Calibration of Advanced Virgo+ and verification of the reconstructed gravitational wave signal with a photon calibrator

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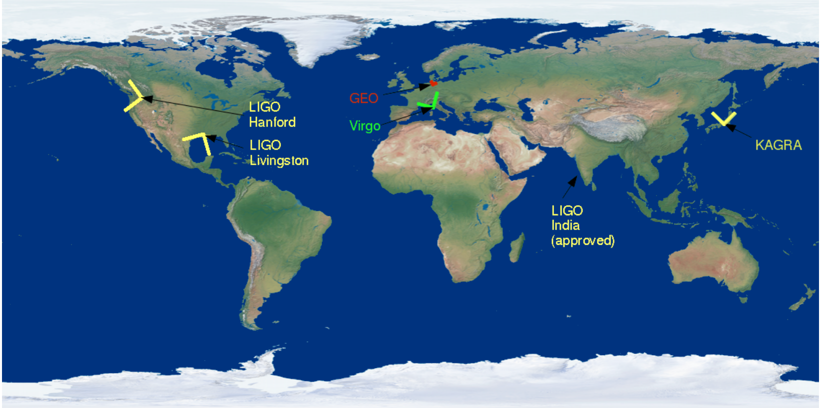
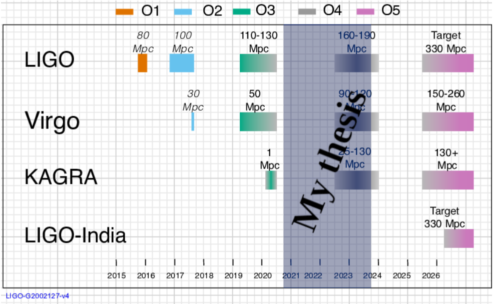
Gravitational waves detector network



My PhD within the evolution of the detector network



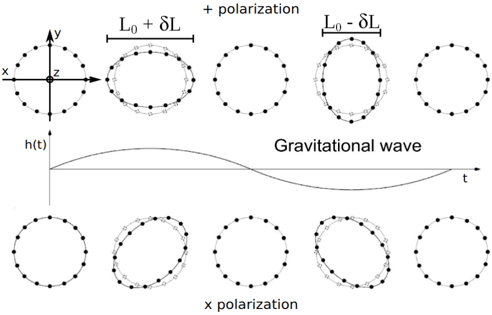
- O1: 3 detections,
  first gravitational waves detection,
- O2: 8 detections,
  first binary neutron stars merger detection + electromagnetic counterpart,
- O3a: 39 detections, and 56 alerts during full O3
  first neutron star black hole merger detection,
- O4 objective: 1 detection per day

Contents

- Gravitational waves
- Interferometer operation
- Strain signal reconstruction
- Photon calibrator (my thesis subject)

Gravitational waves and effect on matter

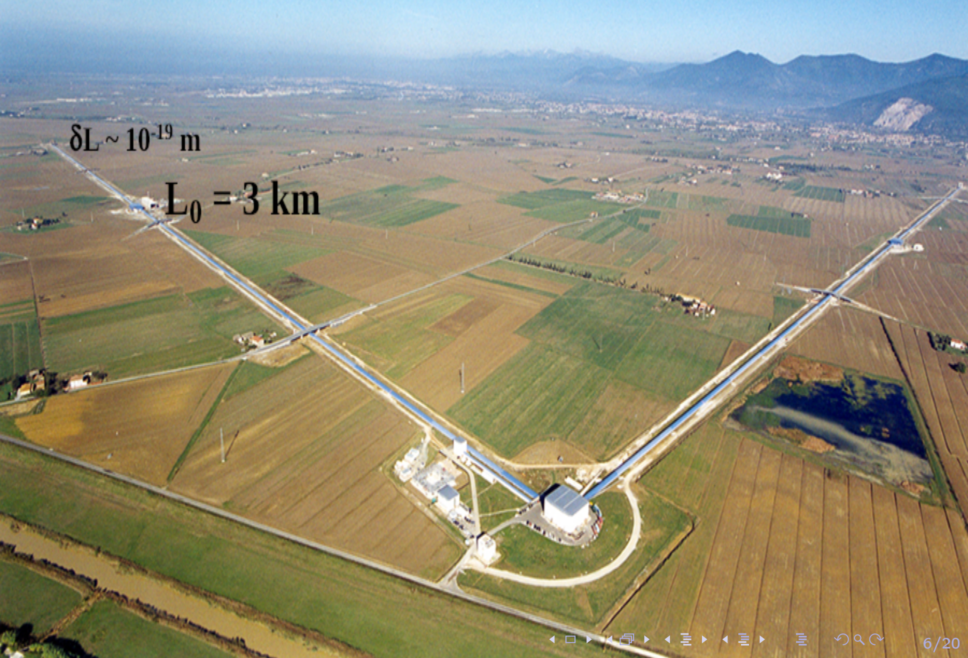
Propagation of space time deformations,
Predicted by Einstein in 1916,



