Improving the calibration of Advance Virgo+

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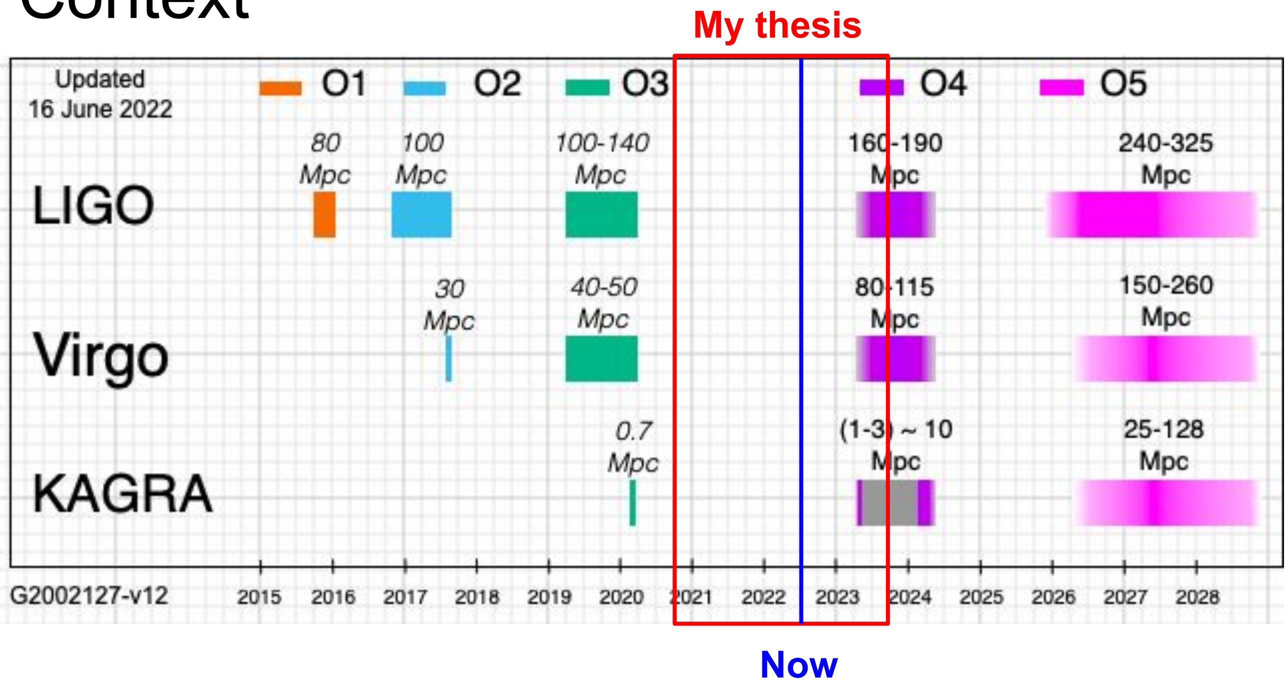
Context

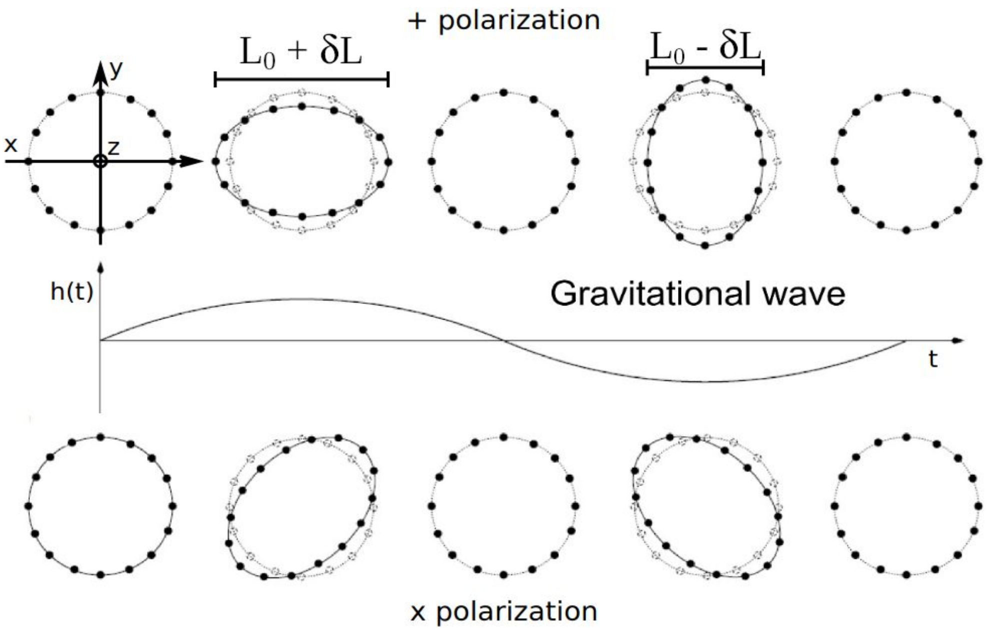


My thesis:
From the 1st of October 2020
To the 30th of September 2023

Start of the O4 run:
March 2023

Goal:
Reduce the uncertainty on Virgo interferometer strain signal h_{rec}.

