

# Optical Metrology Alignment and Impact on the Measurement Performance of the LISA Technology Package

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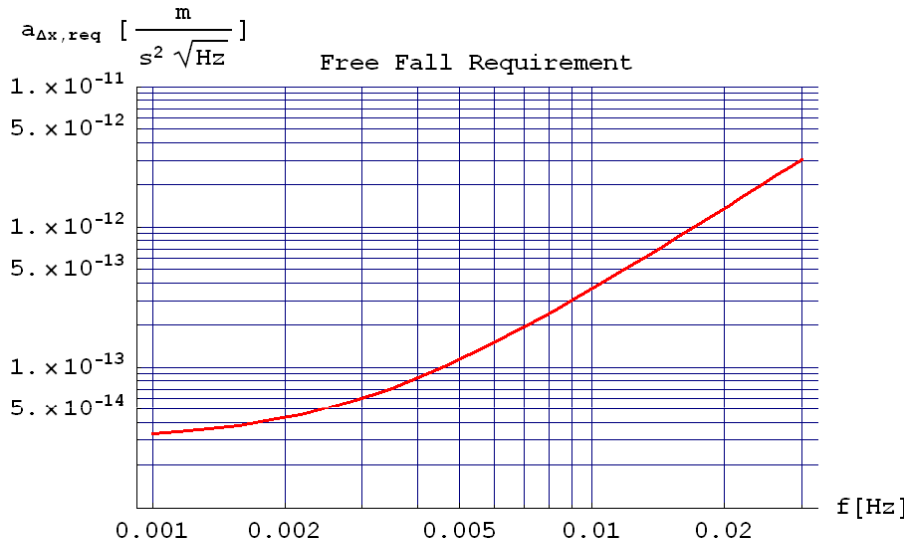
## Outline

- 1 Requirements and Alignment Effects
- 2 Measurement Model
- 3 Requirements in „Absolute“ Coordinates
- 4 Budgets and Optimization
- 5 Current Status

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# Independent Requirements (1mHz < f < 30mHz)



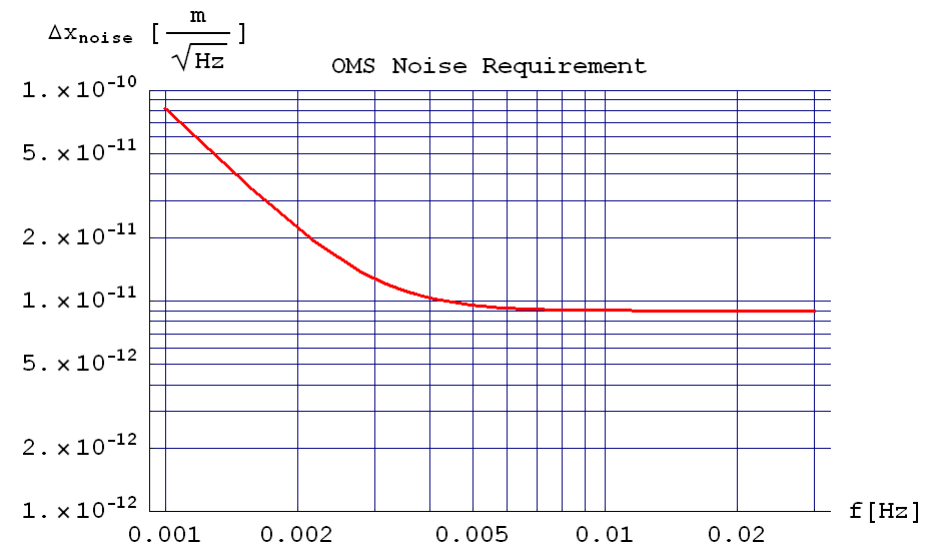
- Acceleration:

$$a_{\Delta x, req} < 3 \cdot 10^{-14} \cdot \left[ 1 + \left( \frac{f}{3\text{mHz}} \right)^2 \right] \frac{m}{s^2 \sqrt{Hz}}$$

- Optical measurement accuracy:

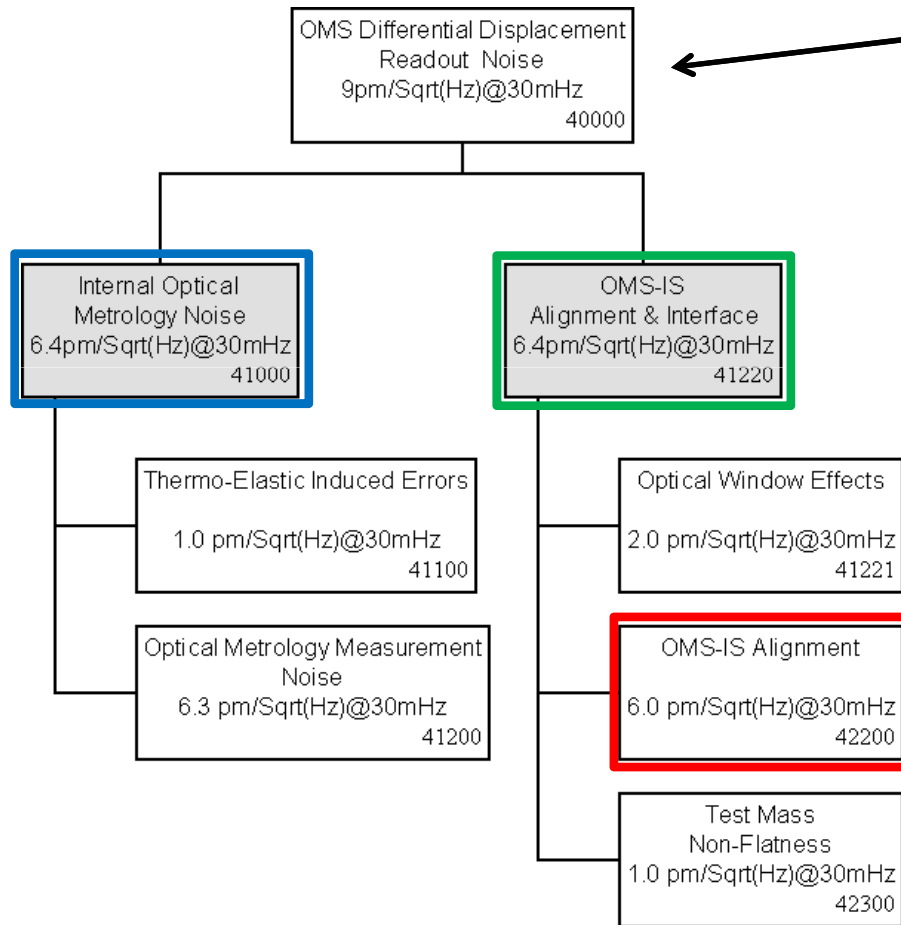
$$\Delta x_{\text{OMS, noise}} < 9 \cdot 10^{-12} \cdot \sqrt{1 + \left( \frac{f}{3\text{mHz}} \right)^{-4}} \frac{m}{\sqrt{Hz}}$$

**→ "new"**



# OMS Requirement

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9pm /√Hz requirement sub-divided in:

a) Internal metrology noise, e.g.

