpha}_0}(\varepsilon_i) = \frac{\mathbf{D}_{\boldsymbol{\alpha}_0+\boldsymbol{\varepsilon}_i} - \mathbf{D}_{\boldsymbol{\alpha}_0-\boldsymbol{\varepsilon}_i}}{2\varepsilon_i}$$

α_0 = Mis-Registration State
ε_i = "delta" mis-registration

Pseudo Synthetic Interaction Matrix



Online Acquisition :

- Invasive Approach
- Non Invasive Approach

An Invasive Approach - Principle

Principle:

Dithering of a few **well selected modes** to retrieve the mis-registrations parameters.

How?

- Fast Push-Pull? Temporal and Spatial modulation?
- SNR required? Time allocated?
- Impact on the science?

Wildi et al. 2004, Esposito et al. 2006, Oberti et al. 2006, Pieralli et al. 2008, Pinna et al. 2012, Kellerer et al. 2012

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How?

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- SNR required? Time allocated?
- Impact on the science?

What Signals?

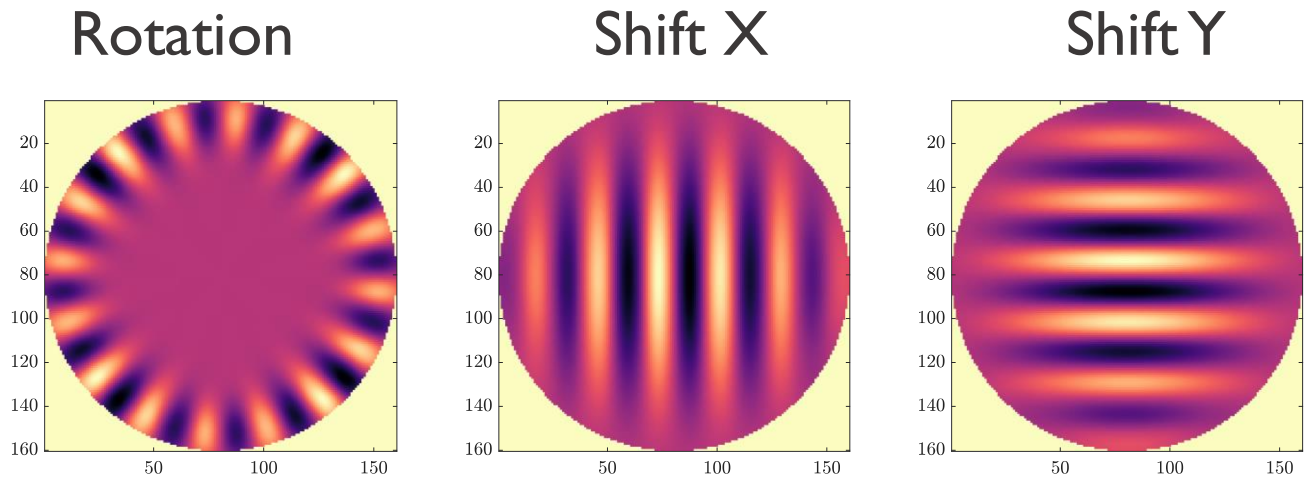
- Spatial properties of the signals?
- Impact on the science?

An Invasive Approach - Choice of the signals

Identifying the optimal set of modes to **maximize the sensitivity to a given mis-registration** and minimize the number of modes required.

$\Rightarrow$ Principal Component Analysis of the **Sensitivity Matrix**

Ex: 20 by 20 subapertures - Cartesian DM with PWFS:

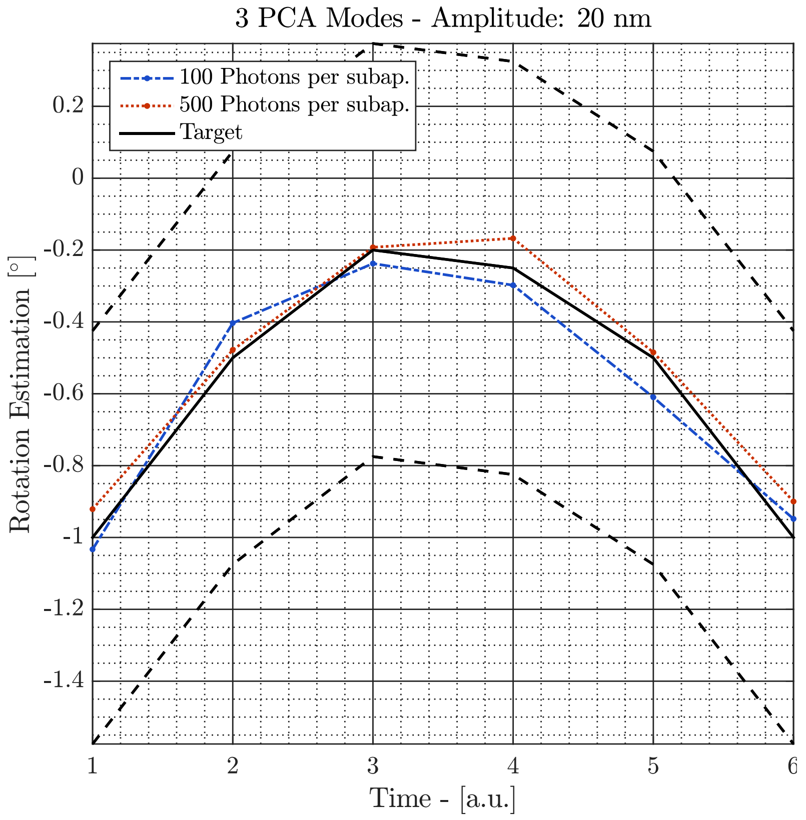


An Invasive Approach - Application

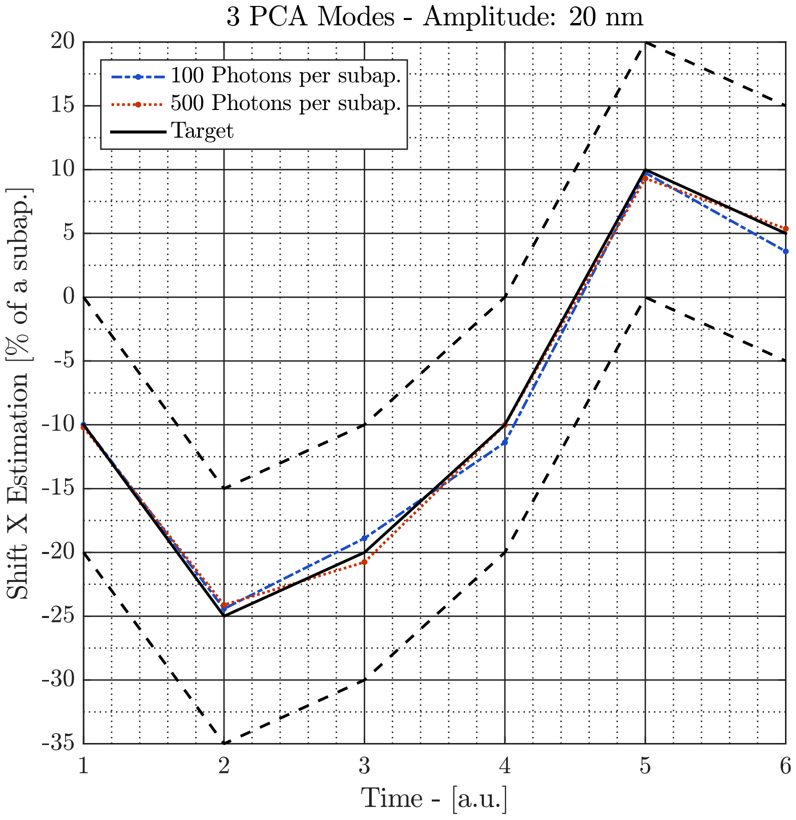
Application: Dynamical tracking of multiple parameters evolving at the same time

