

Calibrating GW detectors using scattered light

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GW detector calibration

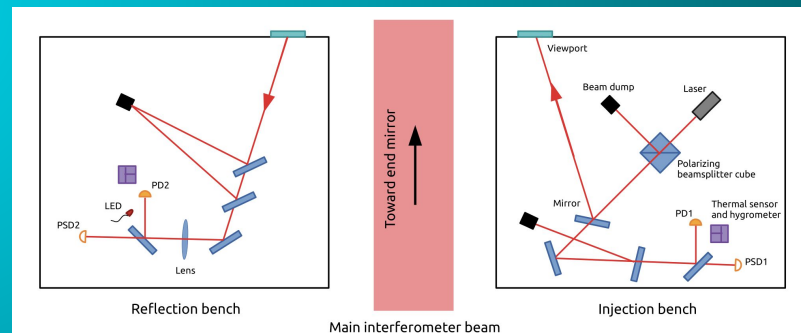
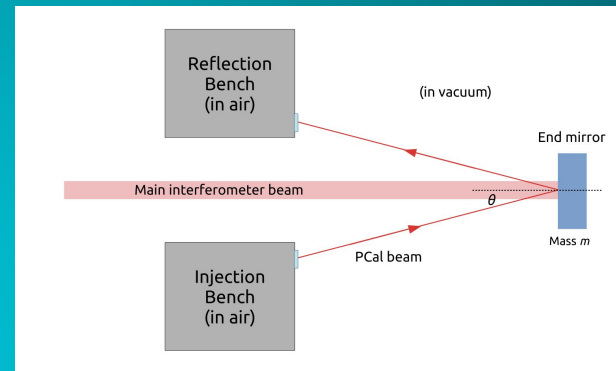
The calibration of gravitational wave detectors is performed by injecting known signals, and measuring their effects on the output signal. To do so, it is necessary to build actuators that induce an accurate displacement of the test masses of the interferometers.

The calibration methods currently used in Virgo are:

- Photon calibrator (PCal)
- Newtonian calibrator (NCal)

Photon calibrator

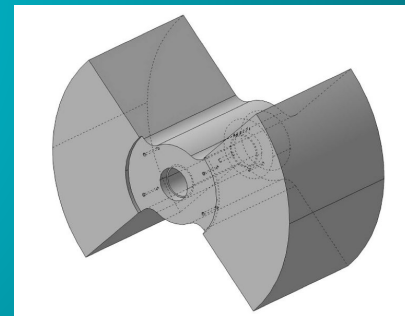
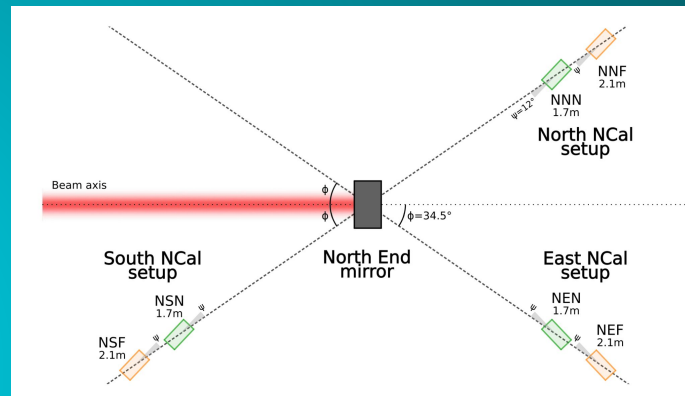
- Calibration using the effects of radiation pressure on the mirrors.
- Composed of two optical benches:
 - the injection bench is used to send the laser beam, stabilized in power, to the HR surface of the end mirror;
 - the reflection bench is used to measure the power reflected by the end mirror.
- For the frequency band of standard GW analysis (20-2000 Hz), it can only be used up to 1500 Hz.
- Continuously operating.
- Used in LIGO, Virgo and KAGRA.



