Improving the Advanced Virgo+ calibration with the photon calibrator for the O4 run

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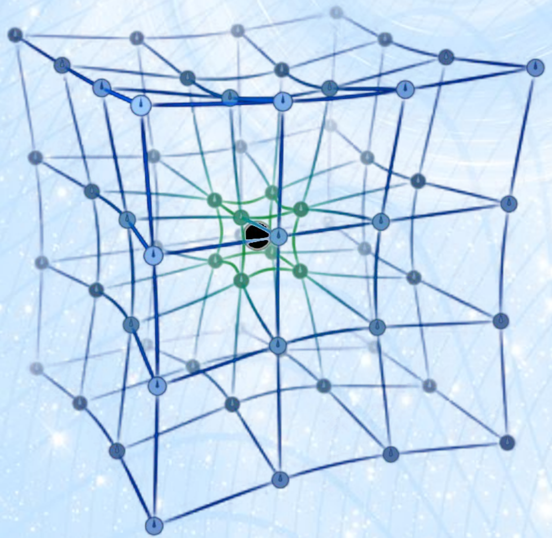
Gravitational waves are perturbations of the space-time propagating at the speed of light.

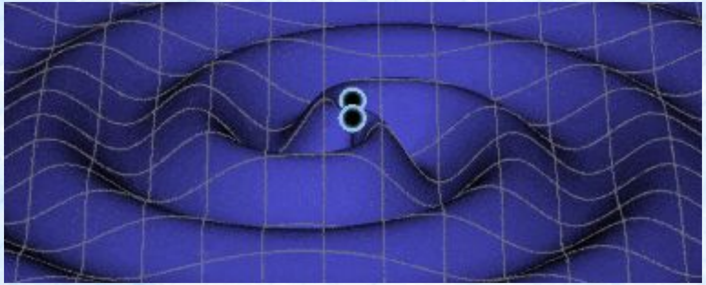
Predicted by Albert Einstein in 1916 as a consequence of the general relativity

Circle of free test masses at rest

Space-time deformation induced by a black-hole



Gravitational waves produced by a binary system of black holes

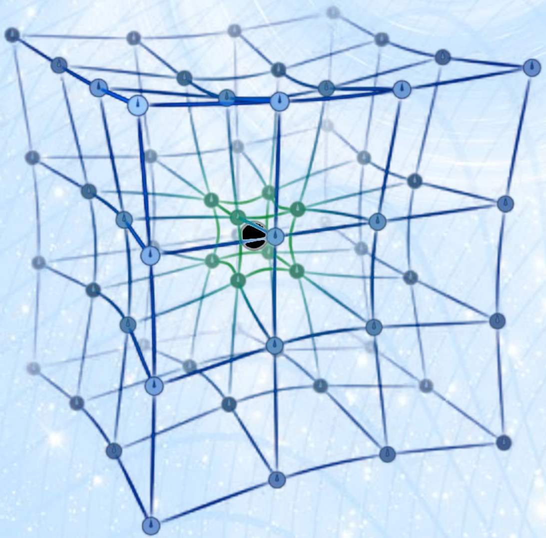


Gravitational waves are perturbations of the space-time propagating at the speed of light.

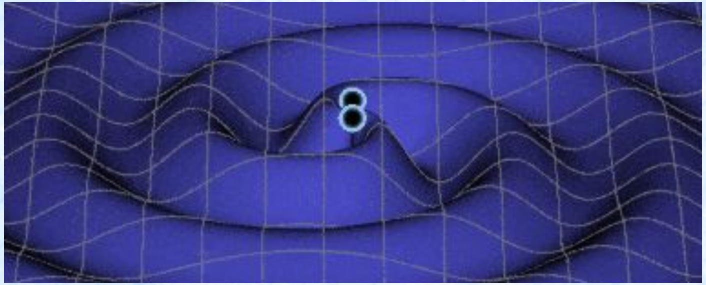
Predicted by Albert Einstein in 1916 as a consequence of the general relativity

Effect of a GW propagating perpendicularly to the screen on a circle of free test masses

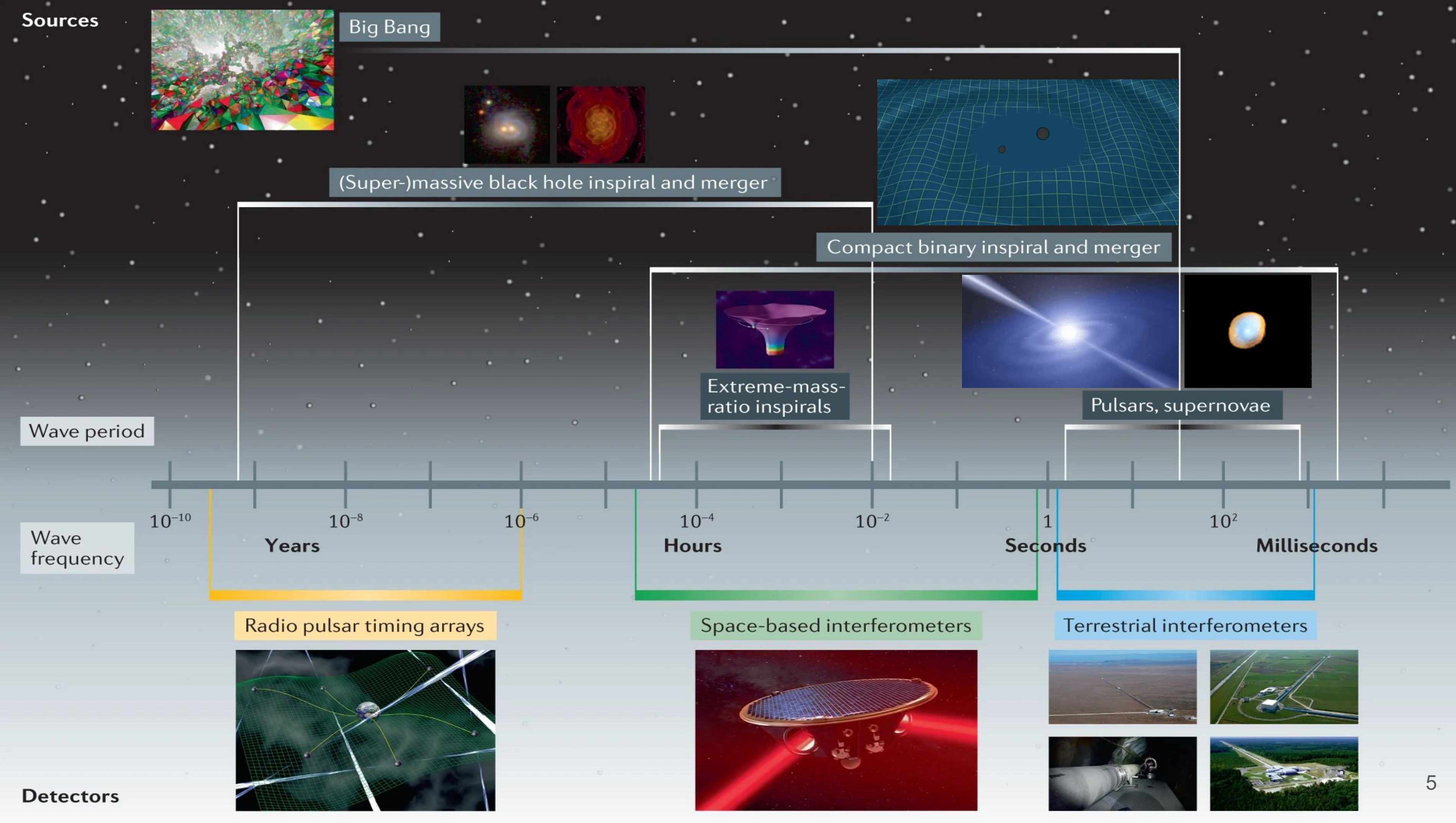
Space-time deformation induced by a black-hole



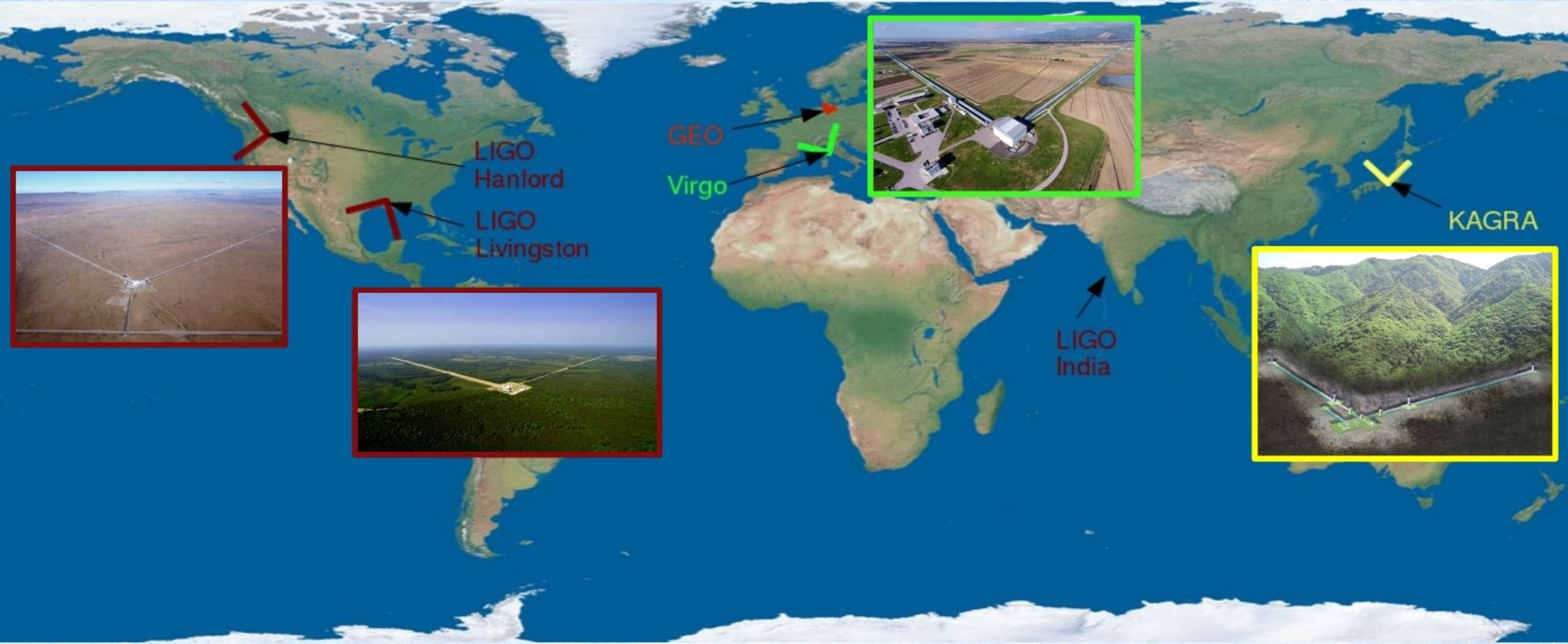
Gravitational waves produced by a binary system of black holes



Gravitational wave amplitude: $h \propto \frac{\delta L}{L_0}$


Sources
Big Bang
(Super-)massive black hole inspiral and merger
Compact binary inspiral and merger
Extreme-mass-ratio inspirals
Pulsars, supernovae
Wave period
Wave frequency
10−10
10−8
10−6
10−4
10−2
1
10²
Years
Hours
Seconds
Milliseconds
Radio pulsar timing arrays
Space-based interferometers
Terrestrial interferometers
Detectors

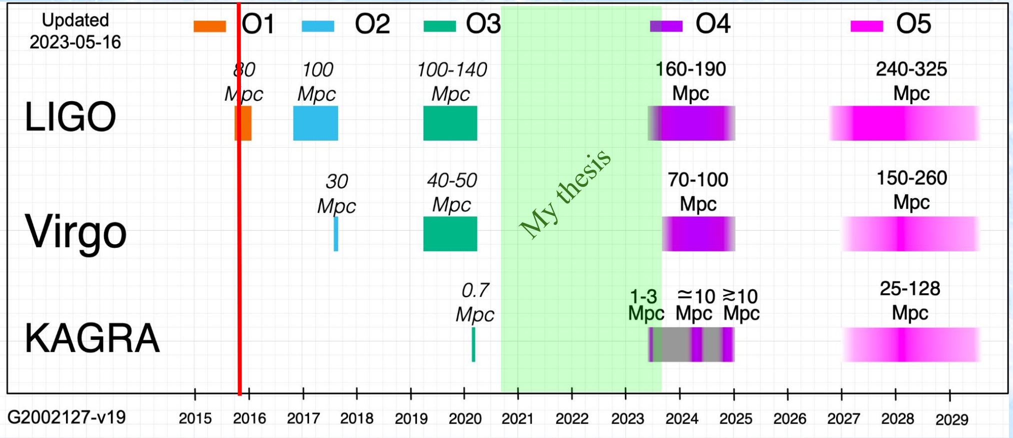
Terrestrial interferometer network

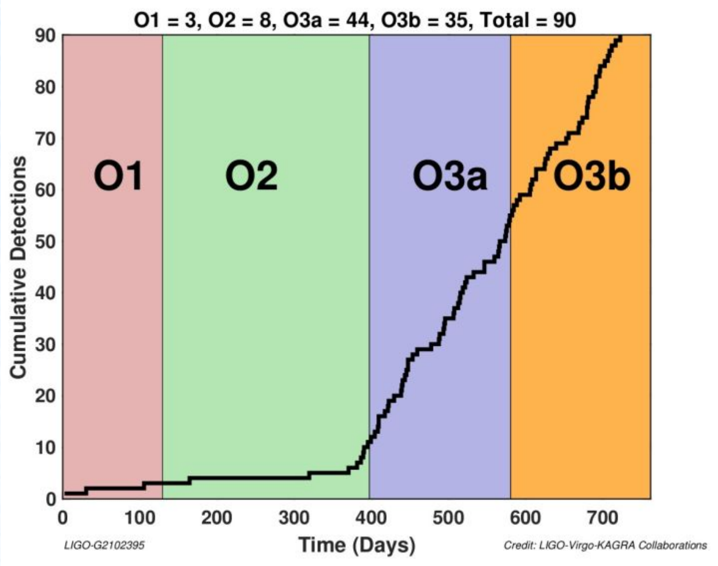


Detection frequency bandwidth [10 Hz, 2 kHz]

Context

- September 14, 2015: First GW detection by LIGO from a binary black hole coalescence

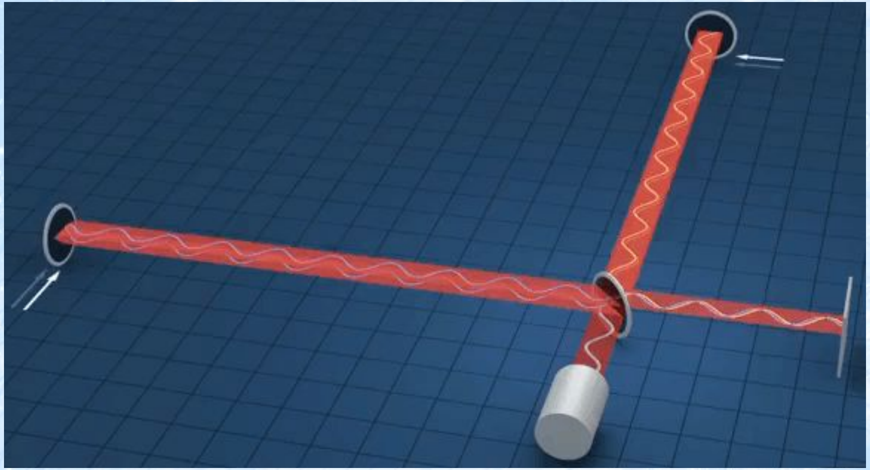


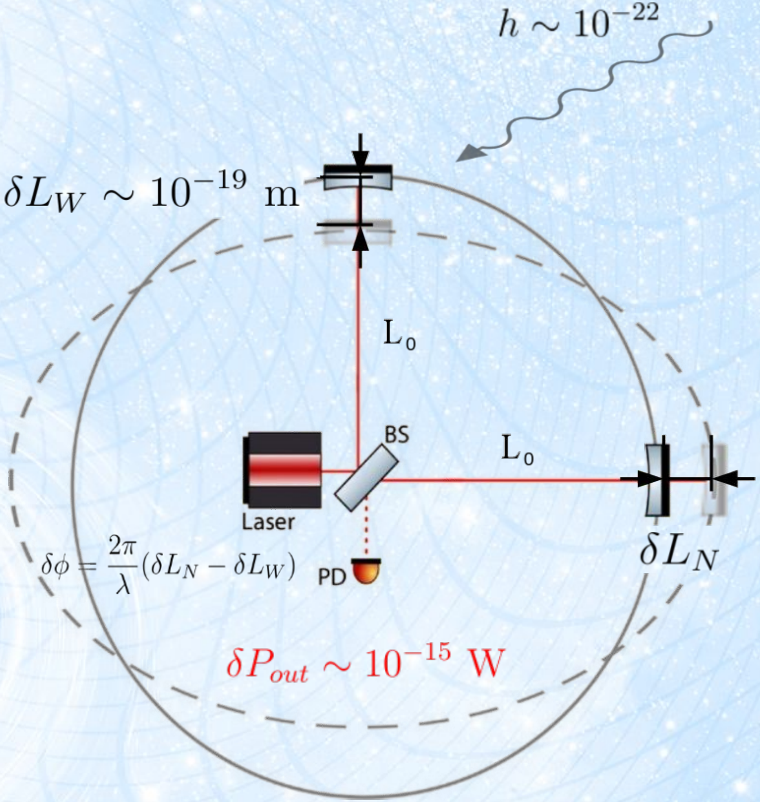


- Virgo is at ~35 Mpc at the moment

- 90 GW detections done until the end of O3
- + ~50 detections during the O4 run by LIGO

