Angular control of Advanced Virgo suspended benches

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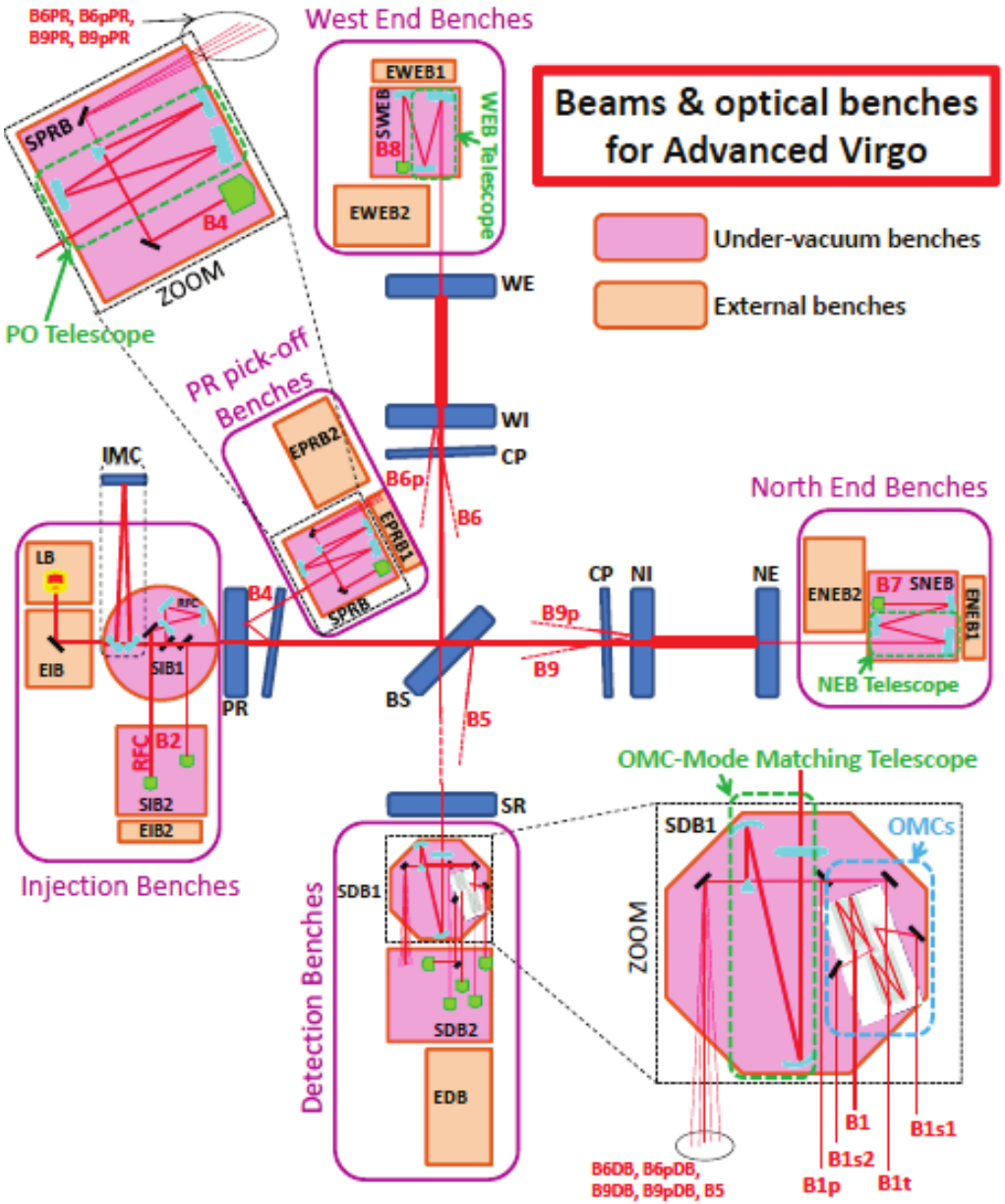
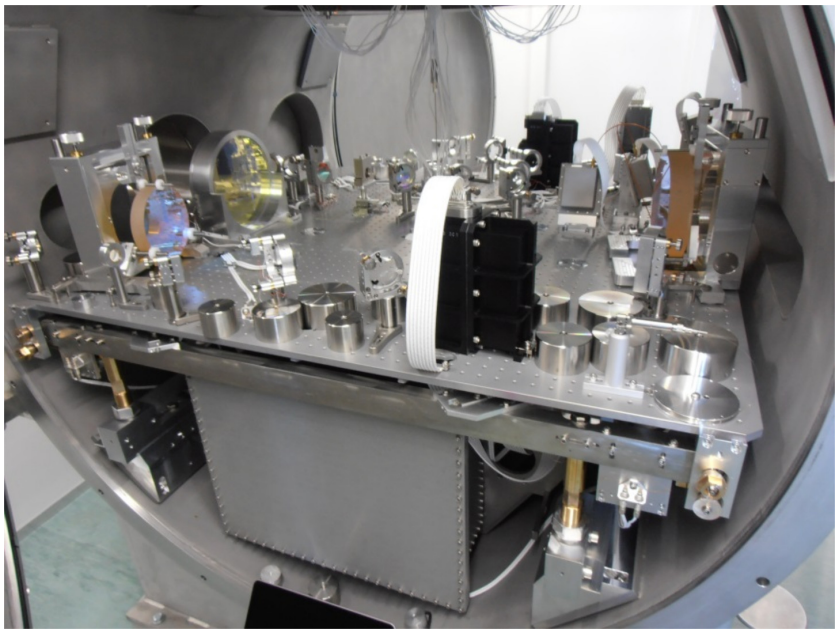
for the DET and SBE team

LAPP/IN2P3 - Annecy

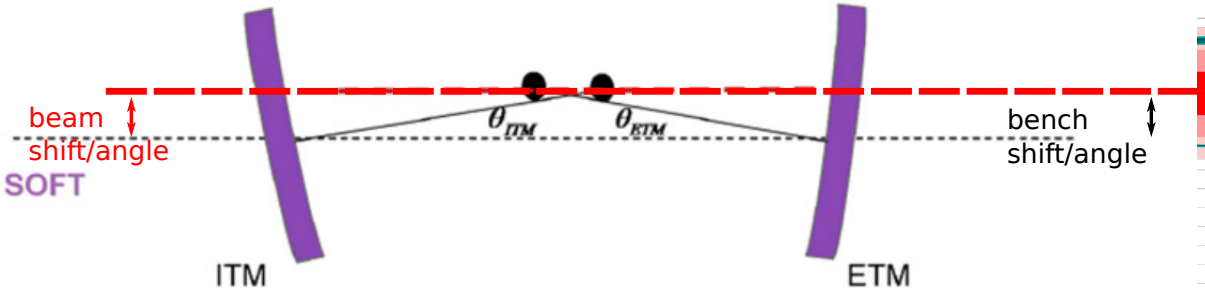
Suspended benches in Advanced Virgo

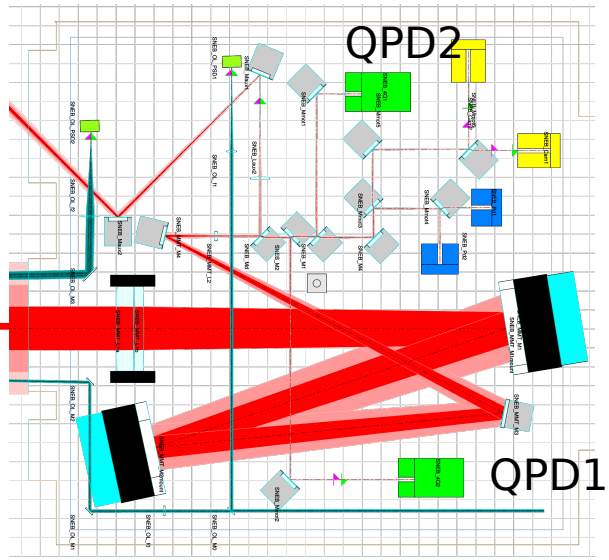


- Support:
  - photo-diodes
  - quadrants
  - wavefront sensors
  - cameras,...
- read-out electronics