- Laser noise (frequency, amplitude)
- Thermal effects

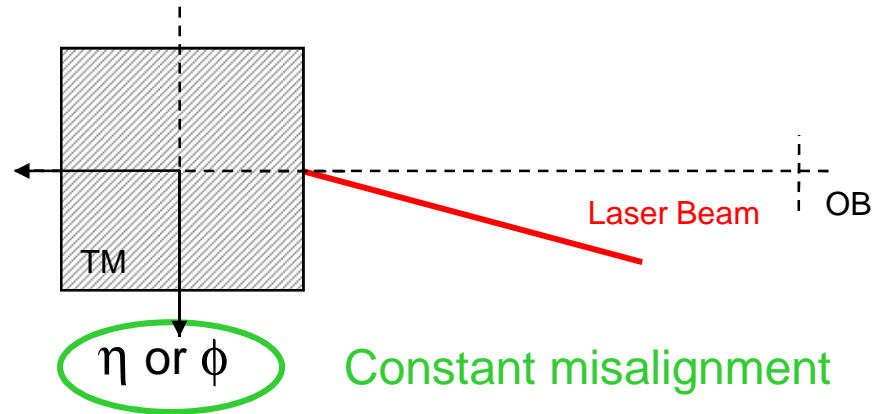
b) Alignment & interface effects, e.g.

- Optical window
- OMS-IS-alignment
- TM non-flatness

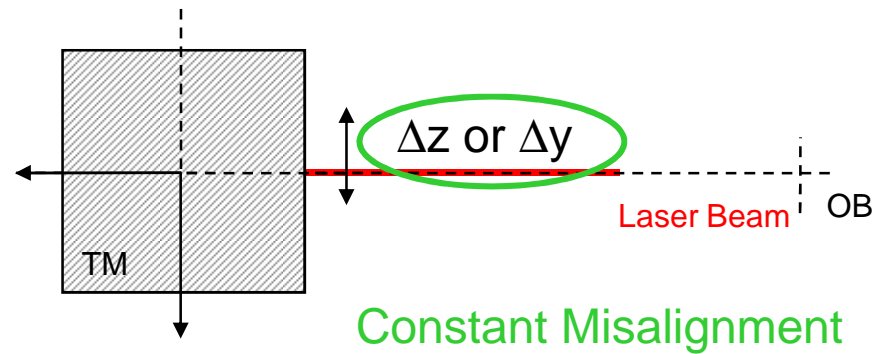
**Focus of this talk**

# Misalignment Contributions to $\Delta x$

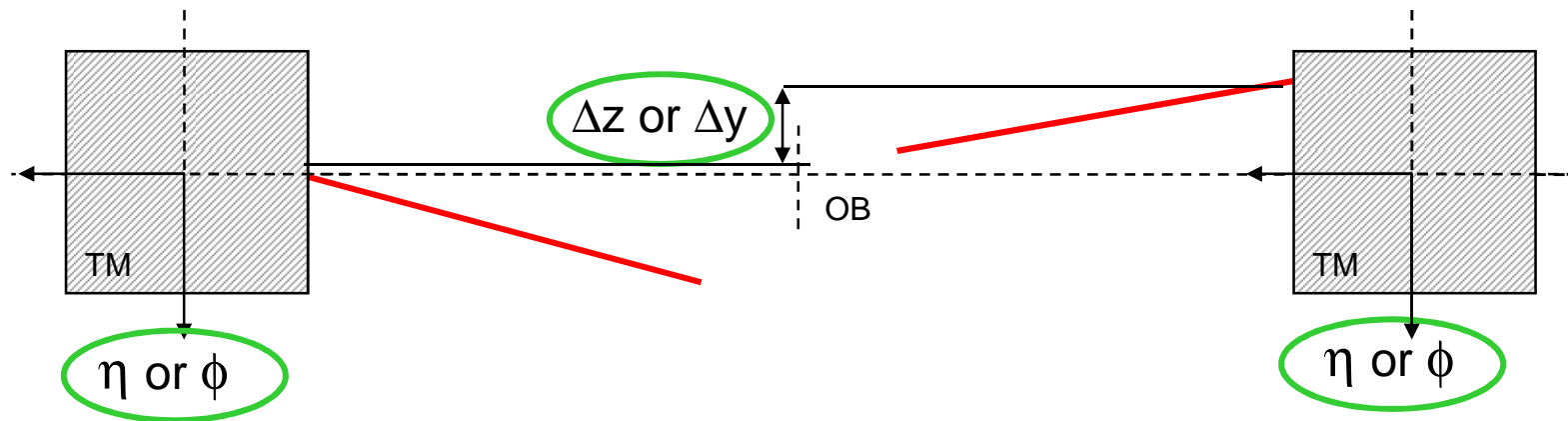
- OB-linear jitter



- TM angular jitter



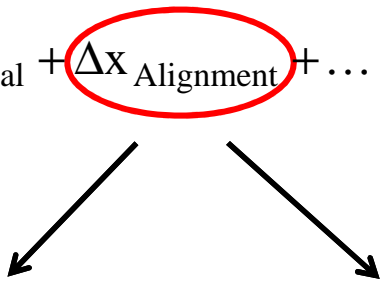
# Misalignment Contributions to $\Delta x$



Combinations of different constant misalignment

## OMS-IS Alignment Requirement

- Allocated requirement:  $6\text{pm}/\sqrt{\text{Hz}}$
- Goal: Further breakdown of requirement into measurable (“budgetable”) quantities

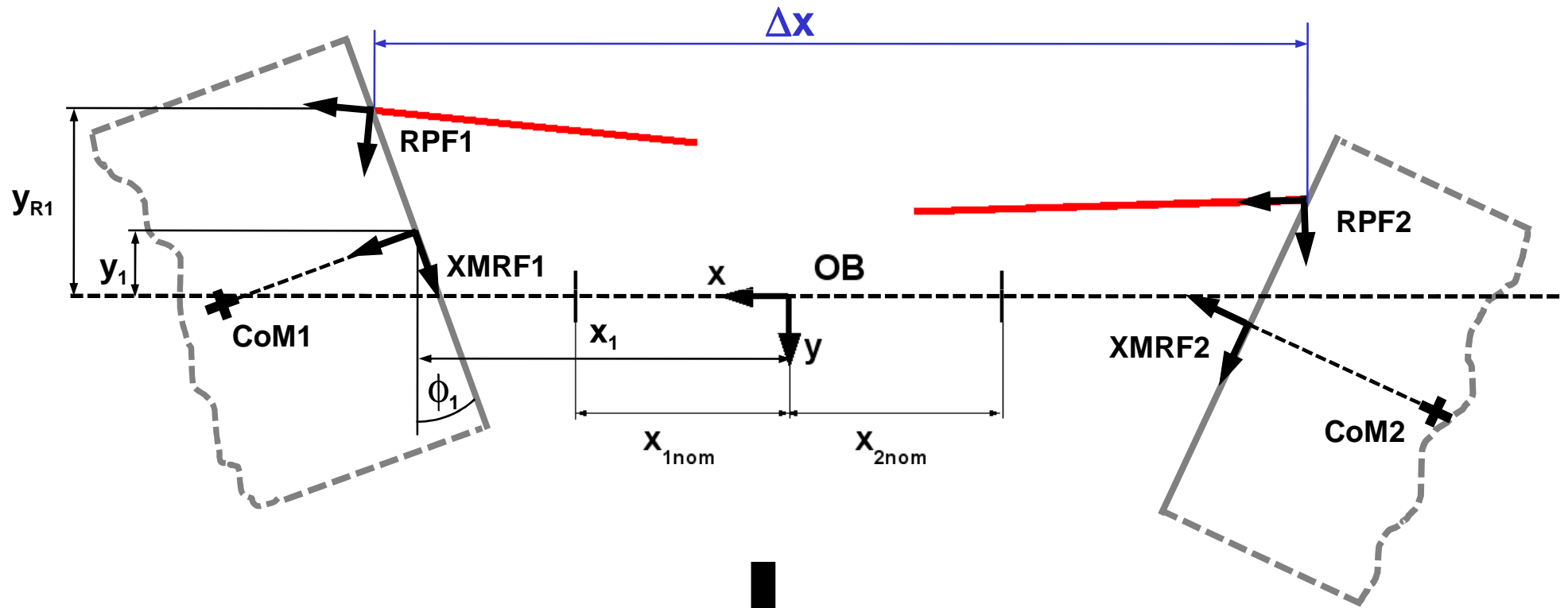
$$\Delta x_{\text{OMS}} = \Delta x_{\text{Real}} + \Delta x_{\text{Alignment}} + \dots$$


