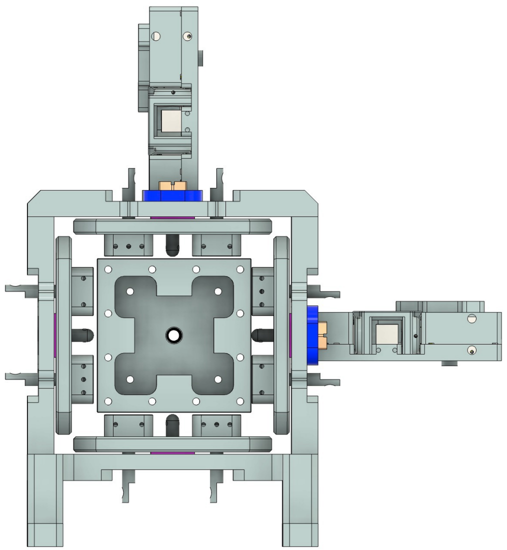
Nikhef

Building Position Sensing System for the Test Mass of OmniSens

- a Technology for the Einstein Telescope Low Frequency Science



Zhao-Qing Lin

QU ATTRACT WORKSHOP, Nov. 24-25 2025

Universiteit van Amsterdam

VU Vrije Universiteit Amsterdam

Content

Low Frequency of Gravitational Waves

OmniSens

Tile-Horizontal coupling

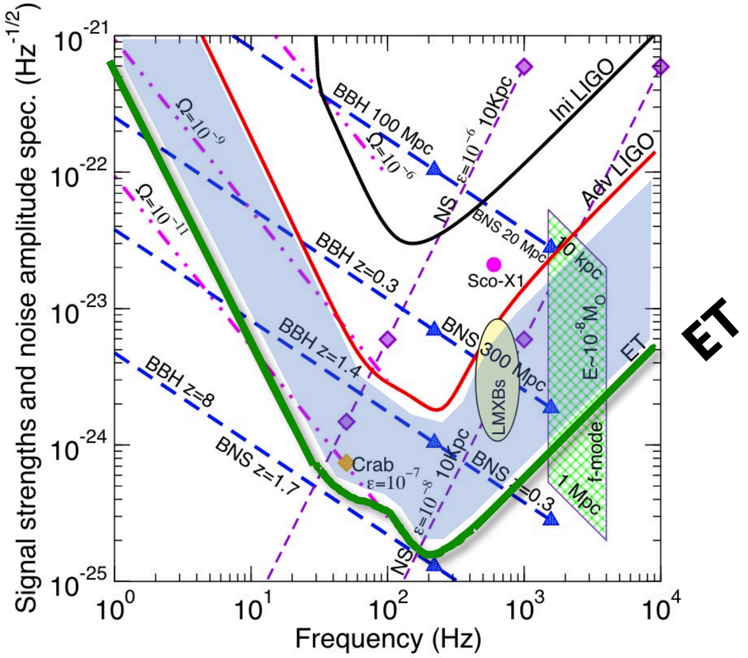
Position Sensing System of Test Mass

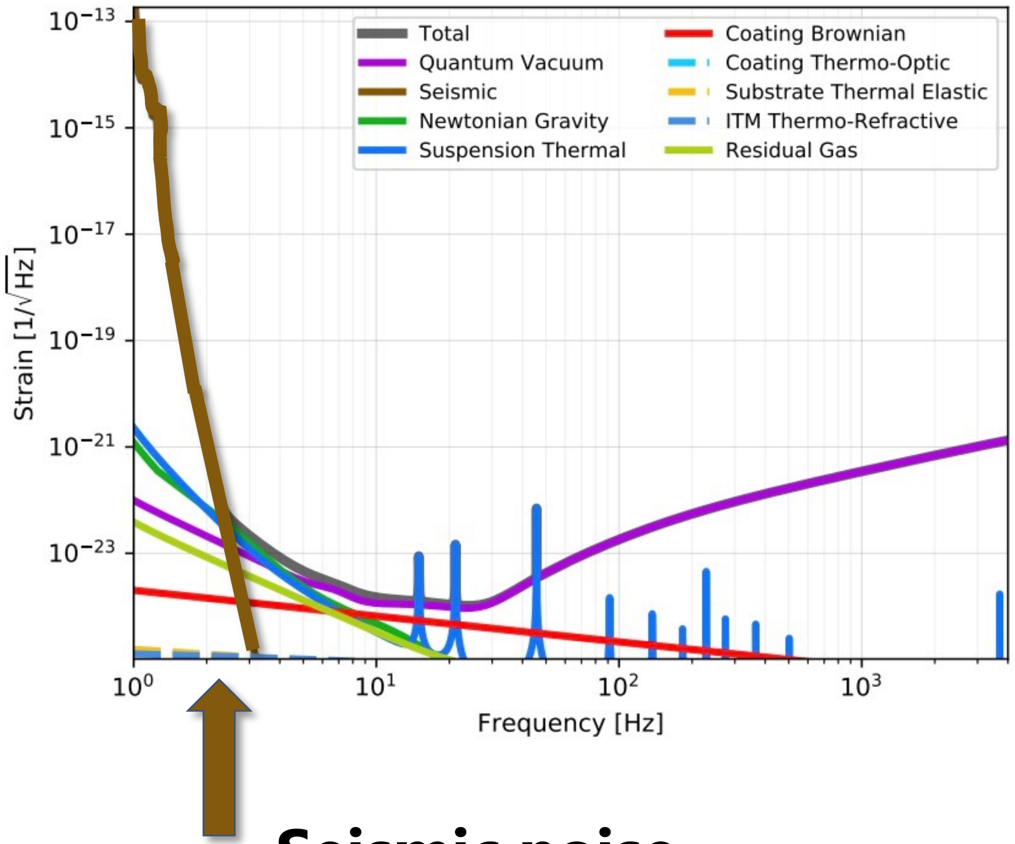
Capacitor Position Sensing (CPS)
Homodyne Quadrature Interferometers (HoQIs)

Results and Discussion

Blended Sensing Test
Offset analysis

Low Frequency of Gravitational Waves





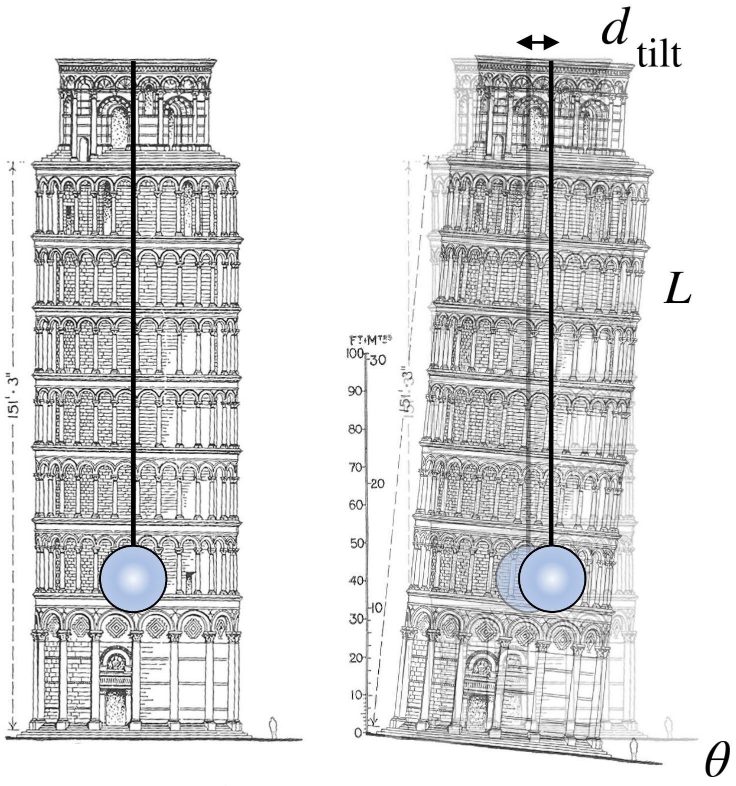
Low frequency:

Bigger redshift -- **earlier universe**
More **massive** binary systems
Longer time in the sensitive band

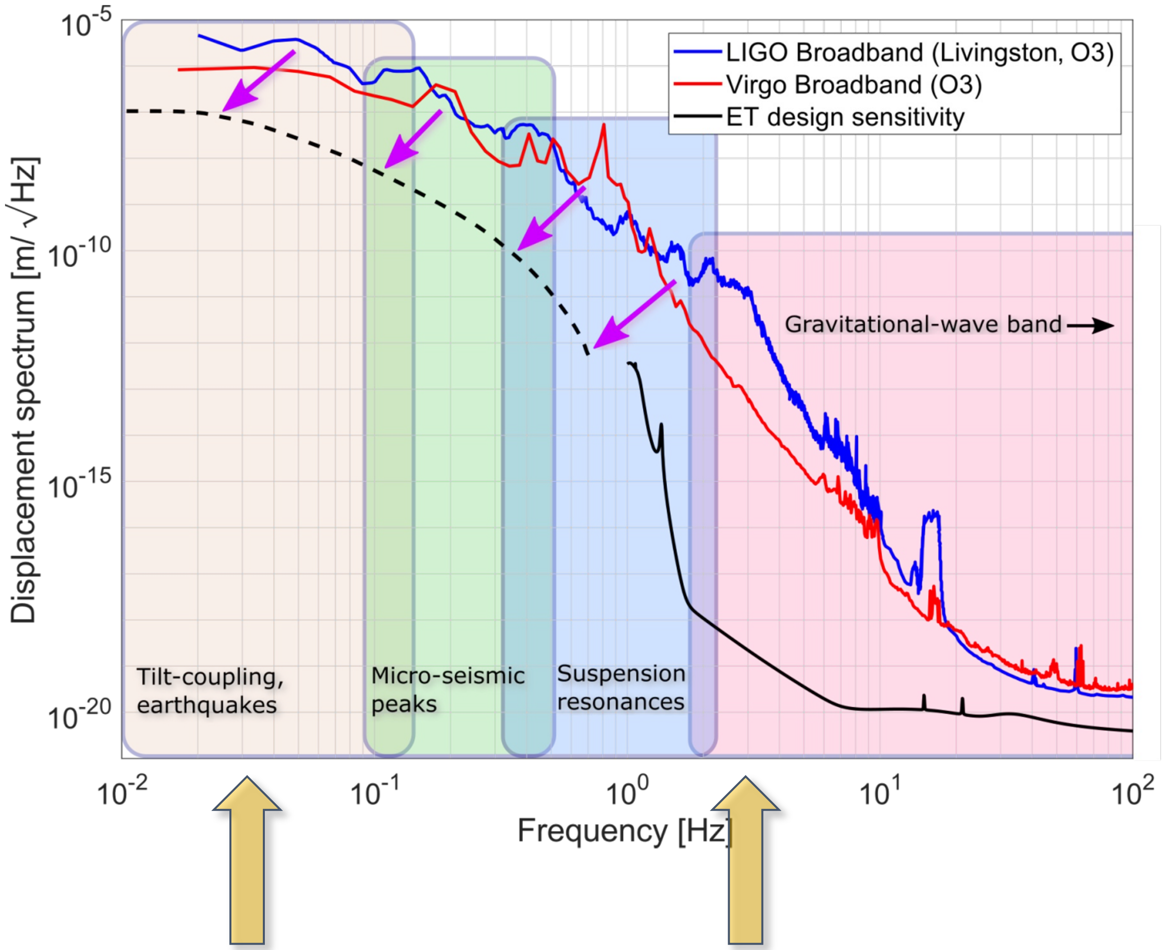
Seismic noise

Becomes dominant ~ 1Hz

Seismic Noise: Tilt-Horizontal Coupling



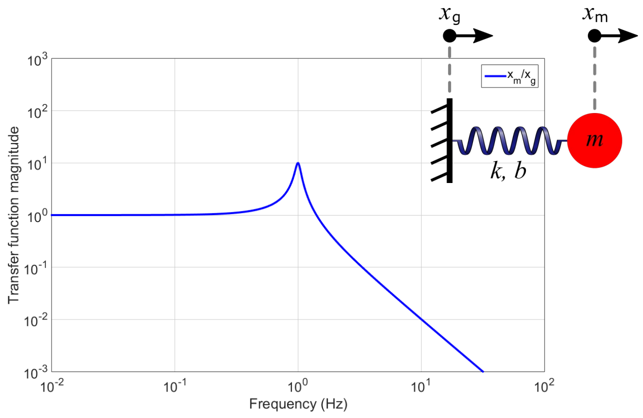
$$d_{tilt} = L\sin\theta$$



3 Hz

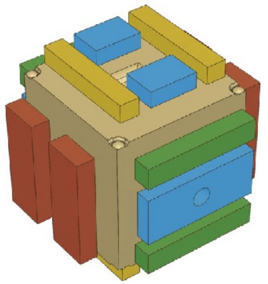
OmniSens: Inertial Isolation System

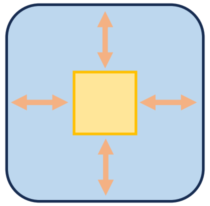
Passive isolation

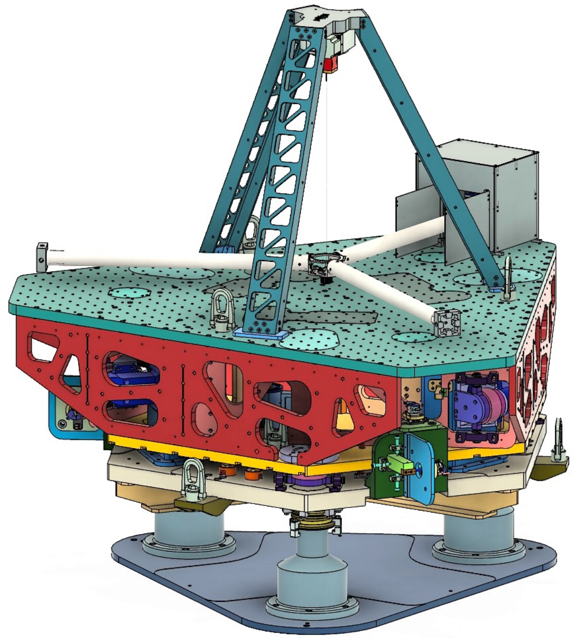


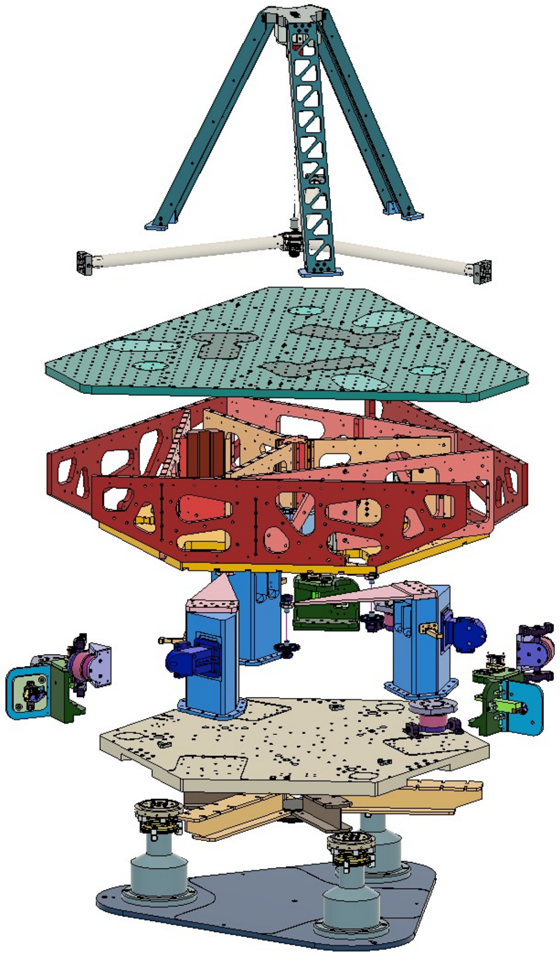
Active isolation

Drag-free control









Test Mass
Omni-directionally
Sensed

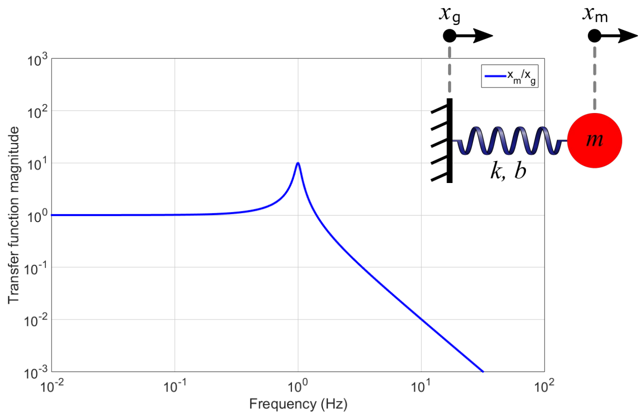
Stage 1
Active Platform

Stage 0
Base

C. M. Mow-Lowry and D. Martynov. "A 6D interferometric inertial isolation system". *Class. Quantum Grav.* 36.24, Nov 2019

OmniSens: Inertial Isolation System

Passive isolation



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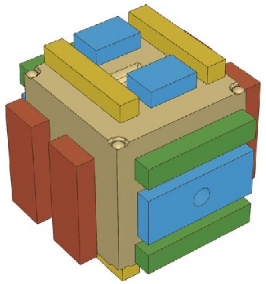

