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Demonstrator for the TTL Coupling Measurement in the LISA Experiment

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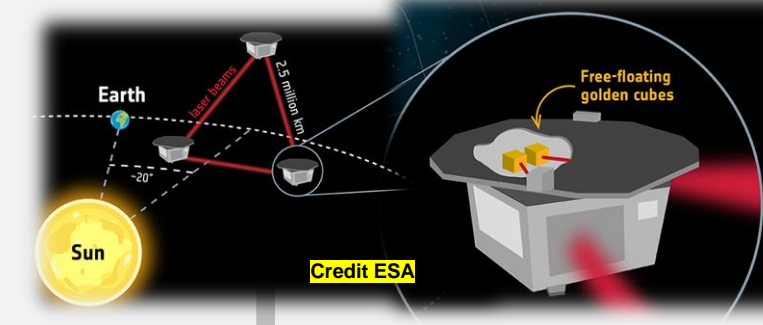
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OVERVIEW We present some of the key functions of a setup aimed at measuring the Tilt-To-Length (TTL) coupling on the LISA optical benches. It integrates off-the-shelf components, a metallic breadboard, servo-loops and position memories for beam alignments and obtained straightforward alignments with submicrometric accuracy. The setup demonstrates an optomechanical stability better than a few microns (130 hours), compliant with the specifications for LISA.

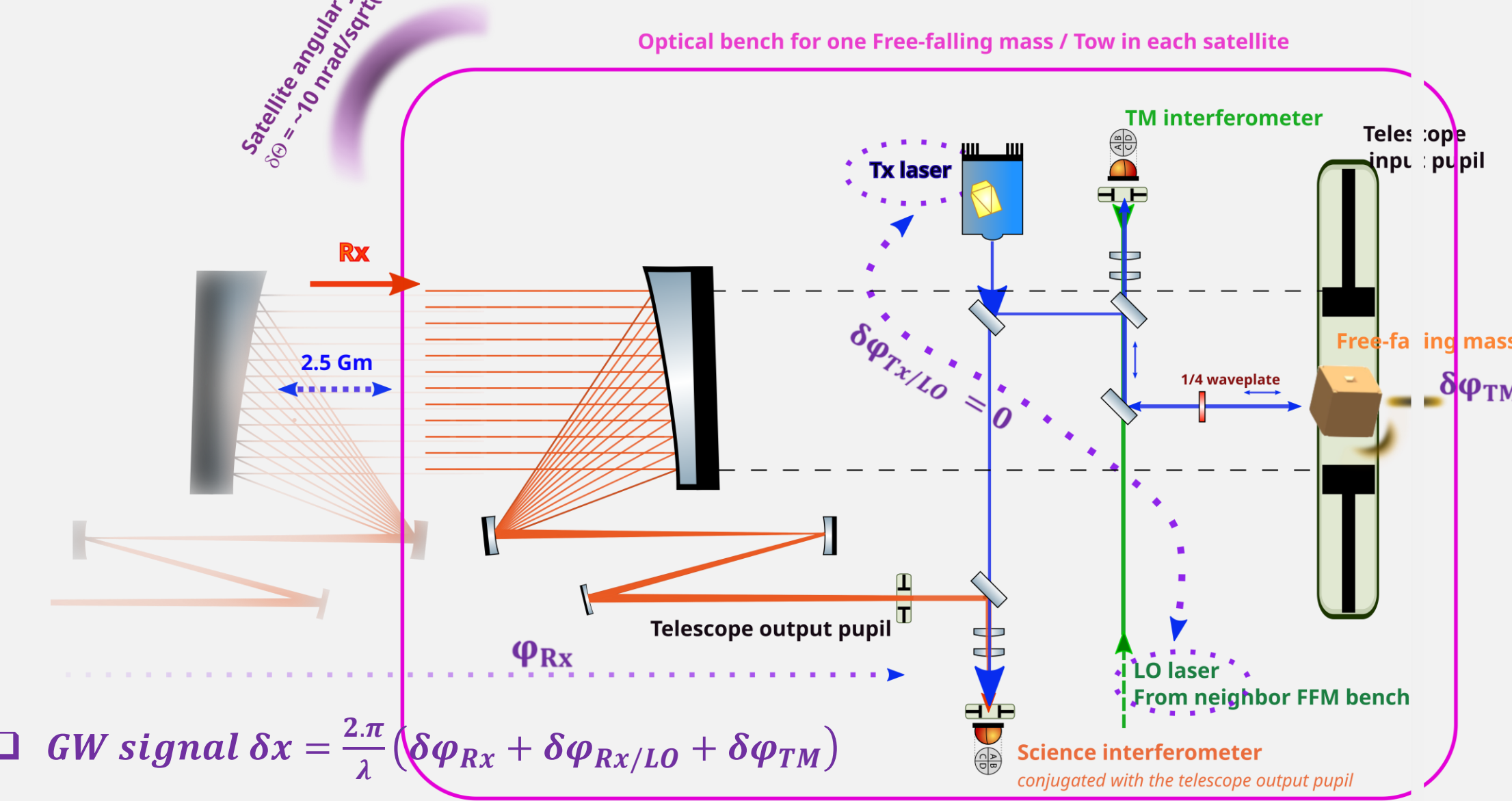
I - LISA mission for Gravitational Waves (GW) detection and TTL coupling

