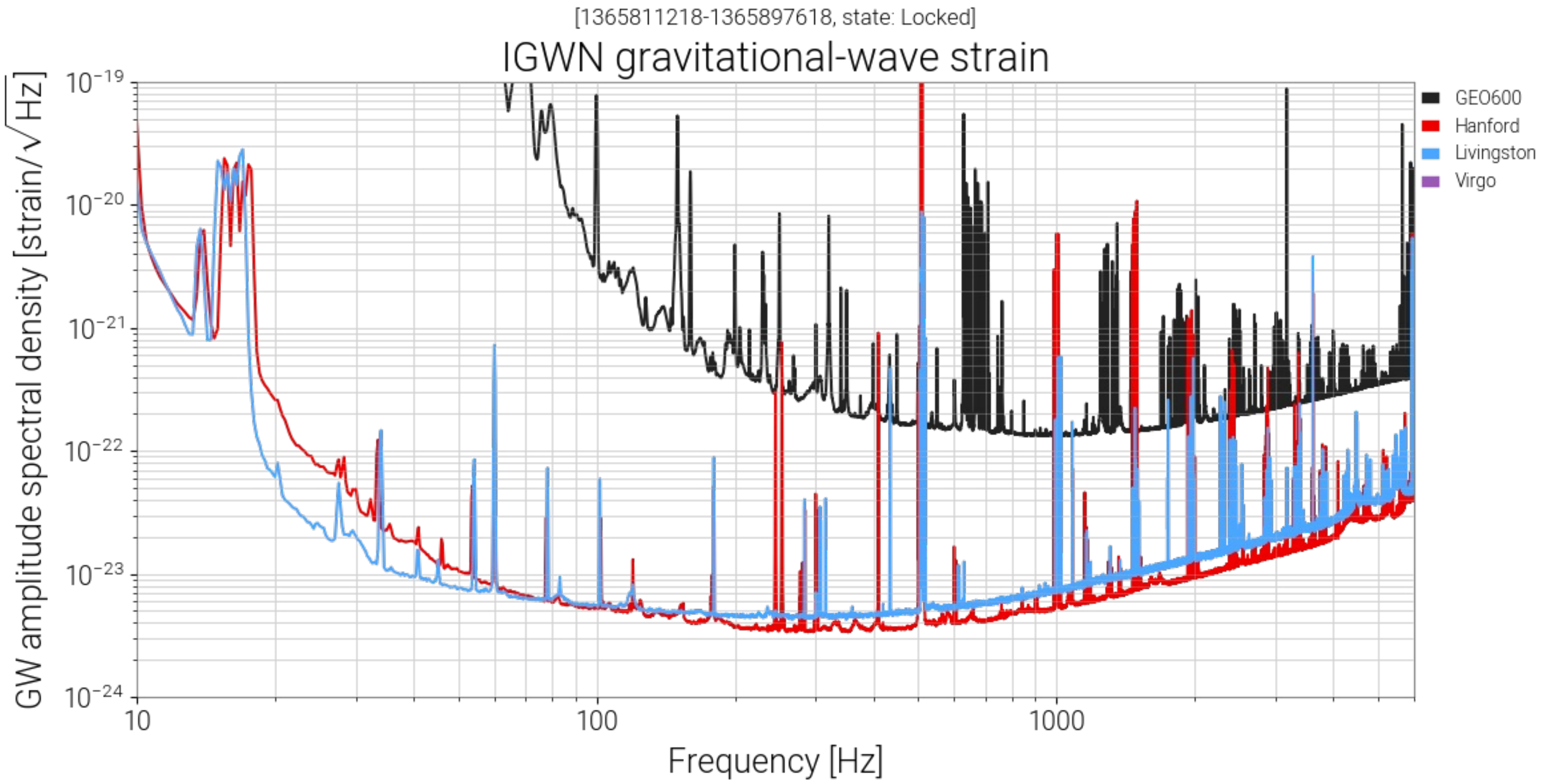
Back-scattered light from OFI at LIGO Hanford

Eleonora Polini and Xinghui Yin in collaboration with LHO commissioners

23st May 2023

Why does LHO lose sensitivity at low frequencies?



Maybe for scattered light…

Effect of scattered light on interferometer sensitivity

Back-scattered light noise spectrum:

$$h_{sc}(f) = \boxed{\sqrt{f_r} \cdot TF(f)} \cdot ASD\left\{ \sin\left[\frac{4\pi}{\lambda}\left(x_0 + \delta x_{sc}(t)\right)\right]\right\}$$

G-factor

$f_r = f_{sc} + f_{sp} + f_{Rayleigh} + f_{extra}$: fraction of re-coupled back-scattered and back-reflected light

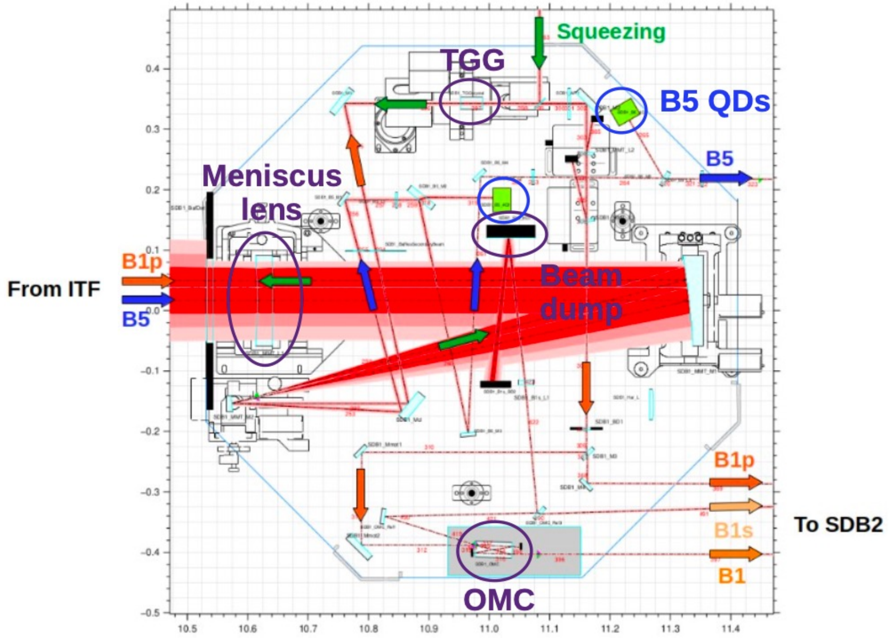
TF(f) : Transfer Function of the interferometer

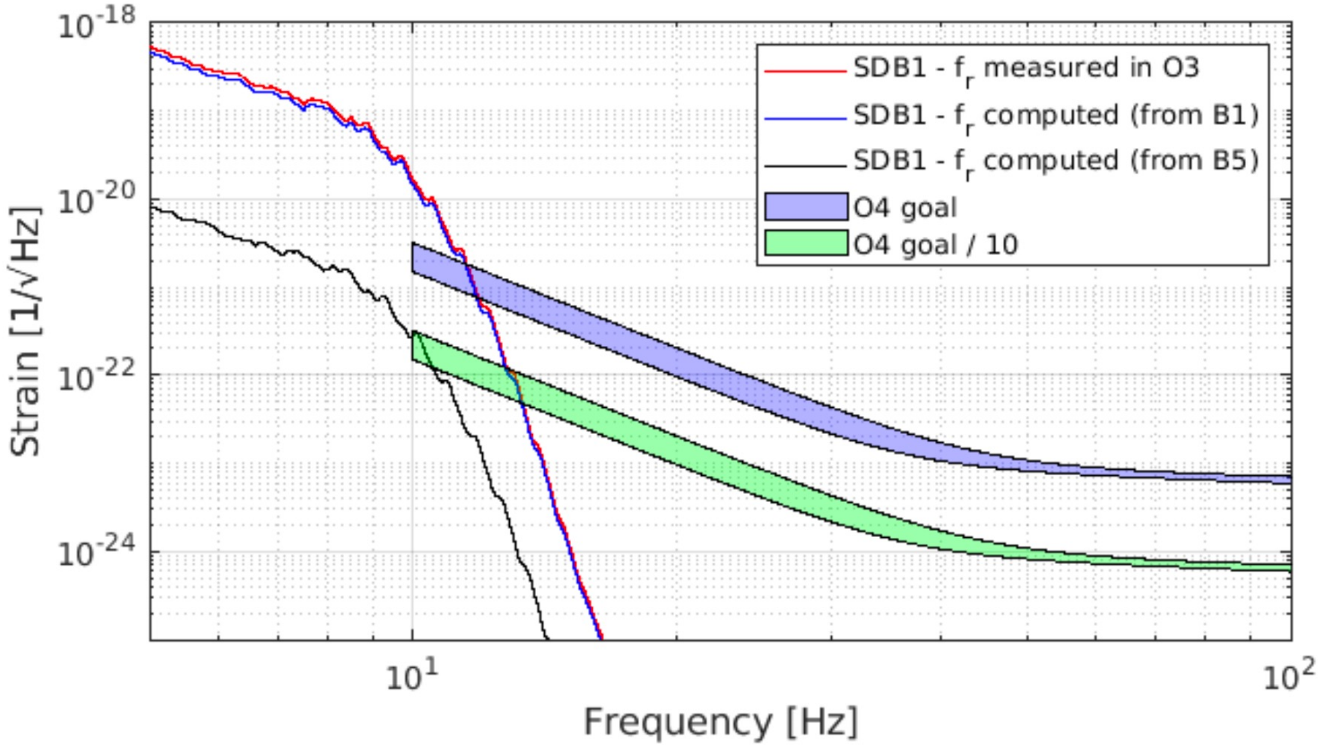
ASD : Amplitude Spectral Density

$\delta x_{sc}(t)$: motion of the scatterer with respect to the IFO

Projection studies at Virgo

- Estimation of f_r from measurements or literature
- Consider $\delta x_{sc}(t)$ during high seismic activity in O4 commissioning
- Compute the scattered light noise projections





Limiting elements:

- TGG in the OFI
- OMC
- Quadrant photodiodes
- Meniscus lens

See my poster this afternoon

Scattering from the TGG crystal in the OFI

$$f_{sc} \sim \alpha_p^2 \cdot \frac{BRDF(\theta) \cdot \lambda^2}{\pi \cdot w(z)^2} \sim \alpha_p^2 \cdot \frac{TIS \cdot \lambda^2}{\pi^2 \cdot w(z)^2}$$

Surface scattering

$$TIS = \left(\frac{4\pi\sigma_{RMS}}{\lambda}\right)^2 \qquad \sigma_{RMS} = 0.2\text{nm} \ (*)$$

(*) E. Genin, G. Pillant, A. Chiummo, and R. Gouaty. Change request: Low-loss faraday isolators for squeezed light injection. *VIR-0441A-17*, 2017.

Rayleigh scattering

$$TIS = 5 \cdot 10^{-4}\text{cm}^{-1} \ (**)$$

TGG length = 18 cm

(**) H. Yoshida *et al*. Optical properties and faraday effect of ceramic terbium gallium garnet for a room temperature faraday rotator. *Opt. Express*, 19(16):15181–15187, Aug 2011.