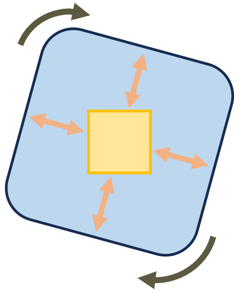

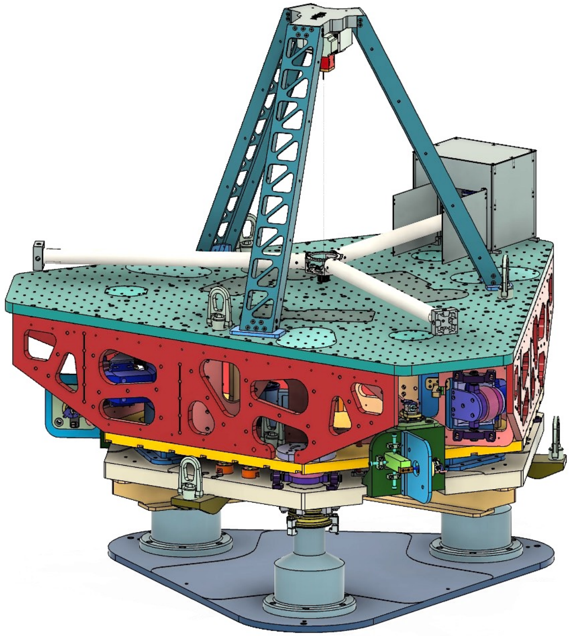

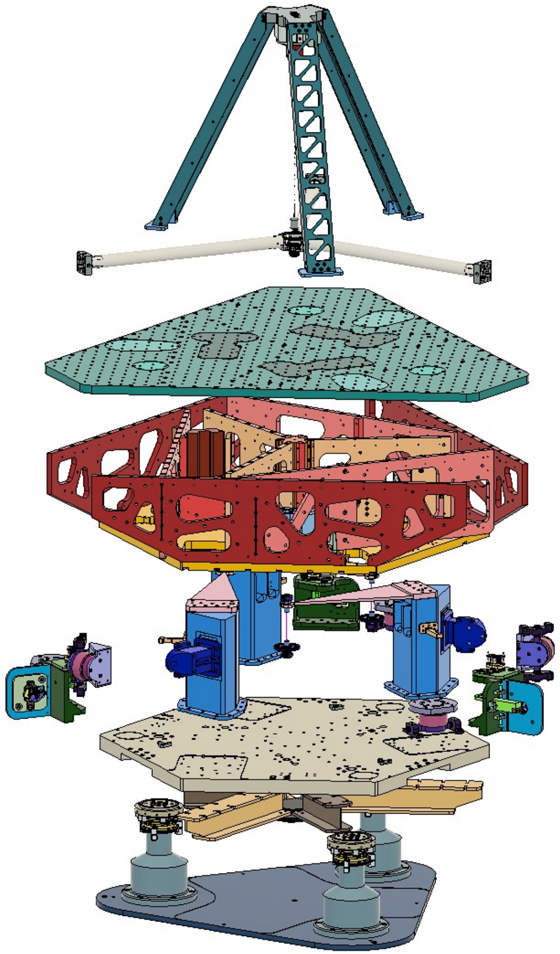

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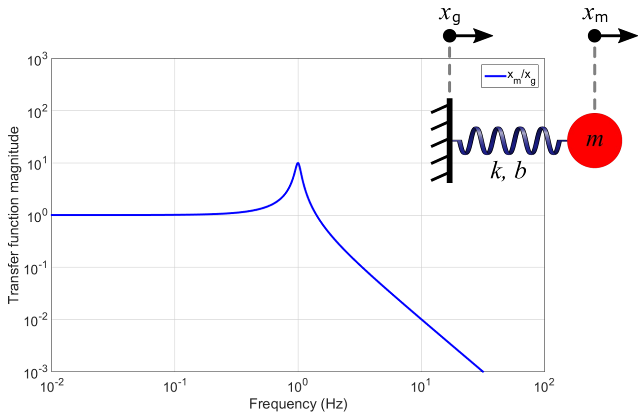

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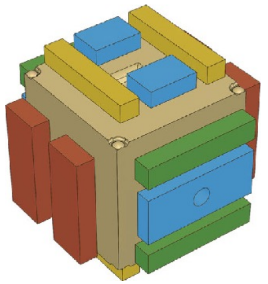

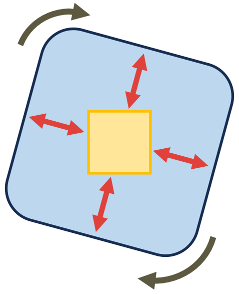

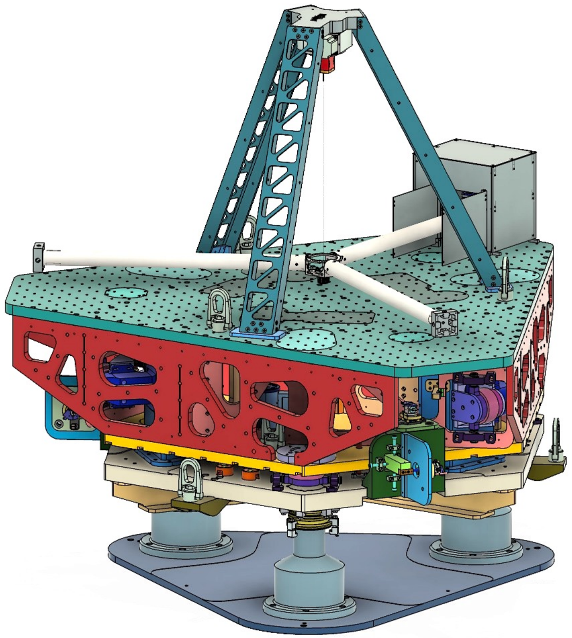

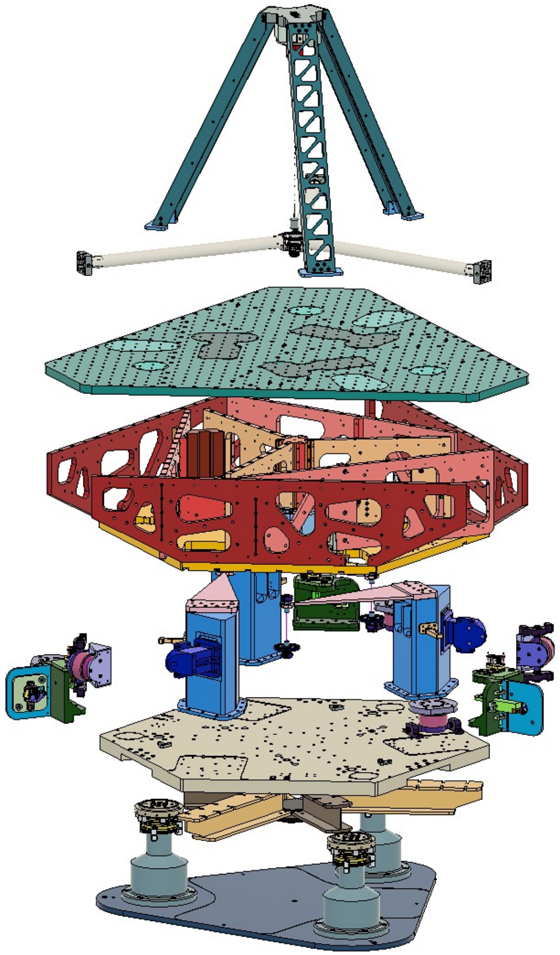

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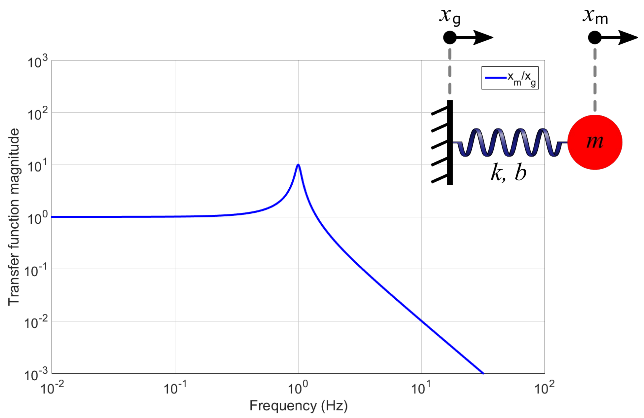

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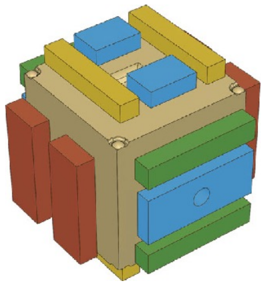

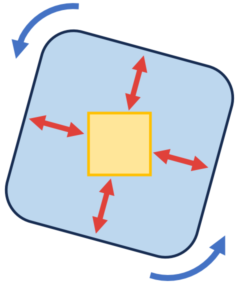

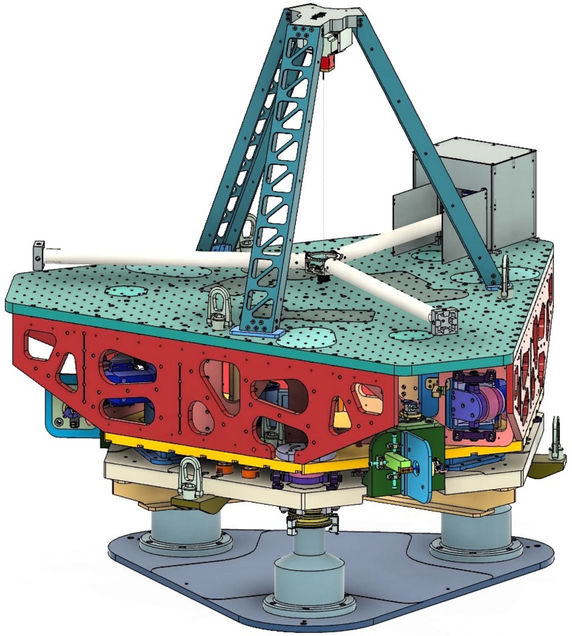

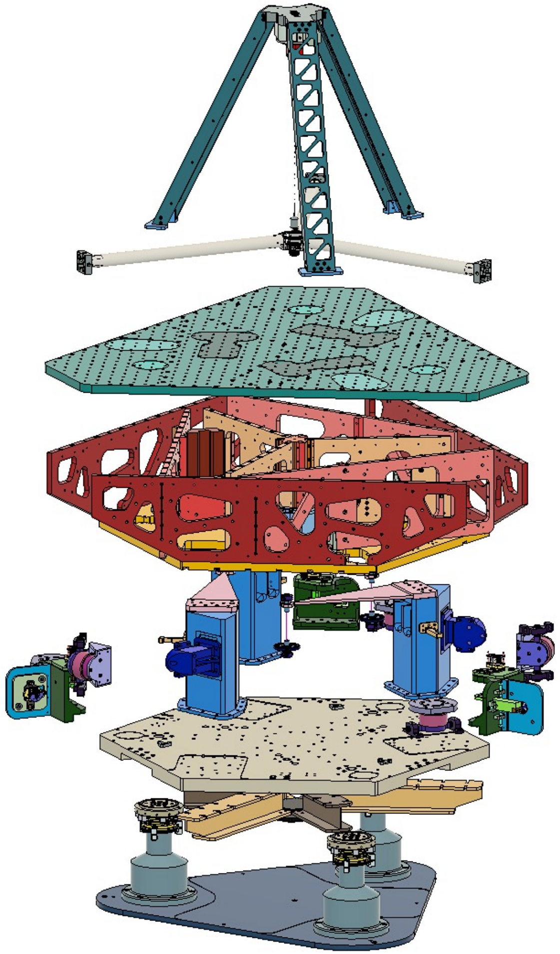

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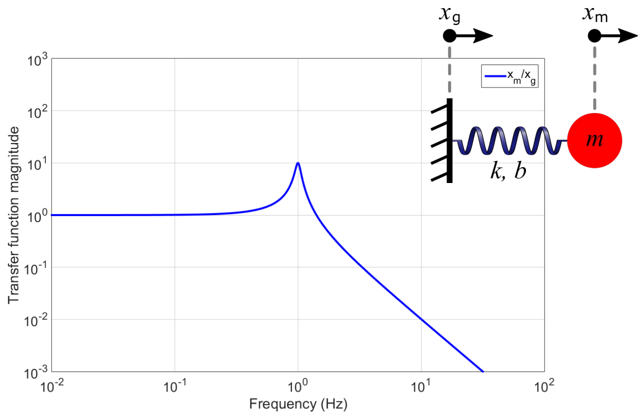

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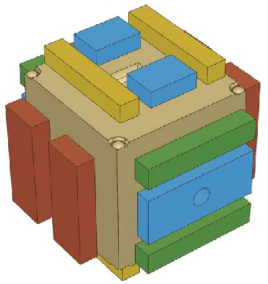