The diagram shows the equation  $\Delta x_{\text{OMS}} = \Delta x_{\text{Real}} + \Delta x_{\text{Alignment}} + \dots$  with the term  $\Delta x_{\text{Alignment}}$  circled in red. Two arrows point downwards from the circled term to the text "Static misalignments" on the left and "Relative test mass motion" on the right.

## Outline

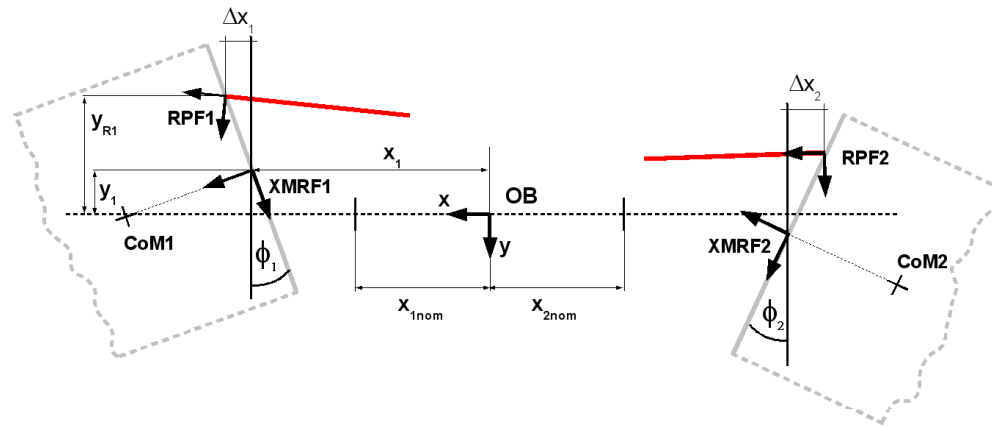
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# Measurement Model (1)



$$\Delta x = x_1 + x_2 - \phi_1 (y_{R1} - y_1) + \phi_2 (y_{R2} - y_2) + \dots$$

## Measurement Model (2)



### ➤ Extensions:

- **Third dimension**
- **Common-mode sensitivity (model parameters)**
- **Quadratic sensitivities (model parameters)**

$$\Delta X = b_{x1}x_1 + b_{x2}x_2 - \phi_1(y_{R1} - y_1) + \phi_2(y_{R2} - y_2) + \eta_1(z_{R1} - z_1) - \eta_2(z_{R2} - z_2) + b_{\phi_1^2}\phi_1^2 + b_{\phi_2^2}\phi_2^2 + b_{\eta_1^2}\eta_1^2 + b_{\eta_2^2}\eta_2^2$$

➡ Simple nonlinear model to cover dominating effects

## Measurement Model (3)

➤ Linearized:

### Misalignment Terms

$$\Delta \mathbf{x}_{\text{Alignment}} = \mathbf{v}_1^T \bar{\mathbf{r}}_1 + \mathbf{w}_1^T \bar{\boldsymbol{\varphi}}_1 + \mathbf{v}_2^T \bar{\mathbf{r}}_2 + \mathbf{w}_2^T \bar{\boldsymbol{\varphi}}_2$$

Relative Position/Attitude Jitter

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# Relative vs. Absolute Coordinates (1)

$$\Delta \mathbf{x}_{\text{Alignment}} = \mathbf{v}_1^T \bar{\mathbf{r}}_1 + \mathbf{w}_1^T \bar{\boldsymbol{\phi}}_1 + \mathbf{v}_2^T \bar{\mathbf{r}}_2 + \mathbf{w}_2^T \bar{\boldsymbol{\phi}}_2$$

Relative Position/Attitude Jitter

Misalignment Terms

Control Requirements

Optical Bench and TM Design Requirements

Drag-Free Loops (SC-jitter)



Suspension Loops (TM-jitter)

➔ Does not show SC and TM impact separately

➔ Intuitive answer: better TM suspension mitigates effects ?

## Relative vs. Absolute Coordinates (2)

➤ How to distinguish between SC and TM impact ?

- Differentiation
- Substitution of linearized equations of motion into measurement equation:

$$\Delta \ddot{\mathbf{x}}_{\text{Alignment}} = \mathbf{v}_1^T \ddot{\mathbf{r}}_1 + \mathbf{w}_1^T \ddot{\boldsymbol{\phi}}_1 + \mathbf{v}_2^T \ddot{\mathbf{r}}_2 + \mathbf{w}_2^T \ddot{\boldsymbol{\phi}}_2$$

$$\ddot{\mathbf{r}}_i = f_r(\mathbf{a}_{\text{OB}}, \mathbf{a}_{\text{OB}}, \mathbf{a}_{\text{TMi}}, \mathbf{a}_{\text{TMi}})$$

$$\ddot{\boldsymbol{\phi}}_i = f_\phi(\mathbf{a}_{\text{OB}}, \mathbf{a}_{\text{TMi}})$$

Optical Bench (=SC)  
Accelerations

Test Mass  
Accelerations

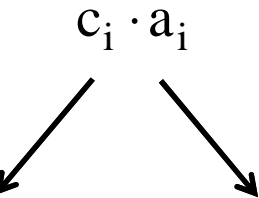
➔ **18 absolute** accelerations replace **12 relative** displacements

# Requirement Derivation

➤ Measurement equation in absolute coordinates:

$$\Delta \mathbf{x}_{\text{Alignment}} = \frac{1}{s^2} \cdot \mathbf{C}_{\text{DC}}^T \cdot \begin{pmatrix} \mathbf{a}_{\text{OB}} \\ \mathbf{a}_{\text{OB}} \\ \mathbf{a}_{\text{TM1}} \\ \mathbf{a}_{\text{TM1}} \\ \mathbf{a}_{\text{TM2}} \\ \mathbf{a}_{\text{TM2}} \end{pmatrix}$$

