Vibration control and black holes

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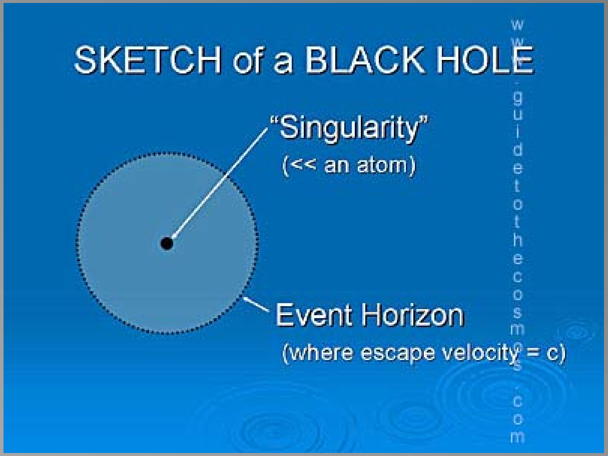
Jörg-Uwe Pott, Michael Böhm
Max-Planck Institute for Astronomy (MPIA), Heidelberg
Institut für Systemdynamik, Univ. Stuttgart

content

- Why and how we observe black holes in astronomy
- Limits of current high angular resolution instruments
- Vibration projects
  - LINC-NIRVANA
  - OVMS
  - MICADO
- Outlook & Summary

Black holes

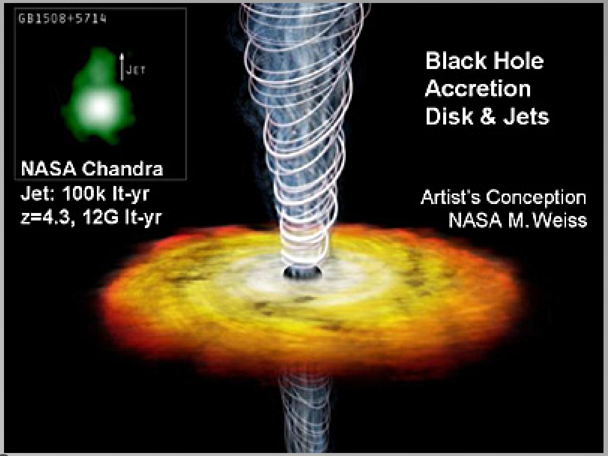


- What is a black hole?
  - A singularity in Einstein's theory of gravity
  - *no-hair* theorem: BHs only have three fundamental properties: mass, electric charge and spin
  - Possible a unique laboratory for the Grand Unified Theory of everything (microscopic quantum and macroscopic normal world)
  - Understanding black holes is basic physics

- Do they really exist?
  - Do not radiate like stars
  - Have an enourmous gravitational energy
    - 3 Million suns within 1 AU (distance sun - earth)
  - > Leaves traces in the environments

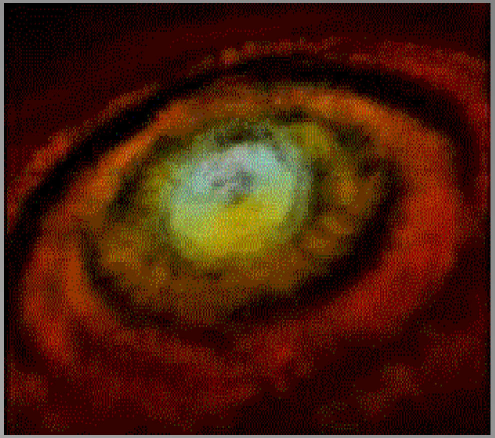
Black hole physics

- Stellar mass black holes
  - Dead massive star (Supernovae remnant)
  - Big brother to the Neutron star
  - 5 to few 10 M_sol
  - Most massive ones may have originated in gamma ray bursts

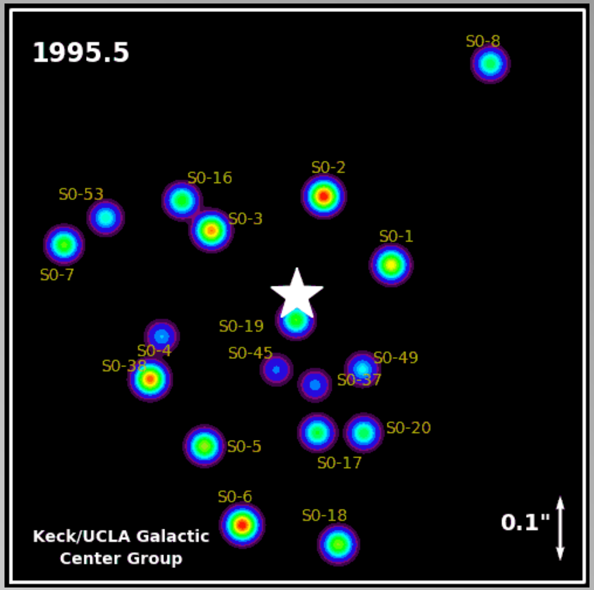


- Supermassive black holes
  - Generate luminous quasars
  - Lurk in the center of galaxies
  - Unknown origin
    - Cosmic growth from stellar mass BH?
    - Primordial blackholes are extremely hard to form
- Intermediate mass black holes the missing link?
  - At the core of globuler clusters in every galaxy?
  - Contribute to the dark matter halo?

Black hole observations



- Thermal radiation and jets from the accretion disk
- Stellar kinematics
- Tidal disruptions
- Newest way: merging black hole binaries as strongest source of gravitational waves



Observing technology

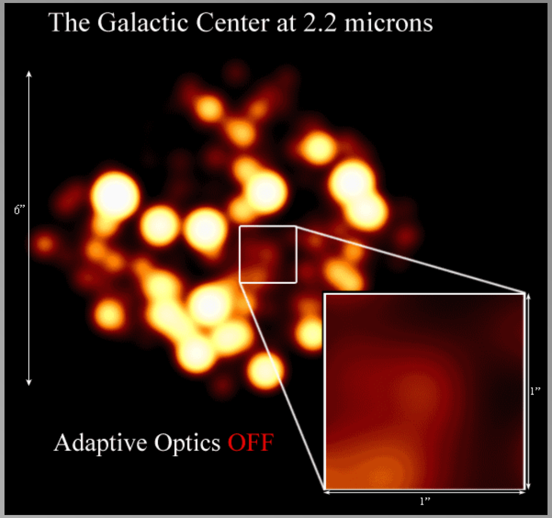
- Jets and non-thermal quasars discovery:
  - radio telescopes
- Stellar kinematics and thermal accretion
  - Optical / infrared telescopes on ground and in space
- Hot corona / plasma
  - X-ray satelittes
- Gravitation waves
  - Dedicated facilityes (LIGO, GEO600)

Ground based large telescope

- Space telescopes
  - Offer good sensitivity and access to photons absorbed by atmosphere (like X-ray / UV)
  - Have limited primary mirror size
    - Small angular resolution: 1.2 lam/D
- Ground-based telescopes
  - Offer complex and up-to-date instruments
  - Resolution suffers from atmospheric turbulence (seeing)

Best angular resolution from the ground

- Two solutions
  - Adaptive optics helps to overcome seeing
  - Segmented mirrors, light-weight telescope construction, and Interferometry helps to overcome single telescope size limit
- Challenge
  - Need to control a 10meter-scale facility to a fraction of the observing wavelength, if we want to reach the fundamental, physical limit (diffraction limit)
  - 10^-8 dynamic range in precision for near-infrared observations (1..2.5micron, just beyond the red light)
  - Three level approach
    - Mechanical construction to the 100um level
    - Active control of the optics to reach diffraction limit
    - Adaptive optics to dynamically control seeing and vibrations (!)



[UCLA web]

Vibrations at telescopes and instruments

- Main structure is exposed to the weather, i.e. wind
- Cooling systems, vacuum pumps and fans
- Self-induced by large, fast moving adaptive optics actuators (e.g. a deformable mirror (DM))

Vibrations at telescopes and instruments

- Relevant vibrations typically have
  - Amplitudes of 100nm up to few micron
    - Lower limit is given by lam/10
    - AO is still too slow and simple for visible wavelengths
  - Frequencies of 10-100 Hz
    - Faster frequencies do not occur at relevant amplitudes due to sufficiently large / stiff structures

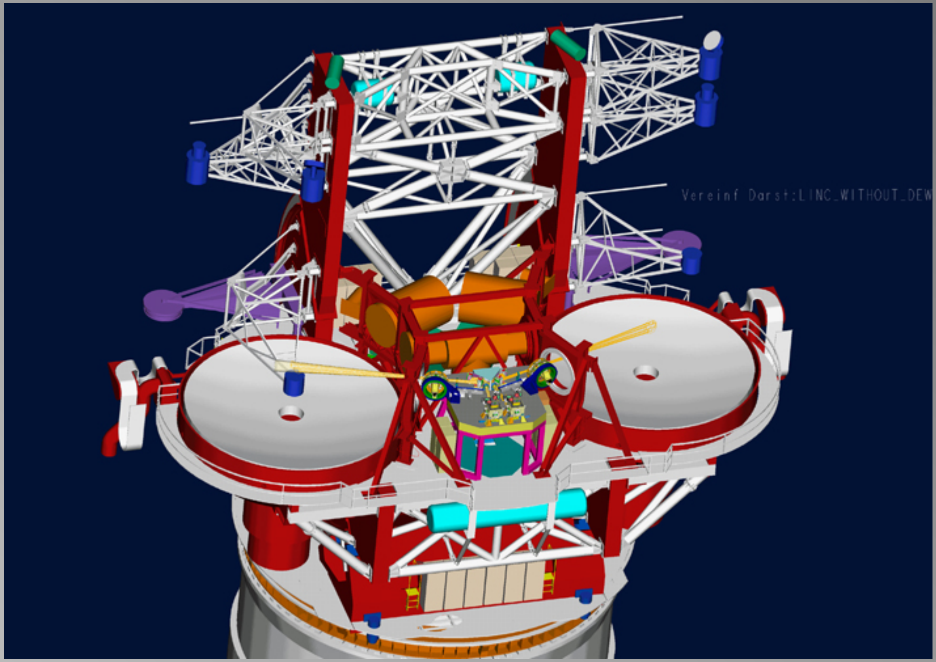
- Limits the vibration-free exposure times to a few 1..10 ms; impact depends on the science wavelengths
  - Require relatively bright stars to be tracked

Vibrations at telescopes and instruments

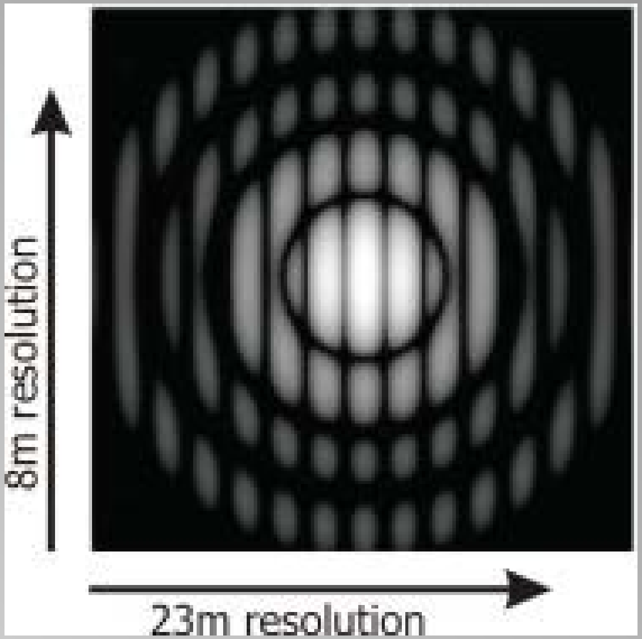
- Typical tools are
  - Piezo actuators (sufficiently fast and precise)
  - Laser metrology
  - Accelerometers