Laser ranging between Free-Falling Masses in space (FFM), 2.5 Mkm length optical link, it targets \sim few picometer/ $\sqrt{\text{Hz}}$. Heterodyne detection of the optical phase between the incoming & local beams attached to the far / local FFM's.



II - LISA optical bench

Aimed at detecting the Opt. Path Length "Input pupil"-to-FFM (" $\delta\phi$ " in rad)

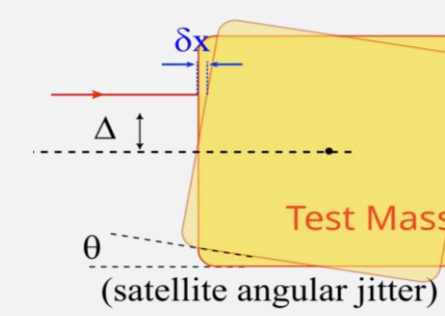


III - TTL coupling : One of the major noise source in LISA

Pupil's-to-Test Mass conjugation \rightarrow OPL FFM-to-detectors unaffected by the bench/satellite angular jitter

!! Residual pupil misalignments \rightarrow deleterious « Tilt-To-Length » coupling $TTL = \frac{\partial \delta x}{\partial \theta} = \Delta, \text{ in } \frac{\text{m}}{\text{rad}}$