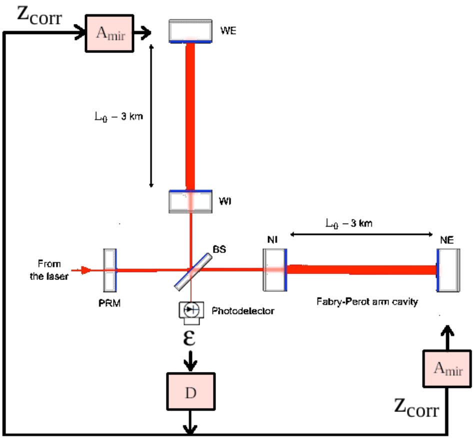
Effect of a gravitational wave propagating perpendicularly to a circle of free masses, for + and x polarizations.

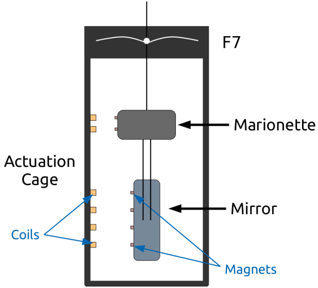
Order of magnitude of a gravitational wave produced the merger of two neutron stars at 10 Mpc
$h \approx 10^{-22}$
$\delta L = 1/2 \times h \times L_0$

Aerial view of Virgo interferometer



Scheme of the interferometer and main control loop





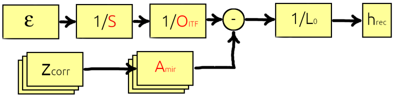
Electromagnetic actuators

Control loops reduce signals mainly at the frequency bandwidth $10Hz - 100Hz$.

Below 100 Hz, the gravitational waves signal is mainly contained in z_{corr}, and in ϵ above 100 Hz.

Reconstruction of detector strain and calibration

Reconstruction of the interferometer strain signal $h_{rec}(t) = \frac{\Delta L}{L_0}$, ΔL is the differential arm length.



We need to calibrate:

- Electromagnetic actuators response A_{MIR}, in $[m/V]$
- Optical response of the interferometer O_{ITF}, in $[W/m]$
- The response of the photodetector S, in $[V/W]$

$h_{rec}(t)$ uncertainty during O3 in the bandwidth 20 Hz - 20 kHz

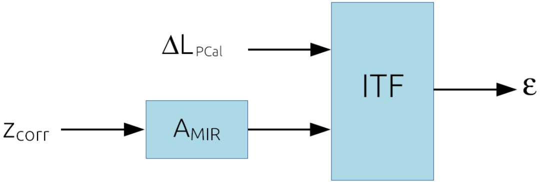
- 5% amplitude,
- 35 mrad phase,
- 10 μs timing,

$\Longrightarrow$

$h_{rec}(t)$ uncertainty objective for O4:

reduce uncertainties,
frequency dependent uncertainty

Calibration of the electromagnetic actuators



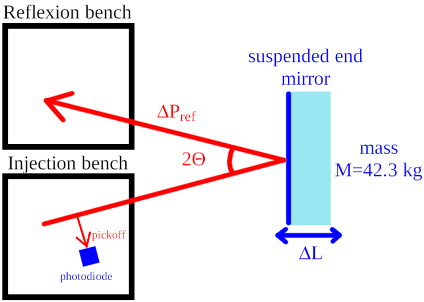
Method

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 $\epsilon(PCal)$ in $[W]$.
2. Then, make the mirror move with the electromagnetic actuators, and observe the output of the interferometer $\epsilon(MIR)$.
3. And compute A_{MIR} with the formula below, comparing the effects of the known and unknown motion in $[m/V]$.

$$A_{MIR} = \frac{\epsilon(MIR)}{z_{corr}} \times \frac{\Delta L_{PCal}}{\epsilon(PCal)}$$

Working principle of the photon calibrator

Mirror pushed by the radiation pressure of a laser.