- ISYS comes in for optimal dynamic use of these tools to offer real time control / correction of vibrations in the optical path

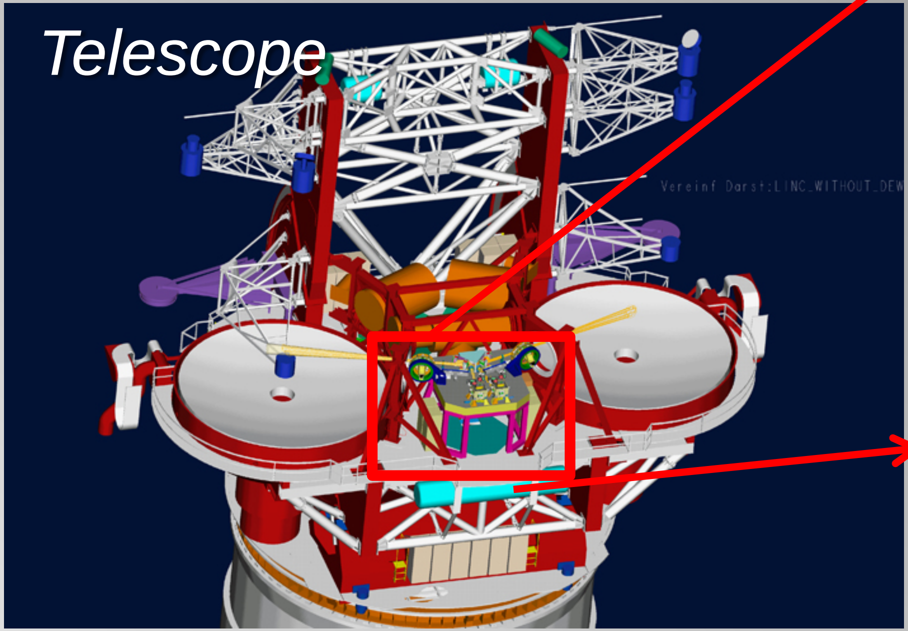
Linc-Nirvana

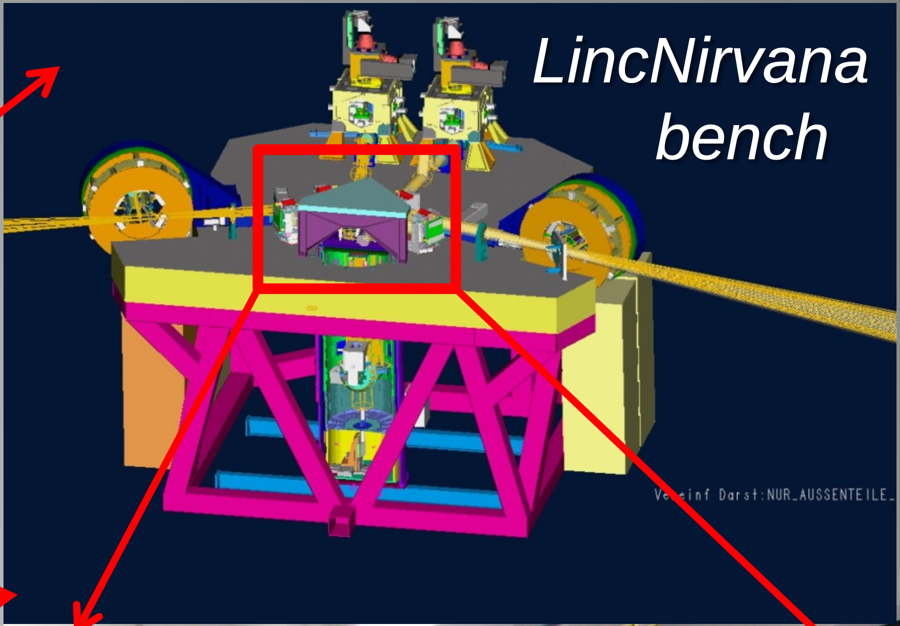


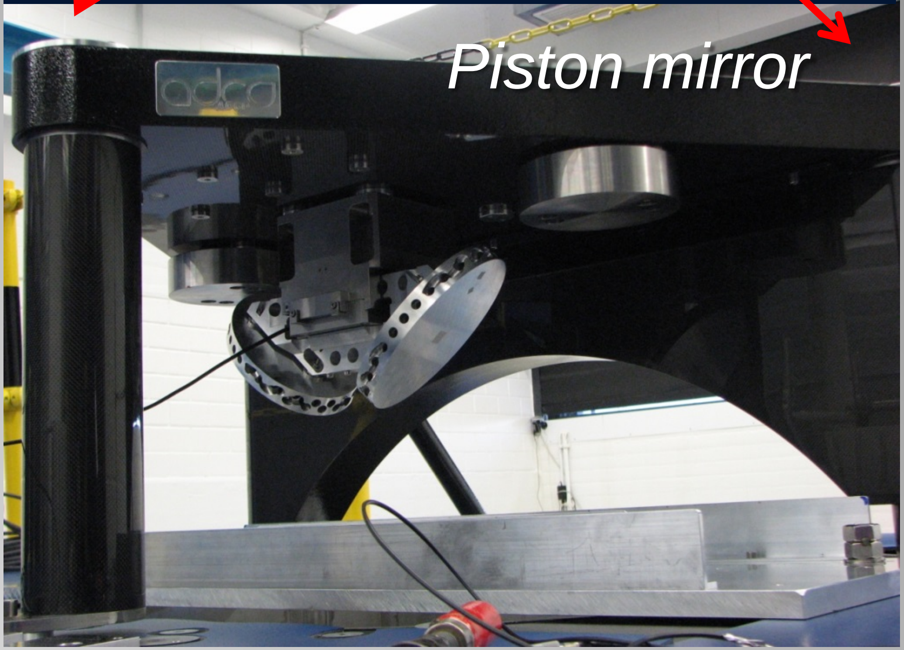
- Imaging interferometer
- broad / narrow band images in J/H/K at 10 mas resolution (like an E-ELT)
- Optical path difference (OPD) control to *stabilize* the PSF fringes



Piston mirror location



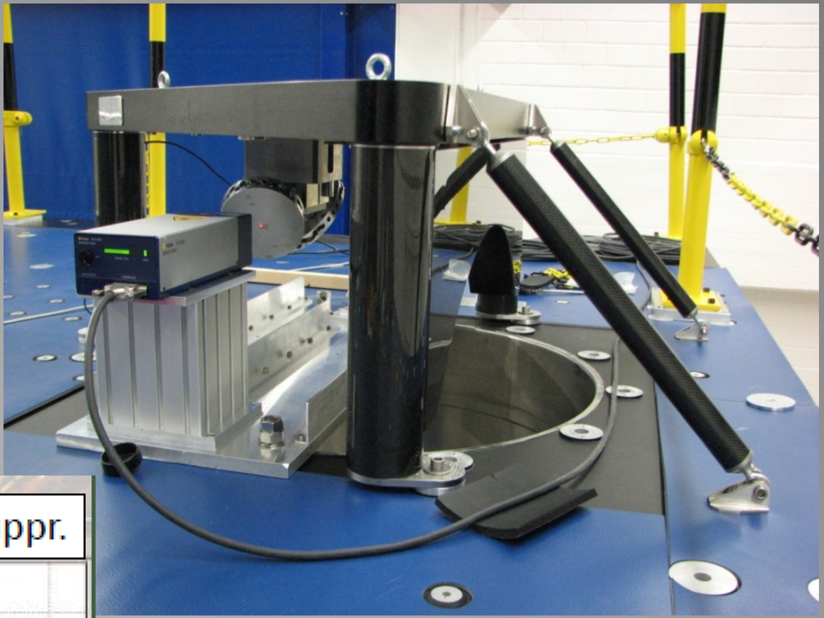


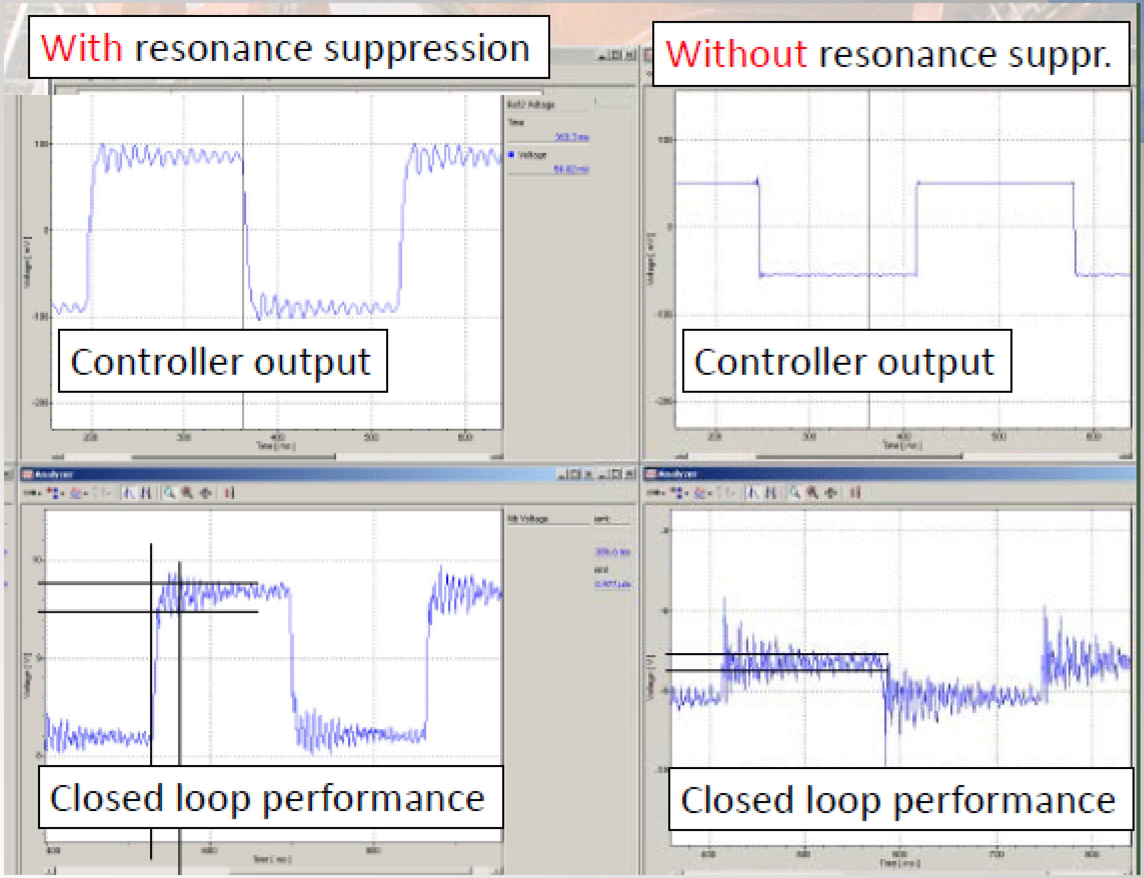


- Dimensions:
  - 200x145 mm surface, λ/10 PV
  - 3.2 kg Aluminium
  - light weight, but stiff construction
  - first resonance at ~ 250 Hz
  - 150 µm OPD stroke at constant beam separation