Gravitational waves



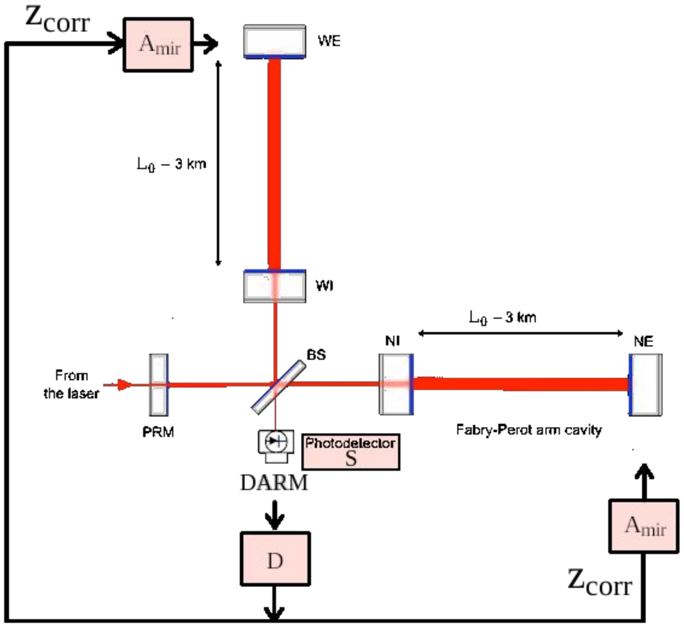
Deformation of a circle of masses due to gravitational wave propagating toward z axis

Gravitational waves (GW) are the propagation of space-time deformations predicted in 1916 by Albert Einstein.

The typical order of magnitude of gravitational waves detected on Earth is $h = 10^{-22}$

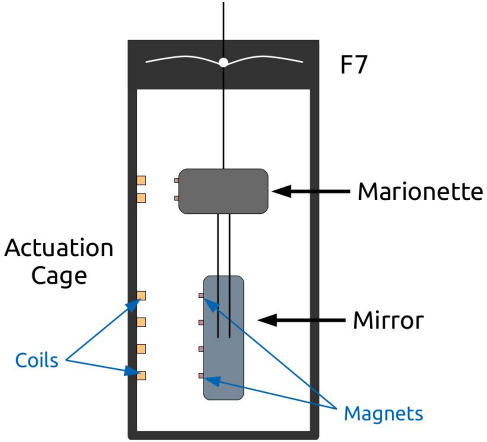
$\delta L = 1/2 \times h \times L_0$

Effect of the GW on the interferometer



Scheme of the interferometer with the control loops of the mirrors.

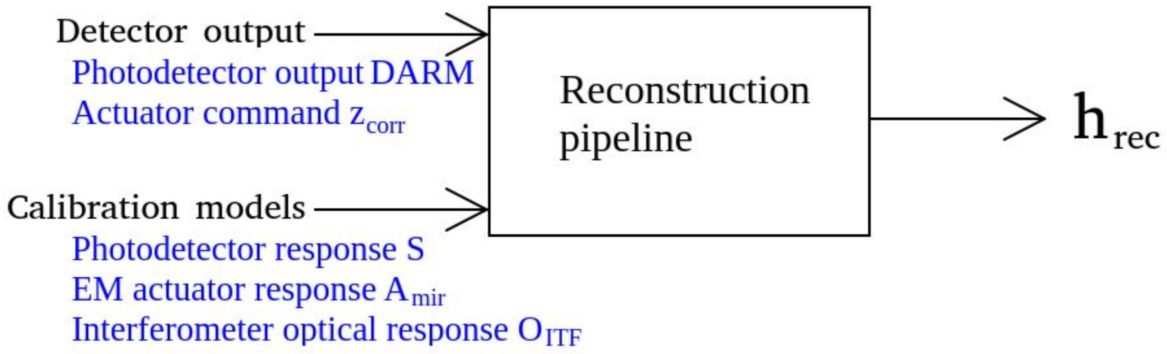
All the mirrors can be displaced by electromagnetic actuators (EM actuators).
The end mirrors (NE and WE) are in control loop with the detector signal.
The GW signal is contained in both z_{corr} and DARM signal, because of this control loop.