Angular control requirements - end of arm benches





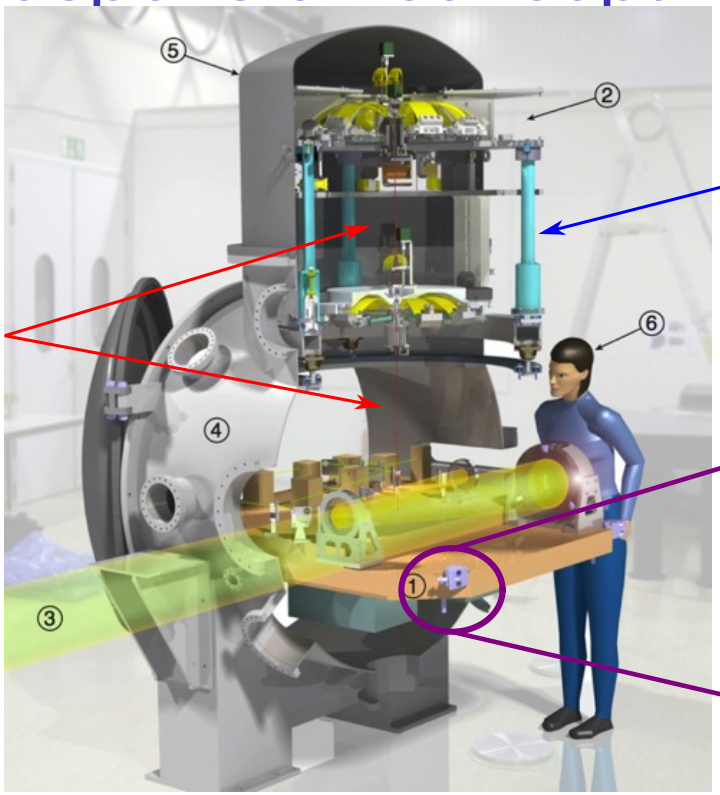
- DC quadrant signals used to control the arm soft mode
- Beam angle/position $\Leftrightarrow$ bench angle/shift
- Losses in arm $< 10^{-3} \Rightarrow < 110$ nrad of beam angle
  $\Rightarrow < 33$ nrad of bench angle (3 times better than test mass local controls achievement)

	RMS	@ 10 Hz
angle	3×10^{-8} rad	3×10^{-15} rad$/\sqrt{\text{Hz}}$
shift	2×10^{-5} m	2×10^{-12} m$/\sqrt{\text{Hz}}$

$\Rightarrow$ shift requirements 3 order of magnitude easier $\rightarrow$ focus on angle

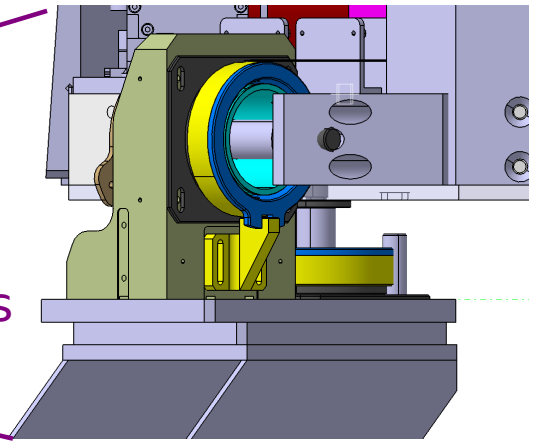
Mantovani 2012, VIR-0101A-12

Bench suspension concept



inverted pendulum

double pendulum



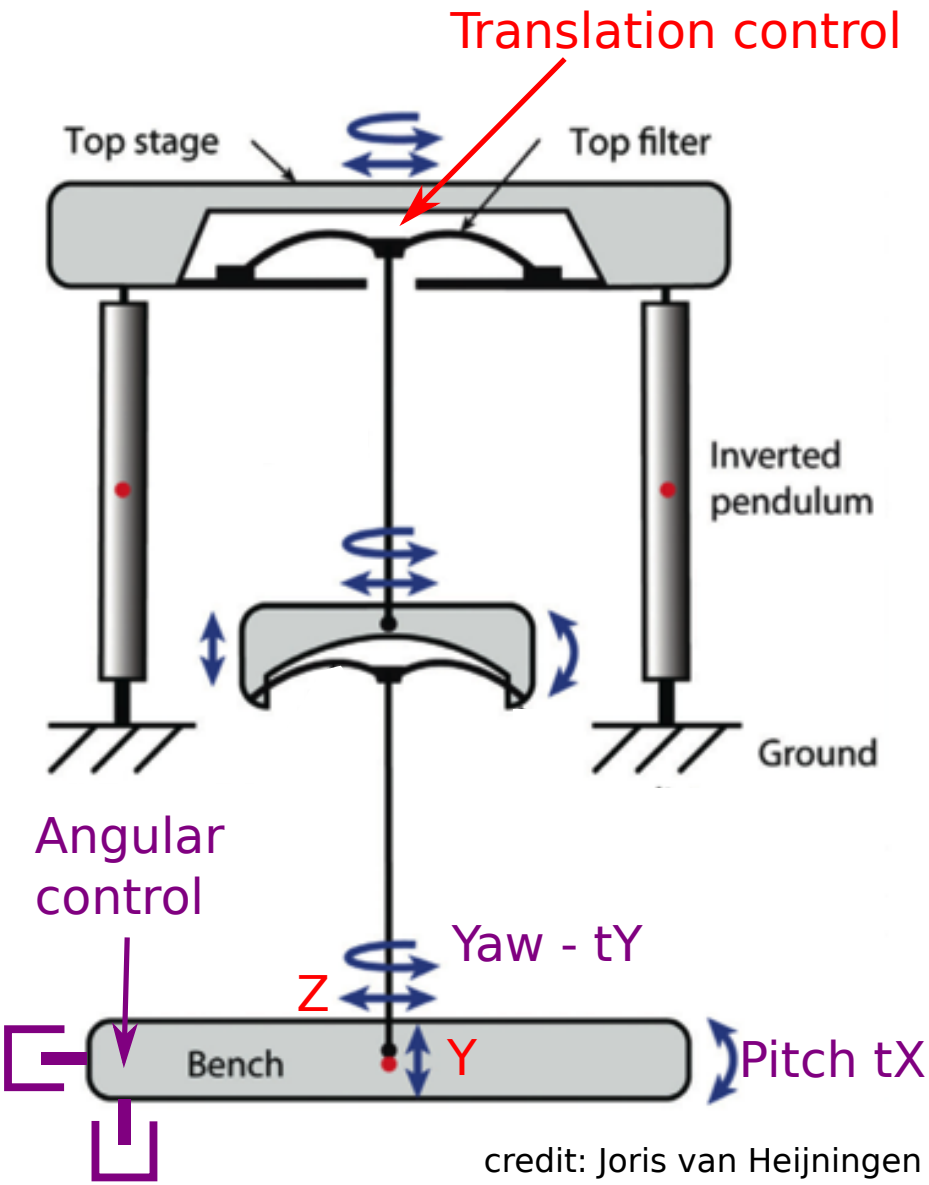
LVDT
local controls

- Pre-isolated double suspension (MultiSAS - NIKHEF)
  - 1 inverted pendulum
  - 2 pendulums + vertical isolation GAS blade stages
- local controls: 2 LVDTs in 4 corners
  - Differential position sensor, sensitivity $\sim 1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$
  - Maxwell pair of coils – Magnet actuator