Piston mirror control

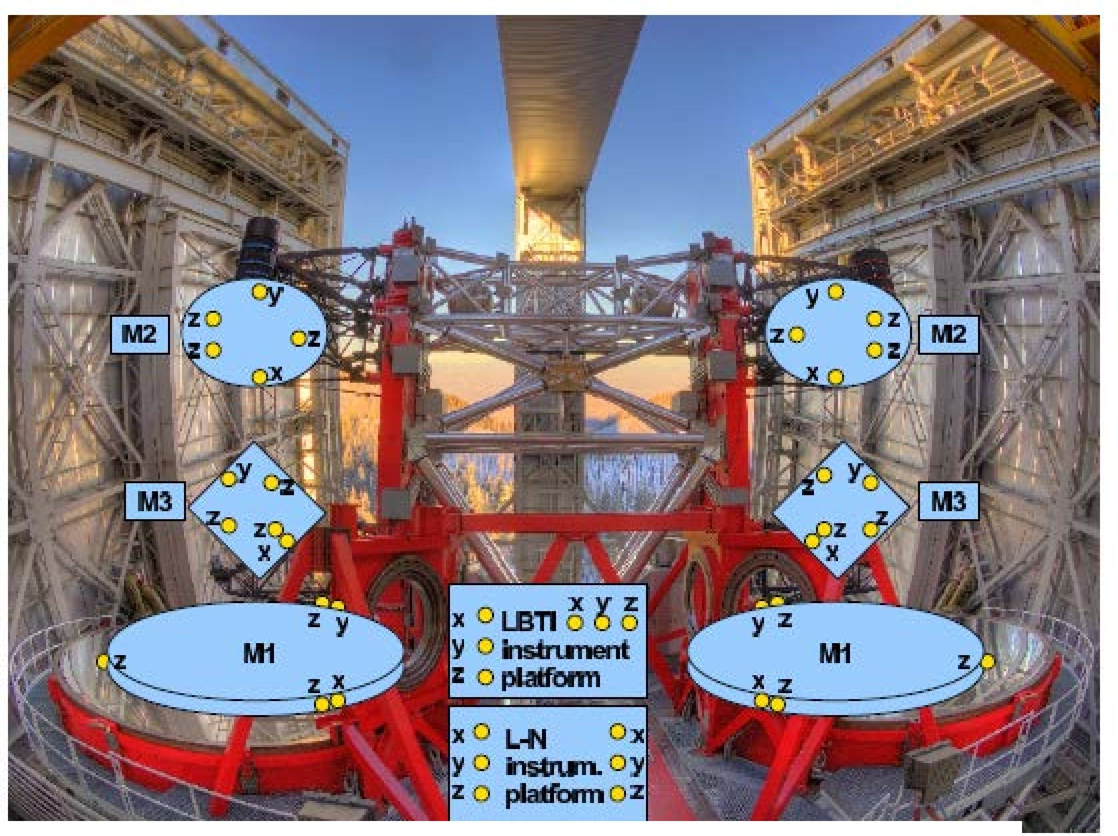
(work by Th. Ruppel, M. Böhm)

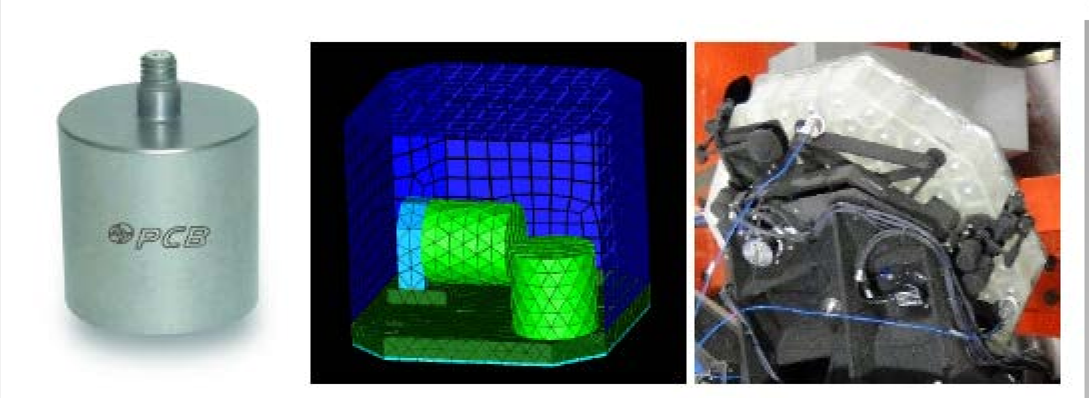




OVMS - the optical path difference vibration monitoring system for LBT

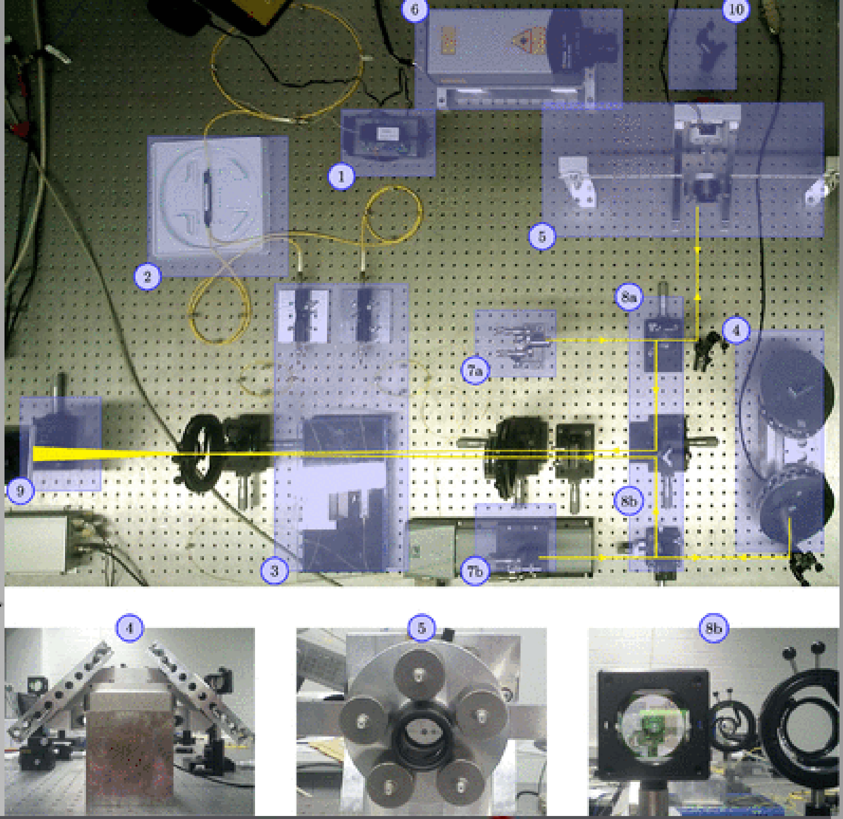
- MPIA-LBTO-UofA collaboration
- 30 sensor and low noise cable / electronics
- Dedicated computer interface development
- Prepare to help the fringe tracking cameras
- Study vibration modes of mirror mounts





Use of OVMS (work by M. Böhm)

- Realistic lab-testing promises 5x reduction of phase noise, which is about 2.5 better than current telescope implementations
  - Important step forward since we talk about <=um scale vibration amplitudes
- Feedforward control will help to stabilize telescope for faint guide star operation
- First on-sky data taken in the last months
  - We are eagerly waiting to see the performance of the OPD estimator
- Versatile approach
  - Identify vibration modes
  - Feed actuators of AO and IF instruments



Boehm, et al. 2014

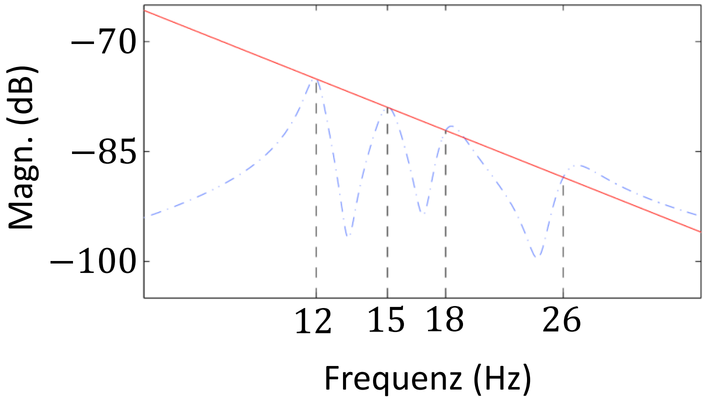
Positionsschätzung – modellbasiert (Kalman-Filter)

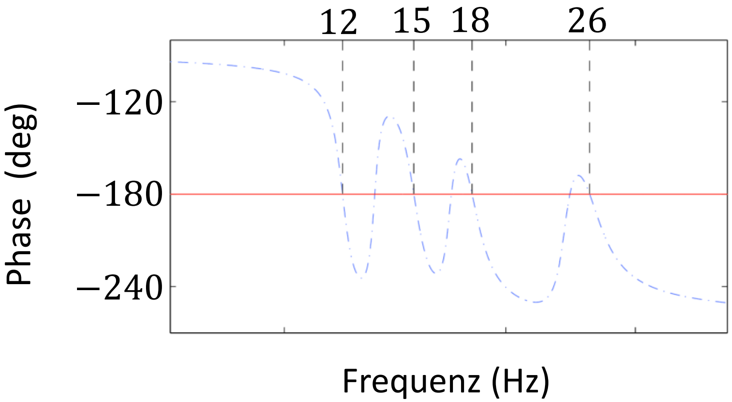
Vorteile

- Sehr gute Trennschärfe der einzelnen Moden
- Gute Rauschunterdrückung
- Einfache Berücksichtigung der Totzeit (modellbasierte Prädiktion)
- Zusätzliche Offset Schätzung als *Random-Walk* Prozess

Nachteile

- Viele Parameter (Modell, Rauschverhalten, …)
- Schlecht bei sehr dichten Moden
- Reduktion auf dominante Moden notwendig für Entwurf