Scheme of the actuation cage of a mirror viewed from the side

Free length of L_0 = 3 km ⇒ Arm length variation $\delta L \sim 10^{-19}$ m

Reconstruction of the detector strain h(t)



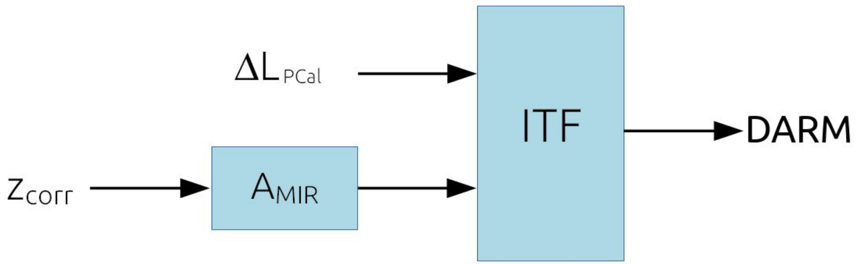
The strain signal is $h_{rec} = \frac{\Delta L}{L_0}$, where ΔL is the differential arm length.

It is reconstructed by a pipeline that uses models of:

- Photodetector response S [V/W]
- **EM actuators A_{mir} [m/V]**
- **Interferometer optical response O_{ITF} [W/m]**

Measured with the photon calibrator

Electromagnetic actuators response measurement



Method:

1. Make the mirror move by a known motion ΔL_{PCal} in [m] with the photon calibrator (PCal), and observe the output of the interferometer DARM(PCal) in [W].
2. Then, make the mirror move with the electromagnetic actuators, and observe the output of the interferometer DARM(mir).
3. And compute AMIR with the formula below, comparing the effects of the known and unknown motion in [m/V]

$$A_{mir} = \frac{DARM(mir)}{z_{corr}} \frac{\Delta L_{PCal}}{DARM(PCal)}$$

- This measurement will be done once the PCal is calibrated, and when the interferometer is stable

Interferometer optical response measurement

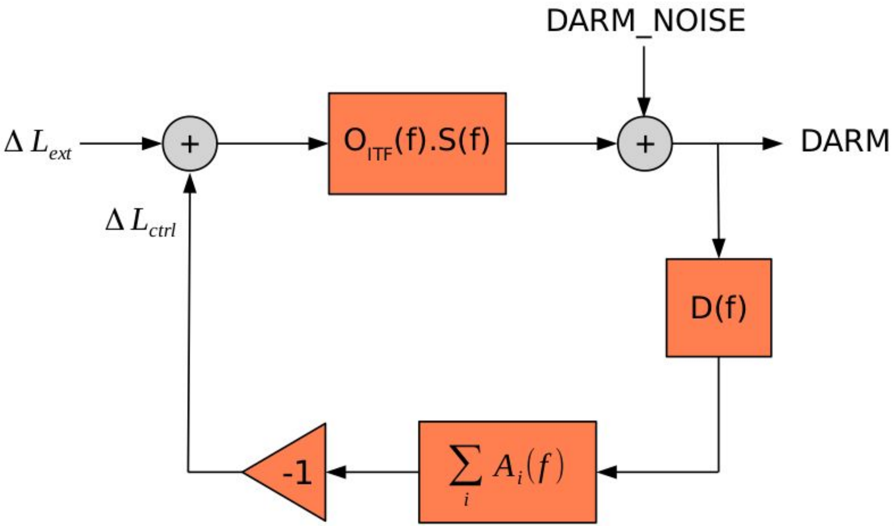


Diagram of the DARM control loop

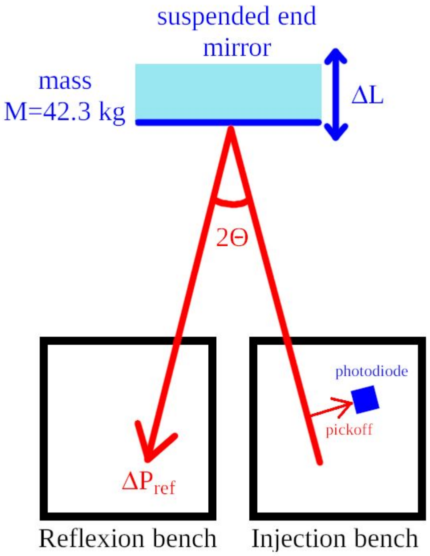
Method:
With the DARM loop closed,

1. Make the mirror move by a known motion ΔL_{ext} in [m] with the photon calibrator (PCal), and observe the output of the interferometer DARM(PCal) in [W].
2. Add a digital signal DARM_NOISE to the loop and observe the output of the interferometer DARM(noise) in [W].
3. Compute O_{ITF} with the formula below.