Credits: D Estevez et al 2021 Class. Quantum Grav. 38 075007

Newtonian calibrator

- Calibration using a locally induced variation of the gravity field.
- Creates a modulated gravitational field produced by rotating masses to induce a displacement of the mirrors.
- Can only operate up to 150 Hz.
- Continuously operating since O4.
- Used only in Virgo.
- KAGRA recently started the installation ([logbook](#)).
- Installed in LIGO Hanford during O3 but not yet used (<https://arxiv.org/abs/2609.01917>)



Credits: F Aubin *et al* 2024 *Class. Quantum Grav.* 41 235003

Calibrator using scattered light

A new method for the calibration of the Virgo detector with scattered light has been proposed [1] and included in the technical design report of Advanced Virgo+ Phase 2 [2].

The project is led by UAntwerpen (Hans Van Haevermaet) and done in collaboration with UGent.

[1] M Was *et al* 2021 *Class. Quantum Grav.* 38 075020 <https://iopscience.iop.org/article/10.1088/1361-6382/abe759>

[2] <https://tds.virgo-gw.eu/?r=24735>

Why do we need a new technique?

While this technique might be less accurate than NCal and PCal it can give additional valuable information:

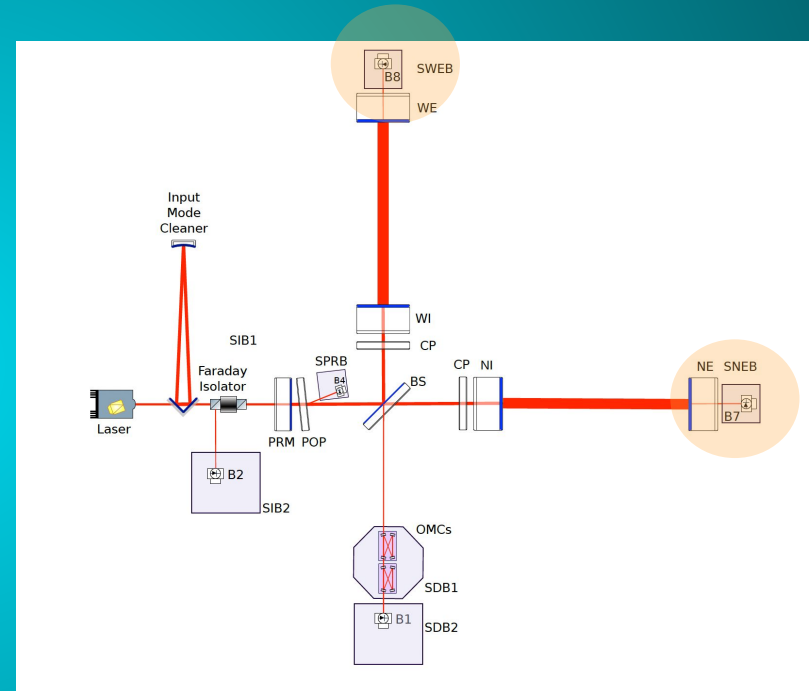
- Absolute calibration in the range 1.5 kHz - 2 kHz
- Calibration signal is injected in the detector without moving any mirror, which may allow us to highlight systematic errors in the suspension modelisation

Scattered light in Virgo

Scattered light affects the sensitivity of GW detectors, especially when high microseism ground motion is present.

In transmission of the north end (NE) mirror and respectively the west end (WE) mirror are located the suspended north end bench (SNEB) and respectively the suspended west end bench (SWEB).

Microseism makes the suspended bench vibrate and the optical components on the bench create scattering light that is injected back in the detector.