Vector of Misalignment Terms



$c_i$  Alignment  
 $a_i$  Acceleration

➔ Requirements for each (non-zero) product

➔ Requirements for single component

# Derived Misalignment Terms

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$$\begin{pmatrix}
 -(b_{x1} + b_{x2}) \\
 -\Delta\phi_{RPF1, RPF2} \\
 \Delta\eta_{RPF1, RPF2} \\
 0 \\
 -\Delta Z_{RPF1, RPF2} - X_{nom} (\eta_{RPF1} + \eta_{RPF2}) - 2 b_{\eta_1^2} \eta_{RPF1} - 2 b_{\eta_2^2} \eta_{RPF2} \\
 \Delta Y_{RPF1, RPF2} - X_{nom} (\phi_{RPF1} + \phi_{RPF2}) - 2 b_{\phi_1^2} \phi_{RPF1} - 2 b_{\phi_2^2} \phi_{RPF2} \\
 b_{x1} \\
 \Delta\phi_{xy1} \\
 -\Delta\eta_{xz1} \\
 0 \\
 -\Delta Z_{XMRF1, RPF1} + 2 b_{\eta_1^2} \eta_{RPF1} \\
 \Delta Y_{XMRF1, RPF1} + 2 b_{\phi_1^2} \phi_{RPF1} \\
 b_{x2} \\
 -\Delta\phi_{xy2} \\
 \Delta\eta_{xz2} \\
 0 \\
 \Delta Z_{XMRF2, RPF2} + 2 b_{\eta_2^2} \eta_{RPF2} \\
 -\Delta Y_{XMRF2, RPF2} + 2 b_{\phi_2^2} \phi_{RPF2}
 \end{pmatrix}^T$$

Requirements on optical bench

Requirements on test mass alignment

Requirements on TM surface orthogonality

# Derived Misalignment Terms

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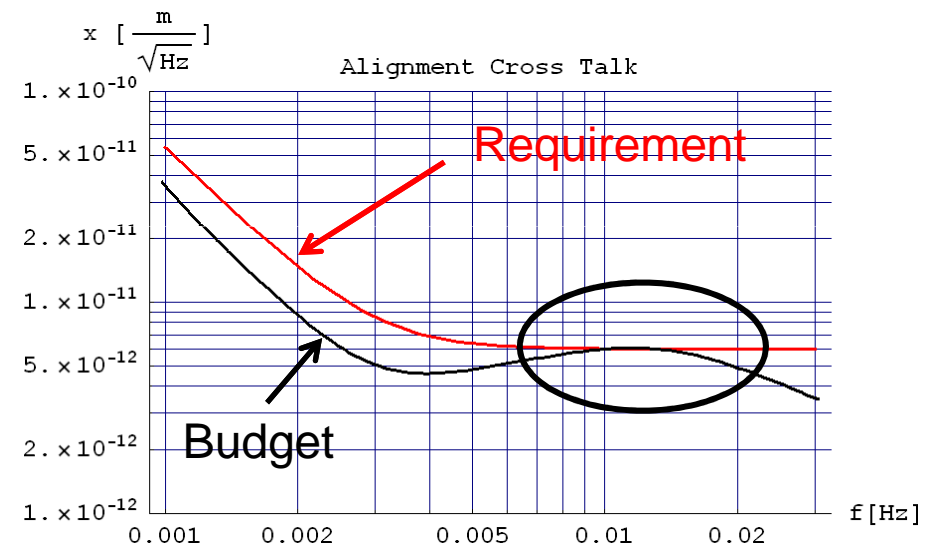
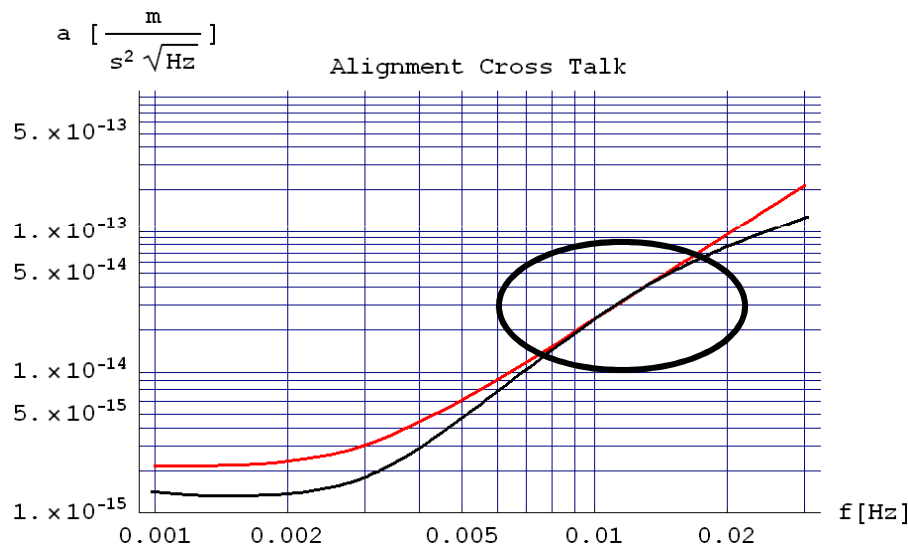
$  \begin{aligned}  &-(b_{x1} + b_{x2}) \\  &-\Delta\phi_{RPF1, RPF2} \\  &\Delta\eta_{RPF1, RPF2} \\  &0 \\  &-\Delta Z_{RPF1, RPF2} - X_{nom} (\eta_{RPF1} + \eta_{RPF2}) - 2 b_{\eta_1^2} \eta_{RPF1} - 2 b_{\eta_2^2} \eta_{RPF2} \\  &\Delta Y_{RPF1, RPF2} - X_{nom} (\phi_{RPF1} + \phi_{RPF2}) - 2 b_{\phi_1^2} \phi_{RPF1} - 2 b_{\phi_2^2} \phi_{RPF2}  \end{aligned}  $	$\begin{matrix} \text{T} \\ \downarrow \\ \text{Allocation} \end{matrix}$	$  \begin{aligned}  &10^{-4} \text{ m / m} \\  &50 \cdot 10^{-6} \text{ rad} \\  &50 \cdot 10^{-6} \text{ rad} \\  &0 \\  &60 \cdot 10^{-6} \text{ m} \\  &60 \cdot 10^{-6} \text{ m} \\  &0  \end{aligned}  $
$  \begin{aligned}  &b_{x1} \\  &\Delta\phi_{xy1} \\  &-\Delta\eta_{xz1} \\  &0  \end{aligned}  $		$  \begin{aligned}  &10^{-5} \text{ rad} \\  &10^{-5} \text{ rad} \\  &0  \end{aligned}  $
$  \begin{aligned}  &-\Delta Z_{XMRF1, RPF1} + 2 b_{\eta_1^2} \eta_{RPF1} \\  &\Delta Y_{XMRF1, RPF1} + 2 b_{\phi_1^2} \phi_{RPF1}  \end{aligned}  $	$  \begin{aligned}  &50 \cdot 10^{-6} \text{ m} \\  &50 \cdot 10^{-6} \text{ m} \\  &0  \end{aligned}  $	
$  \begin{aligned}  &b_{x2} \\  &-\Delta\phi_{xy2} \\  &\Delta\eta_{xz2} \\  &0  \end{aligned}  $	$  \begin{aligned}  &10^{-5} \text{ rad} \\  &10^{-5} \text{ rad} \\  &0  \end{aligned}  $	
$  \begin{aligned}  &\Delta Z_{XMRF2, RPF2} + 2 b_{\eta_2^2} \eta_{RPF2} \\  &-\Delta Y_{XMRF2, RPF2} + 2 b_{\phi_2^2} \phi_{RPF2}  \end{aligned}  $	$  \begin{aligned}  &50 \cdot 10^{-6} \text{ m} \\  &50 \cdot 10^{-6} \text{ m}  \end{aligned}  $	

