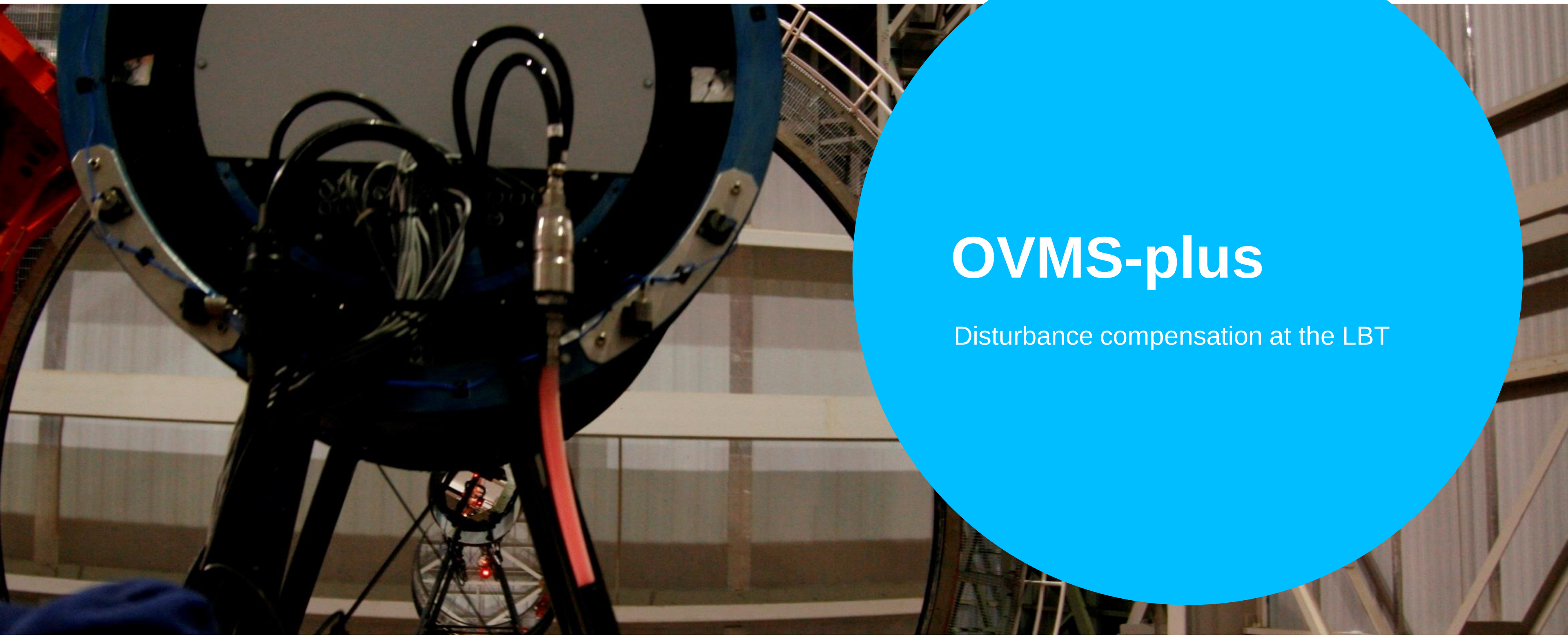
University of Stuttgart
Institute for System Dynamics