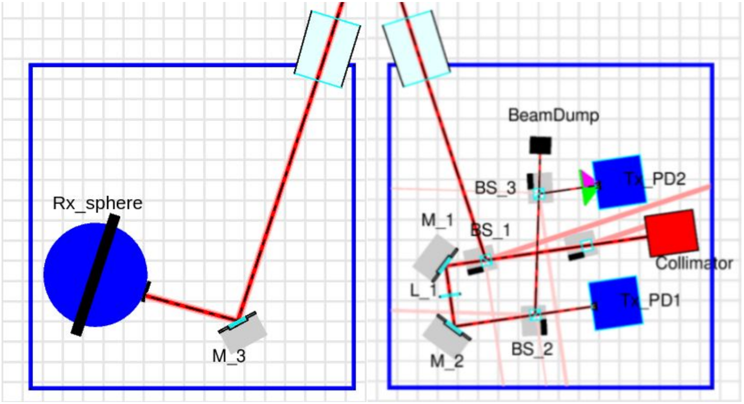
$$O_{ITF} = S^{-1} \frac{DARM(PCal)}{\Delta L_{PCal}} \frac{DARM\_NOISE}{DARM(noise)}$$

▸ This measurement will be done once the PCal is calibrated, and when the interferometer is stable

Photon calibrator



$$\Delta L(f) = \frac{-2cos(\theta)}{cM(2\pi f)^2} \Delta P_{ref}(f)$$



PCal optical layout:
Reflection bench *Injection bench*

Orders of magnitude:

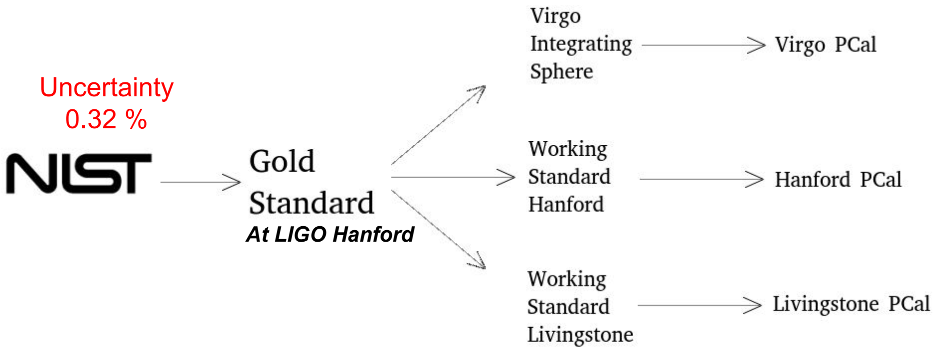
$<P_{ref}>$ = 1.3 W

ΔP_{ref} = 0.1 W

$\Delta L = 10^{-16}$ m

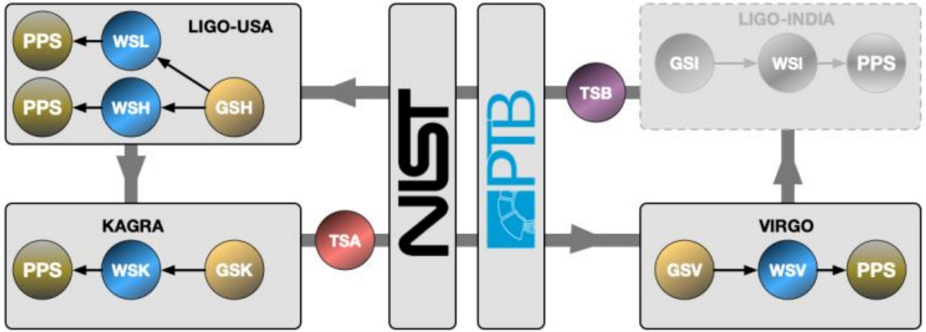
O3 uncertainty on ΔL: 1.34 % ⇒ Uncertainty goal for O4: 0.26 %