Interferometer working principle

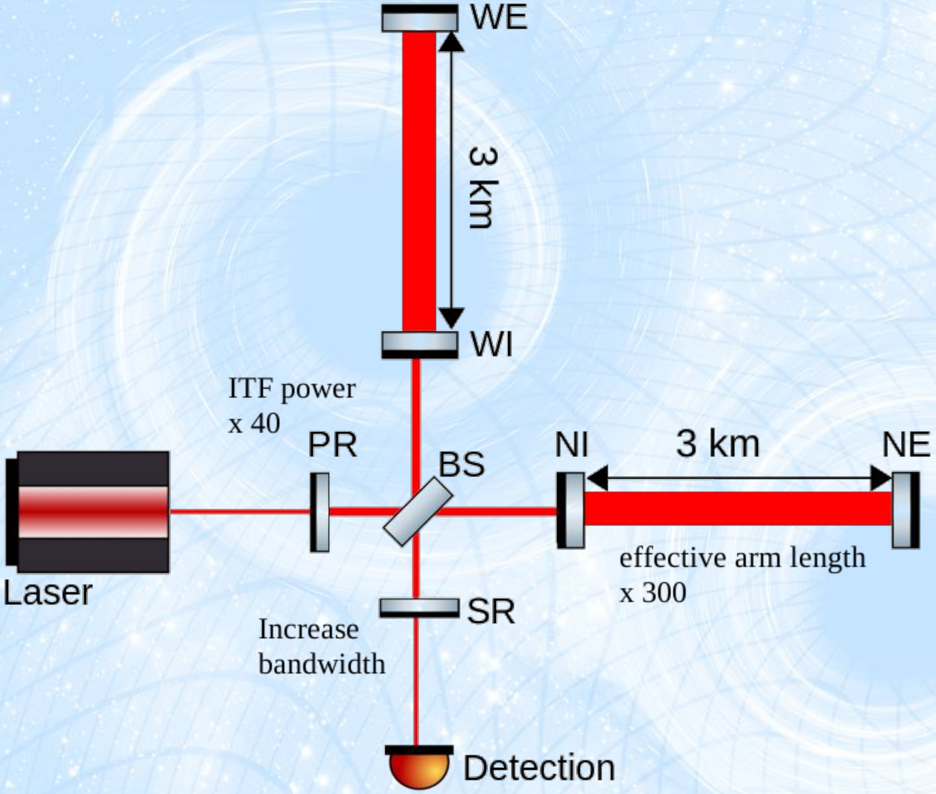




→ The **strain signal** $h = \frac{\delta L_N - \delta L_W}{L_0}$ contains the GW signal

$\lambda = 1064$ nm

More complex interferometer



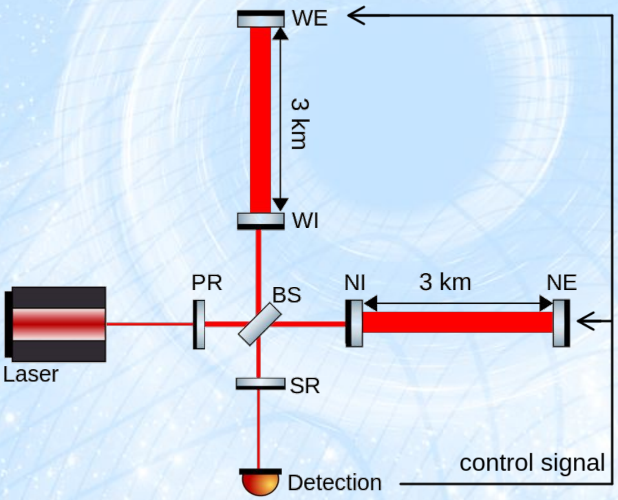
The longitudinal position of the mirrors is controlled to:

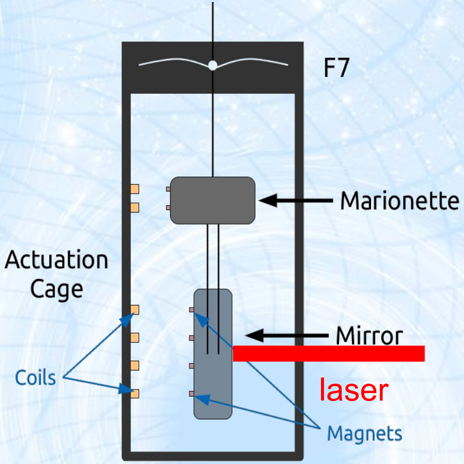
- ➢ Keep the interferometer close to the dark fringe
- ➢ Maintain the cavities at their working point

Longitudinal control of the mirrors

Goals:

- Keep the interferometer in a dark fringe
- Keep the optical cavities at their resonant points





Electromagnetic actuators

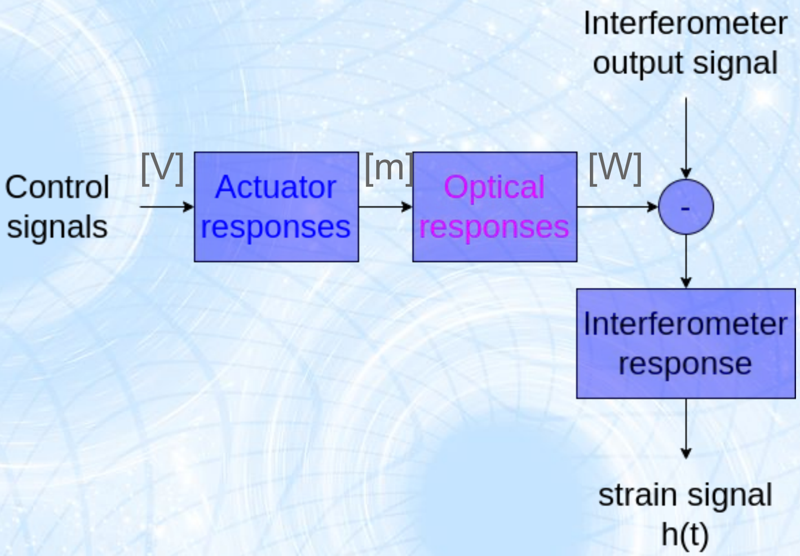
2 electromagnetic actuators to each mirror:

- Marionette
- Mirror

→ The GW signal is contained by both the **output signal of the interferometer**, and the **control signals** of the mirror actuators.

Strain signal reconstruction h(t)

The reconstruction of the strain signal **h** is done in the frequency domain **h(f)**.



The reconstructed signal h(t) used for the commissioning and for data analysis.

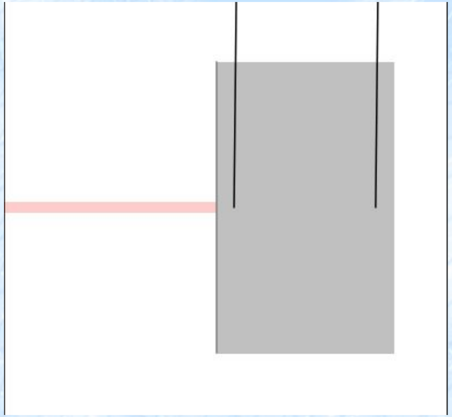
The reconstruction requires the measurement of:

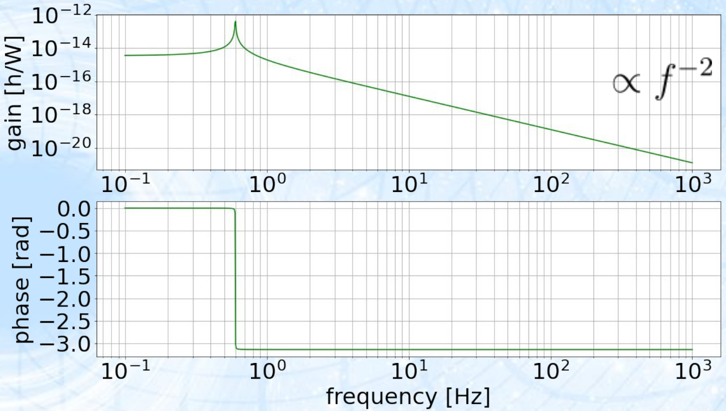
- The actuator responses
- The interferometer optical responses

} Calibration

Calibration of the electromagnetic actuators

- The actuator response (in m/V) mirror displacement (in m) as function of the command signal (in V). It is composed by:
  - The electronic response (in N/V) of the electromagnetic actuator:
  - The mechanical response (in m/N) of the mirror suspension system:





➢ To be measured: The response of the electromagnetic actuator is calibrated with respect to a reference actuator:
  - Newtonian calibrator (NCal)
  - **Photon calibrator (PCal)**

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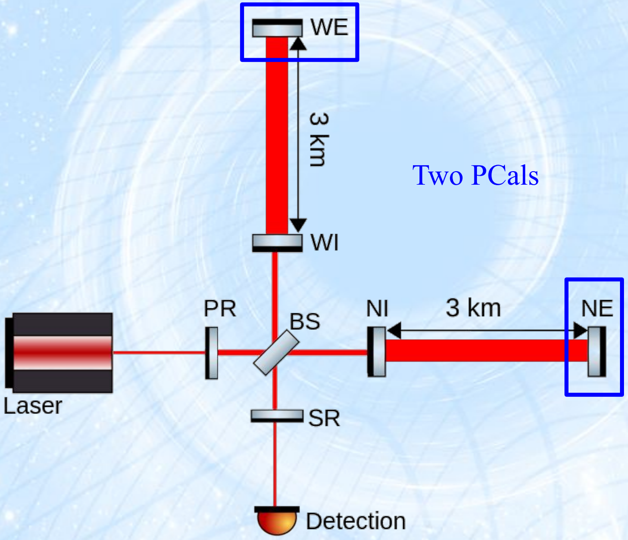
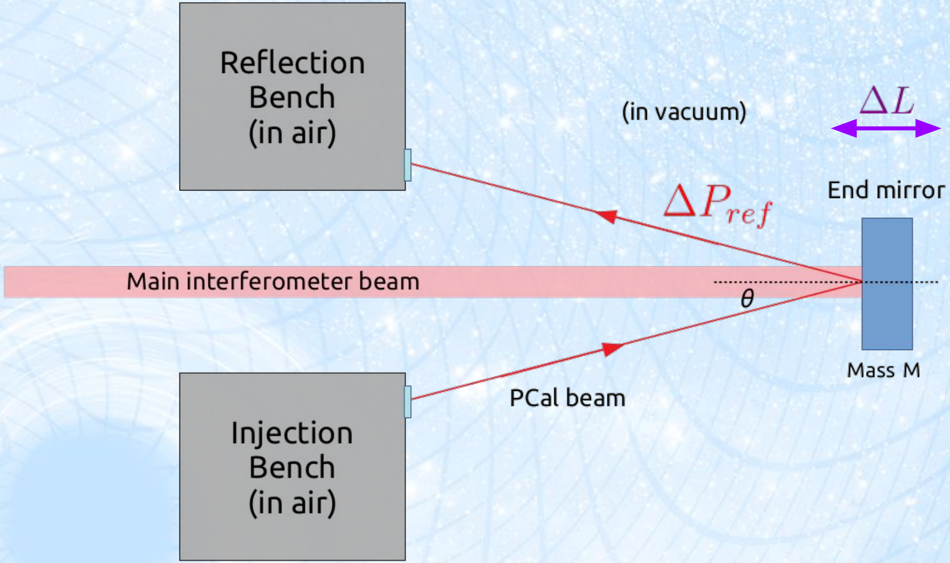
Photon calibrator working principle

The photon calibrator (PCal) makes the end mirrors move by a **known** motion



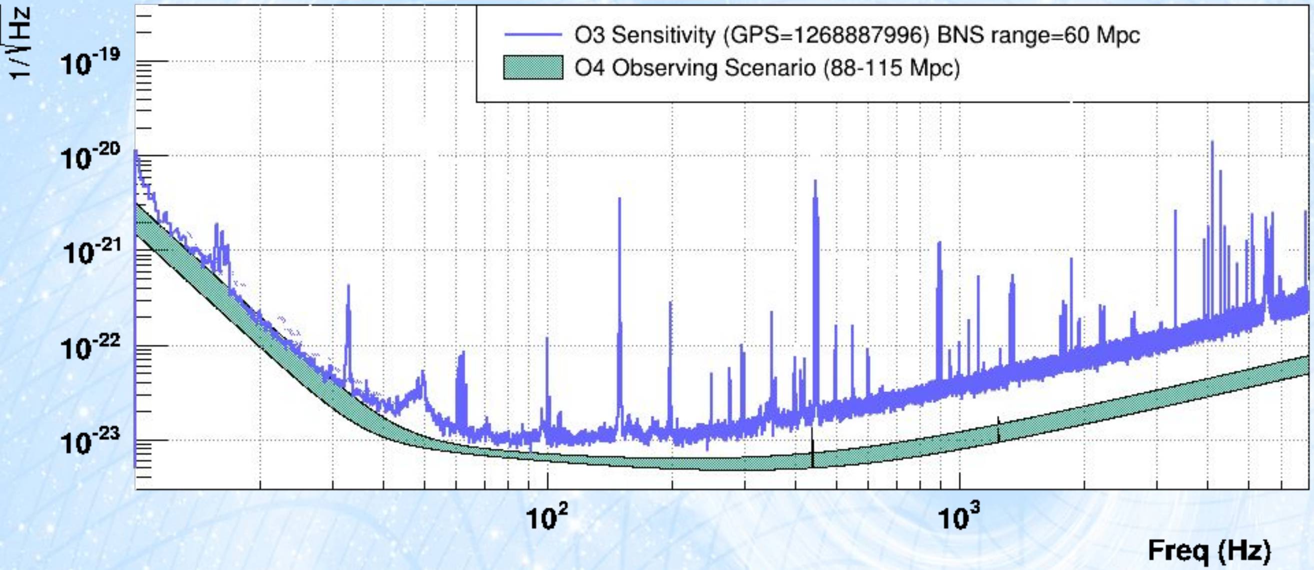


PCal laser **modulated in power** → control mirror motion
Mirror motion ΔL estimated from ΔP_{ref}

Goals for the O4 photon calibrator

Calibration uncertainty → Strain signal uncertainty σ_h → To be reduced for the O4 run
1.34 % (O3) → < 1% (O4)

Virgo sensitivity (noise level)

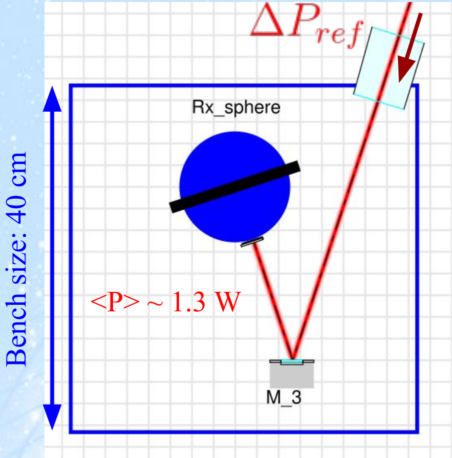


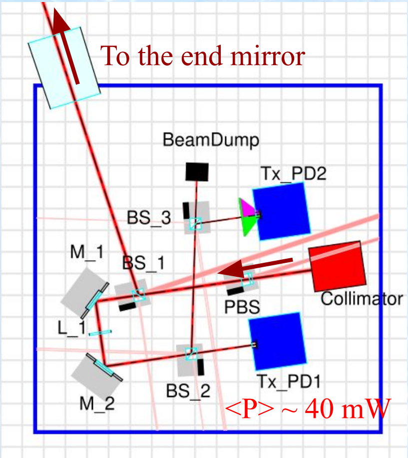
The PCal laser power noise contributes to the interferometer noise

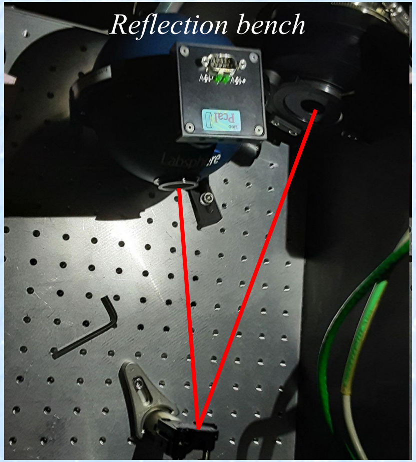
Improvement of the Virgo sensitivity for the O4 run:

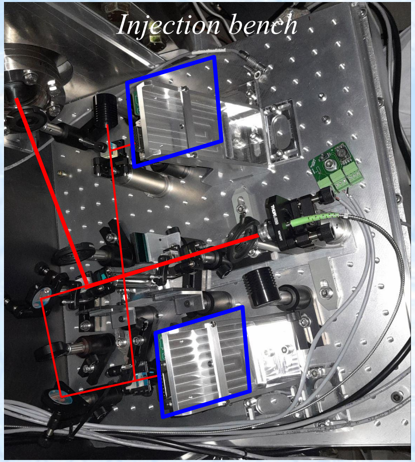
- PCal power noise target = 1/10 of the total interferometer noise