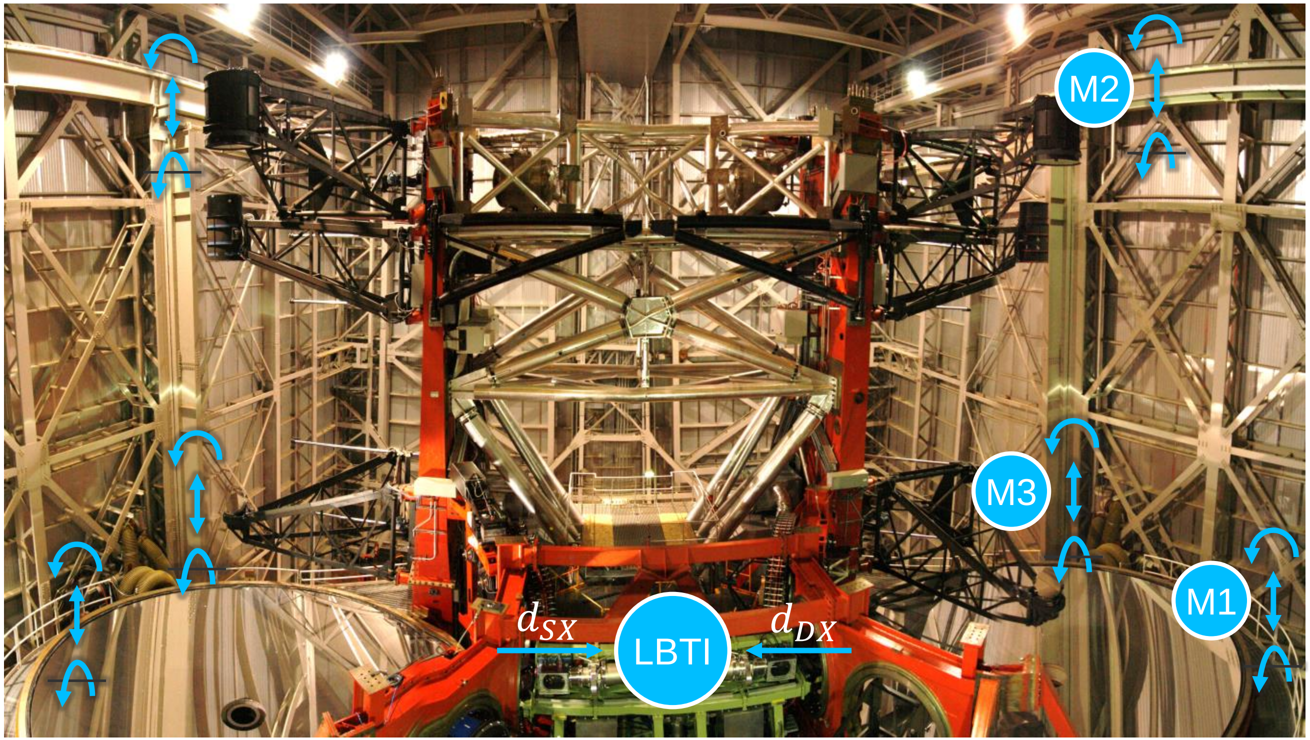
OVMS-plus

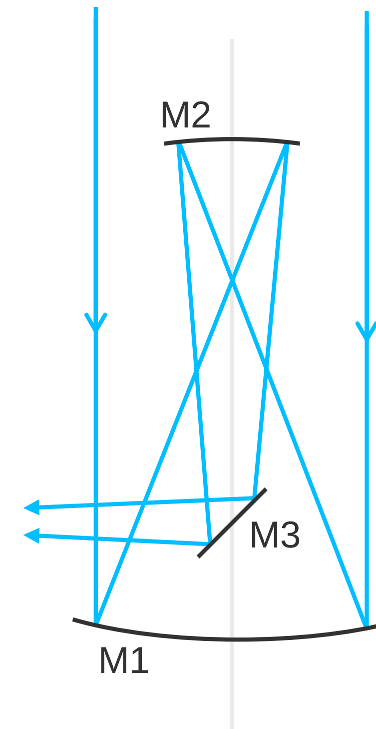
Disturbance compensation at the LBT

LARGE BINOCULAR TELESCOPE

Problem description

Optical setup at the Large Binocular Telescope (LBT)



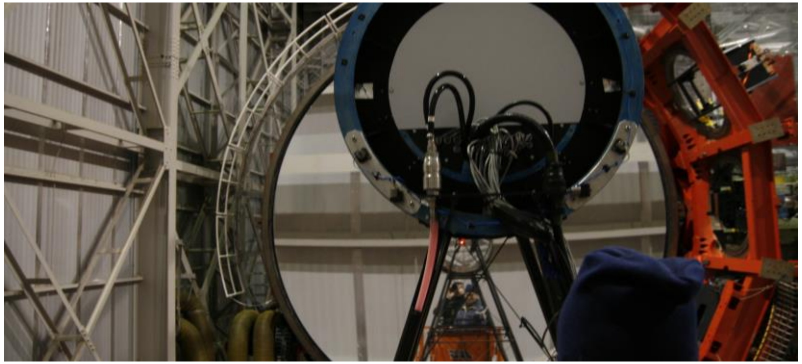


Goal: $d_{SX} - d_{DX} = 0$

Problem description

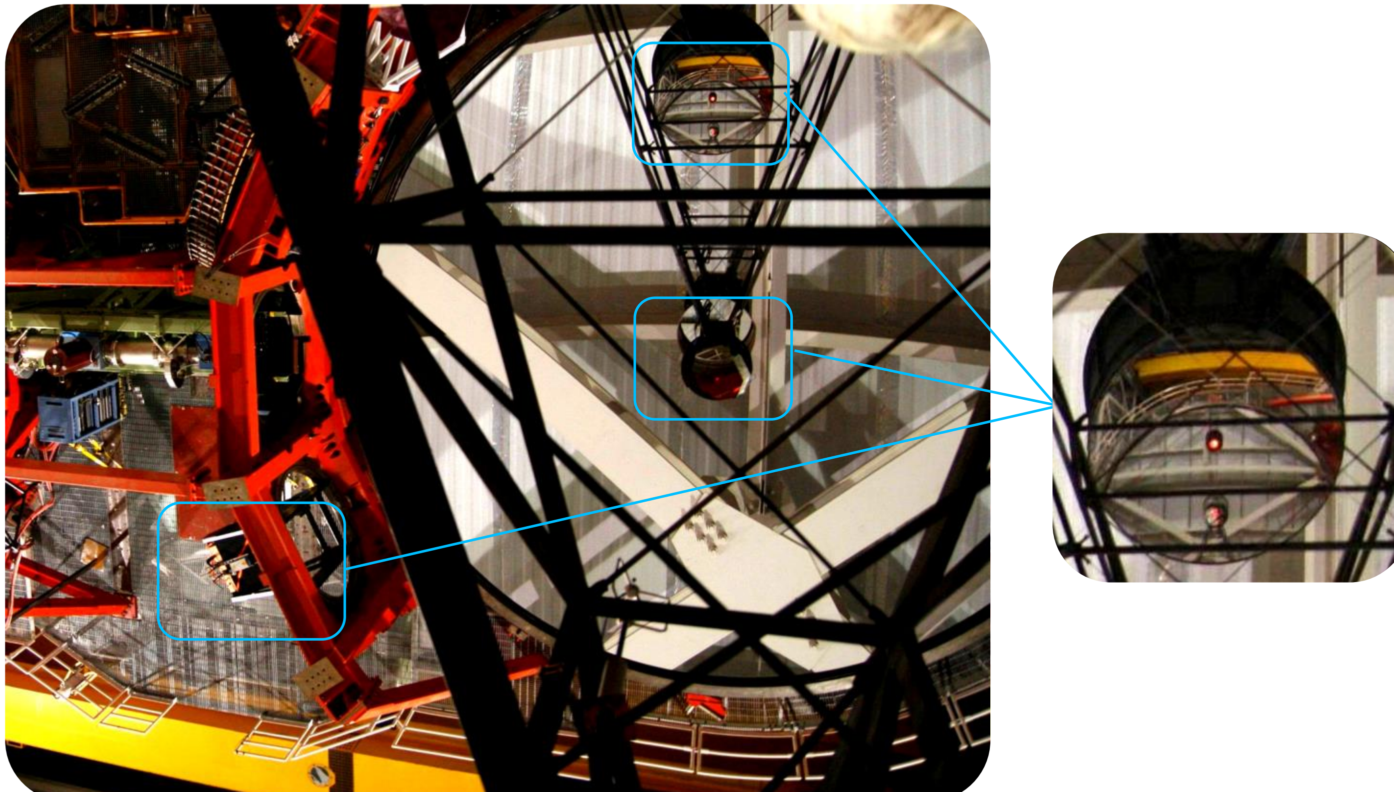
Initial OVMS setup

- Measurement of vibrations with accelerometers
- Task:
  - Reconstruction of mirror motion
  - Distribution to LBT instruments
- Assumptions:
  - Mirrors are rigid bodies
  - No dynamic coupling between low order aberrations