$\Rightarrow$ 2 redundant signals: 1 horizontal, 1 vertical

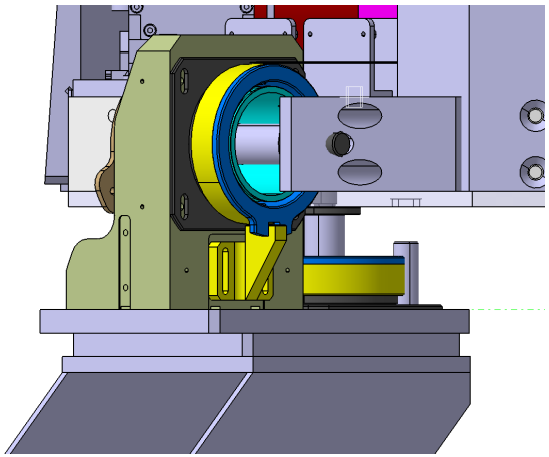
$\rightarrow$ null combinations (stretching, twisting the bench)

Bench control scheme

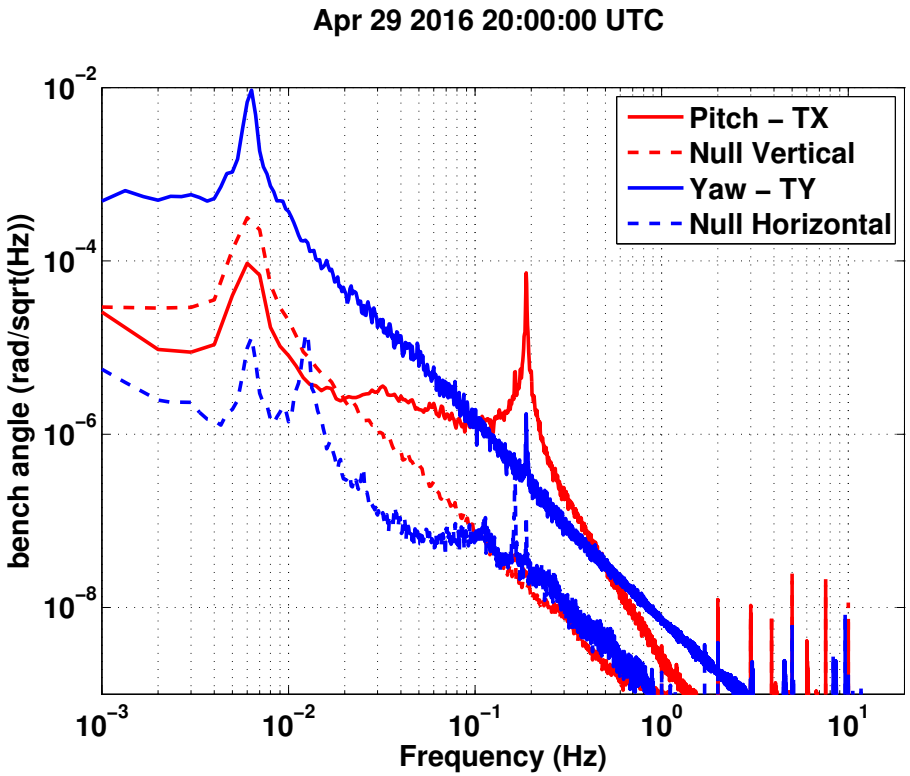


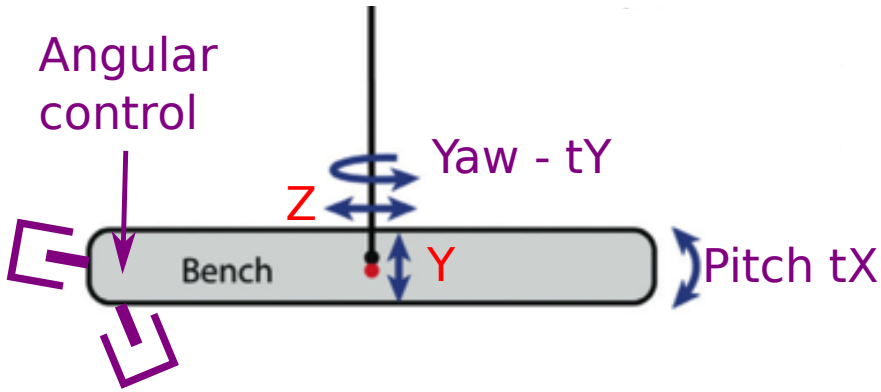
credit: Joris van Heijningen

- Translation control from the top stage
- Angular control on the bench
  - angular actuator & sensor
    $\Rightarrow$ between ground and bench



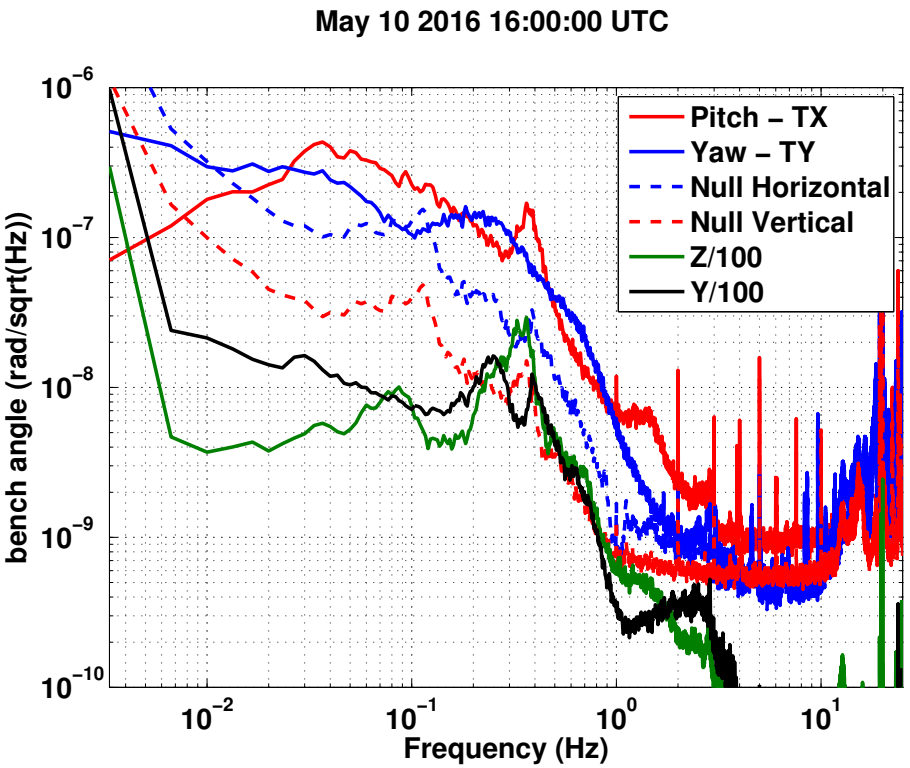
2 redundant sensors $\Rightarrow$ sensor gain cross calibration