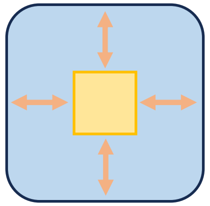

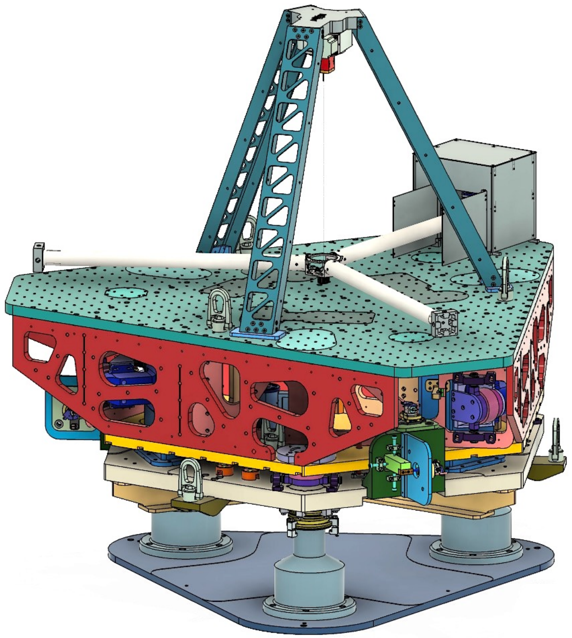

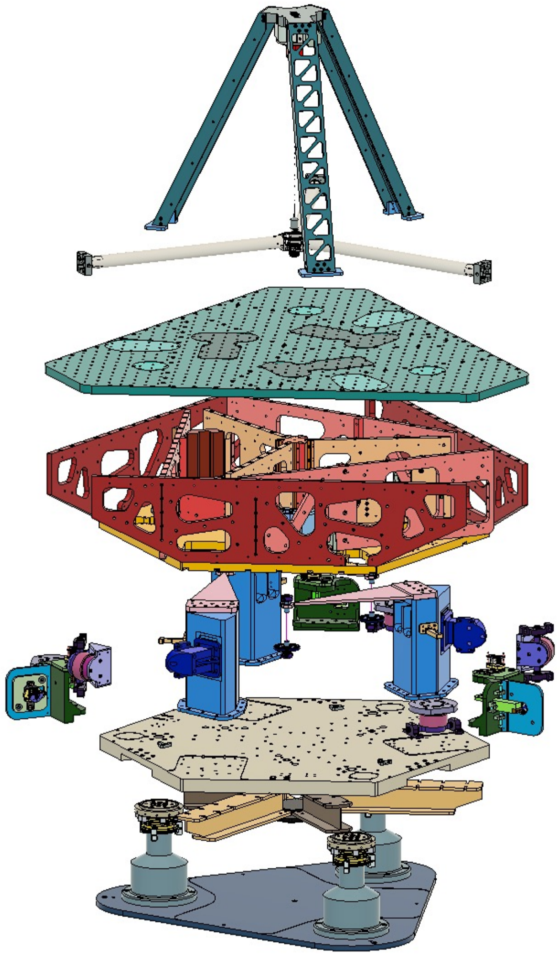

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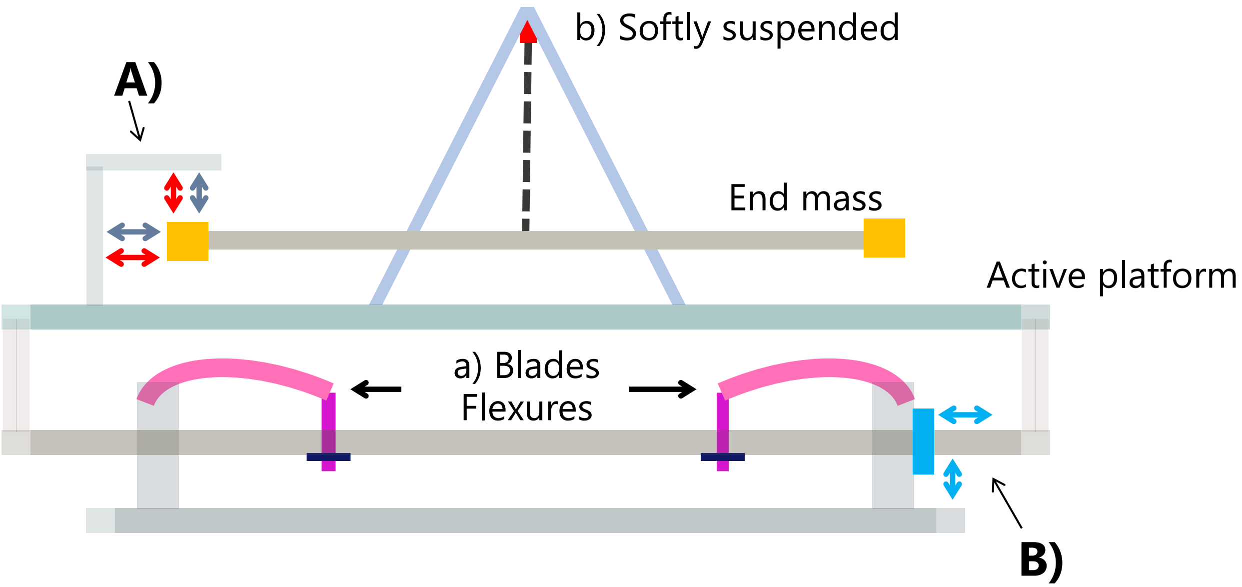
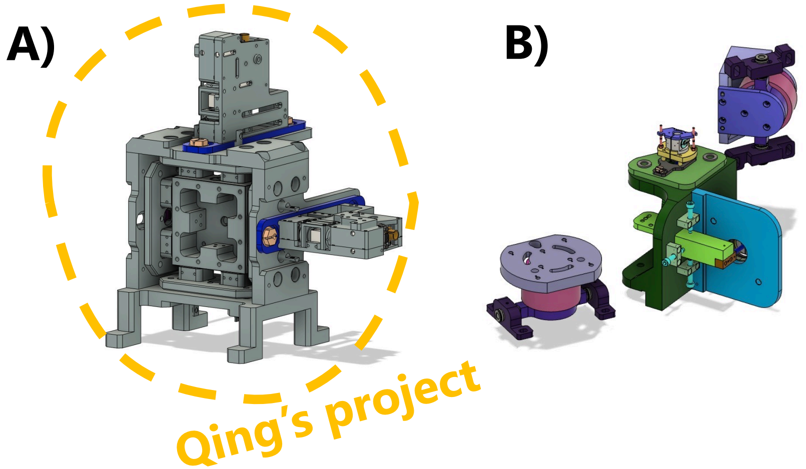
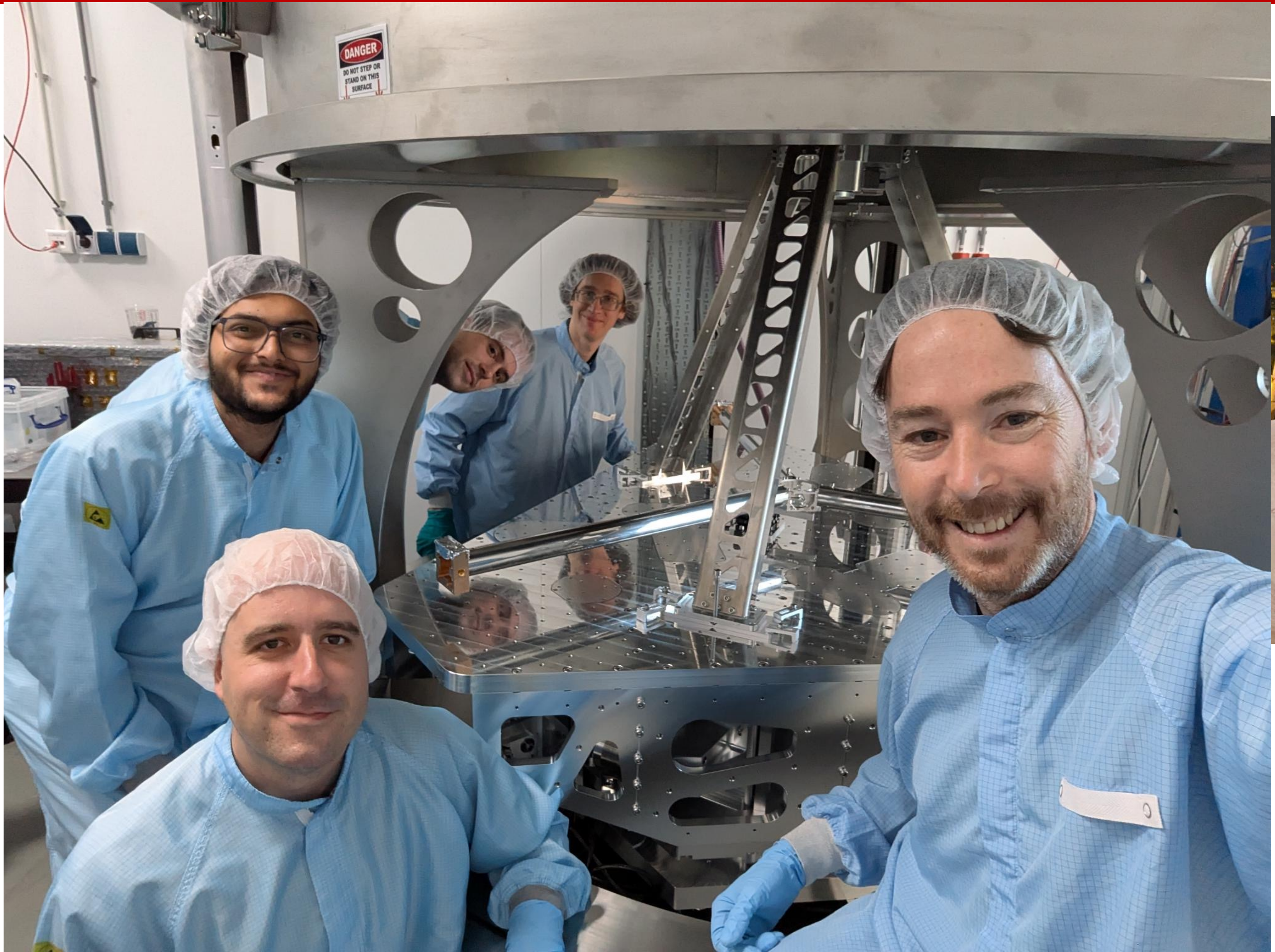
OmniSens



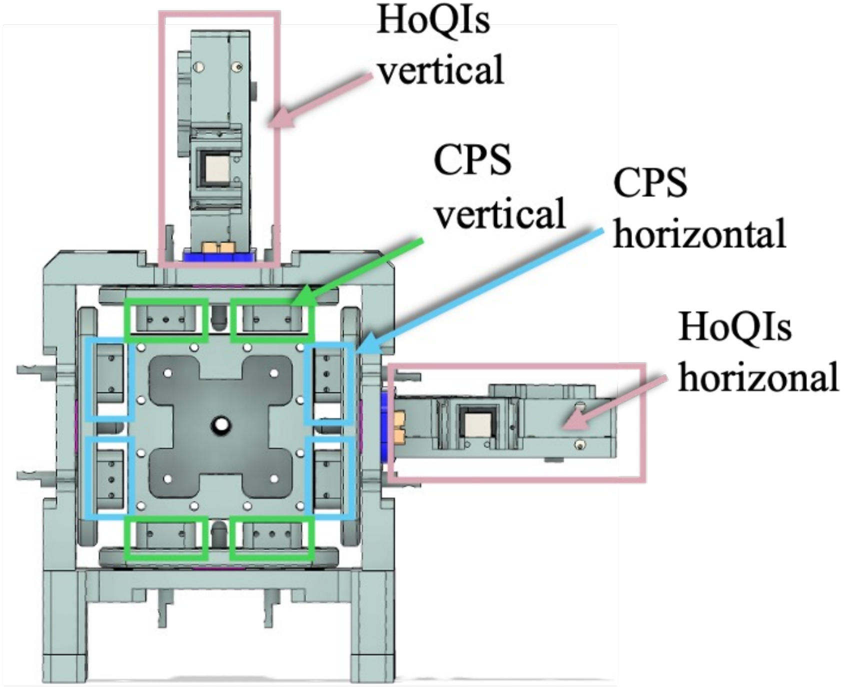
Passive:
a) and b) Blades, flexures and silica fibre

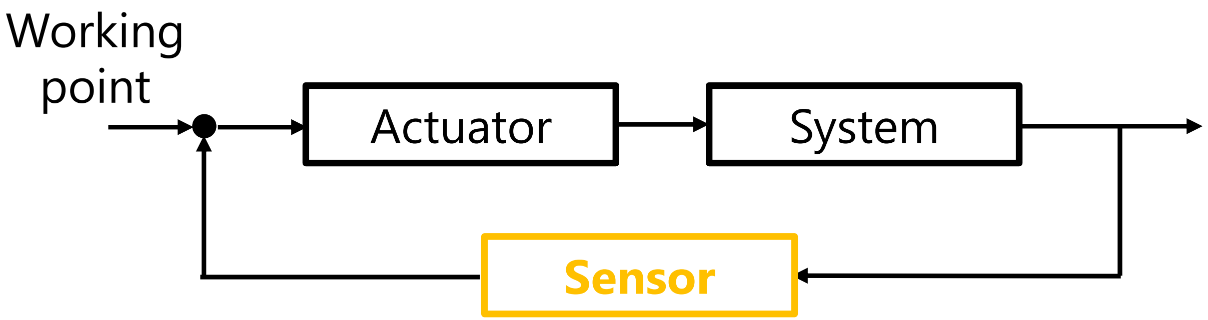
Active:
Displacement sensors and actuators




DANGER
DO NOT STEP OR
STAND ON THIS
SURFACE

Working Principle





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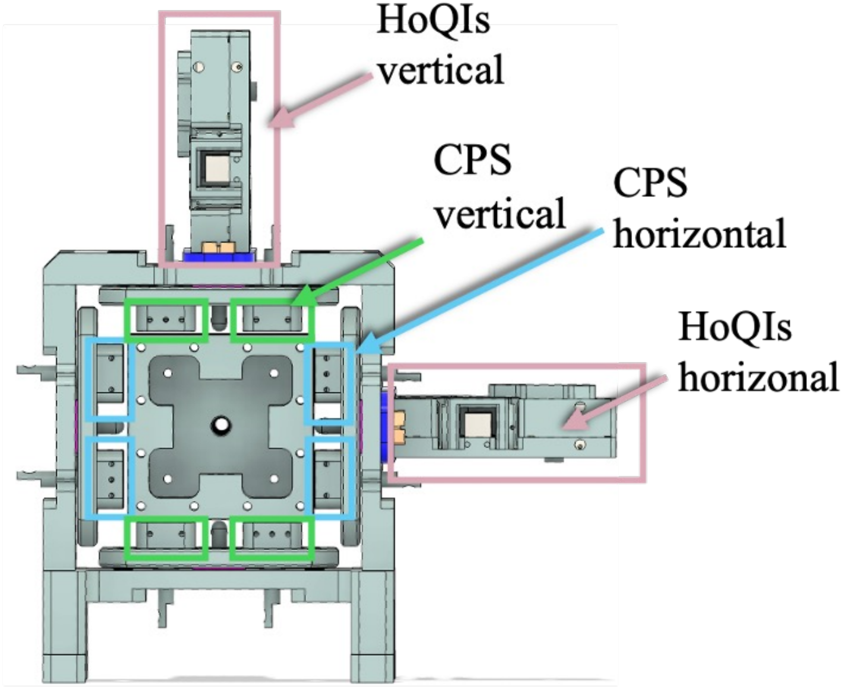
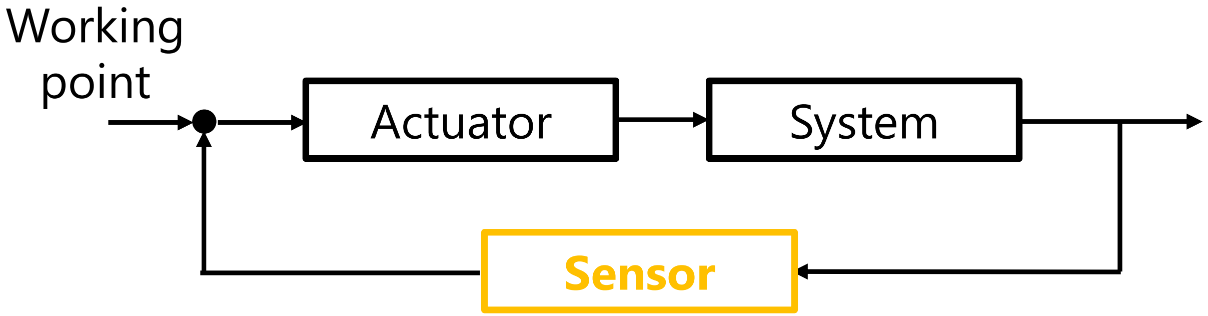
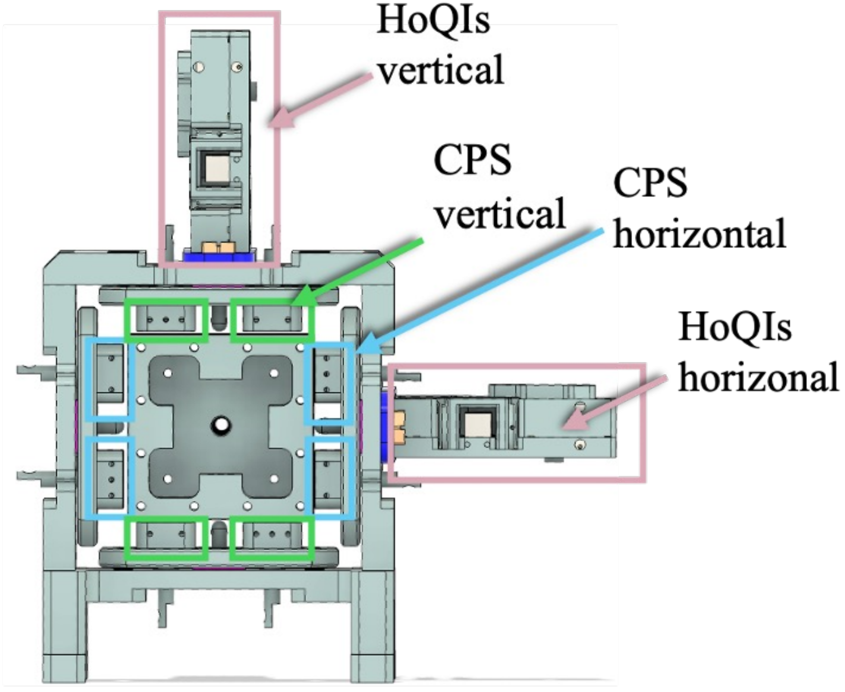
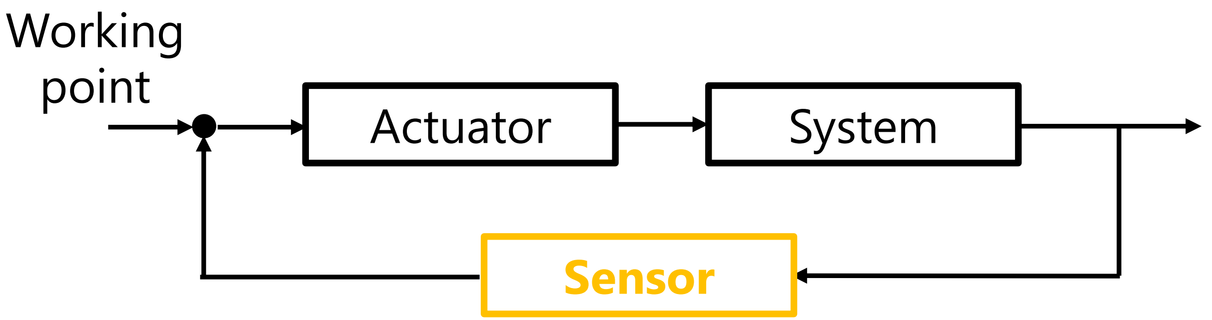




CPS (Differentiate) capacitor position sensors	**HoQIs homodyne quadrature interferometer**
Absolute position	Relative movement
Straight forwards, noise low enough	High fringe visibility, high sensitivity, compact…
Finding the working point	Inertial movement

Working Principle



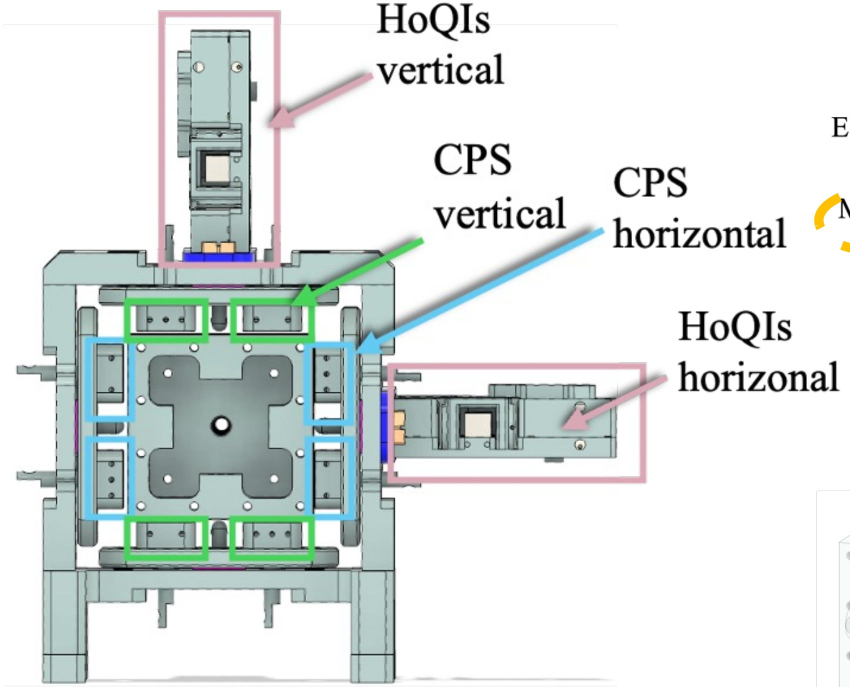


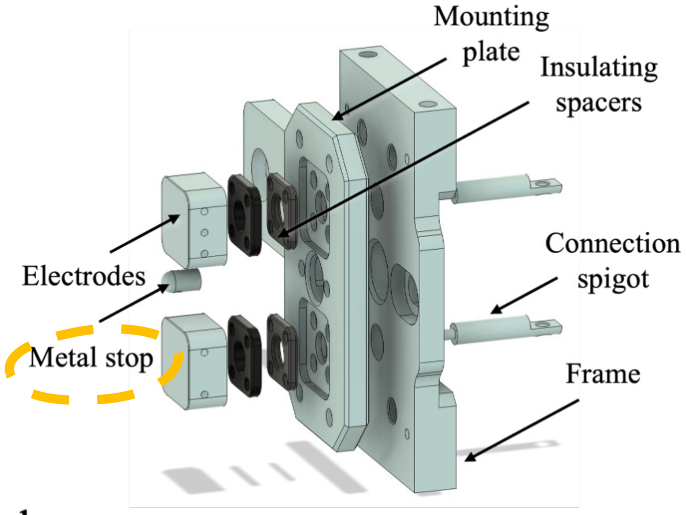
CPS (Differentiate) capacitor position sensors	HoQIs homodyne quadrature interferometer
Absolute position	Relative movement
Straight forwards, noise low enough	High fringe visibility, high sensitivity, compact…
Finding the working point	Inertial movement

