HoQI in the BHQS

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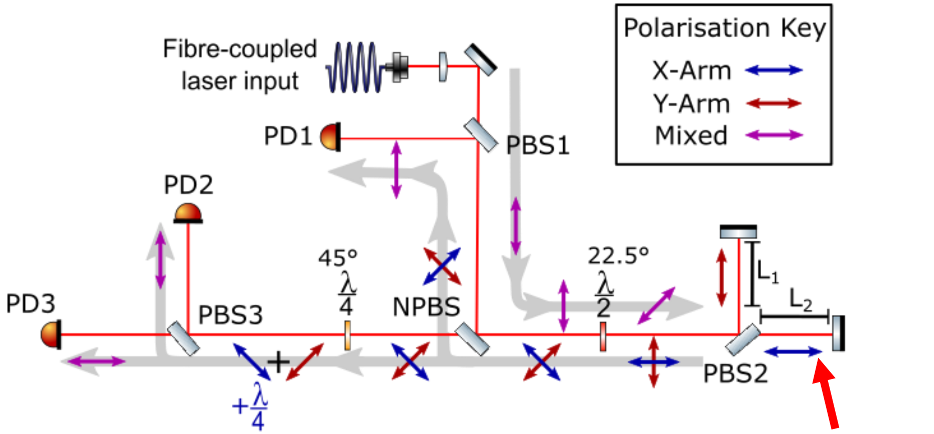
HoQI Brief Introduction



$$P_{PD1} = \frac{P_{in}}{8}(1 + a\sin(\Delta\phi))$$

$$P_{PD2} = \frac{P_{in}}{8}(1 - a\cos(\Delta\phi))$$

$$P_{PD3} = \frac{P_{in}}{8}(1 + a\cos(\Delta\phi))$$

Photodiode measurements

$$P_{PD1} - P_{PD2} = \frac{\sqrt{2}aP_{in}}{8}\sin\left(\Delta\phi + \frac{\pi}{4}\right)$$

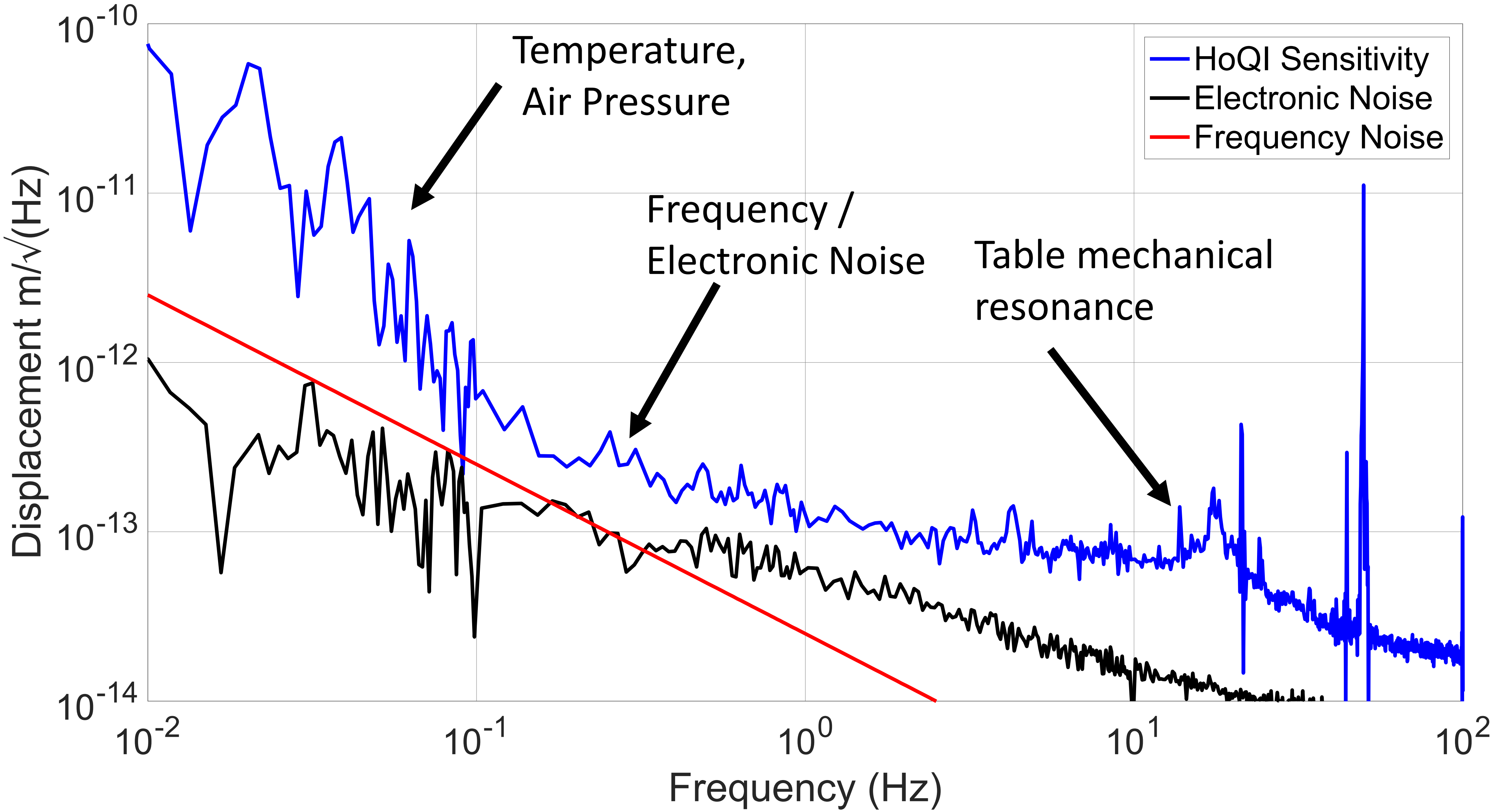
$$P_{PD1} - P_{PD3} = \frac{\sqrt{2}aP_{in}}{8}\sin\left(\Delta\phi - \frac{\pi}{4}\right)$$

Manipulation

$$\frac{P_{PD1} - P_{PD2}}{P_{PD1} - P_{PD3}} = \tan(\Delta\phi)$$

Extracting Δϕ

- Homodyne Quadrature Interferometer
- Uses three photodiode outputs and birefringent elements
- Creates a low noise, high dynamic range displacement sensor



Nikhef

S Cooper et.al Class. Quantum Grav. 35 (2018) 095007

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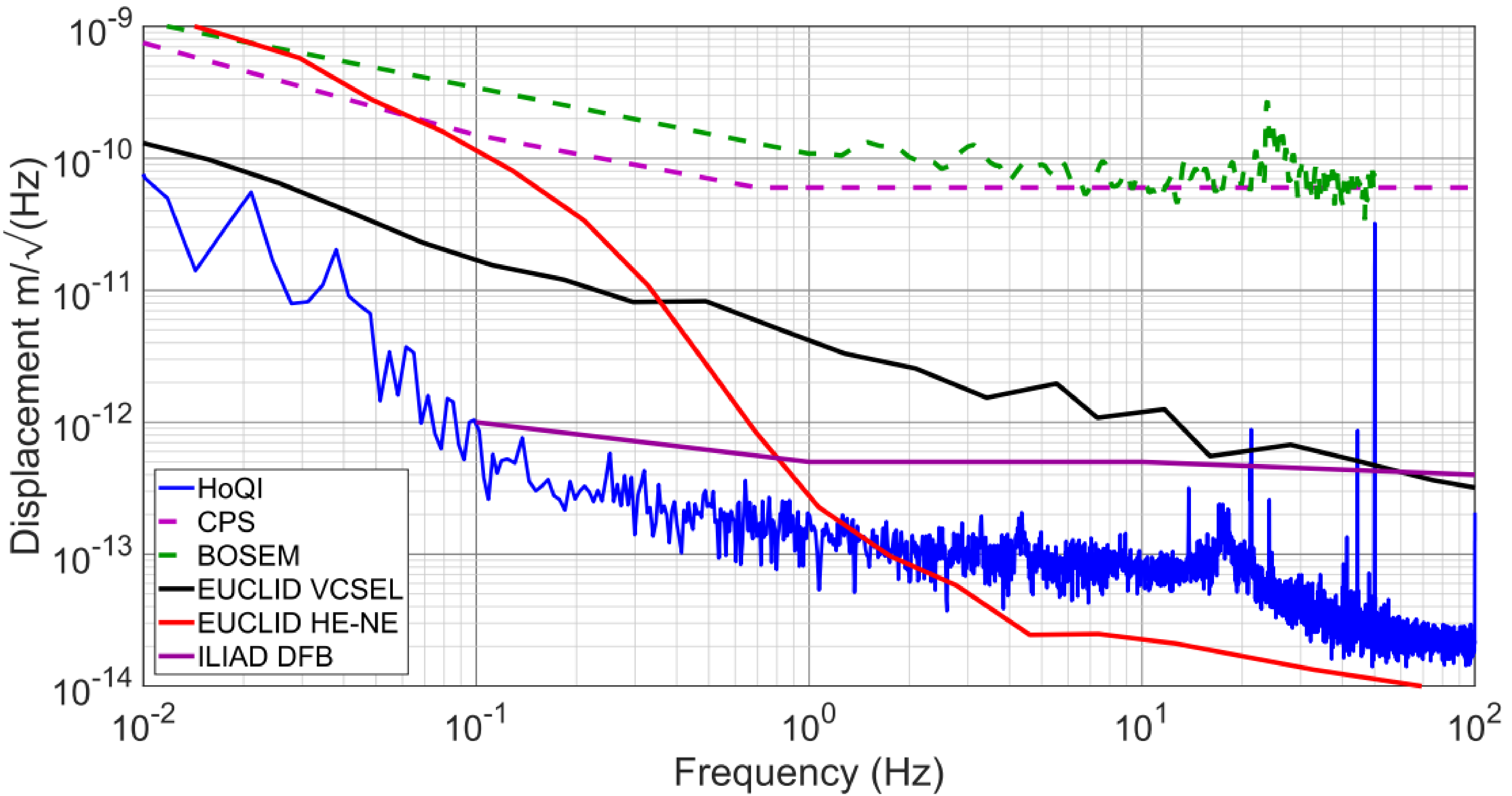
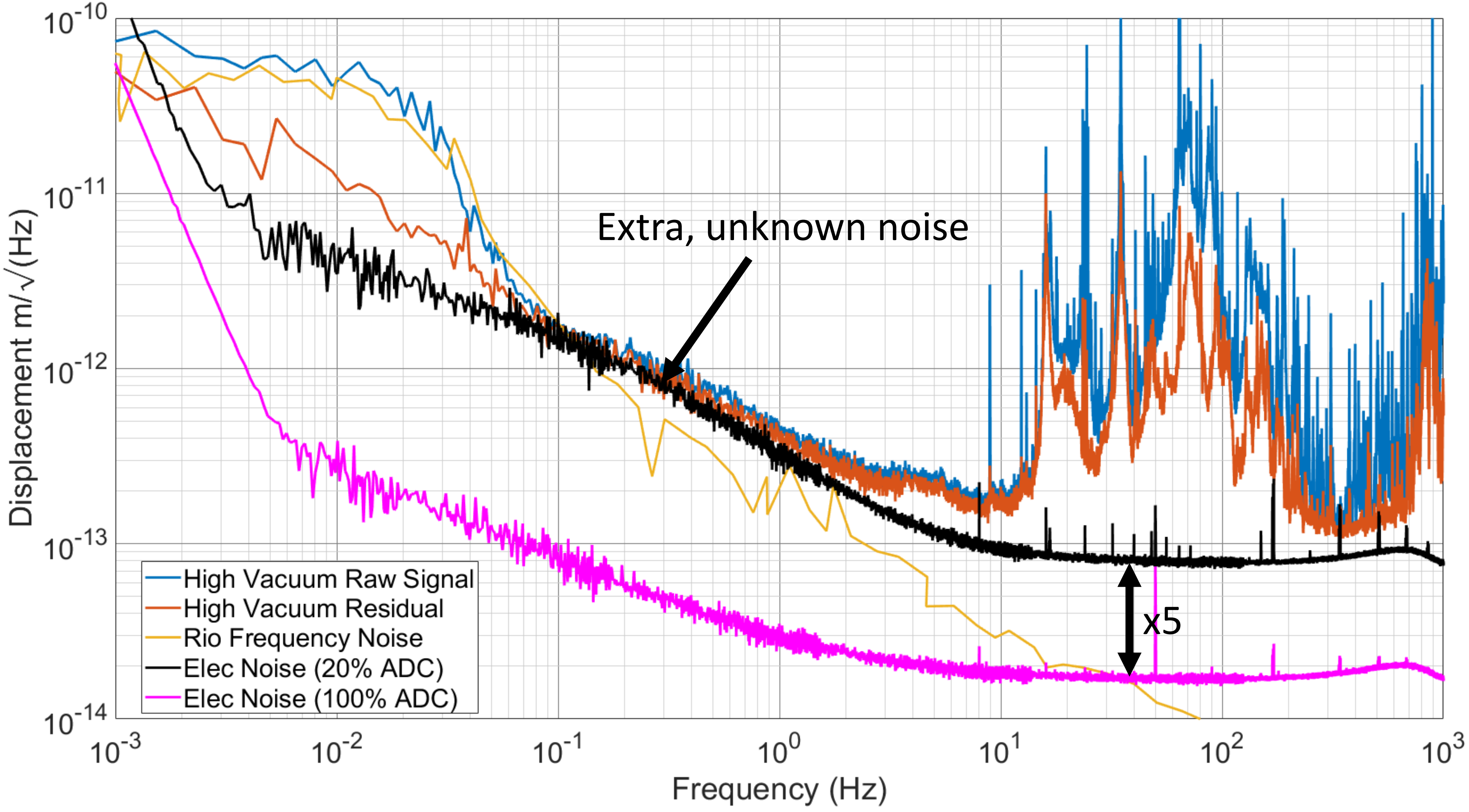
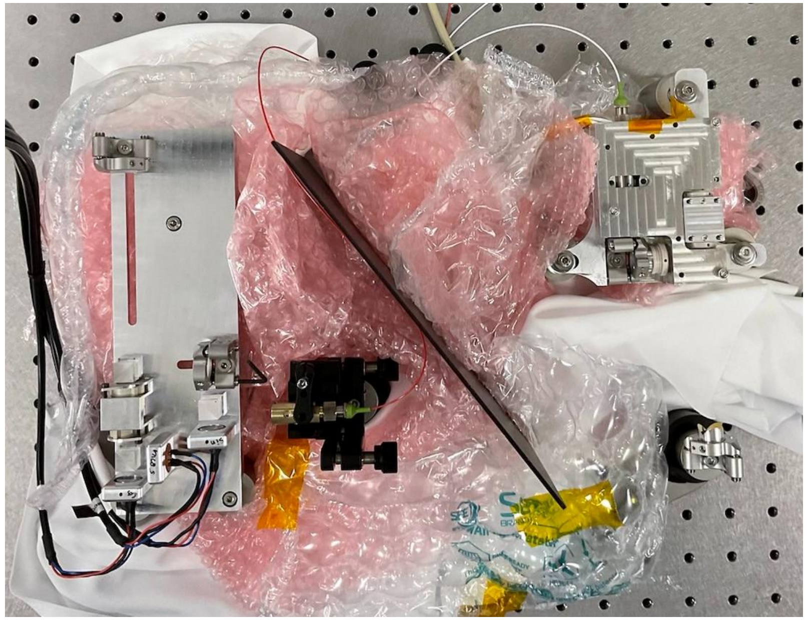