20 Fast push-pull of 3 modes - 20 nm RMS

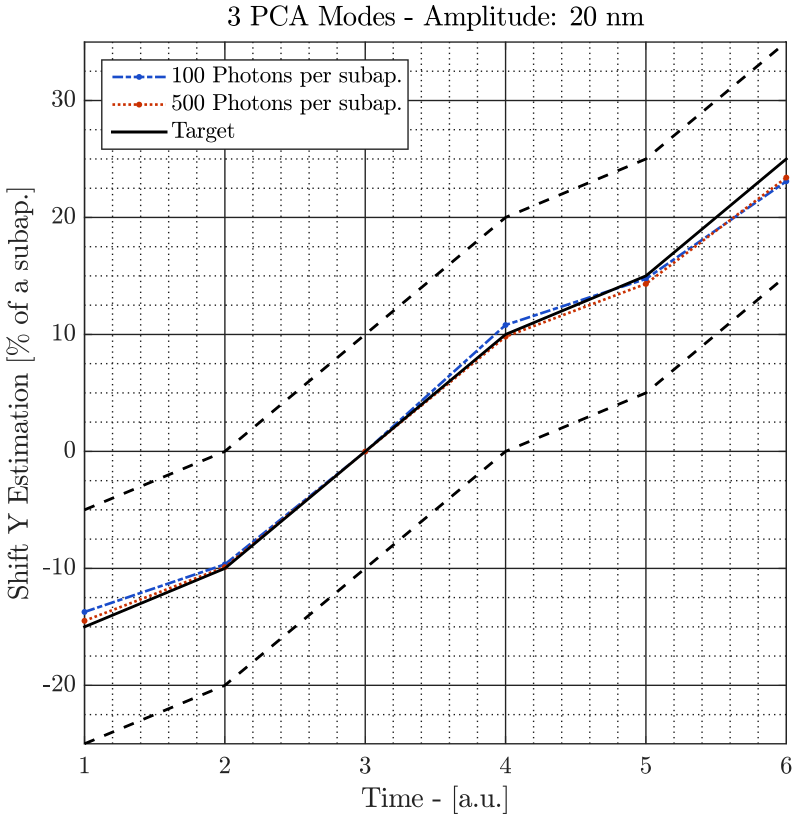
Rotation



Shift X



Shift Y



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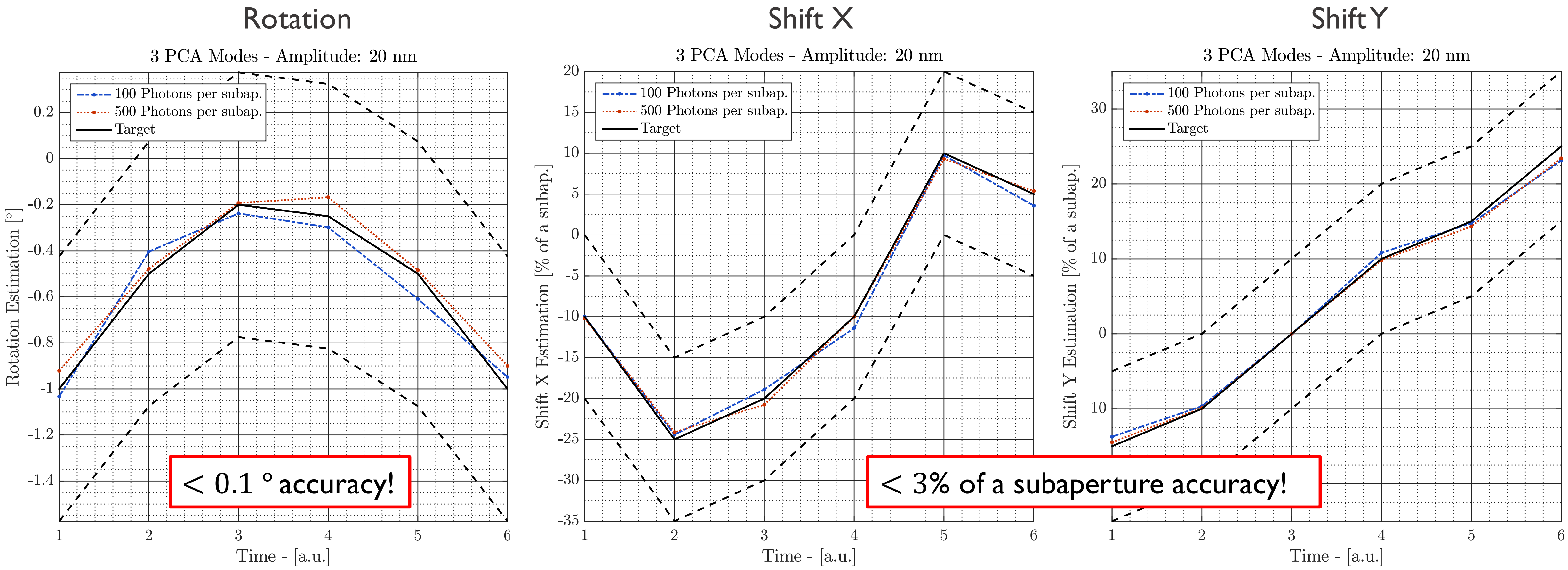
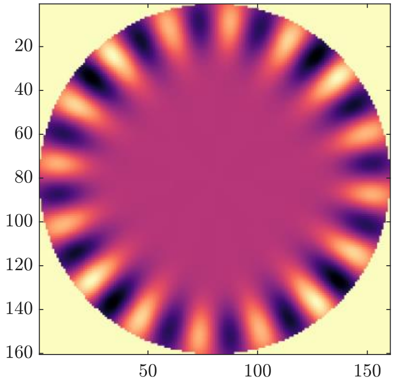
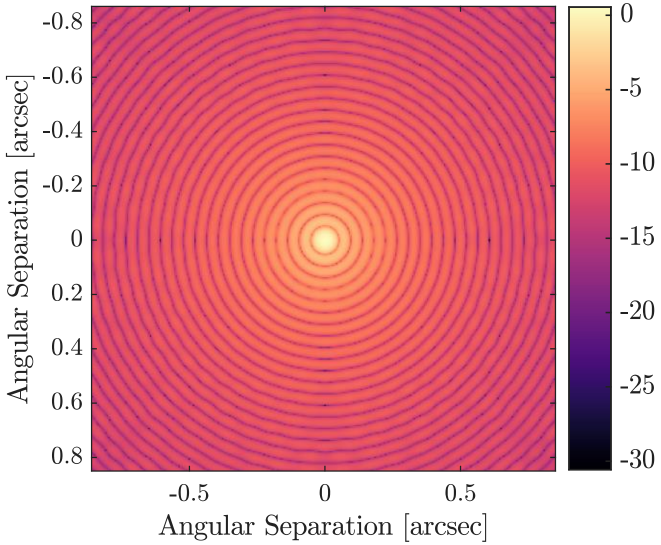


An Invasive Approach - Choice of the signals

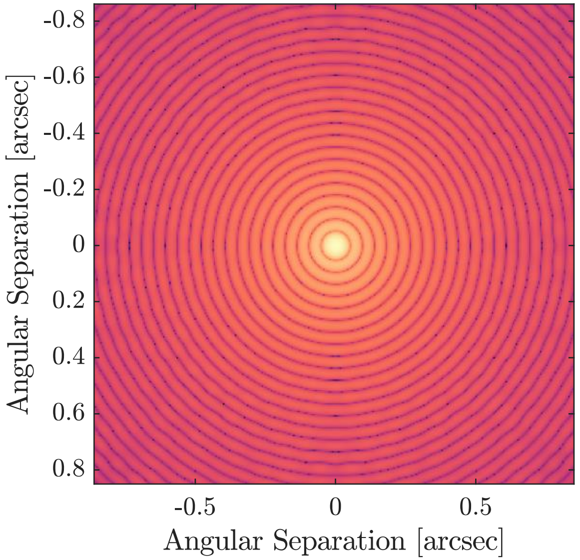
Impact on the science path?



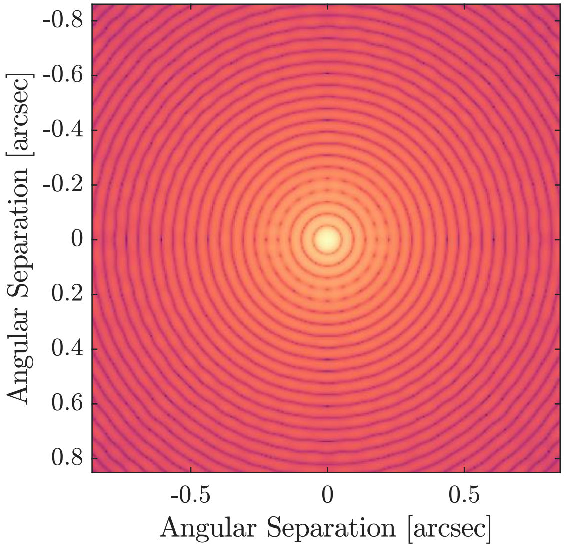
Diffraction-Limited PSF
(log scale)