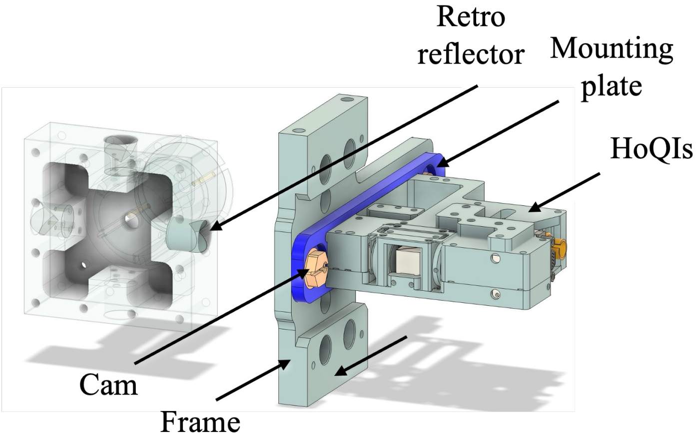
Set working to the centre of the sensing frame

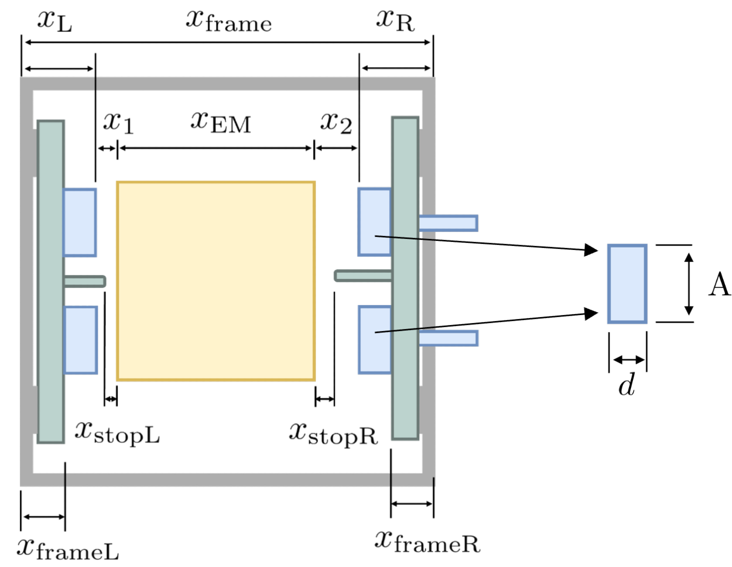
- Zero output
- Small non-linearity

Setup





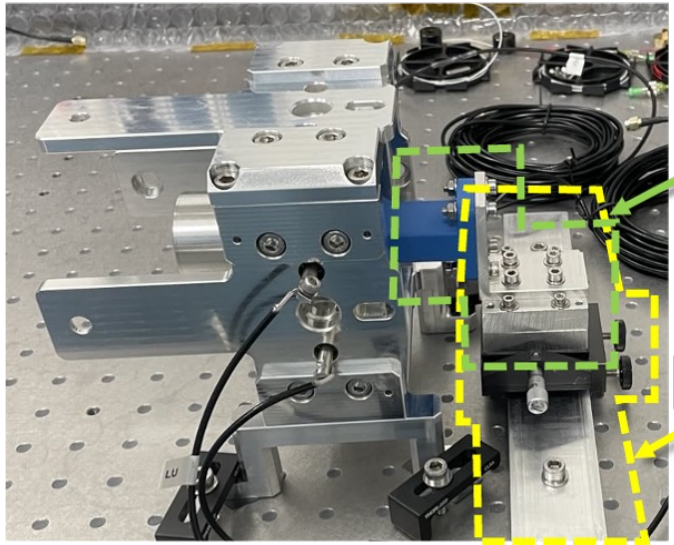




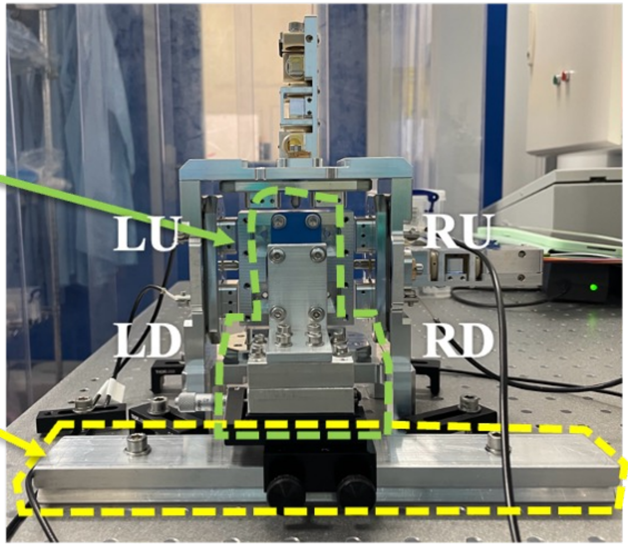
Parameter	Value (Measured)	Value (Designed)
x_{frame}	131.99mm	132.00mm
x_{frameL}	20.00mm	20.00mm
x_{frameR}	19.99mm	20.00mm
x_{L}	29.83mm	30.00mm
x_{R}	29.87mm	30.00mm
x_{EM}	69.99mm	70.00mm
x_{move}	1.48mm	1.50mm
x_0	1.15mm	1.00mm
d	10.00mm	10.00mm
A	4.50cm^2	4.50cm^2

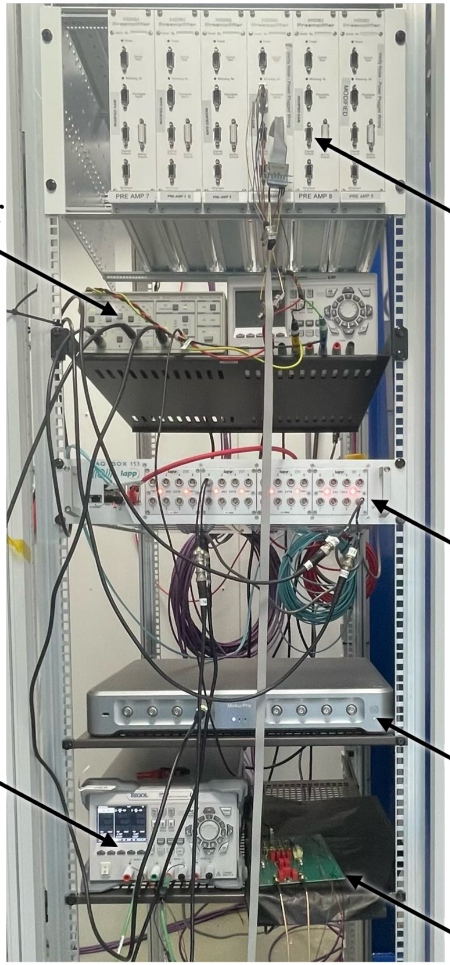
Setup

Left

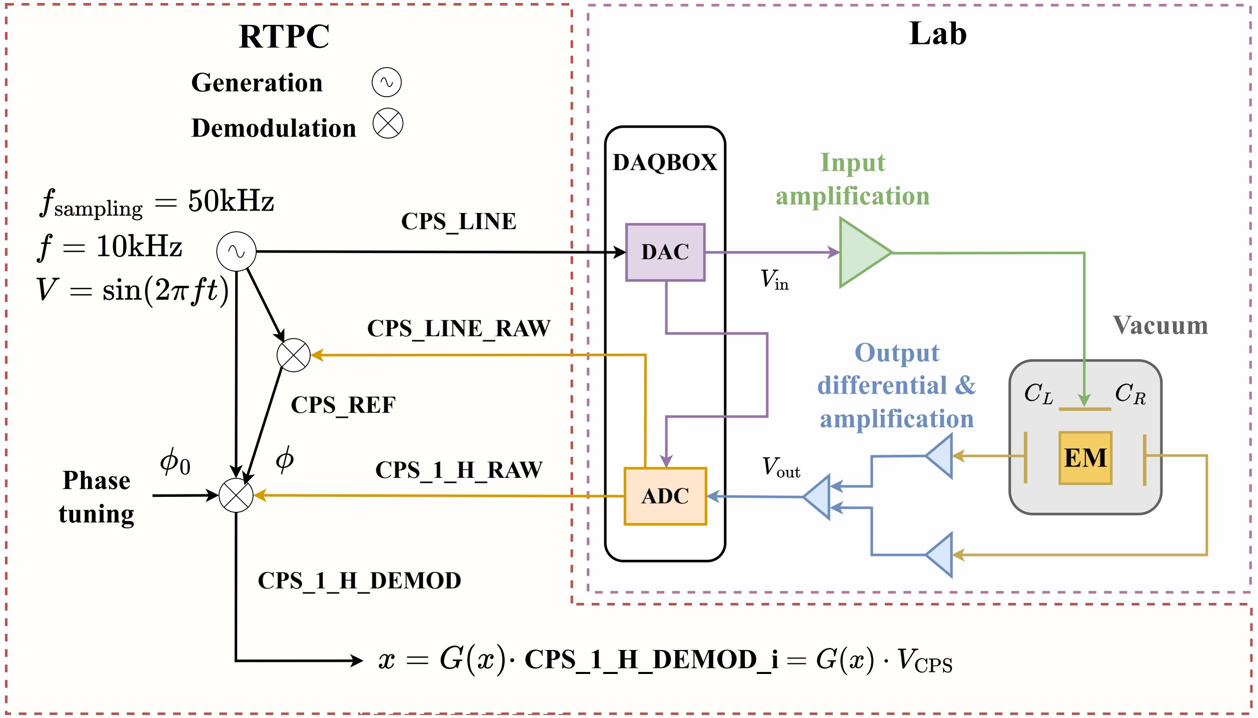


Front





DAQ and Analytical model

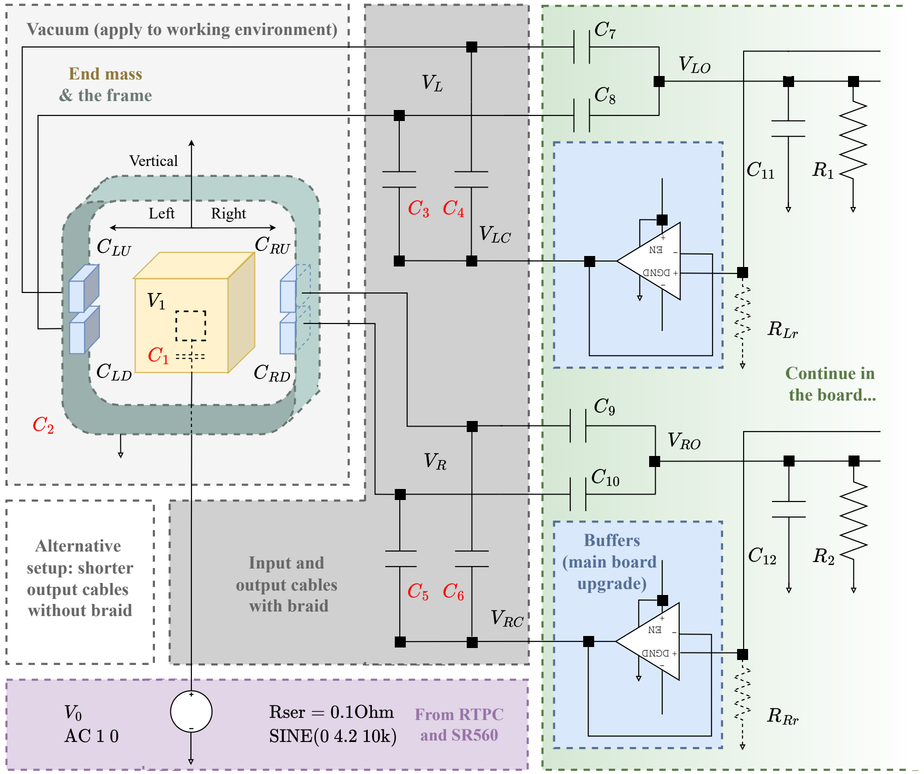


DAQ and working scheme

Analytical model

$$C_{LU} = C_{LD} = C_L = \frac{\epsilon A}{x_0 + x}$$

$$C_{RU} = C_{RD} = C_R = \frac{\epsilon A}{x_0 - x}$$

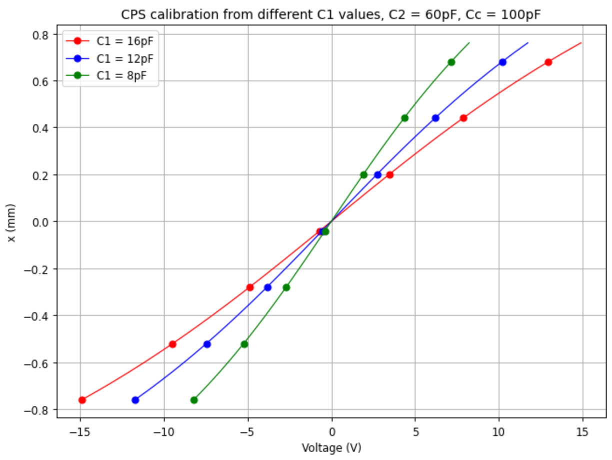


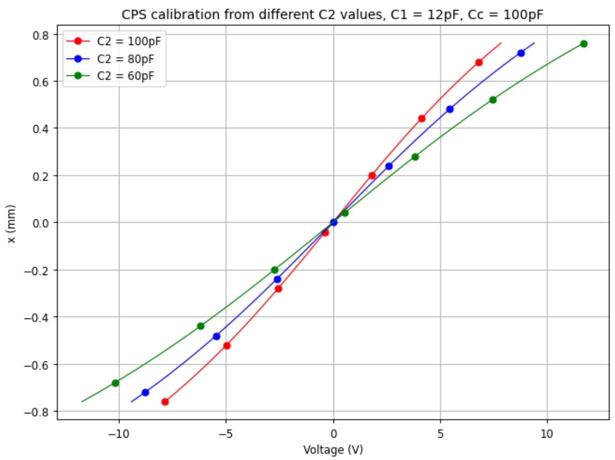
Free parameter	Description
C_1	Capacitance between the input electrode and testmass
C_2	Stray capacitance between the end mass and its surrounding
$C_3,\ C_4,\ C_5,\ C_6$	Capacitance between the output coaxial cables and the guard

Analytical Calculation

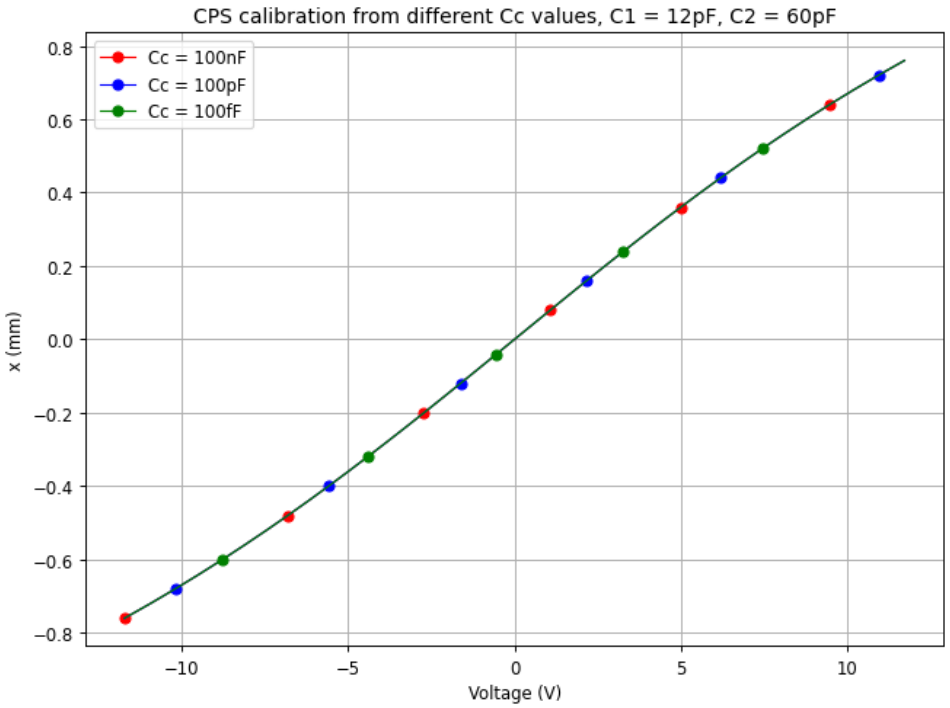
Parameter space

Free Parameter	Discription
C_1	Capacitance between the input electrode and end mass
C_2	Stray capacitance between the end mass and its surrounding
$C_3,\ C_4,\ C_5,\ C_6$	Capacitance between the output coaxial cables and the guard