Cooper 2018, https://arxiv.org/abs/1710.05943

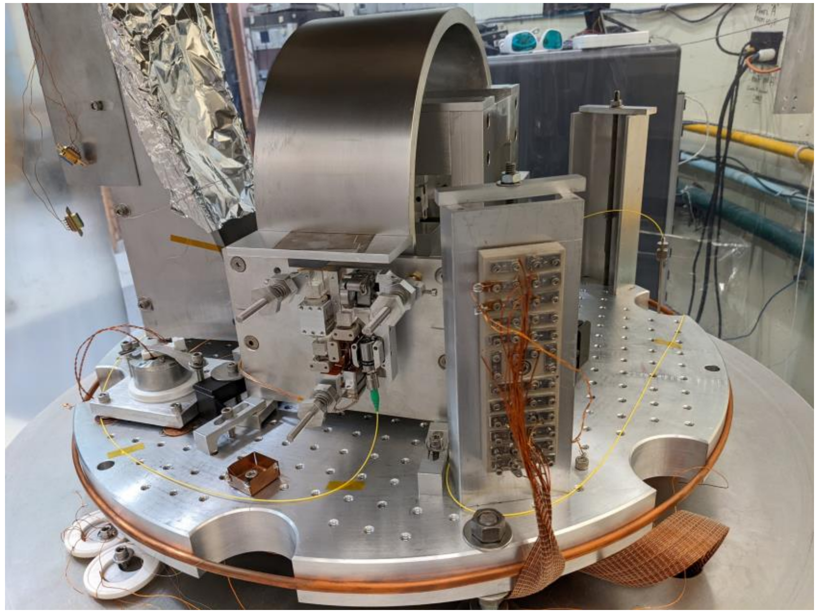


Extra, unknown noise
x5
High Vacuum Raw Signal
High Vacuum Residual
Rio Frequency Noise
Elec Noise (20% ADC)
Elec Noise (100% ADC)
Displacement m/√(Hz)
Frequency (Hz)

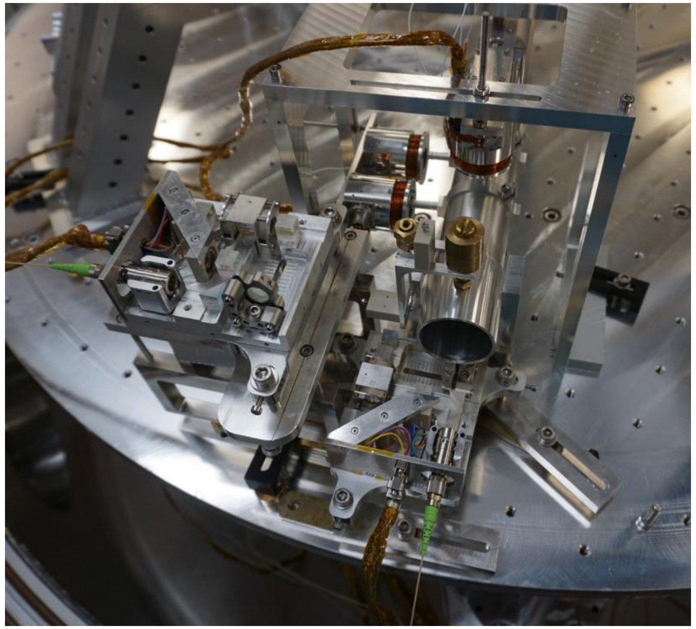
Currently in use…



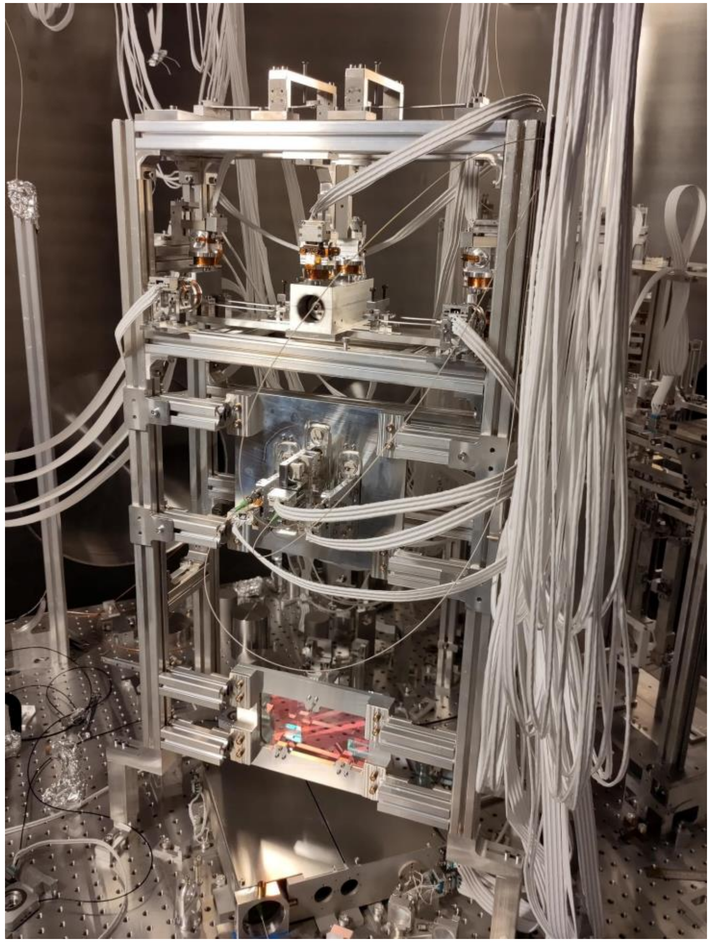
Laser frequency stabilisation experiment in Amsterdam



Cylindrical rotation sensor readout at UW



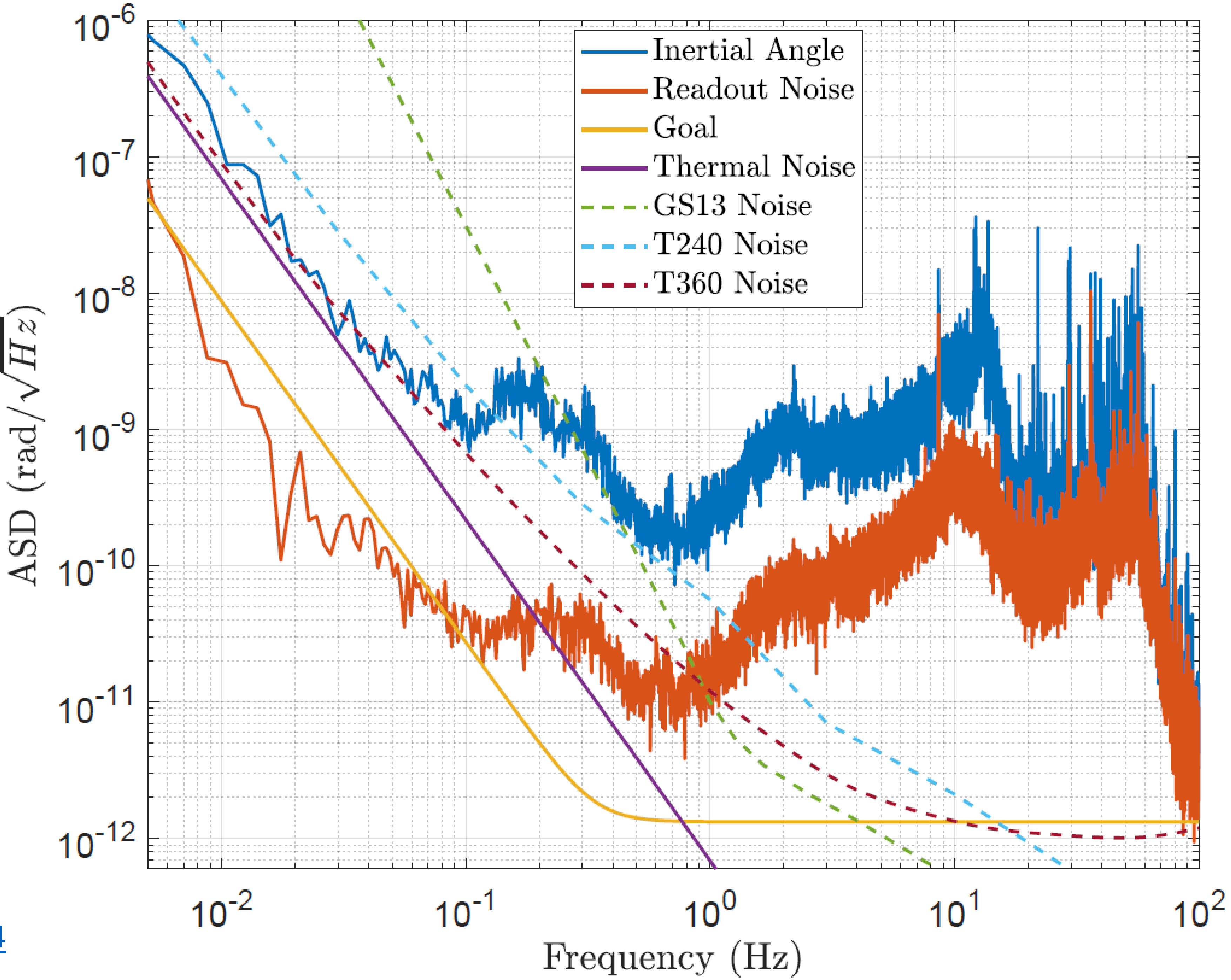
Readout of Birmingham 6D experiment
https://dcc.ligo.org/LIGO-G2300542



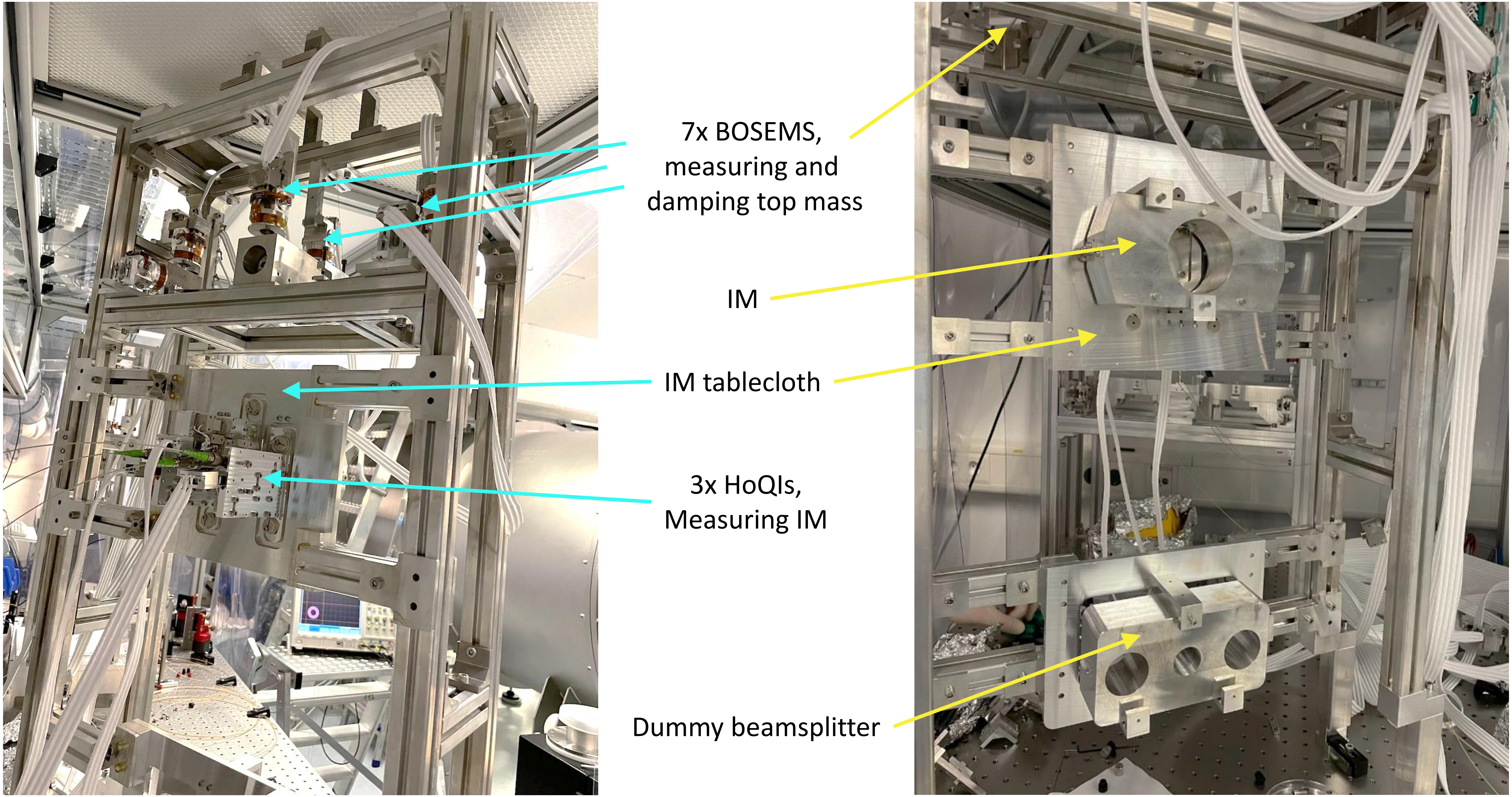
Measuring IM in AEI 10m prototype beamsplitter suspension