PCal calibration procedure



Scheme of the O3 intercalibration procedure

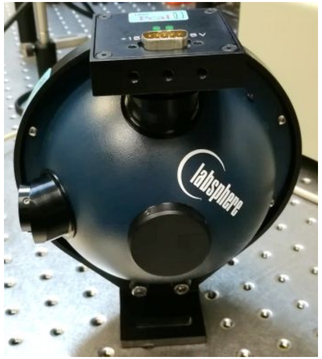
Uncertainty
0.1 %



Scheme of the O4 intercalibration procedure

Integrating spheres names:

- GS: Gold Standard
- VIS: Virgo Integrating Sphere
- (O3) WSV: Working Standard Virgo



Picture of an integrating sphere

Integrating spheres names:

- TSA/B: Transfers Standard
- GSV: Gold Standard Virgo
- WSV: Working Standard Virgo

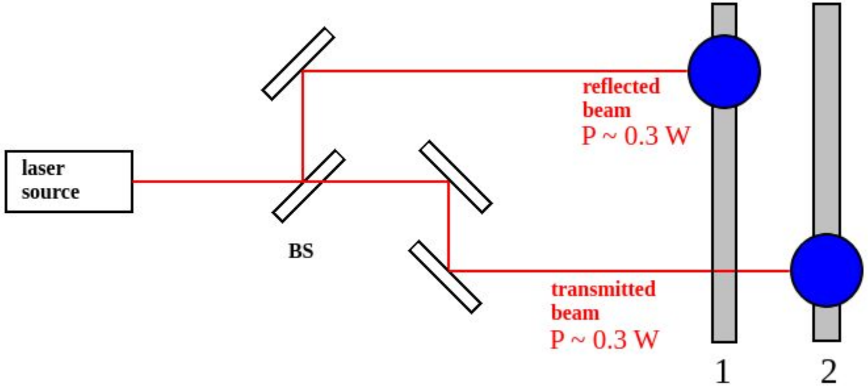
O3 uncertainty budget and O4 uncertainty estimation

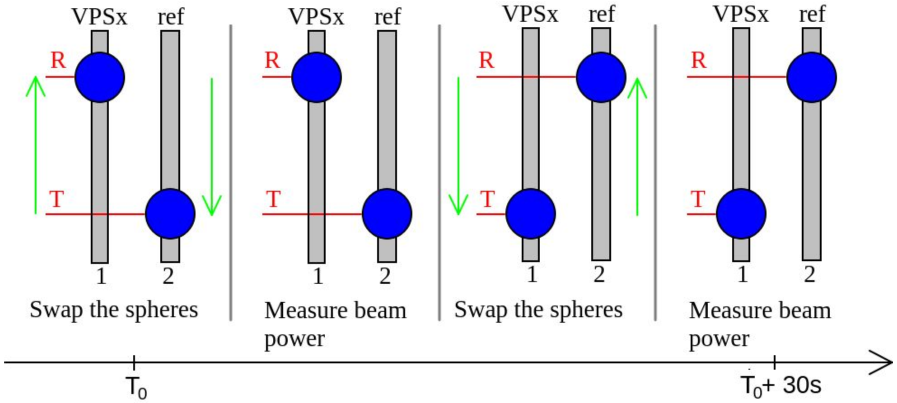
Variable	1σ Uncertainty
GS responsivity (2018)	0.32%
VIS linearity	0.4%
VIS/GS responsivity ratio	0.1%
VIS/WSV responsivity ratio	0.5%
Voltage calibrator	0.007%
Conversion factor [V/W]	1%
Angle cosine	0.12%
Rotation of ETM	0.001%
Mass of ETM	0.05%
PD stability w.r.t temperature (O3a)	0.1%
PD stability in time (O3a)	0.5%
Total	1.34%

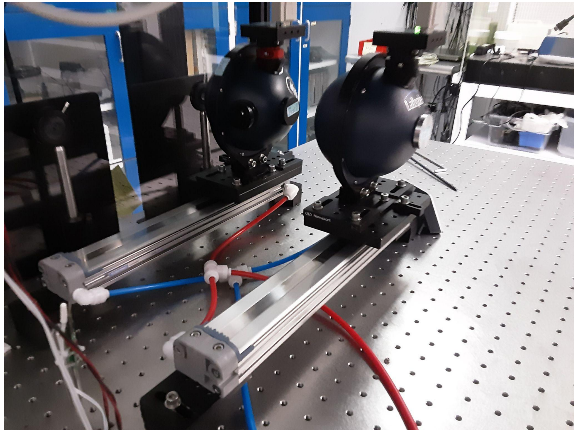
Variable	1σ Uncertainty
TSA, TSB responsivity	0.1%
WSV/TSA, WSV/TSB responsivity ratio	0.02%
Tx_PDx/WSV responsivity ratio	0.1%
Rx_sphere/Tx_PDx responsivity ratio	0.1%
Voltage calibrator	0.007%
Angle cosinus	0.12%
Rotation of EMT	0.001%
Mass of EMT	0.05%
PCal power sensors stability w.r.t. temperature	0.02%
PCal power sensors stability in time	0.1%
Total	0.26%