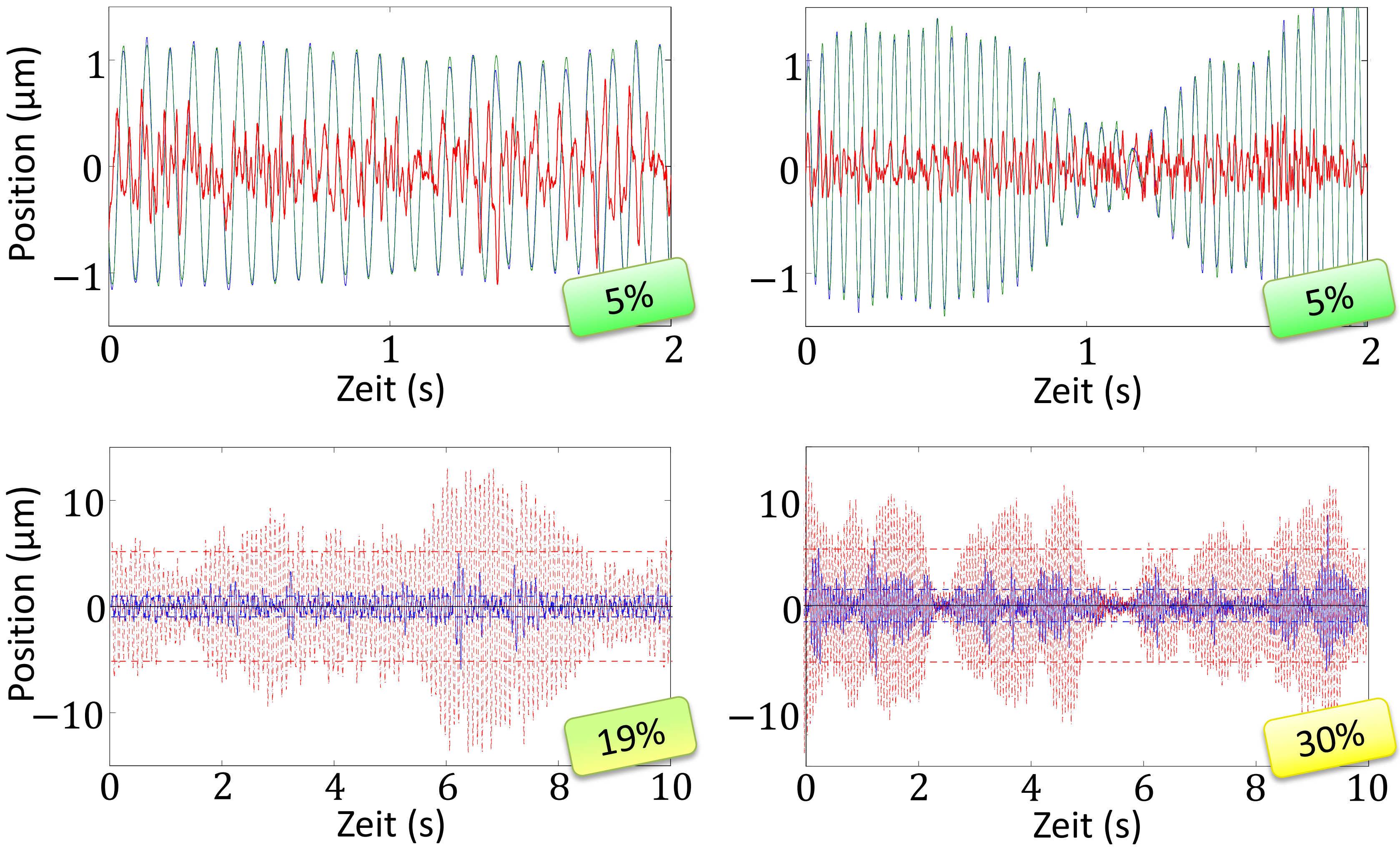
Positionsschätzung modellbasiert – Ergebnisse

$f_0 = 12\text{Hz}$

$f_0 = 19\text{Hz}$

Schätzung

Korrektur



Positionsschätzung – nicht-modellbasierter Filter

- Annäherung an Doppelintegrator für vorgegebenes Frequenzband
  - Unterdrückung von Niederfrequentem Drift
  - Unterdrückung von hochfrequentem Rauschen

- Hintereinanderschalten von Hoch- und Tiefpässen:

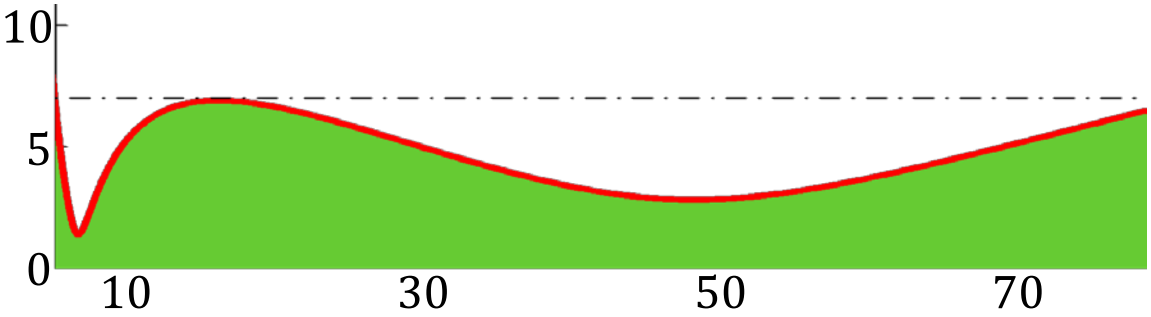
$$G_F = G_H G_L G_H G_L G_H G_{ll}$$

mit

$$G_H = -\frac{R_1 C_1 s}{R_2 C_1 s + 1}, \qquad G_L = -\frac{R_3}{R_3 R_4 C_2 s + R_4}, \qquad G_{ll} = \frac{s + 30\pi}{s + 4\pi} \frac{s + 150\pi}{s + 200\pi}$$

- Leed-Lag Element zur Modellierung der Phase am Anfang und Ende des Frequenzbereichs

$$\sqrt{(1 - M \cos\Delta\varphi)^2 + (M \sin\Delta\varphi)^2}$$



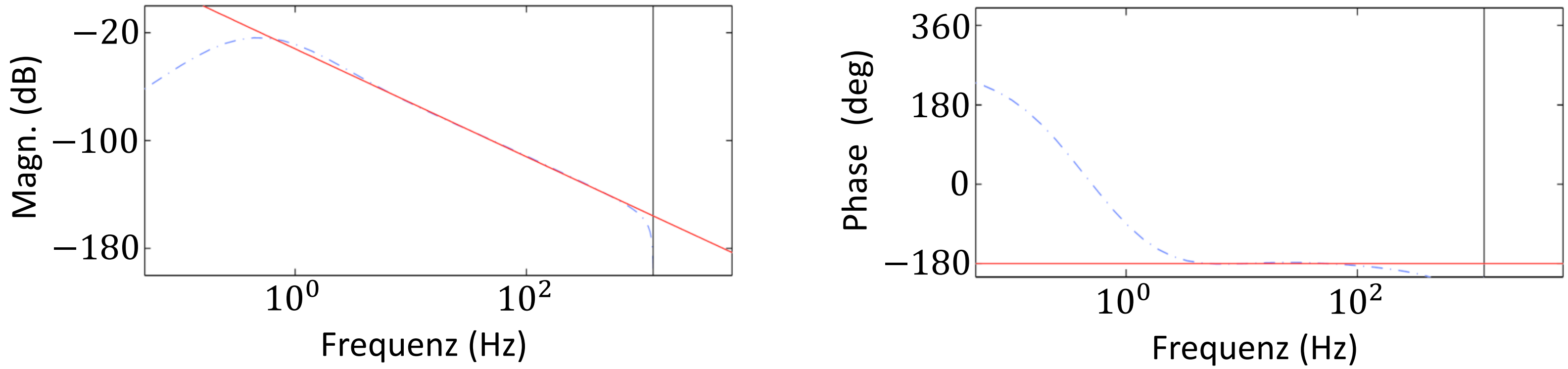
Positionsschätzung – nicht-modellbasierter Filter

Vorteile

- Kaum parametersensitiv
- Breitbandige Approximation des Doppelintegrators
- Damit besonders geeignet zur Beobachtung dichter Moden

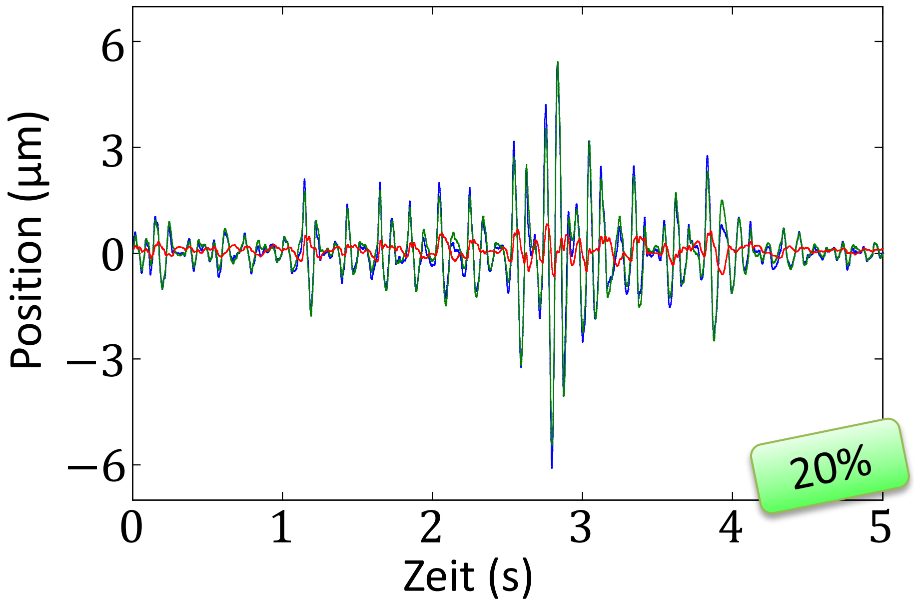
Nachteile

- Geringere Rauschunterdrückung (relevant bei großem Sensorrauschen)
- Keine einfache Totzeitkompensation
- niederfrequenter Drift verbleibt