Scattered light model

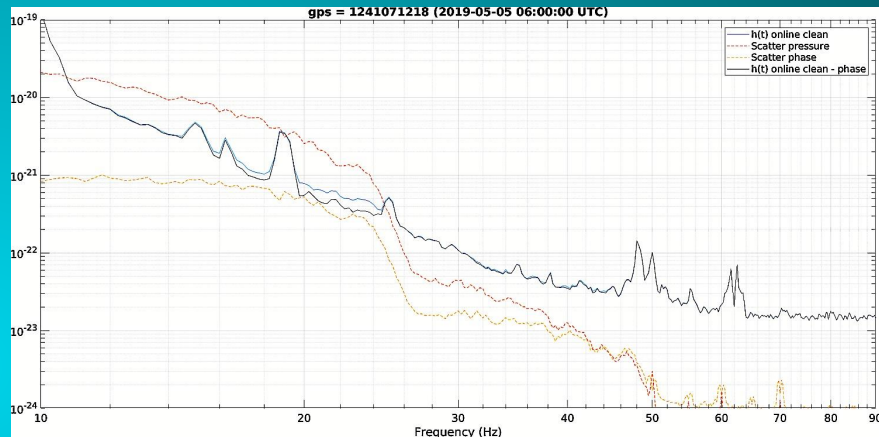
The scattered light is very well modeled in Virgo and a method on how it could be subtracted in h_{rec} has been proved [1].

Scattered light adds 3 contributions to the strain:

$$h_{\text{sc, phase}} = \frac{T_{\text{WE}}}{L} \sqrt{f_r} \frac{\lambda}{4\pi} \sin\phi_{\text{sc}}$$

$$h_{\text{sc, amplitude}} = \frac{\epsilon}{\psi} \frac{T_{\text{WE}}}{L} \sqrt{f_r} \frac{\lambda}{4\pi} \cos\phi_{\text{sc}}$$

$$h_{\text{sc, pressure}} = \frac{G}{L} \text{WE}_{\text{F} \rightarrow \text{z}} \frac{8|E_0|^2}{c} T_{\text{WE}} \sqrt{f_r} \cos\phi_{\text{sc}}$$



T_{WE} $\longrightarrow$ WE transmissivity

ϵ $\longrightarrow$ accounts for asymmetries between the two arms

L $\longrightarrow$ Cavity length

ψ $\longrightarrow$ differential phase offset

f_r $\longrightarrow$ Scattered light fraction

G $\longrightarrow$ Cavity gain

ϕ_{sc} $\longrightarrow$ Phase delay

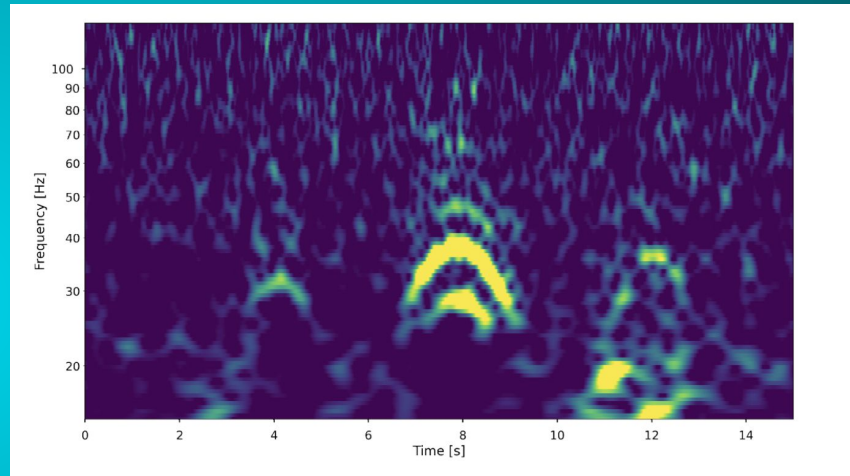
$\text{WE}_{\text{F} \rightarrow \text{z}}$ $\longrightarrow$ mechanical response of the suspended WE mirror

[1] M Was *et al* 2021 *Class. Quantum Grav.* 38 075020
<https://iopscience.iop.org/article/10.1088/1361-6382/abe759>

Scattered light glitches

Scattered light has been studied and modelled very well in Virgo and we are now able to subtract its effects from the output signal in a very efficient way.