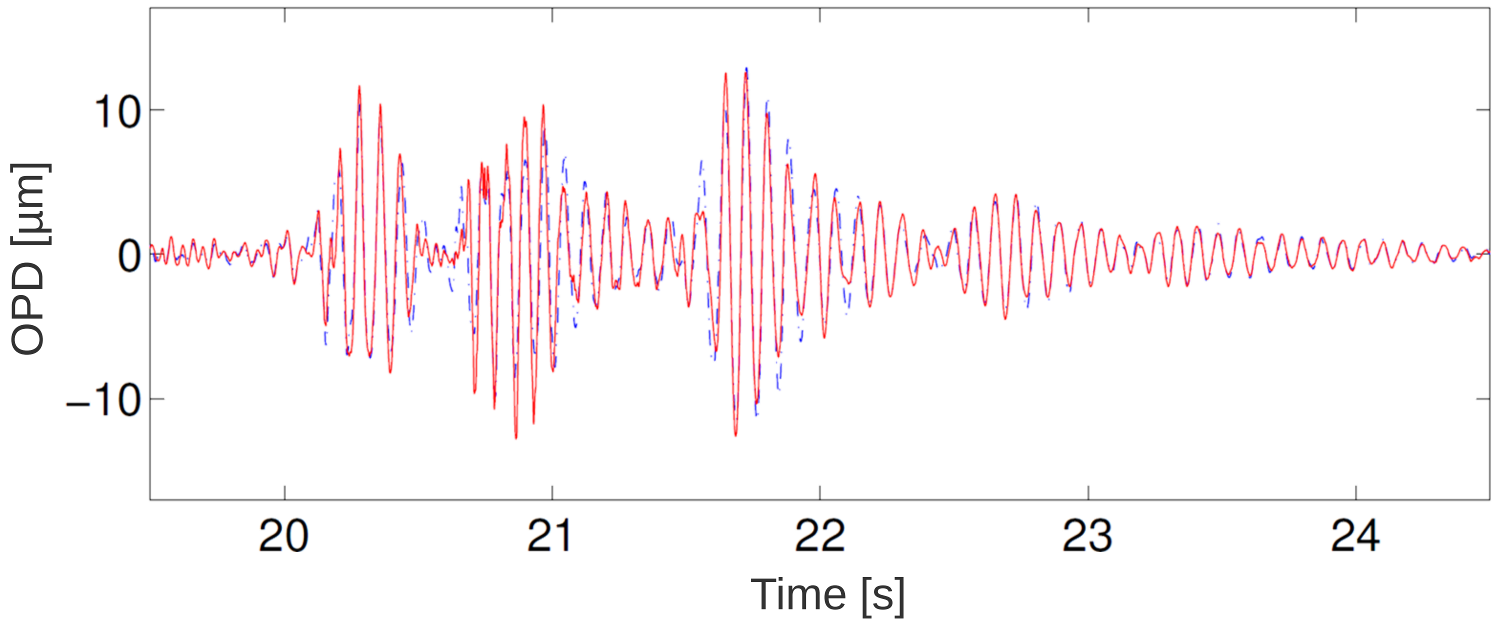
Measurement Campaign

Is it feasible?



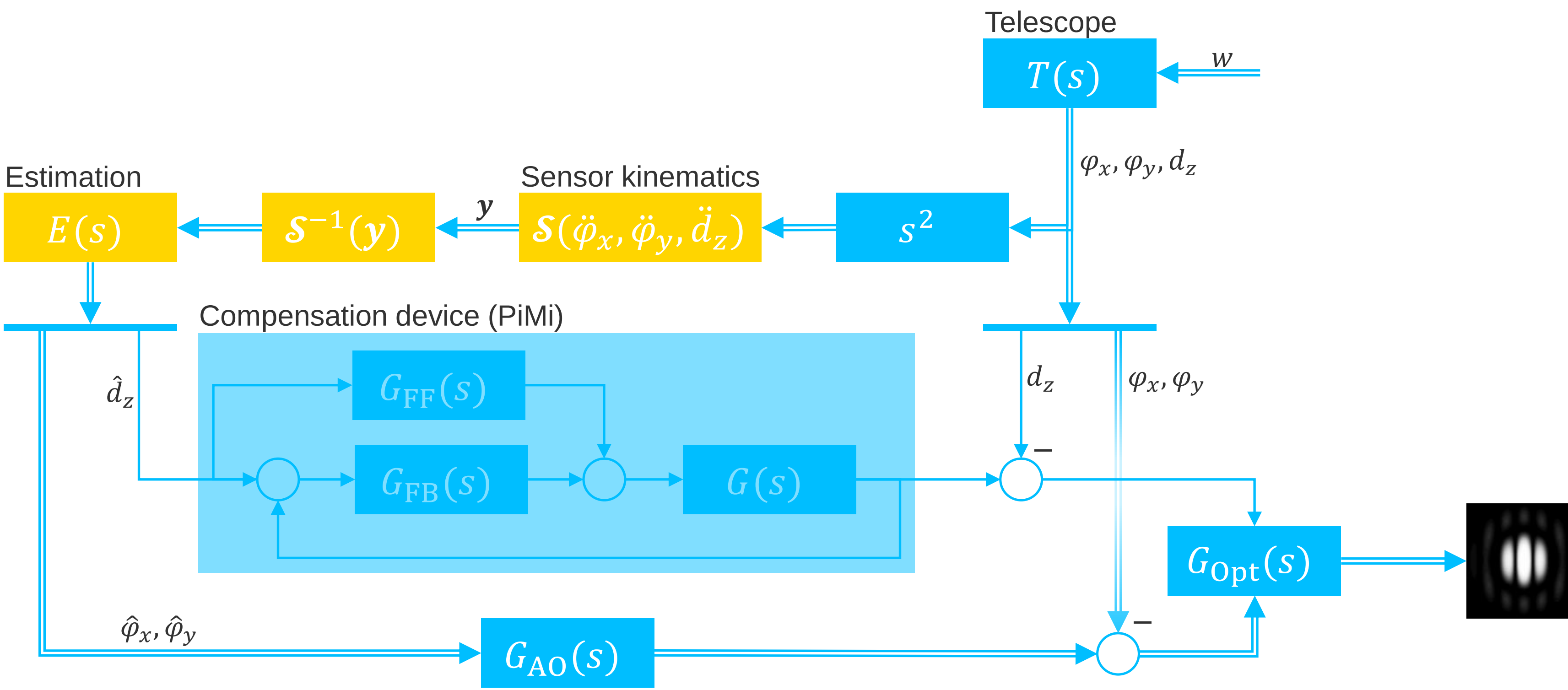
Measurement Campaign

It is feasible!