\rightarrow FOGOB optical bench demonstrator for TTL measurement

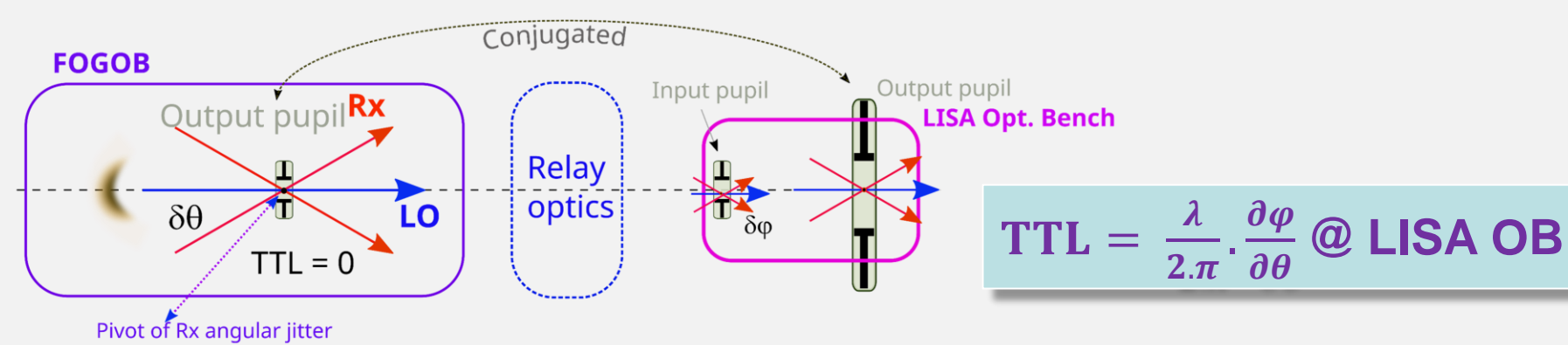


IV - FOGOB - Measurement principle

Provides Rx & LO beams, $\lambda = 1064 \text{ nm}$, $\sim 10 \text{ mW}$

Rx is tilted ($\theta_0 \times \sin(2\pi \cdot f_0 \cdot t)$) at the output pupil center

We conjugate the FOGOB pupil with the LISA OB pupil



Specification: $Rx = (\theta_0 \sim 150 \mu\text{rad}) \times \sin(2\pi \cdot \text{few Hz} \cdot t)$, **Pivot point centring accuracy** $< 15 \mu\text{m}$, **TTL @ FOGOB pupil accuracy** $< 10 \mu\text{m/rad}$, over days. **Std(TTL)** $< 10^{-7} \text{ m/rad}$ for few minutes trends. Rx flattop intensity profile

V - FOGOB demonstrator - Detection scheme

Heterodyne detection scheme, data of interest: $\phi = \text{Rx-to-LO } 1 \text{ MHz beat phase}$

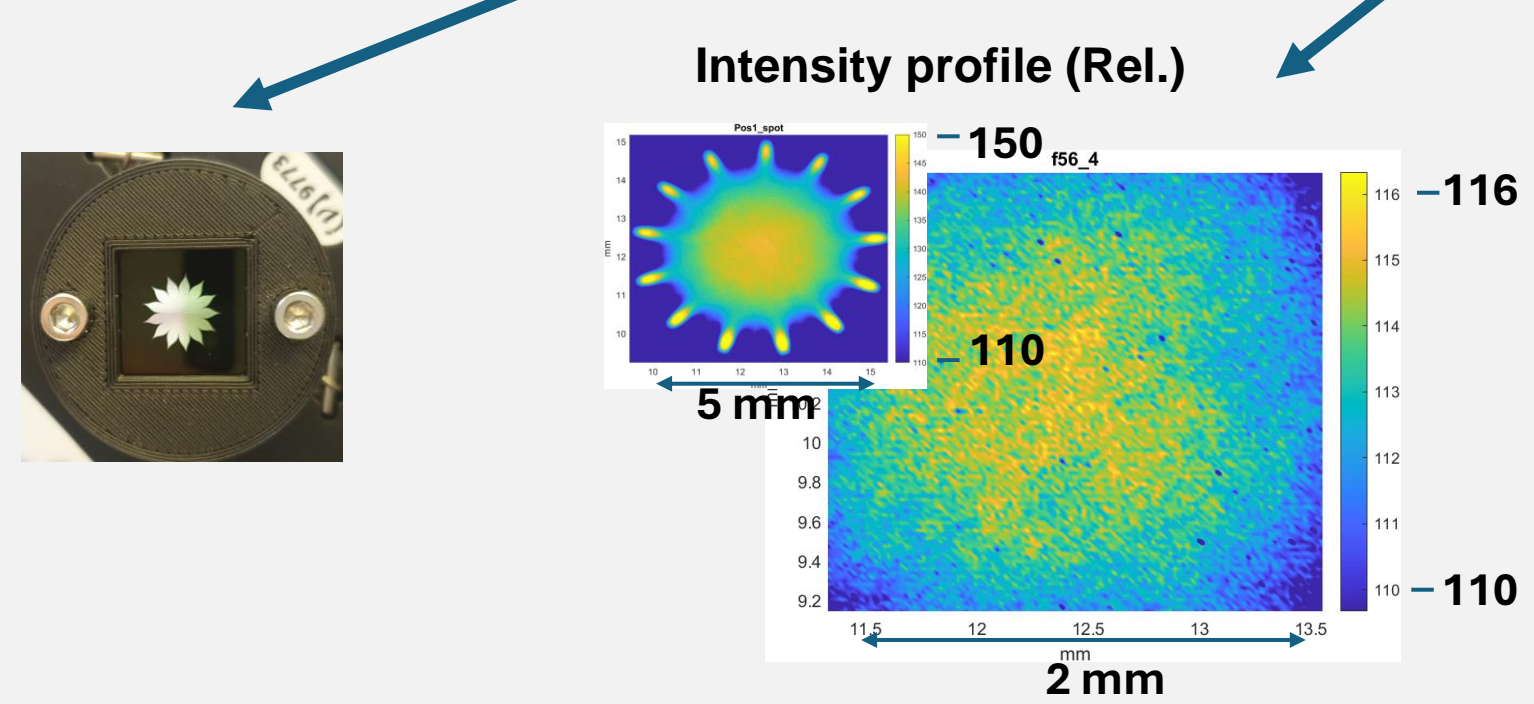
- Detection @ Output pupil, with a Quadrant Photo-Detector (QPD) delivers: residual « piston » $= \sum_{i=1..4} \phi_i$
- Detection @ Twin output pupil, with a QPD delivers: Tilt Rx-wrt-LO, $\theta = \sum_{i=1..4} \pm \phi_i$
- Detection @ Twin output pupil, with a pinhole Single Element PhotoDiode (SEPD), centered @ pupil, delivers: Rx-vs-LO phase lock Err signal $\rightarrow TTL = \text{piston} @ f_0 / \theta @ f_0 \text{ meter/radian}$