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

Typical values at $60Hz$:

$$< P_{ref} >= 2W$$

$$\Delta P_{ref} = 0.1W$$

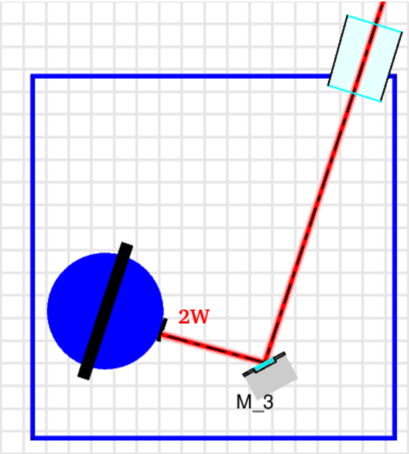
$$\Delta L \approx 10^{-16}m$$

Photodiode $\rightarrow$ ΔP_{ref} $\rightarrow$ ΔL
Photodiodes need to be absolutely calibrated.

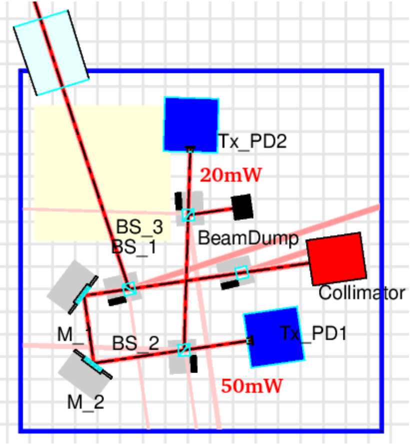
O3: Uncertainty on ΔL: 1.5% $\implies$ O4: Objective $\approx$ 1%