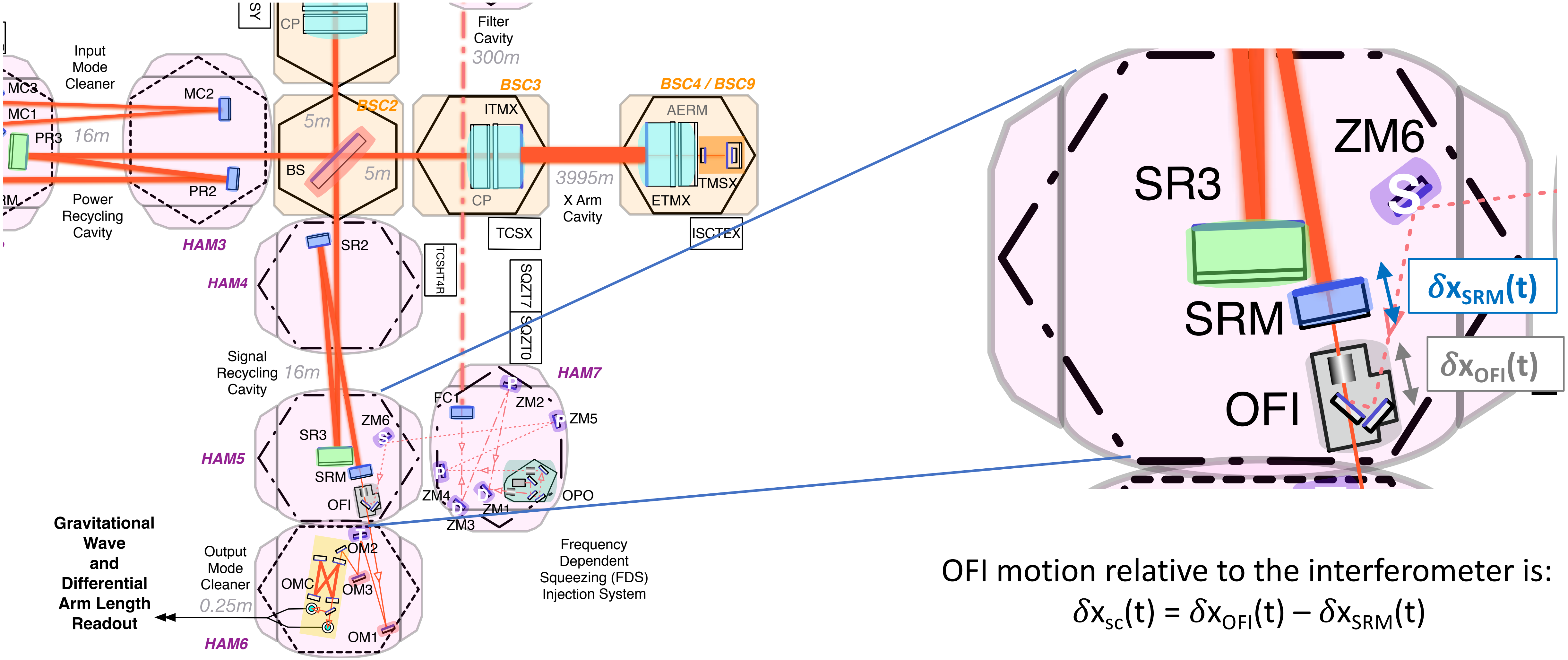
Element	α_p	$w(z)$	$BRDF(\theta)$	f_{sc}
TGG surface	1	1.3 mm	$4 \cdot 10^{-6}$	$8.5 \cdot 10^{-13}$
TGG Rayleigh	1	1.3 mm	$3 \cdot 10^{-3}$	$3.1 \cdot 10^{-10}$

Studies done at LHO

- The OFI at LHO doesn't have a shroud box, while the one at LLO does

- OFI suspension shaking : longitudinally and transversally
- Estimation of the f_r factor from the scattered light noise shelves
- Projections using the f_r estimation:
  - ➢ considering the suspension motion during calm times
  - ➢ considering the suspension motion during earthquake mode

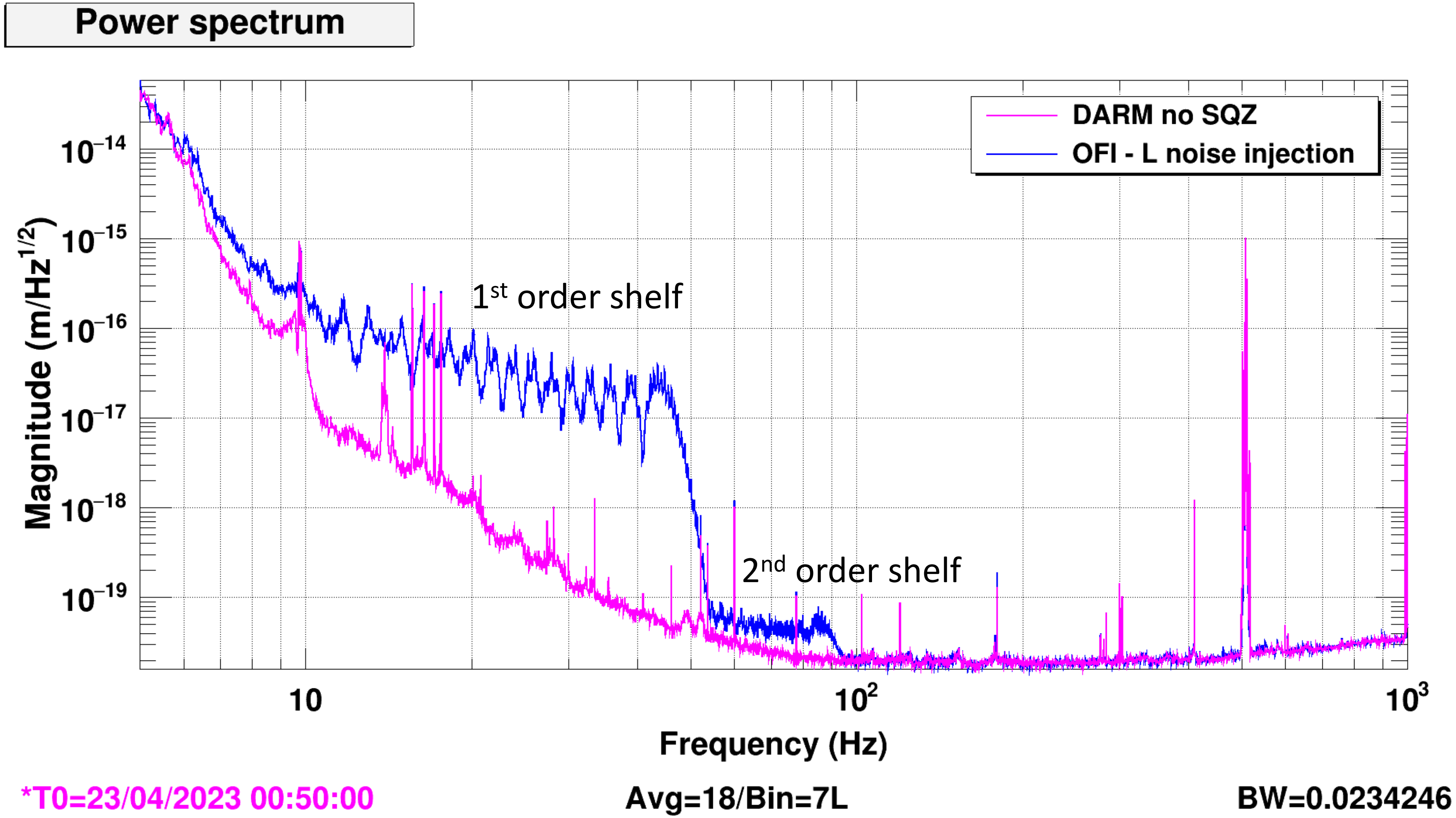
OFI longitudinal displacement wrt IFO



OFI motion relative to the interferometer is:

$$\delta x_{sc}(t) = \delta x_{OFI}(t) - \delta x_{SRM}(t)$$

Longitudinal injections : scattered light recouples to DARM, **no SQZ**



Shelves analysis: 1st and 2nd orders

Scattered light model:

$$h_{sc}(f) = \frac{G}{L} \cdot ASD\Big\{ \sin\left[\frac{4\pi}{\lambda}\Big(x_0 + \delta x_{sc}(t)\Big)\right] + g_2 \cdot \sin\left[\frac{4\pi}{\lambda}\Big(x_0 + 2\cdot\delta x_{sc}(t)\Big)\right]\Big\}$$

We first used the following approximation during the noise injections:

$$\delta x_{sc}(t) = A_{sc}\sin(2\pi f_{sc} t)$$

$$f_{max} = \frac{4\pi}{\lambda} A_{sc} f_{sc} = \frac{2 v_{sc}}{\lambda}$$

To derive the G factor.

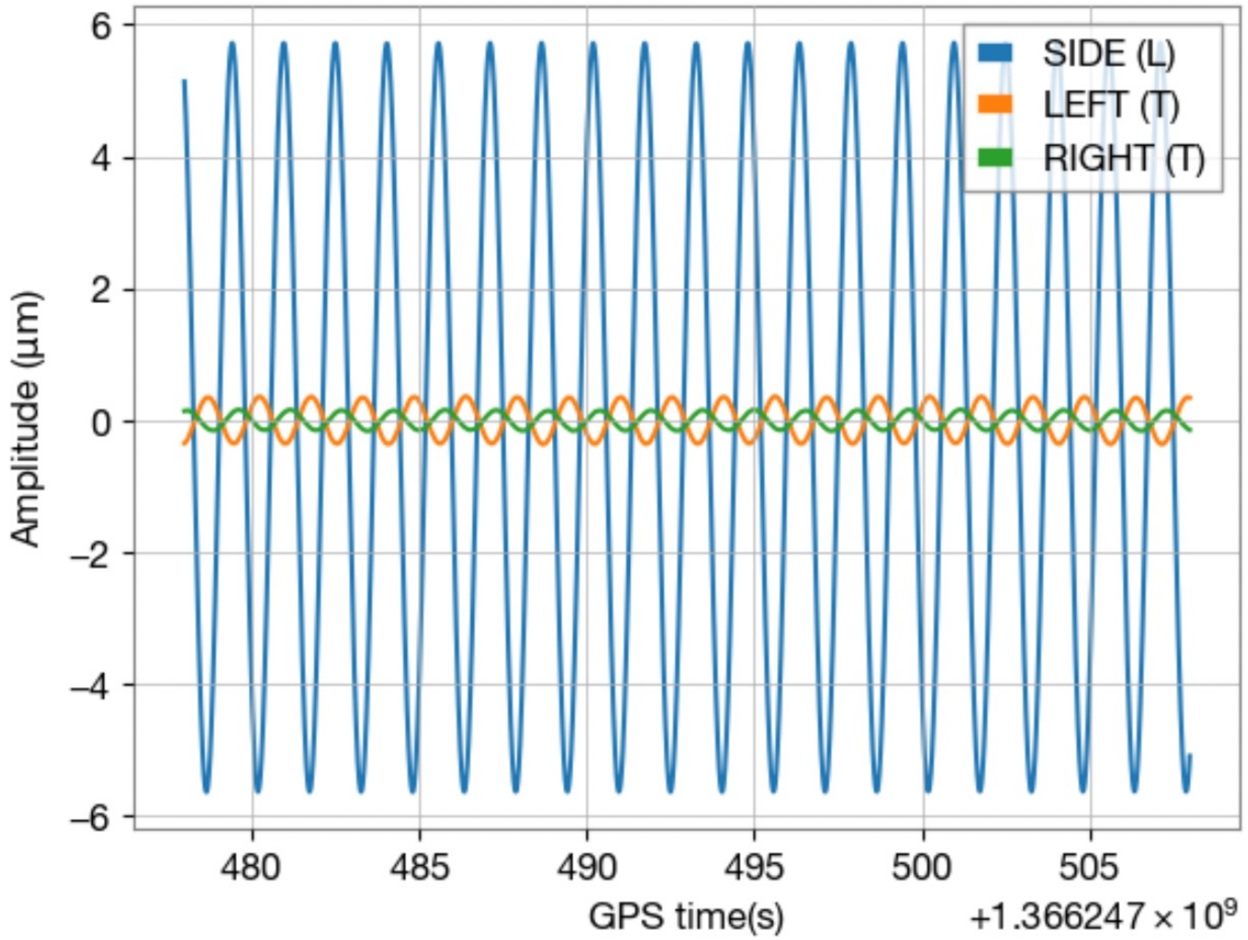
Shelves analysis: 1st and 2nd orders

$$h_{sc}(f) = \frac{G}{L} \cdot ASD\Big\{ \sin\Big[\frac{4\pi}{\lambda}\Big(x_0 + \delta x_{sc}(t)\Big)\Big] + g_2 \cdot \sin\Big[\frac{4\pi}{\lambda}\Big(x_0 + 2\cdot\delta x_{sc}(t)\Big)\Big]\Big\}$$

We injected a sine with frequency 0.65Hz and amplitude 6µm:

$$\delta x_{sc}(t) = 6\mu m \cdot \sin(2\pi \cdot 0.65\text{Hz} \cdot t)$$

The longitudinal motion (SIDE) is 2% coupled with the transverse ones in this configuration.