VI - FOGOB demonstrator - Flattop generation / Beam alignment Ctrl / Mechanical Stability

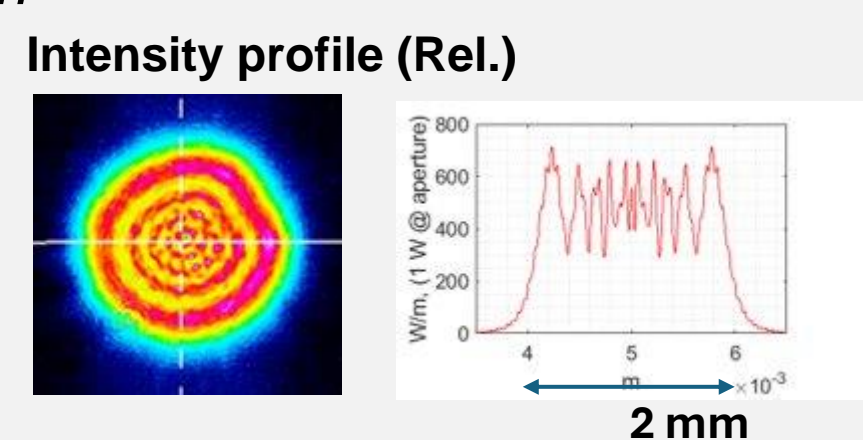
Flat Top intensity profile (Rx beam)

Goal: mimic a plane wave over a 2.5 mm diam. pupil. The pupil is located $\sim 80 \text{ cm}$ away from the source

Setup: SM fiber collimated using a 30 cm lens & apodization for diffraction mitigation (transmissive mask), detection @ 0.8 m



Would have been an Airy diffraction pattern with a naïve setup: 2.5 mm disk diffraction @ 80 cm