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# Preliminary Budget: Total

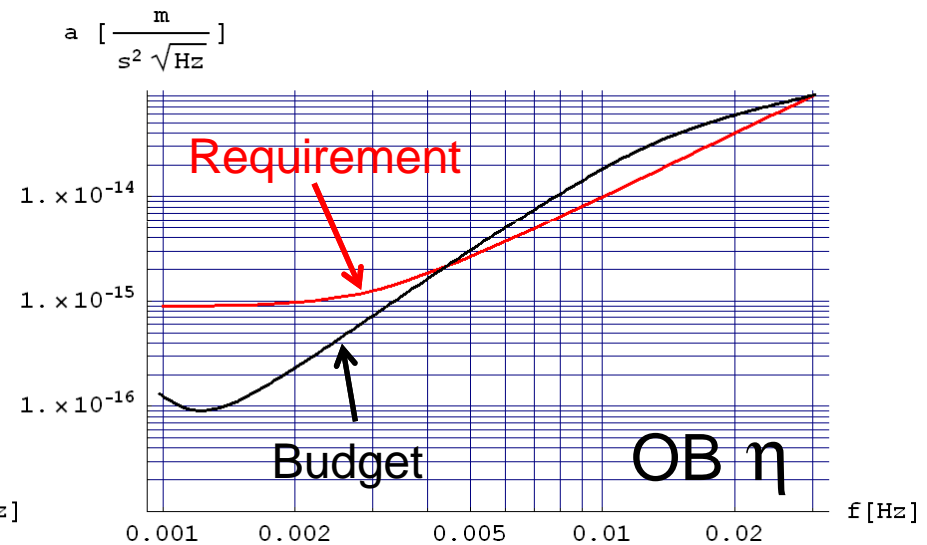
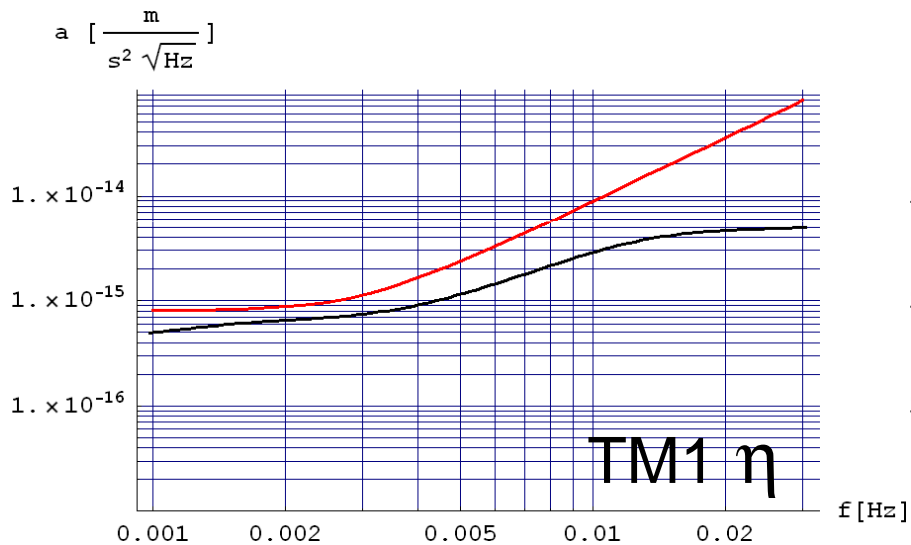
- Alignments: requirement values
- Acceleration jitter: values from frequency analysis



➔ Overall requirement is slightly violated

# Preliminary Budget: Individual

- Alignments: requirement values
- Acceleration jitter: values from frequency analysis