Shelves analysis: 2^{nd} order

g_2 = 0.003

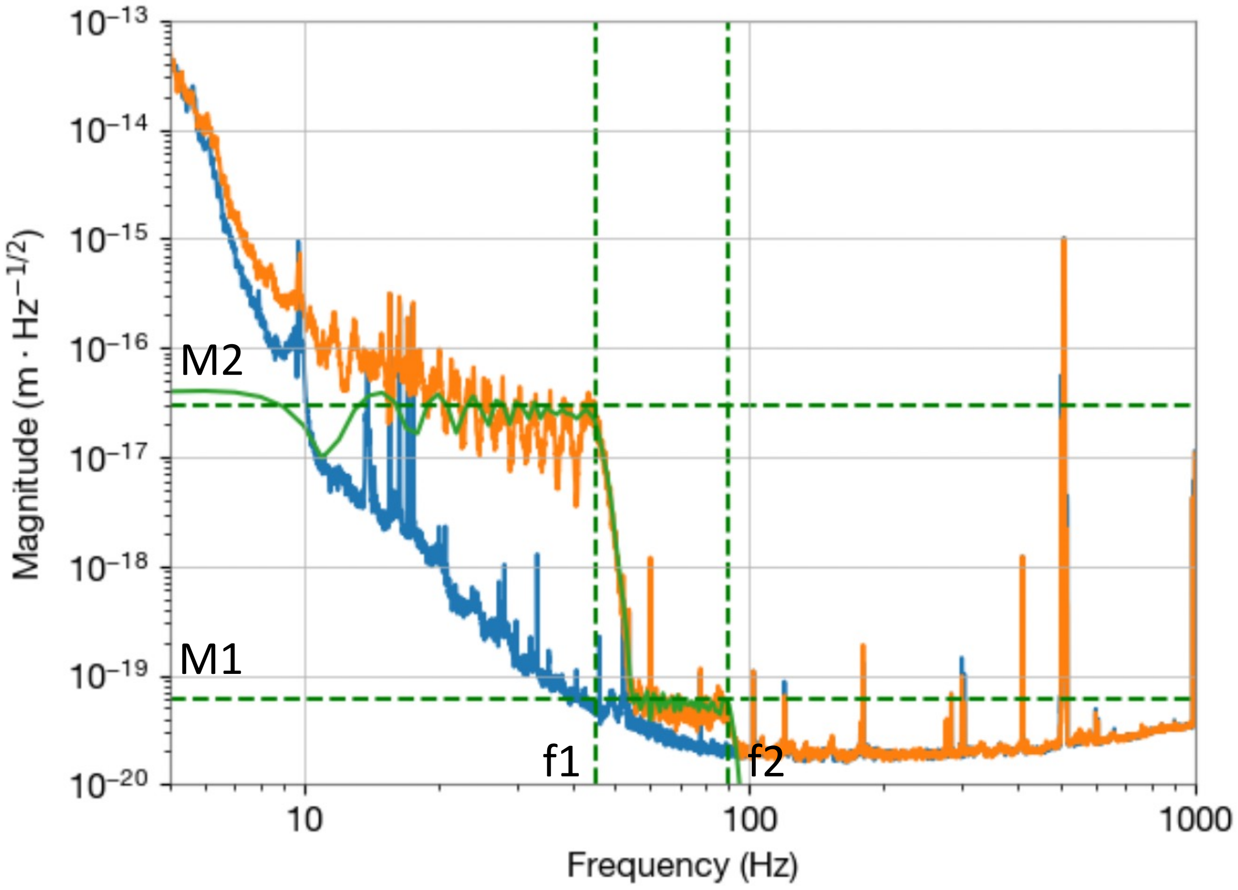
$$h_{sc}(f) = \frac{G}{L} \cdot ASD\left\{ \sin\left[\frac{4\pi}{\lambda}\left(x_0 + \delta x_{sc}(t)\right)\right] + g_2 \cdot \sin\left[\frac{4\pi}{\lambda}\left(x_0 + 2 \cdot \delta x_{sc}(t)\right)\right]\right\}$$

G = 4e-9

We injected a sine with frequency 0.65Hz and amplitude 6µm:

$$\delta x_{sc}(t) = 6\mu m \cdot \sin(2\pi \cdot 0.65\text{Hz} \cdot t)$$

- f1 = 45 Hz
- f2 = 90 Hz
- M1 = 3e-17 m $Hz^{-1/2}$
- M2 = 6e-20 m $Hz^{-1/2}$



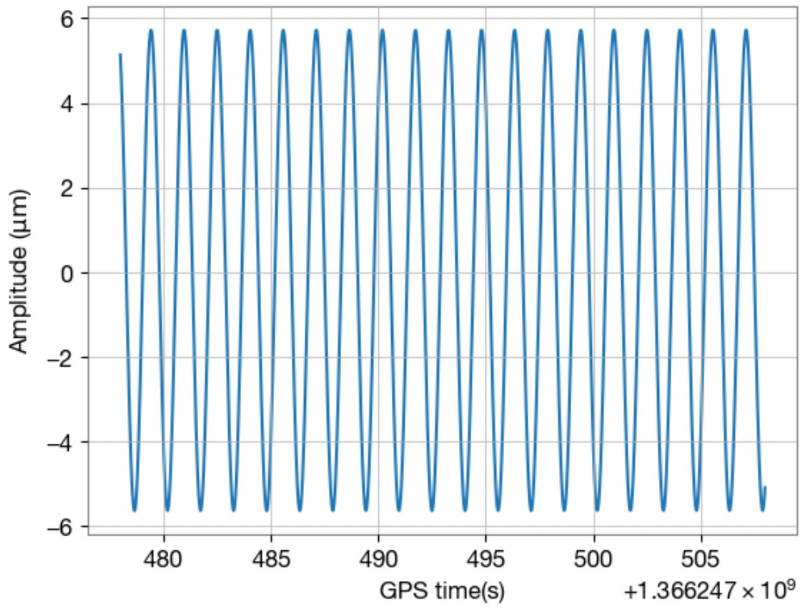
Shelves analysis: using sensed $\delta x_{sc}(t)$ data

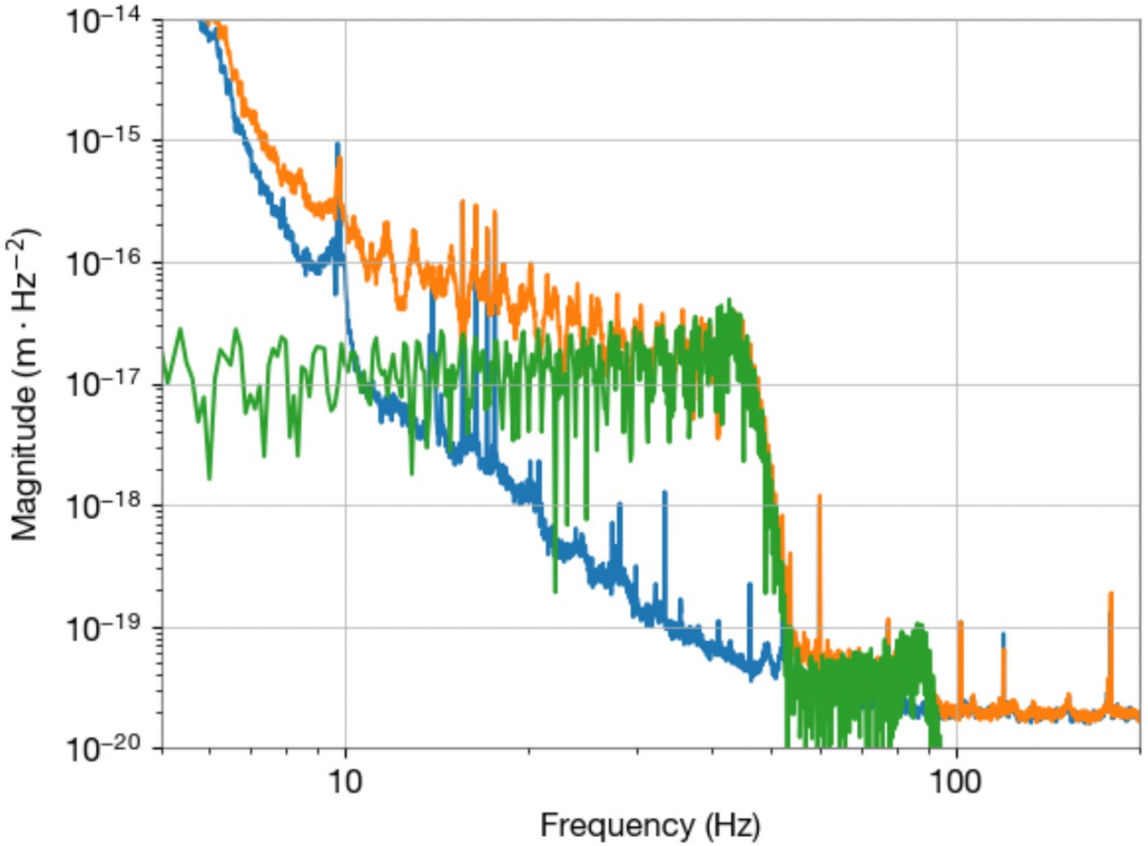
g_2 = 0.003

$$h_{sc}(f) = \frac{G}{L} \cdot ASD\left\{ \sin\left[\frac{4\pi}{\lambda}\left(x_0 + \delta x_{sc}(t)\right)\right] + g_2 \cdot \sin\left[\frac{4\pi}{\lambda}\left(x_0 + 2\cdot\delta x_{sc}(t)\right)\right]\right\}$$