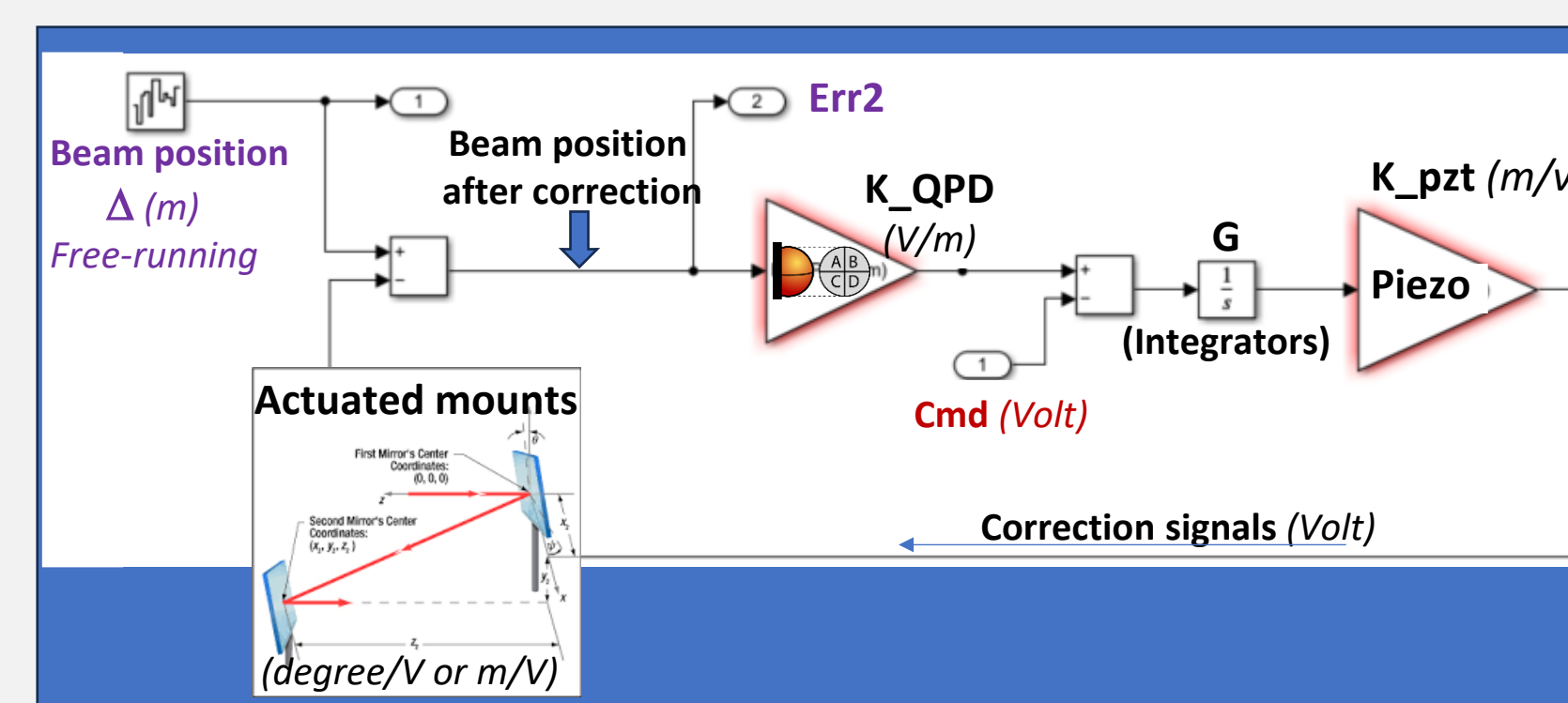


Results

- Intensity variations $< 3\%$ P.V. over 3 mm
- rms. intensity variations $< 1\%$ rms
- Wavefront error $< \lambda/100$ rms (1064 nm)