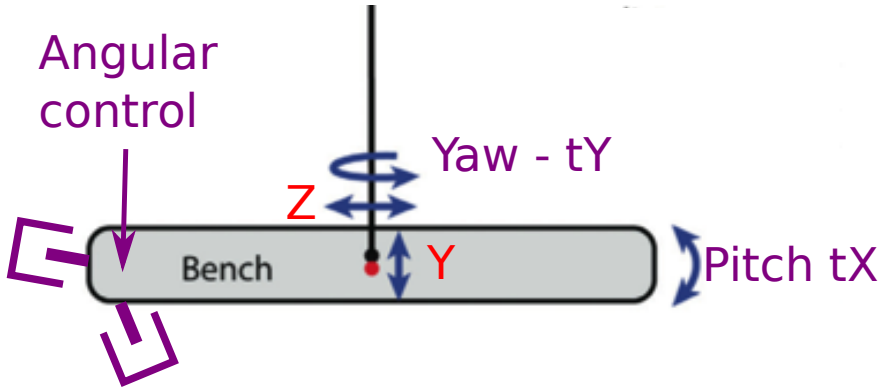




- Sensors absolutely calibrated at $\sim$ 10% level
- Assume perfect geometry (location, orientation of sensors)
- Cross-calibrated vertical sensors, cross-calibrated horizontal sensors
- Degree of freedom coupling at resonances is $\lesssim 10^{-3}$
- horizontal-vertical coupling $\sim 10^{-2} \Rightarrow$ geometry is not perfect

Is an imperfect sensor geometry a problem?





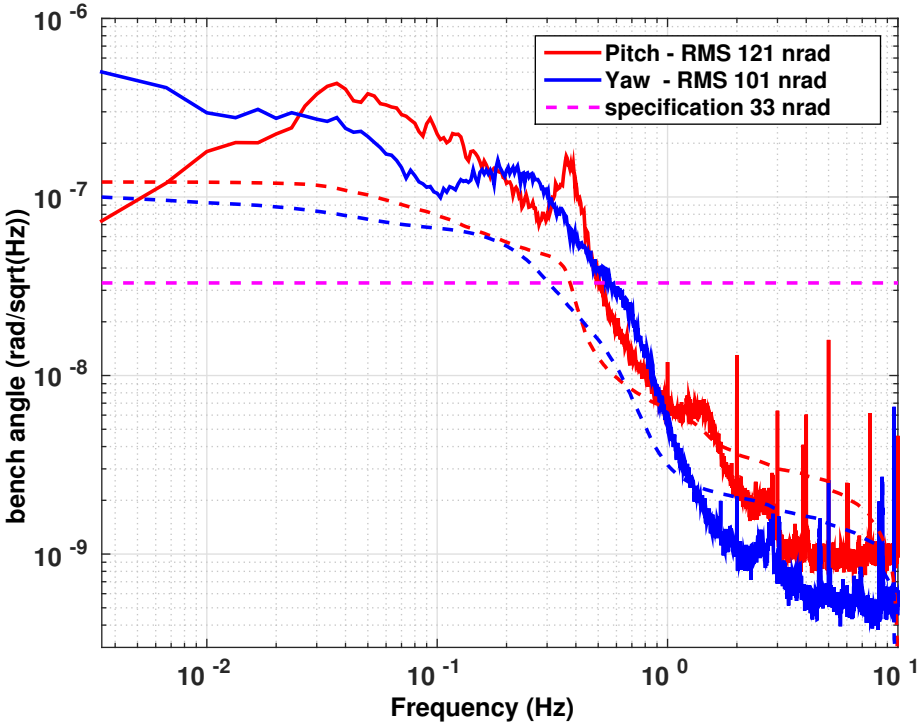
- Shifts: ground motion wrt static bench

$\Rightarrow$ $\sim$ 1% coupling of ground motion to angle sensing

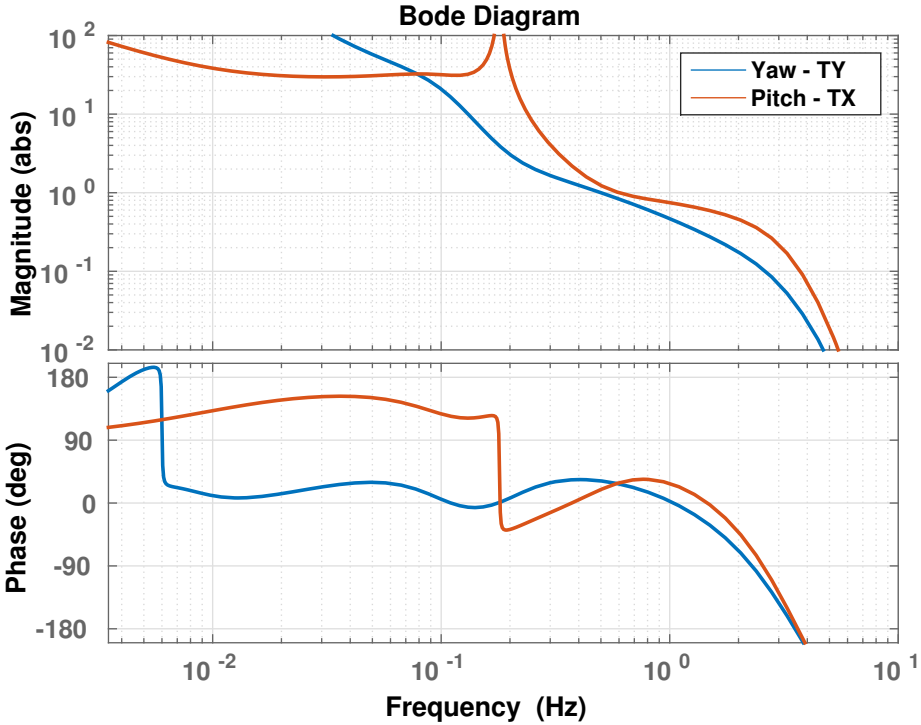
$\rightarrow$ well below the locked spectrum $\Rightarrow$ not a problem

- Null combination is close to locked spectrum
  $\Rightarrow$ electronic noise at large offsets ? ($> 10^6$ above noise floor)