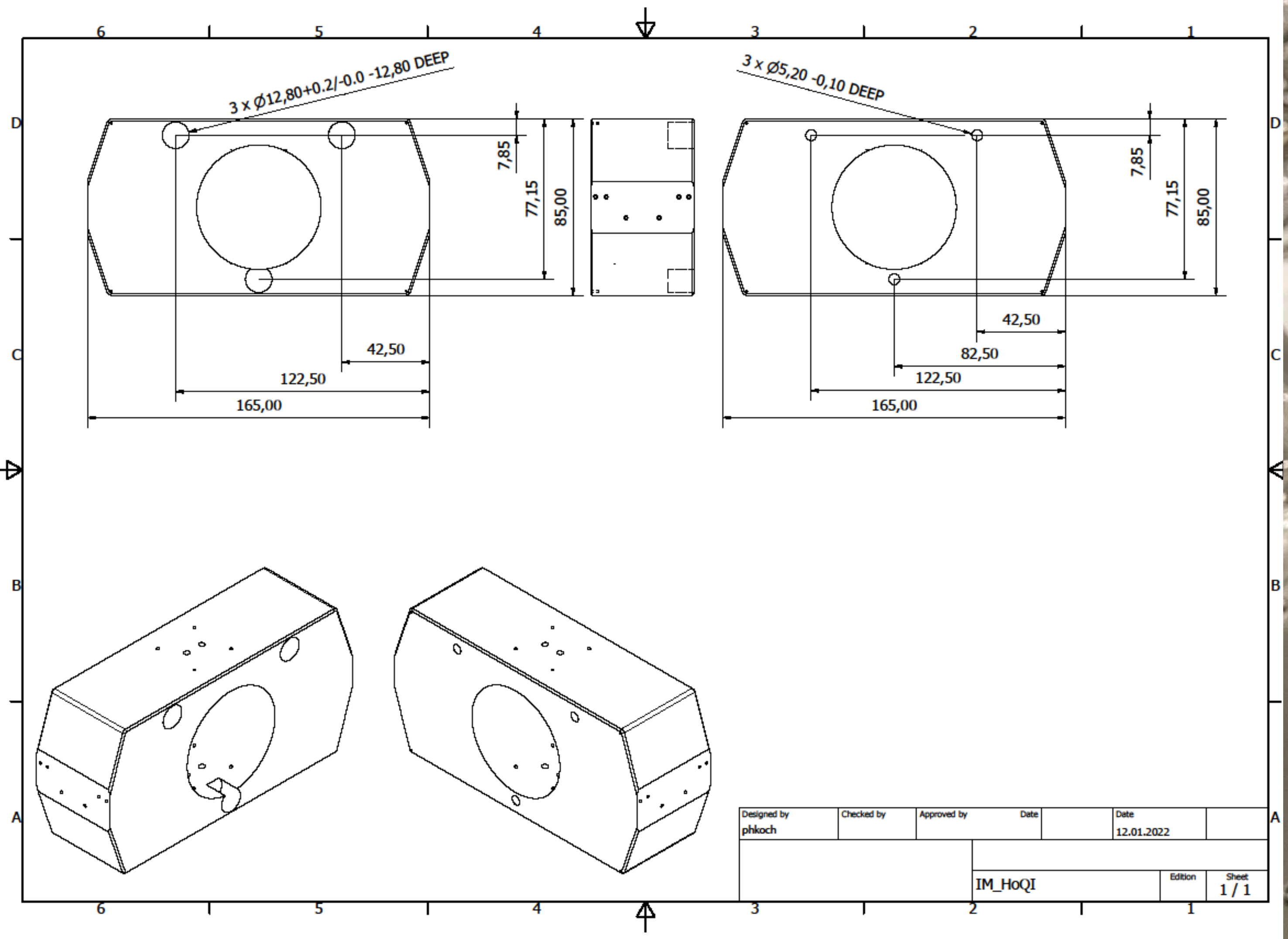
CRS

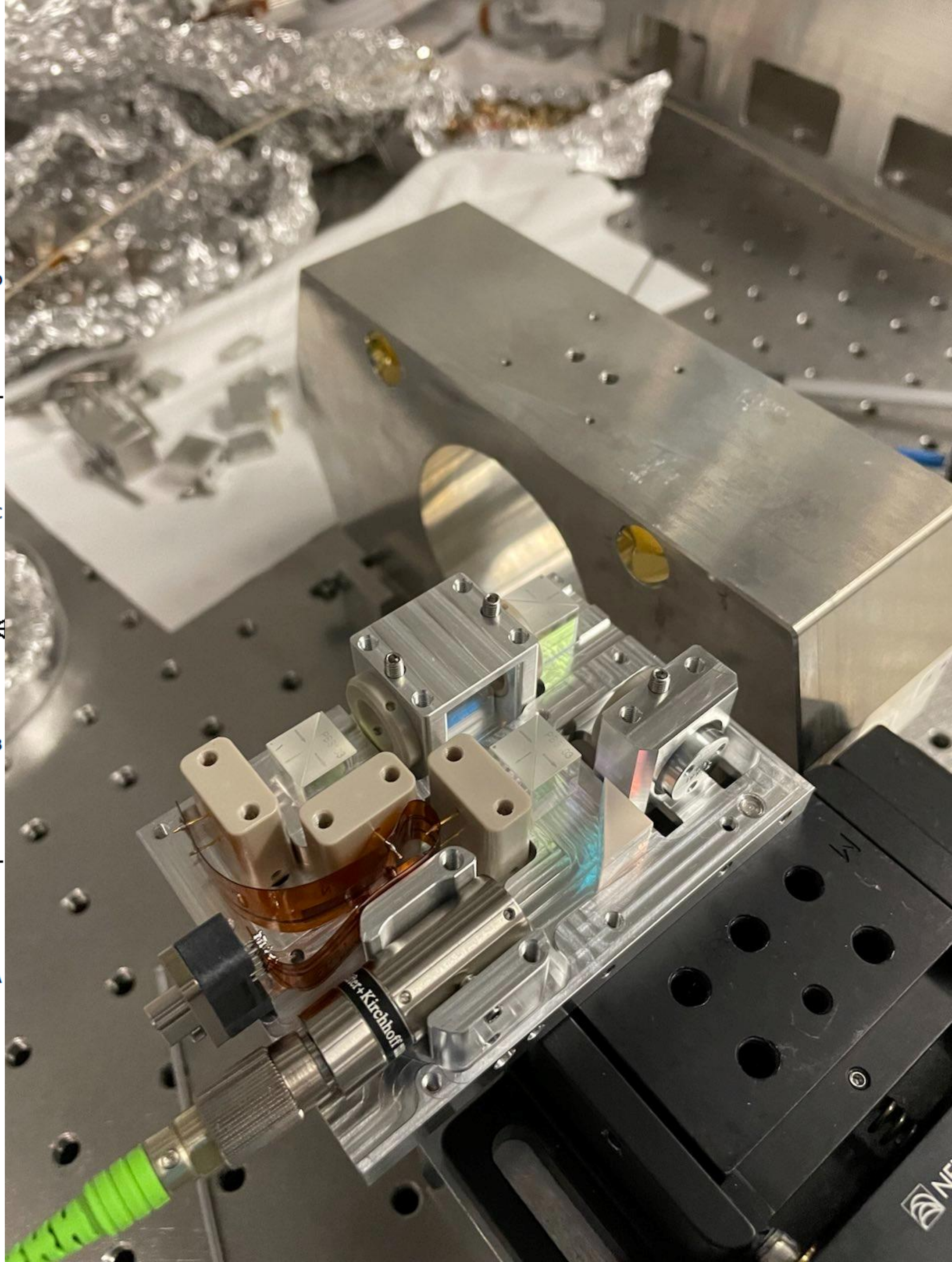
Used as readout for CRS, soon to be tested at Caltech with hopes to install one in LIGO in the O4 break



https://dcc.ligo.org/LIGO-G2300474


7x BOSEMS,
measuring and
damping top mass
IM
IM tablecloth
3x HoQIs,
Measuring IM
Dummy beamsplitter


3 x Ø12,80+0.2/-0.0 -12,80 DEEP
3 x Ø5,20 -0,10 DEEP
7,85
77,15
85,00
42,50
82,50
122,50
165,00
Designed by
phkoch
Checked by
Approved by
Date
Date
12.01.2022
IM_HoQI
Edition
Sheet
1 / 1