G = 2e-9

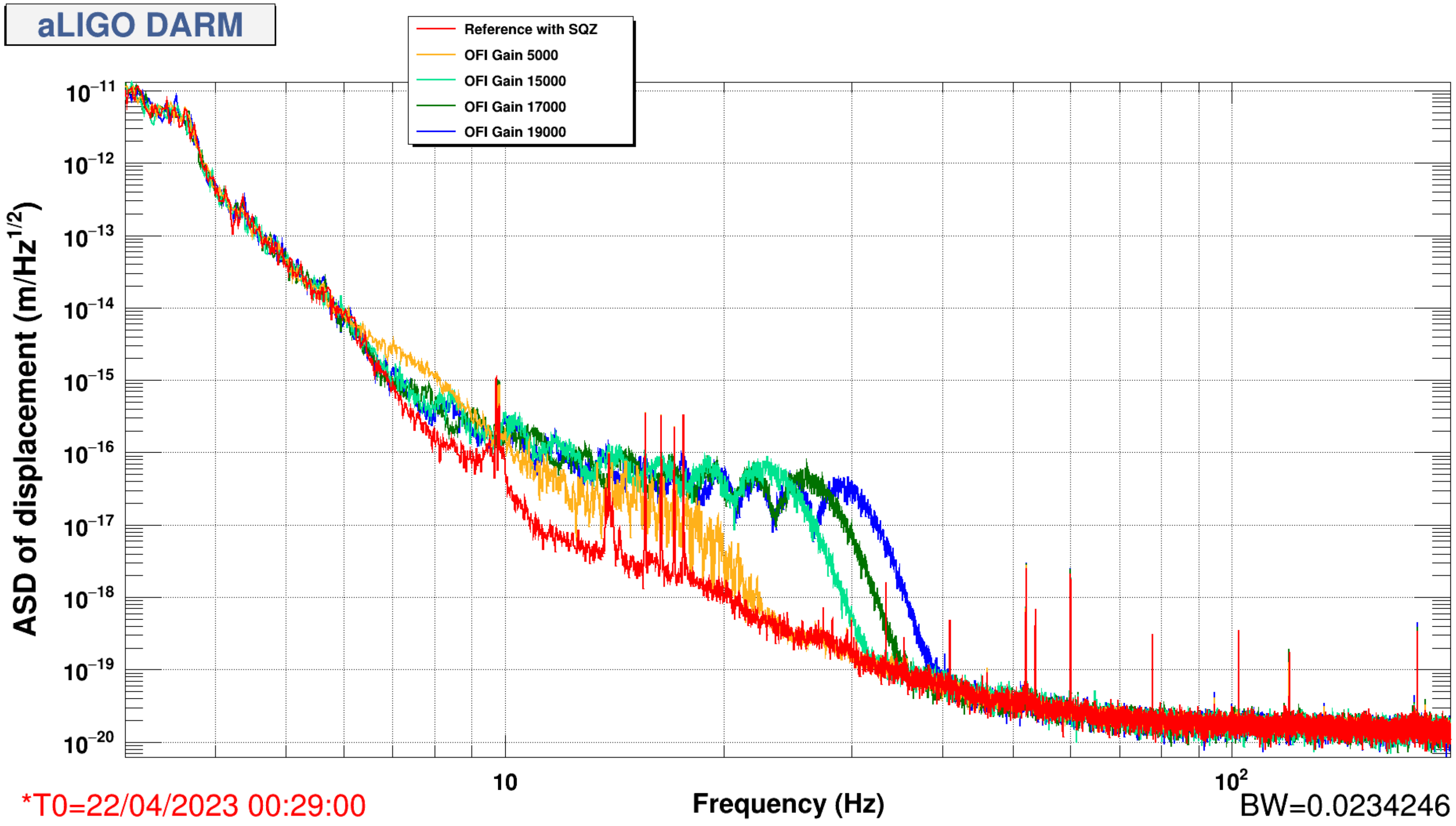
$$\delta x_{sc}(t) = 1.12 \cdot data(t)$$





NB. $\delta x_{SRM}(t)$ is negligible in this case.

Transverse injections : scattering from SQZ



Shelves analysis

The longitudinal motion (SIDE) is 2% coupled with the transverse ones in this configuration.

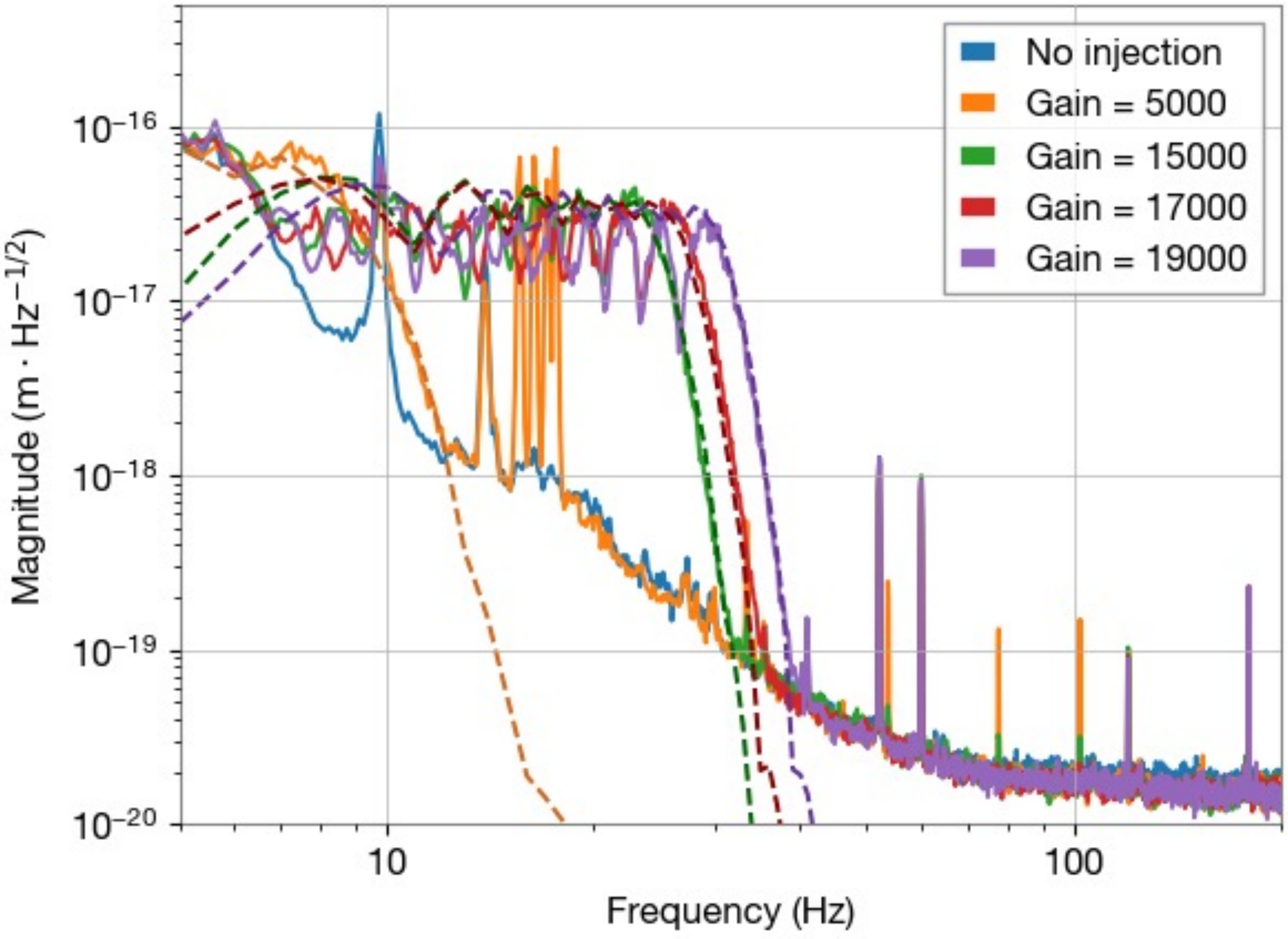
G = 4e-9

$$h_{sc}(f) = \frac{G}{L} \cdot ASD\Big\{ \sin\Big[\frac{4\pi}{\lambda}\Big(x_0 + \delta x_{sc}(t)\Big)\Big]\Big\}$$

$$\delta x_{sc}(t) = A_{sc} \sin(2\pi f_{sc} t)$$

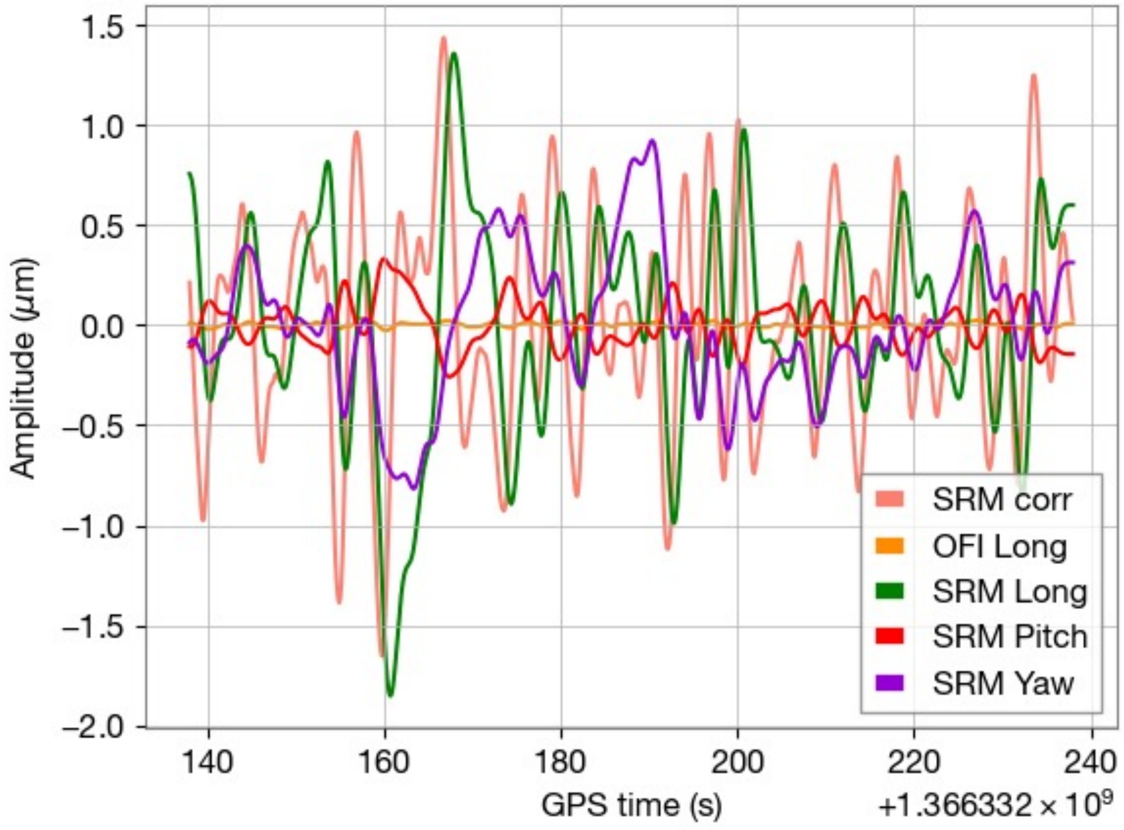
Where:

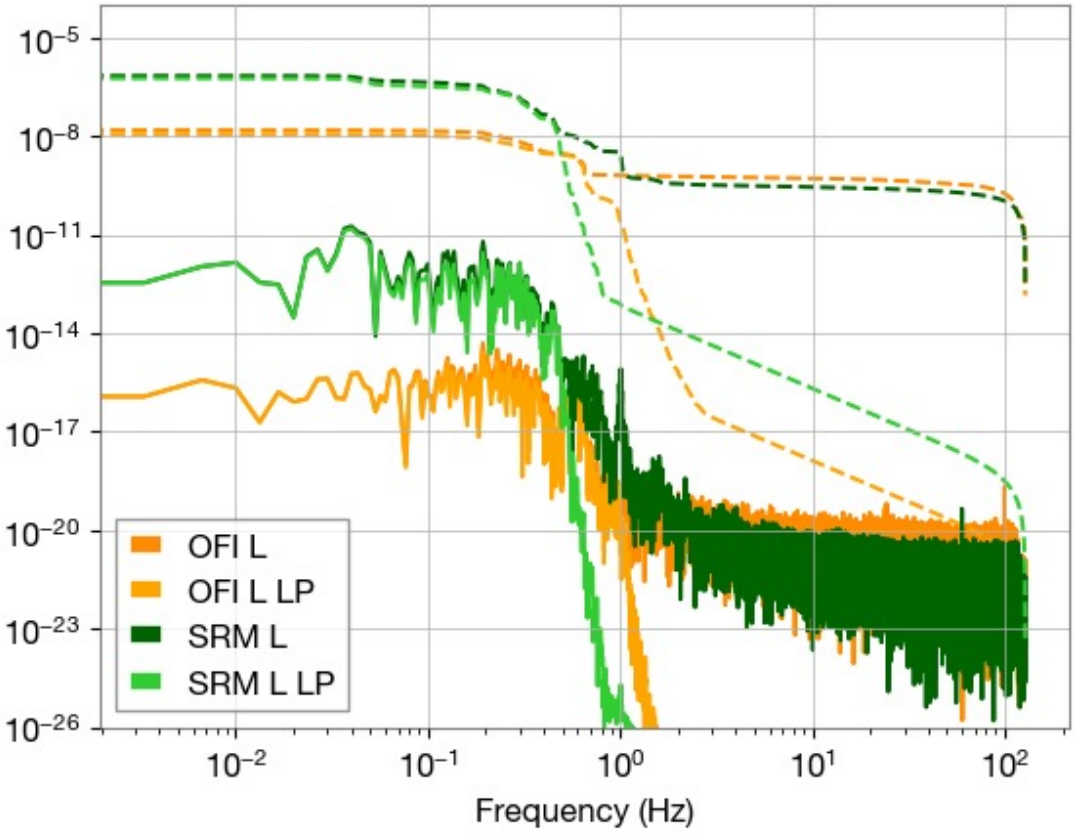
A_{sc}(G=5000) = 1.1 µm
A_{sc}(G=15000) = 3.2 µm
A_{sc}(G=17000) = 3.5 µm
A_{sc}(G=19000) = 4 µm
f_{sc} = 0.65 Hz



OFI and SRM motions: Earthquake NZ (IFO locked)

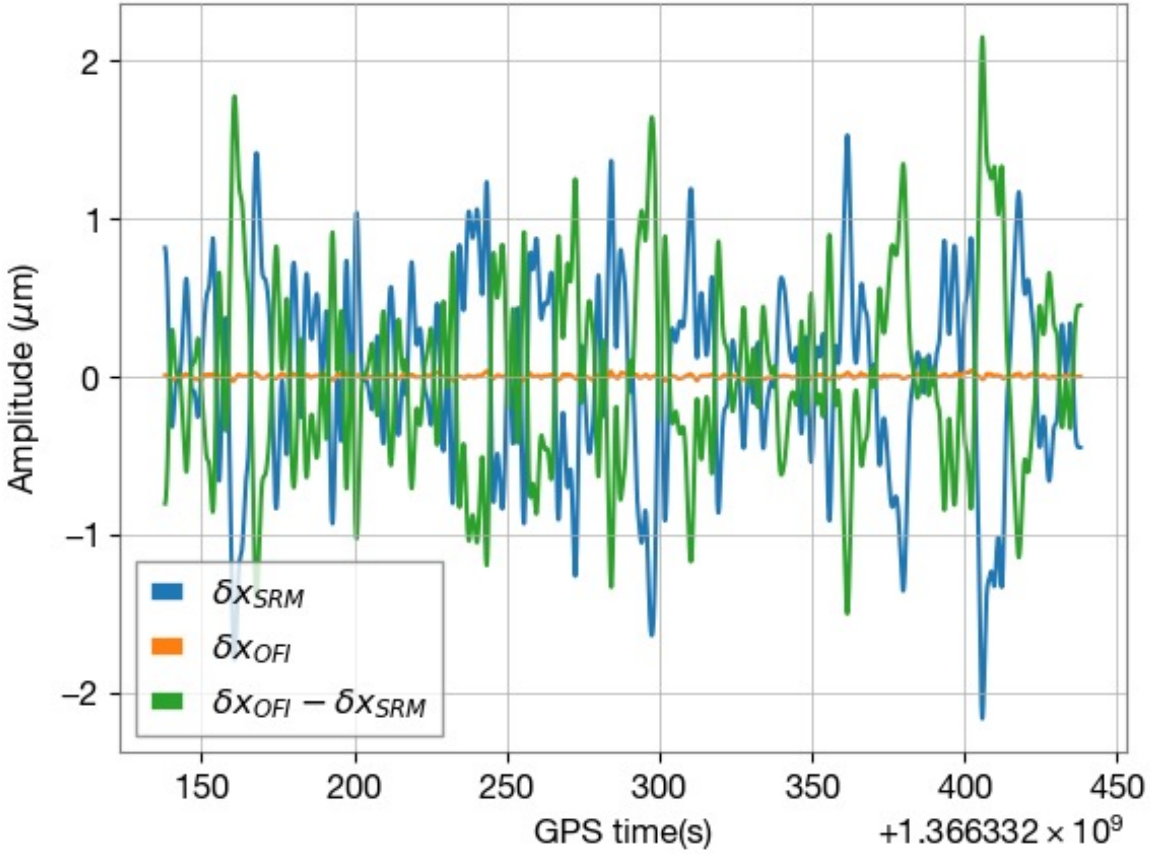
24th April 2023, 00:42:00 UTC

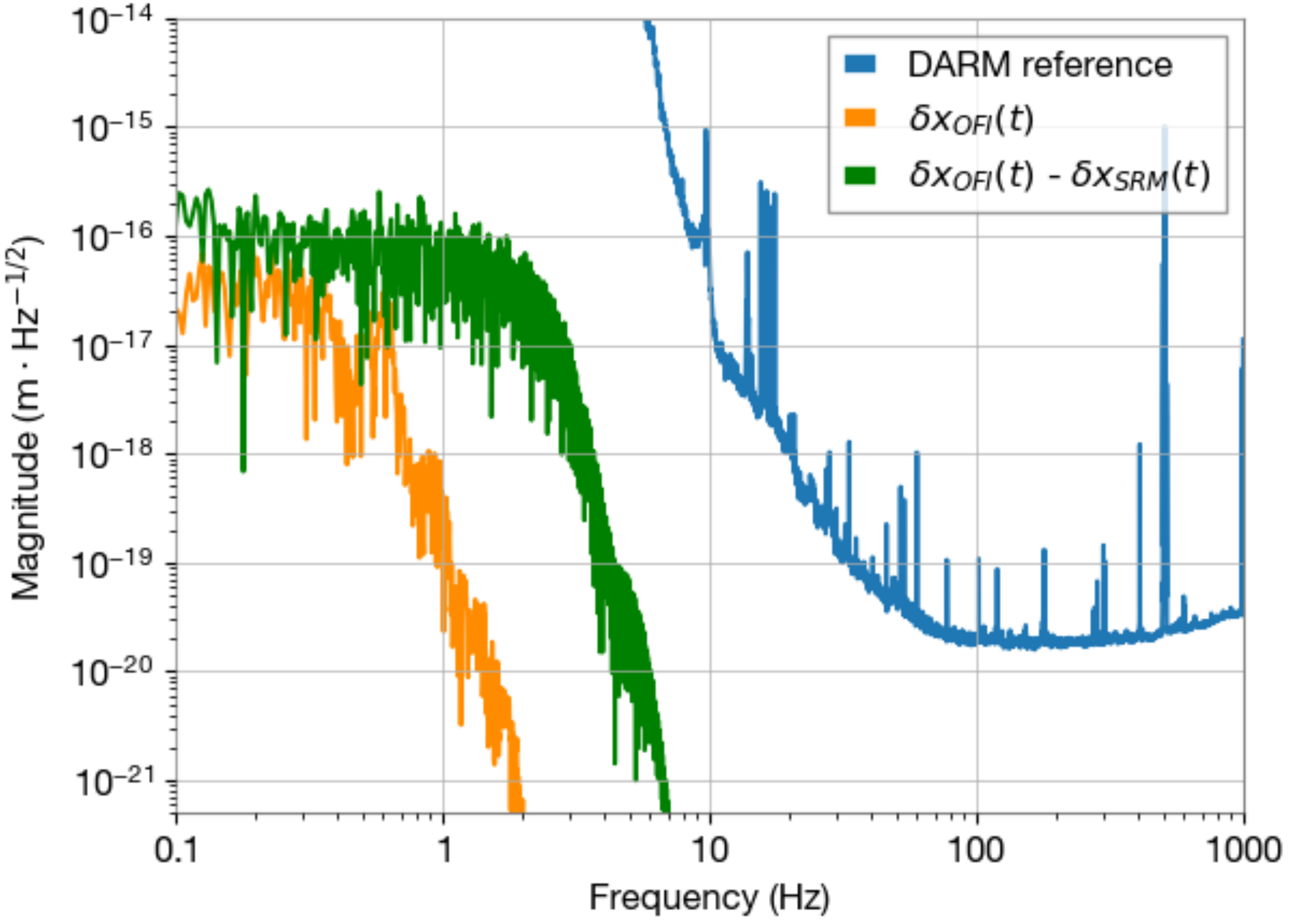




Displacement data low-passed at 1Hz

OFI and SRM motions: Earthquake NZ (IFO locked)