10 nm

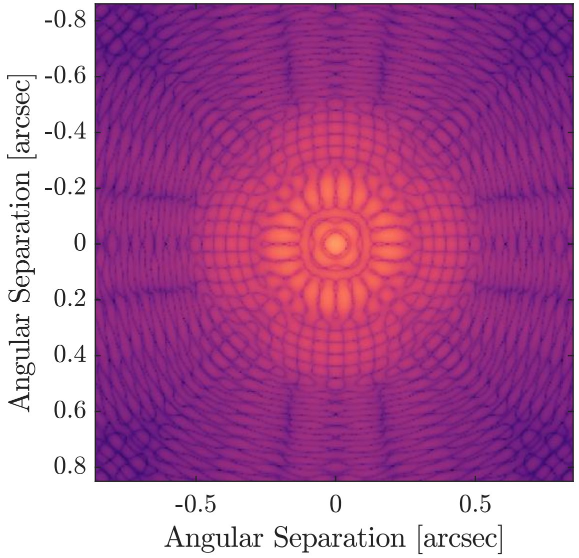


20 nm

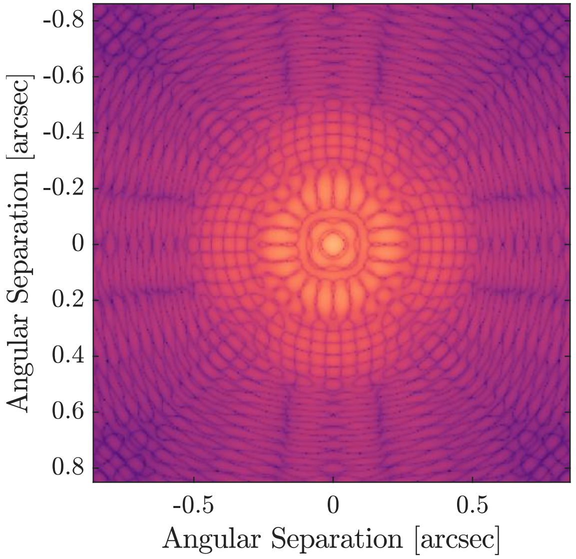


PSF
(log scale)

Max: 1e-6



Max: 1e-4.6



Residual
PSF
(log scale)

An Invasive Approach

Advantages: Robustness and accuracy of the method!

Drawbacks: Impact on science has to be carefully evaluated

An Invasive Approach

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High Contrast? => Non Invasive Approach

The Non-Invasive Approach - Principle

Principle:

1) Estimating an Interaction Matrix using the closed-loop data
2) Identification of the Mis-Registrations using this noisy Interaction Matrix

Bechet et al. (2012), Kolb et al. (2012)

The Non-Invasive Approach - Principle

Principle:

1) Estimating an Interaction Matrix using the closed-loop data

AO – CL Equation

WFS Measurement Model → $\mathbf{M_{WFS}}$; DM Command → $\mathbf{c_k}$

WFS Measurement → $\mathbf{y_k}$

$$\mathbf{y_k} = \mathbf{M_{WFS}} \cdot (-\mathbf{M_{DM_\alpha}} \cdot \mathbf{c_k} + \cdot\, \boldsymbol{\phi}_\mathbf{k}^\mathbf{turb}) + \boldsymbol{\eta}_\mathbf{k}$$

Noise → $\boldsymbol{\eta}_\mathbf{k}$

DM Model → $\mathbf{M_{DM_\alpha}}$; Turbulence → $\boldsymbol{\phi}_\mathbf{k}^\mathbf{turb}$

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1) Estimating an Interaction Matrix using the closed-loop data

AO – CL Equation

$$\mathbf{y_k} = \mathbf{M_{WFS}}.\left(-\mathbf{M_{DM_\alpha}}.\mathbf{c_k} + .\,\boldsymbol{\phi}_\mathbf{k}^\mathbf{turb}\right) + \boldsymbol{\eta}_\mathbf{k}$$

Increments (Linearity + Independence of $\boldsymbol{\delta}\mathbf{c_k}$ and $\boldsymbol{\delta\phi}_\mathbf{k}^\mathbf{turb}$)

$$\boldsymbol{\delta}\mathbf{y_k} = -\mathbf{M_{WFS}}.\mathbf{M_{DM_\alpha}}.\boldsymbol{\delta}\mathbf{c_k} + \mathbf{M_{WFS}}.\boldsymbol{\delta\phi}_\mathbf{k}^\mathbf{turb} + \boldsymbol{\delta\eta}_\mathbf{k}$$

The Non-Invasive Approach - Principle

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The Non-Invasive Approach - Principle

Principle:

1) Estimating an Interaction Matrix using the closed-loop data

AO – CL Equation

$$\delta \mathbf{y_k} = \mathbf{D_\alpha} . \delta \mathbf{c_k} + \delta \mathbf{z_k}$$

Signals of Interest (δy_k, δc_k)

Disturbance (δz_k)

The Non-Invasive Approach - Principle

Principle:

1) Estimating an Interaction Matrix using the closed-loop data

AO – CL Equation

$$\delta y_k = D_\alpha . \delta c_k + \delta z_k$$

Maximum Likelihood Approach:

$$D_\alpha = (C_{\delta y,\delta c}) . \left(C_{\delta c,\delta c}\right)^{+}$$

Covariance
Slopes/Commands

Covariance
Commands/Commands

The Non-Invasive Approach - Principle

<u>Principle:</u>

1) Estimating an Interaction Matrix using the closed-loop data

AO – CL Equation

$$\delta y_k = D_\alpha . \delta c_k + \delta z_k$$

Maximum Likelihood Approach:

$$D_\alpha = (C_{\delta y,\delta c}).\left(C_{\delta c,\delta c}\right)^+$$

<u>Hypothesis:</u>

1. Independence between δc_k and δz_k
2. Perfect WFS

Domain of validity? Limitations?

IV.2 - Analysis of the signals

$$\boldsymbol{\delta y_k = D_\alpha . \delta c_k + \delta z_k}$$

Signal of interest $\boldsymbol{\delta c_k}$ => Propagation on the DM of :

- Noise Propagation
- Calibration Error
- Temporal Error
- Aliasing Error
- …

IV.2 - Analysis of the signals

$$\boldsymbol{\delta y_k = D_\alpha . \delta c_k + \delta z_k}$$

Signal of interest $\boldsymbol{\delta c_k}$ => Propagation on the DM of :

- Noise Propagation — Acts as a **signal of interest**!
- Calibration Error
- Temporal Error
- Aliasing Error
- …

IV.2 - Analysis of the signals

$$\boldsymbol{\delta y_k = D_\alpha . \delta c_k + \delta z_k}$$

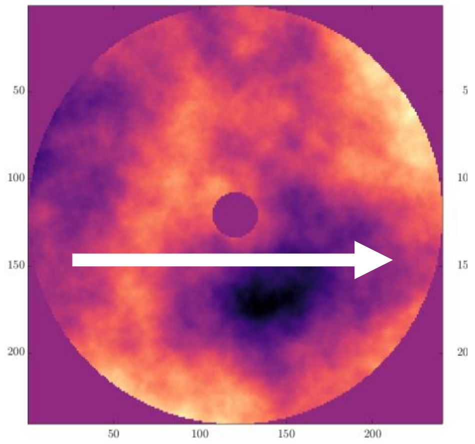
Signal of interest $\boldsymbol{\delta c_k}$ => Propagation on the DM of :

- Noise Propagation
- Calibration Error
- Temporal Error — **Correlated** to the turbulence impacting the measurement!
- Aliasing Error
- …

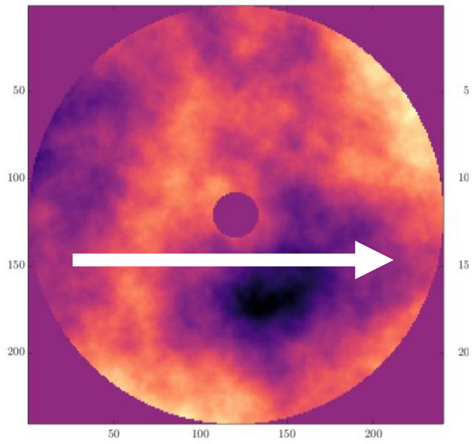
Challenging the hypothesis

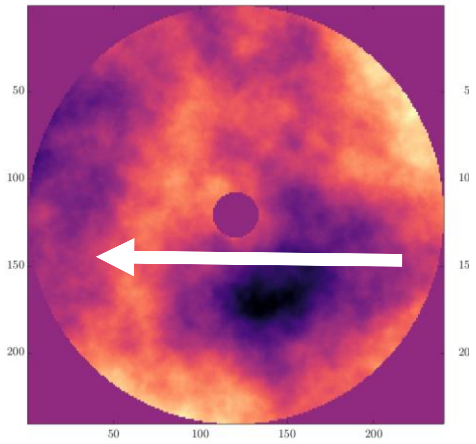
1. Independence between $\boldsymbol{\delta c_k}$ and $\boldsymbol{\delta z_k}$?
   1. Explore different observing conditions : Frozen Flow and Boiling atmosphere