Uncertainty due to the integrating spheres intercalibration

Integrating spheres intercalibration (at LIGO Hanford)



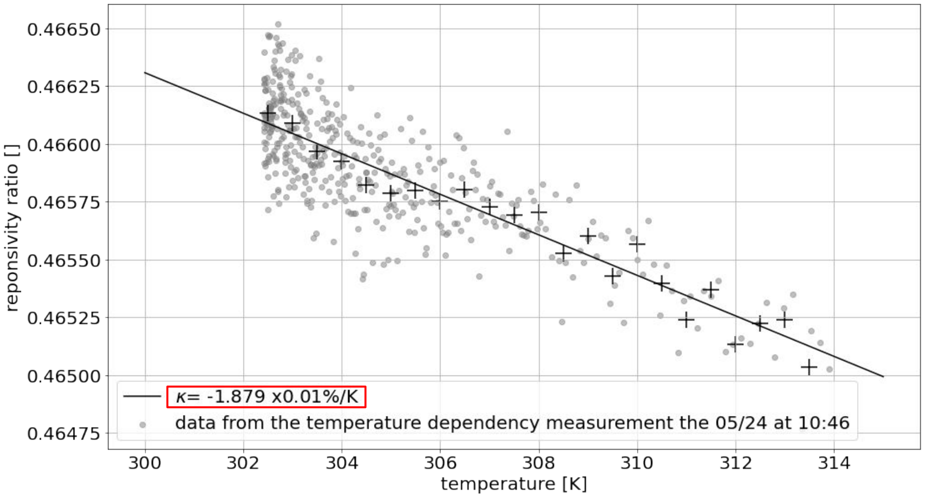


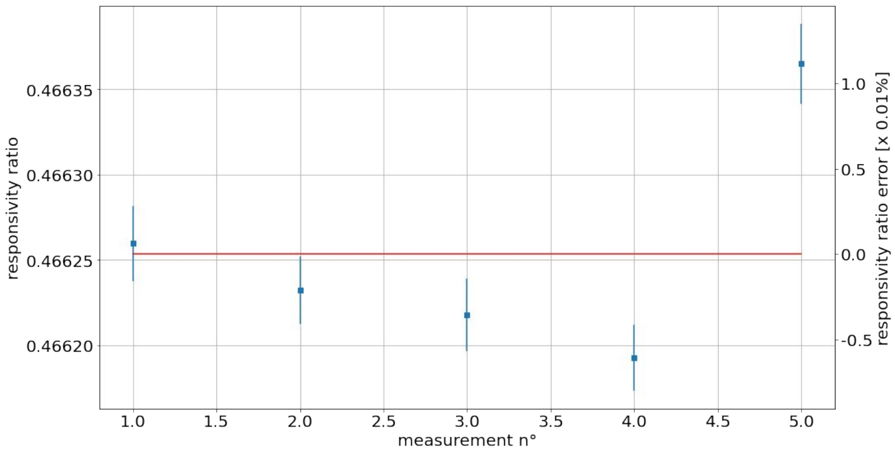


- The spheres are mounted on pneumatic rails, and can be swapped automatically.
- Four values of output voltage are recorded, one for each beam seen by each spheres
- The responsivity ratio between the two spheres is computed.

$$\frac{\rho_1}{\rho_2} = \sqrt{\frac{V_{1,T}}{V_{2,R}} \frac{V_{1,R}}{V_{2,T}}}$$

Integrating spheres intercalibration: results





- The Virgo sphere has been heated at 35°C.
- 400 measurement of the responsivity ratio has been done while it is cooling down.
- The temperature dependency of the responsivity is characterized.
- **The uncertainty due to the temperature dependency is 0.02%**