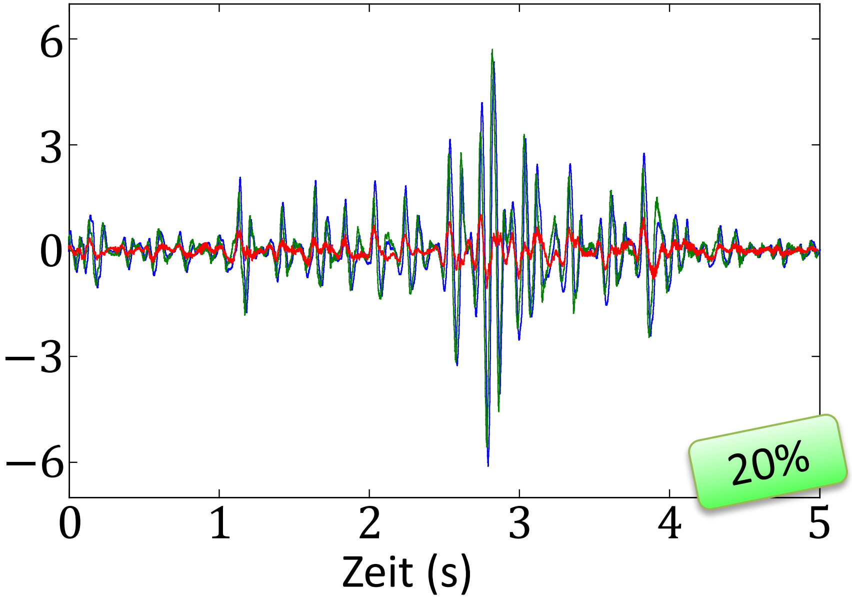


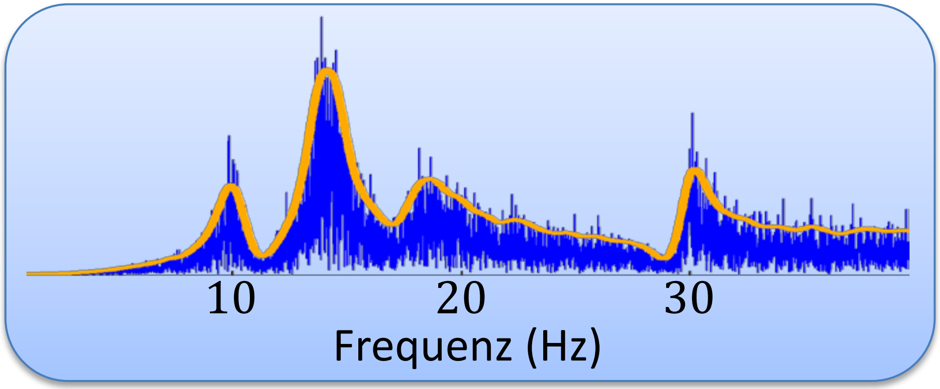
Positionsschätzung nicht modellbasiert – Ergebnisse

Schätzung



Korrektur



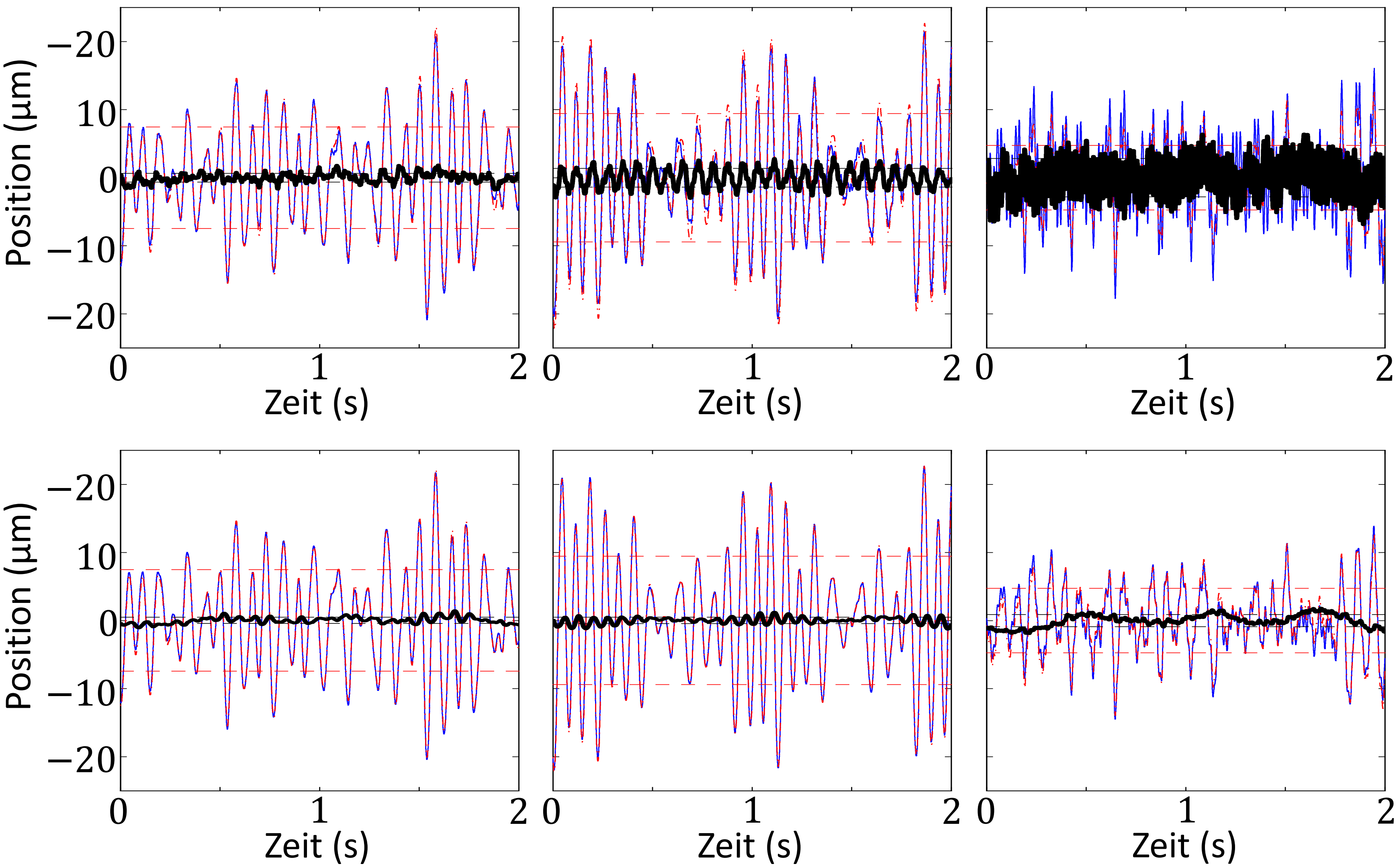


Vergleich der Algorithmen (Simulation)

Simulation | **Eigenfreq. + 10%** | **hohe Dämpfung**

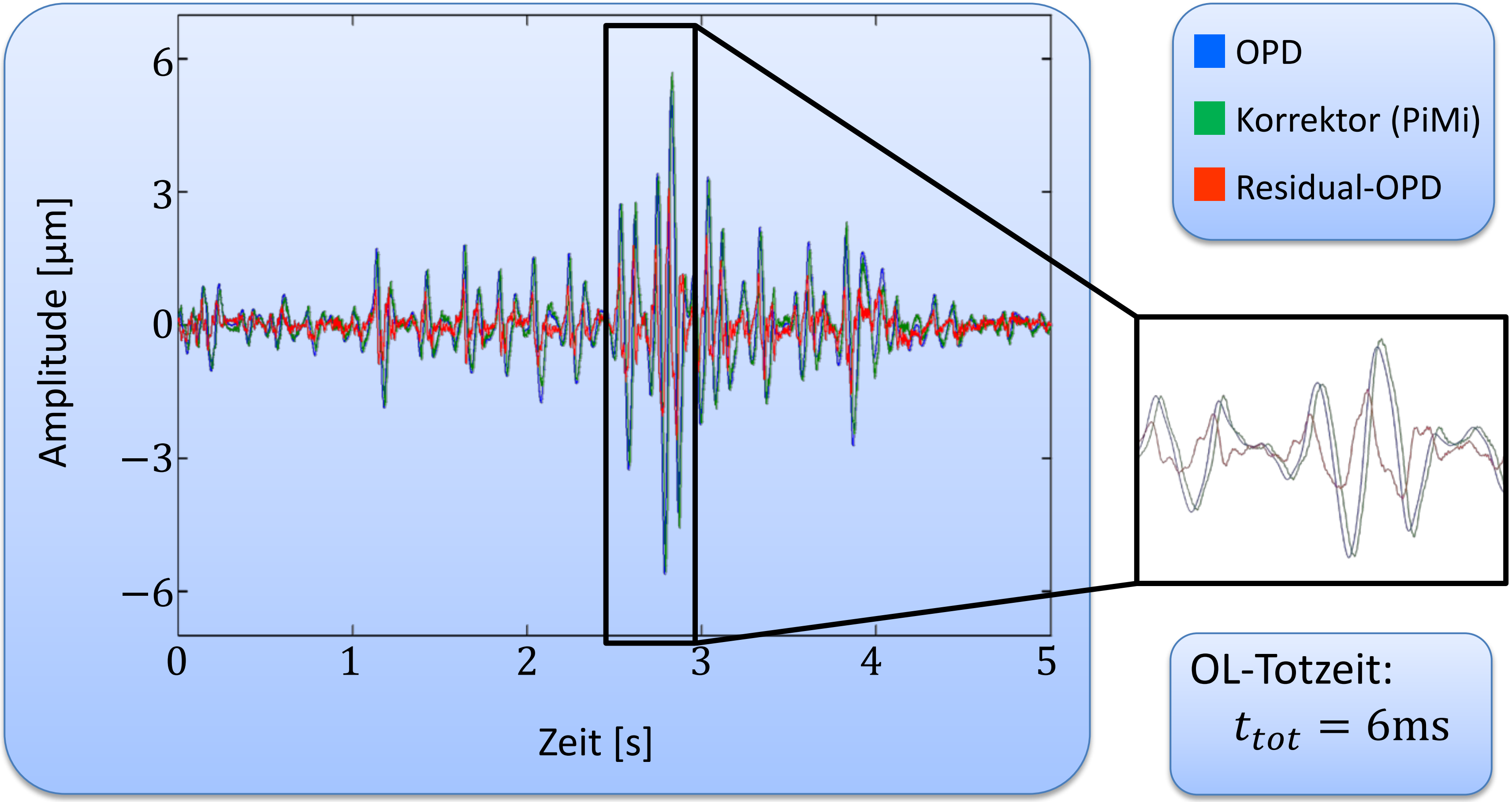
Kalman Filter

Breitbandfilter



Totzeitkompensation – Laborergebnis ohne Kompensation

- Problem: Latenz von insgesamt 6ms (Sensor + Aktor)