Scattered light has a very identifiable arch shape in the spectrogram of the output.

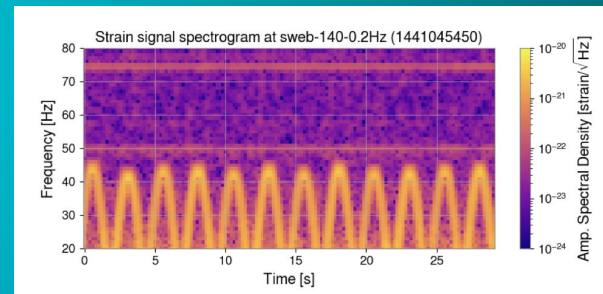
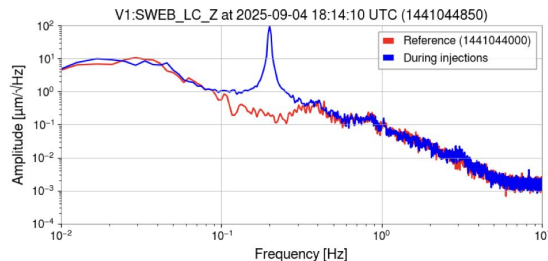
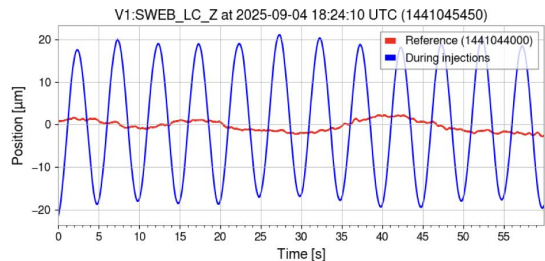


Credits: A. E. Tolley et al 2023 *Class. Quantum Grav.* 40 165005

Injection tests

Able to reproduce the effect of scattered light through injections.

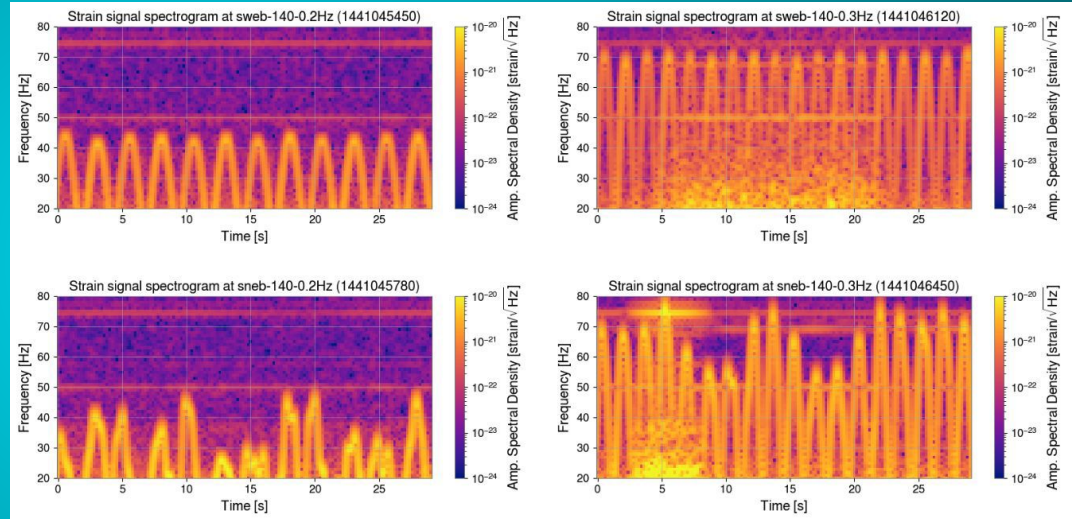
The injection signal is created by vibrating at a specific amplitude and frequency the suspended bench to simulate microseism.



Instabilities of SNEB

Injection tests showed some instabilities of the SNEB.