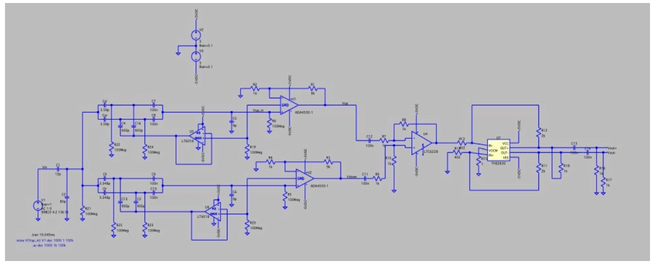
Gain is related to C1 and C2

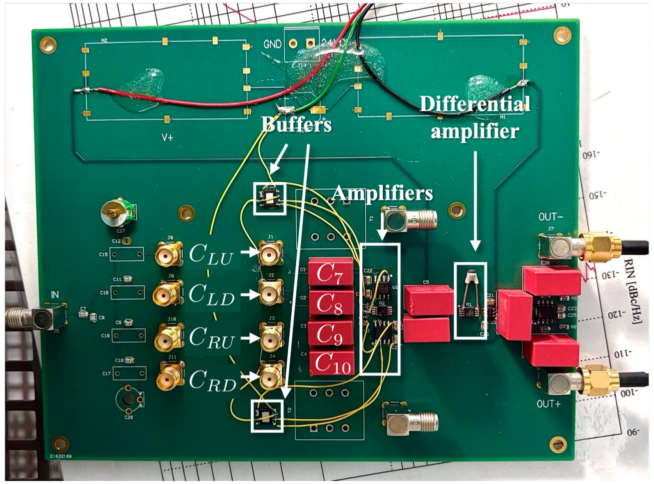


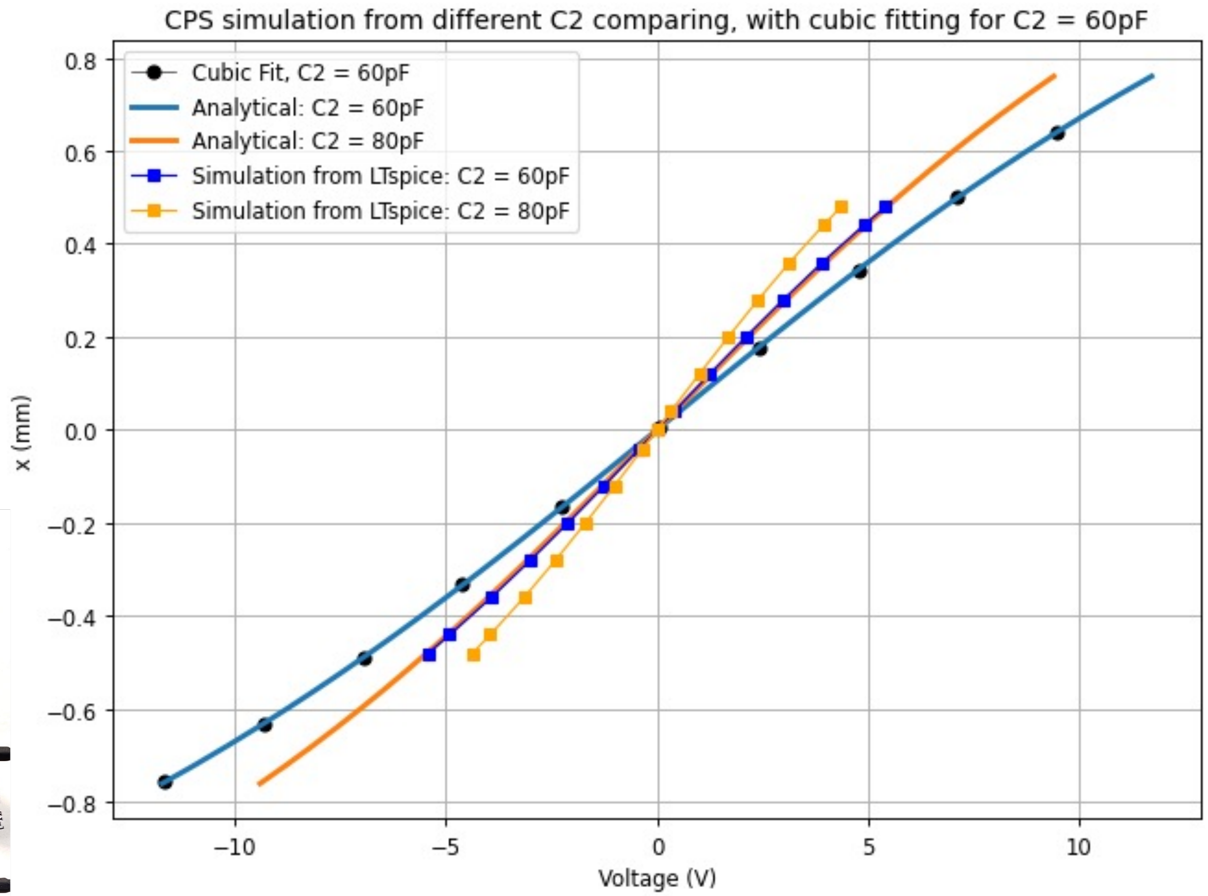
Gain is unrelated to output cables
CPS is stable in a sense of using different cables

Simulation

LTSPICE







Use a 12pF capacitor for C1

Gain increases in simulation

- Losing signal from components' noise

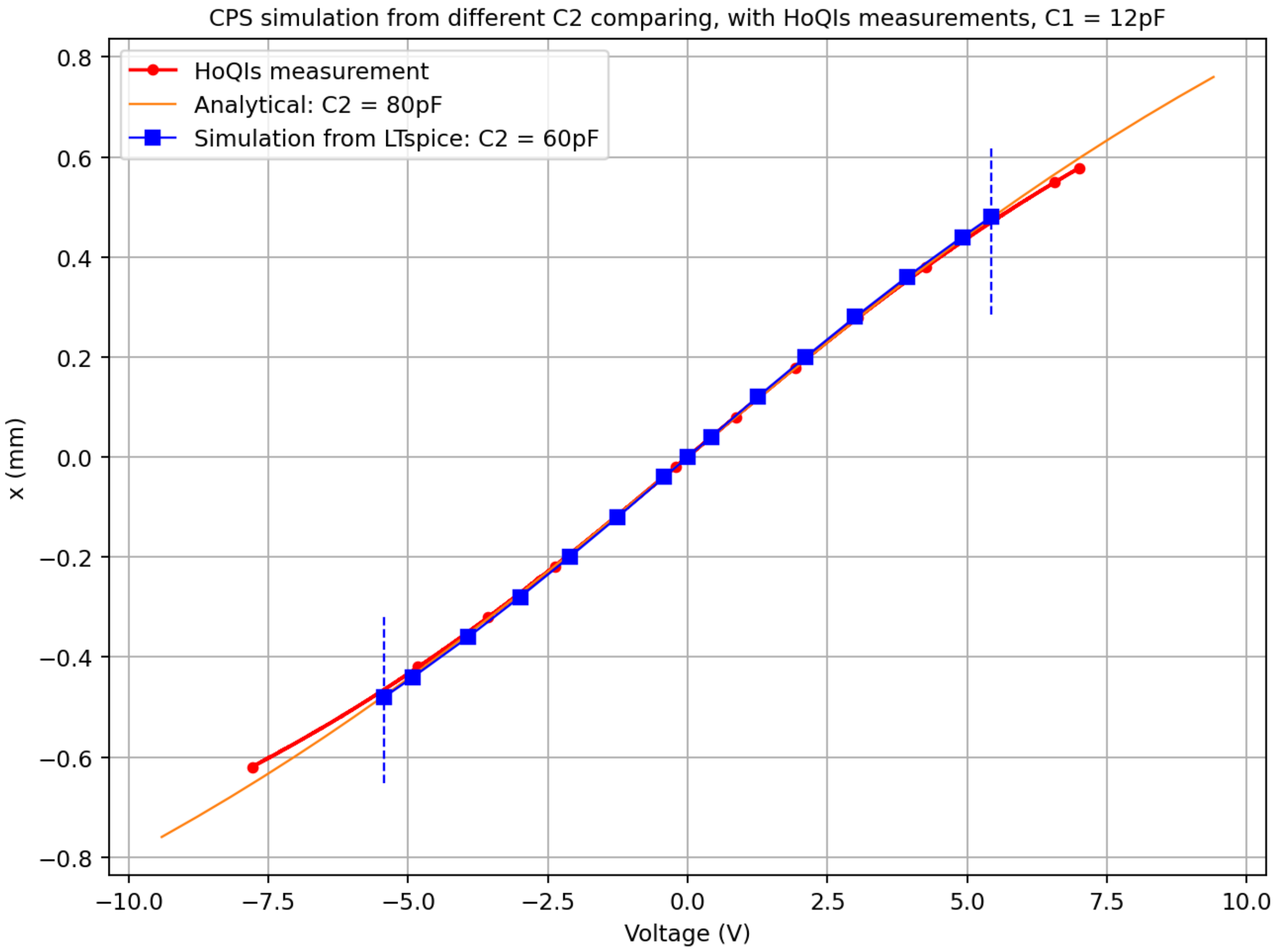
Can use cubit fit for the curve

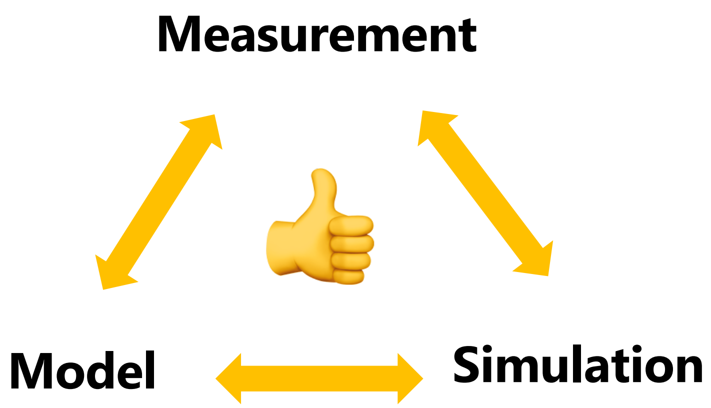
Use a 12pF capacitor for C1, cubic fit for C2 = 60pF

$$x[\mu m] = 73.473[\mu m/V]V_{\text{CPS}}[V] - 0.065[\mu m/V^3]V_{\text{CPS}}^3[V]^3$$

Linear behaviour when working around the centre

Analytical, Simulation and Measurement



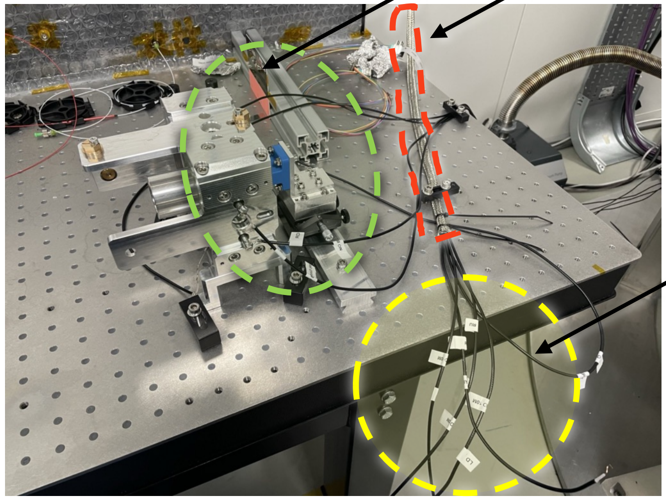


CPS is working as we designed!

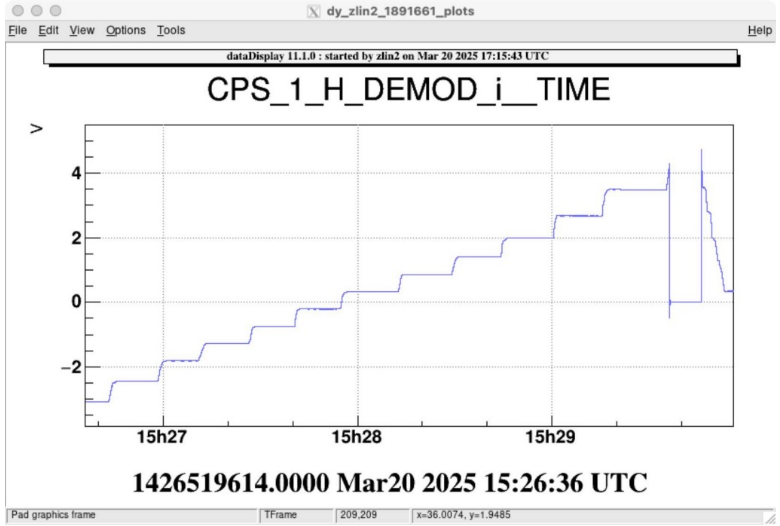
Noise Optimization and Board Upgrade

Action	Distance tuning	Add braid to reduce noise	Change cables to verify signal loss	Upgrade board to amplify signal	Change cables to see CPS' independence of cables
Measurements	10m + old board	10m + old board + braid	5m + old board	10m + new board + braid	5m + new board
Time stamps	21st Mar. 2025	10th Apr. 2025	3rd May 2025	14th May 2025	15th May 2025
Gain	188μm/V (x_0 ~ 1.05mm)	480μm/V	111μm/V	99μm/V	96μm/V

5 m cables braid



10 m cables

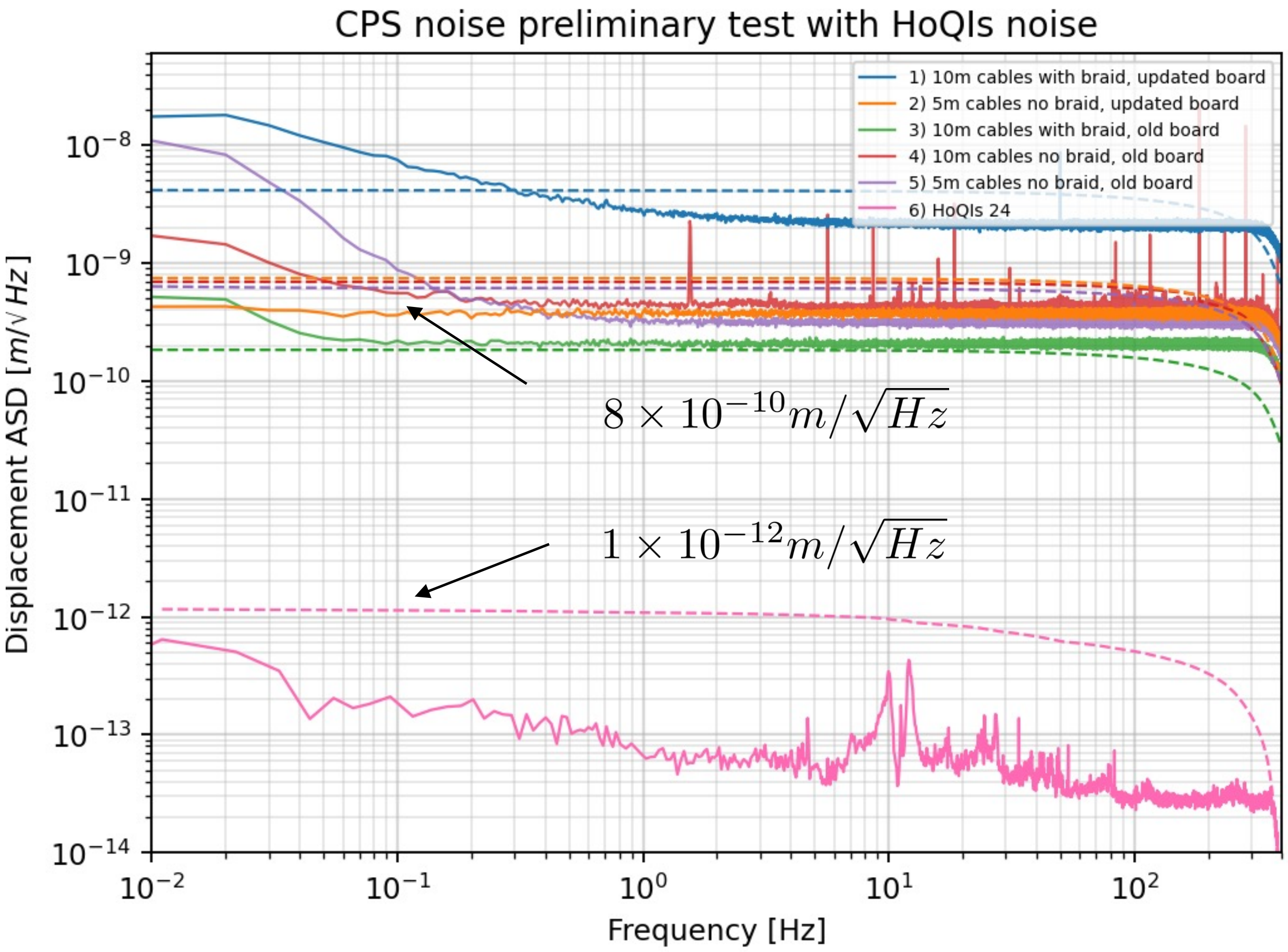


Step scanning with constant distance

Gain measurement with micrometric rail

Gain is stable indeed

Noise Analysis: Optimization of Board and Cabling



For the same cables

n_{braid}

$< n_{\text{old board}}$

$< n_{\text{updated board}}$

For the same board

$n_{\text{short cables}}$

$< n_{\text{long cables with braid}}$

Final decision:

Updated board short cables

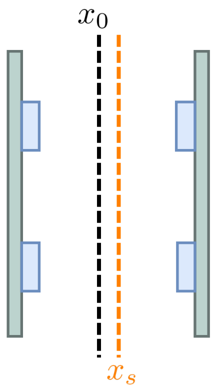
For all frequency

👑

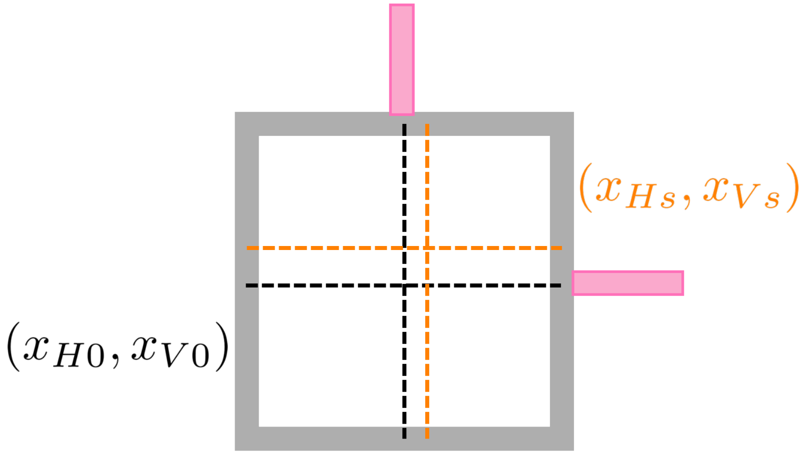
n_{HoQIs}

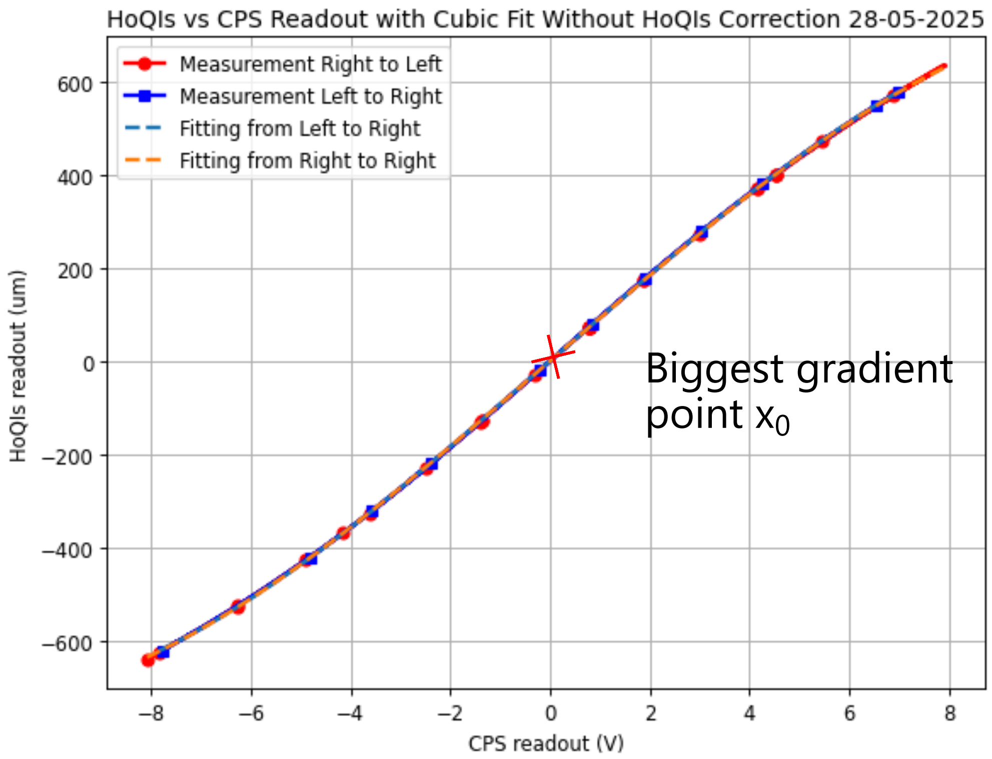
$< n_{\text{CPS}}$

Possible Error: Centre Offset Check



x_0: The geometric centre for surface of the electrodes on two sides.
x_s: The sensing centre where the output voltage $V_{\text{CPS}} = 0V$



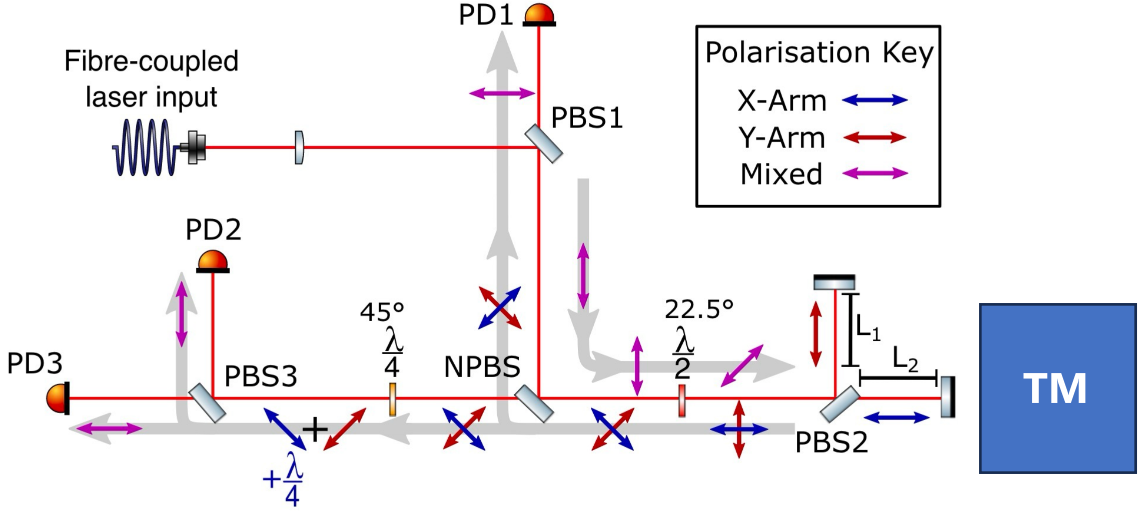


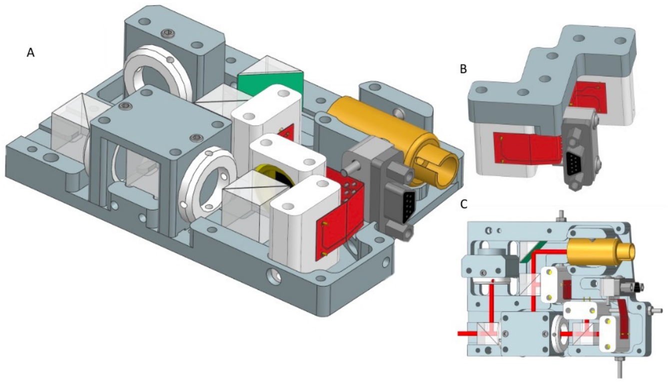
Refit: left to right: $6\mu m$, right to left: $3\mu m$
Comparing with the $x_0 = 1.15mm$

$\frac{|x_0 - x_s|}{x_0} < 0.5\%$ $\longrightarrow$ sensing noise $\ll$ Miscalibration force

Reasonable mechanical variable that are negligible

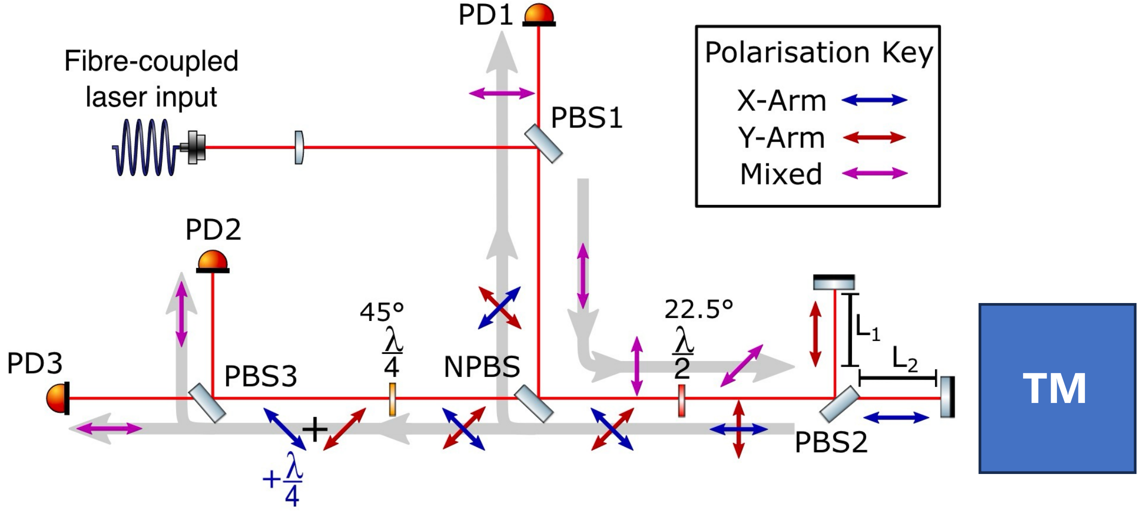
Relative Position Sensing: HoQIs

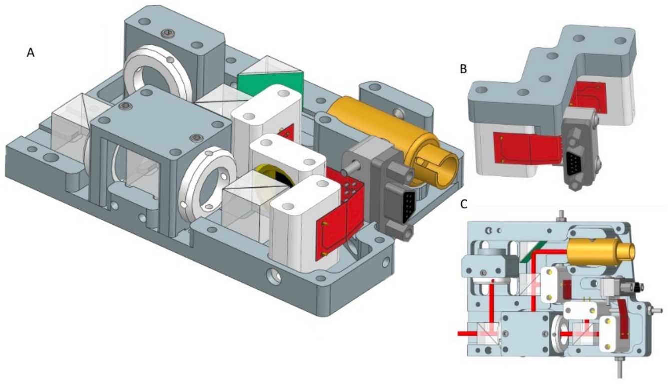




A. Mitchell. et. al. "Integration of high-performance compact interferometric sensors in a suspended interferometer". *Class. Quantum Grav.* 42, 19

Relative Position Sensing: HoQIs

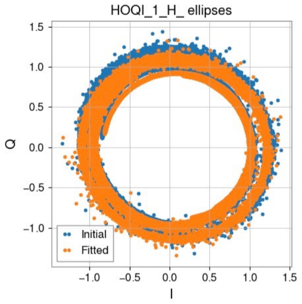




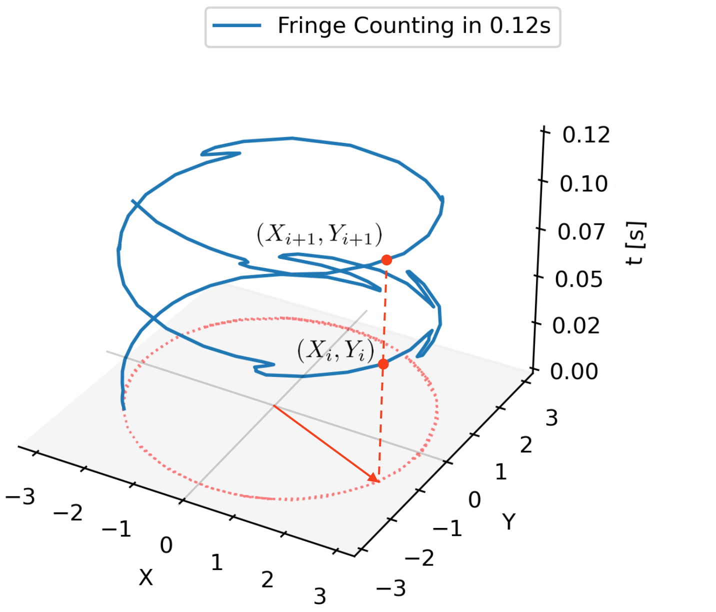
A. Mitchell. et. al. "Integration of high-performance compact interferometric sensors in a suspended interferometer". *Class. Quantum Grav.* 42, 19

$$\arctan\left(\frac{PD1-PD2}{PD1-PD3}\right) = \arctan\left(\frac{X}{Y}\right) = \frac{4\pi}{\lambda}(L_x - L_y) - \frac{\pi}{4}$$

After alignment and ellipse fitting



3D Lissajous pattern for HoQIs fringe counting after ellipse fitting



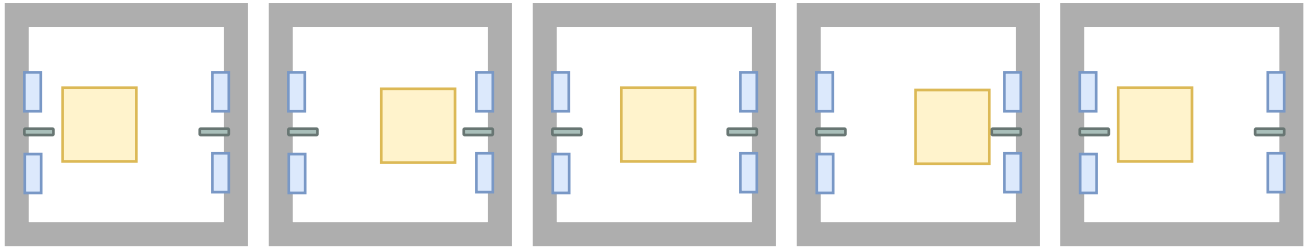
$$v_{max} = \frac{\lambda}{8} \times 10k\text{Hz} = 1.25mm/s$$