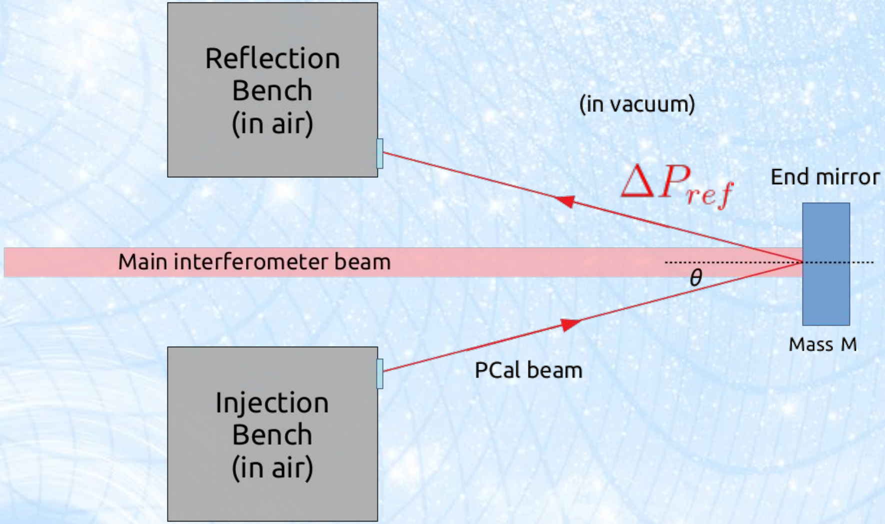
Photon calibrator improvements





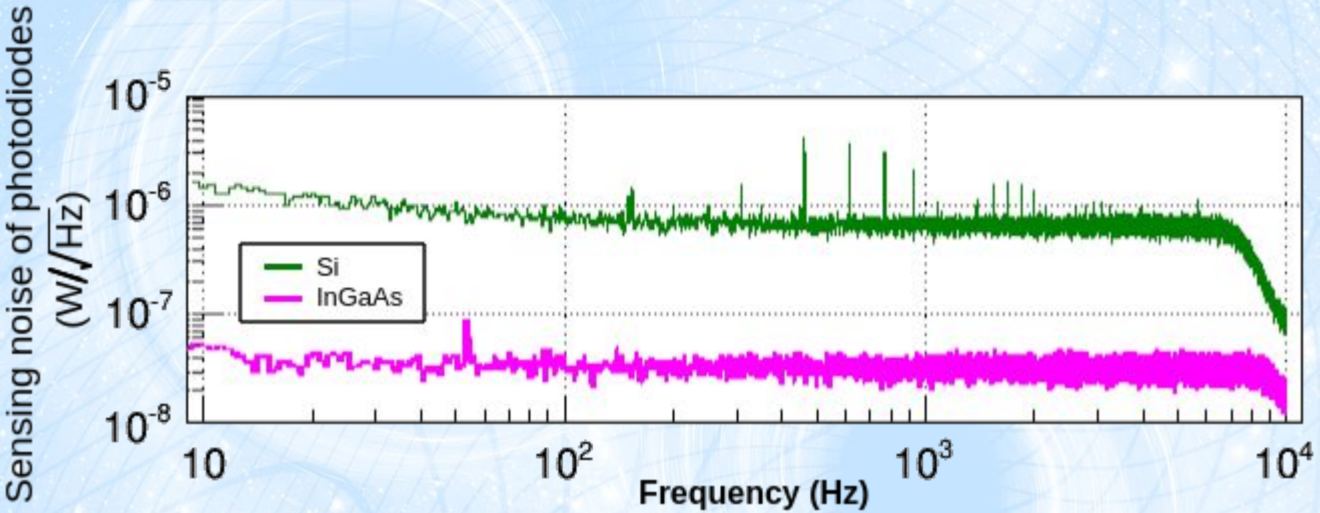


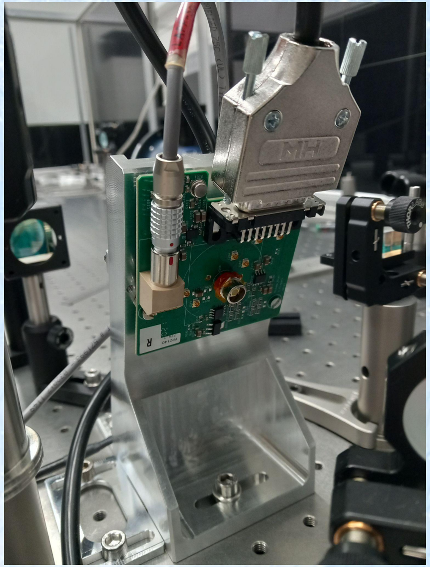




→ ΔP_{ref} is estimated from the **integrating sphere** + monitored by **photodiodes**

PCal photodiodes + preamplifier

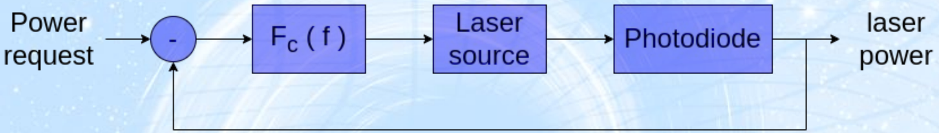




PCal photodiode (InGaAs) + preamplifier

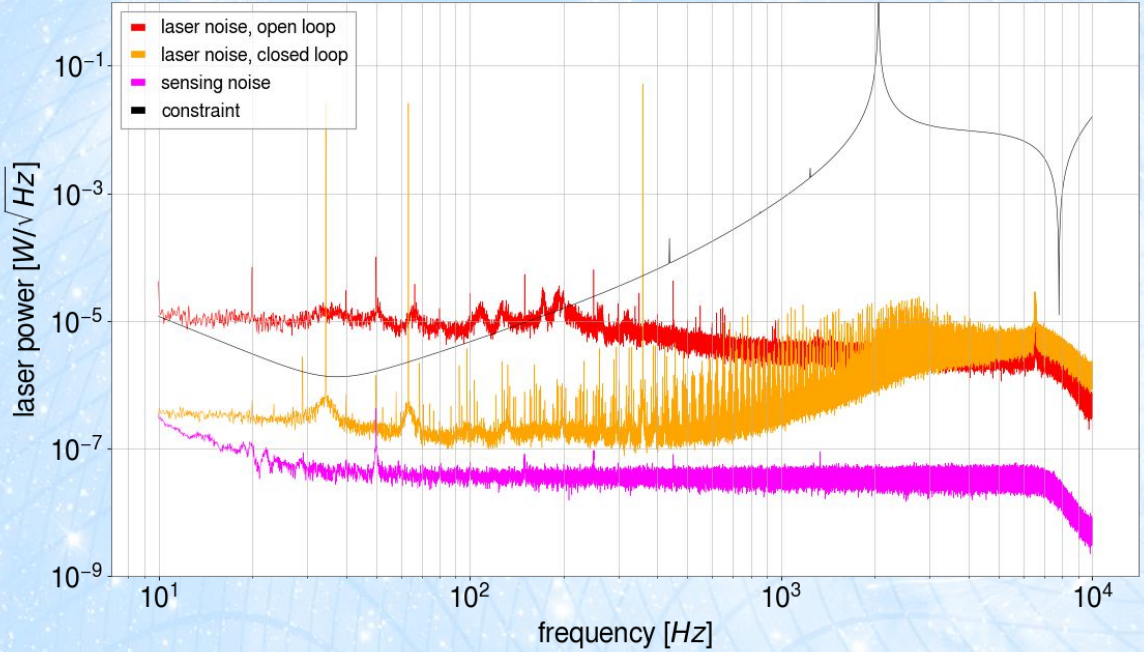
The O4 photodiodes (InGaAs) have a lower sensing noise than the O3 photodiodes (Si)
→ Lower the power noise further with the control loop

Laser control loop



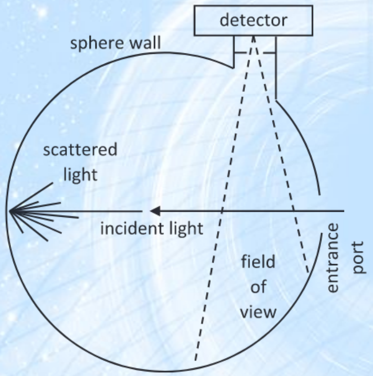
The digital filter $\mathbf{F_c(f)}$ has been updated for the O4 run

PCal laser power noise vs noise constraint for O4



→ Laser power noise below the noise constraint

4 Virgo integrating spheres

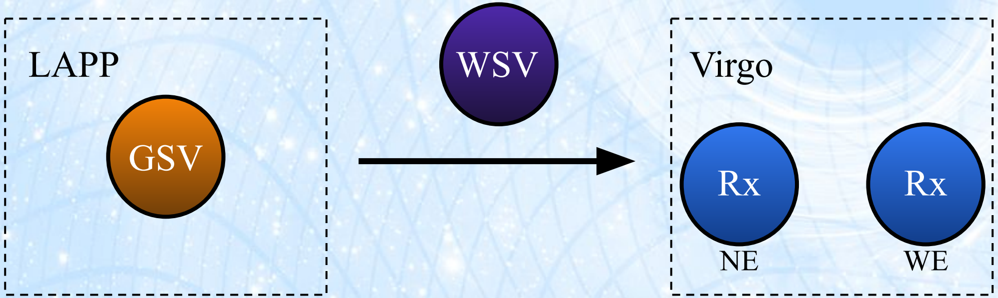


Scheme of the integrating sphere viewed from the side

Integrating sphere

- 2 Rx spheres
  - Installed permanently on PCal benches
- GSV: Gold standard Virgo
  - Main reference at LAPP
- WSV: Working standard Virgo
  - used at Virgo to calibrate PCal

GSV & WSV have a **temperature sensor**



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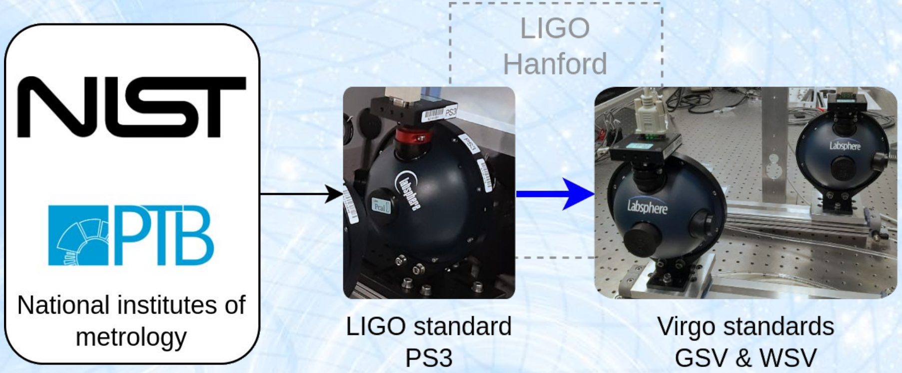
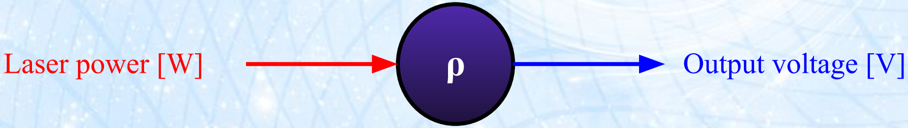
Virgo power standards at LIGO Hanford



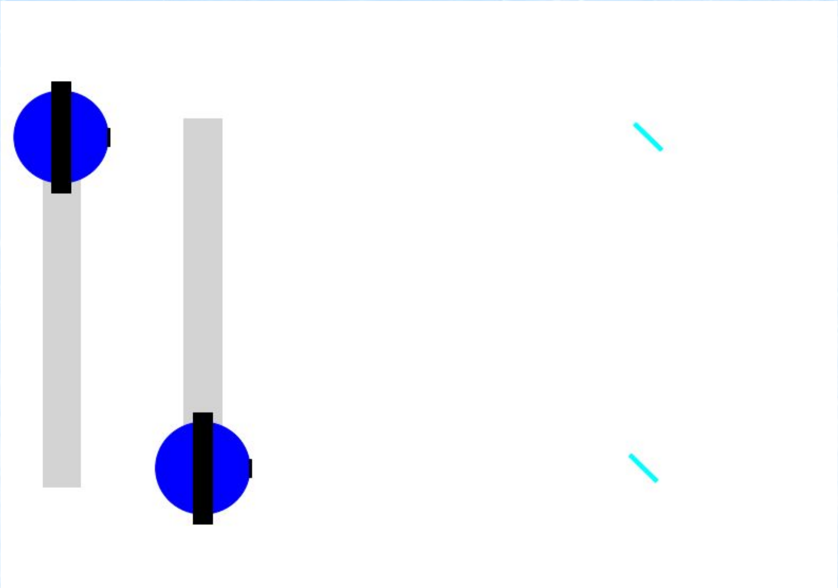
From May 16 to June 3, 2022 @ LIGO Hanford:

- Mounting of the Virgo integrating spheres
- Calibration of the integrating spheres with respect to the LIGO power standards

→ The sphere calibration consists in measuring the responsivity of the sphere **ρ** in [V/W]



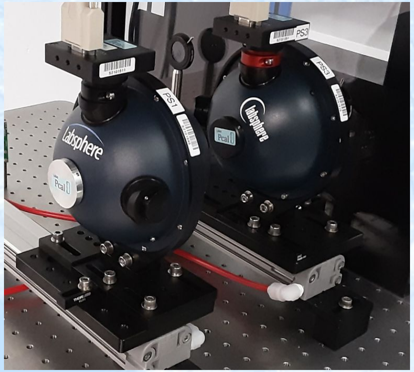
Sphere general calibration method



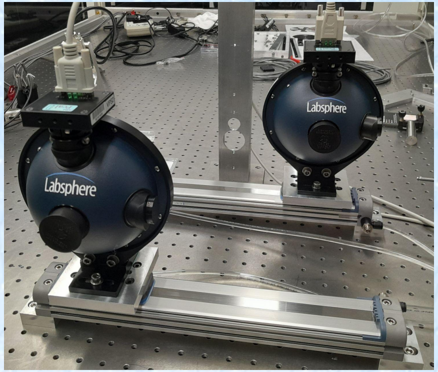
Input laser power: 0.3 W

Calibrated w.r.t. a reference sphere

Ratio: $\alpha_{test/ref} = \frac{\rho_{test}}{\rho_{ref}} = \sqrt{\frac{V_{T,test}}{V_{R,ref}} \cdot \frac{V_{R,test}}{V_{T,ref}}}$



LIGO intercalibration setup



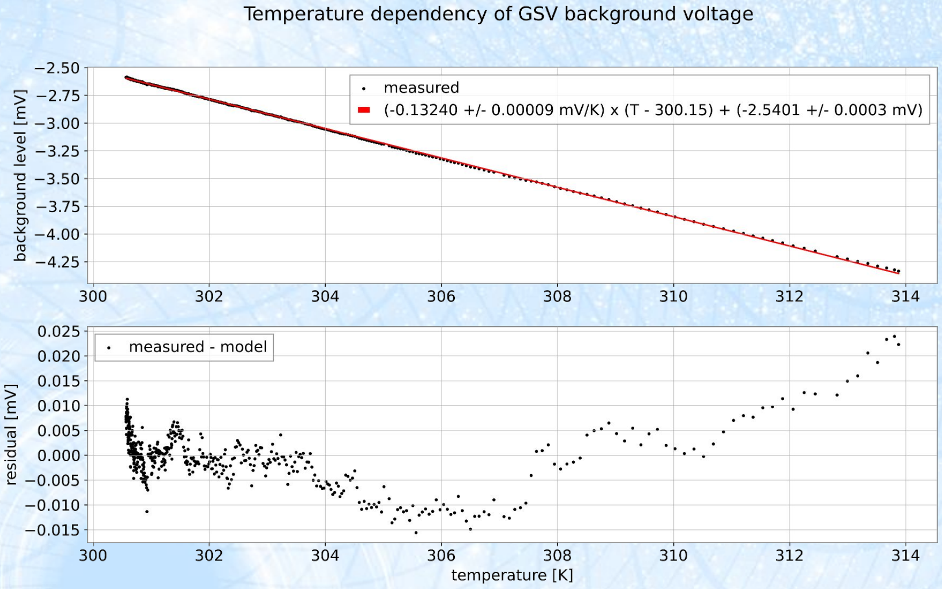
LAPP intercalibration setup

$$P = \frac{1}{\boxed{\rho}} \cdot \frac{V_{raw} \boxed{- V_{bg} - m \cdot (T - T_{bg})}}{\boxed{1 + \kappa \cdot (T - 300.15\ \mathrm{K})}}$$

Power estimated by the sphere from its output voltage

- Sphere responsivity
- Temperature dependant background voltage
- Temperature dependency of the responsivity

Temperature dependency of the background voltage



A linear regression is computed on the measurement.

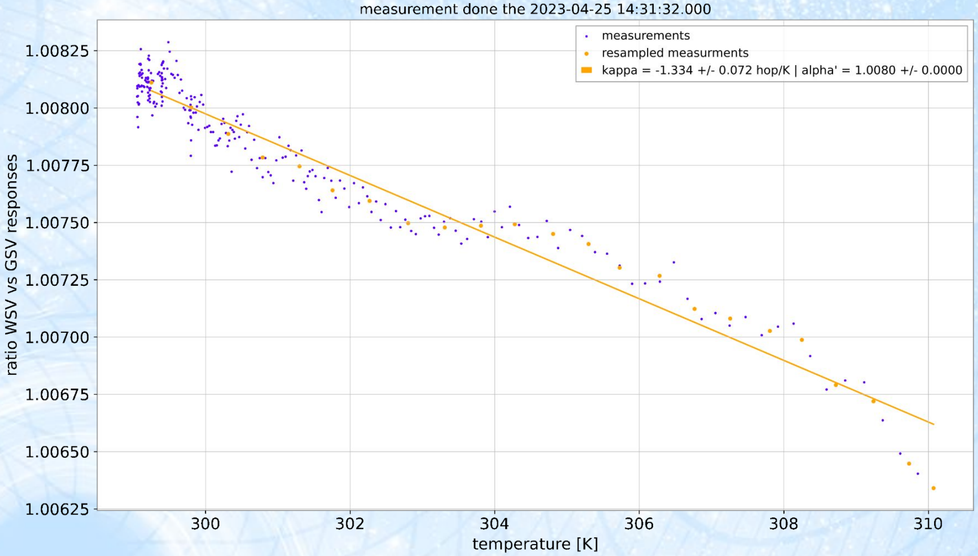
$V_{bg}(T) = V'_{bg} + m \cdot (T - 300.15\text{ K})$

The *m* parameter is characterized to each sphere $m \sim -0.1\text{ mV/K}$

$$P = \frac{1}{\rho} \cdot \frac{V_{raw} - V_{bg} - m \cdot (T - T_{bg})}{1 + \kappa \cdot (T - 300.15\text{ K})}$$

- Temperature dependant background voltage

Temperature dependency of the responsivity



A linear regression is computed between α and the temperature of the test sphere.

$$\alpha(T) = \alpha' \cdot (1 + \kappa \cdot (T - 300.15\ \mathrm{K}))$$

The κ factor characterized for each sphere

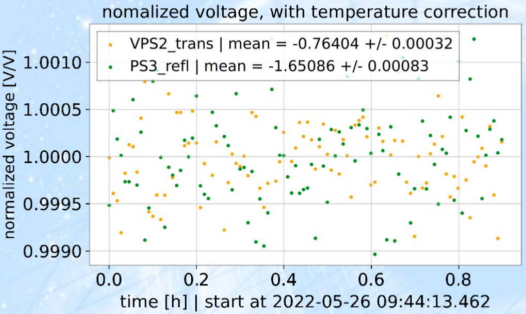
$$\kappa \sim -0.01\ \%/\mathrm{K}$$

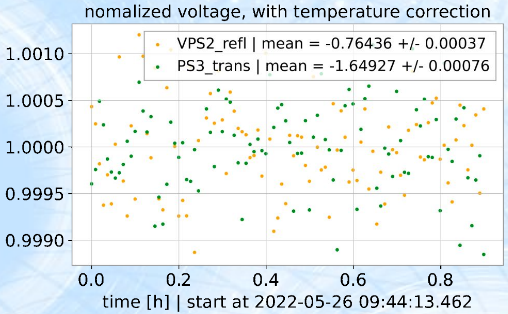
$$P = \frac{1}{\rho} \cdot \frac{V_{raw} - V_{bg} - m \cdot (T - T_{bg})}{1 + \kappa \cdot (T - 300.15\ \mathrm{K})}$$