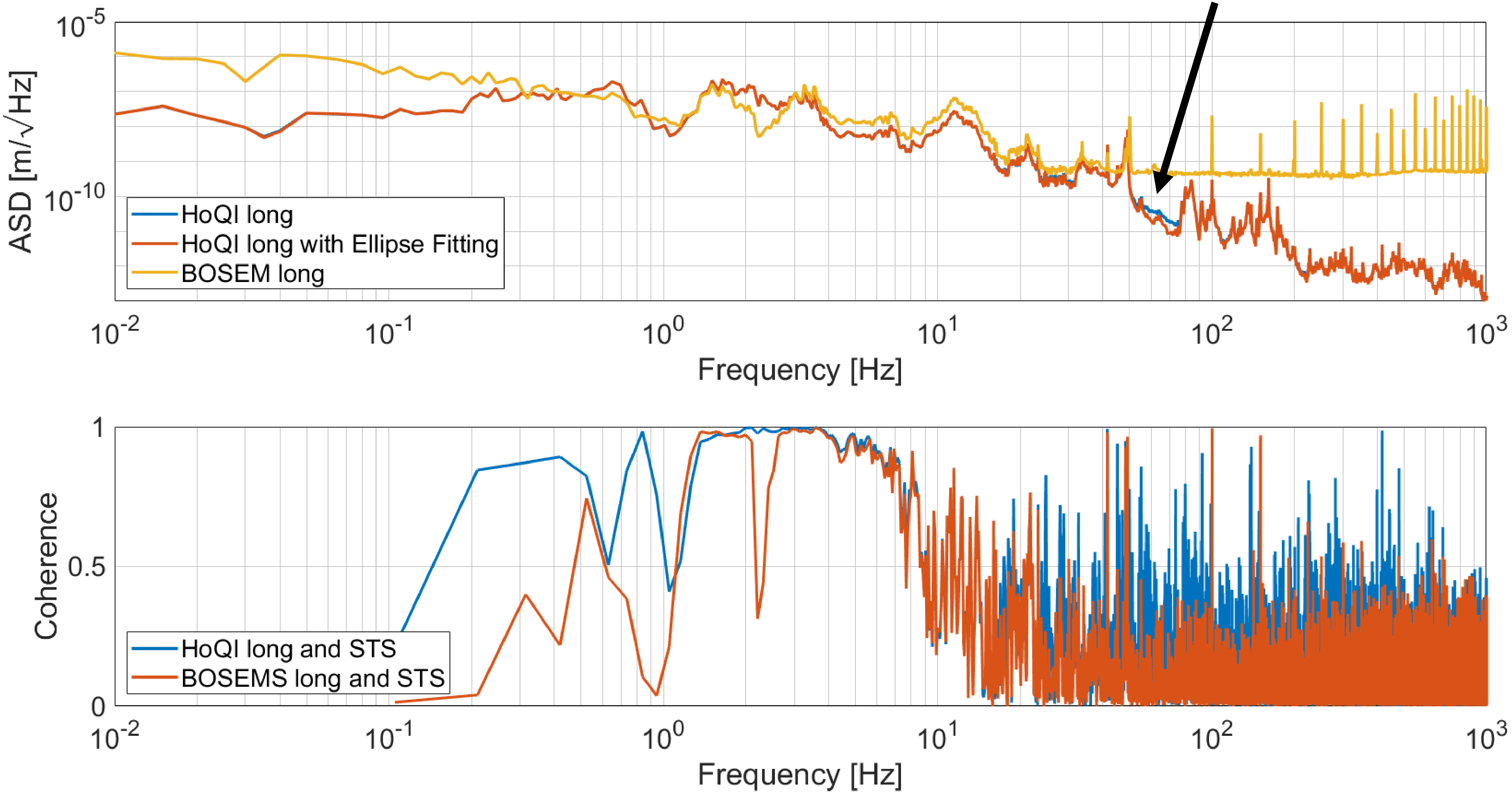


AEI suspension tests

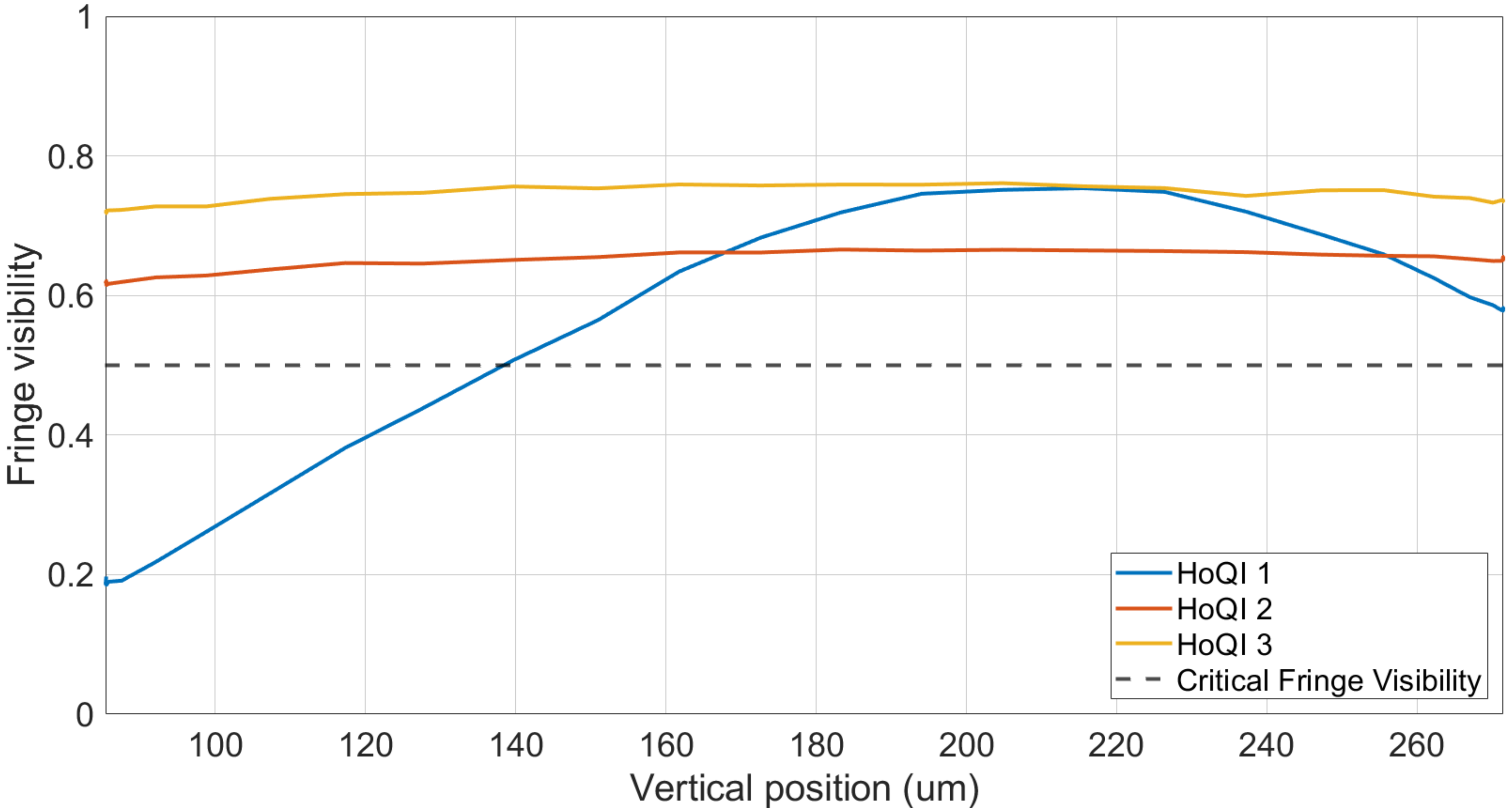
- Installed three HoQIs on beamsplitter triple suspension measuring intermediate mass long, pitch and yaw in February 2022
- Suspension was in clean tent on an optical bench (no table isolation)
- Initial results show coherence with seismometer measurements on ground nearby and high frequency performance better than BOSEMs
- Even with lots of motion (pre BOSEM damping) HoQIs measured motion well
- Suspension moved (with HoQIs attached) onto AEI-SAS early 2023
- Good contrast was gained pretty easily after HoQIs were re-connected but recently been some power loss in H2/3 (think this is coupling problem)
- Most recent measurements are done in air, with the isolation table in the highest control state which is safe in air

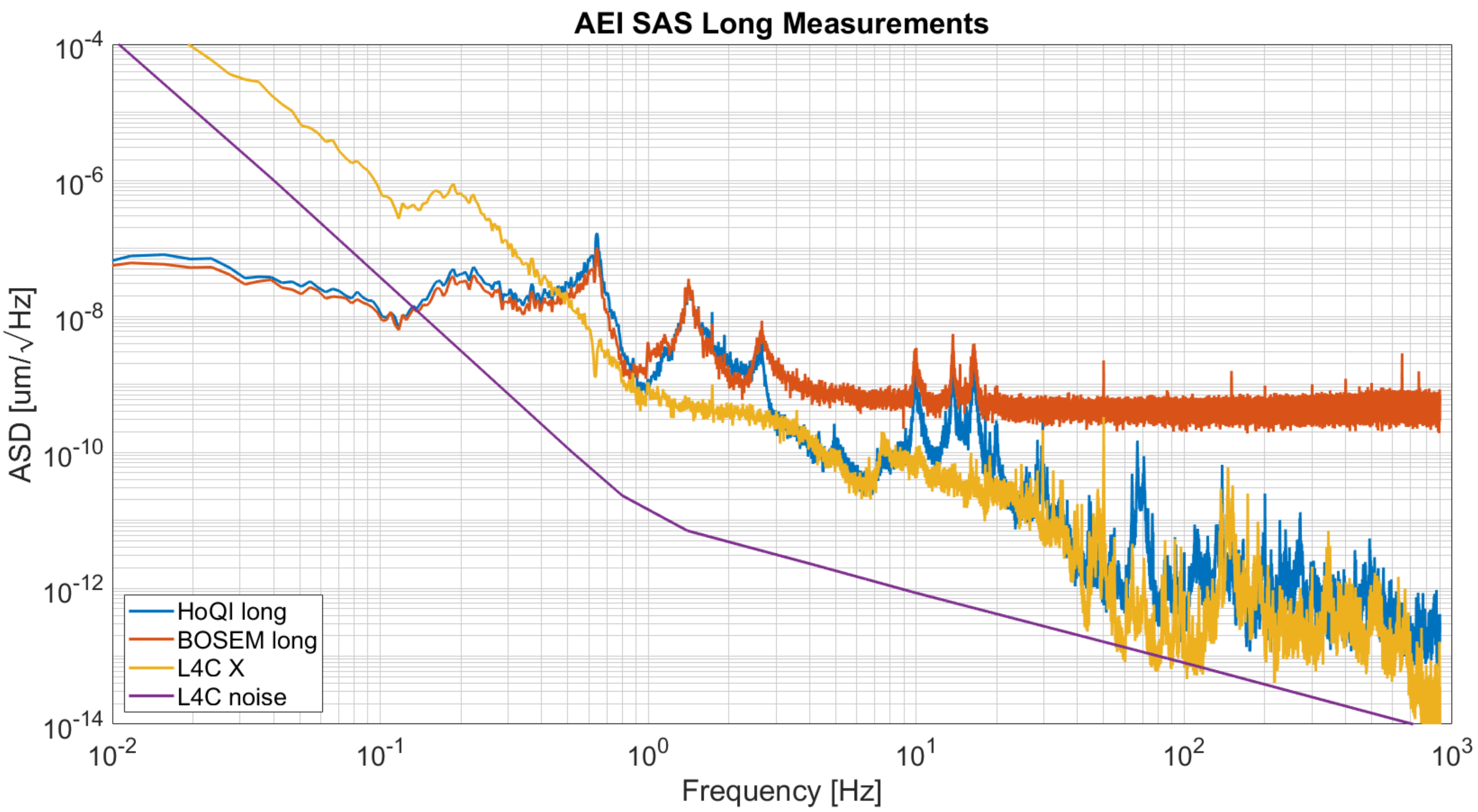
Initial tests

Small effect of EF = not much non-linearity

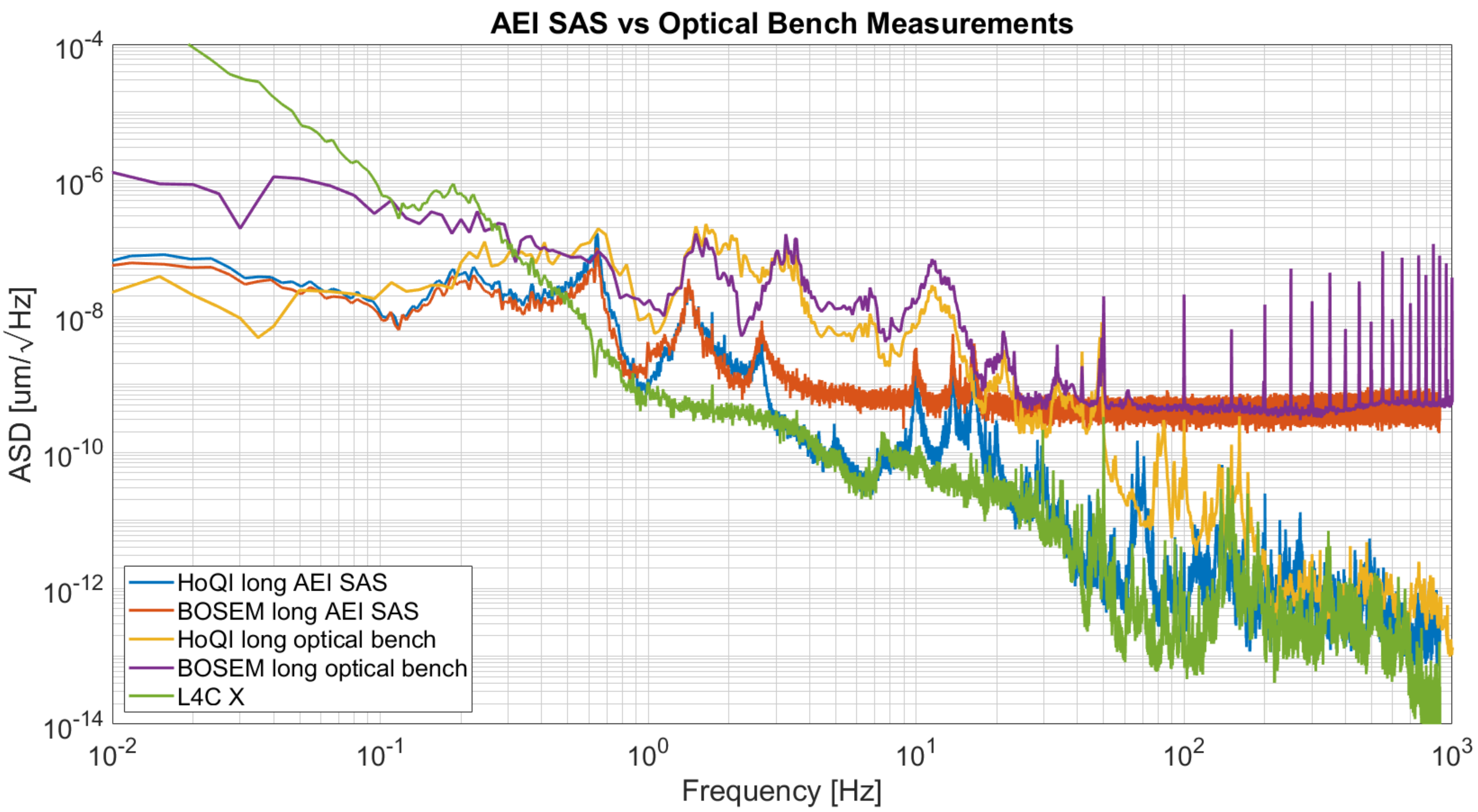


Driving vertical DoF with BOSEMs and measuring fringe visibility change
Critical fringe visibility is the limit at which still get good results