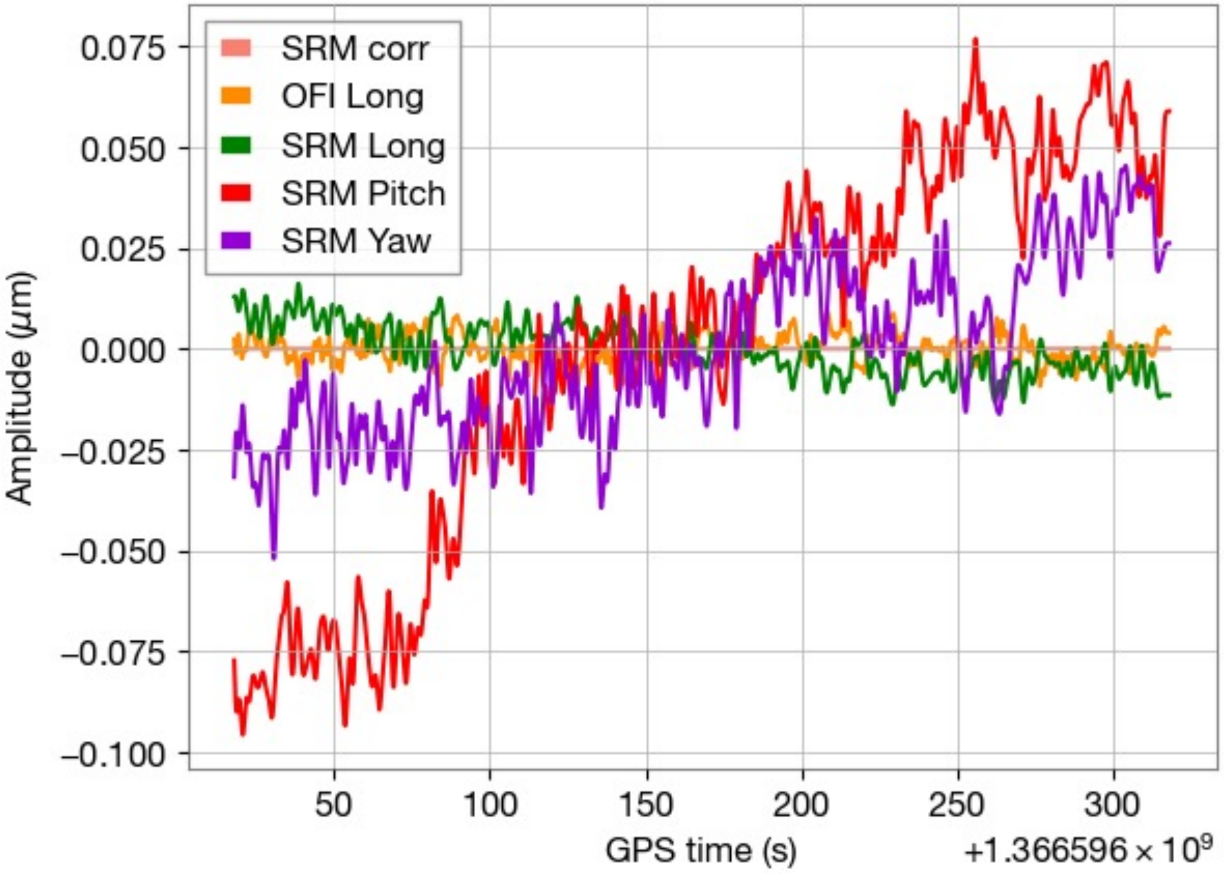


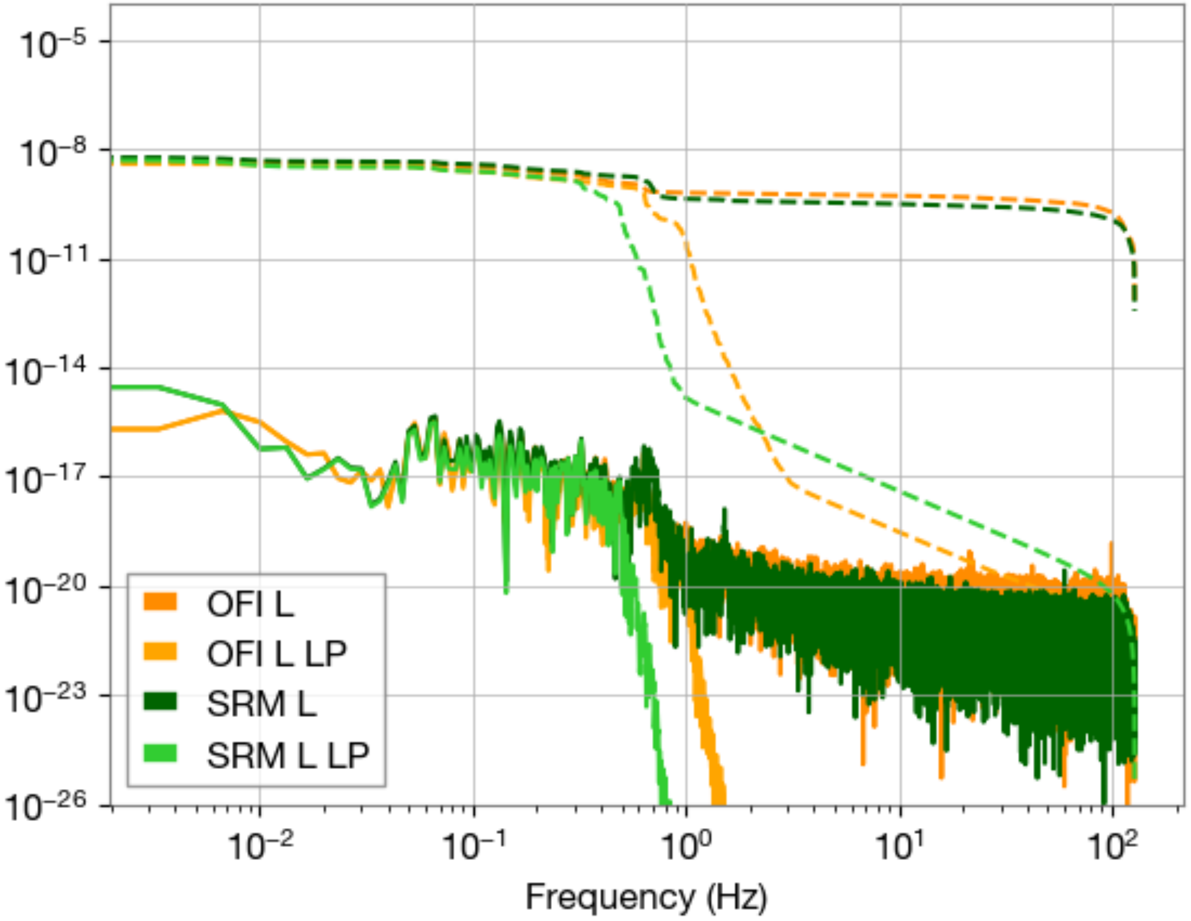


Displacement data low-passed at 1Hz

OFI and SRM motions: IFO unlocked, low seism

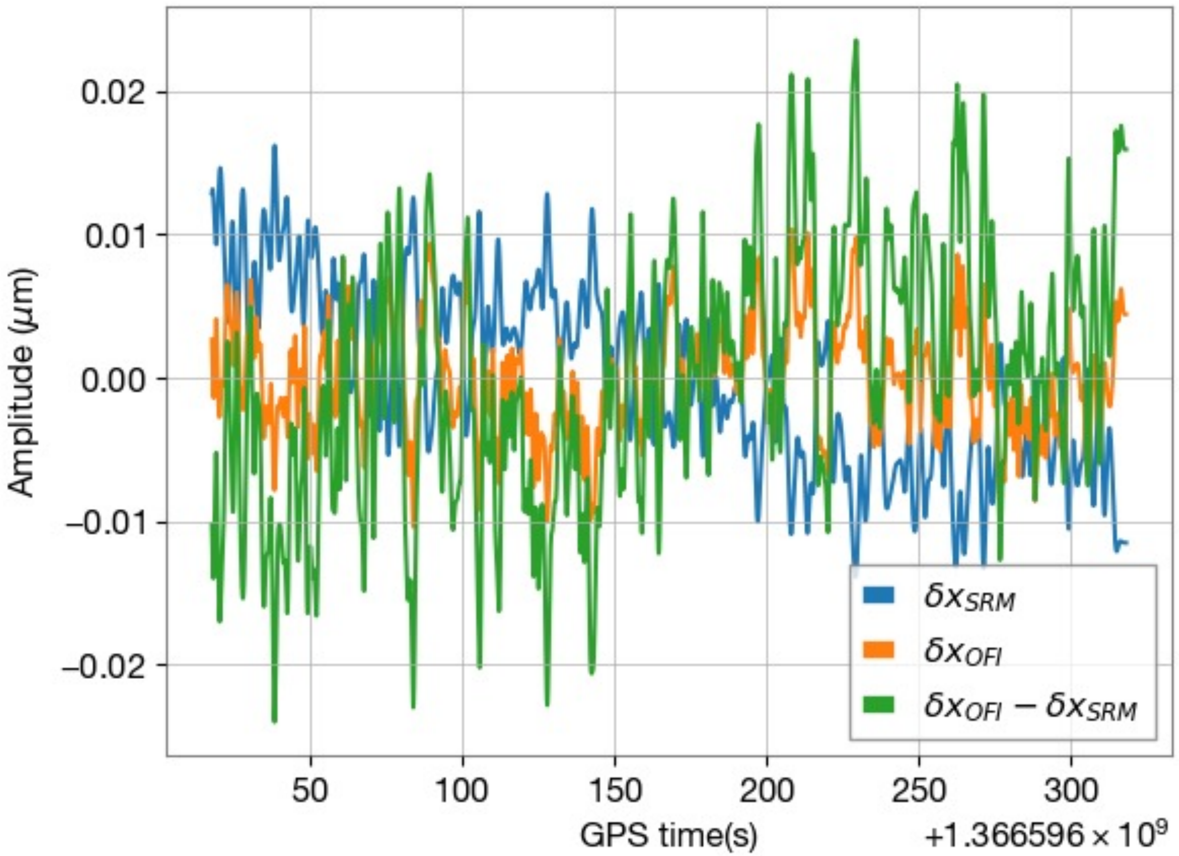
27th April 2023, 02:00:00 UTC

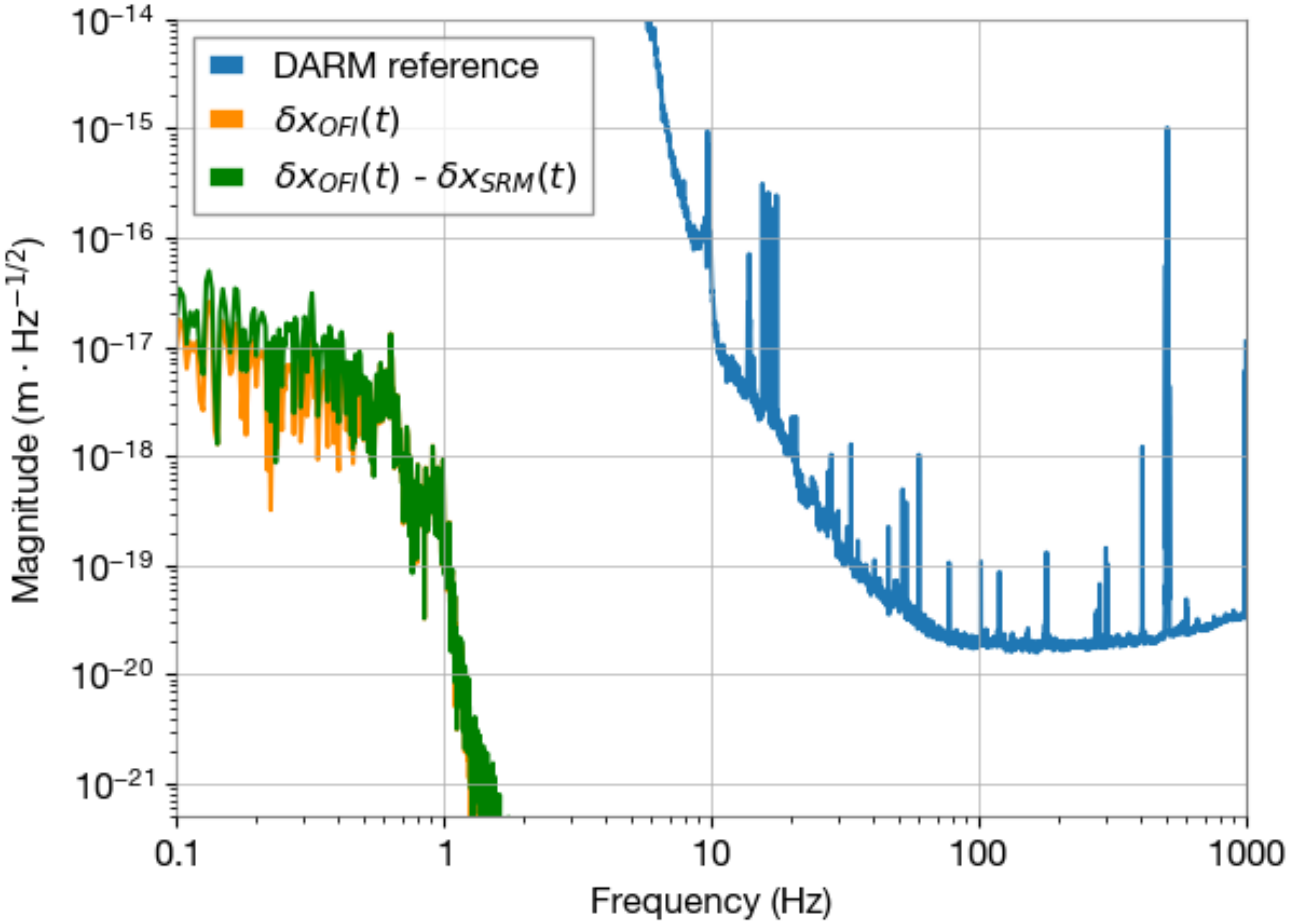




Displacement data low-passed at 1Hz

OFI and SRM motions: IFO unlocked, low seism

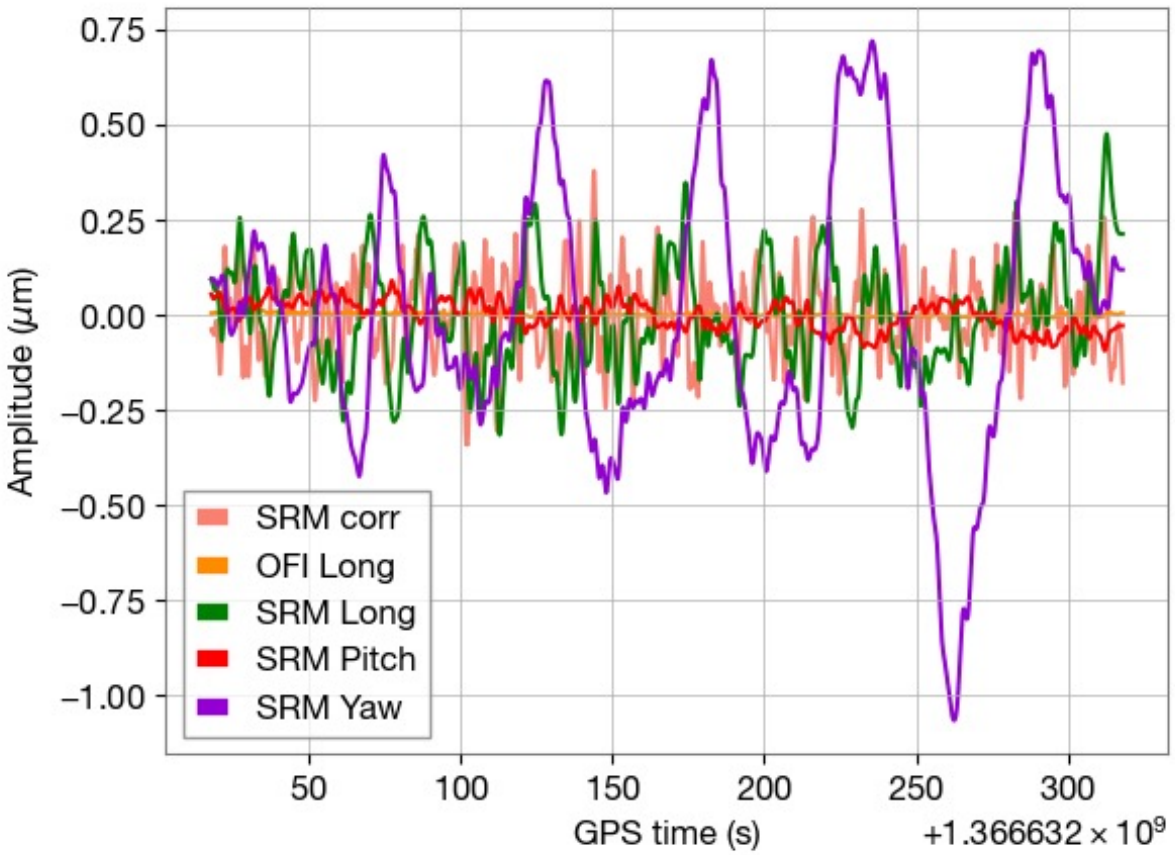


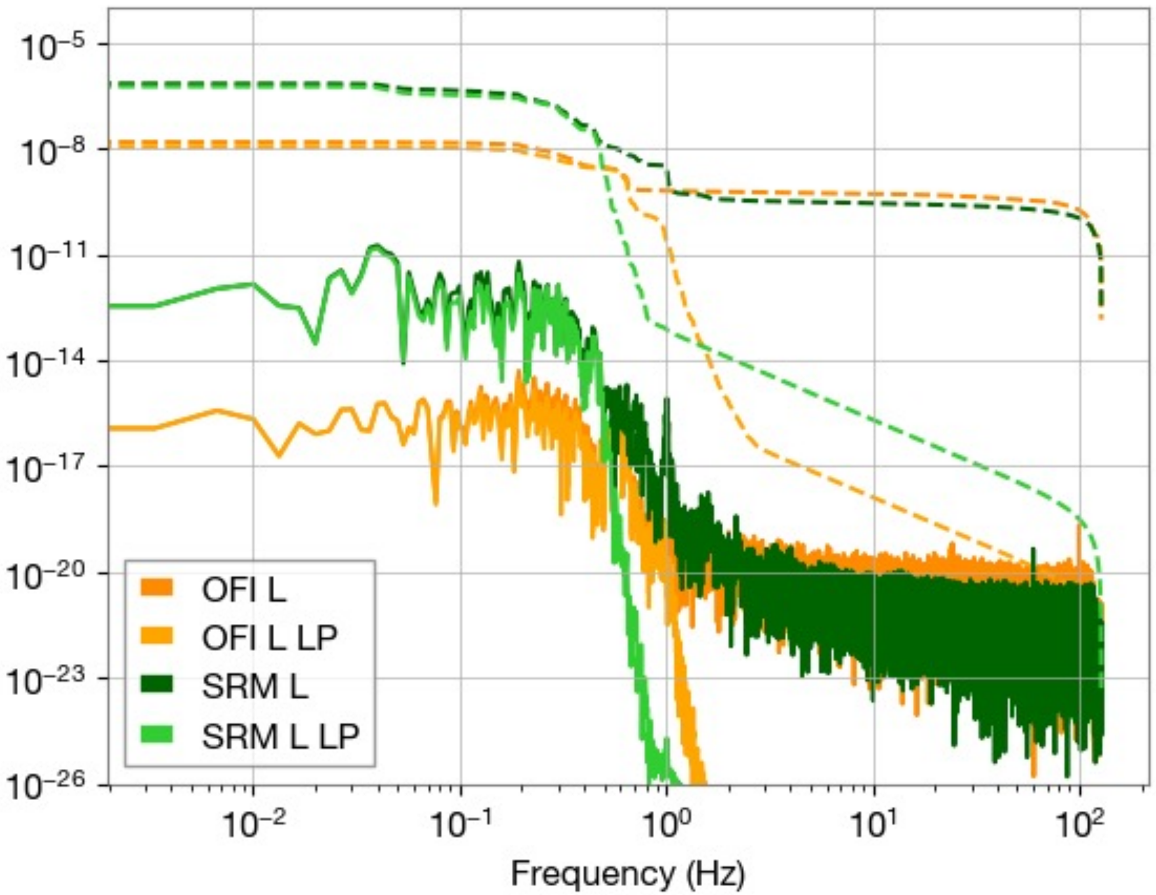


Displacement data low-passed at 1Hz

OFI and SRM motions: IFO locked, low seism