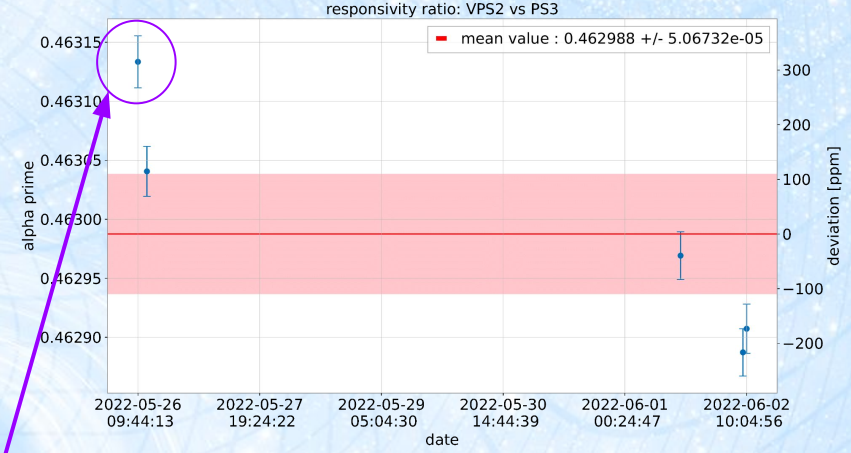
- Temperature dependency of the responsivity

Measurement of the sphere responsivity at LIGO Hanford

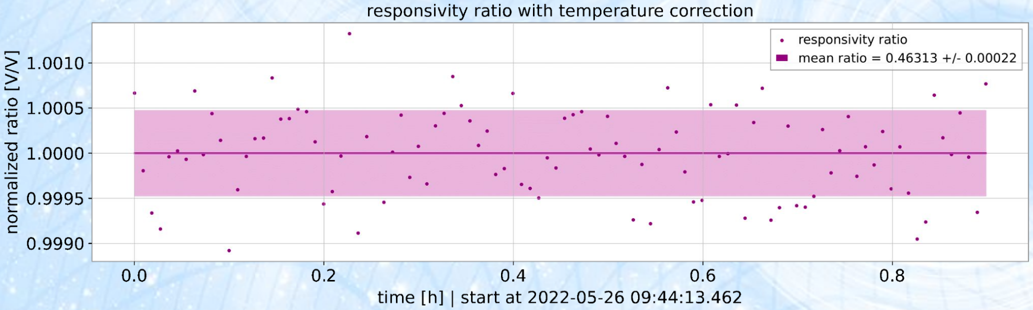
Temperature corrected voltages on different positions





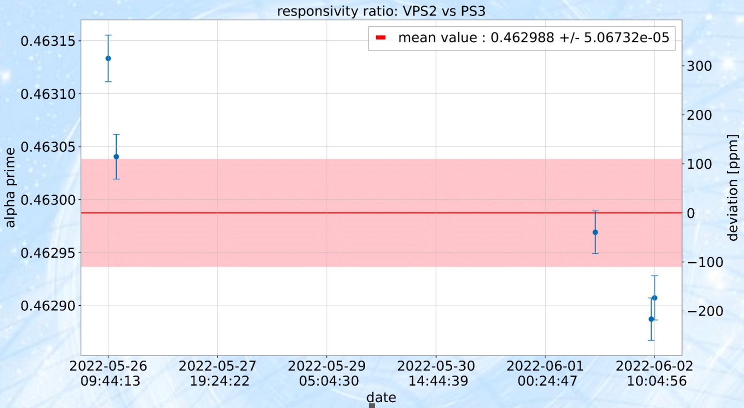


Responsivity ratio α



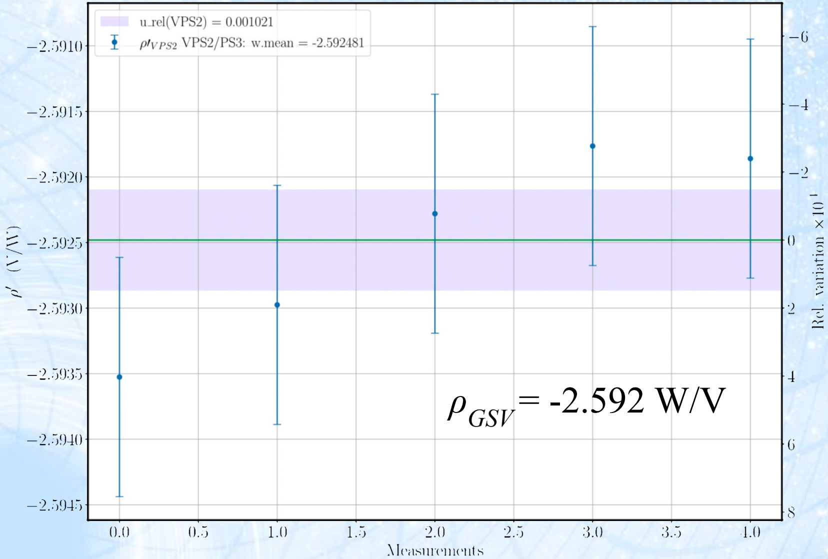
$$\alpha_{test/ref} = \frac{\rho_{test}}{\rho_{ref}} = \sqrt{\frac{V_{T,test}}{V_{R,ref}} \cdot \frac{V_{R,test}}{V_{T,ref}}}$$

Responsivity of the Virgo spheres measured at LIGO



x ρ_{PS3}

GSV



The responsivity is measured with respect to a LIGO standard (PS3). $\rho_{test} = \alpha_{test/ref} \cdot \rho_{ref}$

$$P = \frac{1}{\rho} \cdot \frac{V_{raw} - V_{bg} - m \cdot (T - T_{bg})}{1 + \kappa \cdot (T - 300.15\ \mathrm{K})}$$

- Sphere responsivity

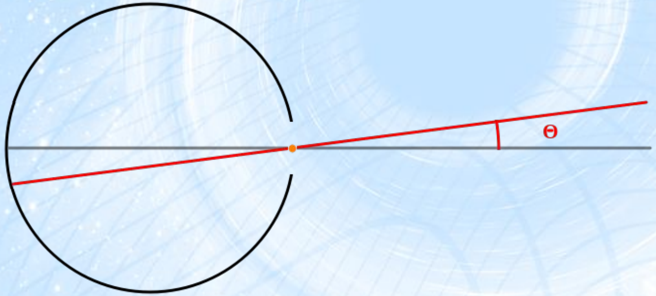
→ characterizations to be done in order to estimate the uncertainty on the responsivity

Characterization of the sphere responsivity

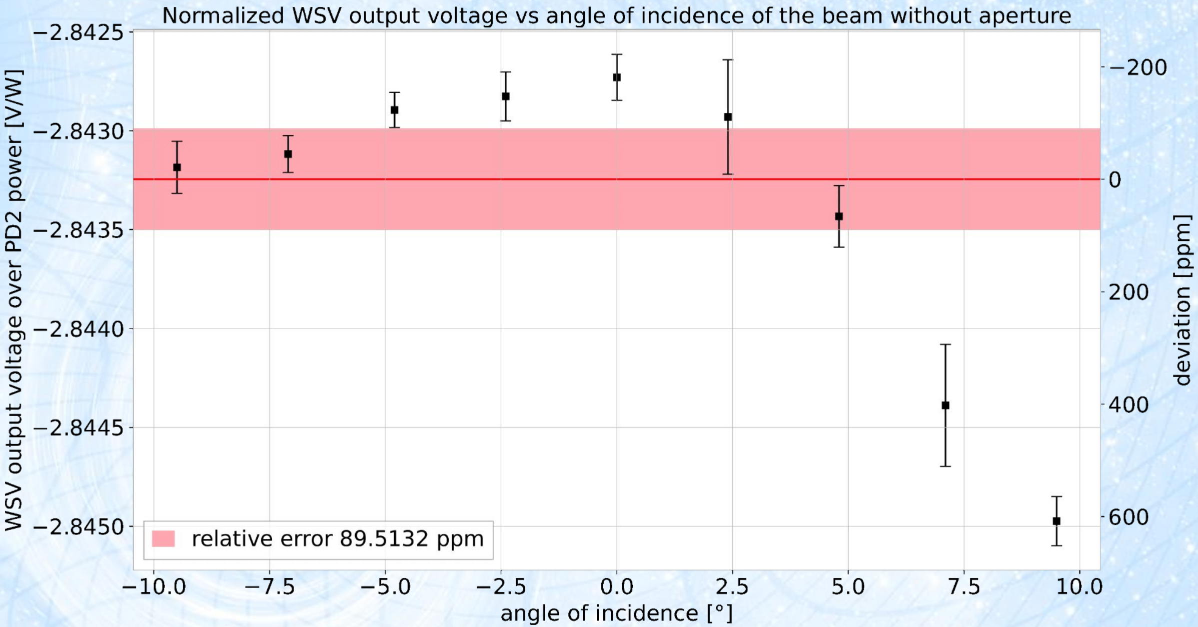
The sphere responsivity variation have been characterized with respect to:

- The beam angle of incidence
- The beam lateral position
- Beam size
- Input power (linearity)

Responsivity vs angle of incidence

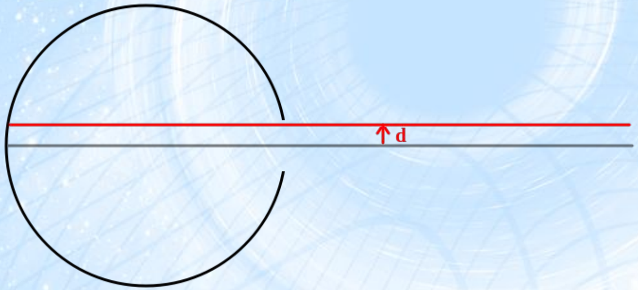


Θ angle of incidence

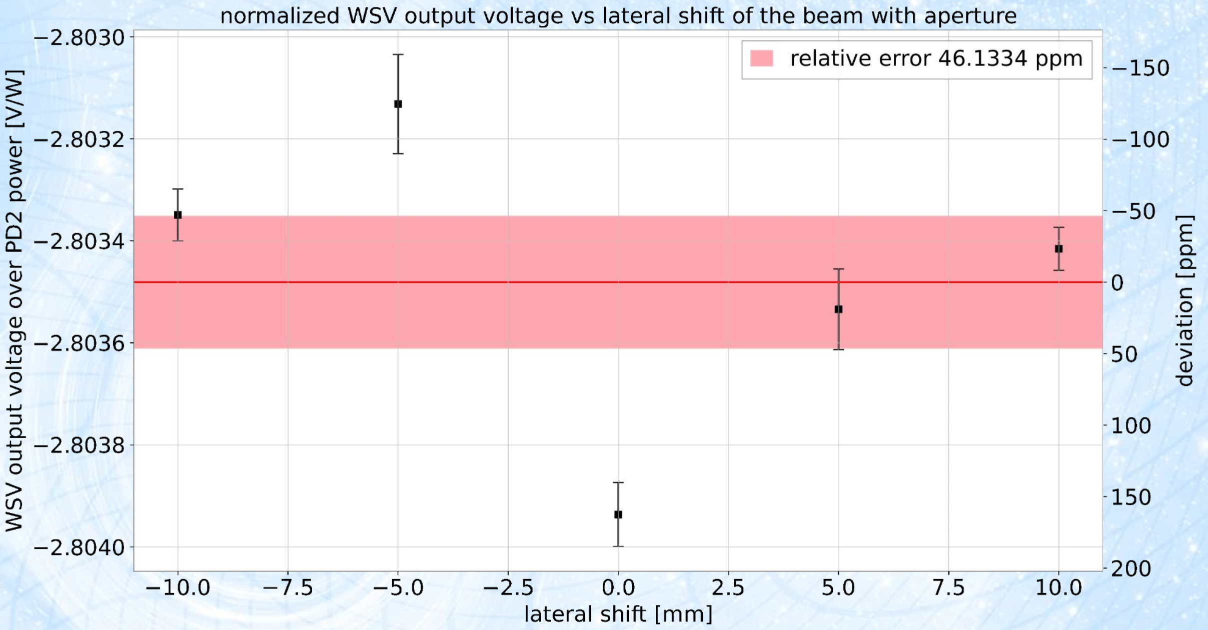


→ Variation of the responsivity with the angle of incidence: ~90 ppm

Responsivity vs lateral position

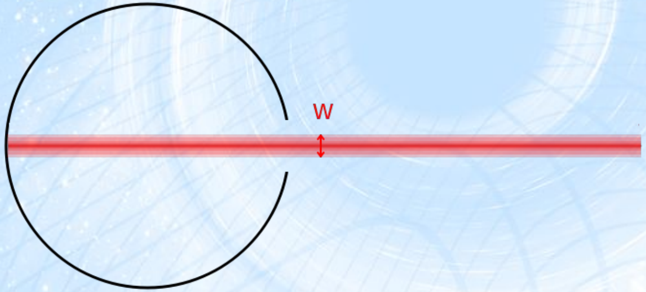


d lateral shift

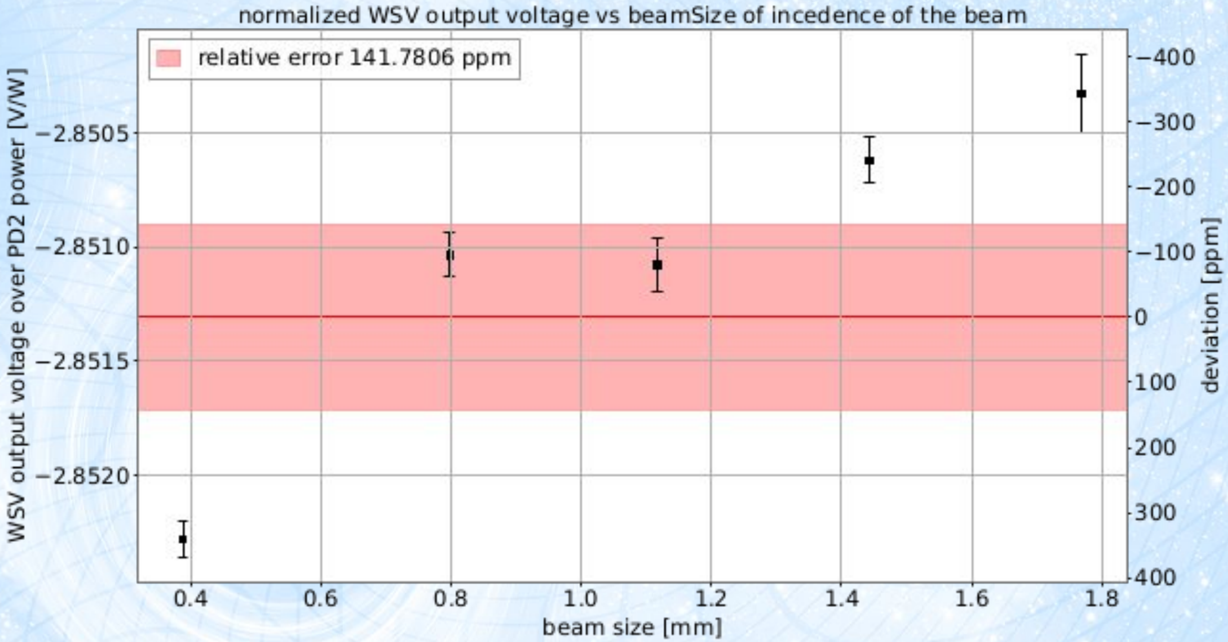


→ Variation of the responsivity with the position: ~46 ppm

Responsivity vs beam size



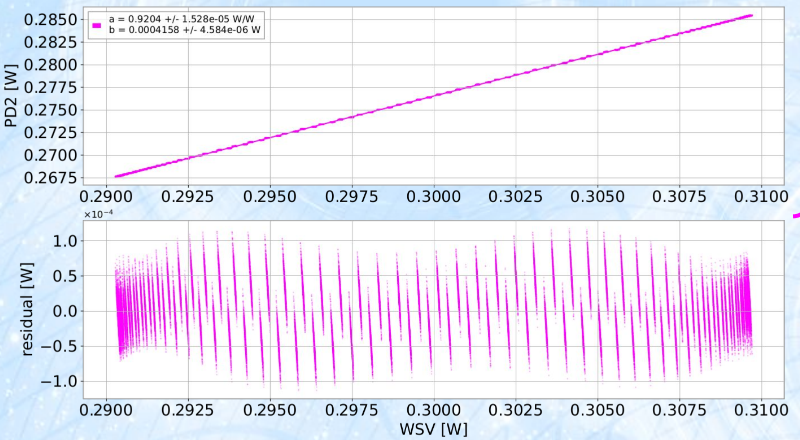
w beam size



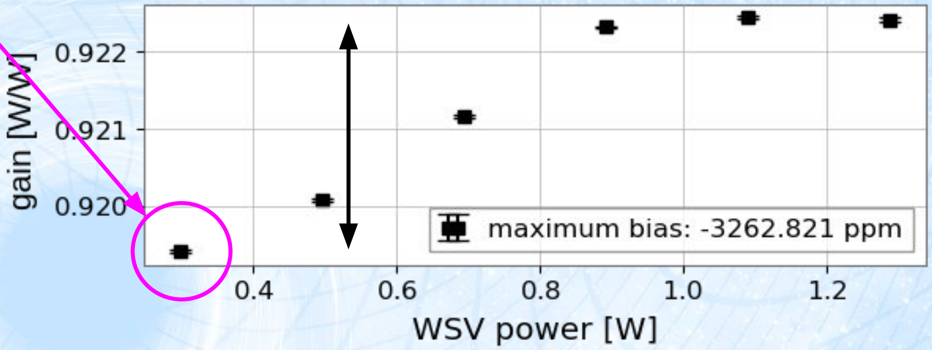
→ Variation of the responsivity with the beam size: ~142 ppm

Linearity of the sphere

Laser power measured by the sphere and a photodiode simultaneously.
Linear regression.