🟦 OPD

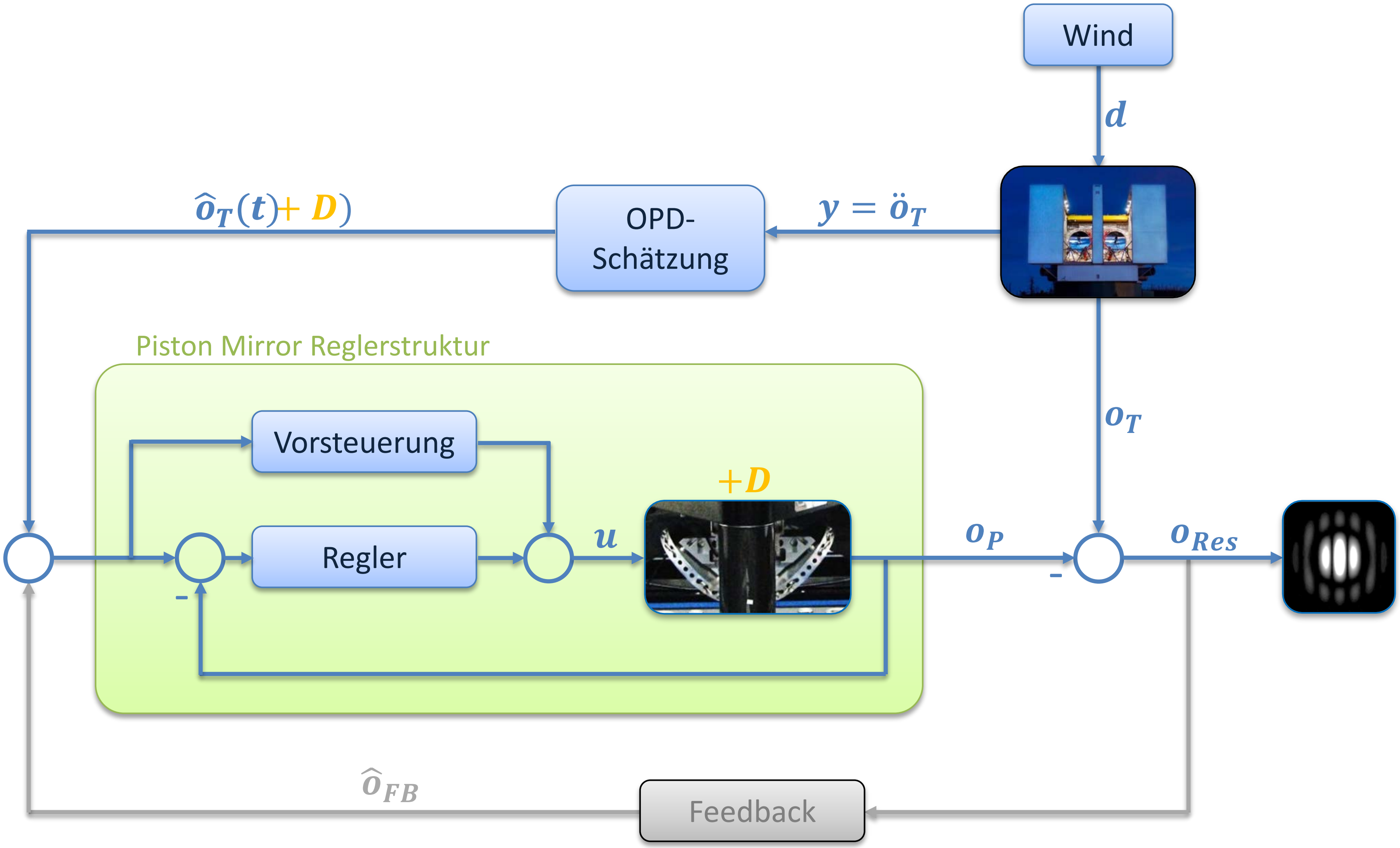
🟩 Korrektor (PiMi)

🟥 Residual-OPD

OL-Totzeit:

$$t_{tot} = 6\text{ms}$$

Einführung – Störgrößenkompensation



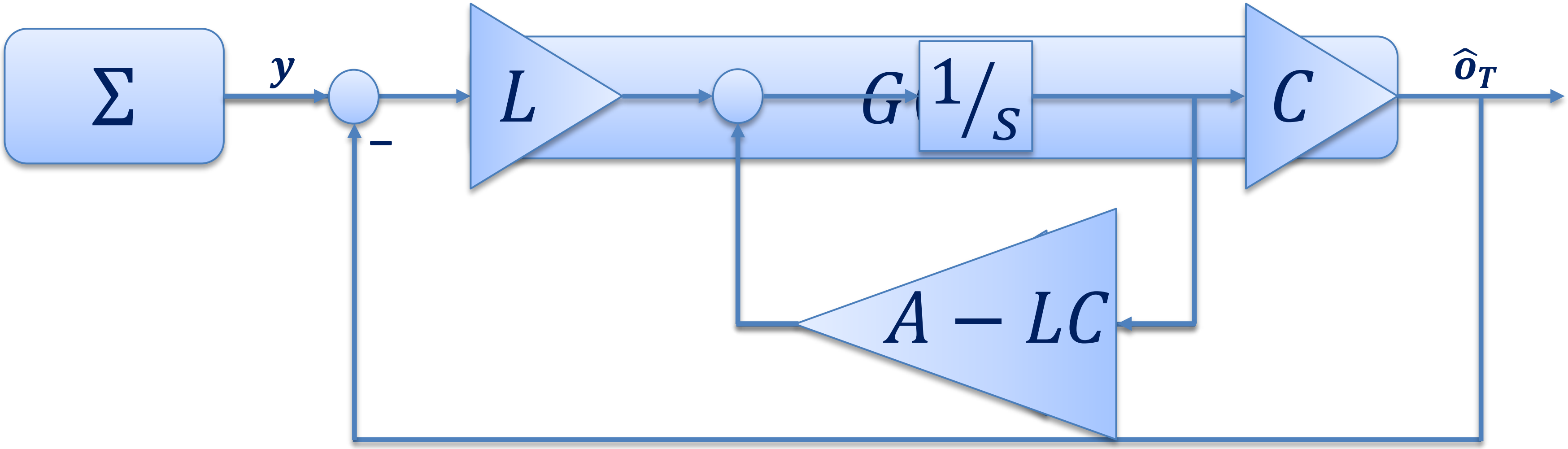
Möglichkeiten der Kompensation

- Kompensation im Regler des Korrekturelementes
  - Erweiterung mit Smith Predictor

- Modellbasierte Prädiktion
  - beobachterseitige Kompensation
  - Problem: kein modellbasiertes Schätzverfahren
  - Varianten:
    - FFT mit einfacher Prädiktion
    - Totzeitkompensation mit Backstepping (nach M.Krstic)

Totzeitkompensation mit Backstepping (1)

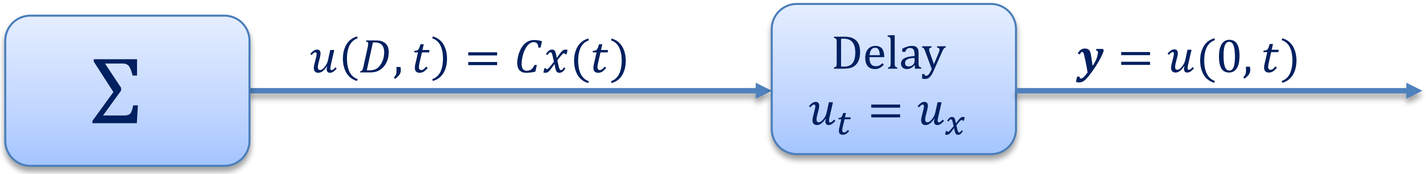
- Kompensation für ein System gegeben als: $\dot{x} = Ax,\ y = Cx$
- Zunächst Herleitung eines Modells aus $G(s)$:
  - Annahme:
    $G(s) = C\big(sI - (A - LC)\big)^{-1}L = \mathbb{Z}_R(A - LC, L, C, 0) = \mathbb{Z}_R(A_G, B_G, C_G, 0)$
- Berechnung der Zustandsraumdarstellung aus $G(s) \mathrel{\widehat{=}} \mathbb{Z}_R(A_G, B_G, C_G, 0)$
- Berechnung der Beobachterdarstellung mit
  - $C = C_G,\ L = B_G,\ A = A_G + LC$



Totzeitkompensation mit Backstepping (2)

- Erweiterung des Modells um zusätzliche Totzeit:
  - $\dot{x} = Ax, \quad y = Cx(t - D)$

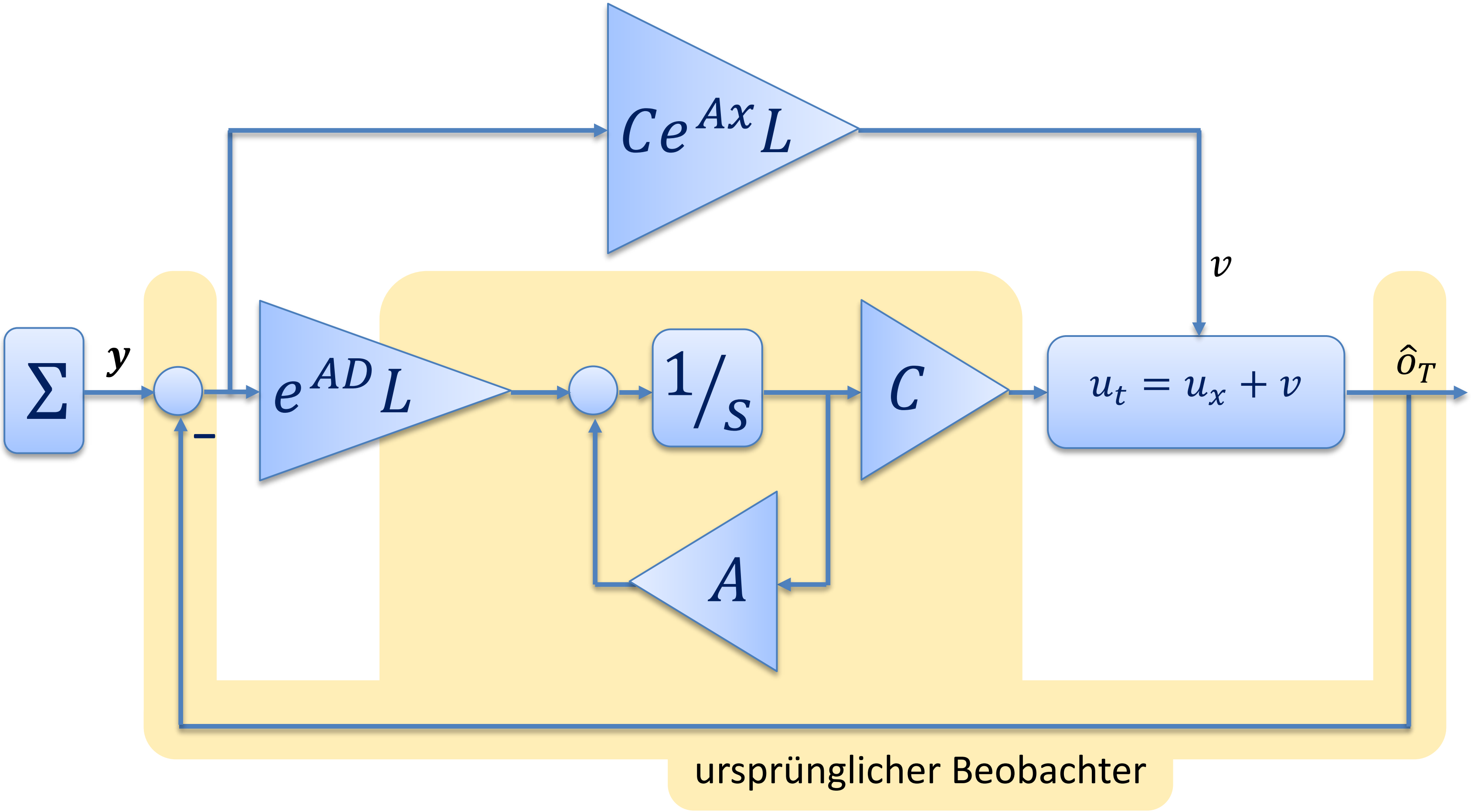
- Umschreiben als ODE-PDE Kaskade:
  - $\dot{x} = Ax, \quad u_t(x,t) = u_x(x,t),\ u(D,t) = Cx,\ y = u(0,t)$