Frozen Flow



Boiling





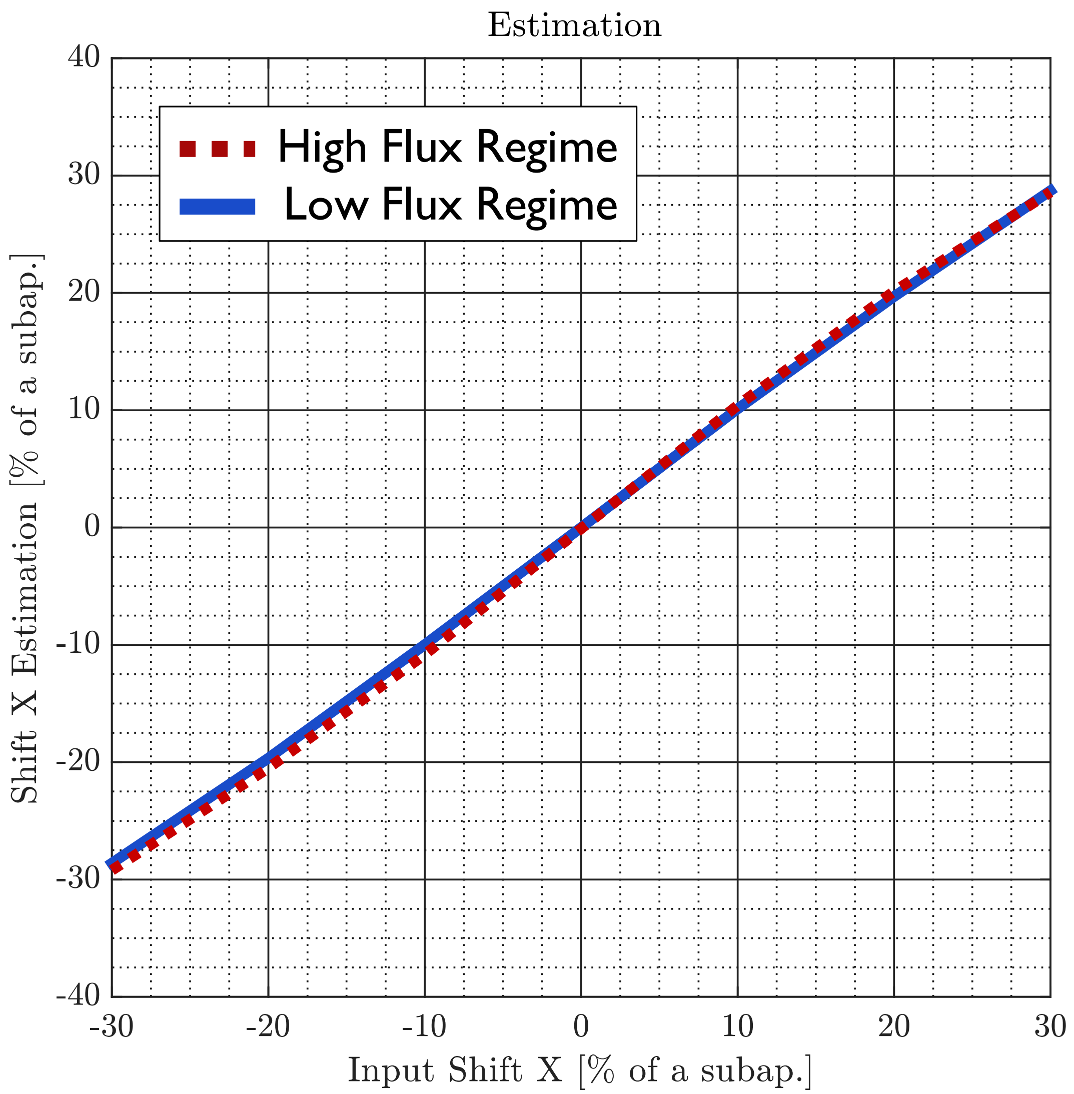
For both cases constant wind in the X direction

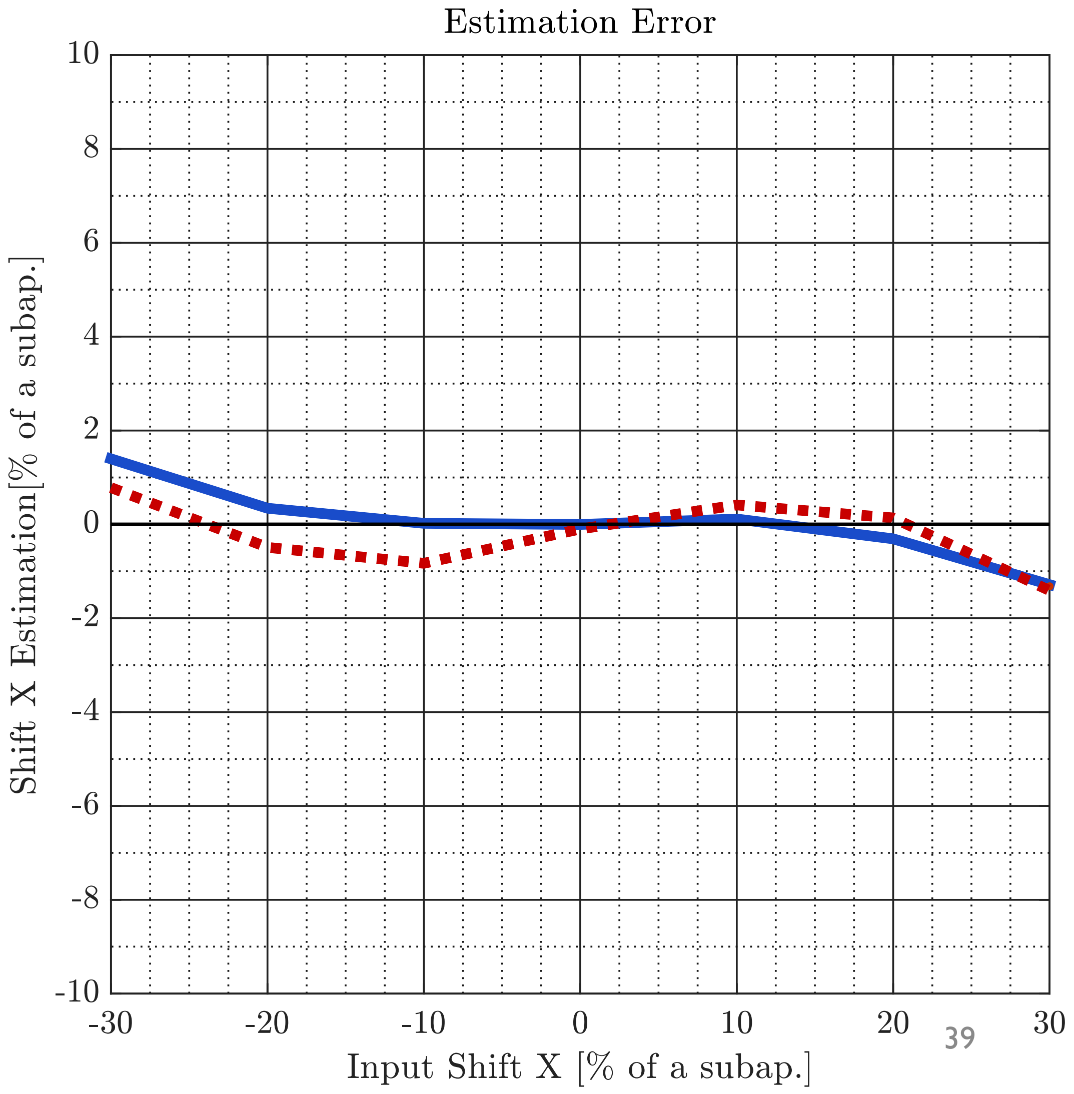
Challenging the hypothesis

1. Independence between $\boldsymbol{\delta c_k}$ and $\boldsymbol{\delta z_k}$?
   1. Explore different observing conditions : Frozen Flow and Boiling atmosphere
   2. Explore different regimes of noise