Need more analysis to understand the cause.

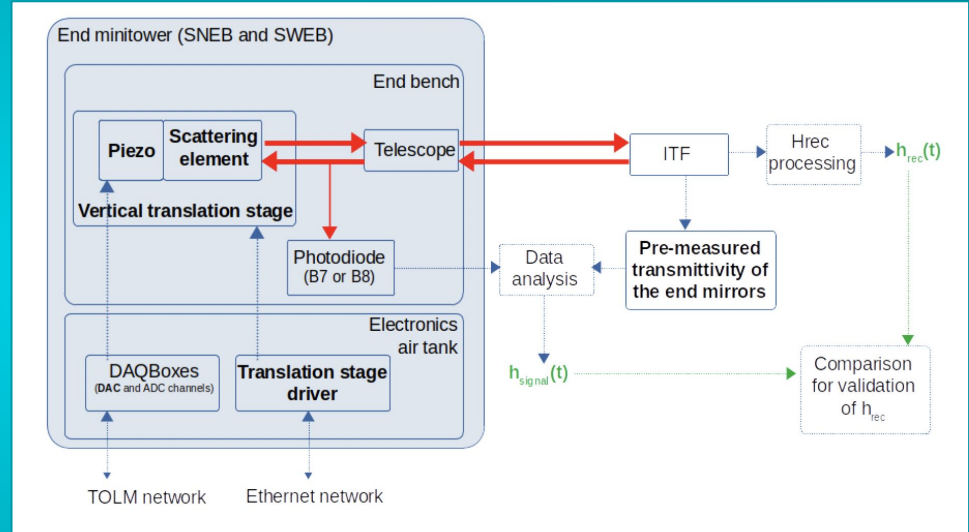


Calibration with scattered light

The method is based on the results published on the modeling and subtraction of scattered light noise in Virgo O3*.

The photodiodes on the end benches are also sensitive to scattered light. The signal can be used to reconstruct a detector-strain-equivalent signal:

$$h_{\text{signal}} = \frac{1}{L} T_{\text{WE}} \frac{\lambda}{4\pi} \frac{1}{2} \mathcal{T} \mathcal{F} \left[\frac{\delta P_{B8}}{P_{B8}} \right]$$

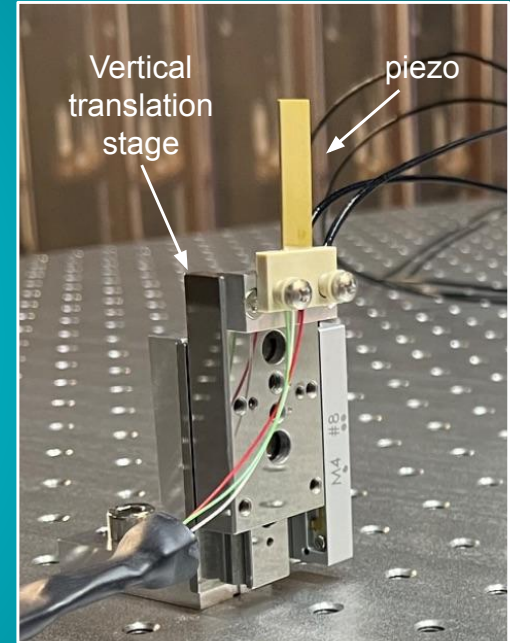
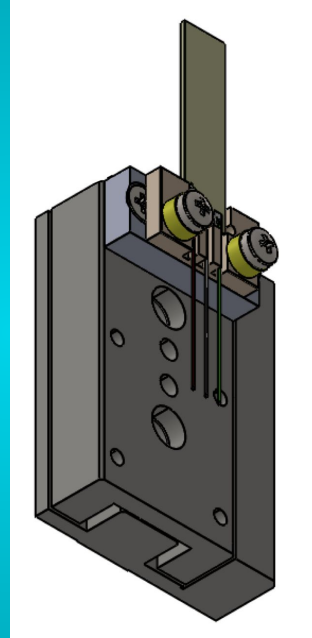


[VIR-0995B-24]

Scattering element

The scattering element is a piezo bender placed on a translation stage.