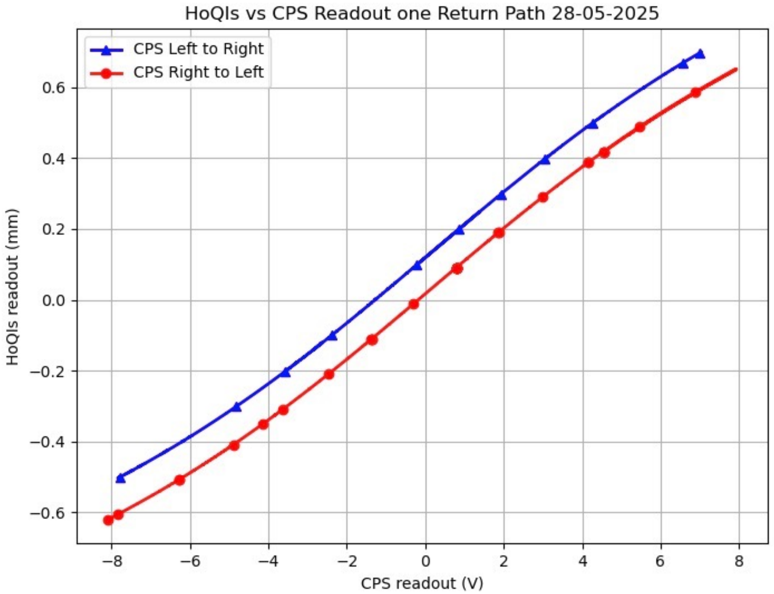
Combined Measurement

Left to Right

Still

Right to Left



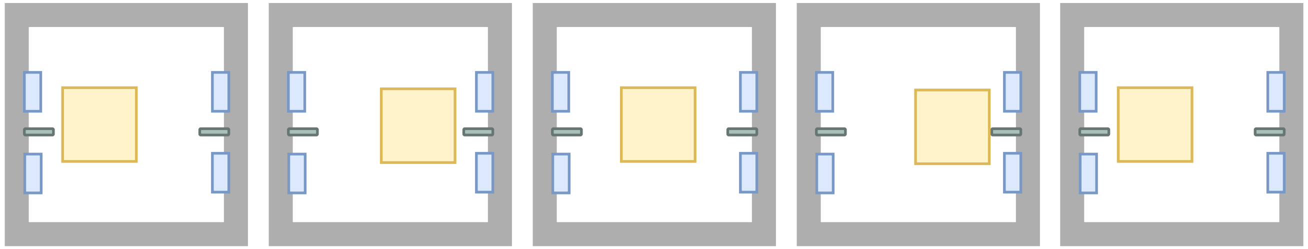


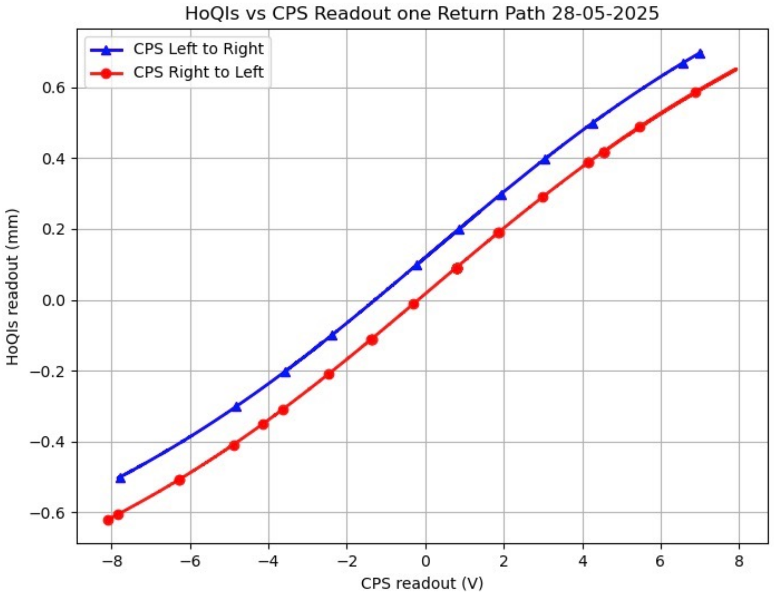
HoQIs vs CPS

An offset for around $100\mu m$

Combined Measurement

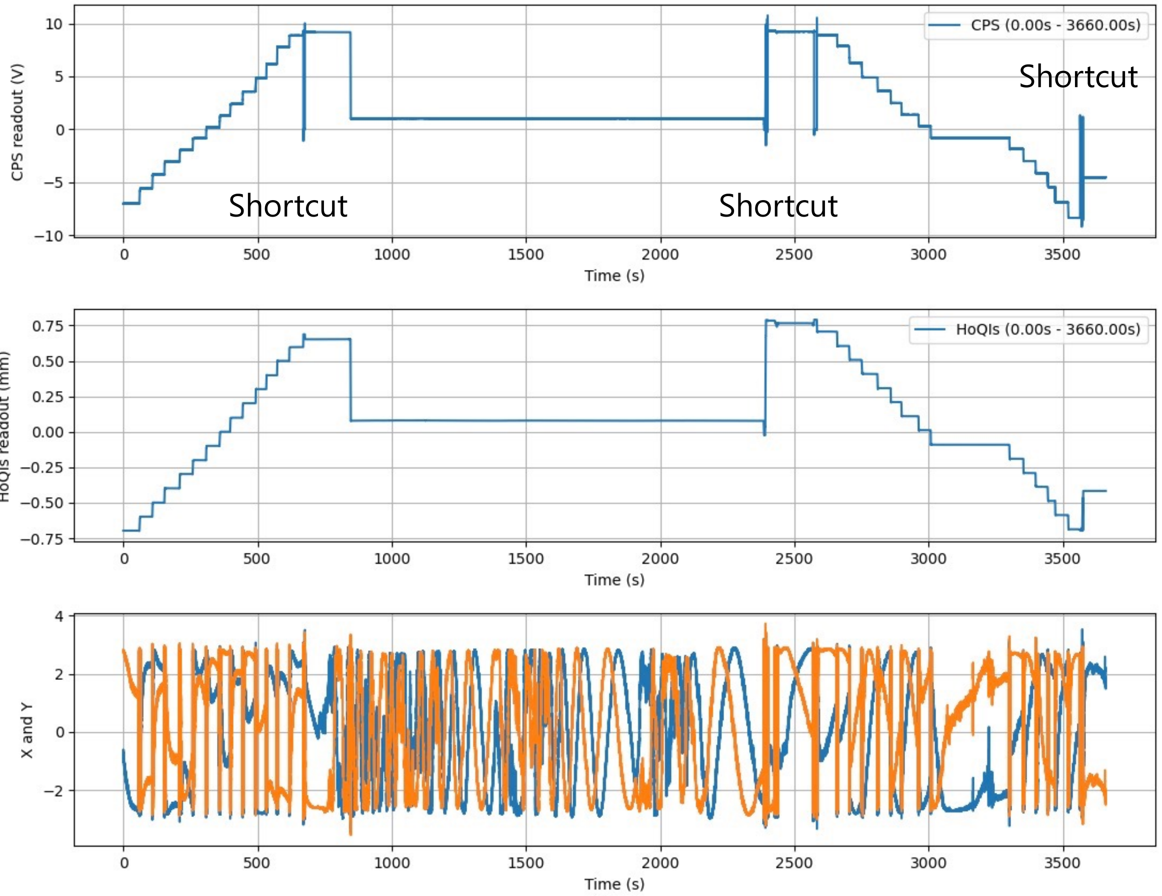
Left to Right Still Right to Left



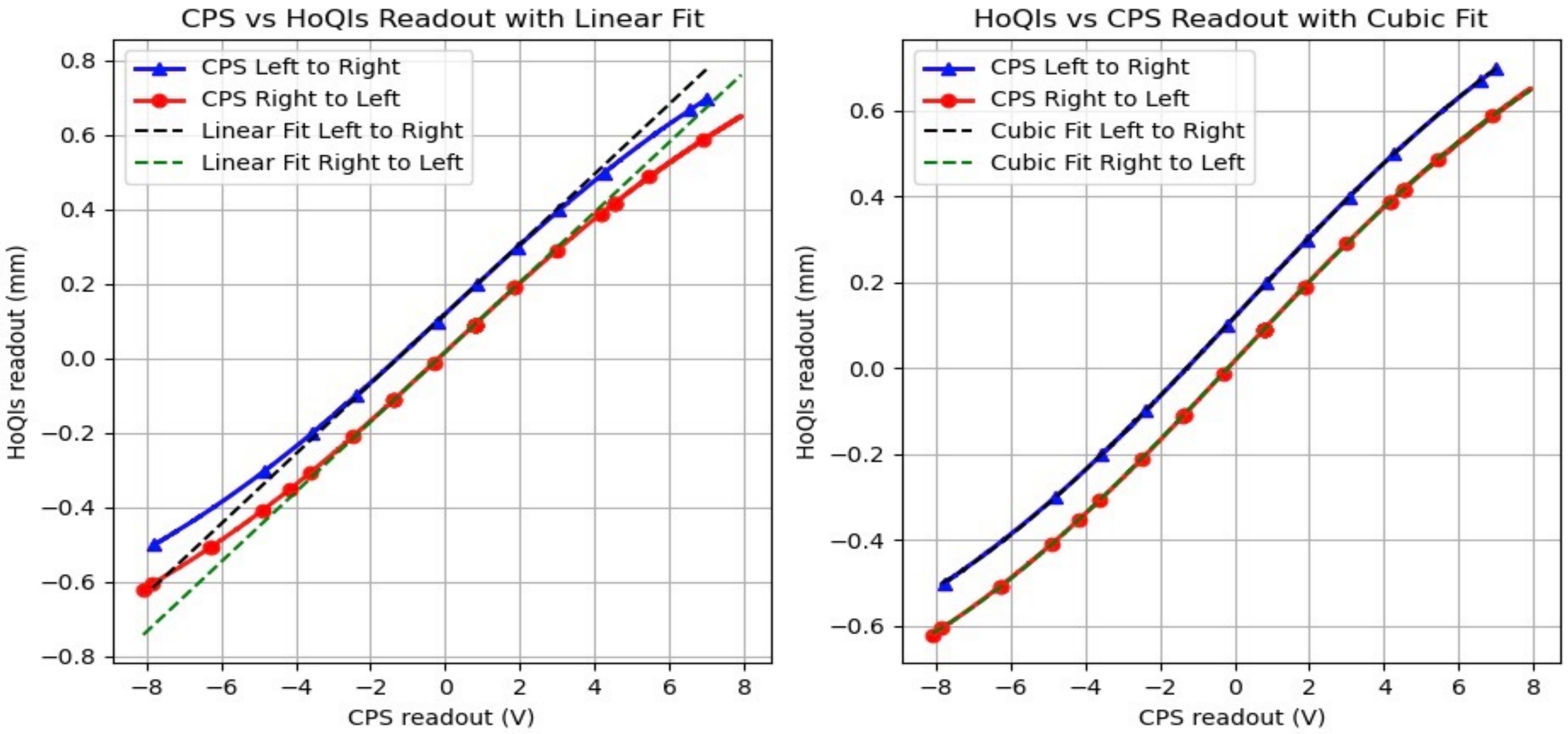


HoQIs vs CPS
An offset for around $100\mu m$

Left to Right Still Right to Left



Fitting: Linear or Cubic

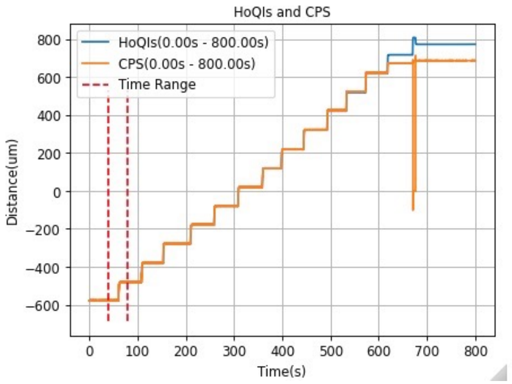


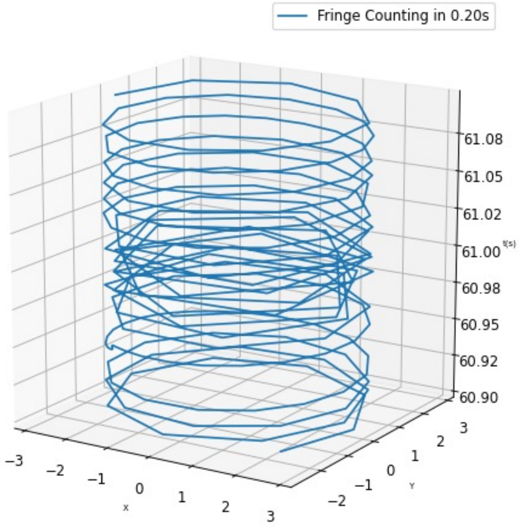
$$\text{Linear Fit: } d(\mu m) = 93.919(\mu m/V)\ \text{CPS}(V)$$

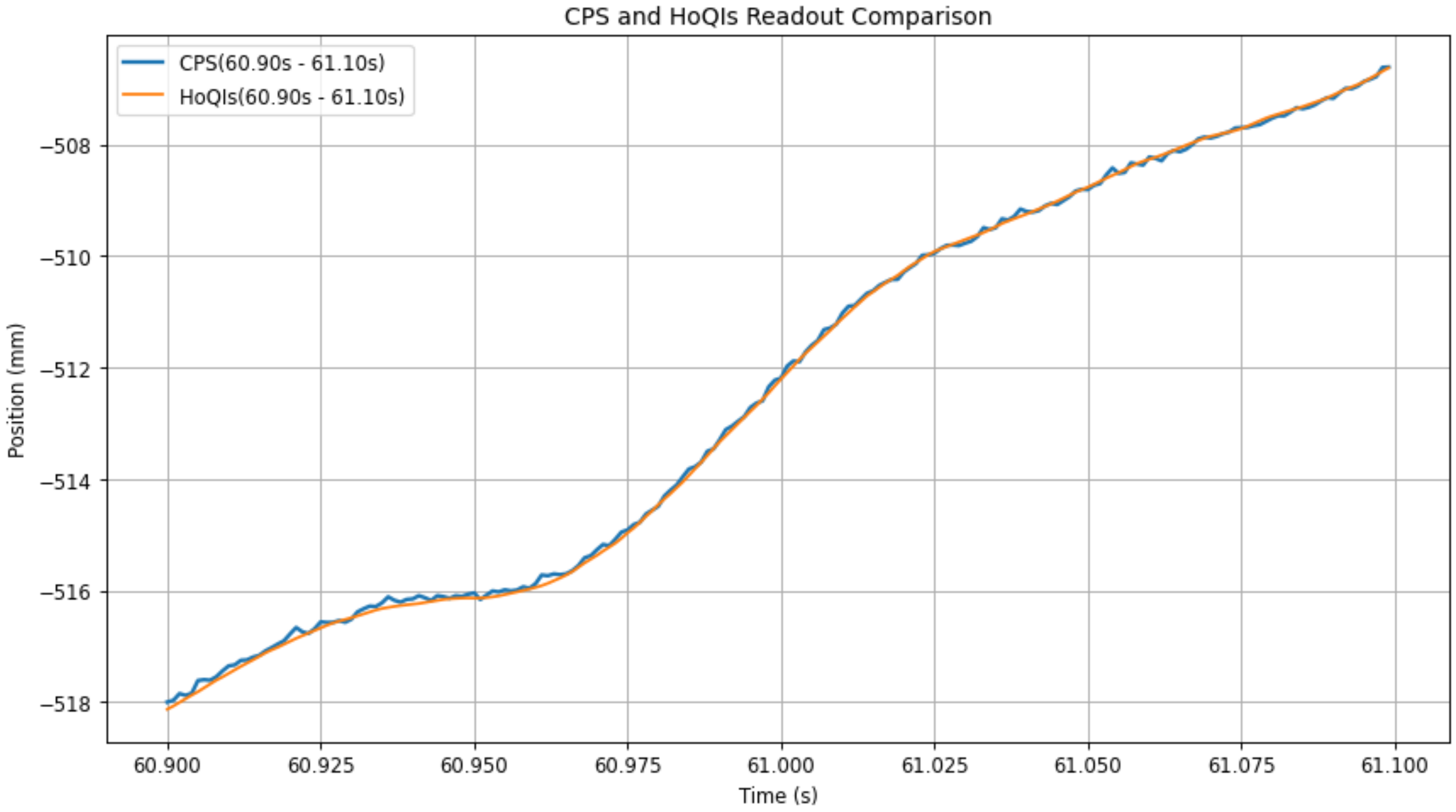
$$\text{Cubic Fit: } d(\mu m) = 92.605(\mu m/V)\ \text{CPS}(V) - 0.215(\mu m/V)^3(\text{CPS}(V))^3$$