New optical setup

reflexion bench



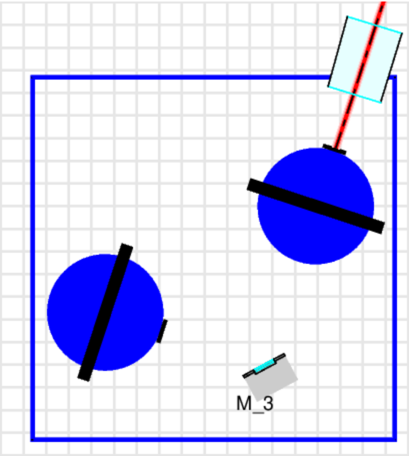
injection bench



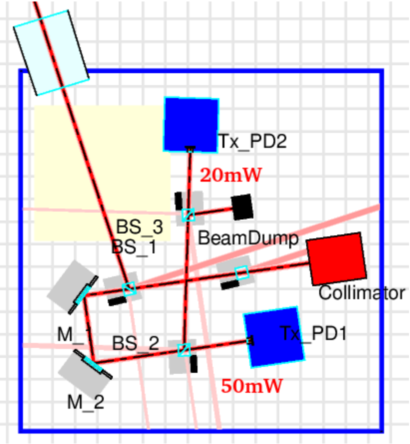
bench design drawn with Optocad

Calibration of photodiodes

reflexion bench

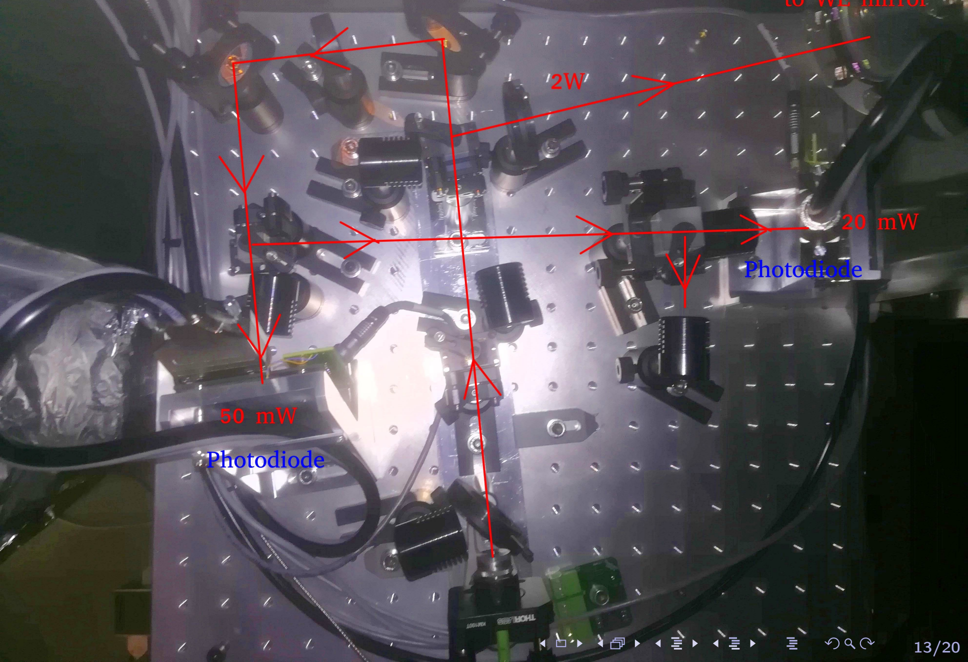


injection bench



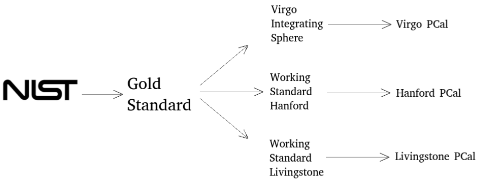
bench design drawn with Optocad

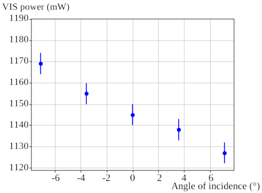
Photon calibrator installed in April



Intercalibration with LIGO and KAGRA

Scheme of the intercalibration process during O3 run

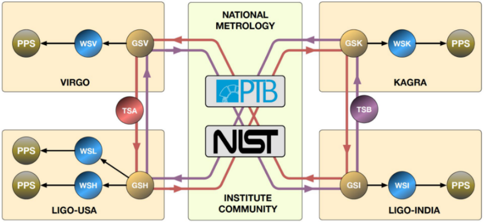




>1% uncertainty due to VIS

We stop using it

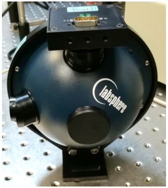
Future intercalibration process



TSx: Transfer Standard GSx: Gold Standard WSx: Working Standard PPS: Pcal Power Sensor

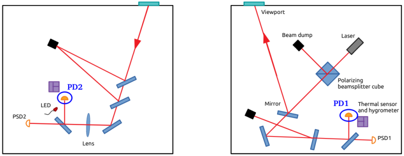
LIGO-G2100941-v3

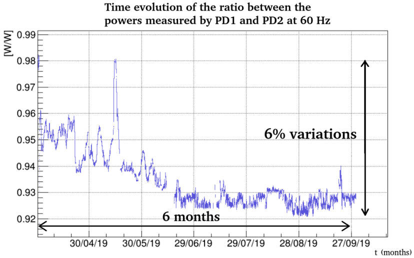
Virgo, LIGO and KAGRA will use the same model of integrating sphere