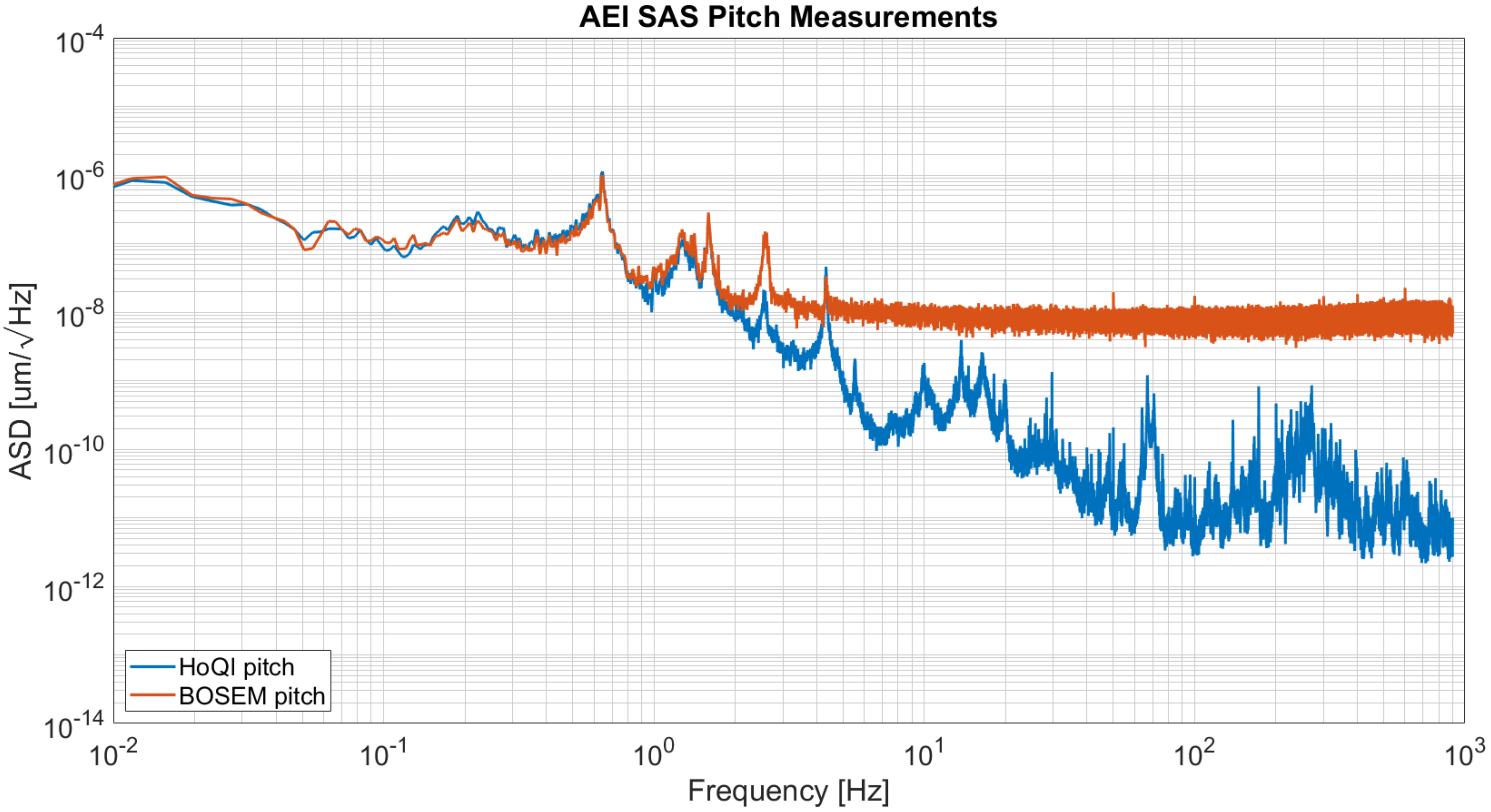




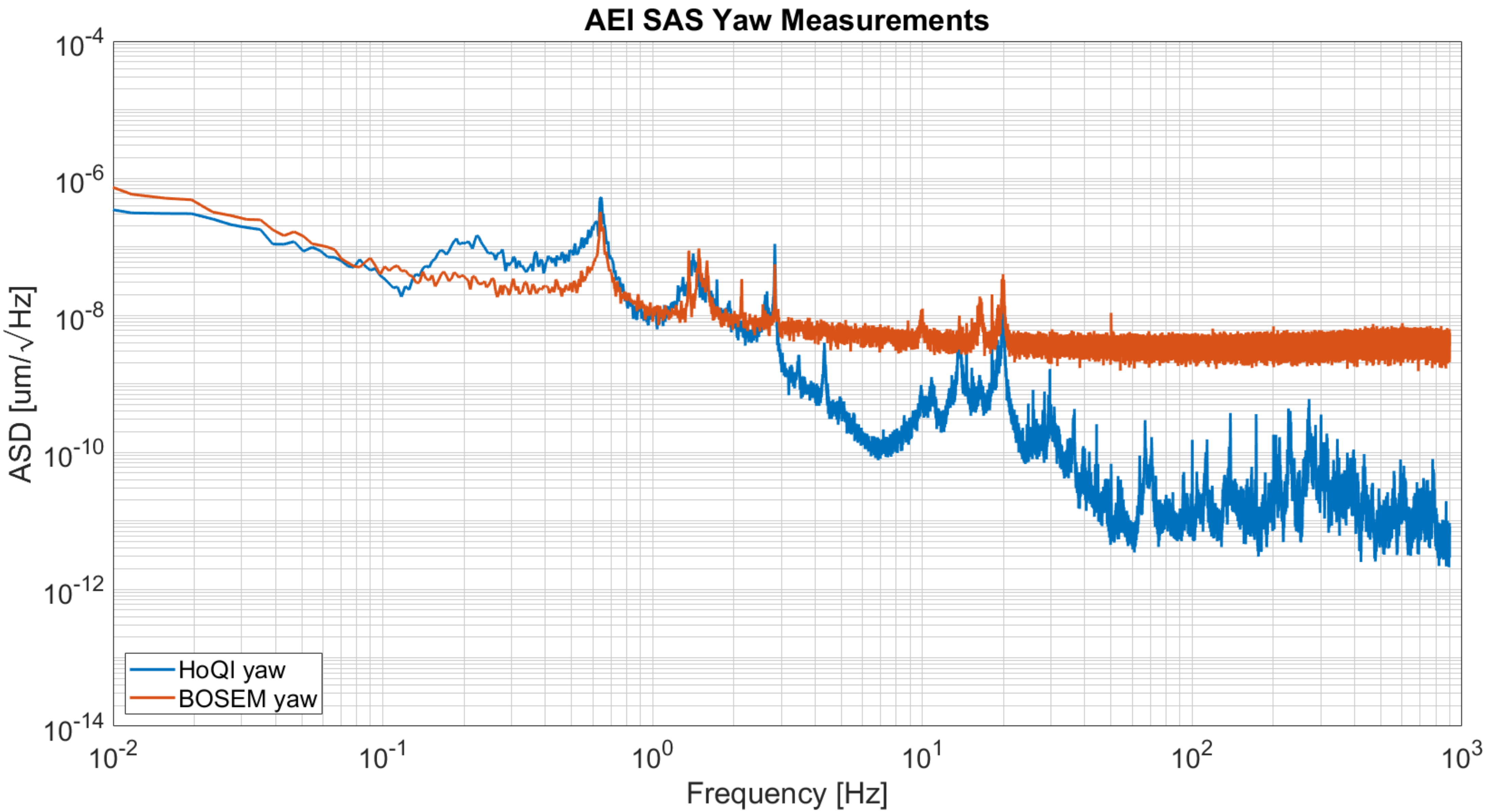
AEI SAS Long Measurements
ASD [um/√Hz]
Frequency [Hz]
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-2
10^-1
10^0
10^1
10^2
10^3
HoQI long
BOSEM long
L4C X
L4C noise



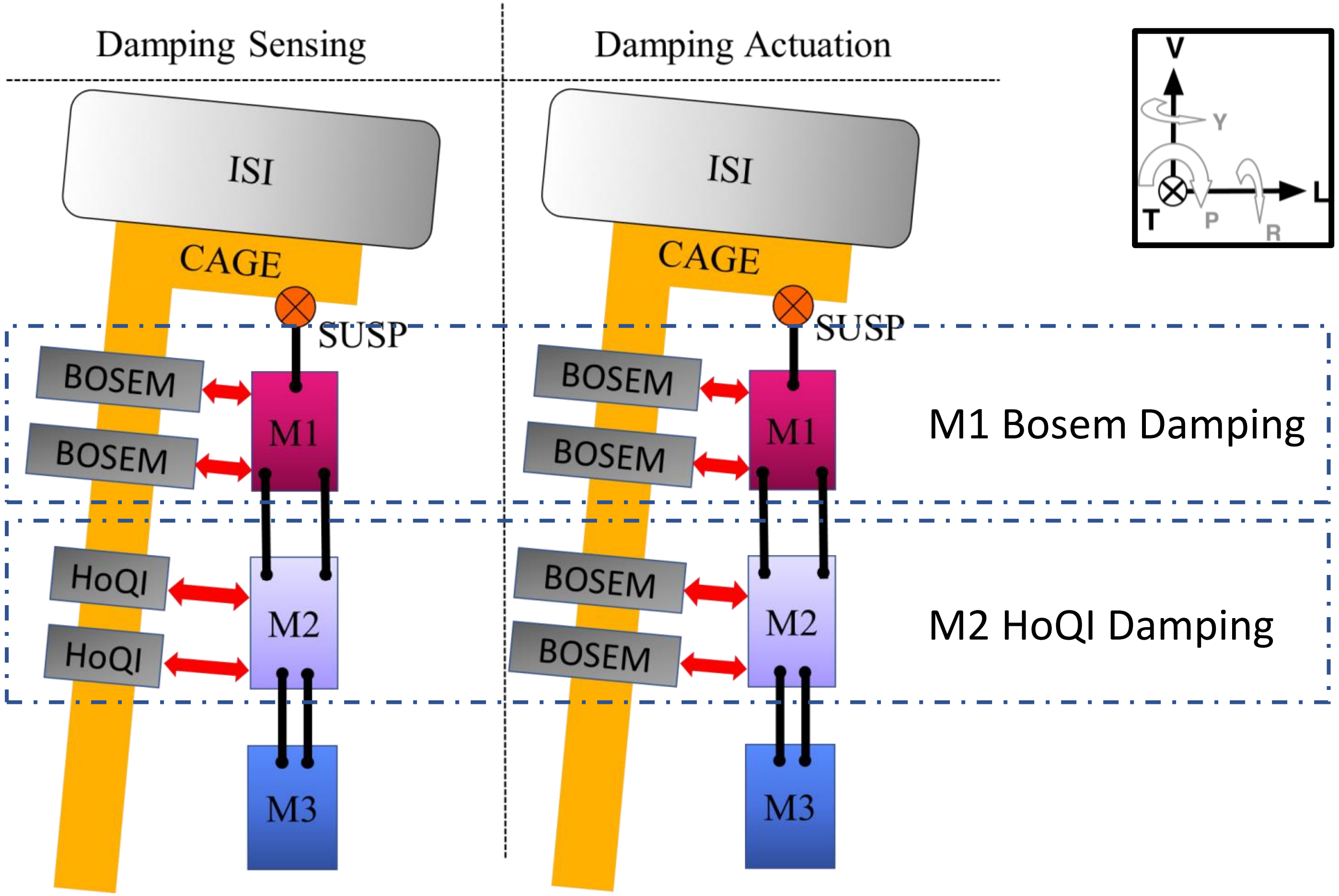
AEI SAS vs Optical Bench Measurements
ASD [um/√Hz]
Frequency [Hz]
HoQI long AEI SAS
BOSEM long AEI SAS
HoQI long optical bench
BOSEM long optical bench
L4C X

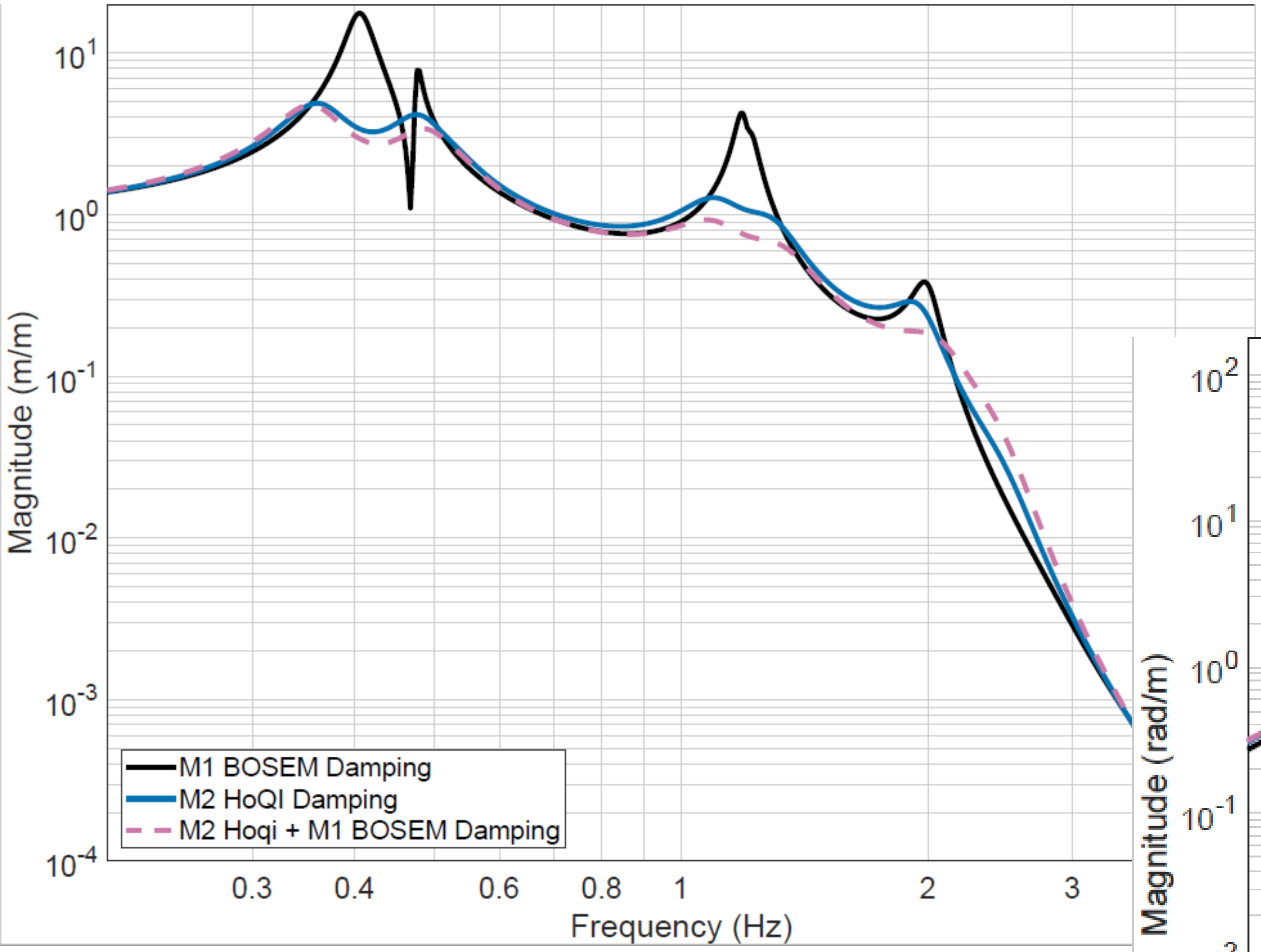

AEI SAS Pitch Measurements
ASD [um/√Hz]
Frequency [Hz]
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-2
10^-1
10^0
10^1
10^2
10^3
HoQI pitch
BOSEM pitch

At low frequencies the yaw bosems and yaw hoqis should see exactly the same (no fundamental cross coupling, probably driven by something like coil driver noise)