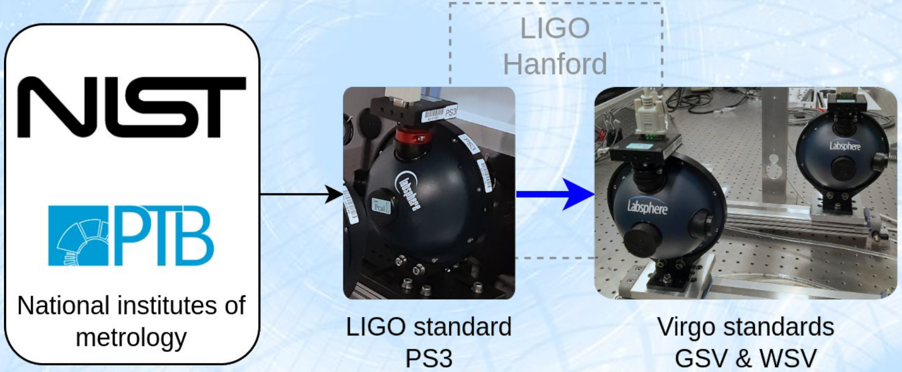
$$P_{PD} = A \cdot P_{WSV} + B$$



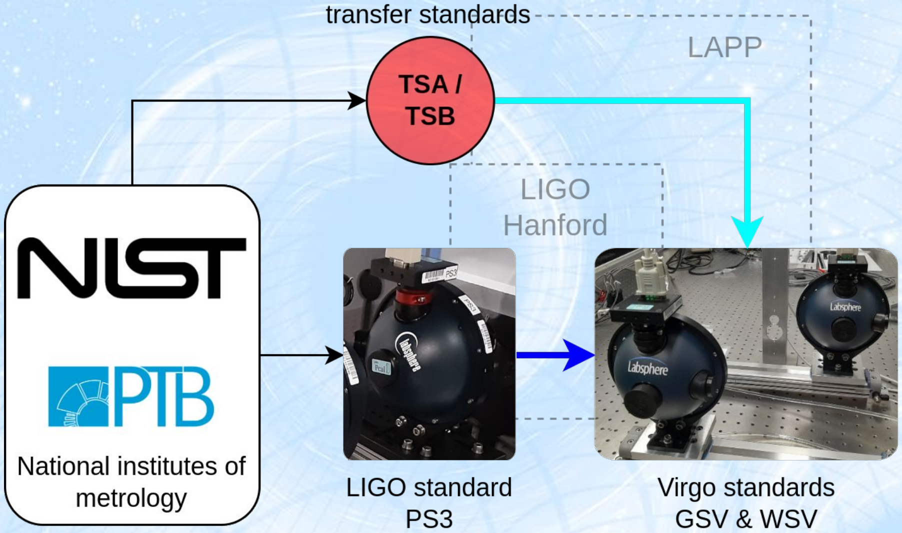
The nonlinearity can be due to either the sphere or the photodiode

→ The gain varies by 0.326 % between 0.3 and 1.3 W. The cause of the nonlinearity is not well understood, further investigation are needed.

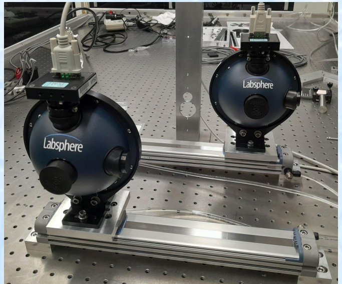
Recalibration of the Virgo spheres



Recalibration of the Virgo spheres



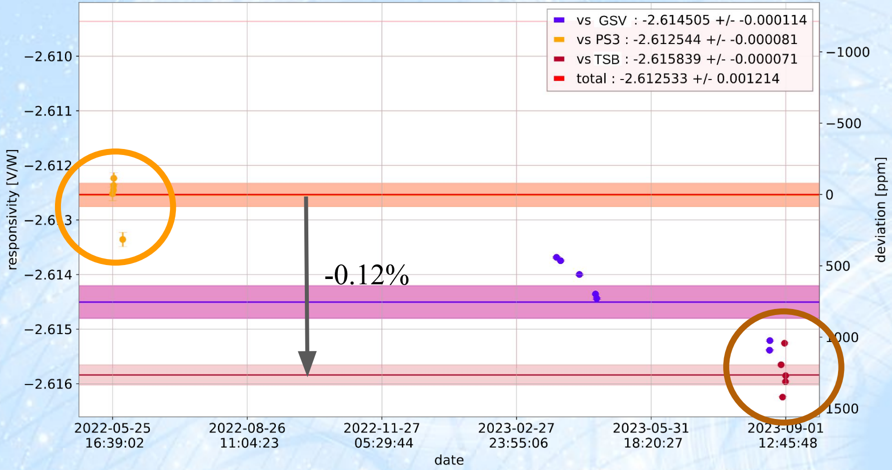
Intercalibration procedure between LIGO, Virgo and KAGRA



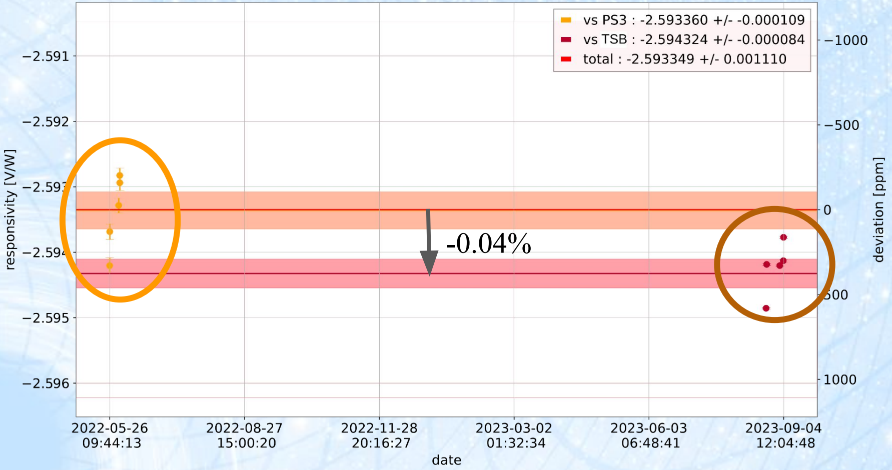
→ A calibration setup was built at LAPP
→ The procedure started in September 2023

Variation of the sphere responsivity over 16 months

WSV



GSV



- Calibration done at LIGO Hanford with respect to PS3
- Calibration done at LAPP with respect to TSB

Variation of the sphere responsivity from June 2022 to August 2023 → included in the PCal uncertainty budget

$\delta\rho_{WSV}$: -0.12 %

$\delta\rho_{GSV}$: -0.04 %

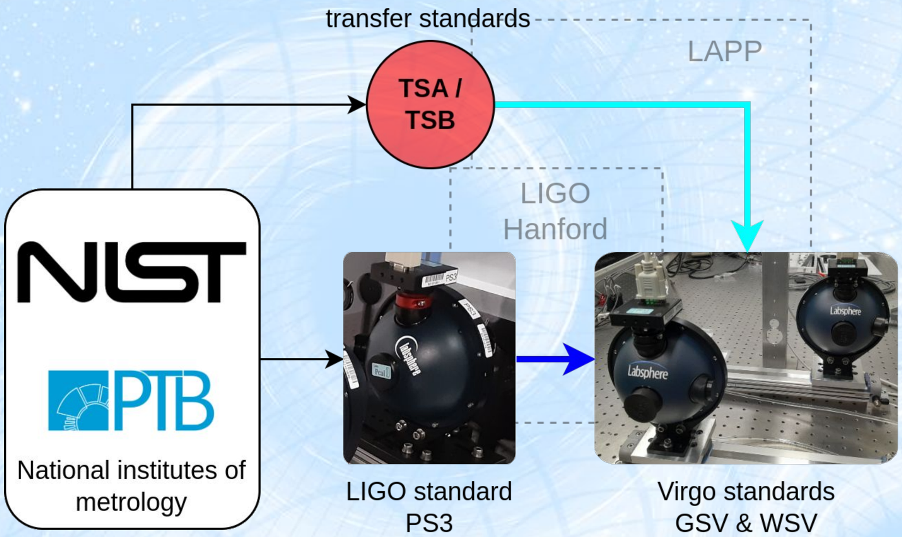
Sphere responsivity and uncertainty

	WSV	GSV
Responsivity [V/W]	-2.6125	-2.5934

Uncertainty source	WSV	GSV
LIGO standard (PS3) response	0.107%	0.107%
Output voltage	0.049%	0.049%
Responsivity ratio	0.003%	0.004%
Angle of incidence	0.012%	0.012%
Beam size	0.014%	0.014%
Linearity	0.326%	0.326%
Responsivity variation	0.125%	0.040%
Total	**0.369%**	**0.349%**

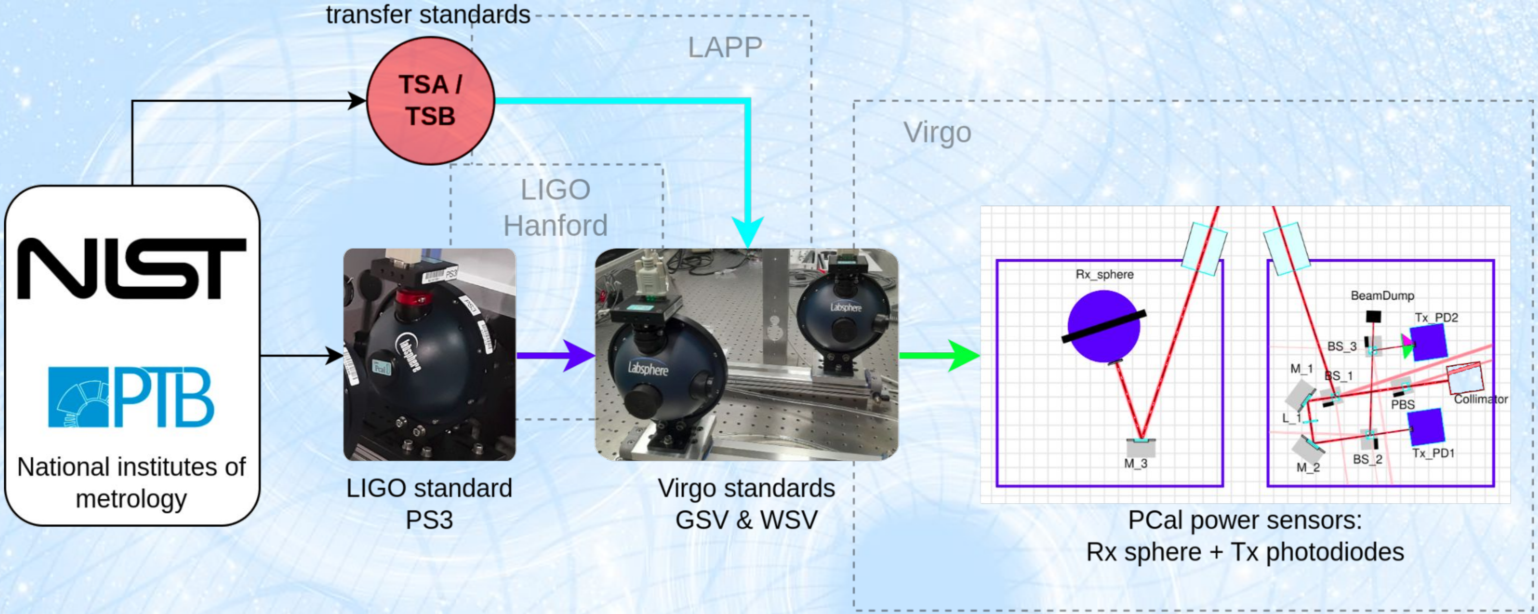
Main contribution (Linearity)

Calibration of the Virgo PCal power sensors w.r.t. WSV



- Sphere responsivity measured
- Uncertainty on the sphere response estimated

Calibration of the Virgo PCal power sensors w.r.t. WSV



2 goals:

- Calibration of the sensors in power → ΔP_{ref}
- Measurement of the mechanical response → ΔL

Calibration in DC of the PCal sensors

Calibration at 1.3 W.
Each sensor has a calibration gain G in [W/V]

Method:

1) Replace the Rx sphere by the WSV sphere and measure the ratio between the output voltages of the sphere and the photodiodes

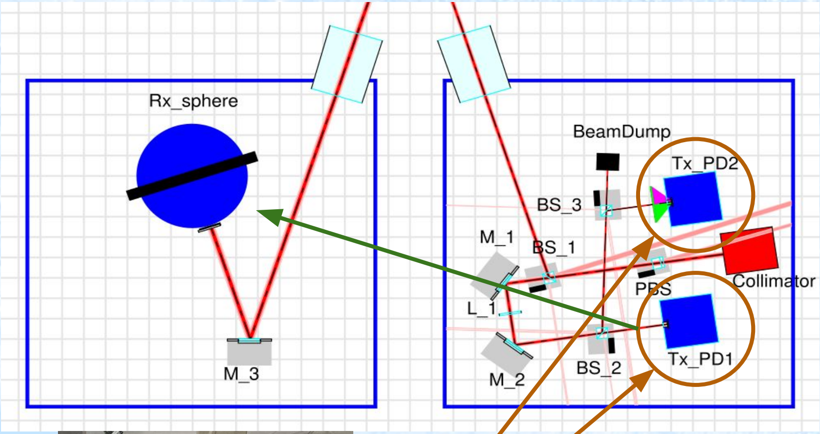
$$G_{PD} = \frac{V_{WSV}}{V_{PD}} \cdot \frac{1}{\rho_{WSV}}$$

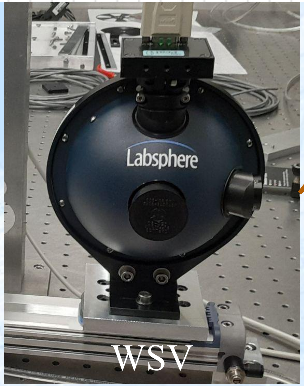
2) Put back the Rx sphere and measure the ratio between the photodiodes and the Rx sphere

$$G_{Rx} = \frac{V_{PD}}{V_{Rx}} \cdot G_{PD}$$

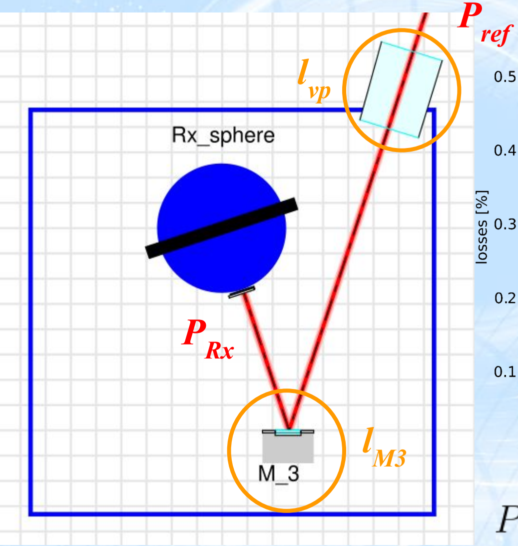
→ Calibration done in November 2022, and done again in June 2023

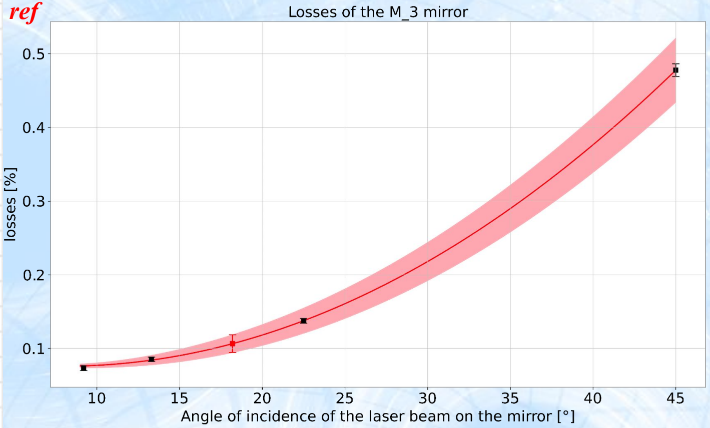
Rx sphere calibration gain variation: 0.2 %





Losses of the viewports and M_3 mirror





$$P_{Rx} = P_{ref} \cdot (1 - l_{vp}) \cdot (1 - l_{M3})$$

Losses measured at LAPP w.r.t. the angle of incidence of the beam.