Calibration stability issue during O3

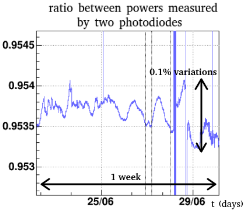
Scheme of the PCal during O3



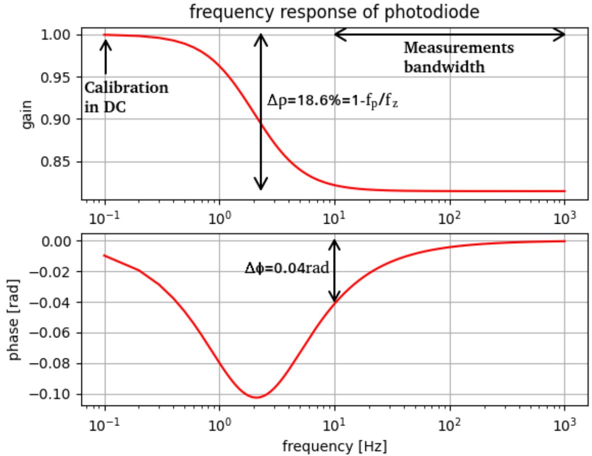


Improvements on the PCal for O4

- Use non polarizing cubes for splitting the beam,
- Put an integrating sphere on the reflexion bench,
- Si photodiodes → InGaAs photodiodes,



New issue: Response of photodiodes



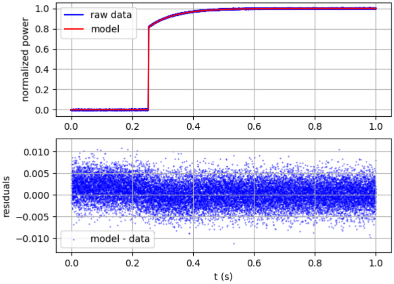
$f_p = 1.9\ Hz$ and $f_z = 2.3\ Hz$

We need to measure the ratio between the frequencies of the pole and the zero f_p/f_z

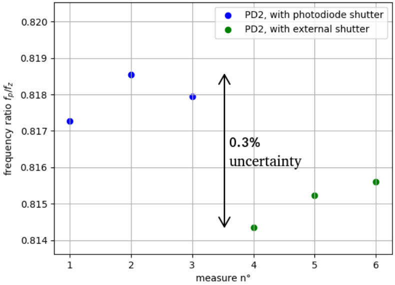
Measure of the frequency response of photodiodes

1. Close and open a shutter in front of the photodiode.
2. Measure of the time response of the photodiodes.
3. Fitting with the step response of a pole/zero filter.
4. Compute the ratio between the frequencies of the pole and zero.

Time response of the photodiode and model and residual.



Ratio between pole frequency and zero frequency, measured with different shutters



- method tested and already usable for interferometer photodiode (sensing S)
- need to sellect/install shutters to calibrate the PCal photodiodes

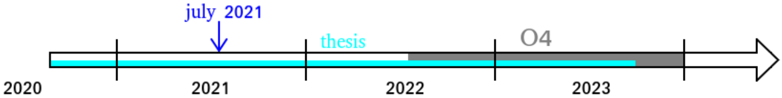
Continuing the preparation and calibration of O4 run

Future improvements on the PCal:

- Check if the PCal stable for a long time (months),
- Install a second PCal on an other mirror,
- Build and install the sphere on reflexion bench,
- Improve control loop of the laser to reduce power noise,
- Start intercalibration,
- Measure absolute timing of the photodiodes

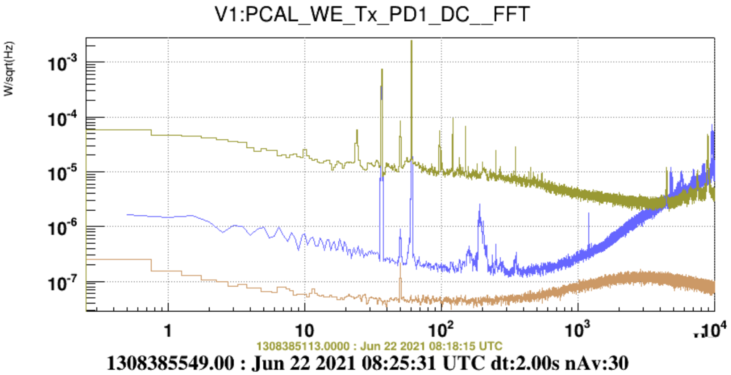
Future tasks using the photon calibrator:

- Calibrate actuators,
- Measure the optical response of the optical response of the interferometer,
- Verify h_{rec},



Thanks for your attention

Results : Laser noise



Sensing noise

laser noise, control loop open

laser noise, control loop on Tx_PD2