Application SH WFS

Nominal case: Frozen Flow 10 m/s X direction





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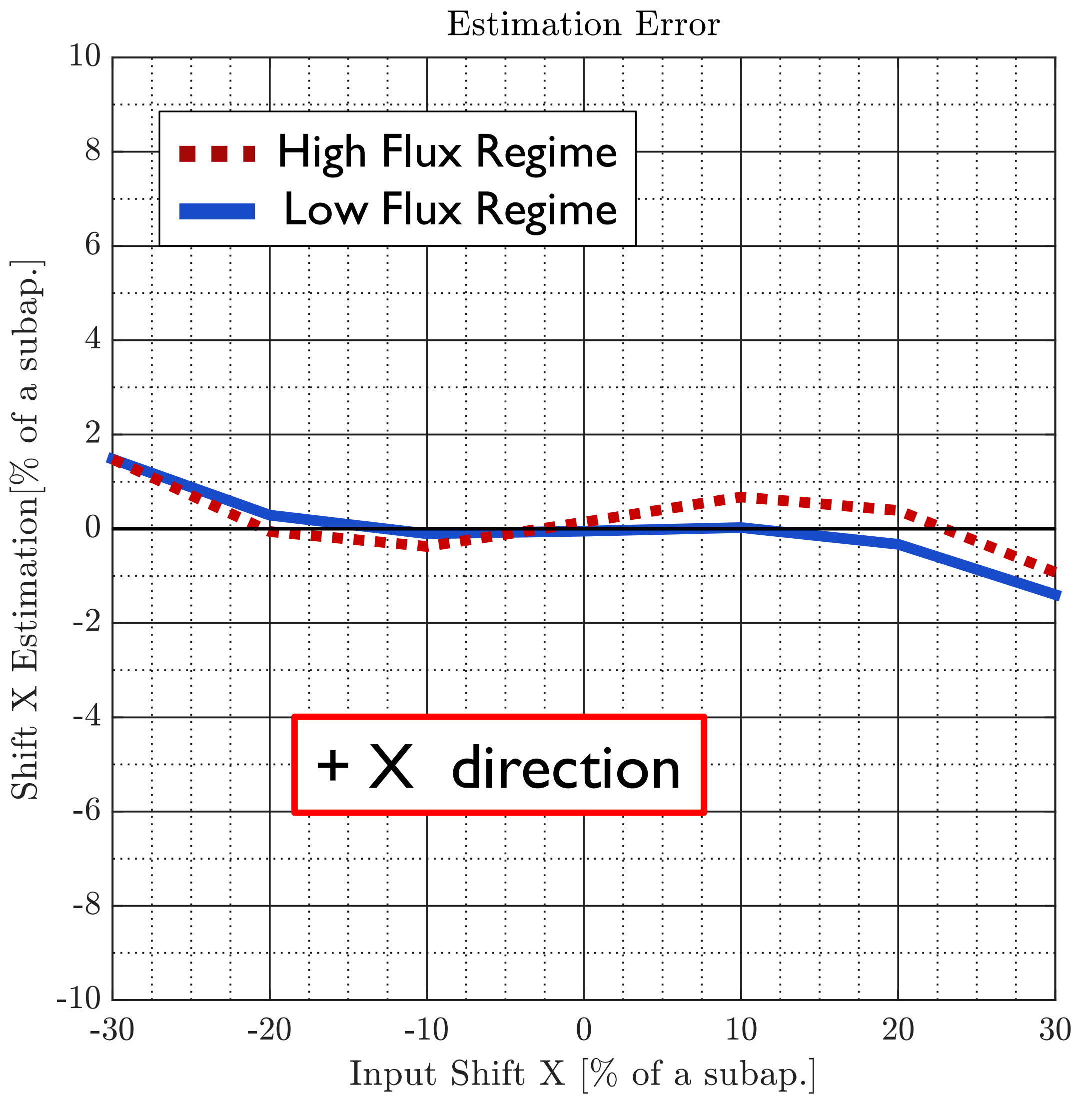
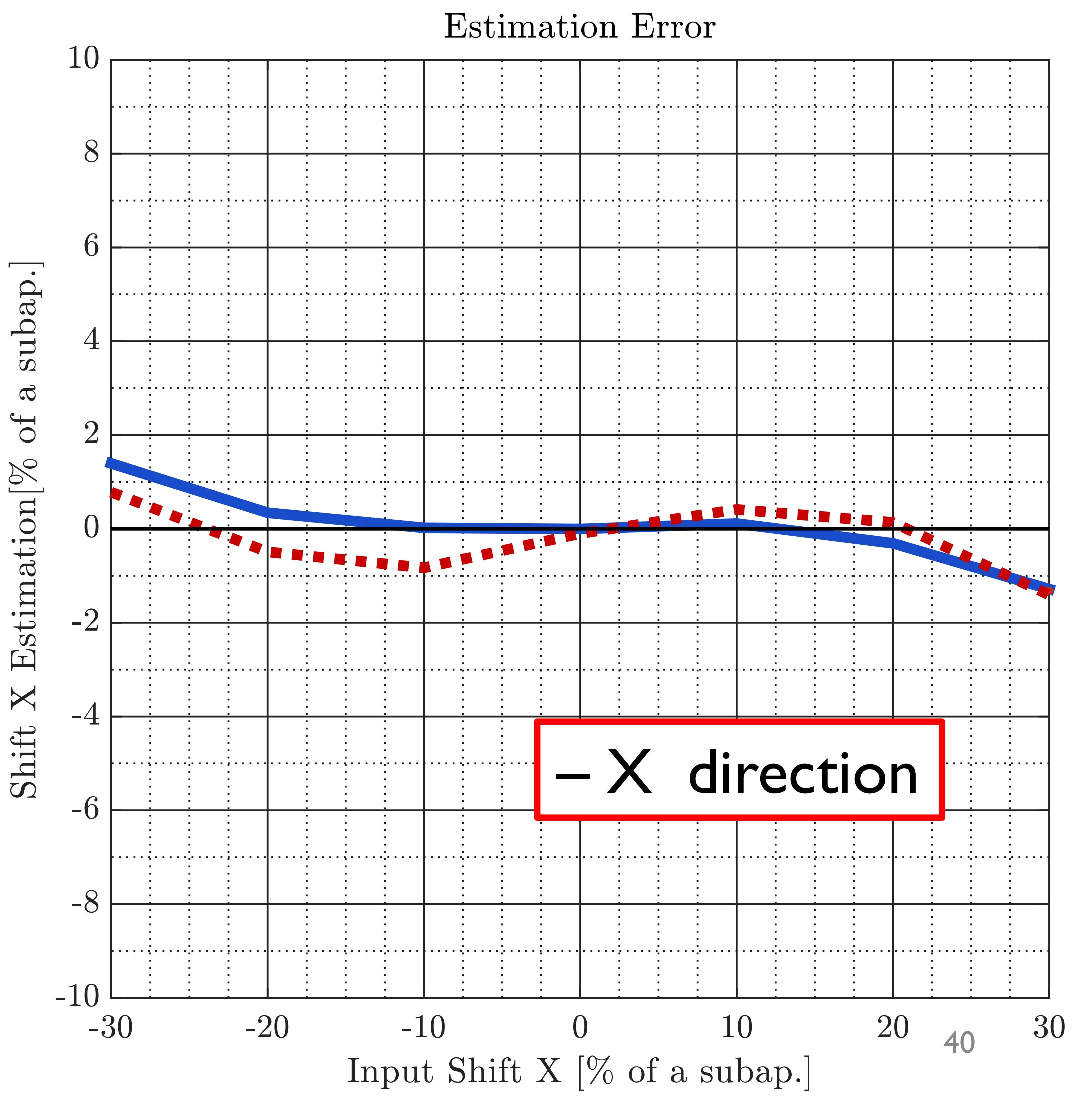
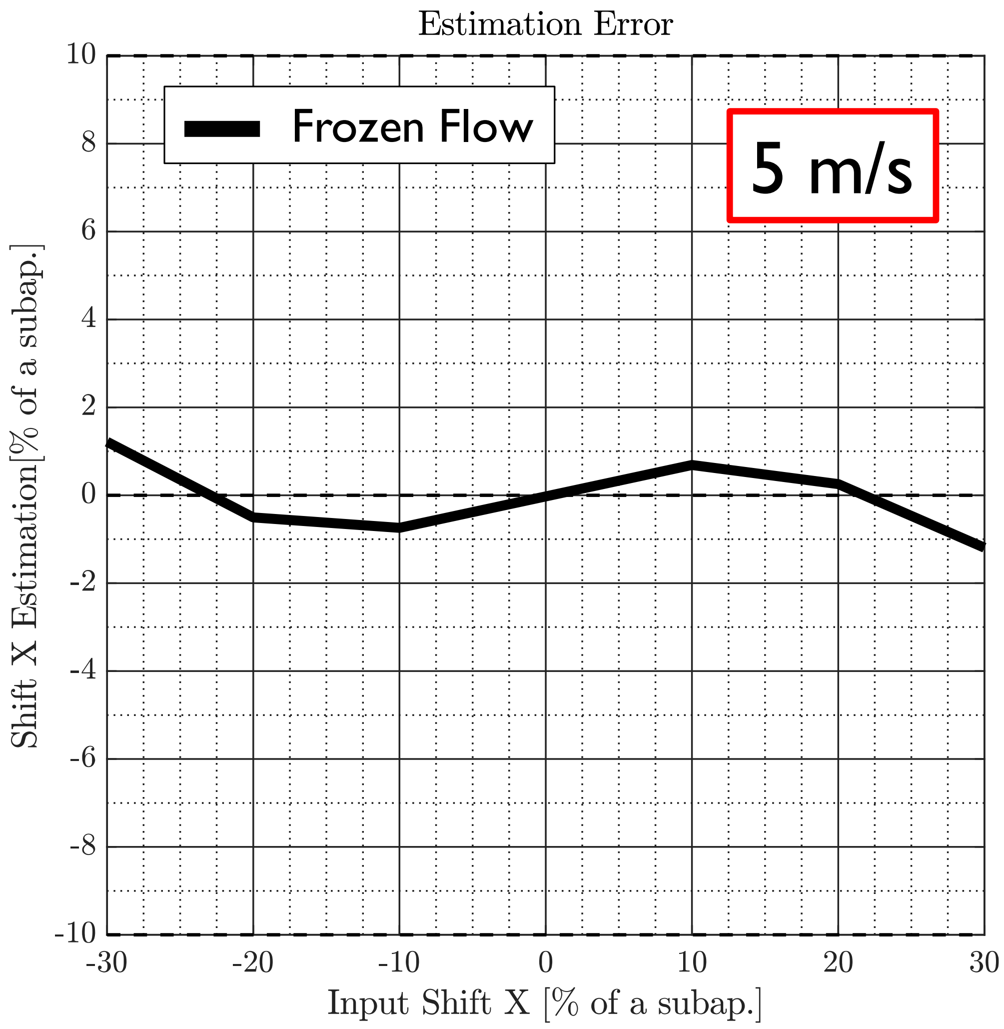
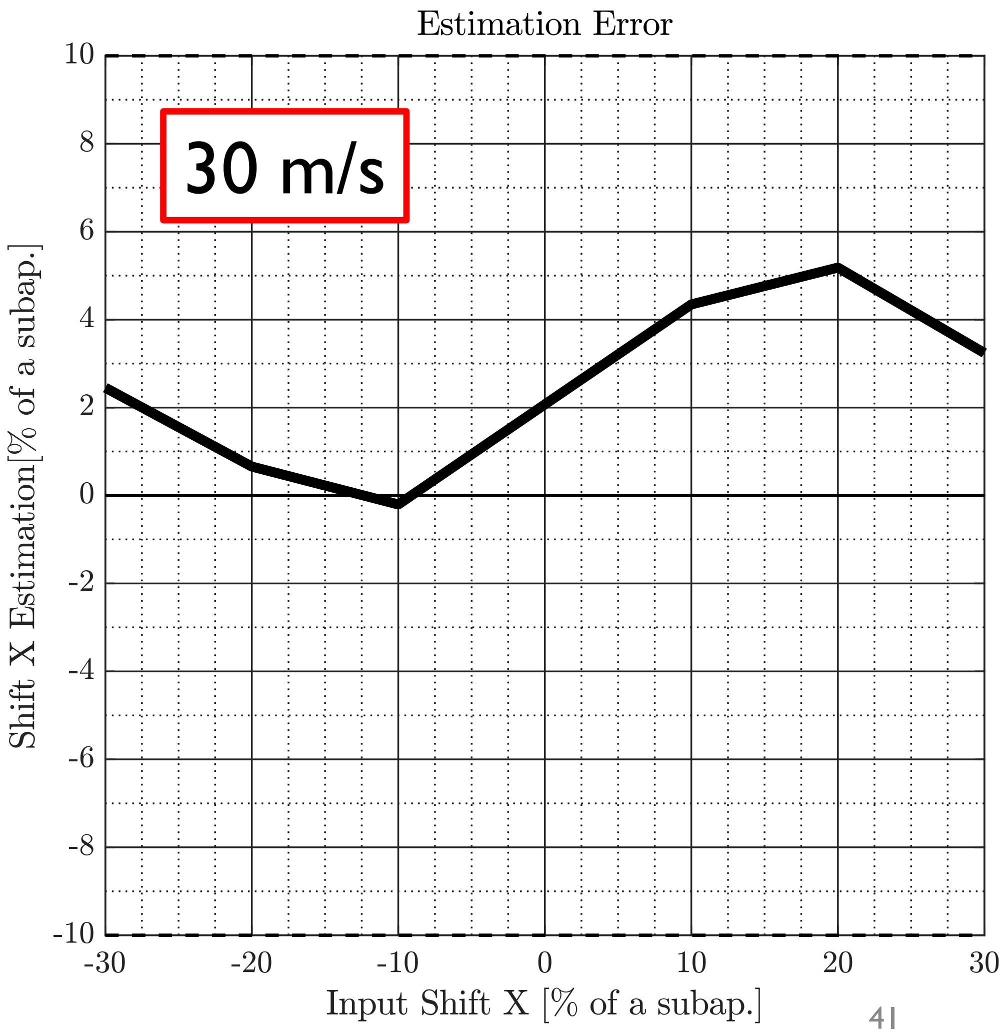