Measured losses:

- $l_{vp} = 0.60 \pm 0.09\%$
- $l_{M3} = 0.11 \pm 0.01\%$

Uncertainty on the laser power measured by the Rx spheres

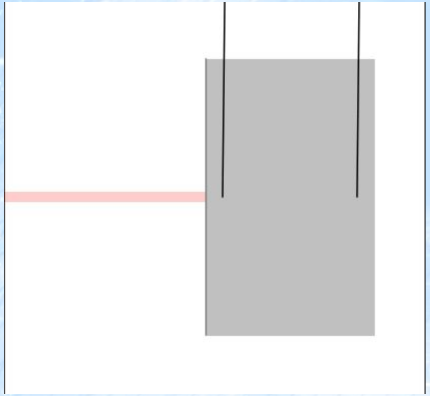
Uncertainty source	WSV	GSV
LIGO standard (PS3) response	0.107%	0.107%
Output voltage	0.049%	0.049%
Responsivity ratio	0.003%	0.004%
Angle of incidence	0.012%	0.012%
Beam size	0.014%	0.014%
Linearity	0.326%	0.326%
Responsivity variation	0.125%	0.040%
Total	**0.369%**	**0.349%**

Variable	1σ uncertainty value [%]
WSV response	0.369
Calibration of the Rx sphere	0.201
Losses of the viewport	0.095
Losses of the M_3 mirror	0.012
Reflected power $\frac{\sigma_{P,ref}}{P_{ref}}$	0.431

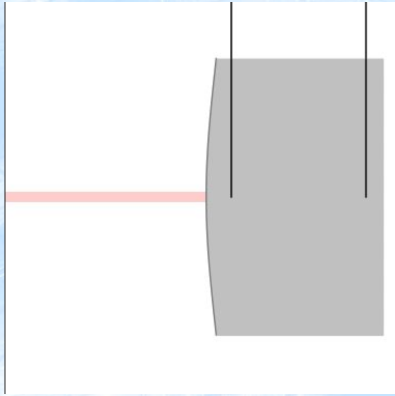
(1.24% uncertainty on the reflected power during O3)

Mechanical response with mirror deformations

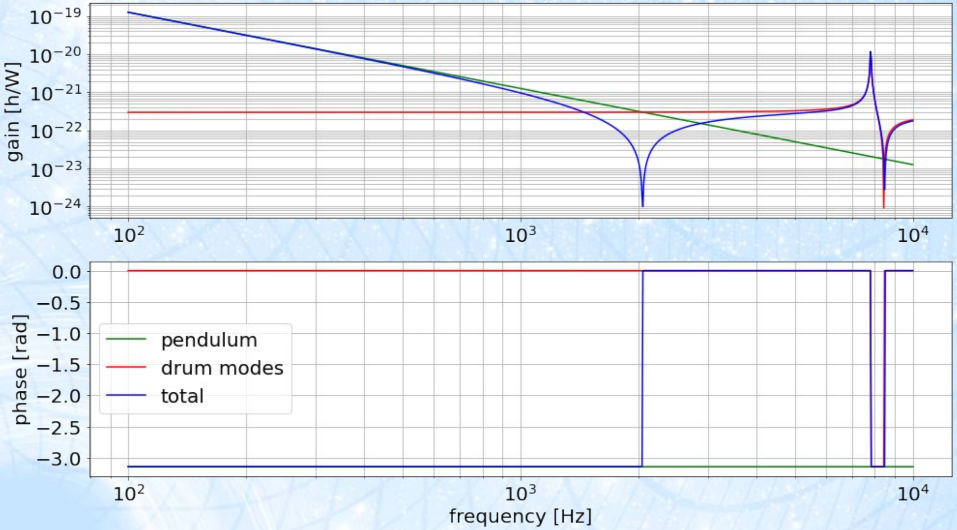
Computes the mirror displacement with respect to the PCal laser power



Pendulum



Drum modes



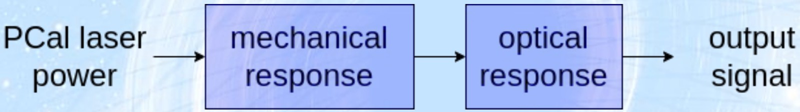
$$H_{pend}(f) = \frac{G_p}{1 + \frac{i}{Q_p}\frac{f}{f_p} - \left(\frac{f}{f_p}\right)^2}$$

$$H_{drum}(f) = \frac{G_d}{1 + \frac{i}{Q_d}\frac{f}{f_d} - \left(\frac{f}{f_d}\right)^2} + G_c$$

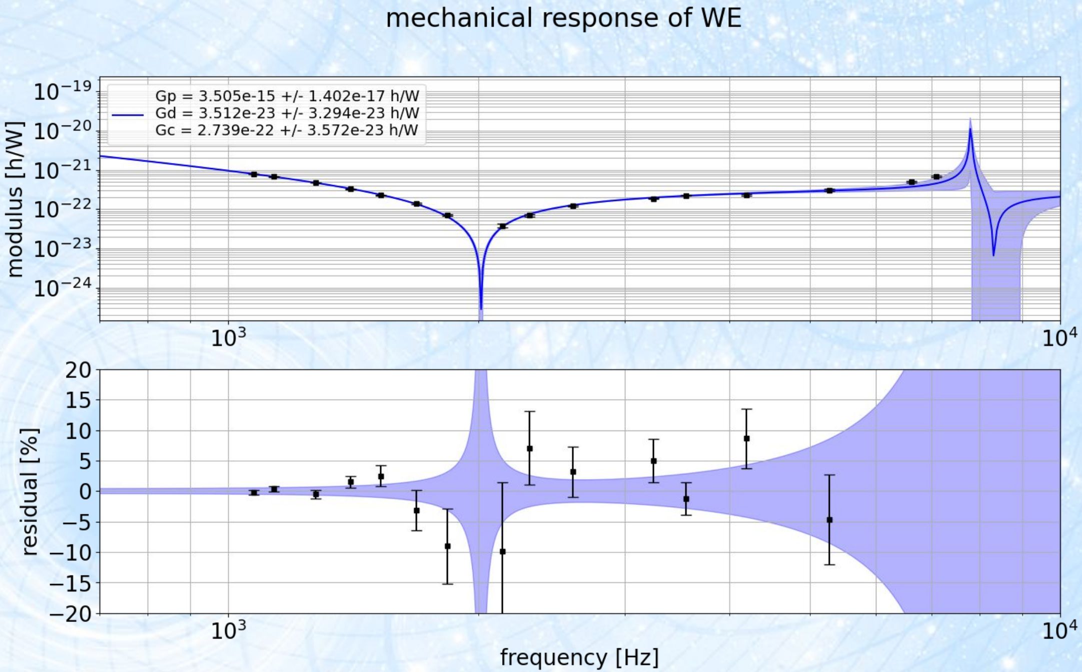
→ The parameters G_d and G_c must be fitted to a measurement of the mechanical response, the other parameters are known

Measurement of the mechanical response

Sinusoidal signals are injected with the PCal.



Optical response = simple pole at 400 Hz.

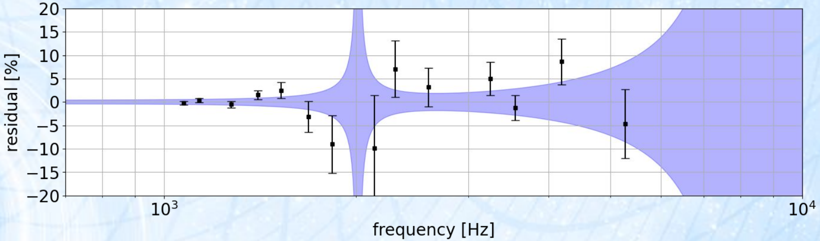


→ Mechanical response used to estimate the mirror displacement induced by the PCal ΔL from the laser power ΔP_{ref}

Uncertainty on the mirror displacement

Variable	1σ uncertainty value [%]
WSV response	0.369
Calibration of the Rx sphere	0.201
Losses of the viewport	0.095
Losses of the M_3 mirror	0.012
Reflected power $\frac{\sigma_{P,ref}}{P_{ref}}$	0.431

Uncertainty on the mechanical response (> 1 kHz)

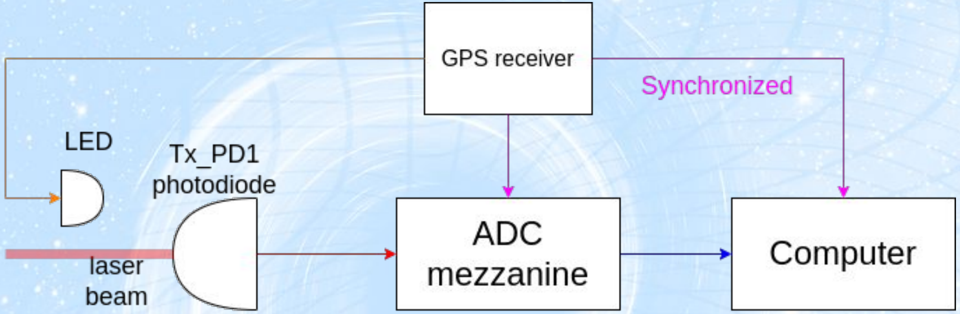


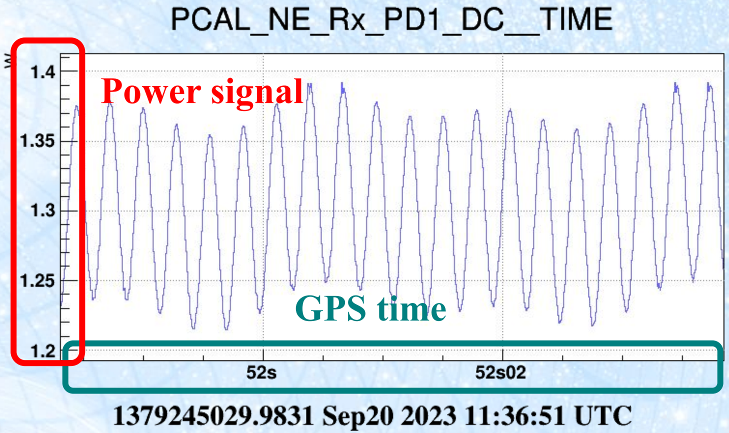
Variable	1σ uncertainty value [%]
Reflected power $\frac{\sigma_{P,ref}}{P_{ref}}$	0.431
Mechanical response (< 1 kHz)	0.40
Mirror displacement $\frac{\sigma_{\Delta L}}{\Delta L}$	0.59

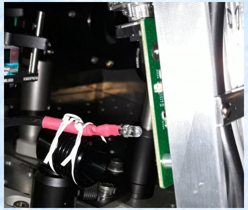
The uncertainty on the reconstructed mirror displacement ΔL has been improved from 1.34% (O3), to 0.59% (O4)

→ How much is ΔL delayed from the real mirror displacement ?

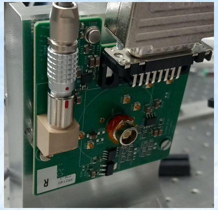
Sensing chain frequency response







Tx_PD1 photodiode with LED



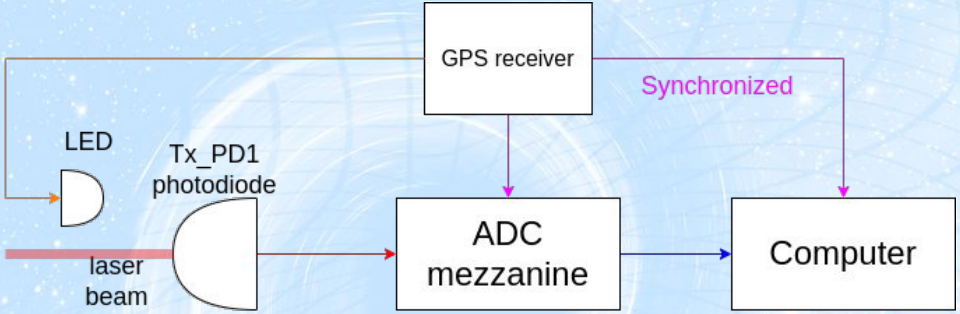
photodiode

ADC mezzanine

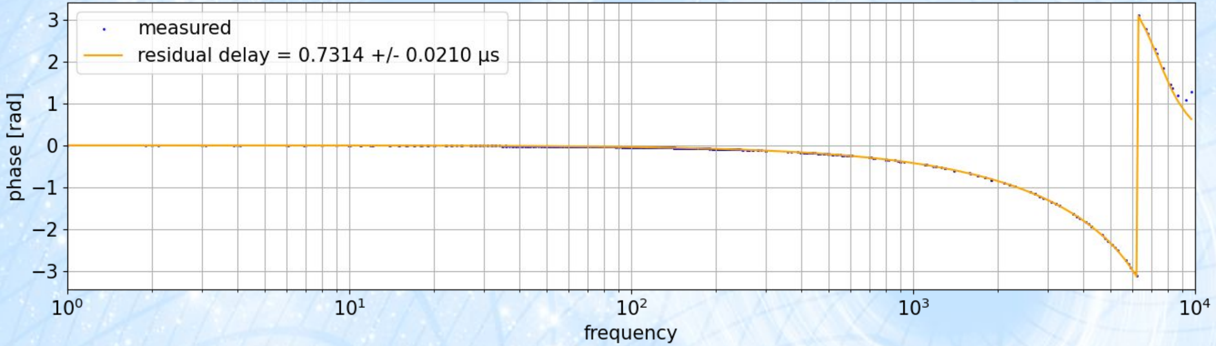
The output digital signal is delayed from the input analog signal by the ADC (analog digital convertor)

Goal: Reconstruct the input power signal of the ADC from the output signal

Measurement of the sensing chain response



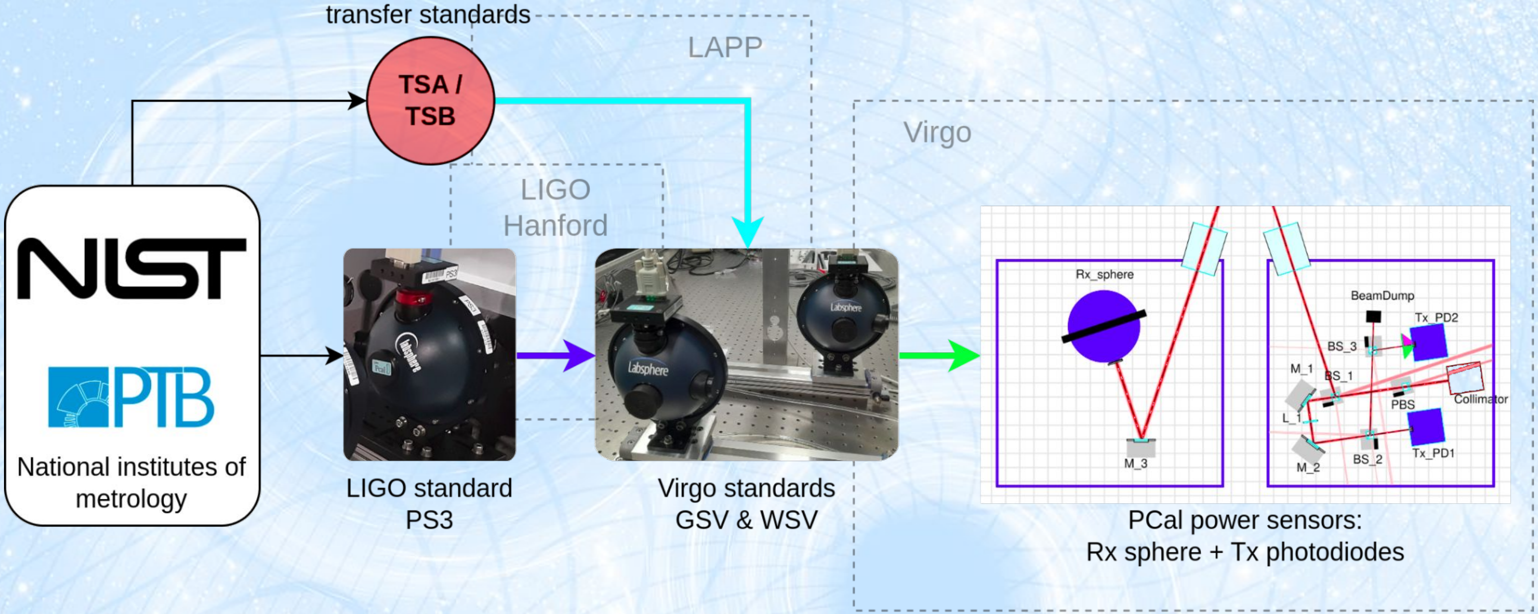
TF from the LED input signal to the digital signal



The phase of the TF is fitted with a model

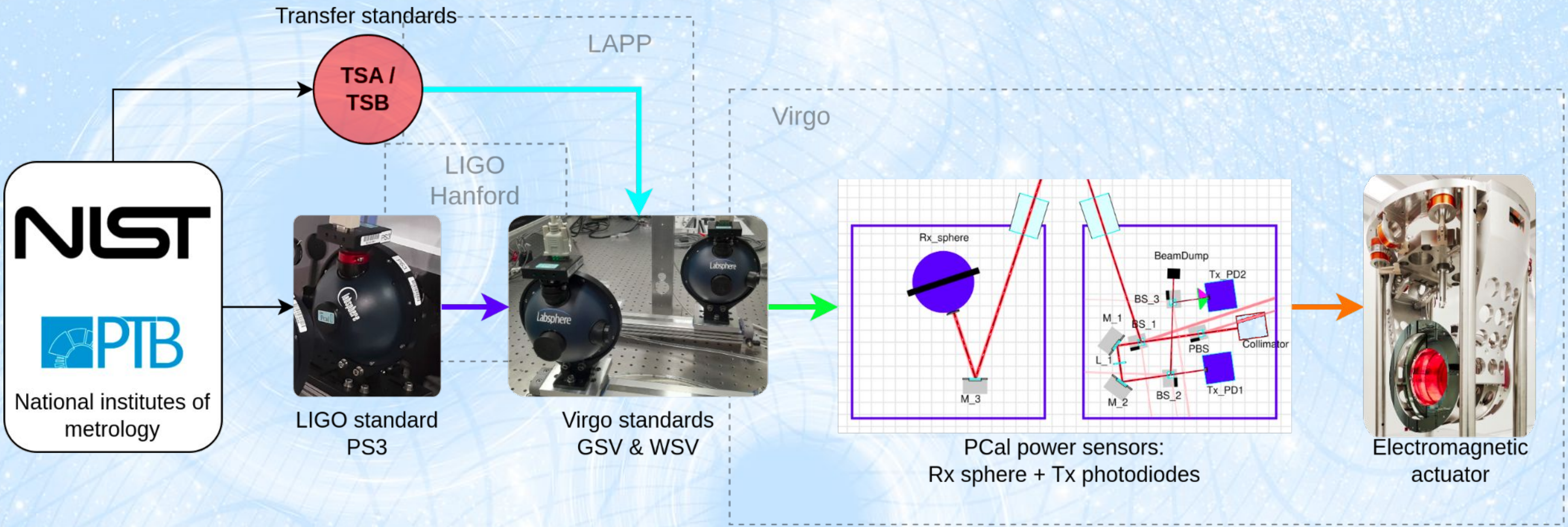
→ Residual delay between measurement and model < 1µs (5 µs during O3)
→ In the data analysis, the model is used to compensate the photodiode sensing chain response.