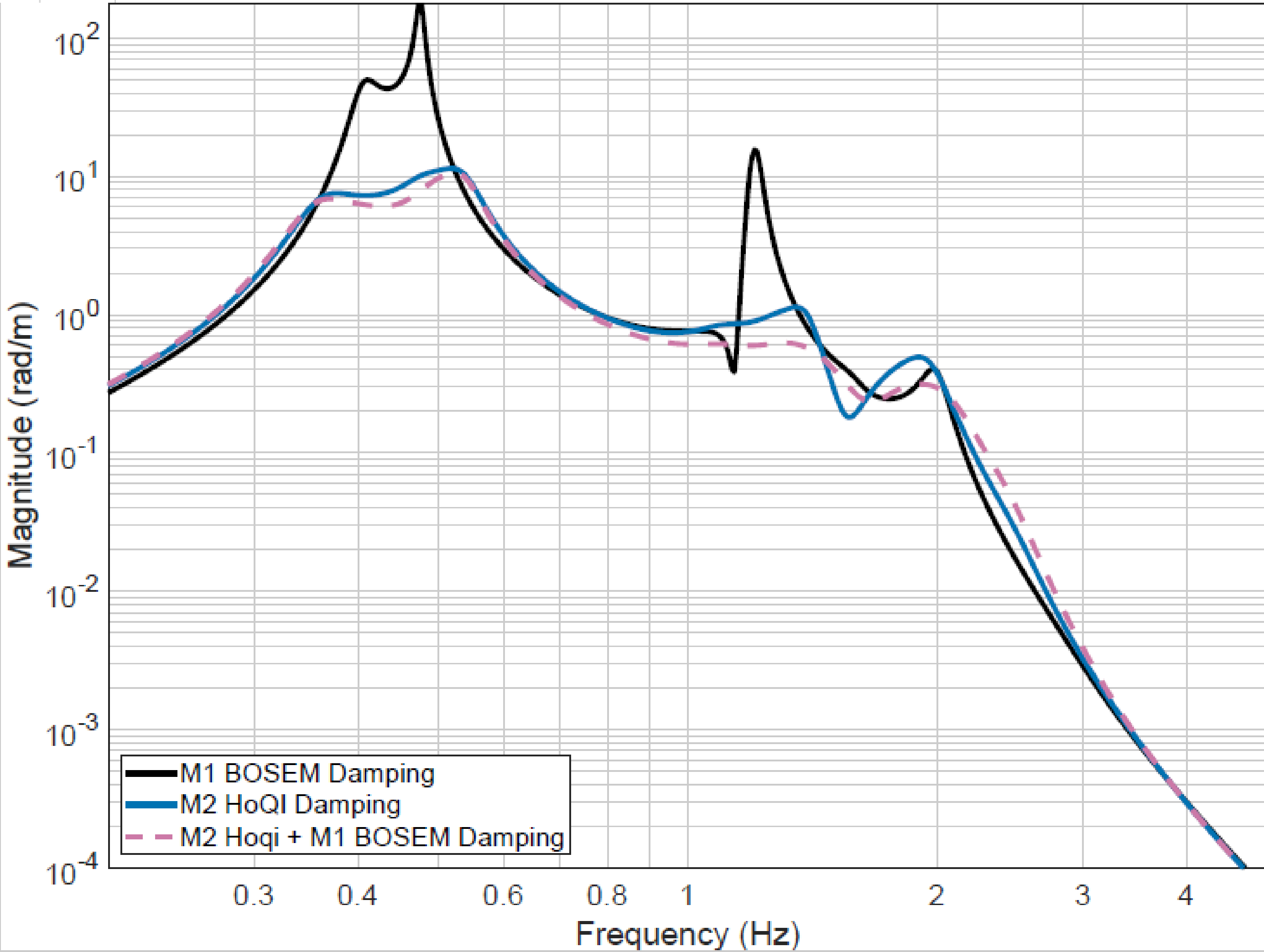
HoQI damping modelling in BBSS

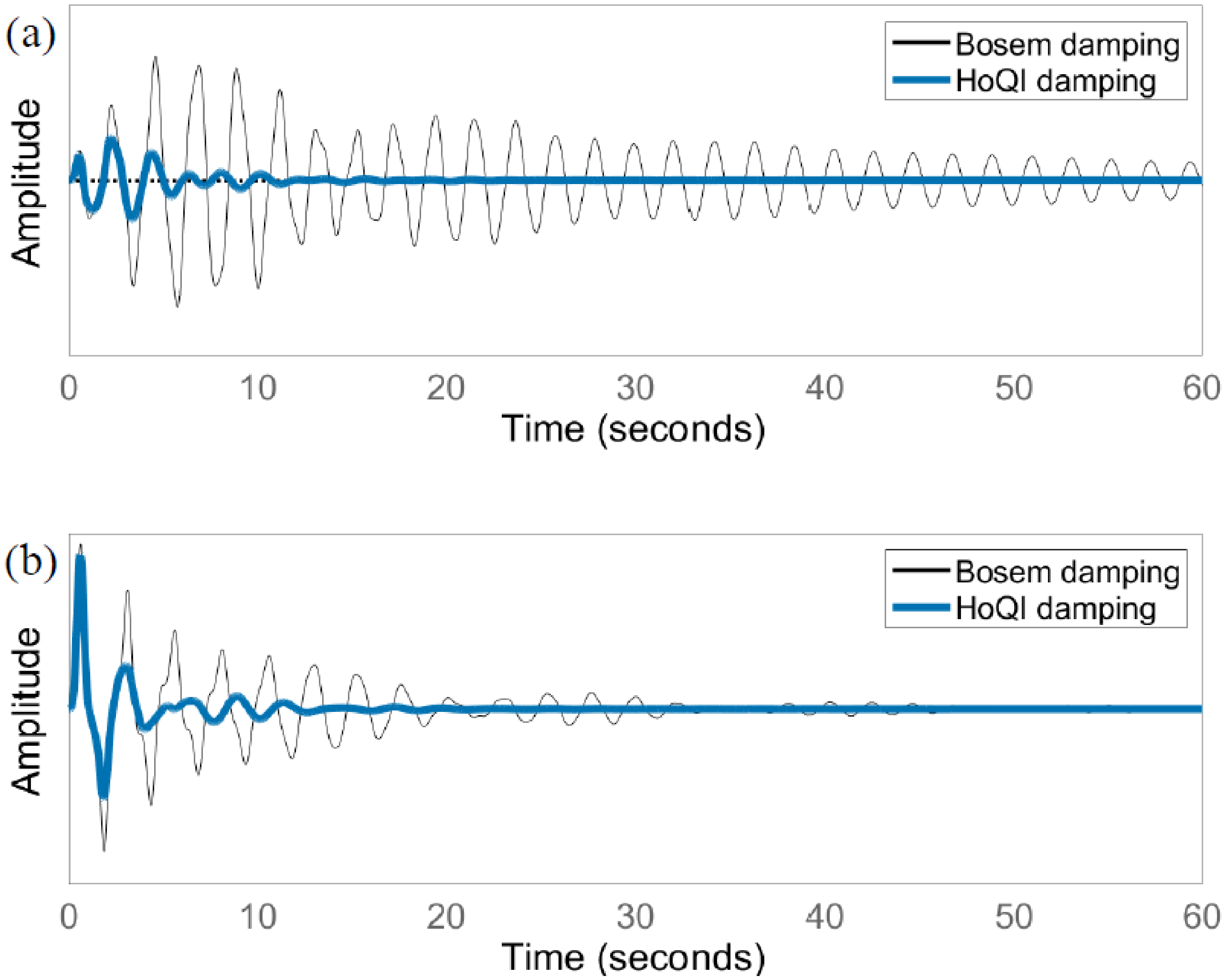




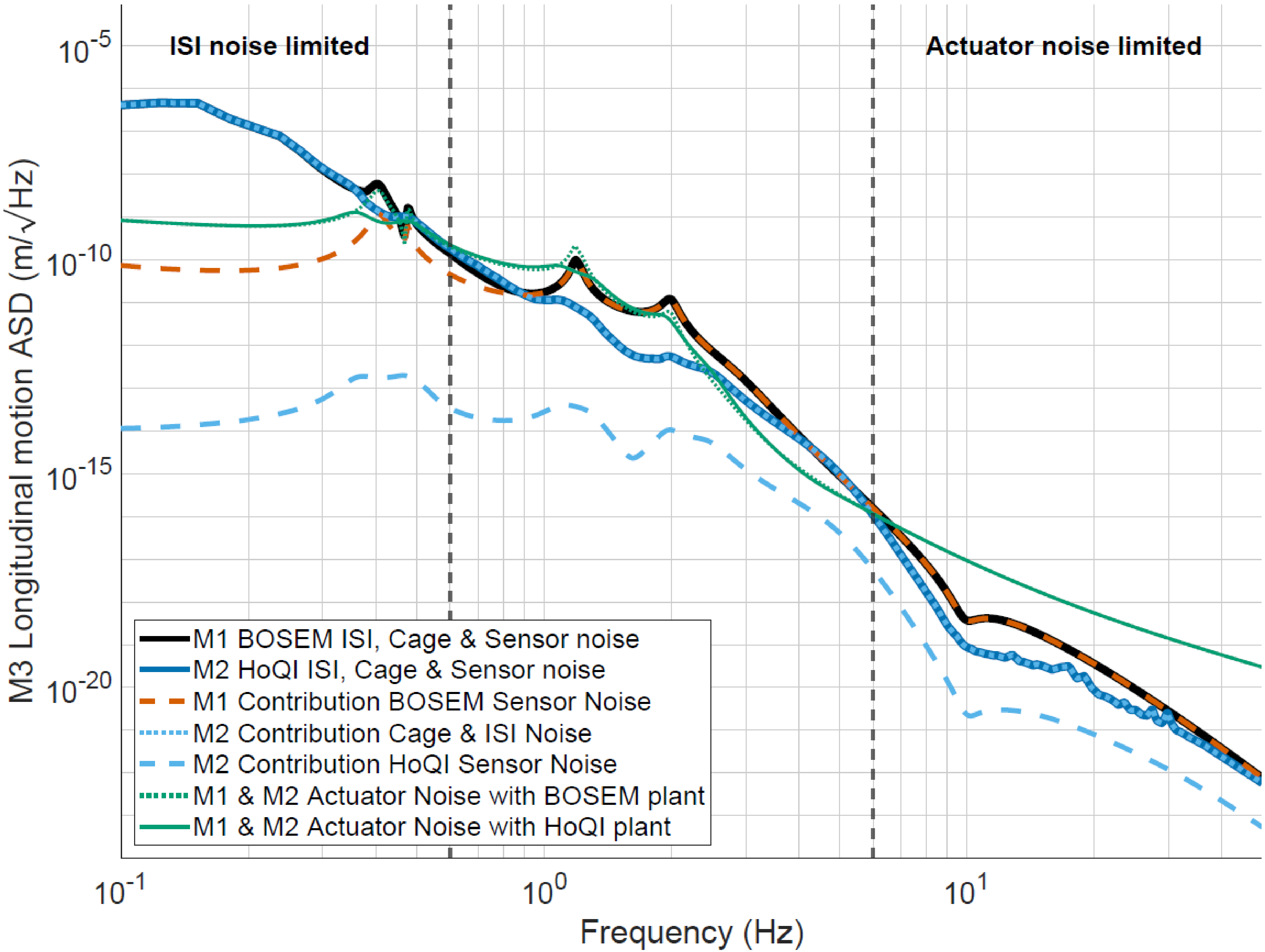
transfer function from ISI translation to optic translation in the length direction

transfer function from ISI translation to optic rotation in the pitch direction

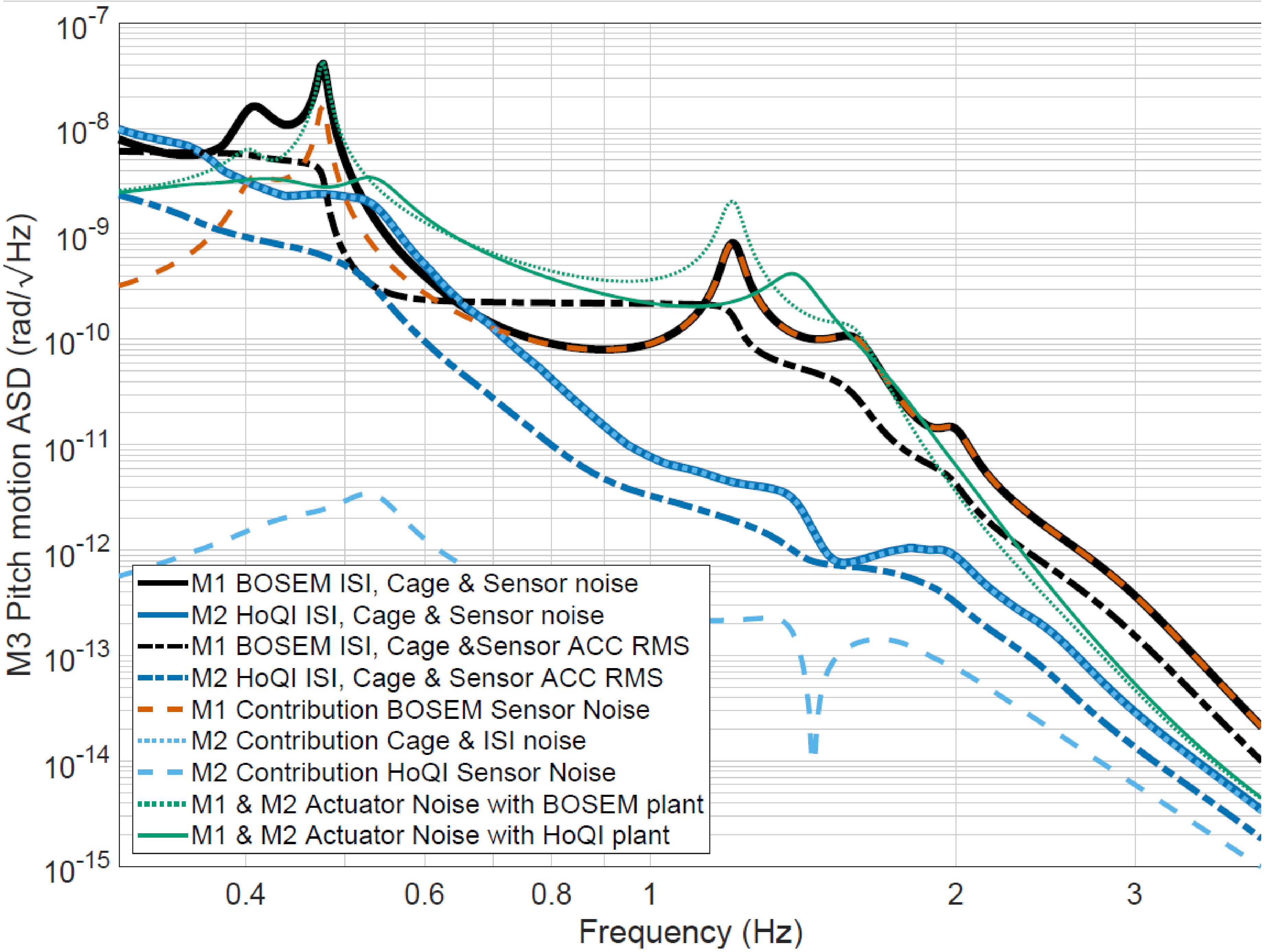




(a)
Bosem damping
HoQI damping
Amplitude
0
10
20
30
40
50
60
Time (seconds)
(b)
Bosem damping
HoQI damping
Amplitude
0
10
20
30
40
50
60
Time (seconds)