Closed loop performance - low frequency

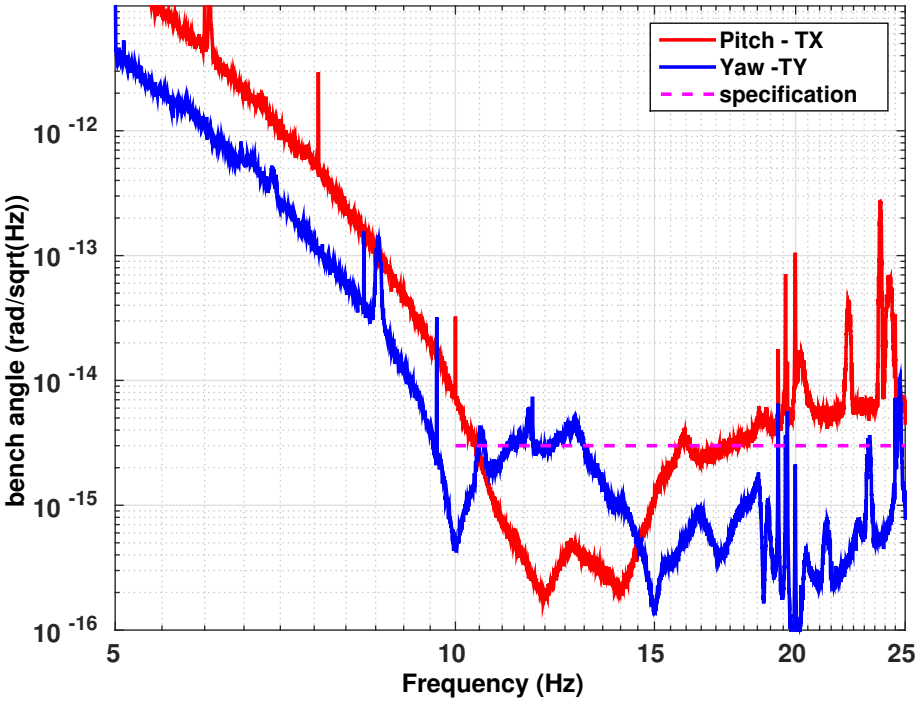


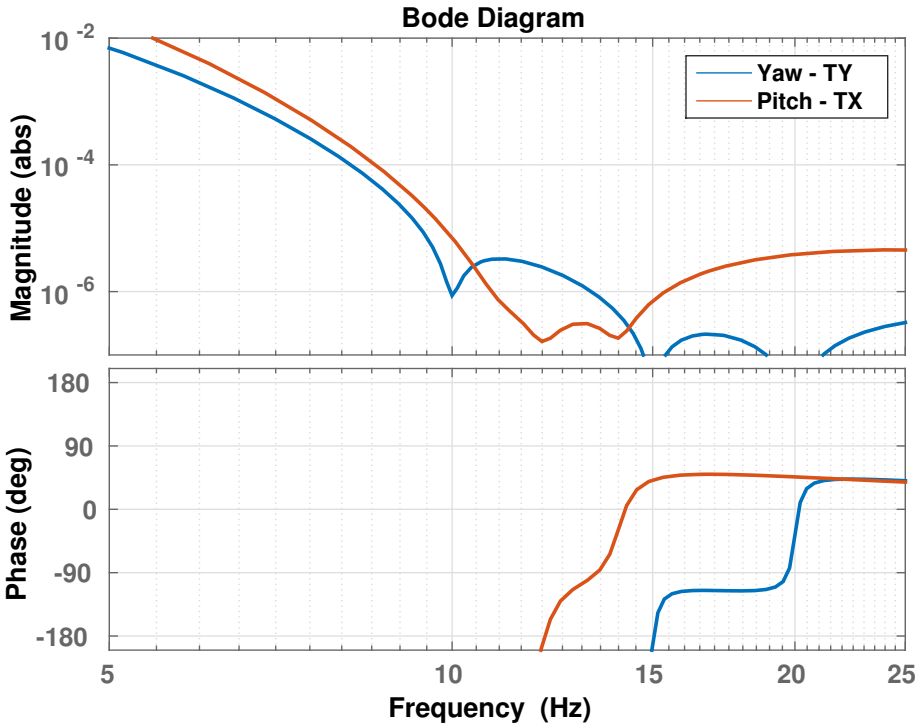
Open Loop Transfer Function



- A few days of work
- Traditional approach of moving poles and zeros around until it works
- RMS is a factor 3-4 above specification (33 nrad) – moderate microseismic

Closed loop performance - in band

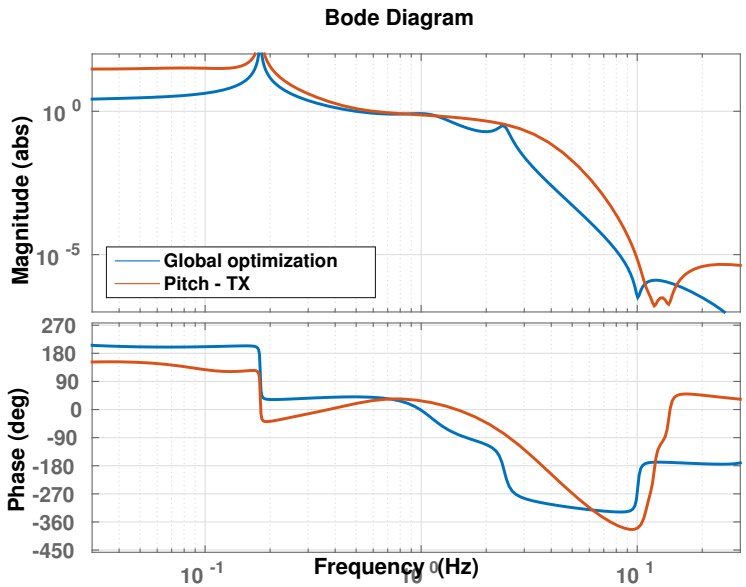




- Traditonal approach: adding low-passing once the low-frequency part looks ok
- Good for Yaw, needs improvement for Pitch
- Measurement done in air with airflow shaking the tower, should be better in vacuum
- Specification is $3 \times 10^{-15}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$

How to get the remaining factor 3: global cost function

https://git.ligo.org/rana-adhikari/ModernControls/tree/master/OptimalFeedback/GlobalCost

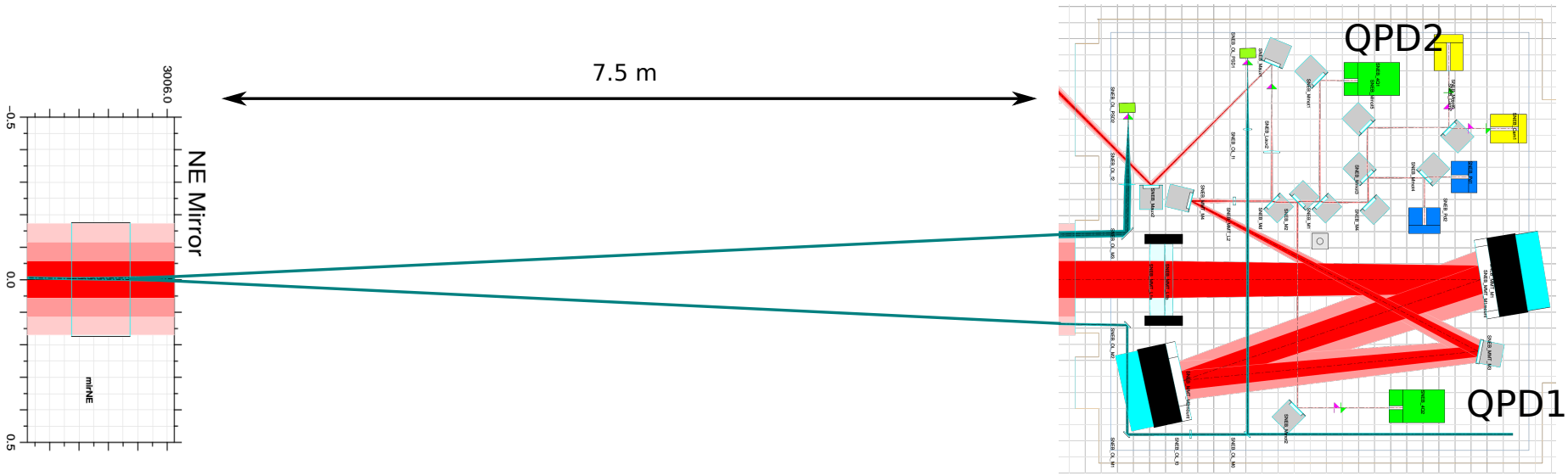


- Nice framework, highlights different aspects of a good loop
- Blindly optimize the loop using a cost function
- Starting from random or current filter
- Stuck at local minima solutions
  - no control, just let the system free
  - no stability, just put 3 poles at 0 Hz (phase looks good at unity gain)
- Cost function require lots of tuning

  $\rightarrow$ not better than by hand filter tuning?