Application SH WFS

Limit cases: High Flux Regime X Direction





Application SH WFS

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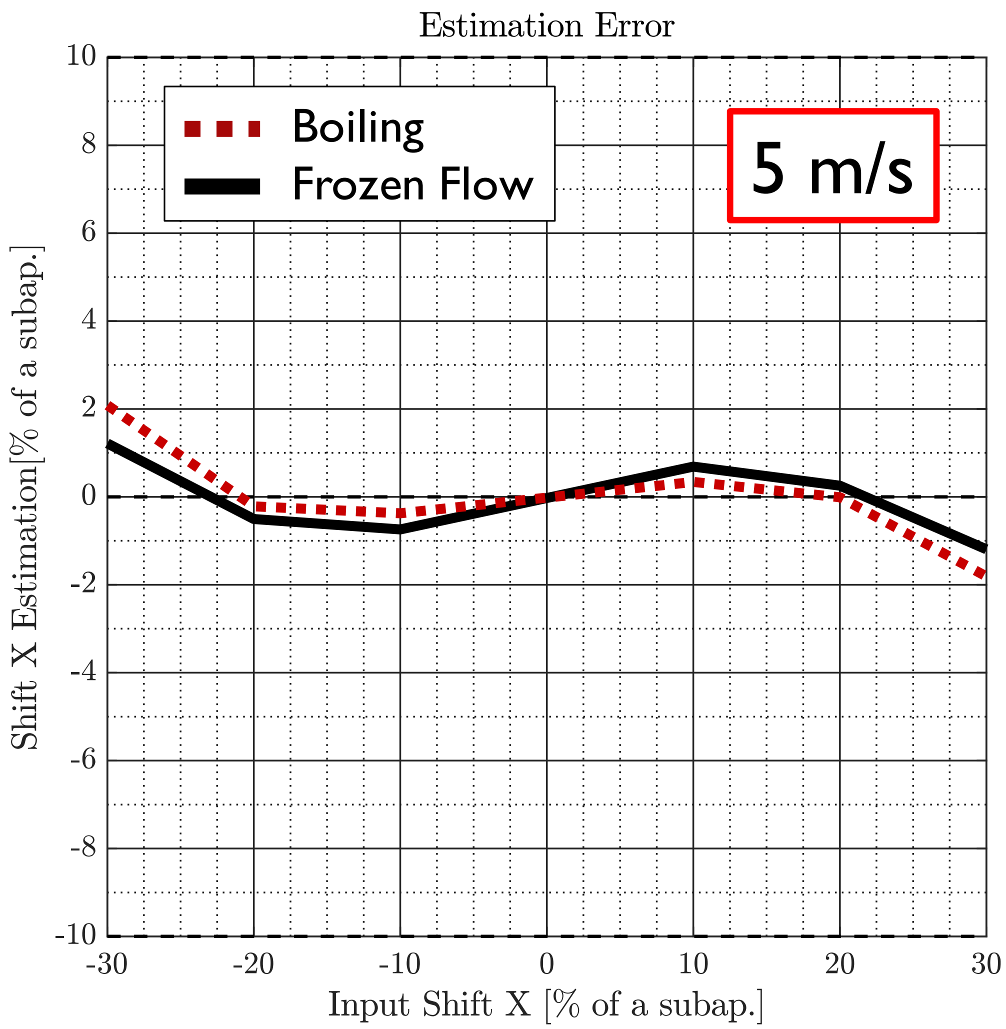
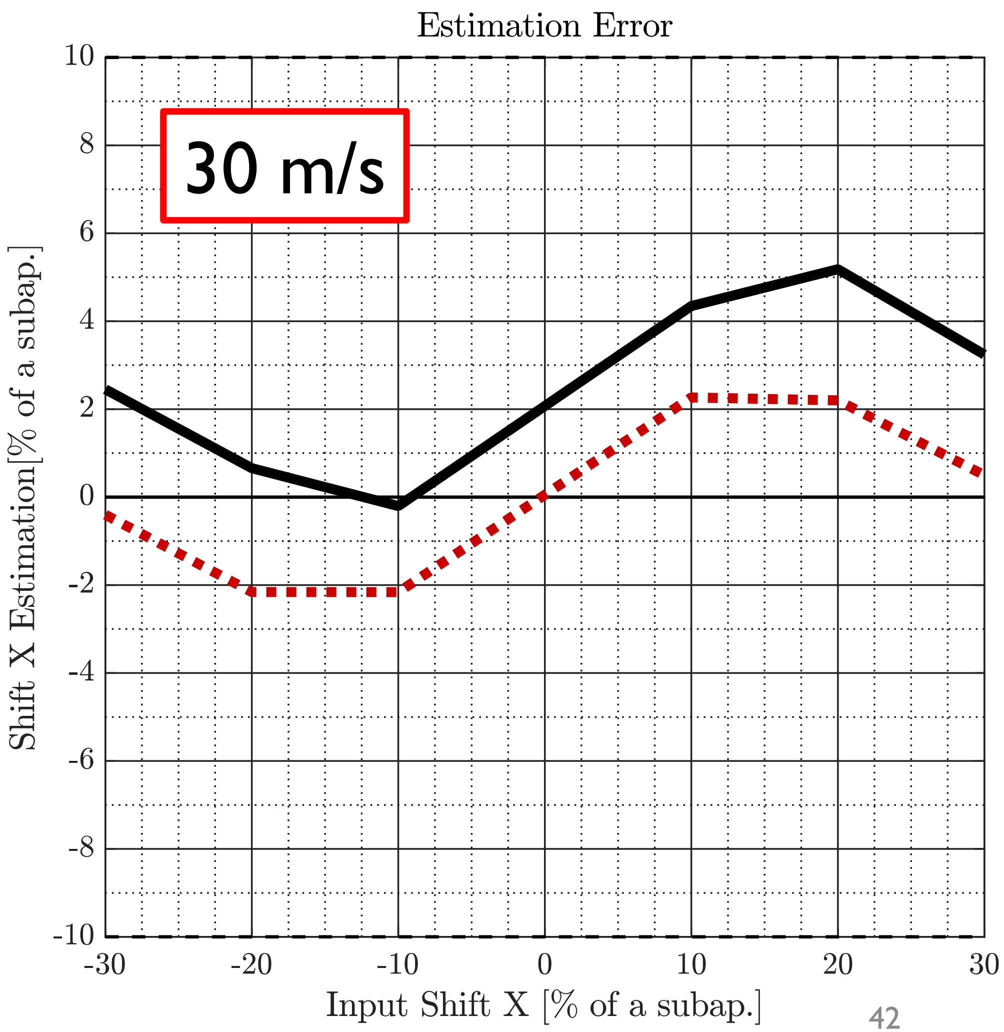