\rightarrow Associated TTL $< 0.1 \mu\text{m/rad}$

Beam position Ctrl



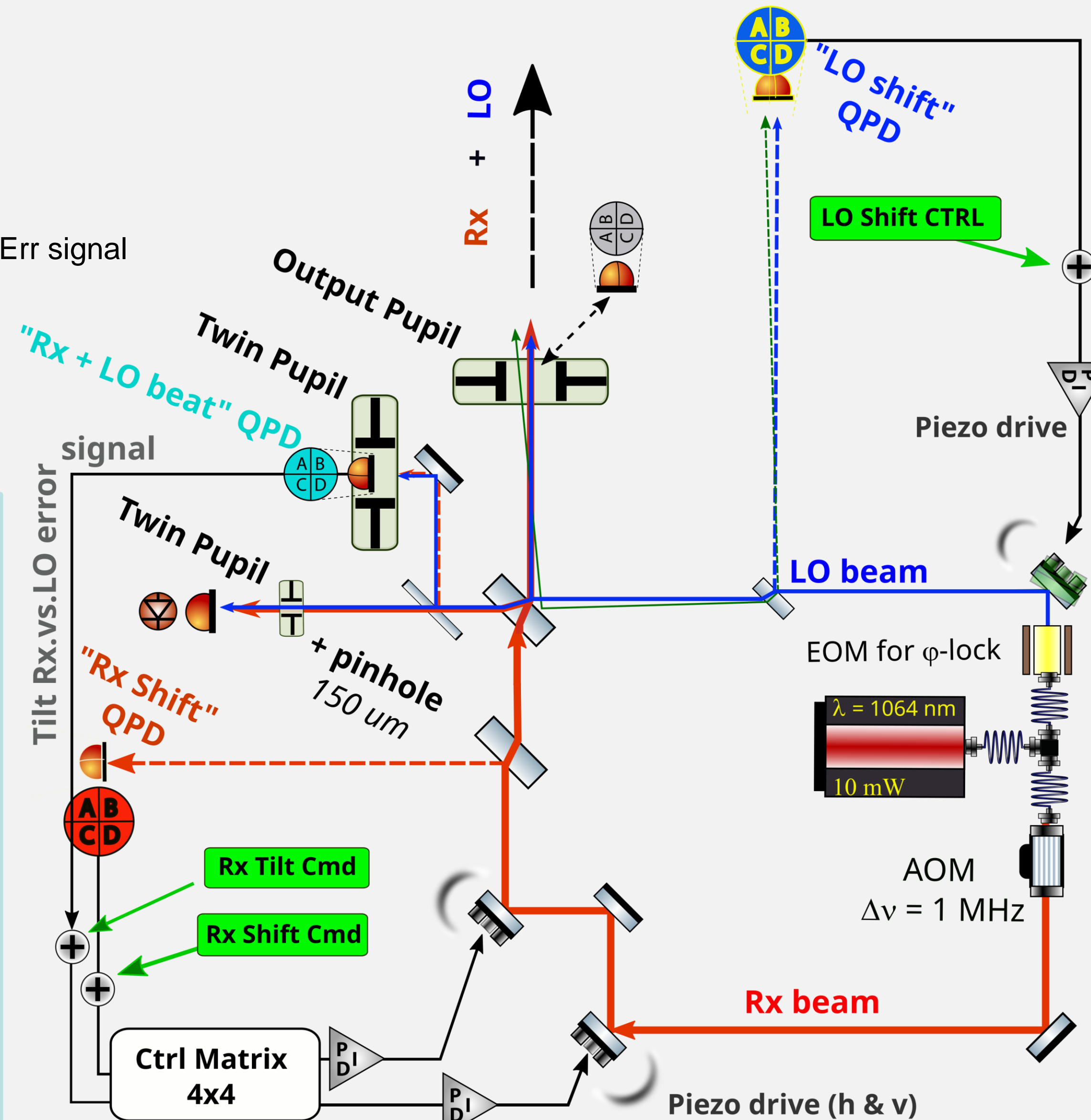
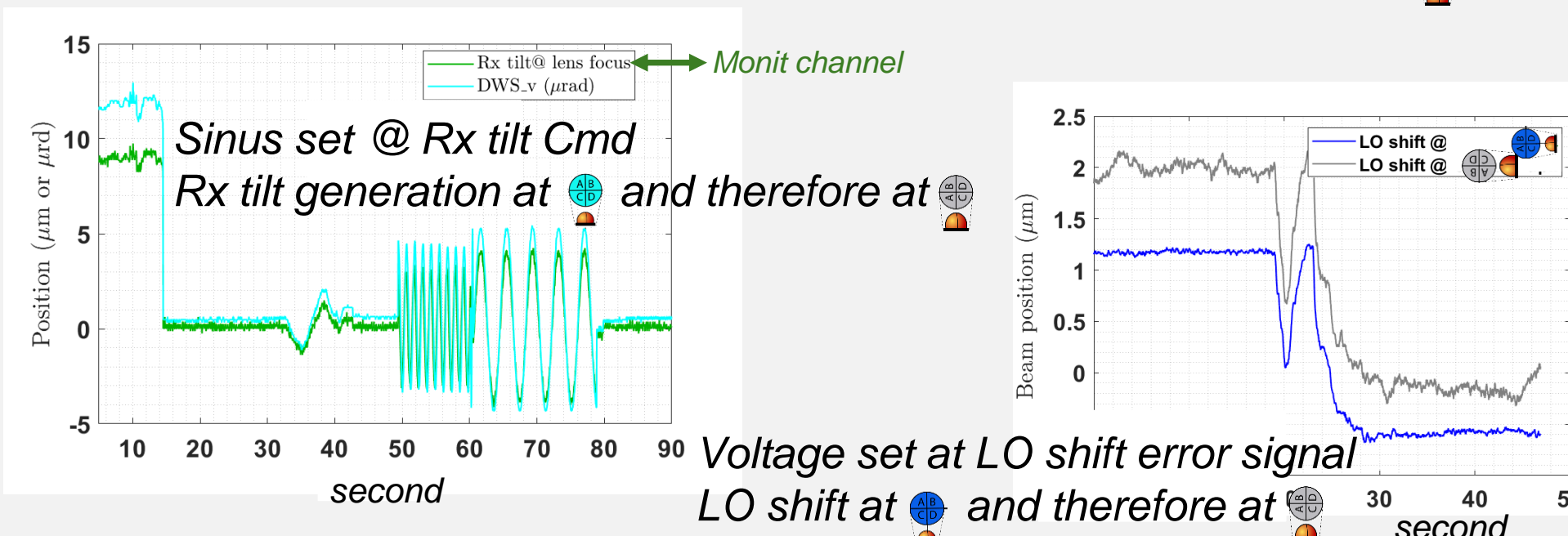
$$\text{Err2} = \Delta / \text{OLTF} + \text{Cmd} / K_{\text{QPD}} \approx \text{Cmd} / K_{\text{QPD}} \text{ with } \text{OLTF} \gg 1$$