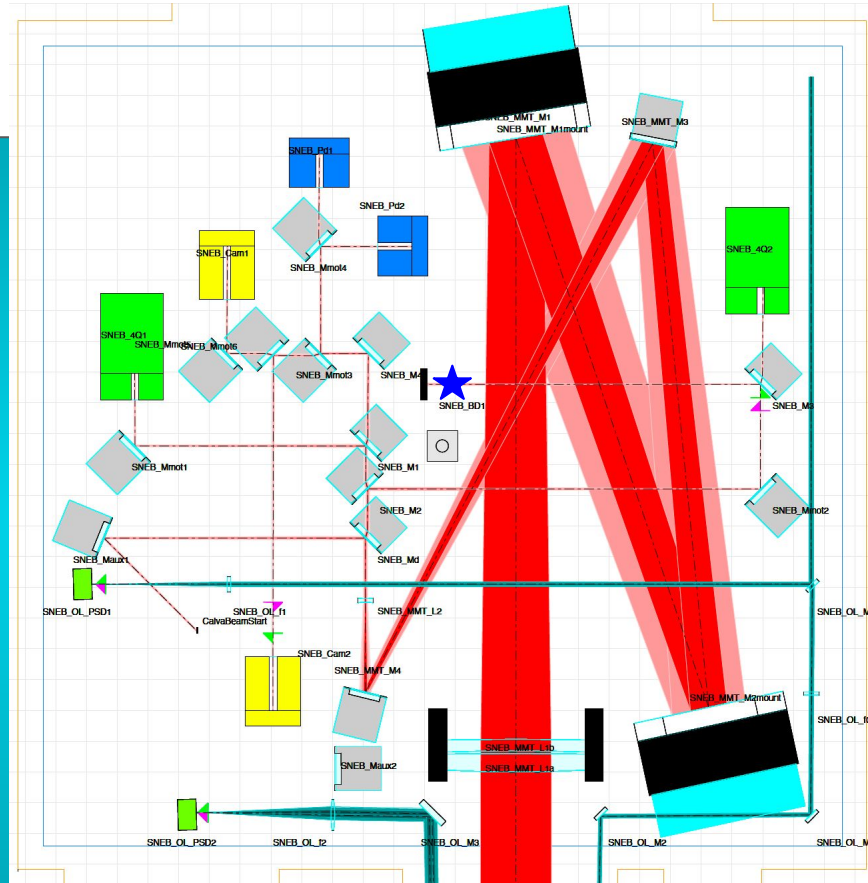
- Piezo bender → create a scattered light that can be modulated in amplitude and frequency.
- Translation stage → give us the option to remove the scatterer from the beam path when the calibration process is complete.



Position on the bench

To decide the scatterer position on the end bench, different factors need to be taken into account, i.e. space available and weight balance.

An option was found and indicated in the drawing with a blue star.