$\Rightarrow$ Not a magic solution ... yet?

How to get the remaining factor 3: better sensing



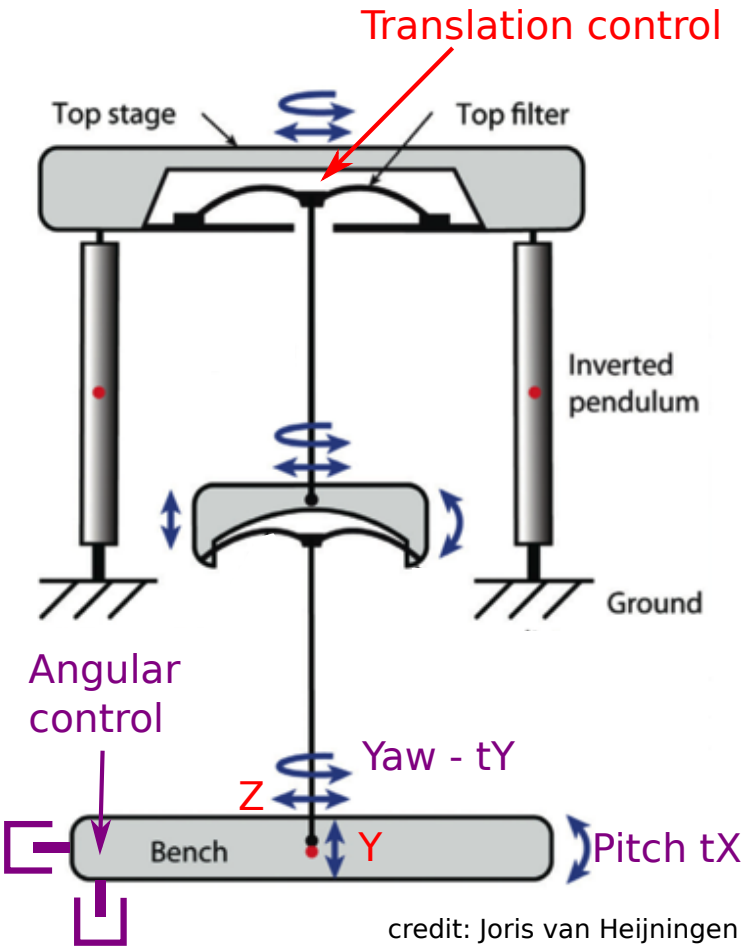
- Optical lever with long arm
  - Should have a $\times 10$ better sensing noise at $\sim 10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$
- Measure directly the angle between bench and end mirror
  - No issues with tower shaking
  - Bench follows the mirror, signal usable only well above 1 Hz?

    $\Rightarrow$ blend the signals and increase the gain

    $\rightarrow$ figure out the coupled 3 body alignment of 2 cavity mirrors + bench

    $\Rightarrow$ more complicated, no longer local control

Summary



credit: Joris van Heijningen

- A simple angular sensing & control from the ground works
- Redundant sensors are useful
  - cross-calibration
  - understanding couplings
  - measuring sensing noise
- Brute force optimization might be useful
- Better sensing is possible but more complicated

$$\begin{pmatrix} \frac{x_{QPD1}}{w_{QPD1}} \\ \frac{x_{QPD2}}{w_{QPD2}} \end{pmatrix} = \begin{pmatrix} 85 & -1.05 \times 10^5 \\ 121 & -1.30 \times 10^5 \end{pmatrix} \begin{pmatrix} x \\ \theta \end{pmatrix}_{\text{bench}}$$

$$\begin{pmatrix} \frac{x_{QPD1}}{w_{QPD1}} \\ \frac{x_{QPD2}}{w_{QPD2}} \end{pmatrix} = \begin{pmatrix} 54 & -2.4 \times 10^4 \\ 88 & 2.9 \times 10^4 \end{pmatrix} \begin{pmatrix} x \\ \theta_- \end{pmatrix}_{\text{beam}}$$

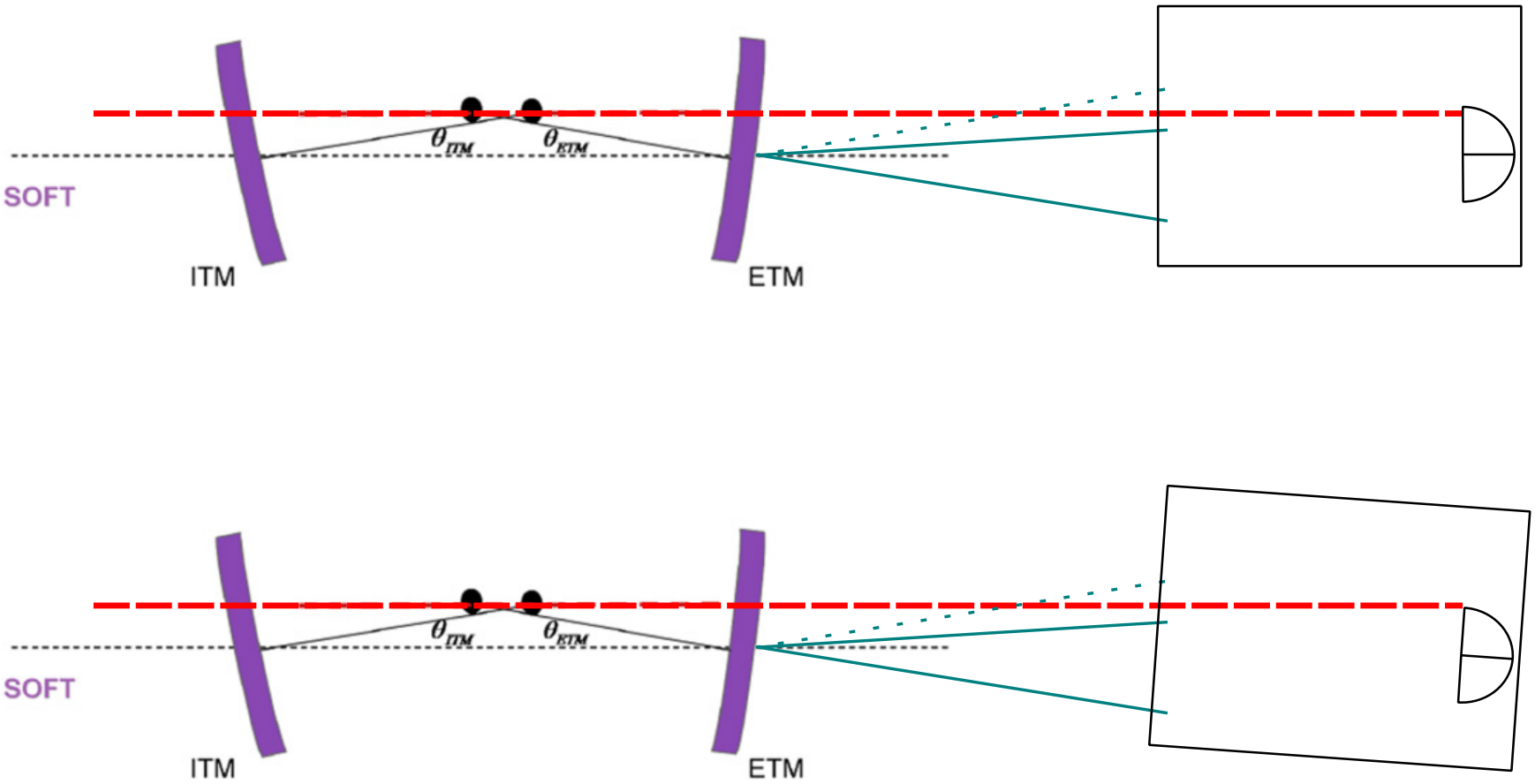
$$\theta_+ = 0.6470\theta_{IM} - 0.7625\theta_{EM}$$
$$\theta_- = 0.7625\theta_{IM} + 0.6533\theta_{EM}$$

$$RMS(\theta_+) \sim 1 \text{ nrad}$$

if bench locked to end mirror

$$\theta_{\text{bench}} = \theta_{EM} = -0.7594\theta_+ + 0.6444\theta_- \simeq 0.6444\theta_-$$