Linear behaviour around centre position

Offset Analysis: Functioning Well



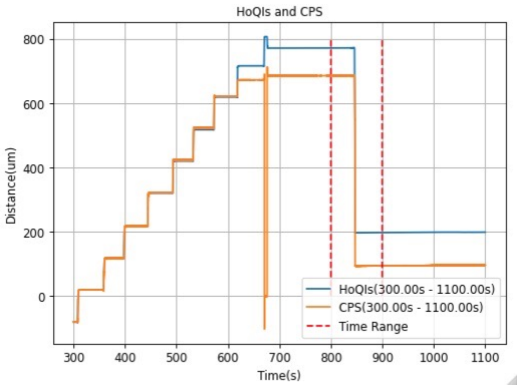


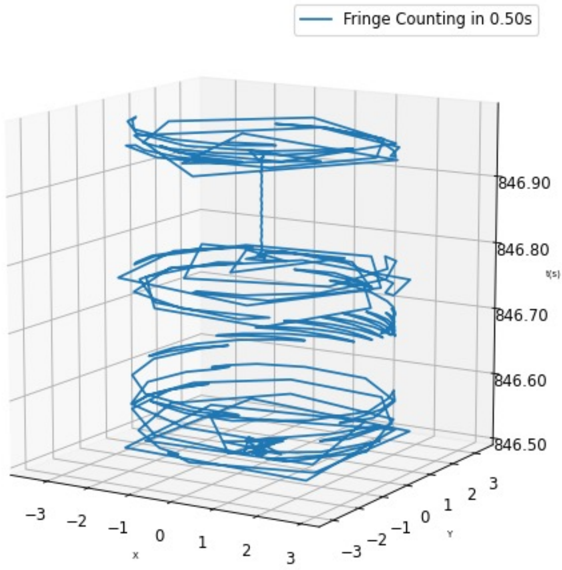


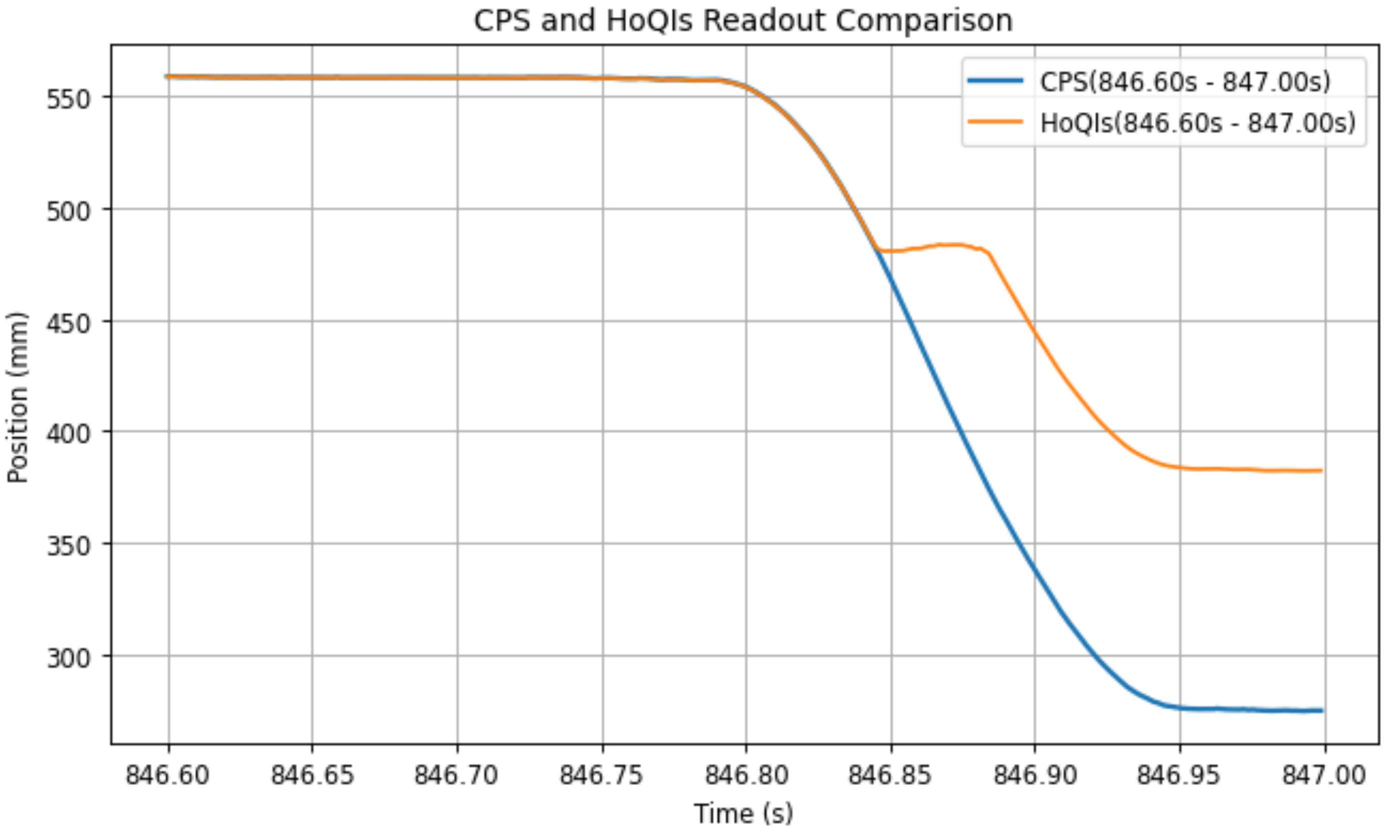
Continuous and smooth for HoQIs

Less smooth for CPS

Offset Analysis: Fringe Slipping





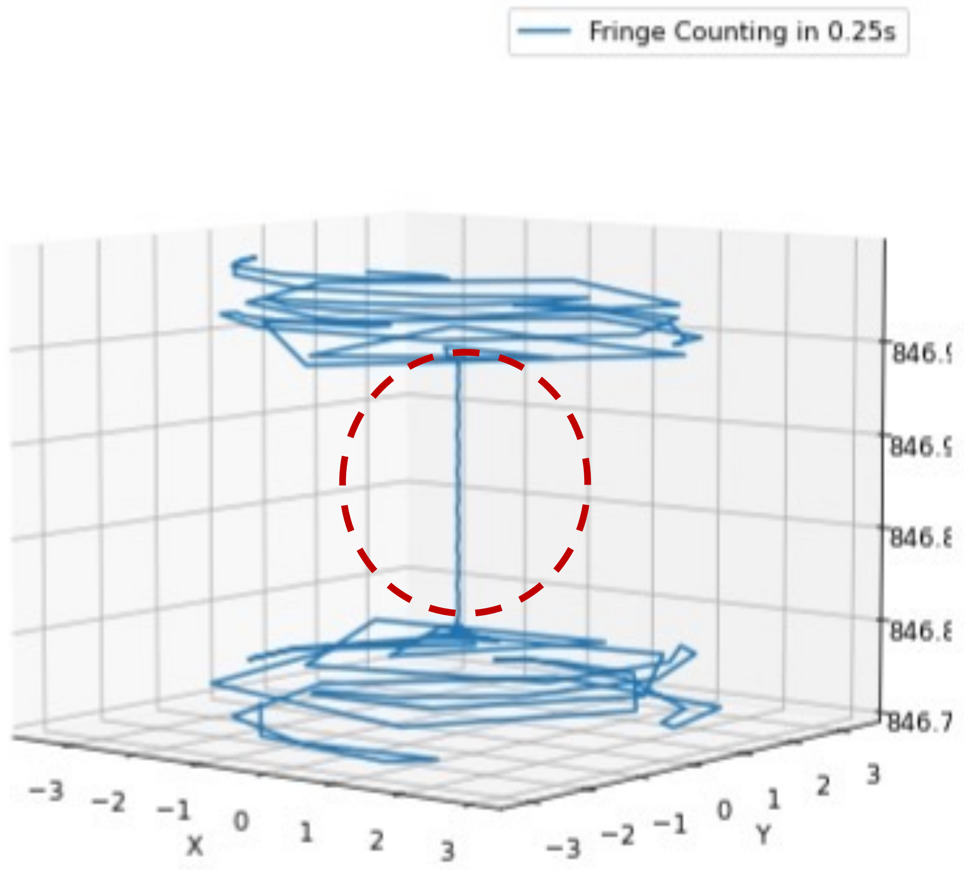


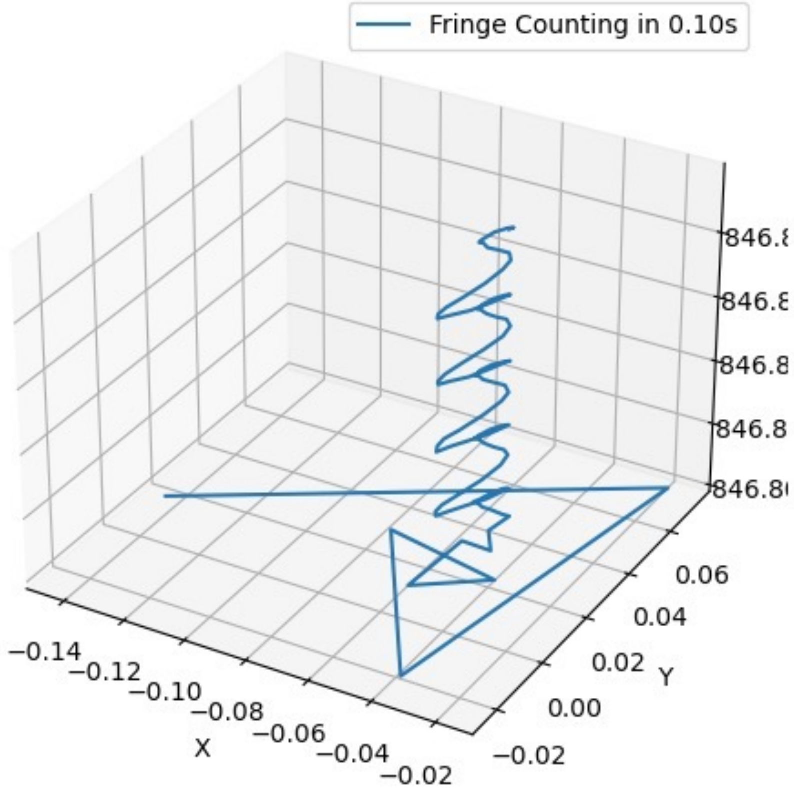
$100\mu m$ offset

$v = 67\mu m/s$

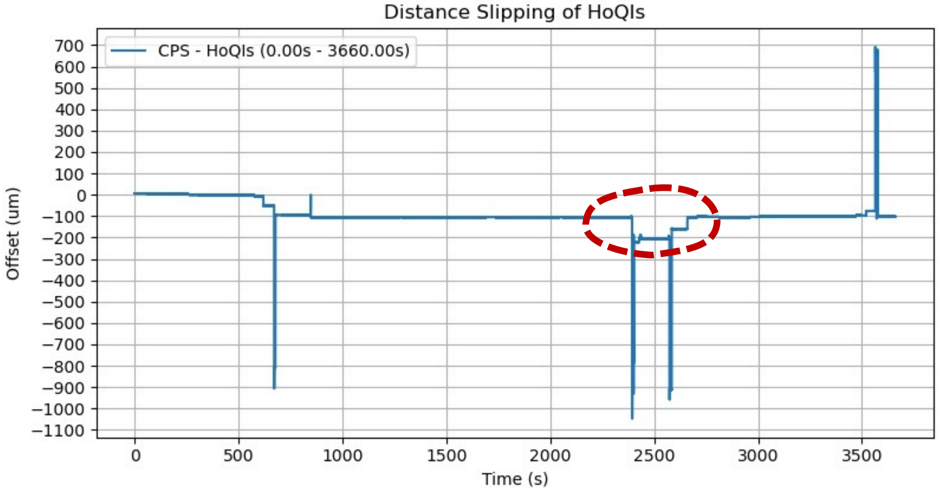
HoQIs levels out for a small range, losing the record of the movement

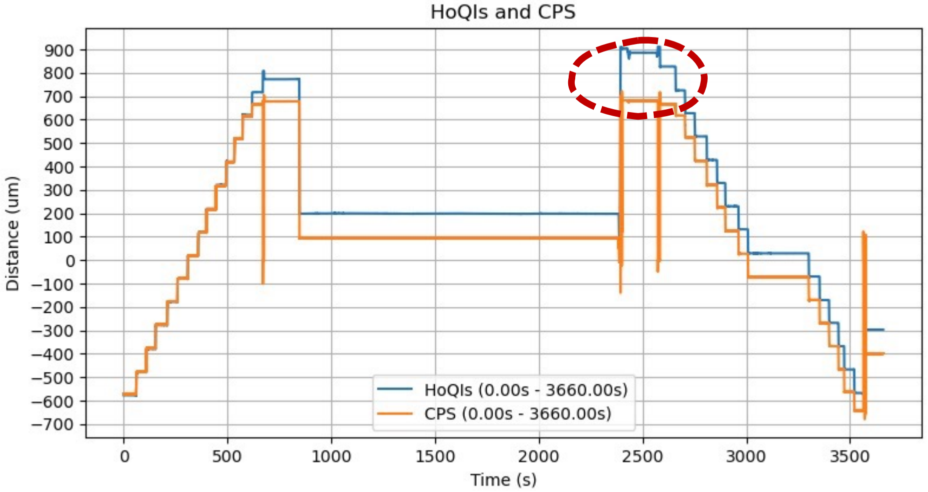
Offset Analysis: Fringe Slipping

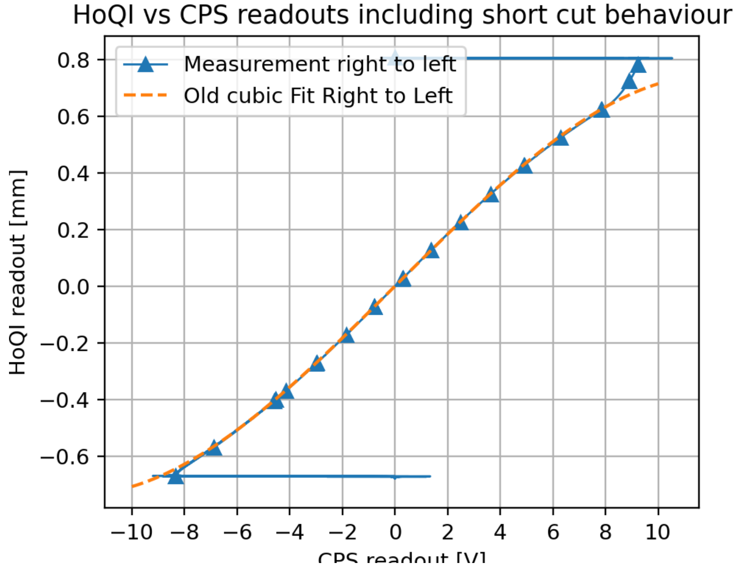


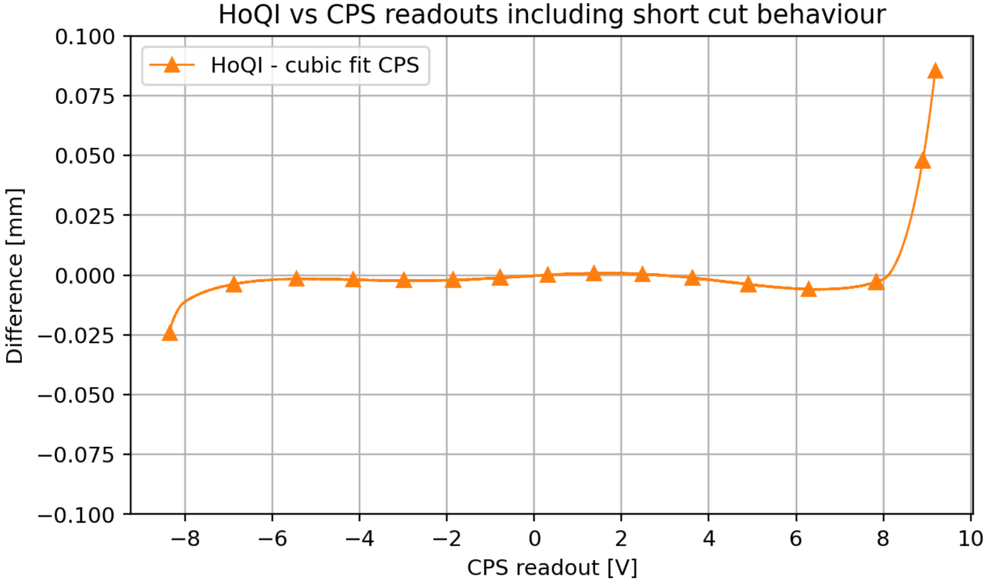


Zero Net Gross Offset



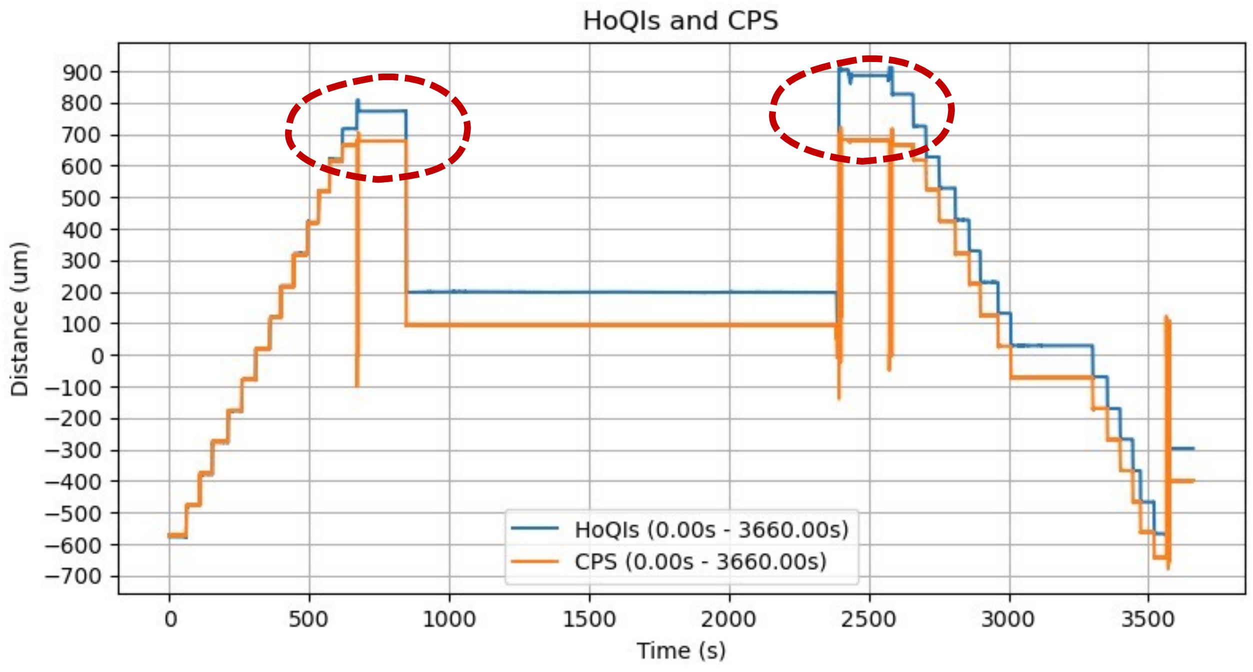


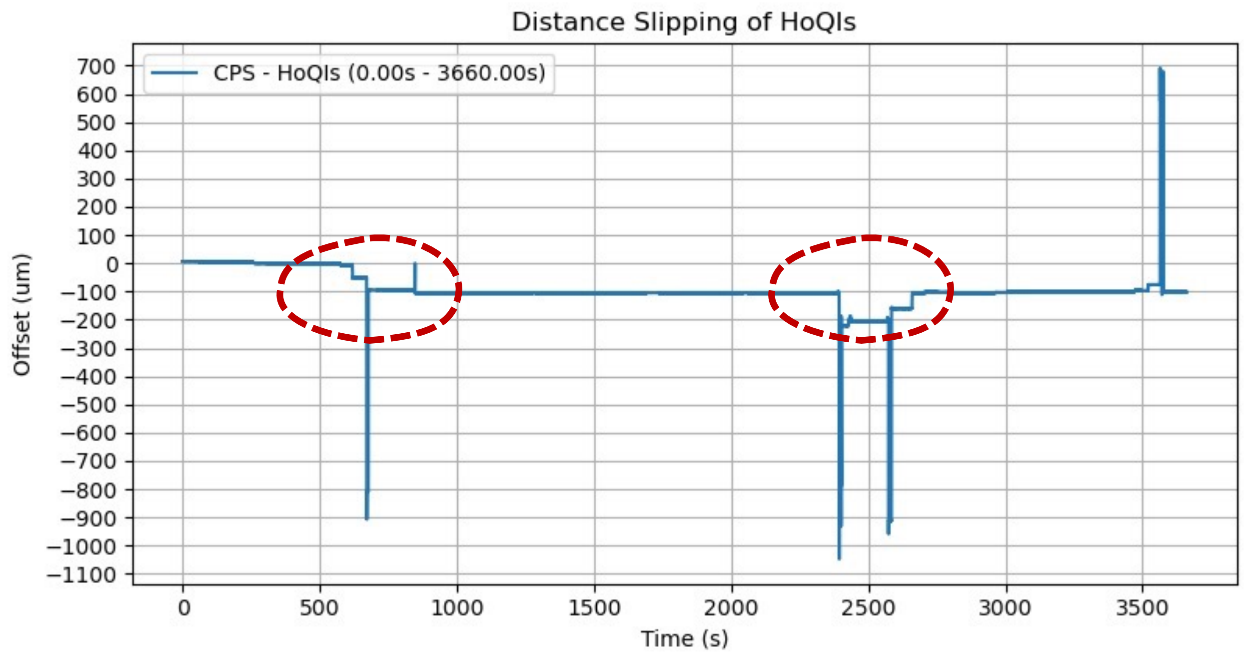




Fitting reconstruct smaller displacement near short cut point

CPS Calibrating HoQIs





Bouncing at the edge
Low fringe visibility
Lose interference
...

→

Not the biggest worry,
can be avoid by working around the centre

Result: a Functional Sensing System

For CPS:
- Model ~ Simulation ~ Measurement
- Independent of cables
- Small centre offset

For HoQIs:
- High fringe visibility
- HoQIs largely reduces the noise of inertial moving readout

Working Condition:
- CPS and HoQI are helping each other
- Slow moving
- Small dynamic range around centre

What it can be used for the OmniSens:
- Provide a sensitive inertial movement sensing for drag-free control -- help to reach OmniSens' sensitivity target
- Enable to find the new equilibrium (e.g. change in buoyancy..)
- Can use CPS to check HoQIs fringe slipping

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