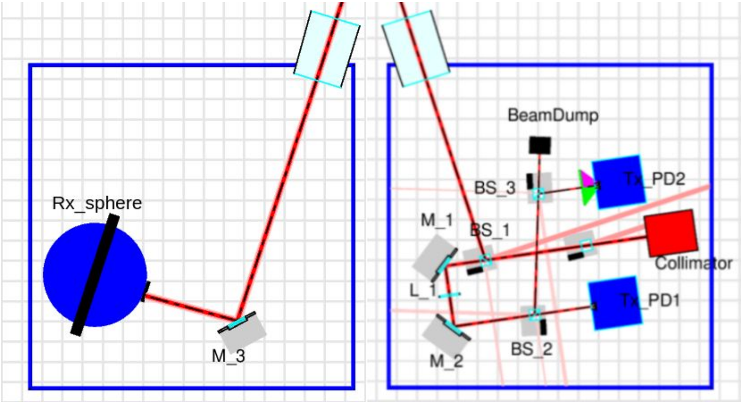
- The Virgo sphere is at ambient temperature.
- The temperature dependency is corrected
- **The value of the responsivity ratio is known with an uncertainty of 0.02%**

Upgrades on PCal

- O4 optical setups of the injection bench have been installed in front of both NE and WE mirrors
- New photodiodes (laser-component IG17x3000i) are used
- New photodiode preamplifier designed at LAPP, with a flat frequency response by design
- PCal sensor calibrated with respect to O3-WSV

Next tasks:

- Install Rx integrating spheres on reflection benches
- Calibrate power sensor with respect to O4-WSV
- Monitor the stability of the calibration

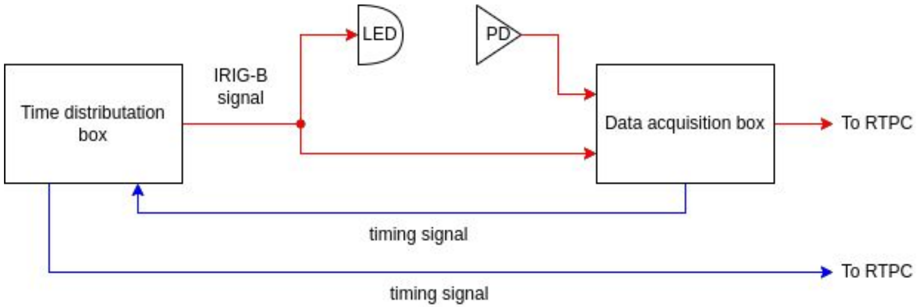


PCal optical layout:
Reflection bench (not installed yet) *Injection bench (installed)*

Photodiode timing measurement

The photodiode preamplifier and the data acquisition box have filters that induce the delay of the measurement readout.

The timing of the data acquisition box and the timing of the photodiode are measured.

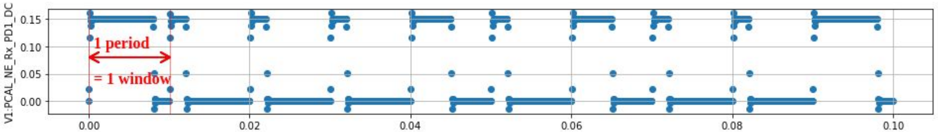


Scheme of the measurement setup

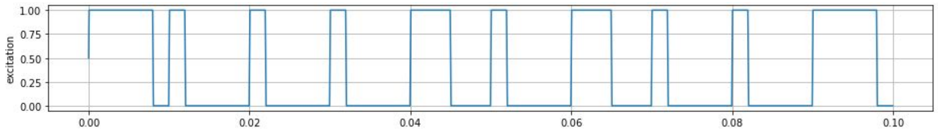
Experiment setup:

- A LED is placed in front of the photodiode.
- This LED is supplied with a signal that is synchronized with the clock of the Data Acquisition Box.
- The input of the LED and the output of the photodiode are measured by a data acquisition box

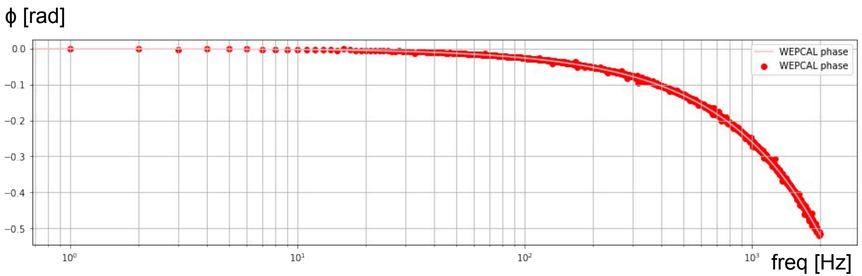
Photodiode timing: data analysis



Measured signal



“Perfect” signal



Data Analysis:

- A “perfect” signal is generated numerically to modelize what would be seen if the sensor readout had no delay.
- The transfers function from the perfect signal to the measured signal is computed.
- A linear regression is computed between the frequency and the phase of the transfer function.