Application SH WFS

Frozen Flow

Bias for the shift estimation!

- Depends on the wind speed
- Depends on the wind direction
- Depends on the regime of noise

Boiling

No bias for the shift estimation!

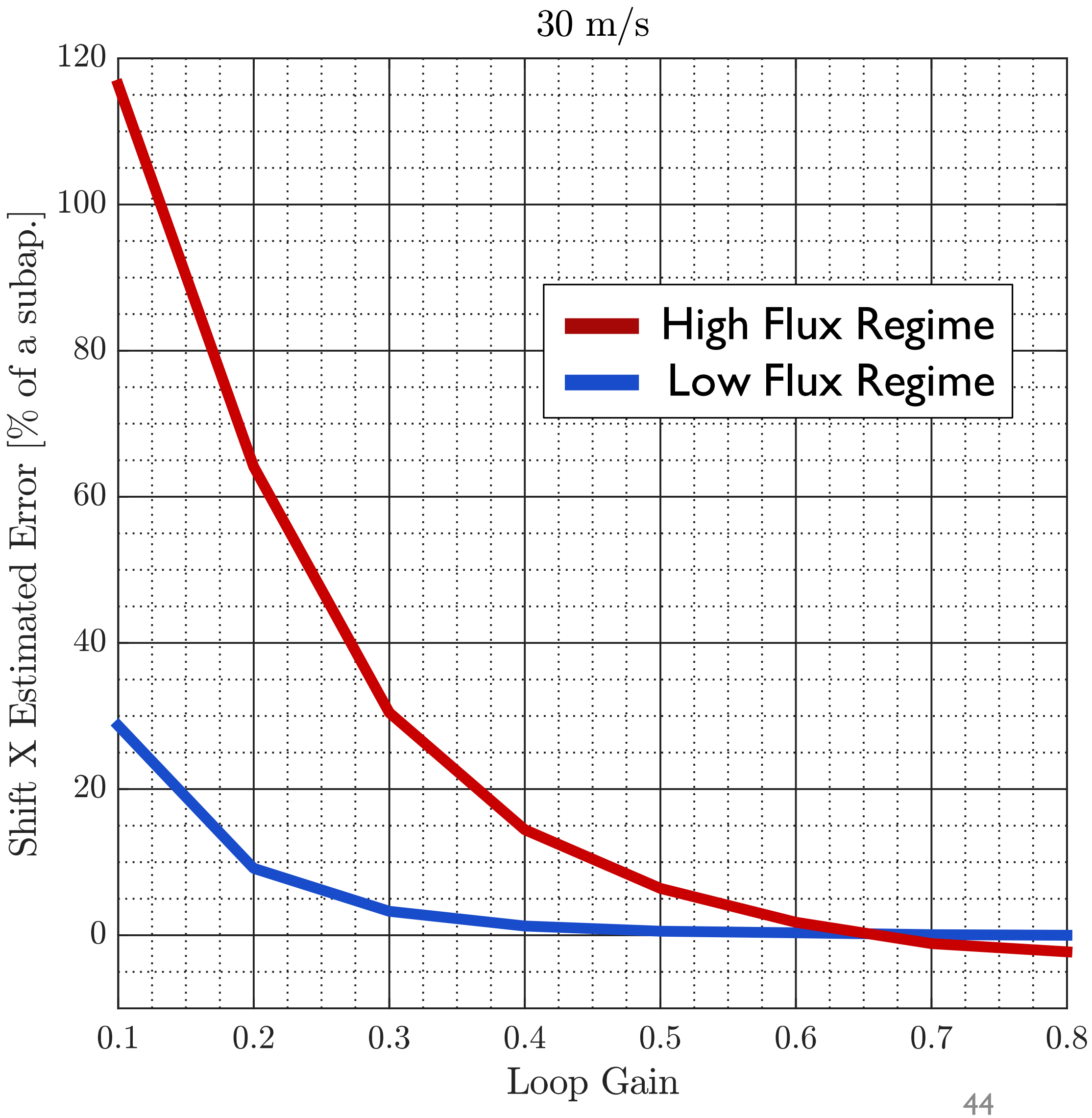
Application SH WFS

Problem comes from the Temporal Error..

Impact of the bandwidth?

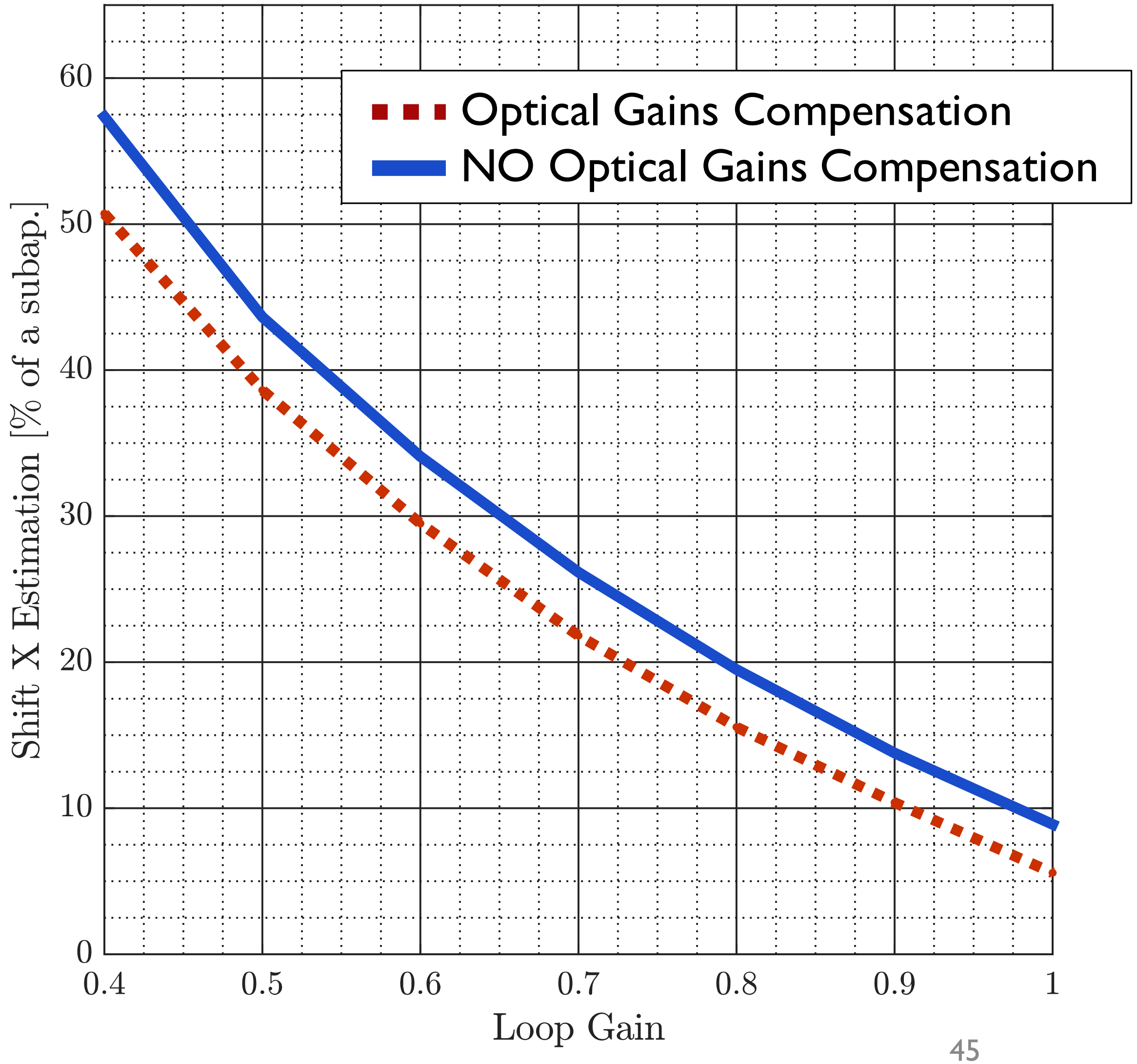
Bias correlated to the bandwidth!