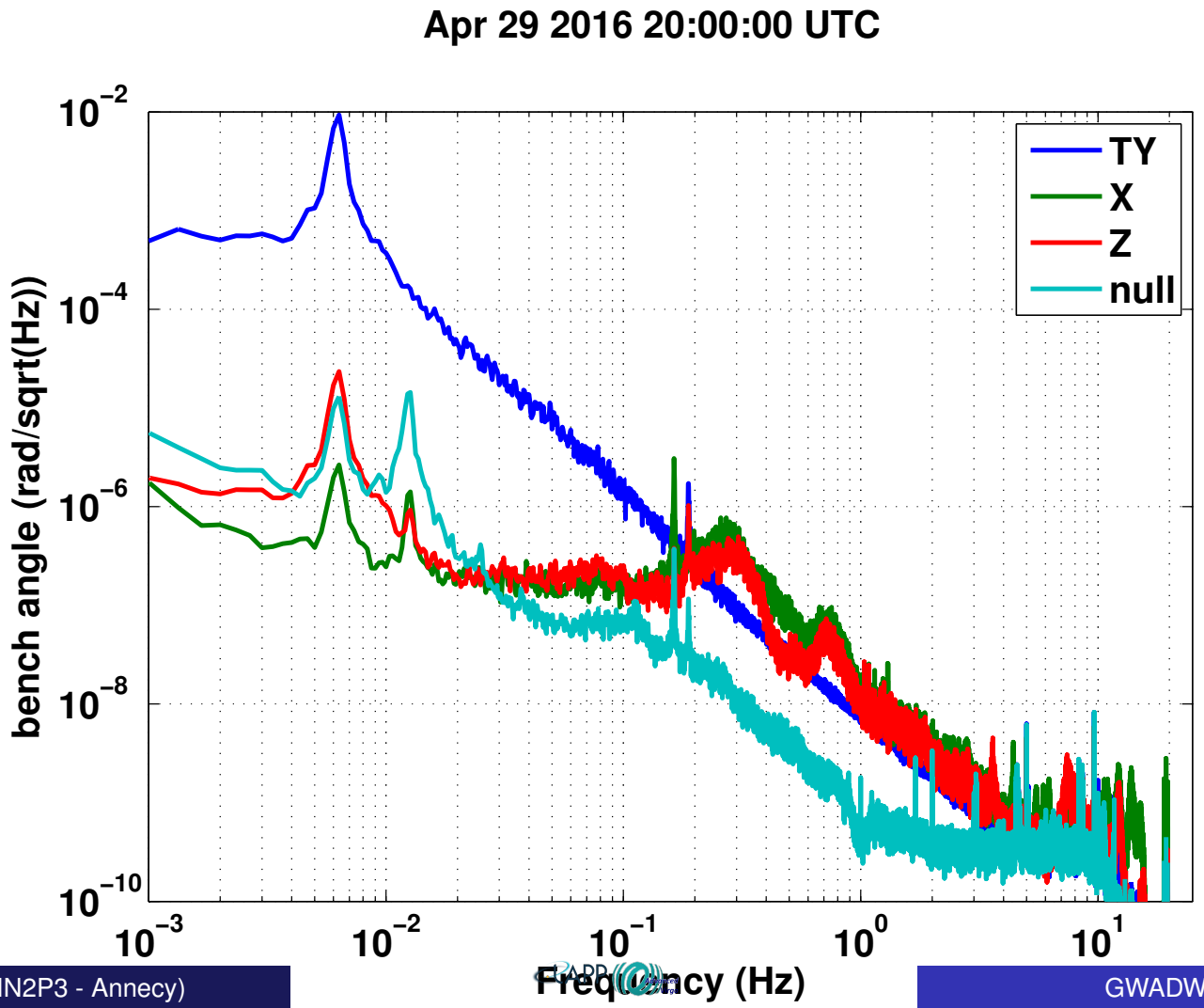
$$\begin{pmatrix} \frac{x_{QPD1}}{w_{QPD1}} \\ \frac{x_{QPD2}}{w_{QPD2}} \end{pmatrix} = \begin{pmatrix} 54 & -9.2 \times 10^4 \\ 88 & -5.5 \times 10^4 \end{pmatrix} \begin{pmatrix} x \\ \theta_- \end{pmatrix}_{\text{beam}}$$



Locking the bench to the mirror might actually work, just amplifies the error signal for soft mode alignment

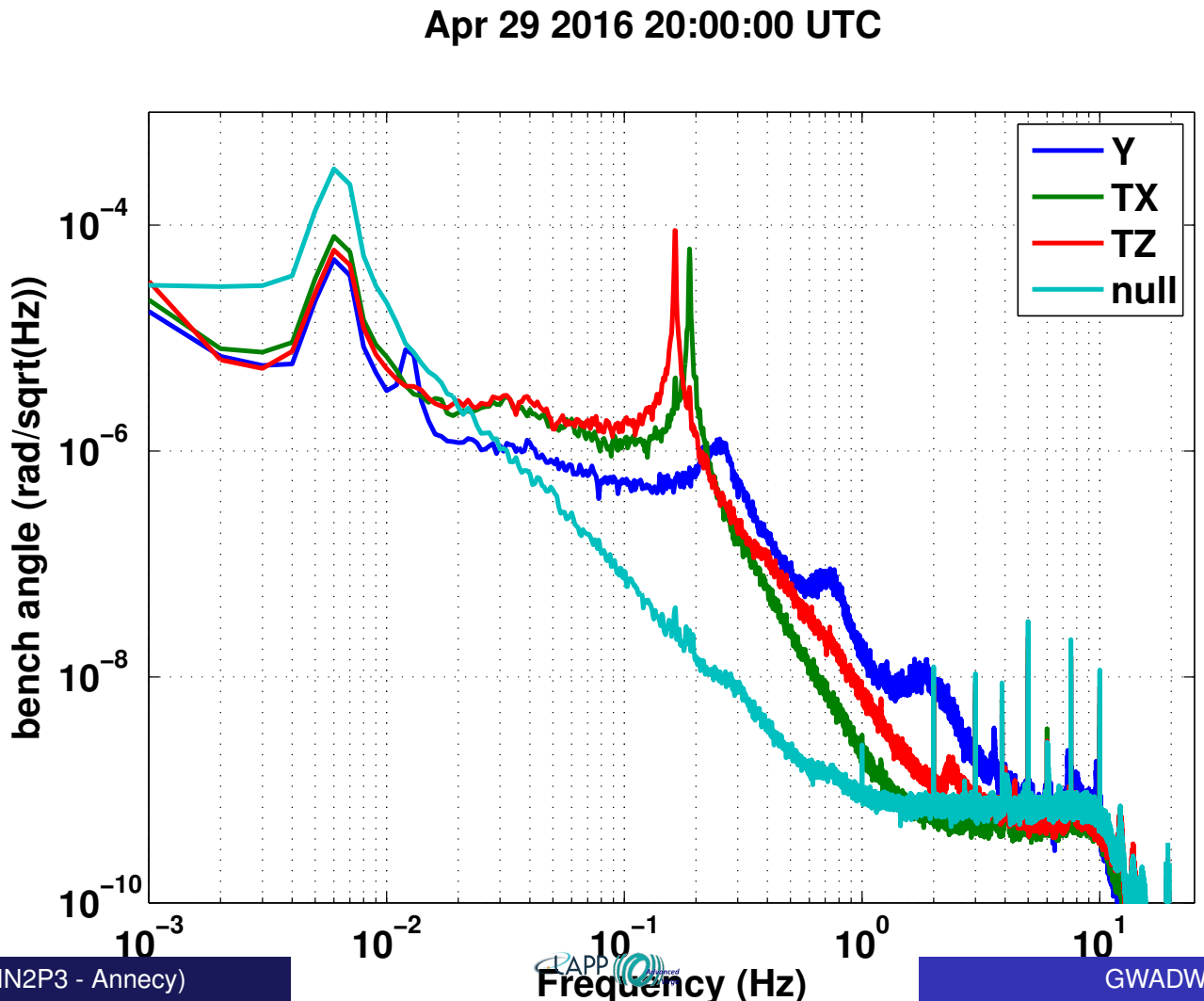
Free SNEB horizontal DoF - mSAS controlled