Calibration of the electromagnetic actuators



- Calibration of the PCal power sensor
- Reconstruction of the mirror motion signal ΔL

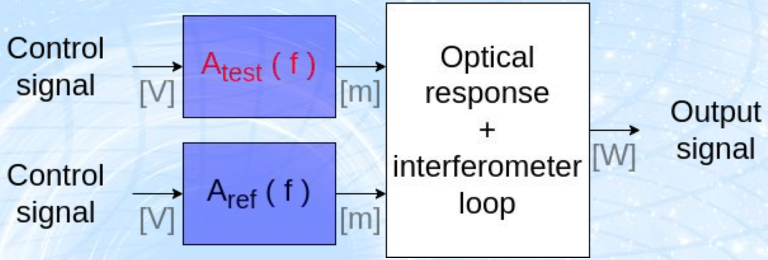
Calibration of the electromagnetic actuators

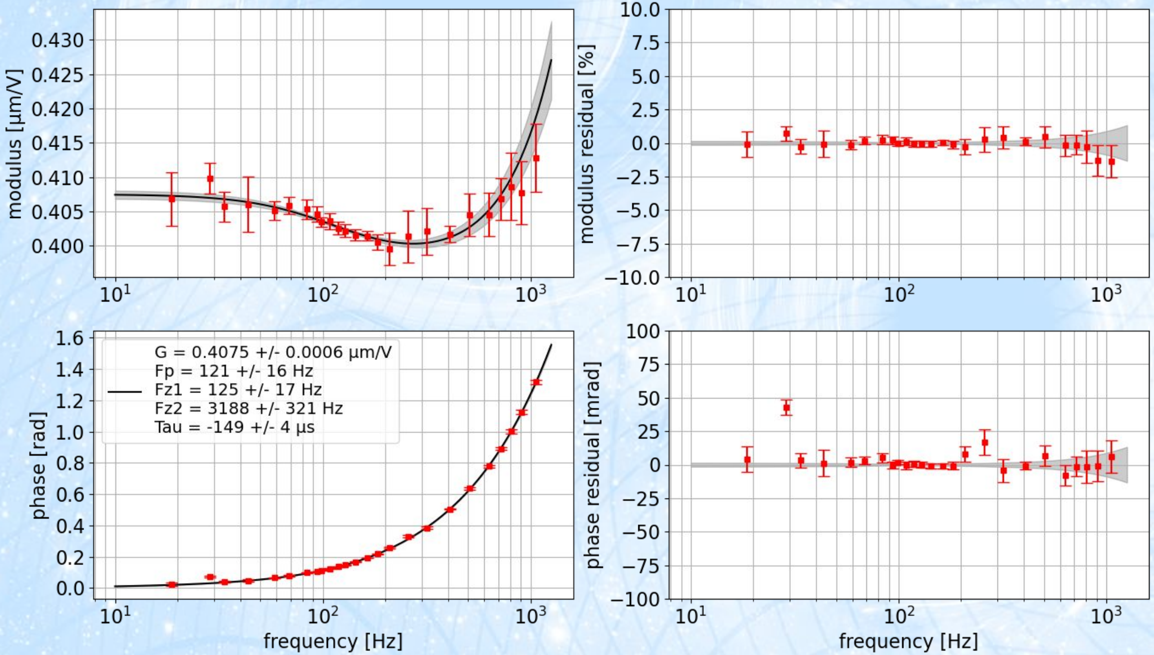


- Calibration of the EM actuator using the PCal as reference
- Measurement of the optical response

→ Reconstruct the strain signal

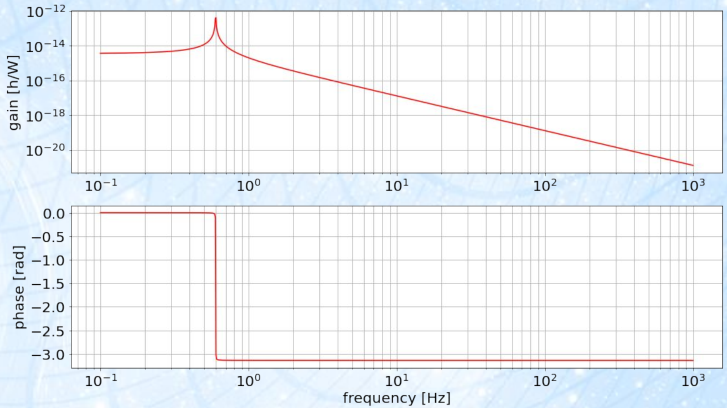
Electromagnetic actuator calibration





To be multiplied with the pendulum response:

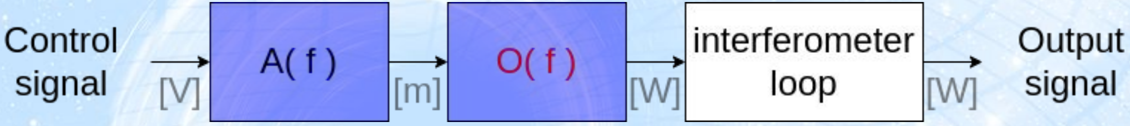
$$A_{mir}^{mech}(f) = \frac{1}{1 + \frac{i}{Q_p}\frac{f}{f_p} - \left(\frac{f}{f_p}\right)^2}$$

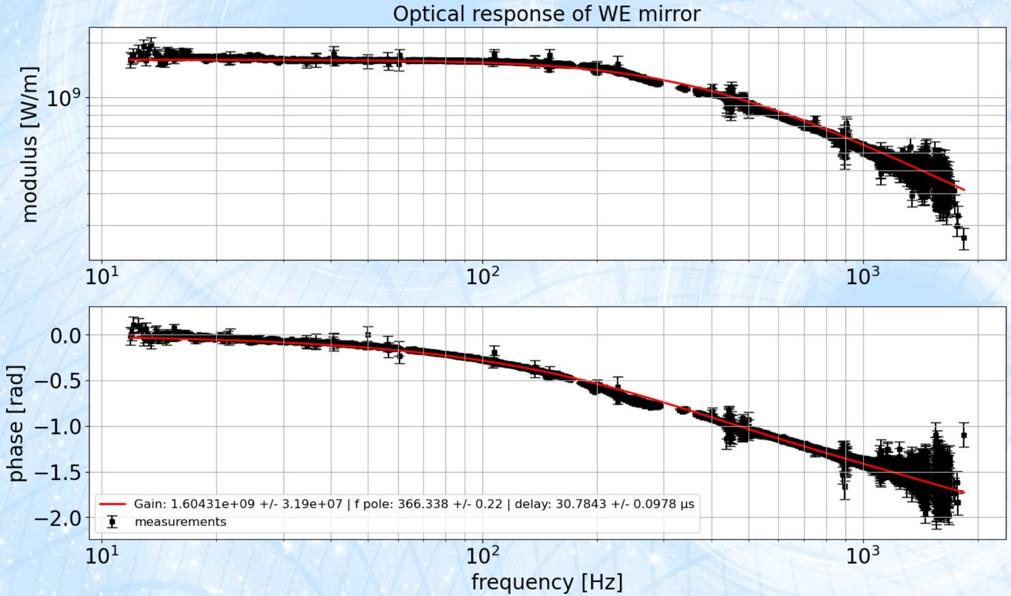


→ Model used to calibrate the **optical response** of WE, and to reconstruct the **strain signal** h(t)

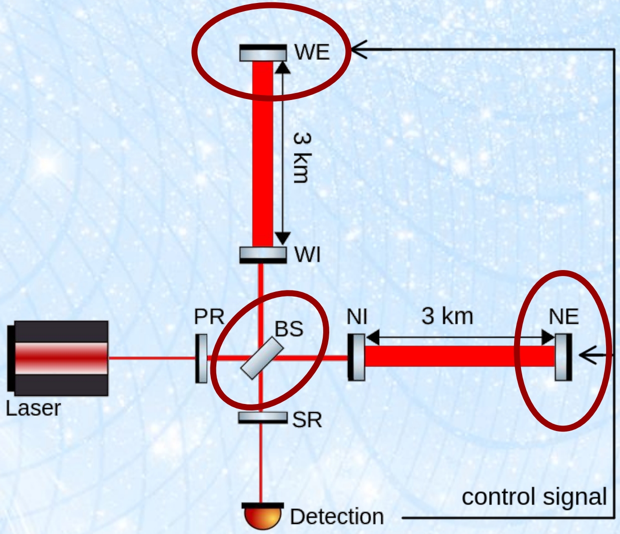
Measurement of the optical response

The optical response O(f), describes how the output power signal of the detector varies when a mirror moves.





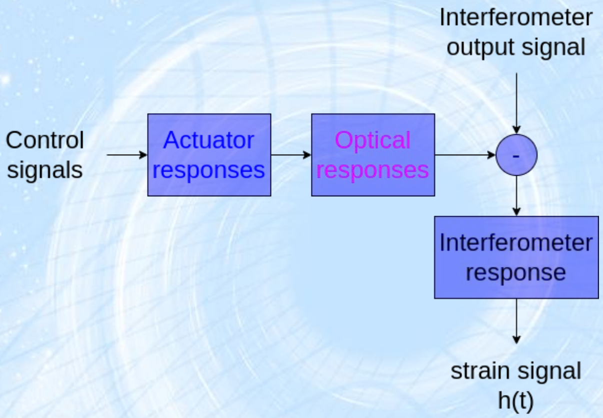
The pole frequency is ~400 Hz, it can vary with SR alignment.

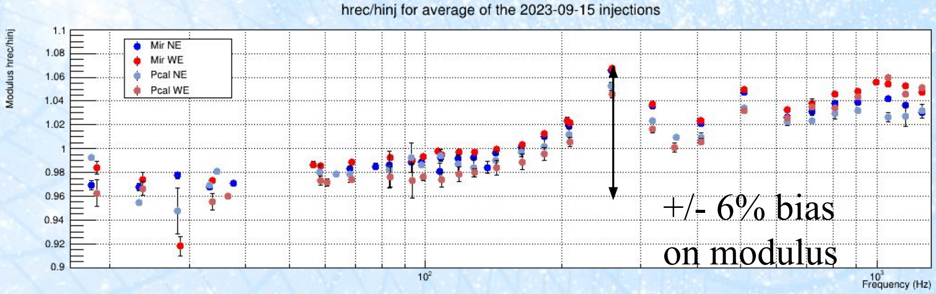


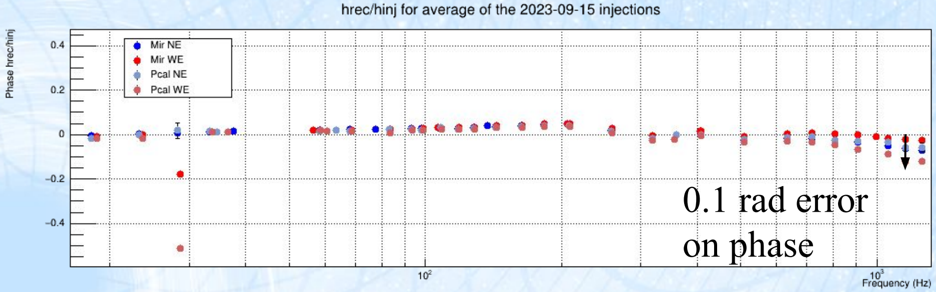
The optical responses of NE, WE and BS are measured

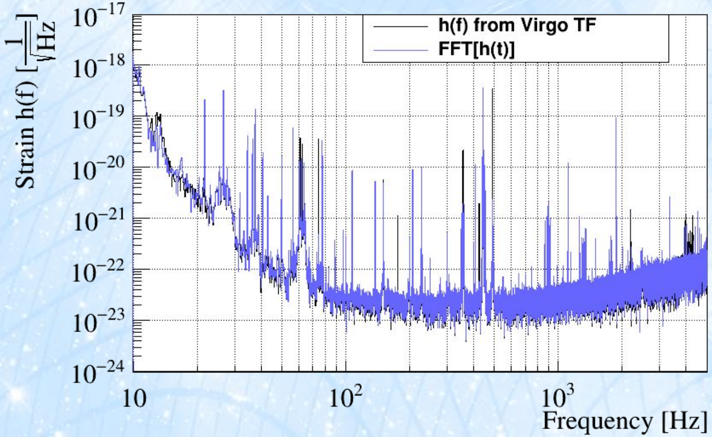
Measurement fitted with a simple pole model.
→ Model used to reconstruct the strain signal

Current state of the interferometer calibration









Current error on reconstructed h(t)

- Maximum modulus bias = 6%
- Phase bias = 0.1 rad

Virgo sensitivity → to be used by commissioning team

Current state of the interferometer calibration

- New PCal setup designed and installed on the Virgo site
- Virgo standards mounted and calibrated at LHO w.r.t. PS3
- Intercalibration procedure between LIGO-Virgo and KAGRA has started, w.s.t. TSB
- PCal power sensors installed at Virgo have been calibrated twice
- Preliminary calibration of the mirror actuators and optical response
  - Calibration procedure automatized and can be done weekly

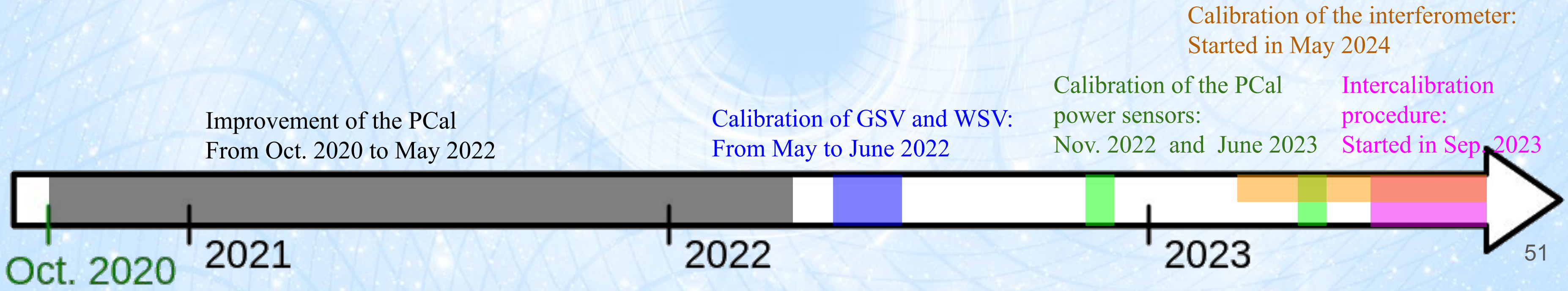


Table of contents

Prospects for O4

Uncertainty source	WSV	GSV
LIGO standard (PS3) response	0.107%	0.107%
Output voltage	0.049%	0.049%
Responsivity ratio	0.003%	0.004%
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Total	**0.369%**	**0.349%**

Variable	1σ uncertainty value [%]
WSV response	0.369
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Losses of the viewport	0.095
Losses of the M_3 mirror	0.012
Reflected power $\frac{\sigma_{P,ref}}{P_{ref}}$	0.431

Variable	1σ uncertainty value [%]
Reflected power $\frac{\sigma_{P,ref}}{P_{ref}}$	0.431
Mechanical response ($<$ 1 kHz)	0.40
Mirror displacement $\frac{\sigma_{\Delta L}}{\Delta L}$	0.59

Improve the uncertainty on the PCal calibration:

- Measure linearity w.r.t. another sensor
  - Expected uncertainty: 0.1%
- Correct the WSV responsivity variation
  - Uncertainty after correction: 0.04%
- Improve the PCal calibration procedure
  - Expected uncertainty: 0.01%

→total expected uncertainty on the reflected power:

0.187%

→total expected uncertainty on the mirror displacement:

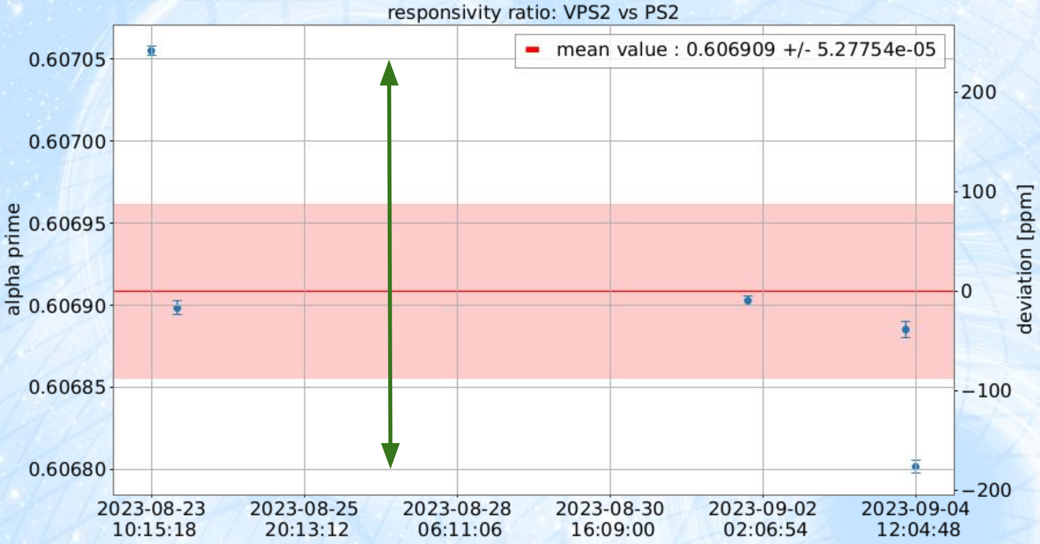
0.44%

Thank you for your attention !

Backup slides:

Prospect: integrating spheres calibration

Responsivity variation greater than statistical uncertainty



- Responsivity variation
- Statistical uncertainty

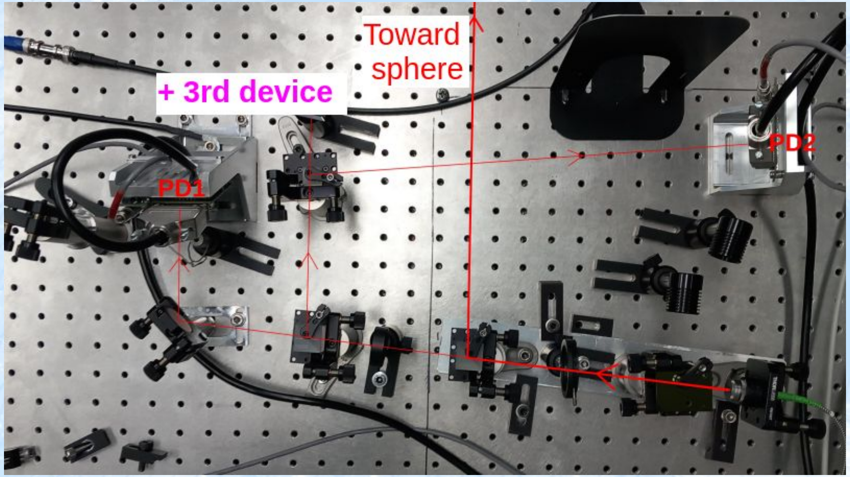
- More accurate characterization of the sphere response with respect to the angle of incidence of the beam.
- Monitoring the response with respect to the environment, (temperature, air humidity, pressure)

→ 0.05% reduction on the sphere response uncertainty

Prospect: integrating spheres linearity

0.3% uncertainty on the sphere due to the non linearity with respect to an InGaAs photodiode → main contribution

Possible solutions:
Characterize sphere linearity w.r.t. another reference device, (Si photodiode?)