- Beobachter für dieses System ergibt sich als:
  - $\dot{\hat{x}}(t) = A\hat{x}(t) + \mathrm{e}^{AD}L\big(y(t) - \hat{u}(0,t)\big),$
  - $\hat{u}_t(x,t) = \hat{u}_x(x,t) + C\mathrm{e}^{Ax}L\big(y(t) - \hat{u}(0,t)\big),$
  - $\hat{u}(D,t) = C\hat{x}(t)$

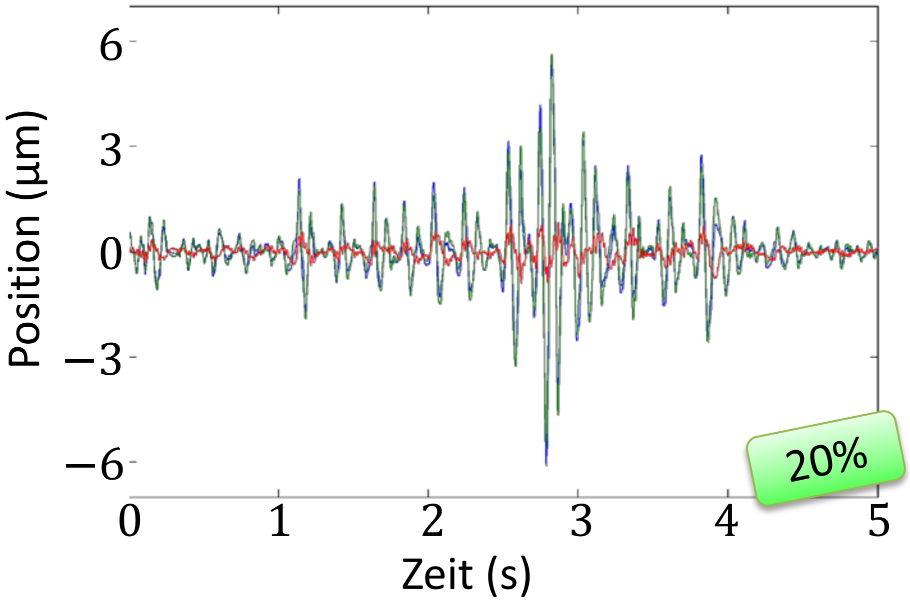
Totzeitkompensation mit Backstepping (3)

- Blockschaltbild des totzeitkompensierenden Beobachters:



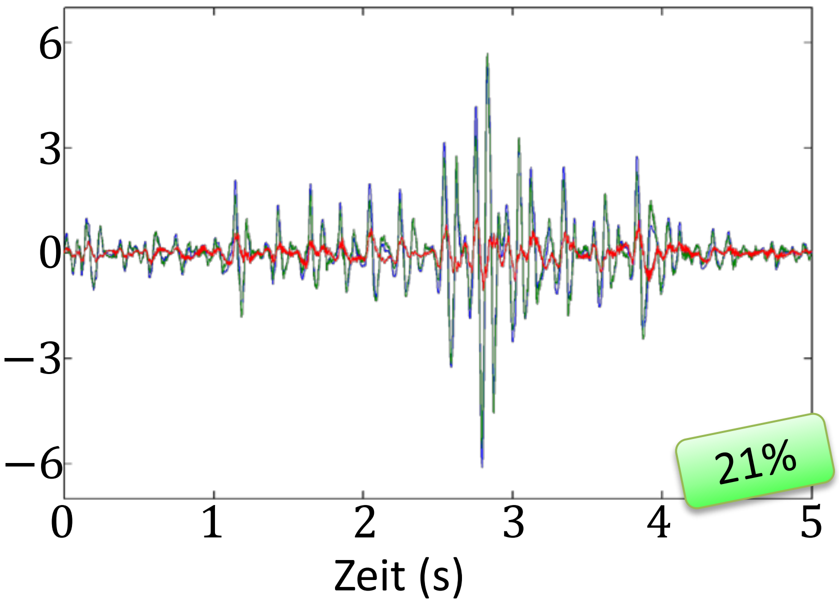
Totzeitkompensation – Ergebnisse

Schätzung



20%

Korrektur



21%

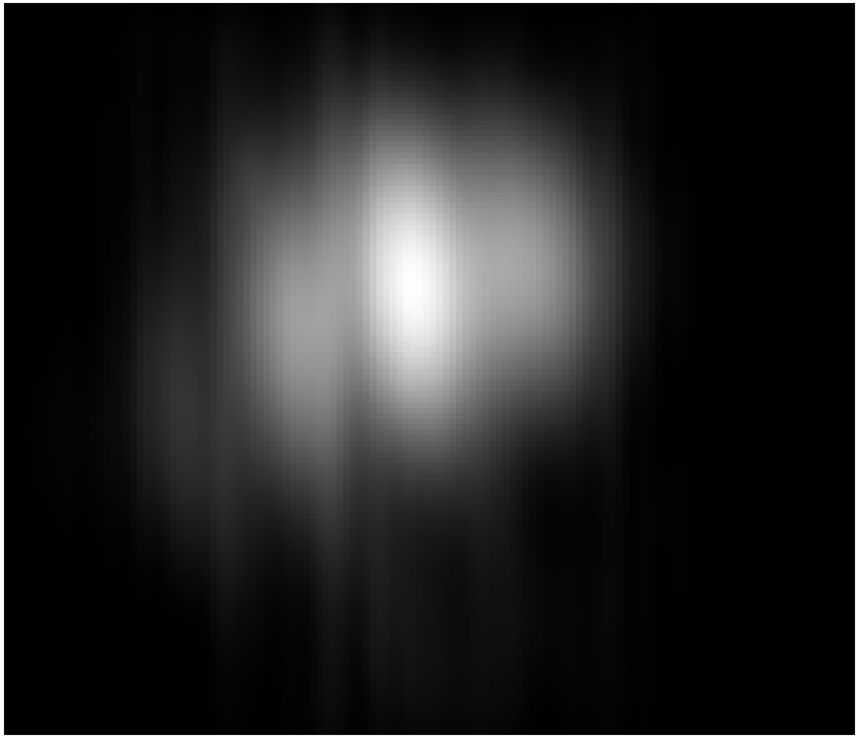
Zusammenfassung

- Modellierung
  - Modales Modell mit identifizierten Resonanzen
  - Spiegel entkoppelt

- Positionsschätzung
  - Kalman Filter gut bei:
    - ausgeprägten, schwach gedämpften Resonanzen
    - sehr verrauschten Sensorwerten
  - Breitbandfilter gut bei:
    - Verschmierten Resonanzen
    - Hoher Modendichte in bestimmtem Frequenzband
    - Rauscharmen Sensorwerten

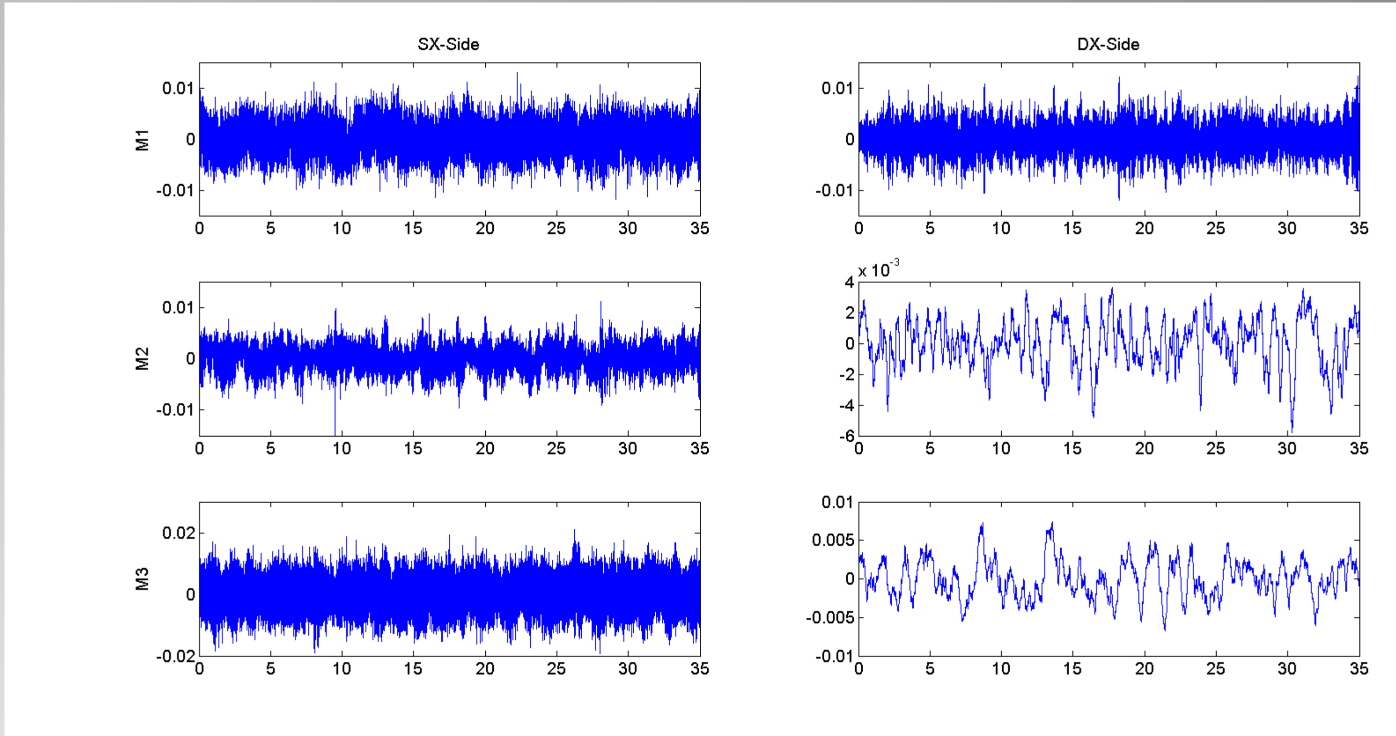
- Totzeitkompensation
  - Einfach bei Kalman Filter
  - Komplizierter bei Breitbandfilter, aber auch da möglich