ISI noise limited
Actuator noise limited
M3 Longitudinal motion ASD (m/√Hz)
Frequency (Hz)
10^-5
10^-10
10^-15
10^-20
10^-1
10^0
10^1
M1 BOSEM ISI, Cage & Sensor noise
M2 HoQI ISI, Cage & Sensor noise
M1 Contribution BOSEM Sensor Noise
M2 Contribution Cage & ISI Noise
M2 Contribution HoQI Sensor Noise
M1 & M2 Actuator Noise with BOSEM plant
M1 & M2 Actuator Noise with HoQI plant

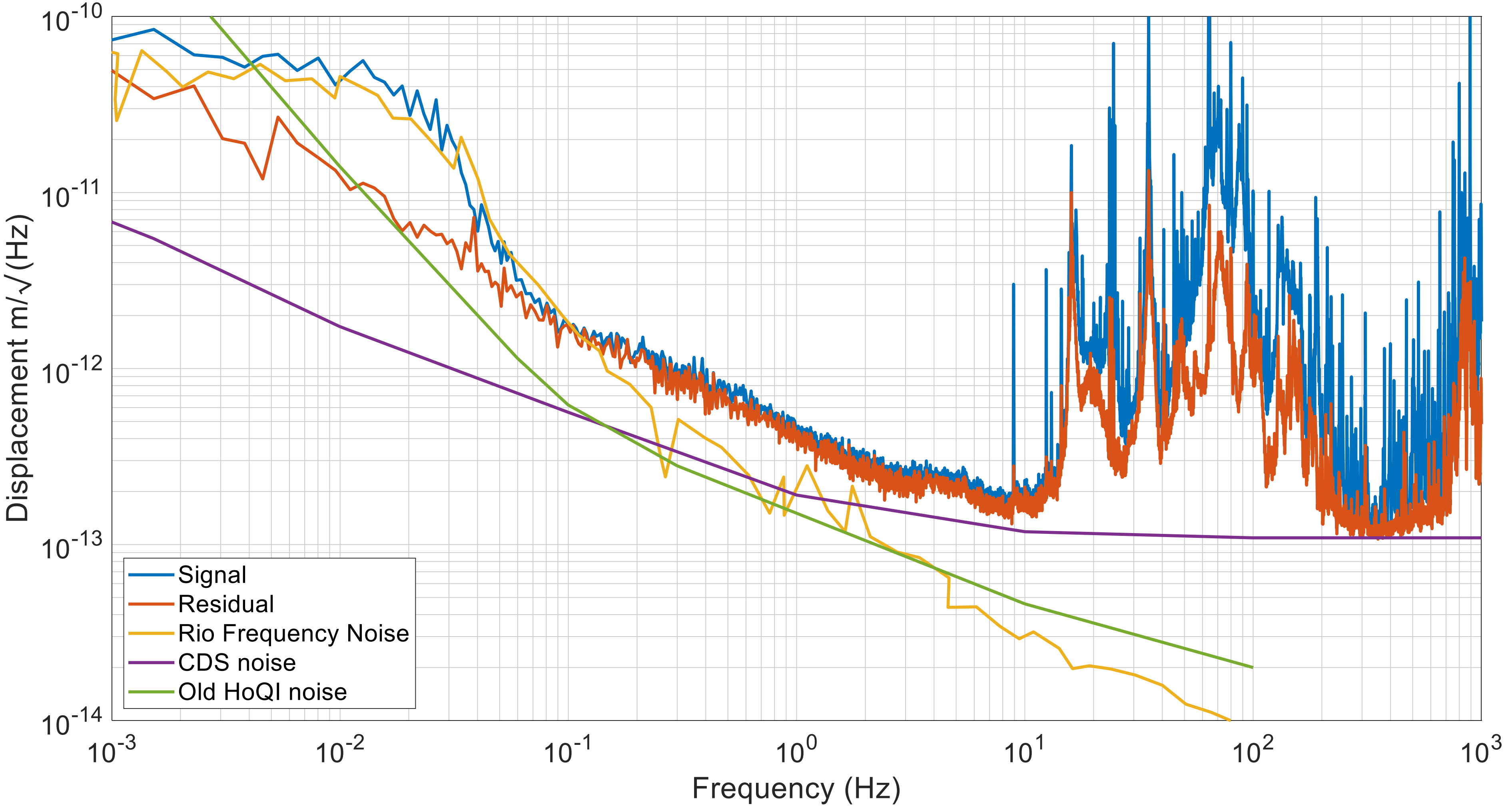


M3 Pitch motion ASD (rad/√Hz)
Frequency (Hz)
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
10-15
0.4
0.6
0.8
1
2
3
M1 BOSEM ISI, Cage & Sensor noise
M2 HoQI ISI, Cage & Sensor noise
M1 BOSEM ISI, Cage &Sensor ACC RMS
M2 HoQI ISI, Cage & Sensor ACC RMS
M1 Contribution BOSEM Sensor Noise
M2 Contribution Cage & ISI noise
M2 Contribution HoQI Sensor Noise
M1 & M2 Actuator Noise with BOSEM plant
M1 & M2 Actuator Noise with HoQI plant

Useful Links

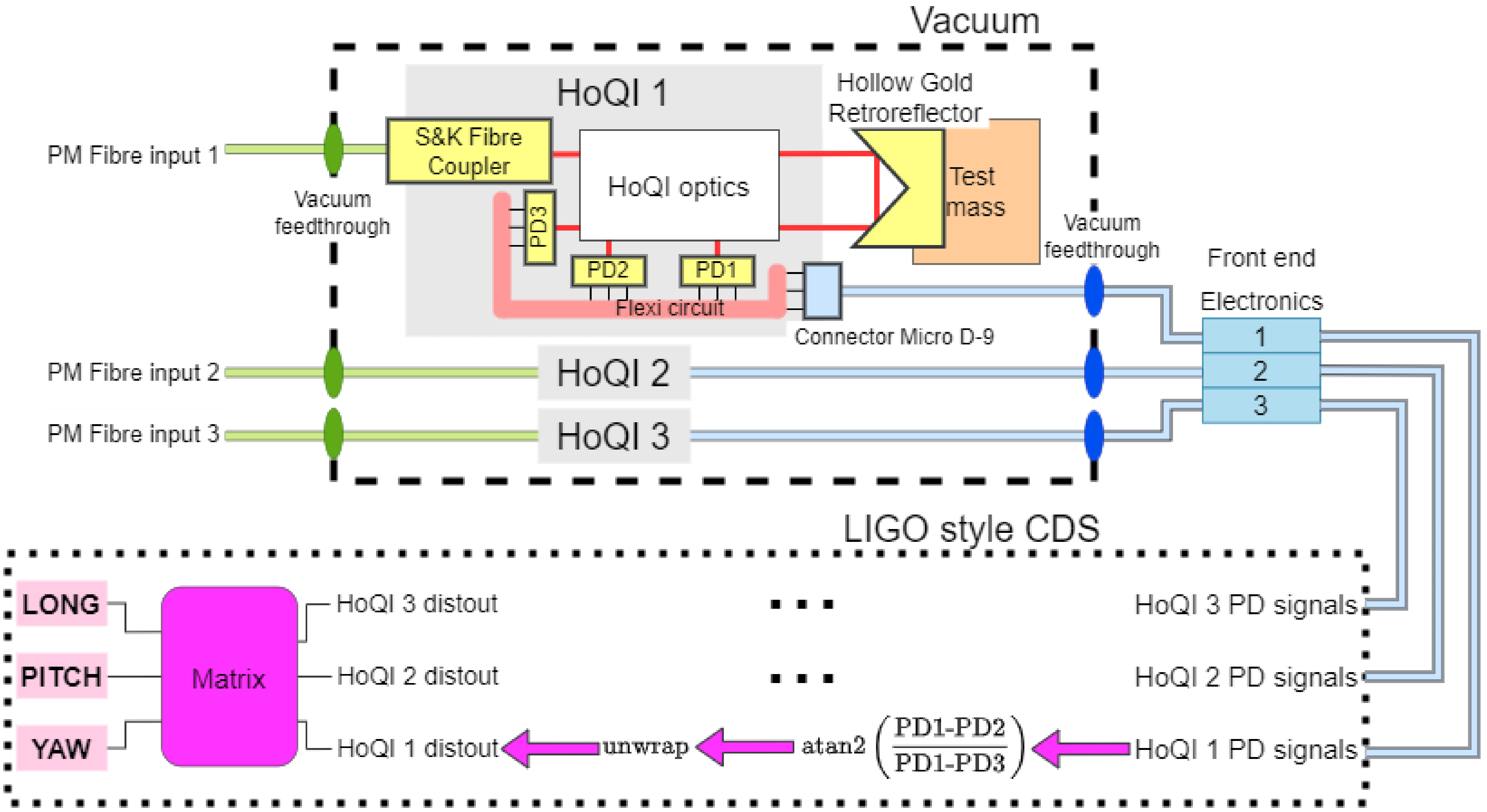
- GWADW talk HoQI construction, modelling of BBSS HoQI damping
- BBSS HoQI damping preliminary paper (Jesse van Dongen)
- SWG presentation, in-vacuum measurements
- HoQI CDS readout board pre-amp details
- CAM plate for HoQI suspension in BBSS
- Technical Readiness of HoQI LIGO systems call presentation

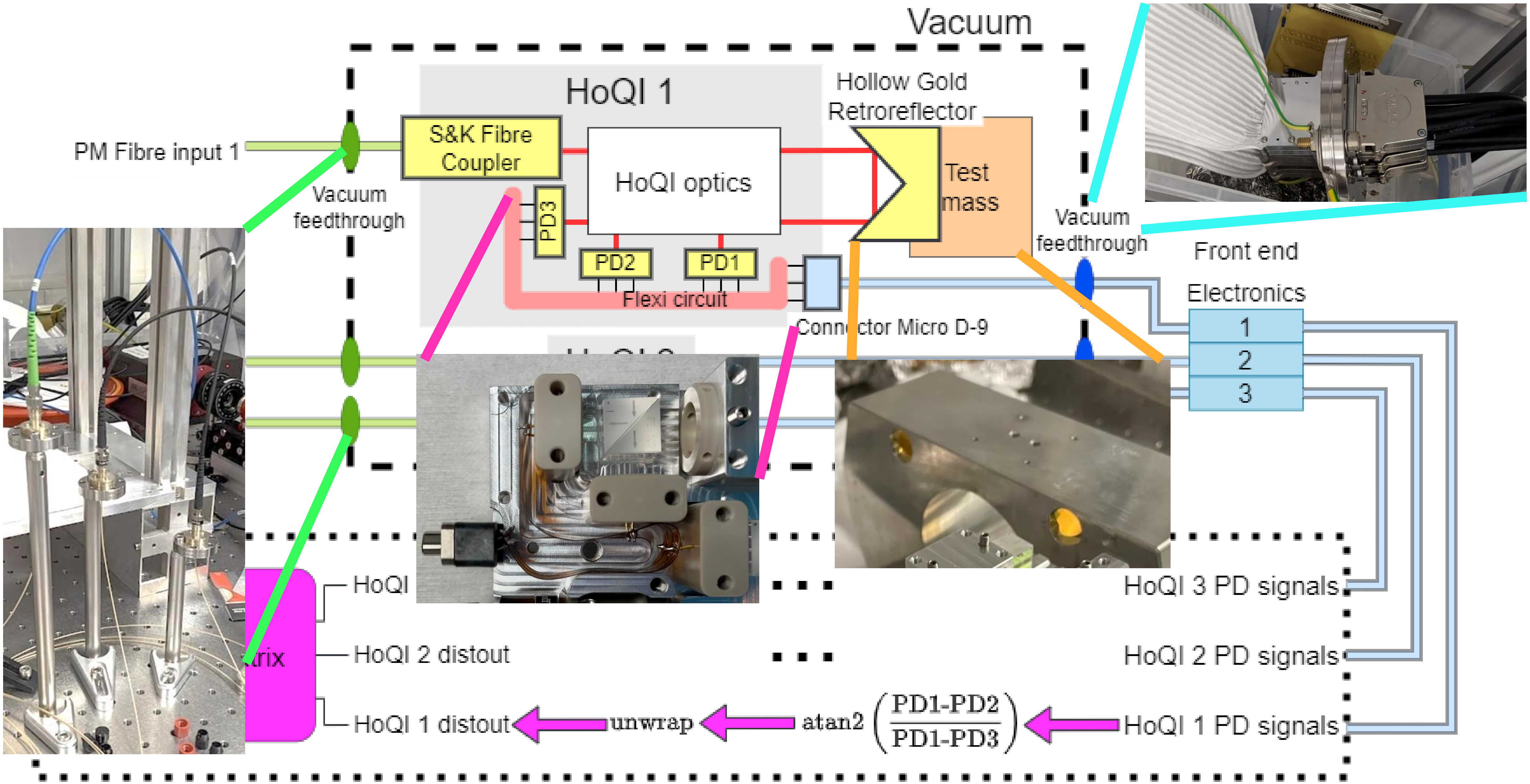
Alternate plot



What is important for HoQI?
(Practically and for good performance)