- « Err2 »: in-loop error signal
- OLTF = $G \cdot K_{\text{pzt}} \cdot K_{\text{QPD}}$
- OLTF $\propto 150/f$
- $K_{\text{QPD}} \propto P/w$
- « Cmd »

Results

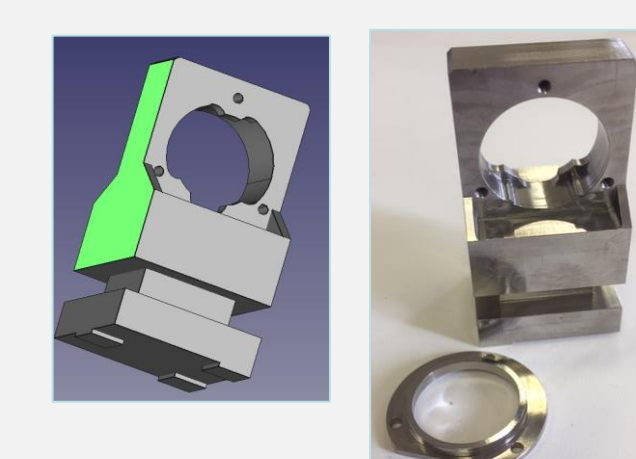
- Beams position (shift & Tilt) locked at (all 3 conjugated)
- Beams tilt & shift : fine Cmd added to the servo loop error signals