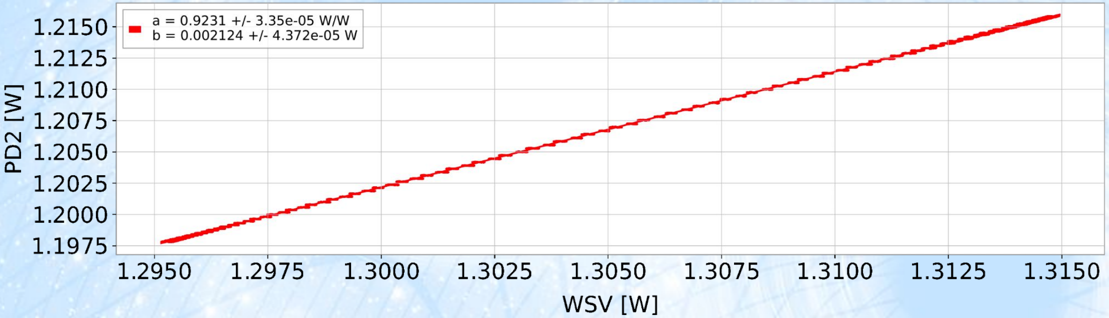
→ up to 0.3% reduction on the sphere response uncertainty

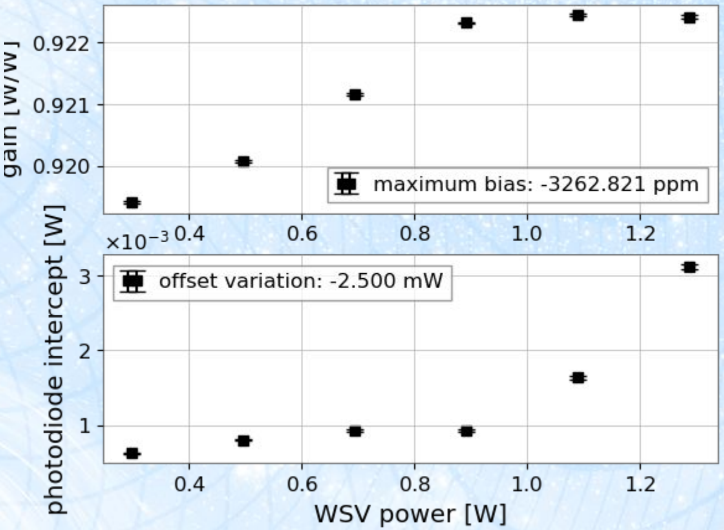
Prospect: Calibration of the PCal sensors

PCal photodiodes background voltage may vary with temperature
Possible solution: change the PCal sensors calibration method.

Laser signal: 1.3 W + permanent lines
And linear regression between WSV and photodiodes

$$P_{PD} = A \cdot P_{WSV} + B$$



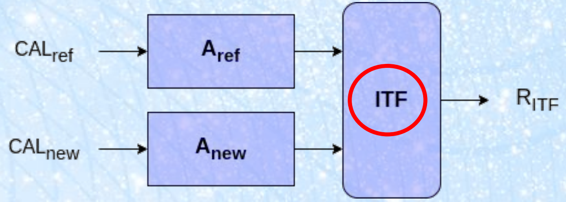


During the characterization of the sphere linearity, the photodiode background voltage varied with the input power

→ 0.2% reduction on the PCal calibration uncertainty

Prospect: calibration of the electromagnetic actuators

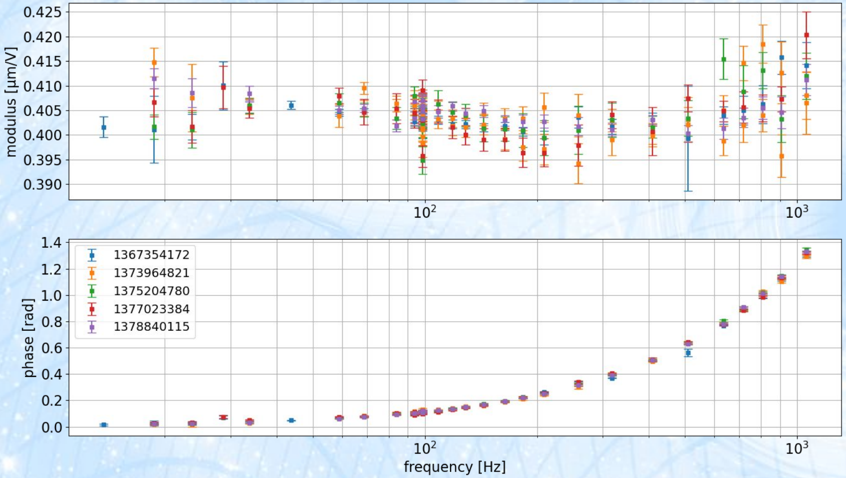
Actuator response stable with time, but measurement varies due to the optical response variation.

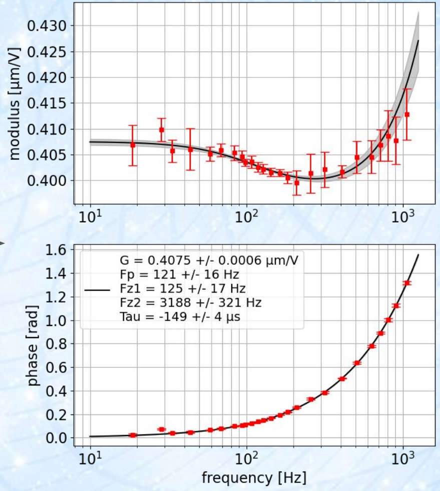


Interferometer response may be not the same between each injection.

Possible ideas:

- Monitor and correct optical response variations
- Compute the mean over many actuator response measurements
- Use machine learning model to fit the measurements

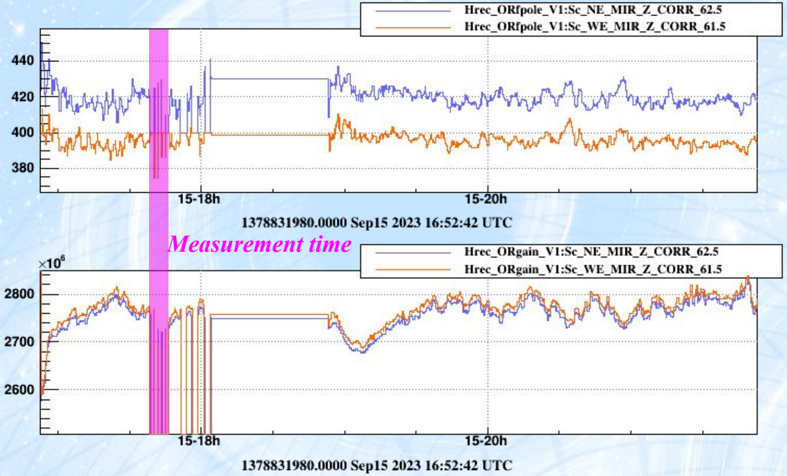


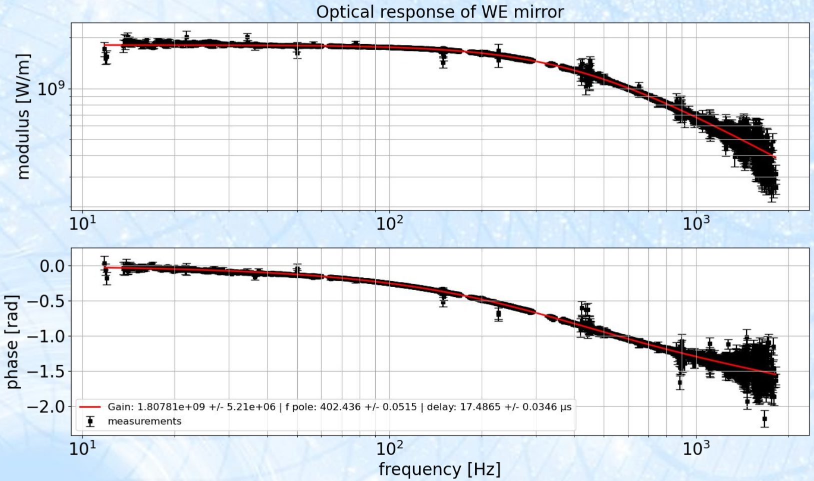


→ up to 1% reduction on the actuator response uncertainty

Prospect: optical responses

Comparison with the optical response computed to reconstruct the strain signal h(t).

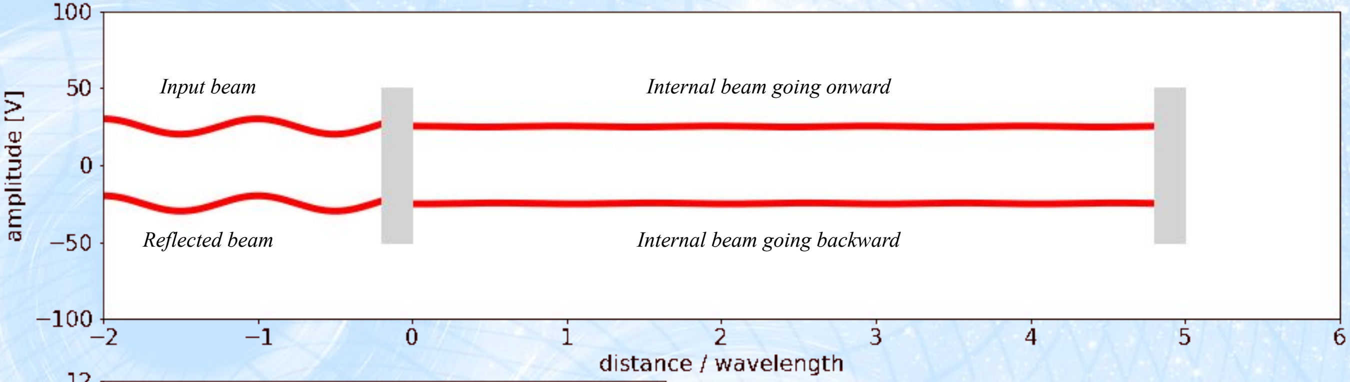


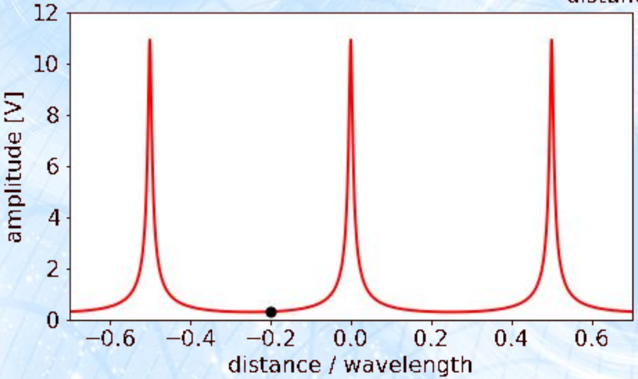


Variation of the optical response gain and pole frequency due to the SR alignment, possible correlation between SR position and optical response parameters.

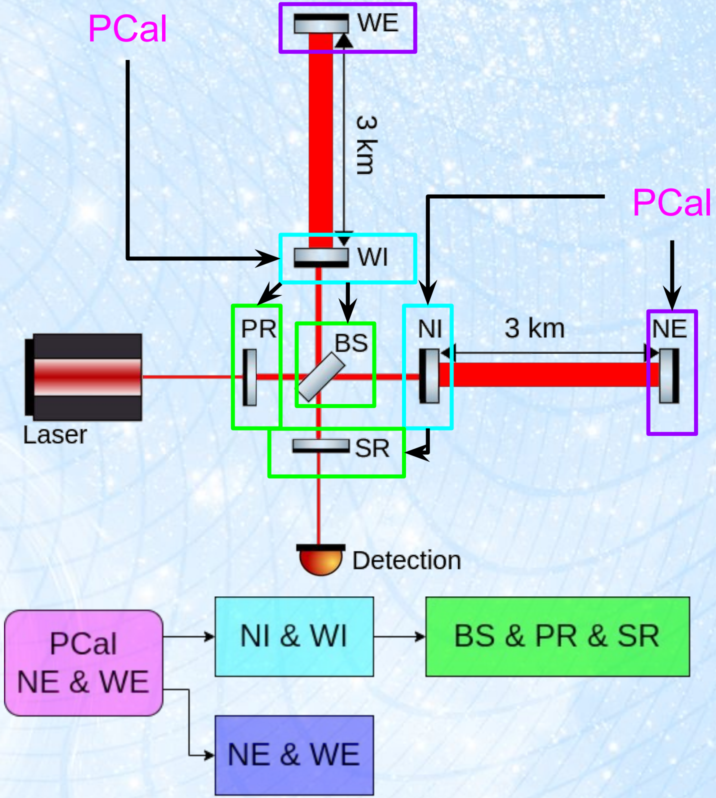
→ Better understanding of the optical response behaviour

Fabry-Perot cavities



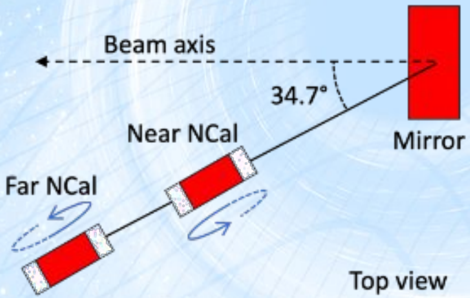


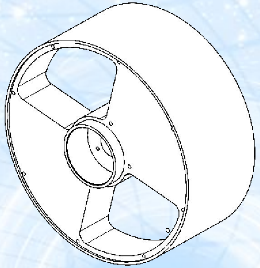
Resonant cavity: $L = n \cdot \frac{\lambda}{2}$ with $n \in \mathbb{N}$

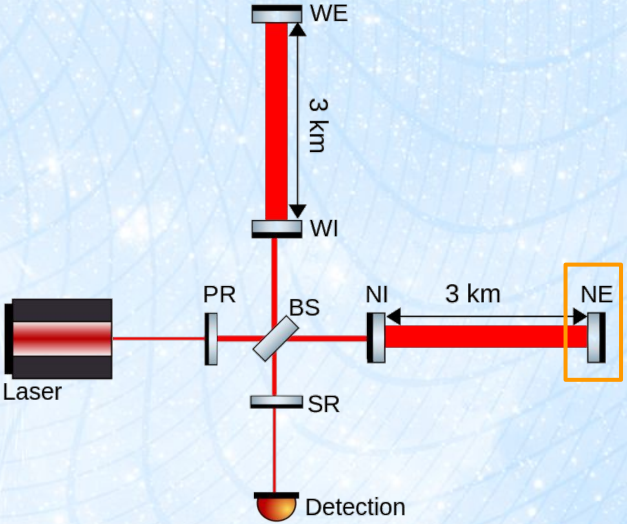

PCal
WE
3 km
PCal
WI
PR
BS
NI
3 km
NE
Laser
SR
Detection
PCal
NE & WE
NI & WI
BS & PR & SR
NE & WE

The newtonian calibrator

Consists in a rotor with two rotating masses which produce a local variations of the gravitational field around the mirror, which makes it moves.



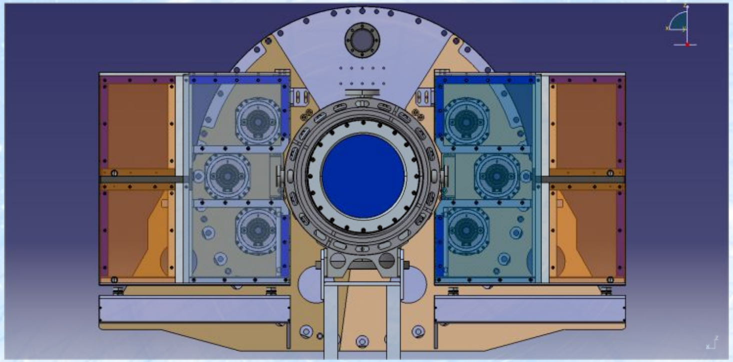
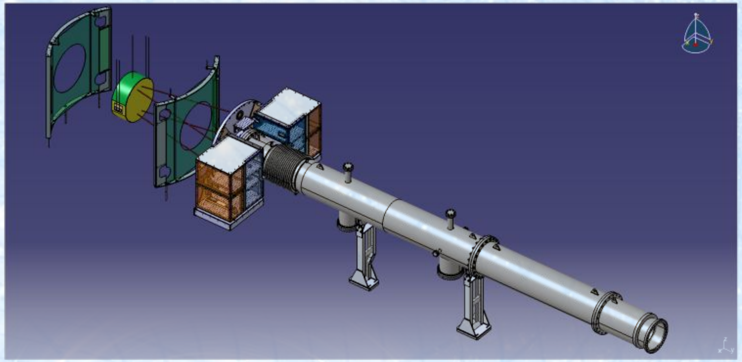




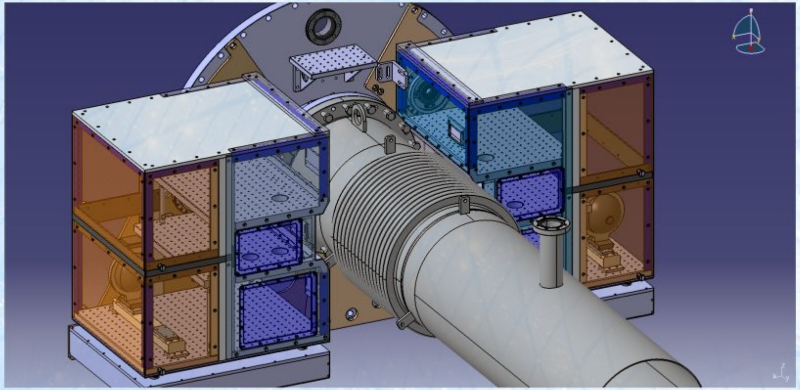
The NCal is installed around the NE mirror

→ One of the reference actuator for the actuator calibration.
→ Used to verify the strain signal h(t) reconstruction.

New constraints on the PCal

CAD design of the future PCal benches



- Beam splitted in two, in order not to excite the drum modes
- Bigger PCal benches with several levels
- PCal installed on the rear flange of the mirror due to space constraint

O5 PCal optical layout (prospect)