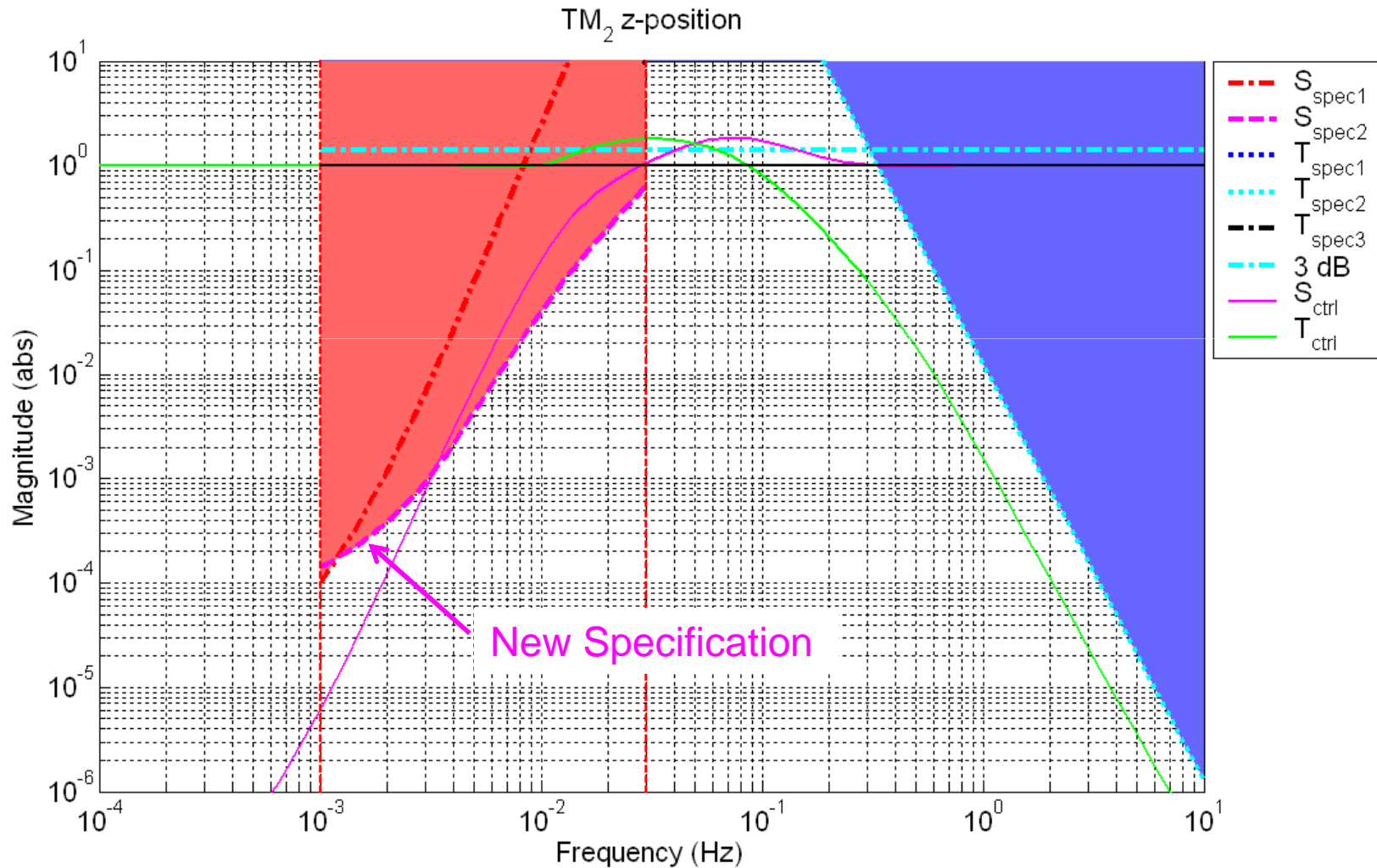


- Similar situation for other SC and TM axes

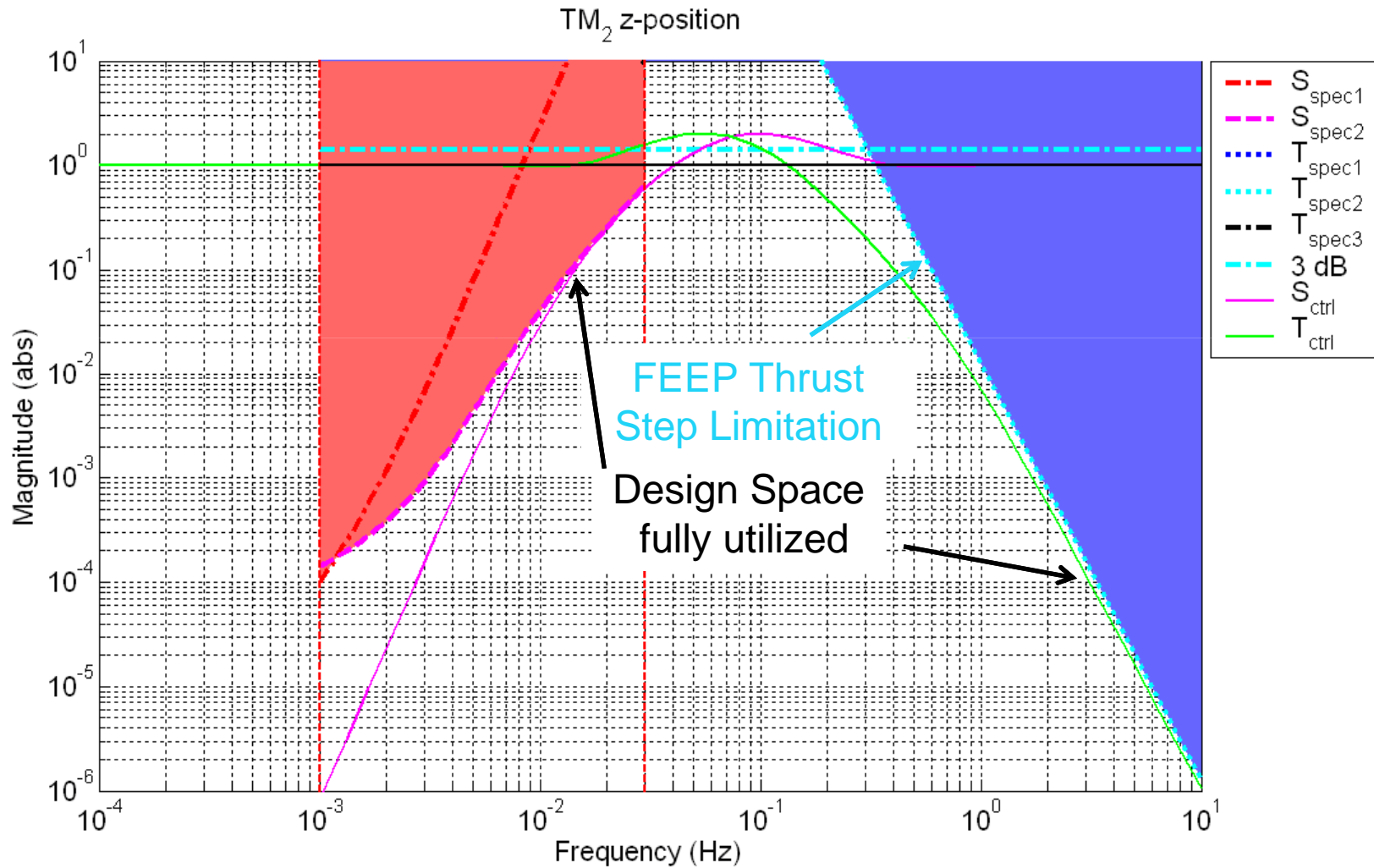
## Consequences

- SC acceleration noise drives alignment cross-coupling
  - ➔ Better suspension does not help
  
- Update of DF controllers necessary for mitigation:
  - New controller specifications due to alignment requirements
  - Never considered before

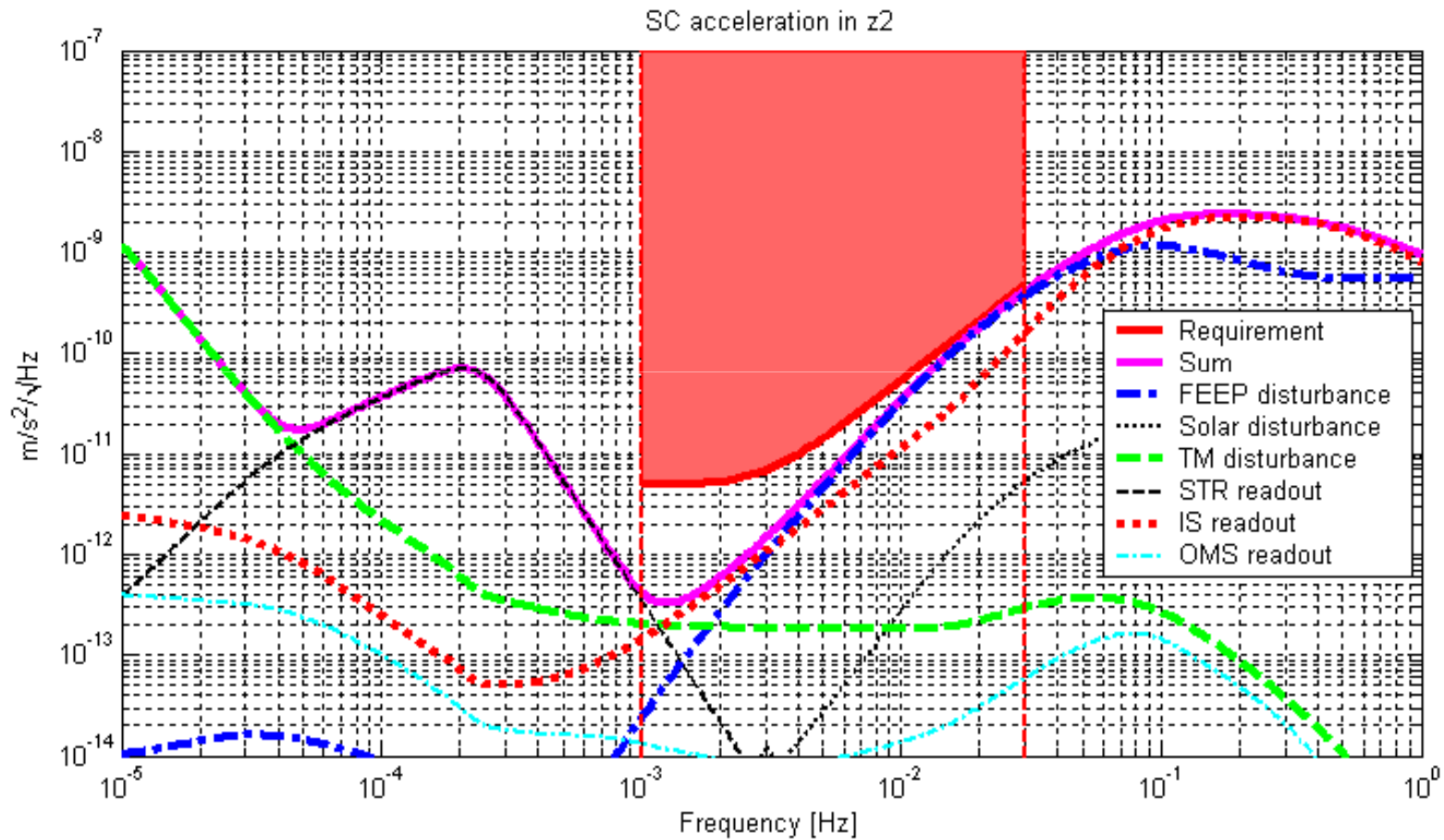
# Controller Update (1)