Problem description

Disturbance compensation overview

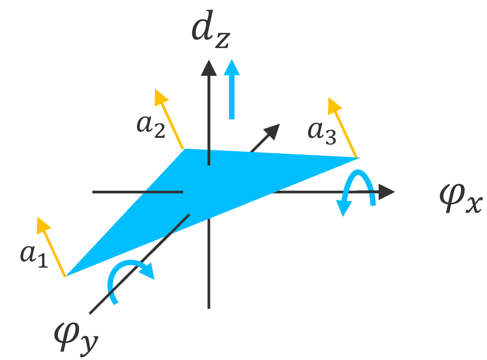


Sensor kinematics

Sensor kinematics

Forward kinematics

- Calculate sensor values from rigid body motion
  - Mirror is a moving reference frame, transformation to fixed frame using $T_{K_0}^{K_1}(t)$
- Linearization around zero yields:



$$a_{k,m}(t) = u_{k,m}^{\top} \begin{pmatrix} 0 & -\ddot{\varphi}_{z,m} & \ddot{\varphi}_{y,m} & \ddot{d}_{x,m} \\ \ddot{\varphi}_{z,m} & 0 & -\ddot{\varphi}_{x,m} & \ddot{d}_{y,m} \\ -\ddot{\varphi}_{y,m} & \ddot{\varphi}_{x,m} & 0 & \ddot{d}_{z,m} \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_{k,m} \\ y_{k,m} \\ z_{k,m} \\ 1 \end{pmatrix}$$

$$= u_{k,m}^{\top} \begin{pmatrix} 0 & z_{k,m} & -y_{k,m} & 1 & 0 & 0 \\ -z_{k,m} & 0 & x_{k,m} & 0 & 1 & 0 \\ y_{k,m} & -x_{k,m} & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \ddot{\eta}_m \quad \Rightarrow \quad \boldsymbol{a}_m(t) = \mathcal{S}(\ddot{\boldsymbol{\eta}}_m, \boldsymbol{\theta}_m)$$

Sensor kinematics

Inverse kinematics

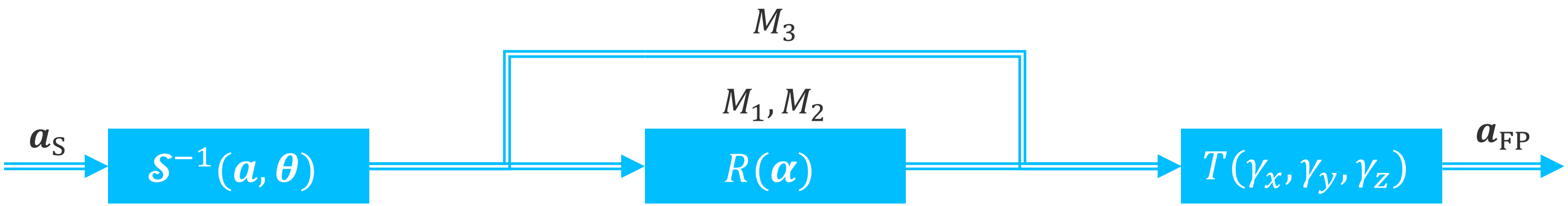
- Calculate rigid body motion from sensor values
  - Inversion of $\mathcal{S}(\ddot{\boldsymbol{\eta}}_m, \boldsymbol{\theta}_m)$
  - Overdetermined for more than sensors than degrees of freedom
  - Use of pseudo inverse yields:

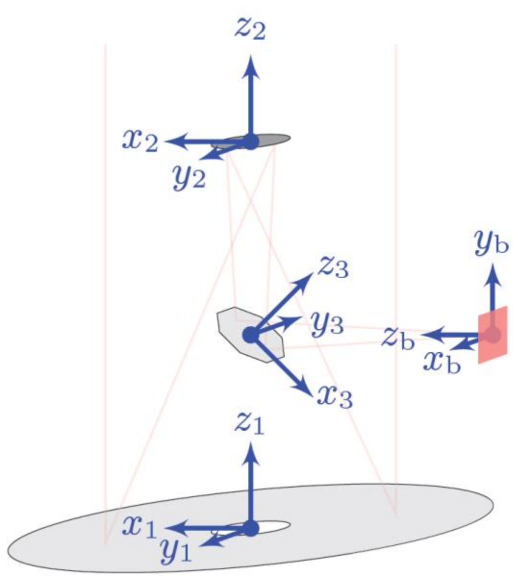
$$\ddot{\boldsymbol{\eta}}_m(t) = \mathcal{S}^{-1}(\boldsymbol{a}_m, \boldsymbol{\theta}_m)$$

- LBT:
  - 3 out-of-plane sensors → 3 out-of-plane degrees of freedom ✓
  - 2 in-plane sensors → 3 in-plane degrees of freedom ✗

Sensor kinematics

Concluding block diagram





	α
LUCI	25.9°
LBTI	0°
LINC	18.5°

	LUCI/LBTI	LINC
$\gamma_{1,x}$	1175	1198
$\gamma_{1,y}$	−1175	−1198
$\gamma_{1,z}$	−2	−2
$\gamma_{2,x}$	130	133
$\gamma_{2,y}$	−130	−133
$\gamma_{2,z}$	2	2
$\gamma_{3,x}$	37	38
$\gamma_{3,y}$	−52	−54
$\gamma_{3,z}$	$-\sqrt{2}$	$-\sqrt{2}$