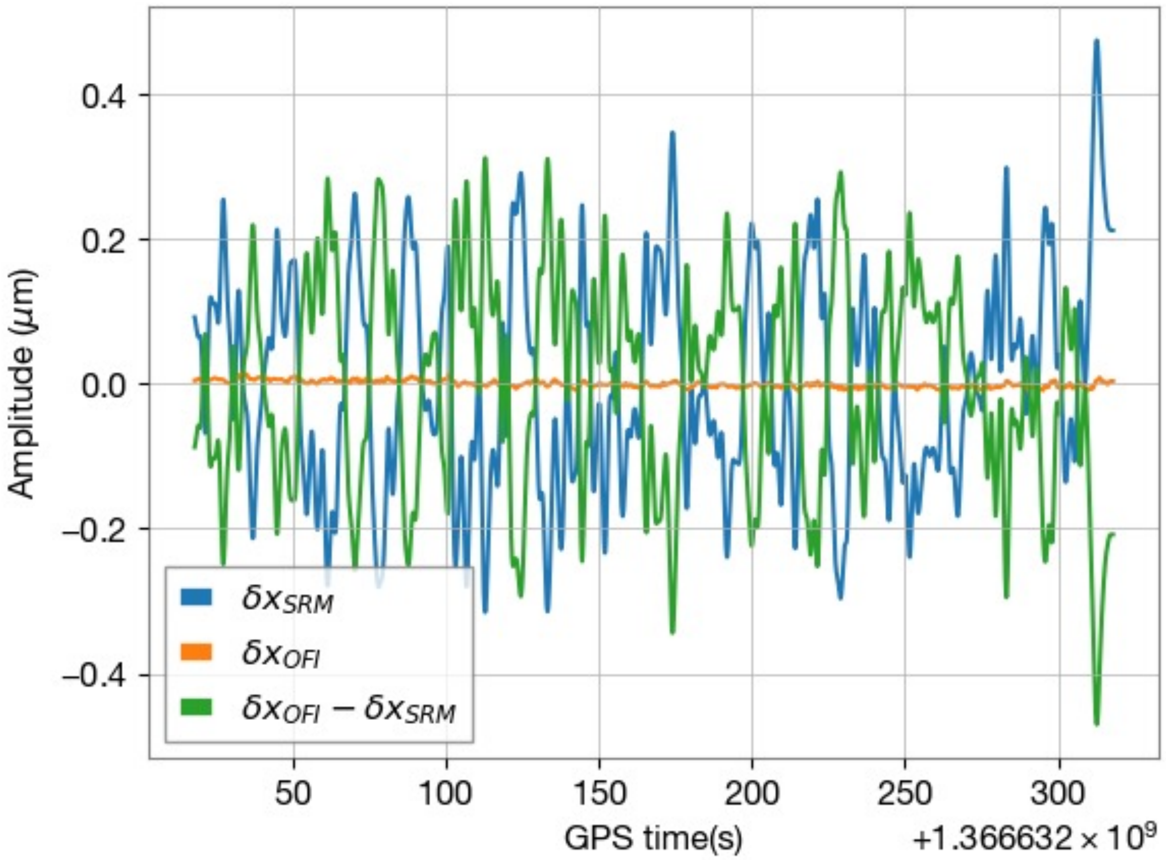
27th April 2023, 12:00:00 UTC

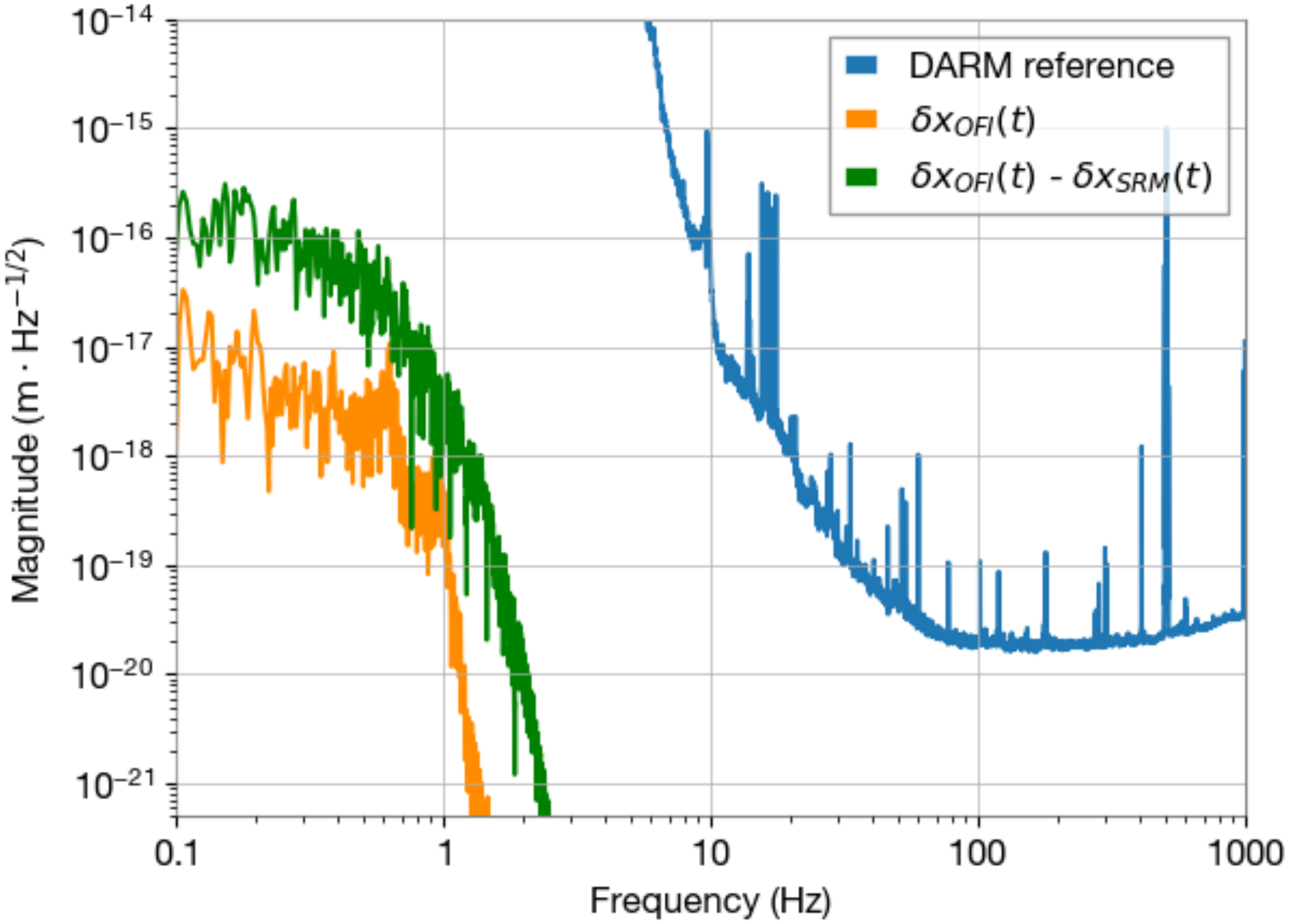




Displacement data low-passed at 1Hz

OFI and SRM motions: IFO locked, low seism





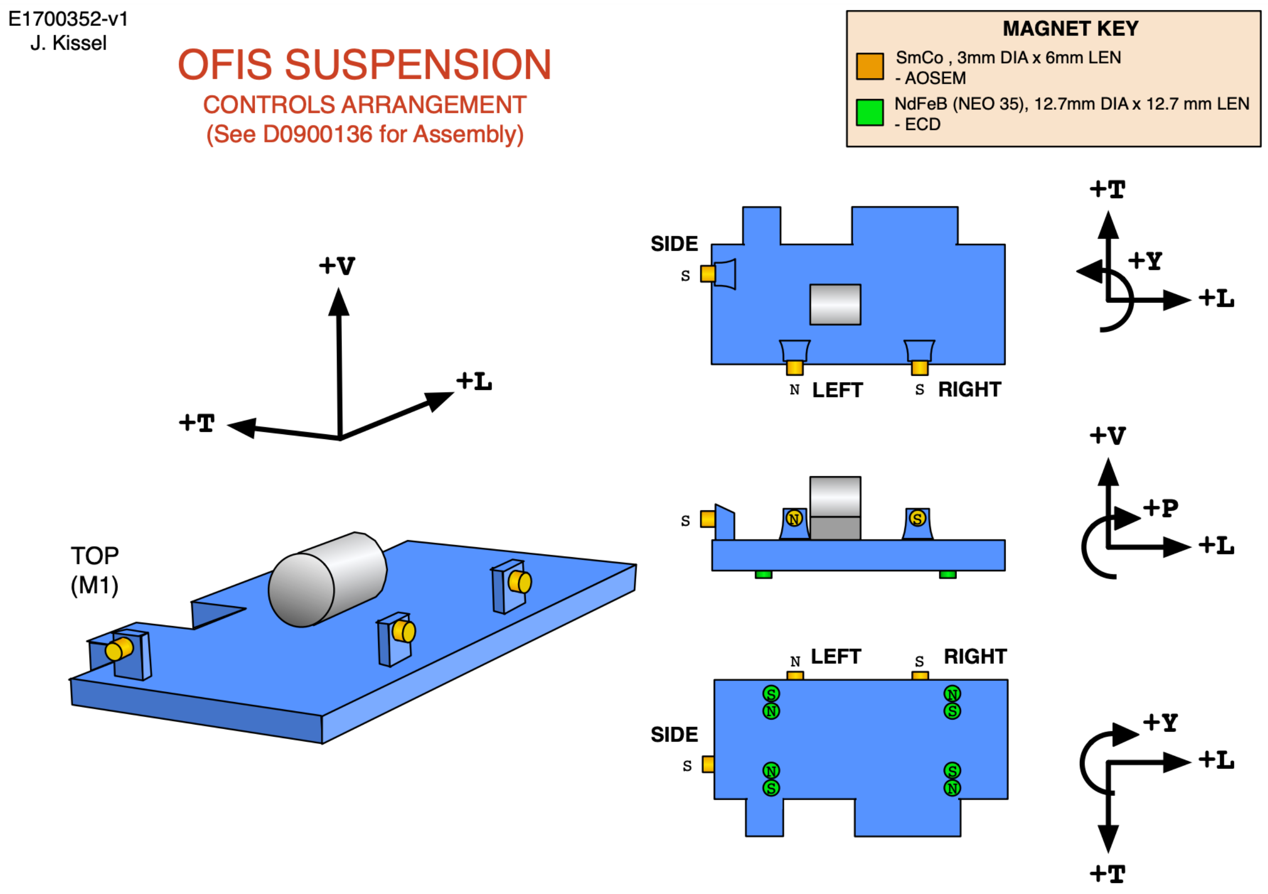
Displacement data low-passed at 1Hz

Conclusions and next steps

- Scattered light from the OFI should not be critical

- Compare G-factor with LLO to check the effect of the shroud?
- Continue scattered light investigation by shaking
  - the OMC
  - OM2
  - OM3
  - OPO
  - Filter cavity