- TY (yaw) torsion pendulum resonance at 6.3 mHz
- resonance cross-coupling $\sim 10^{-3}$
- sensing noise 10^{-9} m level
- anti-alias at 10 Hz



Free SNEB vertical DoF - mSAS controlled

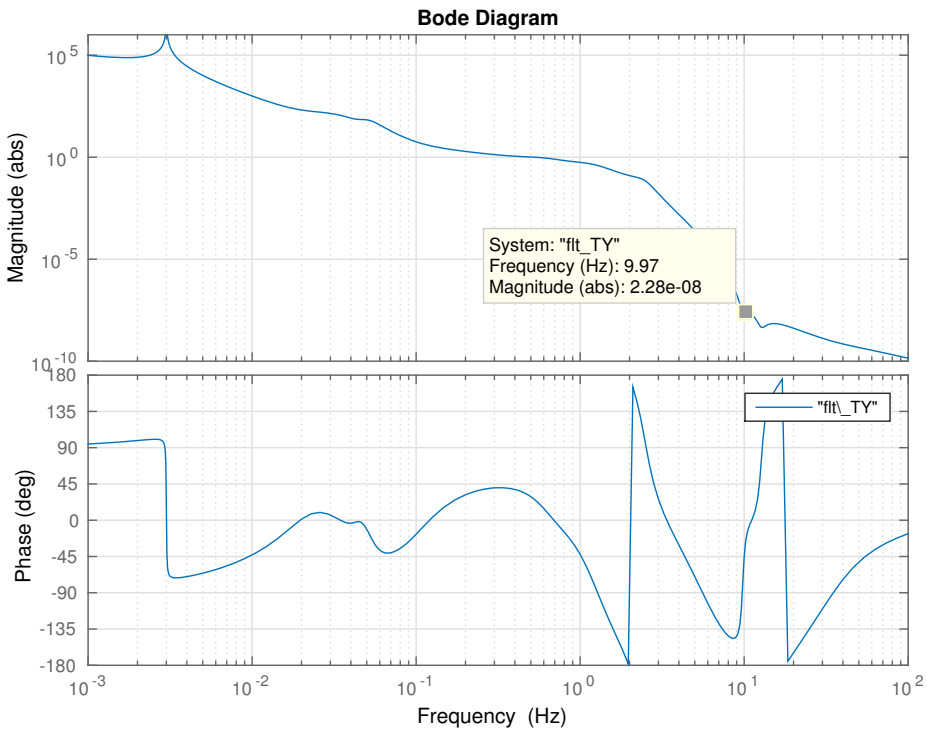
- TX (pitch) resonance at 189 mHz
- TZ (roll) resonance at 163 mHz
- TX/TZ resonance cross-coupling $\sim 10^{-4}$
- TY cross-coupling is $\sim 10^{-2}$, don't know why

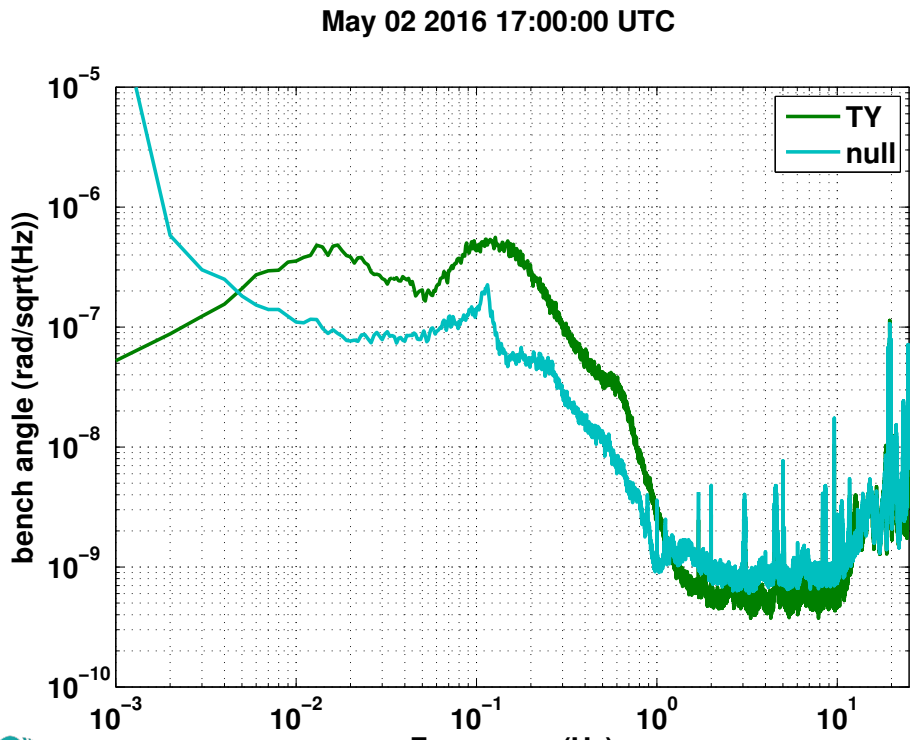


SNEB TY angular control

- Angular requirements for end benches (VIR-0101A-12)
  - 3.3×10^{-8} rad rms
  - 3.3×10^{-15} rad$/\sqrt{\text{Hz}}$ above 10 Hz
- Current performance on TY (yaw) - after a few hours of work
  - filter with $\sim 10^{-8}$ gain at 10 Hz
  - sensing resonances $\sim 10^{-7}$ rad$/\sqrt{\text{Hz}}$

  $\Rightarrow$ loop reintroduce noise at $\sim 10^{-15}$ rad$/\sqrt{\text{Hz}}$ level
  - lock RMS at 1.9×10^{-7} rad, factor 6 above specification
  - excess gain below 10 mHz





SNEB TX/TZ angular control

- Angular requirements for end benches (VIR-0101A-12)
  - 3.3×10^{-8} rad rms
  - 3.3×10^{-15} rad/$\sqrt{\text{Hz}}$ above 10 Hz
- Current performance on TX/TZ (pitch/roll)
  - lock RMS at 7×10^{-7} rad, factor 20 above specification
  - haven't worked on that loop yet
  - No translation (X, Y and Z) control

$\Rightarrow$ Ground shakes and the bench is still