Position estimation

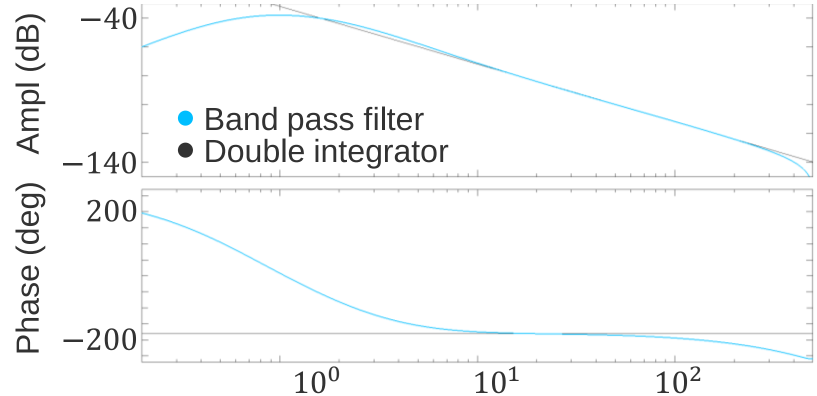
Position estimation

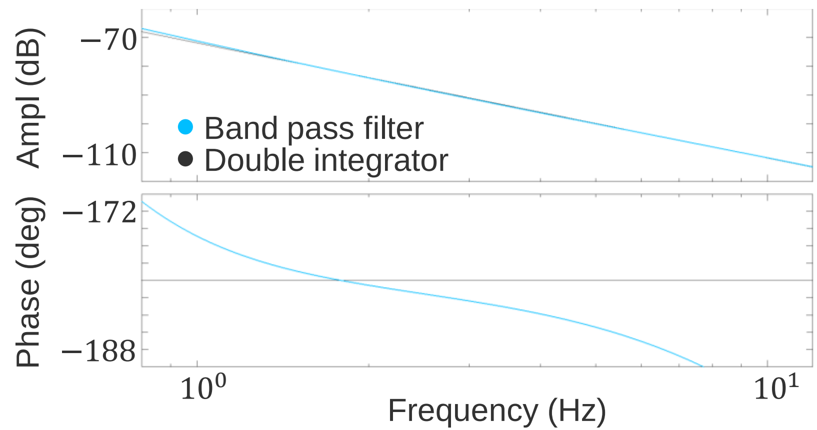
Broad band filtering

- Filter with broad pass band aiming at a perfect double integration from 10 – 60 Hz
- State space equations:

$$\dot{\xi}(t) = A\xi(t) + By(t)$$
$$x(t) = C\xi(t)$$

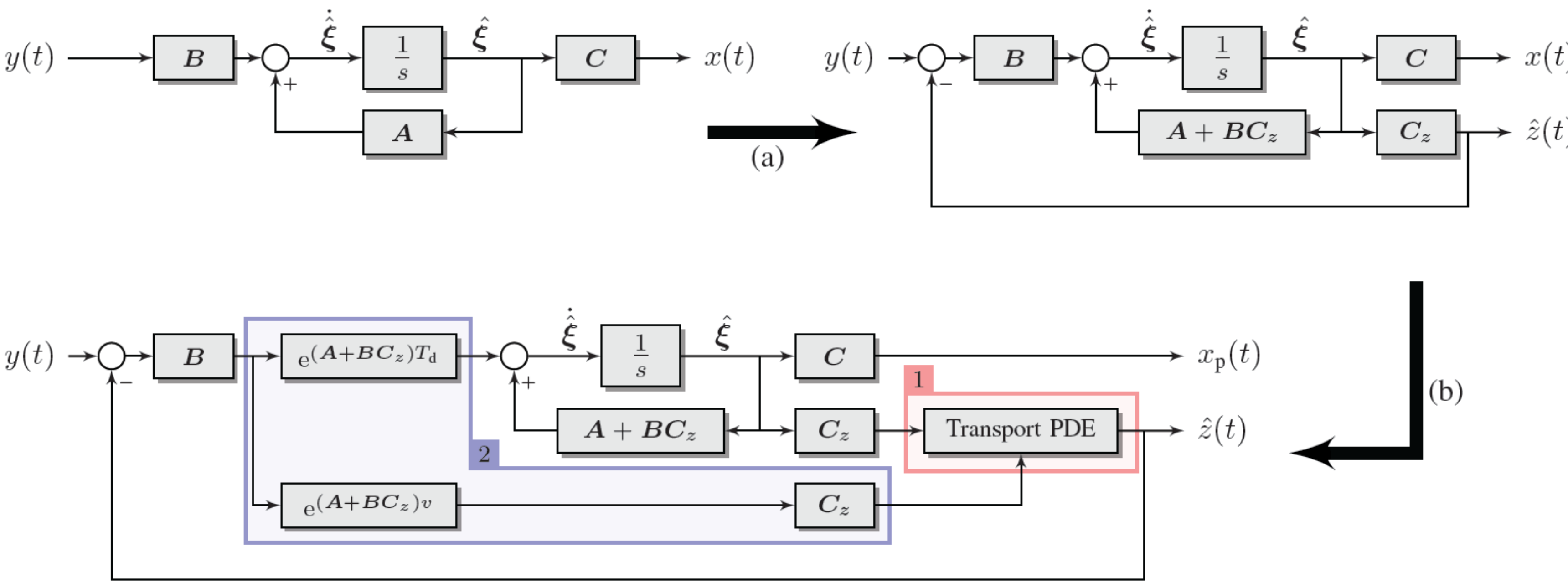
$$A = \begin{pmatrix} -p_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ z_2 - p_2 & -p_1 & 0 & 0 & 0 & 0 & 0 \\ z_2 - p_2 & z_1 - p_1 & -\omega_H & 0 & 0 & 0 & 0 \\ z_2 - p_2 & z_1 - p_1 & -\omega_H & \omega_L & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -\omega_H & 0 & 0 \\ 0 & 0 & 0 & 1 & -\omega_H & -\omega_L & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -\omega_H \end{pmatrix}$$
$$B = (1 \quad 1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0)^T$$
$$C = (0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad -\omega_H)$$