\rightarrow Submicrometric & fast alignments ($< 60 \text{ sec}$) at

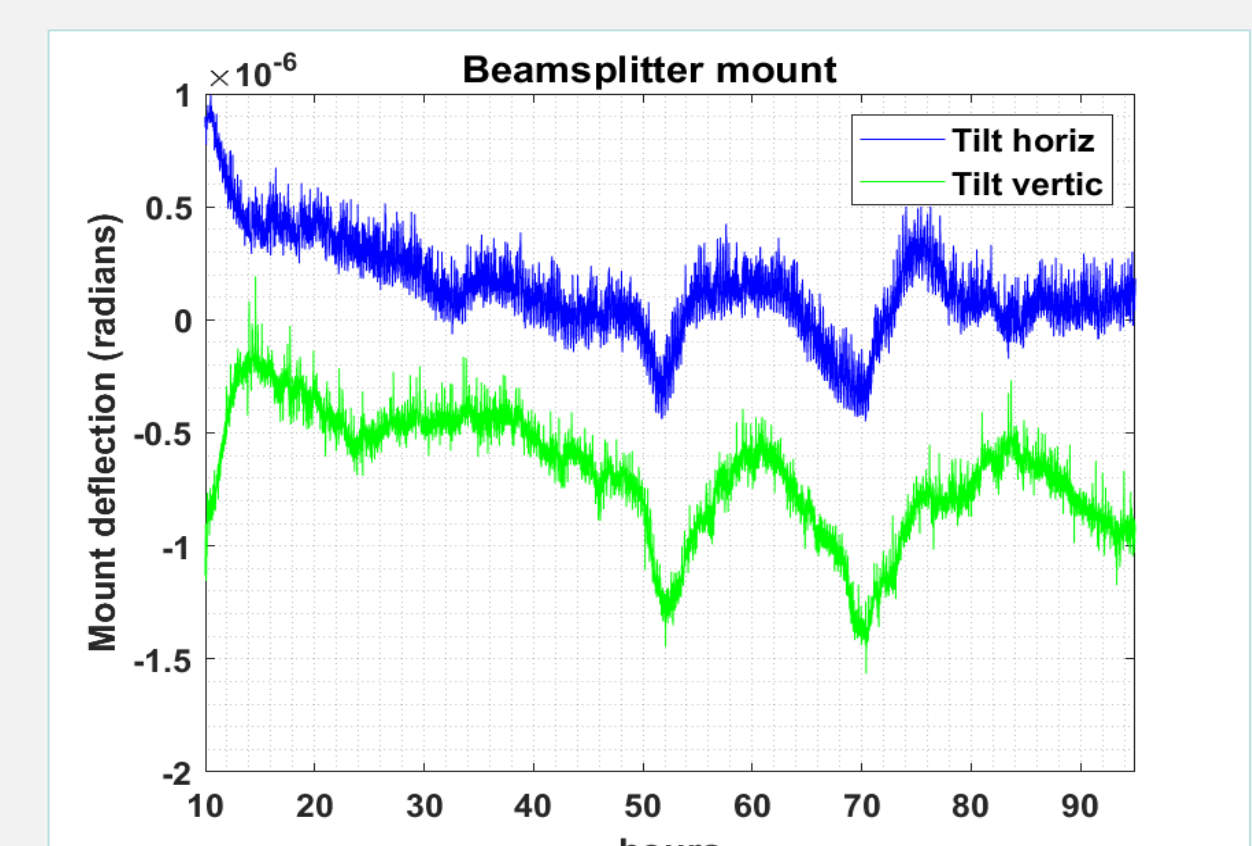


Opto-mechanical mounts stability *

Invar-based design



* Measured with SIOS triple laser interferometer



\rightarrow Beam deflection $< 2 \cdot 1.5 \mu\text{rad}$ over long term

ie $1 \mu\text{m}$ beam drift @ pupil (assuming $\approx 0.25 \text{ m}$ lever arms)

VII - Conclusion

- $TTL_{\text{Meas.}}^{(5)}$ accuracy $< 5 \mu\text{m/rad}$
- $TTL_{\text{Meas.}}^{(5)}$ drifts $< 1 \mu\text{m/rad}$, 130 h run
- Std($TTL_{\text{Meas.}}^{(5)}$, 60 s. data trends) $< 10^{-7} \text{ m/rad}$, 130 h run

\rightarrow Compliant with the FOGOB specifications

- Sub-micrometric and straightforward beam alignments
- Operated with off-the-shelf components, in a « standard » Laboratory environment

- Missing
 - Flattop integration
 - TTL meas. @ output pupil

(5) measured at the "Rx-to-LO" QPD, rather than at the output pupil