$$\phi(f) = (-2\pi\tau)f$$

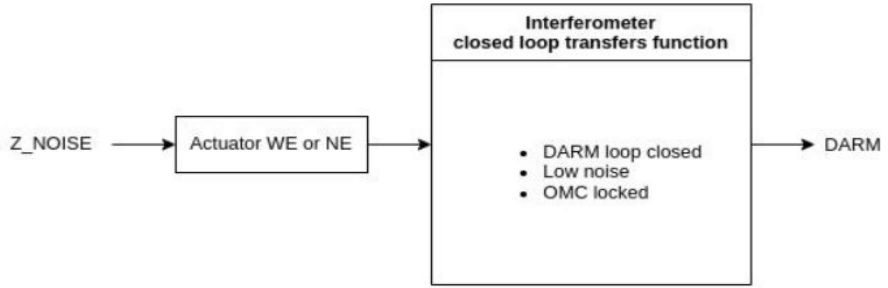
- Measurement made at LAPP. It is still to be done on the PCal at Virgo.
- A LED has been installed in front of one of the photodiode of each PCal.
- The timing of the PCal will be measured weekly

Sensitivity curve measurement

Noise level of the strain signal of the interferometer.

Requirements:

- A calibrated actuator, (PCal or EM actuator), its response has to be modelized.
- The interferometer has to be “locked”: DARM loop closed, at its stable working point



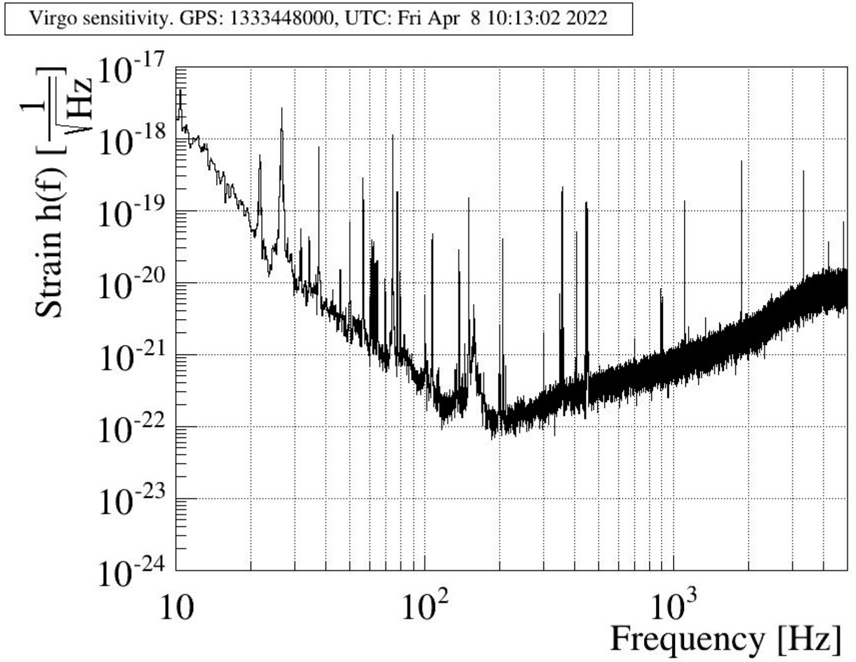
Method:

- Give a noise signal in an actuator of an end mirror “Z_NOISE”
- Compute the transfer function from the “Z_NOISE” to “DARM”
- Divide this transfer function by the model of the response of the interferometer.
- Stop generating noise, and compute the amplitude spectral density of DARM
- Divide this ASD by the transfer function, and by L_0 = 3 km

Sensitivity curve of Virgo, in April 2022

The associated detection range of Binary Neutron Stars can be computed: ~2 Mpc (O4 goal 80 Mpc)

The sensitivity curve can be computed with the ASD of the reconstructed strain h_{rec}



Limitations:

- The interferometer wasn't "complete", some systems were missing.
- The models of the actuator weren't updated and doesn't really match with reality (~20% difference at 60 Hz)
- This method provide "snapshots" of the sensitivity curve,
- We can't observe GW while using the method

Next tasks

- Build calibration setup at LAPP, similar to LIGO Hanford setup.
- Cross check the sphere calibration.
- Start inter-calibration procedure.
- Calibrate PCal sensor with respect to the new standards.
- Measure the timing of the PCal.
- Model the full PCal response.
- Start calibration of the electromagnetic actuators and the optical response of the interferometer.
- Characterize integrating spheres uncertainty on its responsivity
- Compute a more accurate sensitivity curve of the interferometer in science mode.