Position estimation

Delay compensation



(a) Transformation to Luenberger observer

(b) Extension for delay compensation

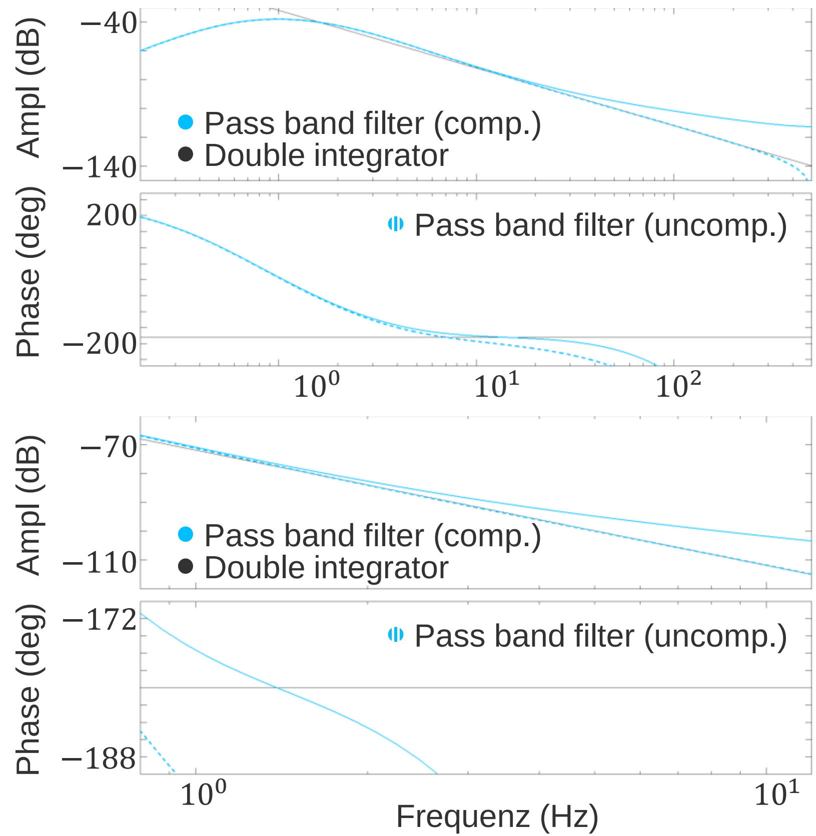
Position estimation

Delay compensation

- Transfer function:

$$X_p(s) = \frac{C(sI - A - BC_z)^{-1} e^{(A+BC_z)T_d} B}{1 + C_z(sI - A - BC_z)^{-1} B} Y_d(s)$$

- Example bode plot for $T_d = 5\,\text{ms}$



Implementation

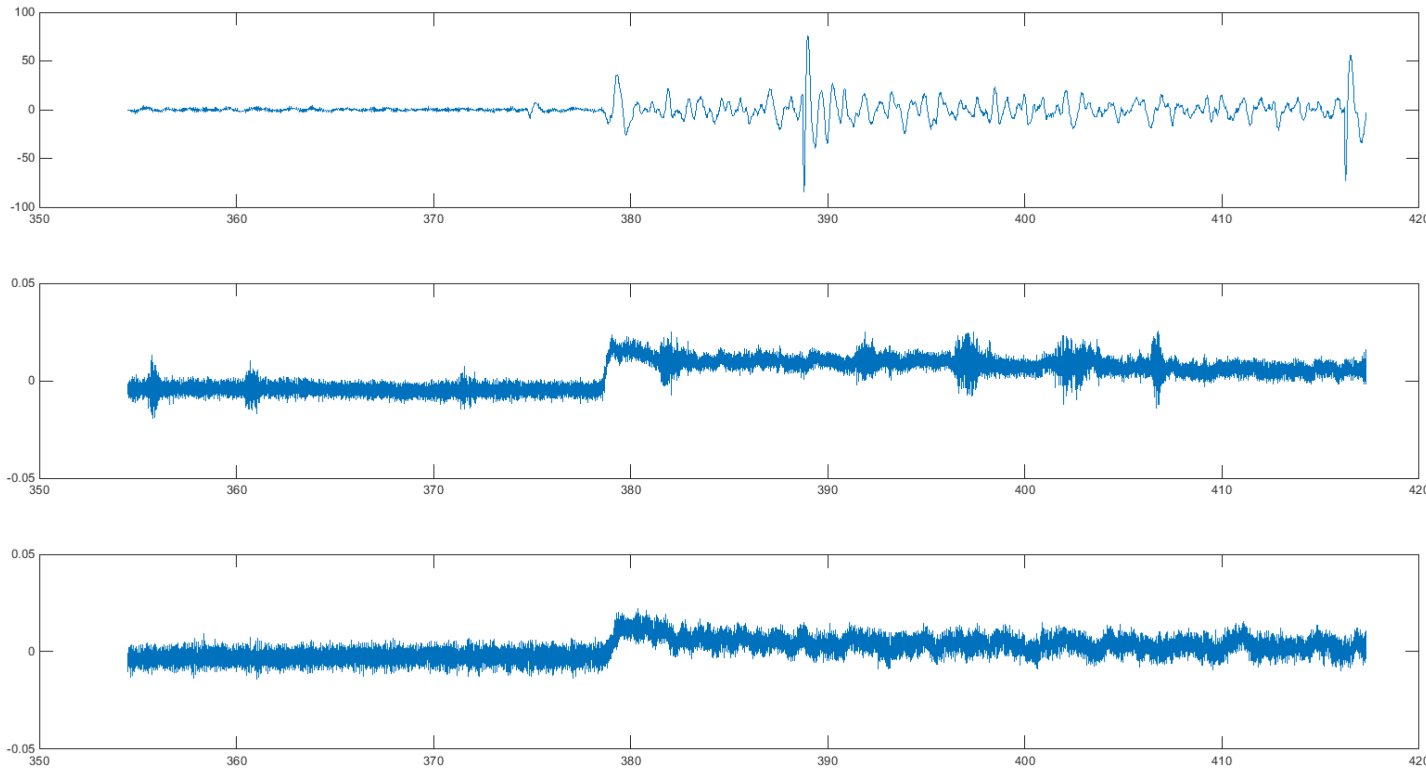
Implementation

Constraints

- Many users with different affinity to the overall system
  - LBTO operational and technical staff
  - Instrument scientists and astronomers
- Change of the observing instrument
  - Modification of frame of reference
- Detect failure of components and minimize loss of functionality
- Delay depends partly on the observing instrument
- Sensor parameters might change