=> Correction of the temporal error!



Application with PWFS

- Same Trends Identified!
- Higher impact of the bias:
- Optical Gains Compensations



A Non Invasive Approach

Summary:

Limitation of the method in a strong Frozen Flow and High Flux regime

BUT…We have to keep in mind that we considered:

- A pure Frozen Flow (constant wind speed and direction) => not so realistic
- Large Wind-speeds >20 m/s

Conclusions

AO Calibration in the ELT context

$\Rightarrow$Pseudo Synthetic models to provide regular updates of the calibration

Invasive approach:

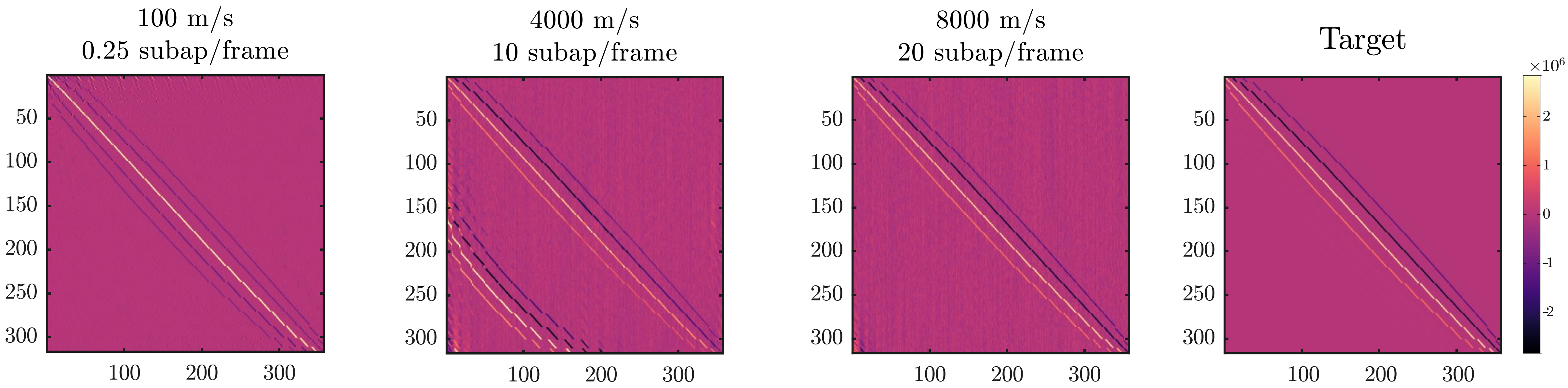
- Robust and behaving as we expect it to be.
- Impact on science

Non Invasive Approach

- NO impact on science
- Limitations in High Flux regime and Pure Frozen Flow => Priors?

Application SH WFS

Origin of the Bias in High Flux Regime?



Structures in the interaction matrix estimation = replicas of actuators signals!

Application SH WFS

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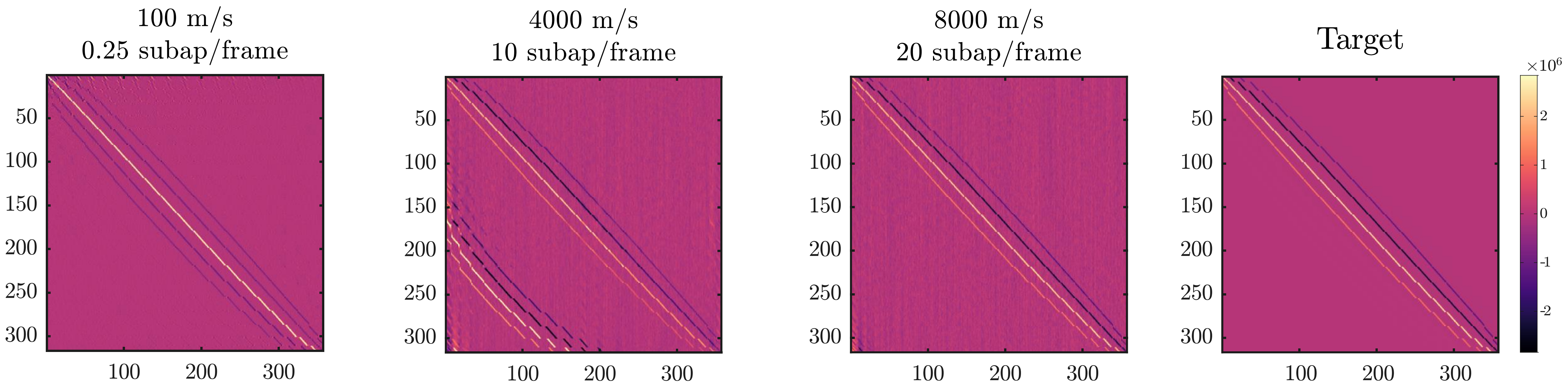

Structures in the interaction matrix estimation = replicas of actuators signals!

When overlapping with signal of interest => Bias the algorithm!

Identification Algorithm

Principle: Projection of an Interaction Matrix onto **Sensitivity Matrices**

Taylor's Development of the interaction matrix

$$\mathbf{D}_{\boldsymbol{\alpha}} \approx \gamma\left(\mathbf{D}_{\boldsymbol{\alpha}_0} + \sum_{\mathrm{i}} \alpha_{\mathrm{i}}.\,\boldsymbol{\delta}\mathbf{D}_{\boldsymbol{\alpha}_0}(\varepsilon_{\mathrm{i}})\right)$$

$\mathbf{D}_{\boldsymbol{\alpha}}$= Input Interaction Matrix for mis-registration α

$\mathbf{D}_{\boldsymbol{\alpha}_0}$= Synthetic Interaction Matrix for mis-registration α_0

Identification Algorithm

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Taylor's Development of the interaction matrix

Sensitivity Matrix

$$\mathbf{D}_{\alpha} \approx \gamma \left(\mathbf{D}_{\alpha_0} + \sum_{i} \alpha_i . \boldsymbol{\delta}\mathbf{D}_{\alpha_0}(\varepsilon_i) \right)$$

Scaling Factor

Mis-Registration parameter of type *i*

Sensitivity Matrix

$$\boldsymbol{\delta}\mathbf{D}_{\alpha_0}(\varepsilon_i) = \frac{\mathbf{D}_{\alpha_0+\varepsilon_i} - \mathbf{D}_{\alpha_0-\varepsilon_i}}{2\varepsilon_i}$$

Identification Algorithm

Principle: Projection of an Interaction Matrix onto **Sensitivity Matrices**

Taylor's Development of the interaction matrix

$$\mathbf{D}_{\alpha} \approx \gamma \left(\mathbf{D}_{\alpha_0} + \sum_{i} \alpha_i . \boldsymbol{\delta}\mathbf{D}_{\alpha_0}(\varepsilon_i) \right)$$

Least Square Minimization:

Iterative Estimation of γ and $\boldsymbol{\alpha}$ (A few iterations required)

$\Rightarrow$ All the mis-registration parameters identified simultaneously