Vibrationskompensation für LINC/NIRVANA



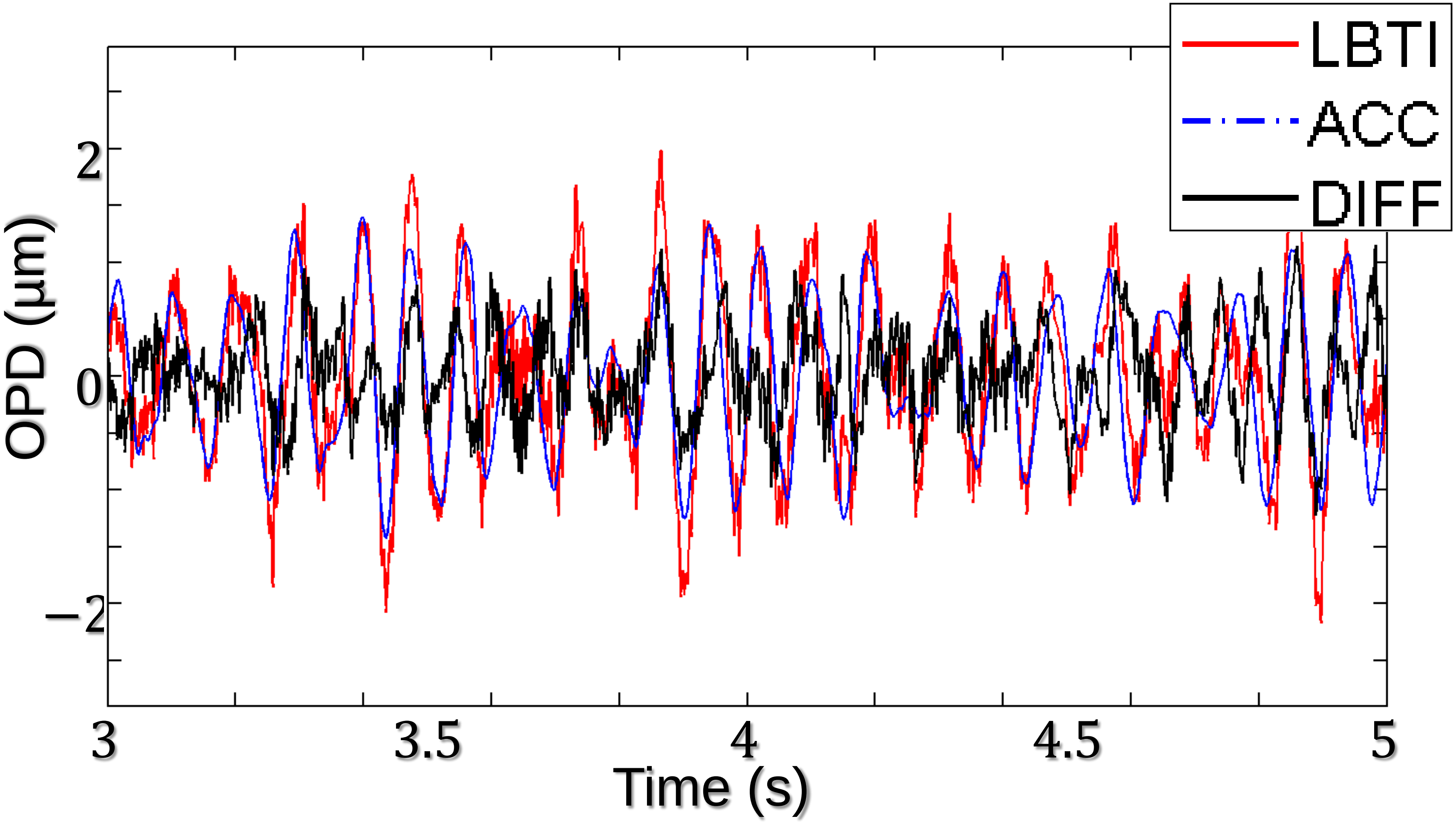
Viblab testing finished

- Let’s go to the telescope and see fringes
  - OVMS has been commissioned, and is ready to use
    - Well, if the cables have been connected…
  - Use LBTI as pathfinder



  - Provide LBTO with an efficient vibration monitoring and quality control tool

Vergleich LBTI phasecam (open loop) vs. OVMS



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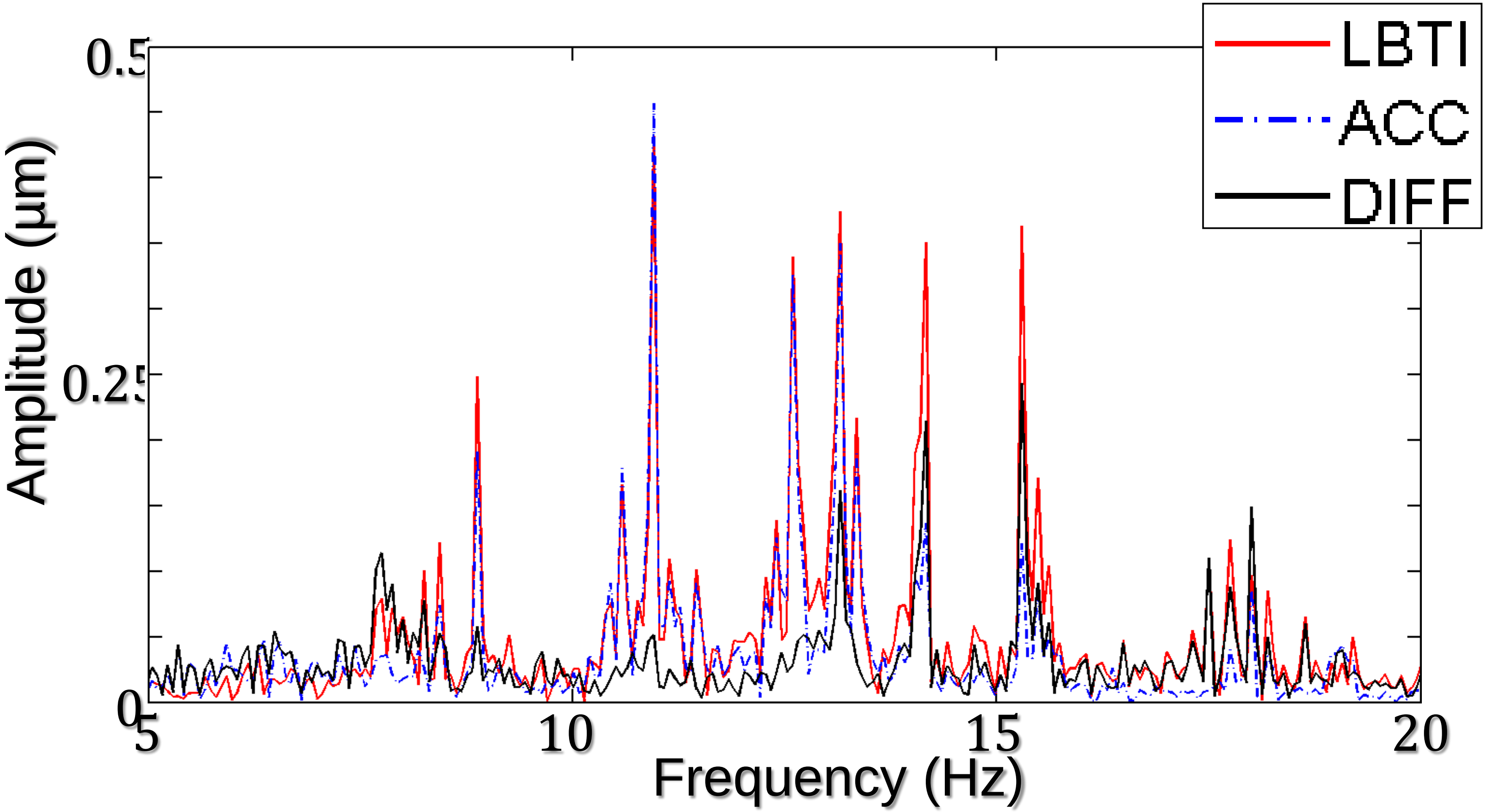


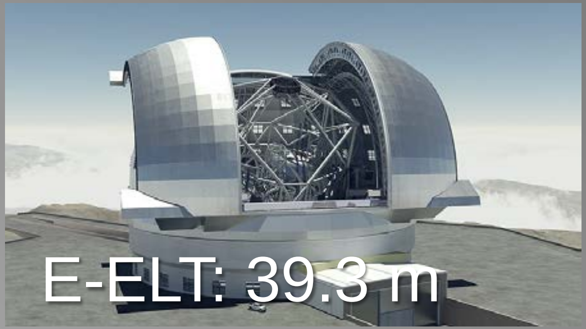
Summary LBT vibrations

- 100nm rms seems possible, at least / in particular > 10 Hz, where it is mostly needed

- Open-loop implementation has maximum flexibility, causes no conflict with instrument internal feedback loops

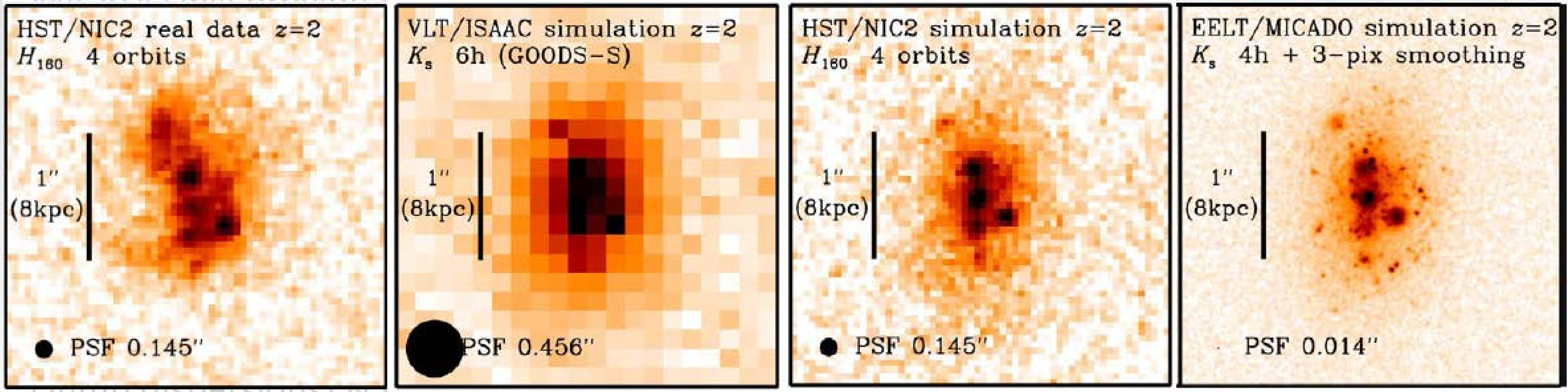
- We currently try to implement the OPD calculation directly in the electronics to make the interface to the instrument easier
  - OPD filtering always the same, latency correction is instrument dependent, but there is only two instruments…

Outlook: E-ELT Micado



E-ELT: 39.3 m

- New optical / IR telescope in Chile
- Largest diameter in the world, now and in the future
  - 798 segments, 2 recoatings every day (instead of once per year !)
  - 6 times bigger than JWST
  - Main structure will way about 2800 tons
  - Dome will have half the size of a football stadium
- MICADO is the diffraction limited NIR camera and first light instrument



MICADO schedule

- < 2014: PhaseA+ level design studies to get an idea of the precision + complexity (= costs) needed
- 2015: E-ELT and MICADO kick-off
- 2015-16: design trade studies
- 2016-18: preliminary design
- 2018-20: final design
- 2020-22: construction
- 2023: on-sky, SCAO commissioning, start of science
- 2025+: MAORY commissioning

MICADO-SCAO

(work by A. Keck, M. Glück)

- Instrument will only come with a WFS, and use the adaptive M4
  - 1000 actuators
  - Separate M5 for tiptilt control
  - M4/M5 system replace the classical instrument DM
  - Speed / vibrations could be an issue, since the mirrors are large
- We prepare for this, and develop vibration suppression without starlight to reduce the WFS control speed
  - Current task is to co-develop a GPU-based AO simulation tool, and have vibrations, and control algorithms implemented