Implementation

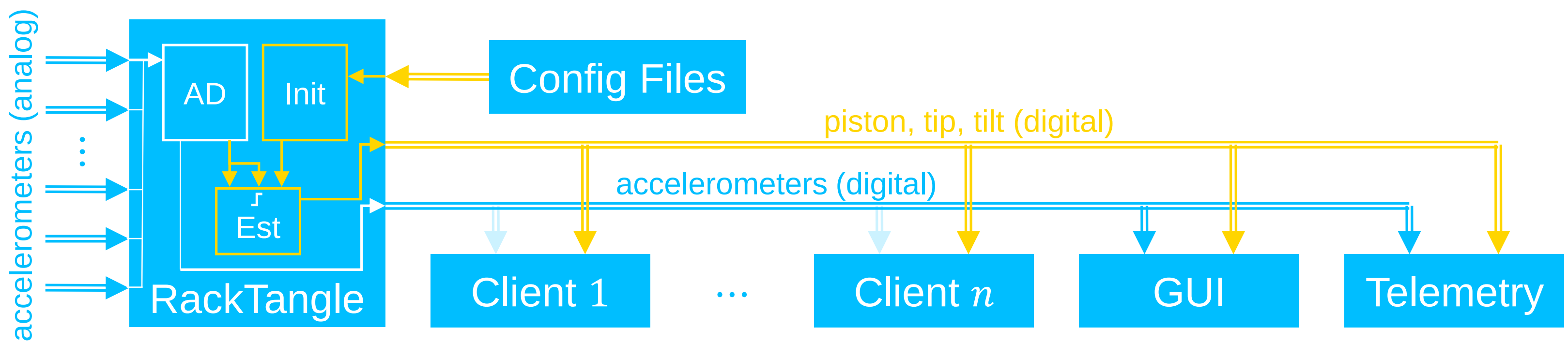
Process



Implementation

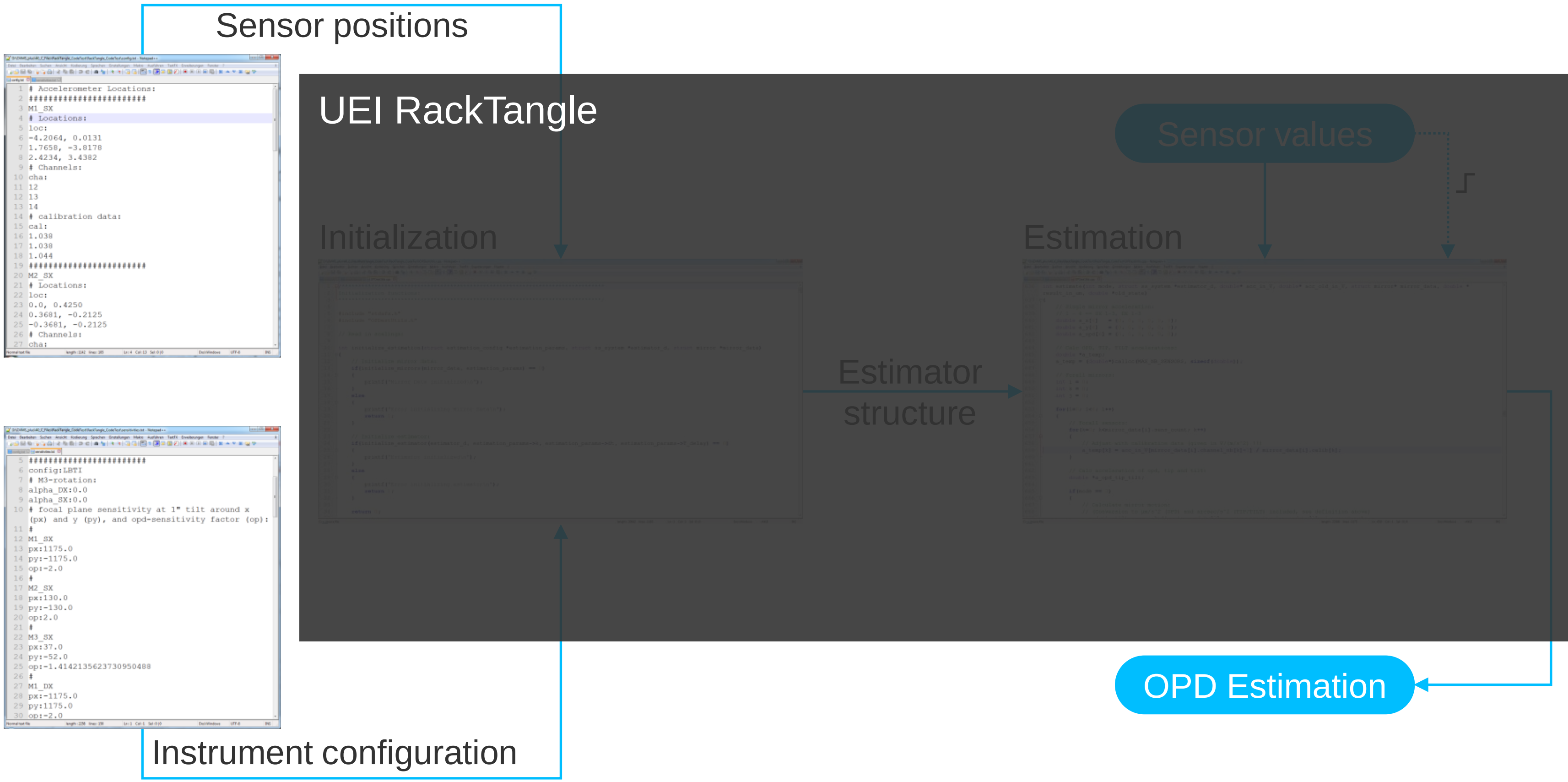
Idea of OVMS-plus

- OVMS
  - Distribution of sensor values via UDP-Multicast
  - Calculations are left to the instrument
- OVMS-plus
  - Calculations are centralized on the RackTangle
  - Distribution of sensor values and piston, tip, tilt via UDP-Multicast