# Controller Update (1)



# Controller Update (2)

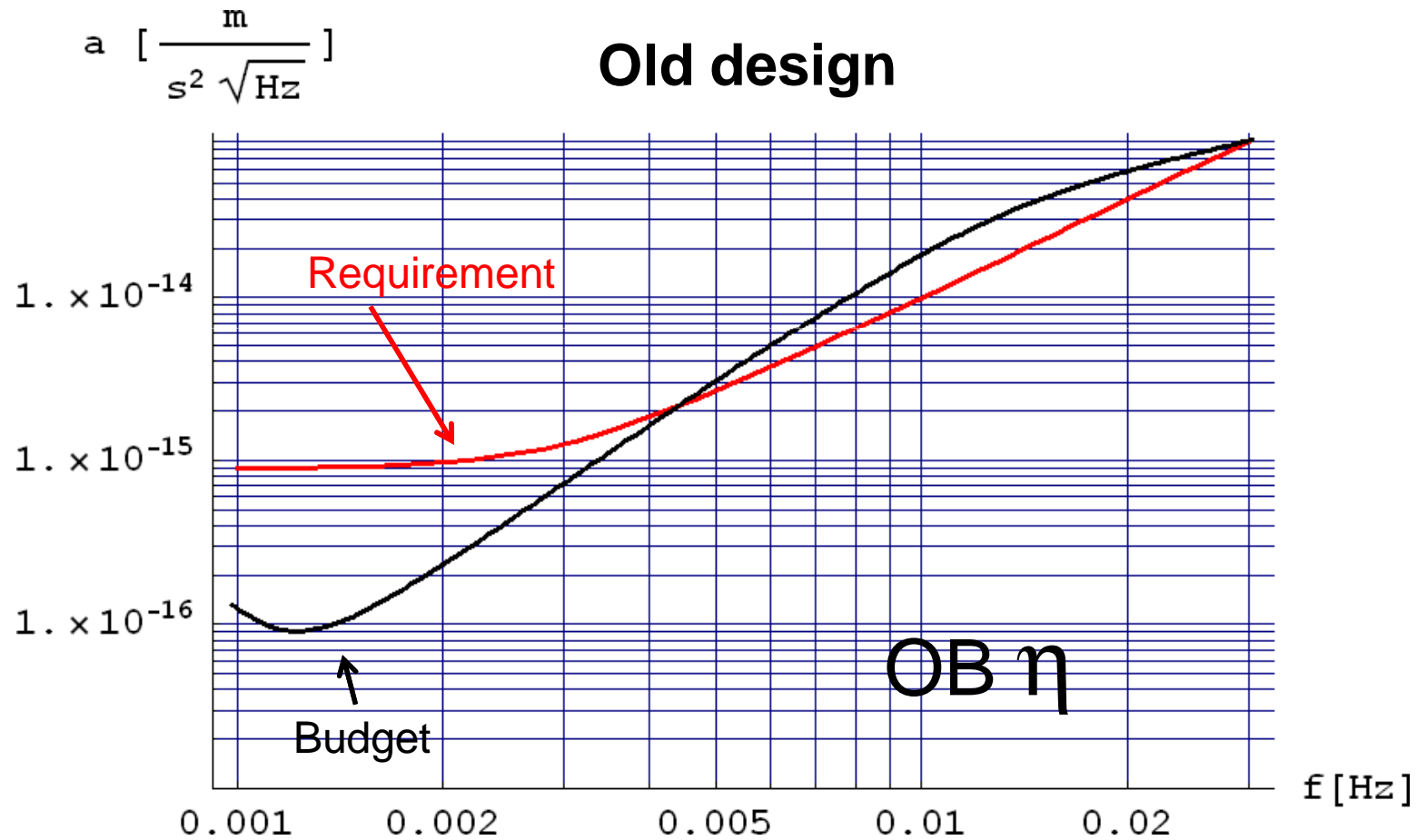


➔ IS readout-noise as limiting factor in MBW

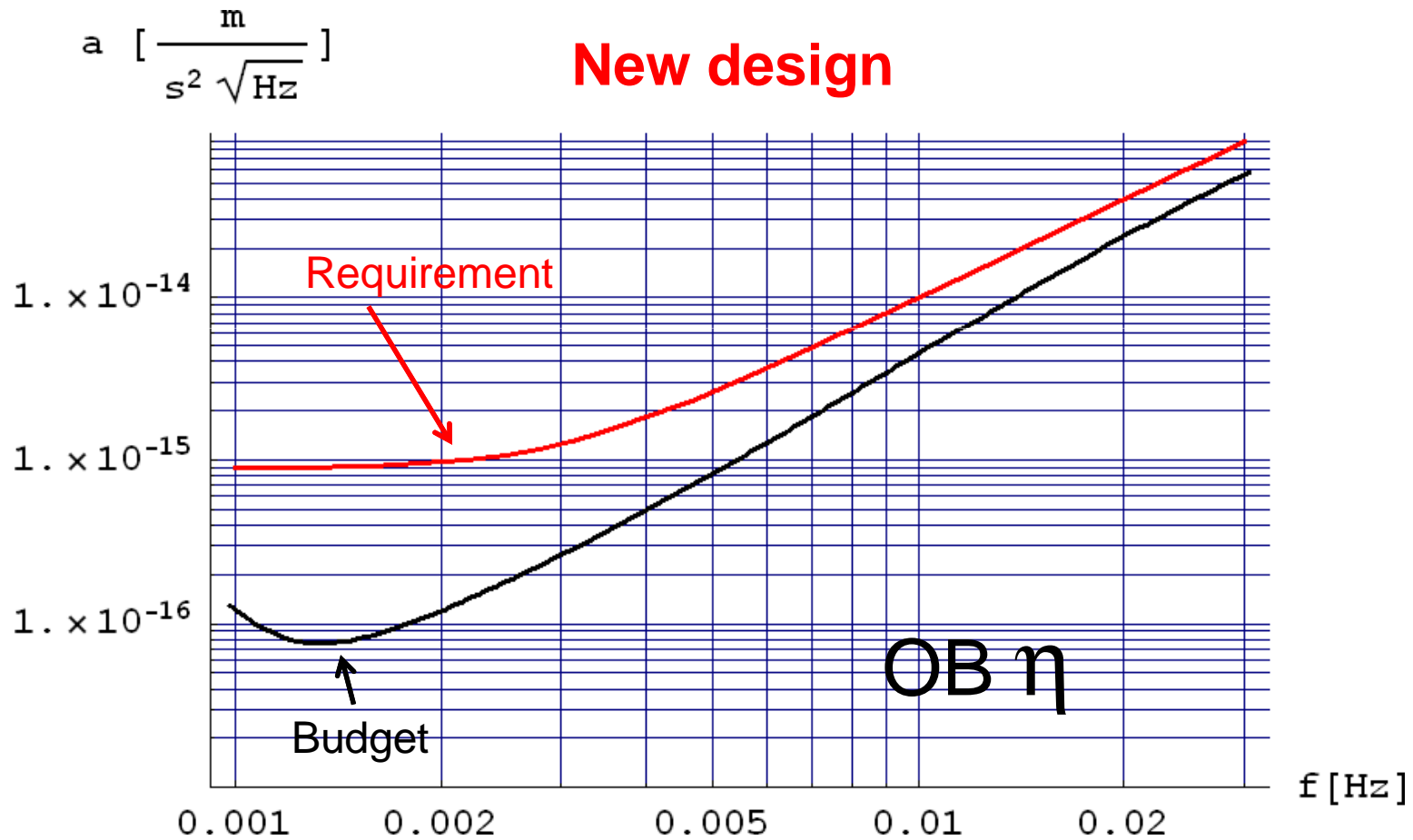
## Controller Update: Summary

- Update for all DF-axes except  $\theta_1$  (as coupled alignment negligible)
- Change in bandwidth from  $\approx 0.1$  Hz to  $\approx 0.2$  Hz
- Further increase of BW limited by maximum FEEP step limit
- Additional limit: IS readout noise
- Redesign shows significant improvements