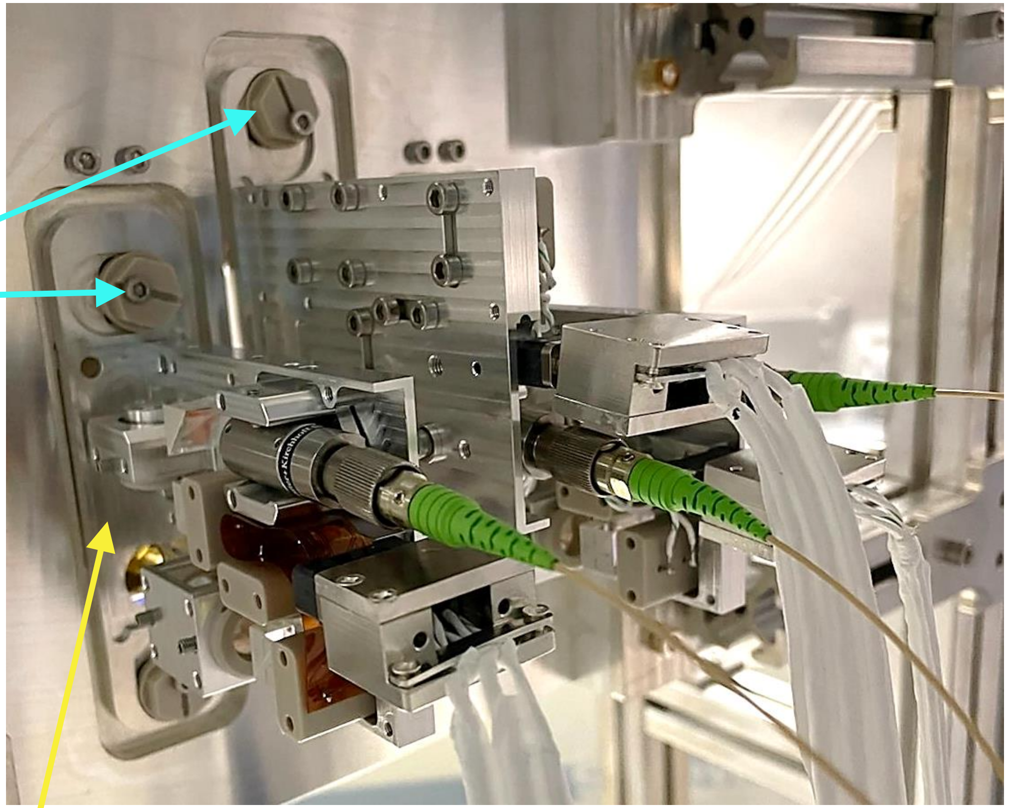
- Repeatability in units
- Robust signal and optics chain
- Vacuum compatibility
- Quality, frequency stabilised laser
- Fringe visibility above 0.5


Vacuum
HoQI 1
Hollow Gold
Retroreflector
PM Fibre input 1
S&K Fibre
Coupler
HoQI optics
Test
mass
Vacuum
feedthrough
PD3
PD2
PD1
Flexi circuit
Vacuum
feedthrough
Front end
Electronics
Connector Micro D-9
1
2
3
PM Fibre input 2
HoQI 2
PM Fibre input 3
HoQI 3
LIGO style CDS
LONG
PITCH
YAW
Matrix
HoQI 3 distout
HoQI 2 distout
HoQI 1 distout
unwrap
atan2 (PD1-PD2 / PD1-PD3)
HoQI 3 PD signals
HoQI 2 PD signals
HoQI 1 PD signals

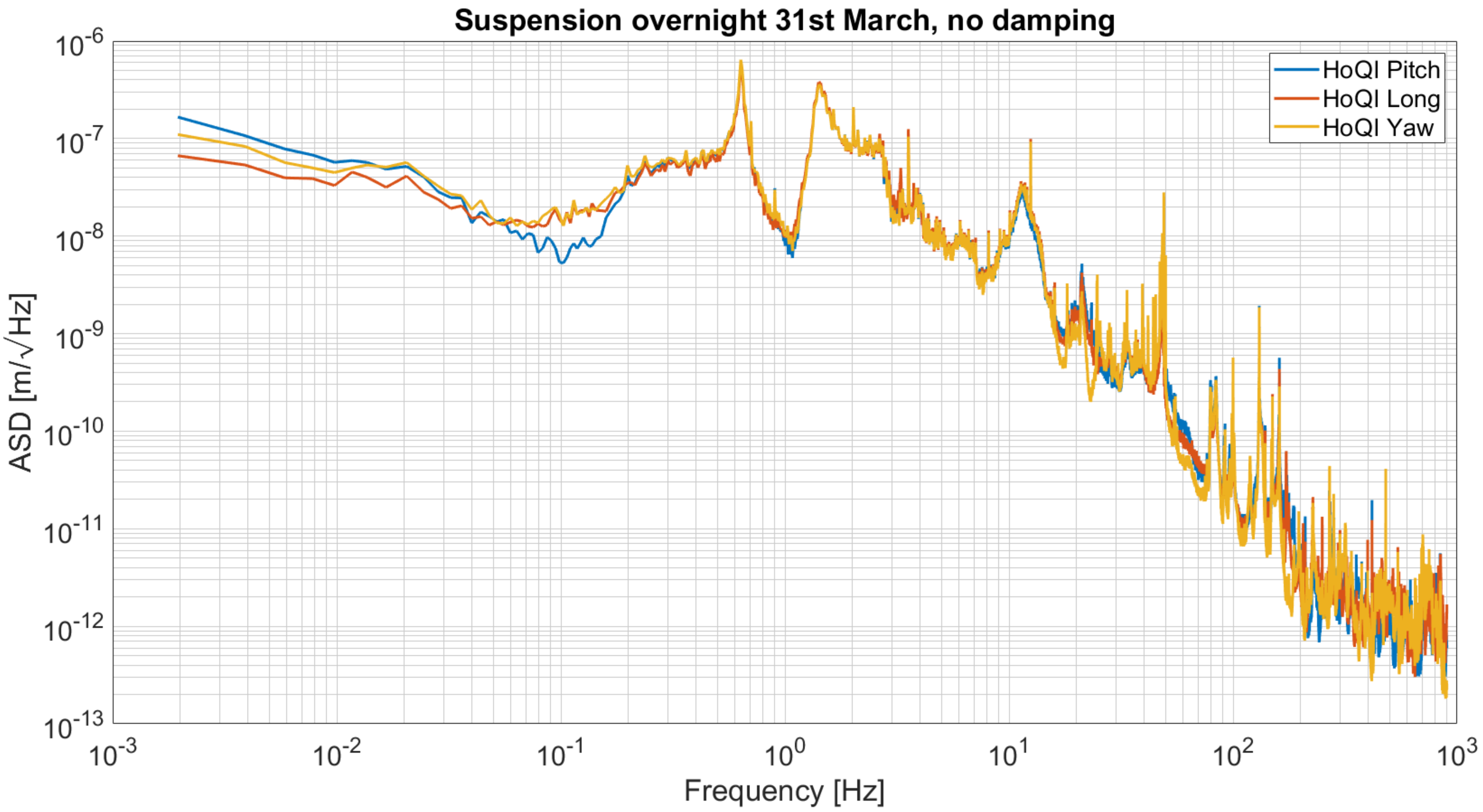

Vacuum
HoQI 1
PM Fibre input 1
S&K Fibre Coupler
HoQI optics
Hollow Gold Retroreflector
Test mass
Vacuum feedthrough
PD3
PD2
PD1
Flexi circuit
Connector Micro D-9
Vacuum feedthrough
Front end Electronics
1
2
3
HoQI
HoQI 2 distout
HoQI 1 distout
unwrap
atan2 (PD1-PD2 / PD1-PD3)
HoQI 3 PD signals
HoQI 2 PD signals
HoQI 1 PD signals
trix

Aligning and Mounting on the Suspension

- HoQIs first aligned to test mass on ground (stationary)
  - Once mounted, harder to adjust components
- HoQI baseplate screwed to mounting plates
- CAM adjusters give +/- 2mm of adjustment in vertical and horizontal
- Maximise fringe visibility for signal processing

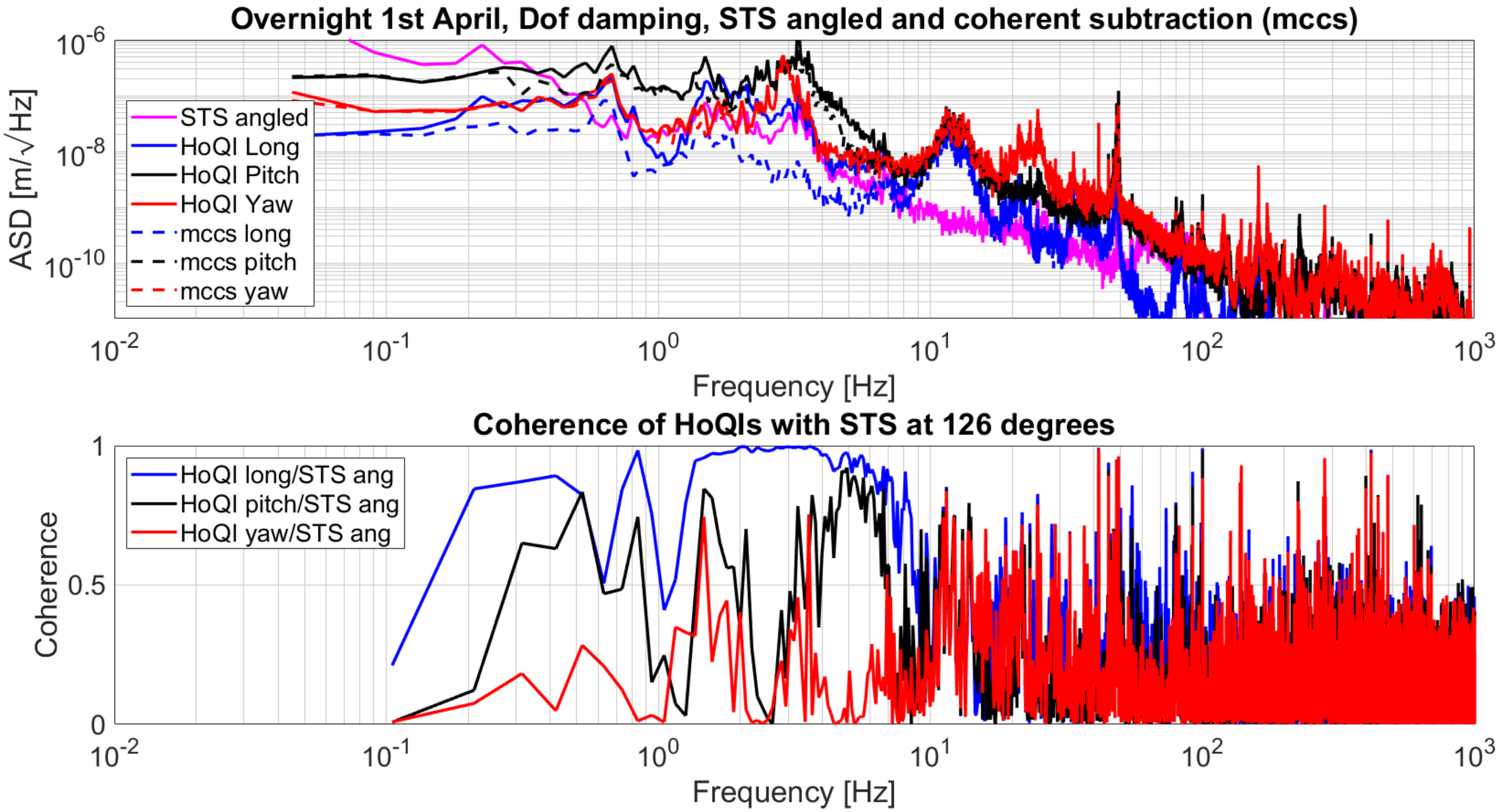


CAM DCC reference: T2000670 - v2 HRTS Final Design Document, page 18
Fringe visibility reference: S Cooper thesis, 2020, chapter 3



Suspension overnight 31st March, no damping
HoQI Pitch
HoQI Long
HoQI Yaw
ASD [m/√Hz]
Frequency [Hz]

Comparison to ground motion



Notes on most recent AEI measurements

L4C signals are AC-coupled.
To compensate multiply horizontal channels (RZ,X,Y) with zpk filter with 4 poles at 0Hz, 4 zeros at 0.03Hz and gain 1 at high frequencies
and vertical channels (RX,RY,Z) with zpk filter with 4 poles at 0Hz, 4 zeros at 0.1Hz and gain 1 at high frequencies.

The measurement was done in air with the isolation table (AEI-SAS) in the highest control state which is safe in air:
-Horizontal LVDT damping with unity gain frequency 0.15Hz, LVDTs are sensor corrected with STS2 seismometer
--> effectively passive isolation with resonance frequency 0.1Hz
-Vertical LVDT damping with blended L4Cs and sensor correction with STS2 but also in low-gain setting (UGF~0.3Hz)
--> effectively also just passive isolation with resonance frequencies 0.3Hz (Z) and 0.4Hz (RX,RY)

Only 4 degrees of freedom were damped with BOSEMs (long, pitch, vert, yaw) and the loop gain is lower than in the previous
mesurements outside the vacuum chamber so we can see more features of the suspension instead of simply bosem noise.

The calibration of all bosems seems to be too low by a factor ~3.