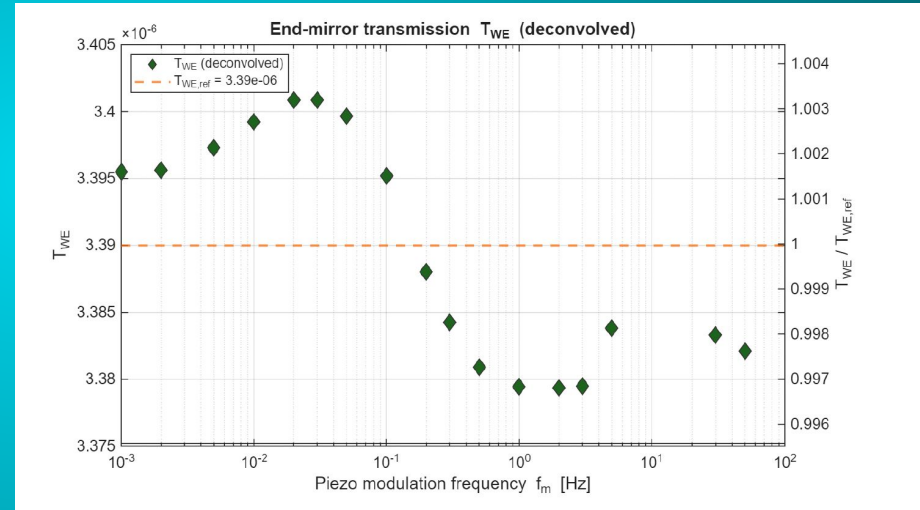


Simulations results: mirror transmissivity

The ratio between the injected signal (scattered light) and the reconstructed signal (at the detector output) depends only from the end mirror transmissivity.

$$h_{\text{signal}} = \frac{1}{L} T_{\text{WE}} \frac{\lambda}{4\pi} \frac{1}{2} \mathcal{F} \mathcal{F} \left[\frac{\delta P_{\text{B8}}}{P_{\text{B8}}} \right]$$

$$\frac{h_{\text{rec}}}{h_{\text{signal}}} = \frac{T_{\text{WE}}}{T_{\text{WE}}^{\text{LMA}}}$$



Simulations results: zero-crossing

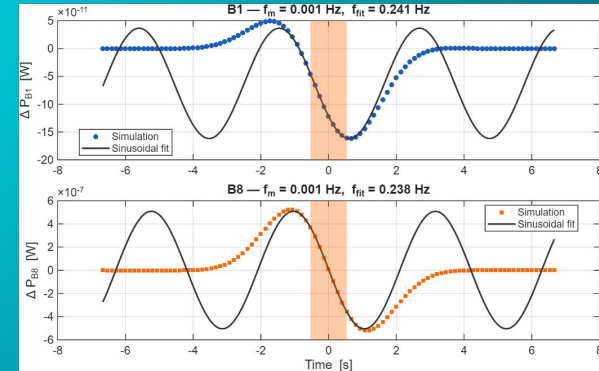
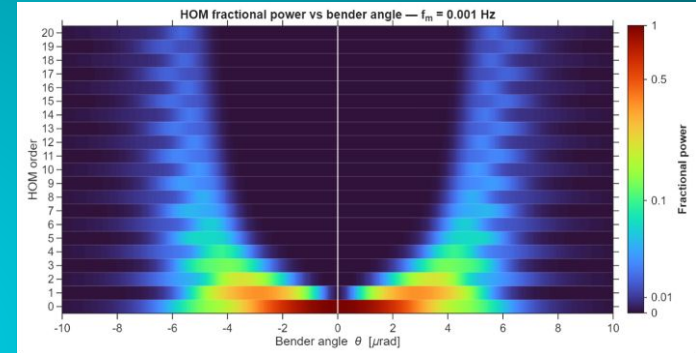
- Close to the zero crossing all power stays in TEM₀₀ and the motion is approximately linear.
- With the increase of the bender angle the power migrates to HOM and there is no calibration signal.

$$\text{Expected value} \rightarrow f_{\text{fit}} = \frac{4\pi x_0}{\lambda} f_m = 0.118 \text{ Hz}$$

f_m → bender modulation frequency (1 mHz)

f_{fit} → fitted frequency

→ Discrepancy due to the fact that the bender has finite length



Work plan

- Working principles of the calibrator have been tested through simulations (UGent) and analysis on signal injections at Virgo (UAntwerpen).
- Currently preparing setup for hardware tests (UGent):
 - scatterer surface damage threshold;
 - backscattered light fraction;
 - scatterer top speed.
- Consider alternative hardware to the piezo bender if necessary.
- First tests will be done in air, following by tests in vacuum.
- Expected to be installed in Virgo before O5 commissioning (end of 2027?).

Thanks a lot for your attention