# Improvements with new DF Controllers



# Improvements with new DF Controllers



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# Budget Data Base

Acceleration jitter from closed-loop simulations

Alignment values from ~~requirements~~

OptoCad simulation

~~Measurements~~



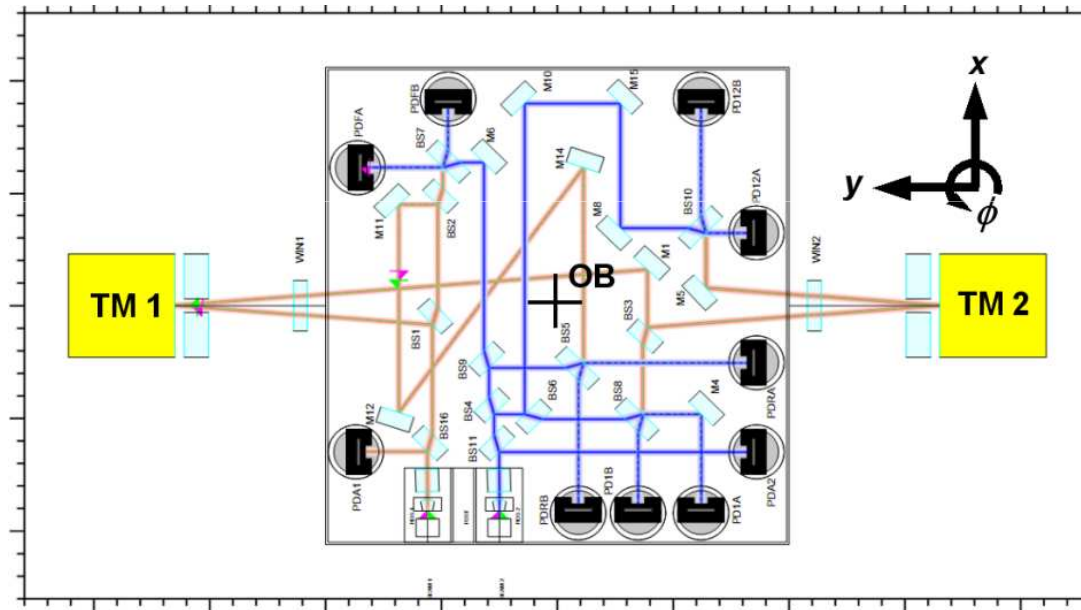
**➔** Measurements of final FM-hardware

- No measurement data available for misalignments

**➔** Intermediate stage:  
Expected misalignments from complex optical model at AEI

## OBI-Alignment Simulation (AEI)

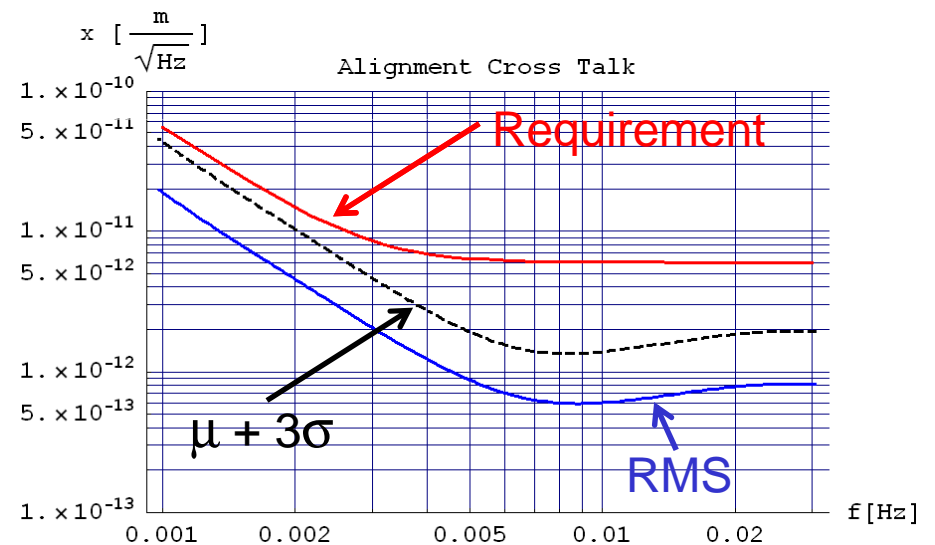
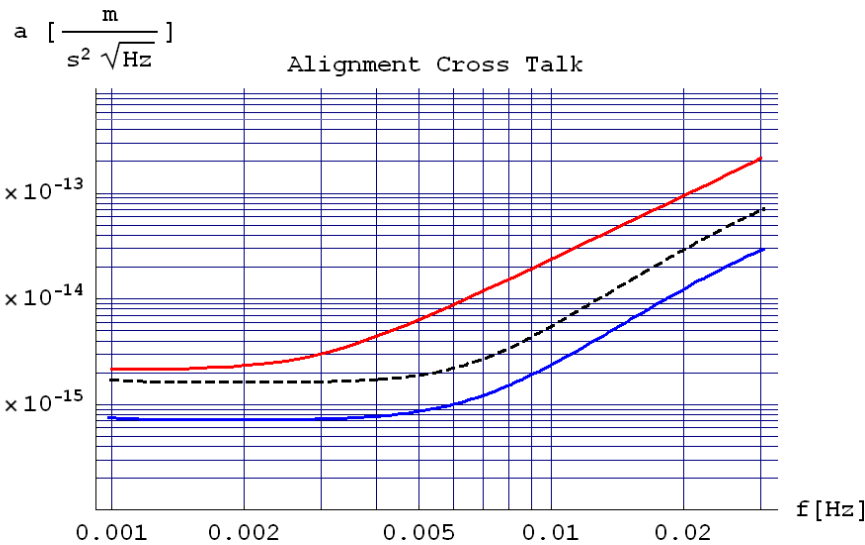
- Represents OB bonding procedure with „mechanical“ uncertainties
- Monte-Carlo simulations of bonding and IFA procedure, >4000 runs



- Additional use: verification of measurement model

# Budget: „Realistic Case“

- Alignments: values of each single MC-run
- Acceleration jitter: values from frequency analysis (new DF)
- RMS** over all performance results



## Summary & Conclusion

- Simple (but sufficient) optical metrology model
- Method for requirement breakdown into alignment and DF design
- $6\text{pm}/\sqrt{\text{Hz}}$  requirement met
  - For “realistic” optical bench setups with margin
- In progress:
  - Model cross-check: simple model vs. OptoCad model