  - … ?

OFI suspension diagonalization attempts

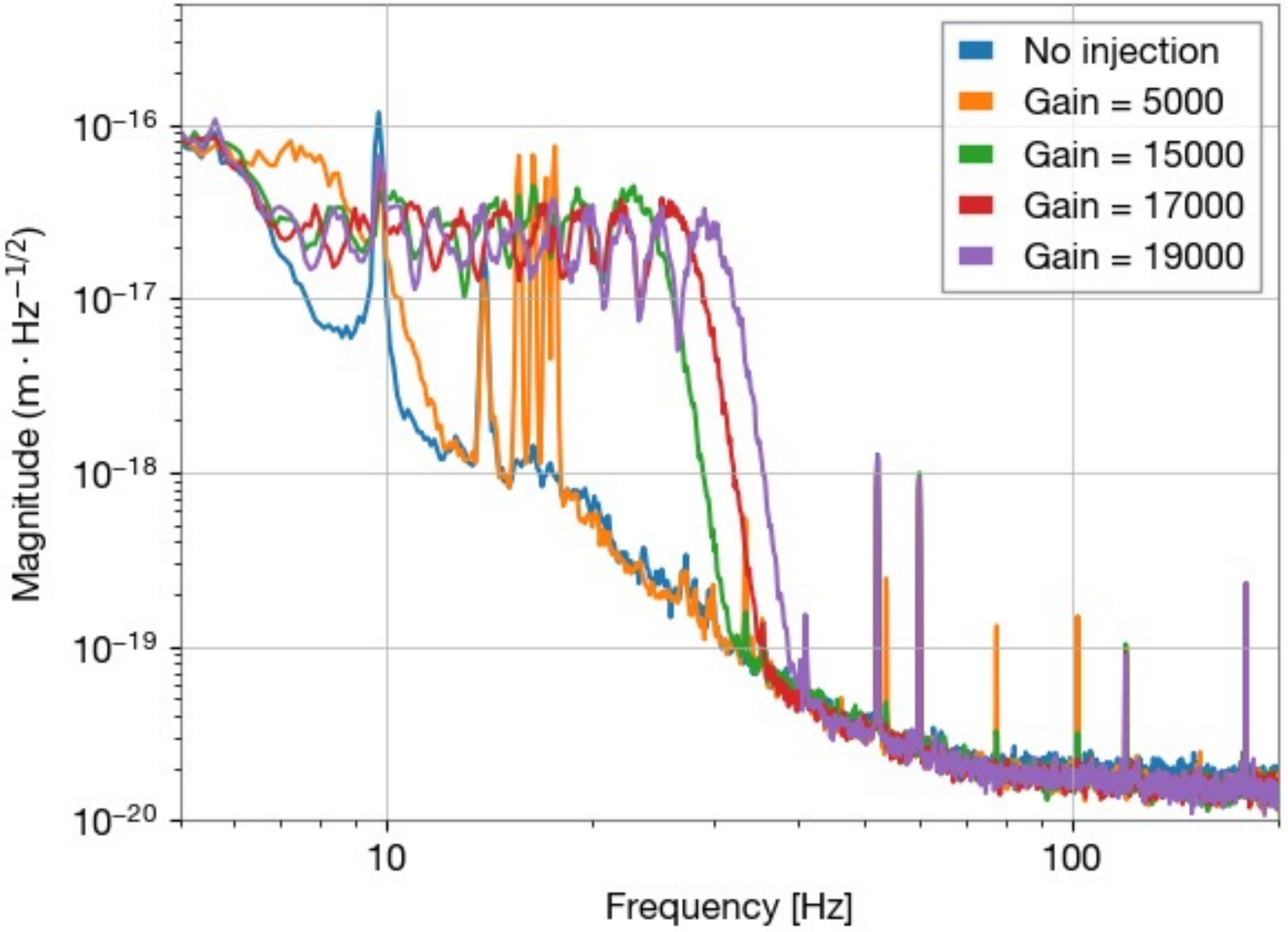


The L, T and Y degrees of freedom are strongly cross-coupled – exciting T results in 5 times more movement in L.

We derived the sensing and driving matrix using geometrical considerations and tried to adjust driving gains to decouple the dofs.

We experimentally decoupled L and T for our measurements.

Noise injection with different amplitudes



The longitudinal motion (SIDE) is 2% coupled with the transverse ones in this configuration.