Implementation

Software architecture

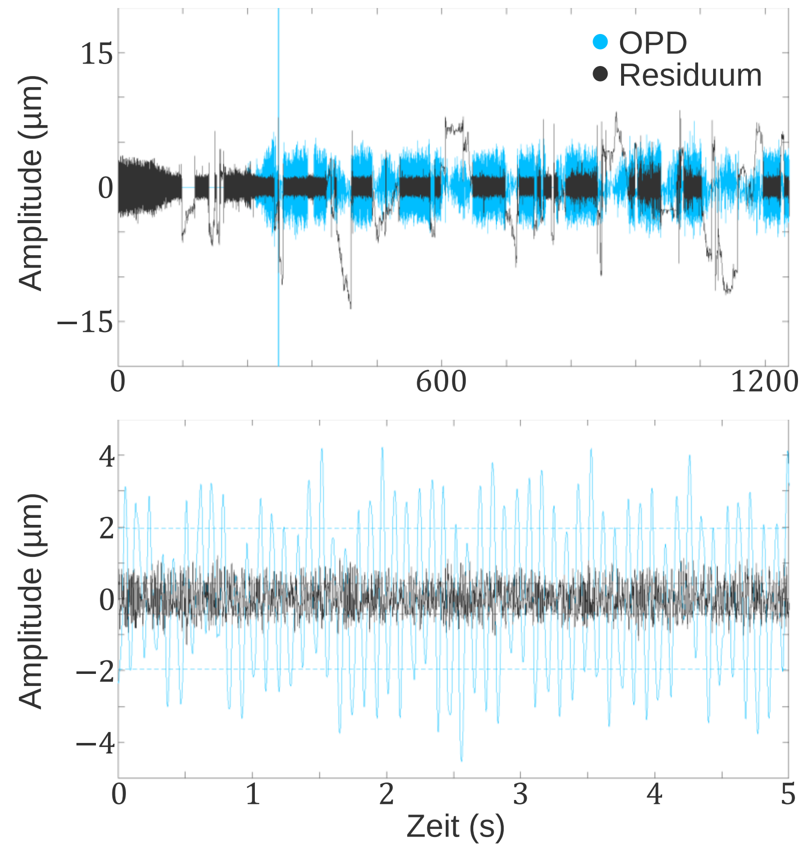


Results

Results

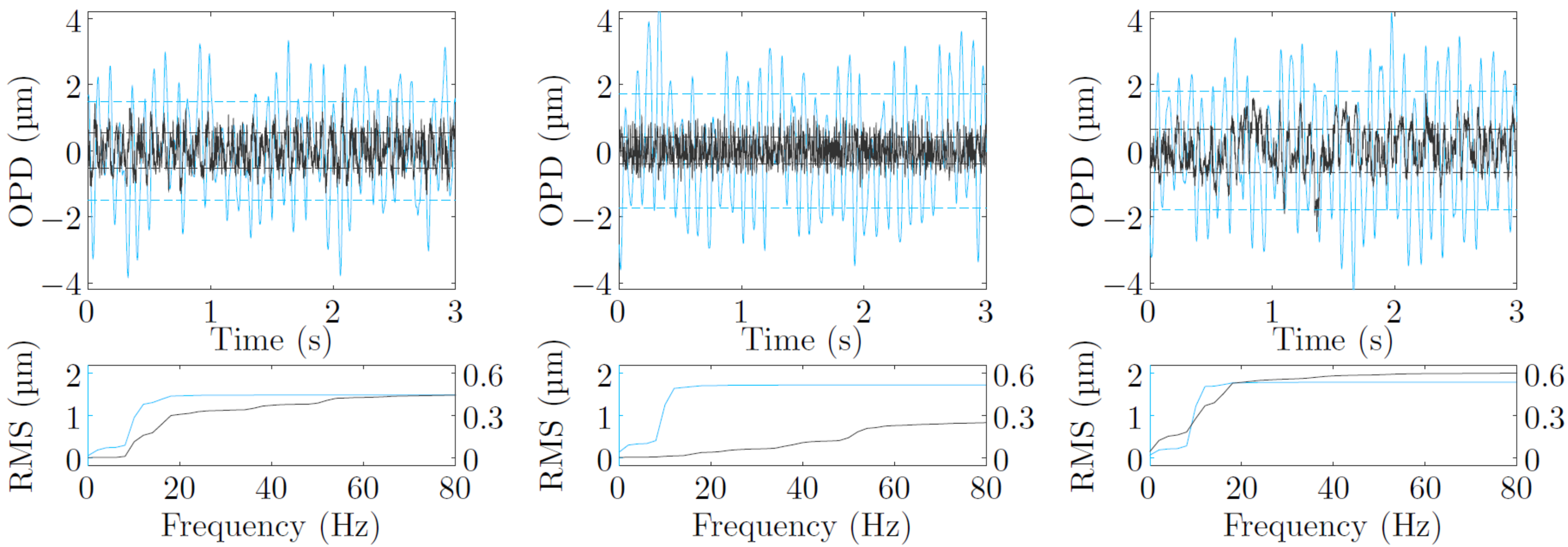
Measurements using LBTI (1/2)

- OPD reduction from $1.9545\,\mu\text{m}$ (RMS) to $0.4213\,\mu\text{m}$ (RMS) ($-\mathbf{78.5}\%$)
- Problems with malfunctional sensor channel (fixed now)
- LBTI Phasecam feedback gain reduced by a factor of 3
  - Permits longer integration times



Results

Measurements using LBTI (2/2)



(a) OVMS$^+$ OFF, $K_i = 300$ (b) OVMS$^+$ ON, $K_i = 300$ (c) OVMS$^+$ ON, $K_i = 30$

Conclusion

Conclusion

- Estimation of mirror motion possible using a broad band filter
- Delay compensation up to 15ms using backstepping for PDEs
- Successful implementation at the LBT (called OVMS-plus)
  - Flexible change of parameters using config-files
  - Variable output-modes allow for flexible use
  - Delay can be individually set at service start-up
- Routine use by LBTO engineers and staff and LBTI instrument scientists and astronomers
- Proved very valuable for LBTI (and potentially for LINC-NIRVANA)

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Thank you!

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