Preparation of the AdvanceVirgo+ calibration for the run O4

Improvement of the photon calibrators

Laboratoire d'Annecy de physique des particules (LAPP)
Paul Lagabbe

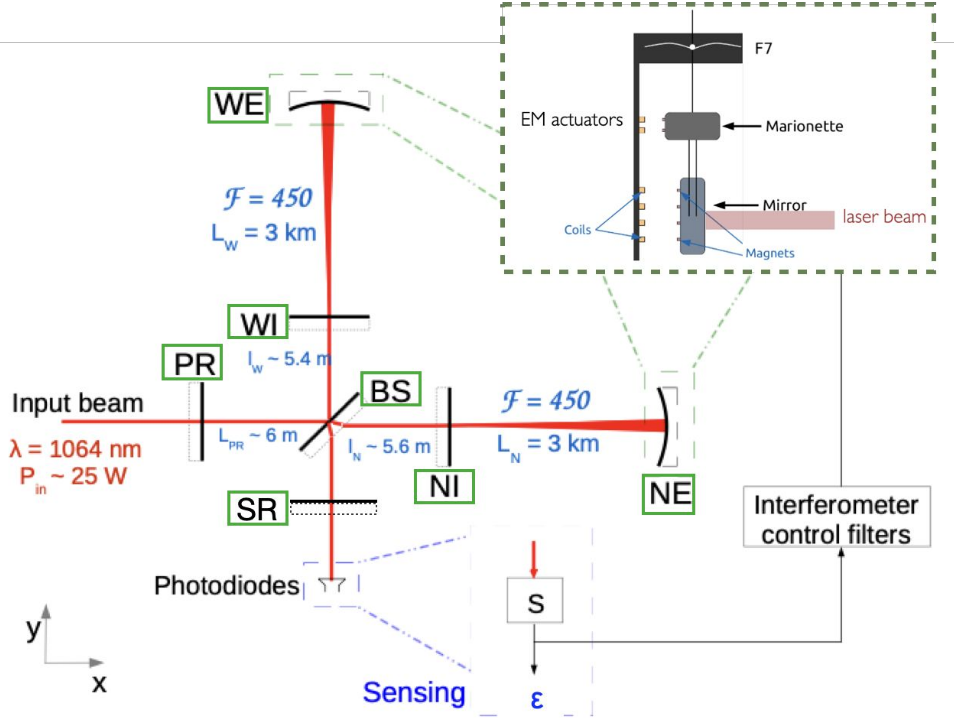
Antoine Syx (IPHC)
Benoit Mours (IPHC)
Cervane Grimaud (LAPP)
Didier Verkindt (LAPP)
Dimitri Estevez (IPHC)
Loïc Rolland (LAPP) *superviser*
Mónica Seglar Arroyo (LAPP)
Paul Lagabbe (LAPP) *speaker*
Thierry Pradier (IPHC)

Groupement de recherche Ondes gravitationnelles

VIRGO

LAPP Laboratoire d'Annecy de Physique des Particules

Control of the differential arm length of the Virgo interferometer



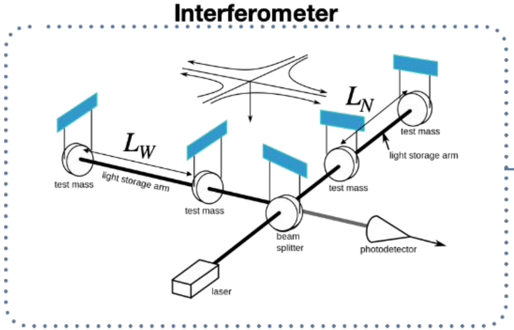
Scheme of the interferometer with DARM control loop.

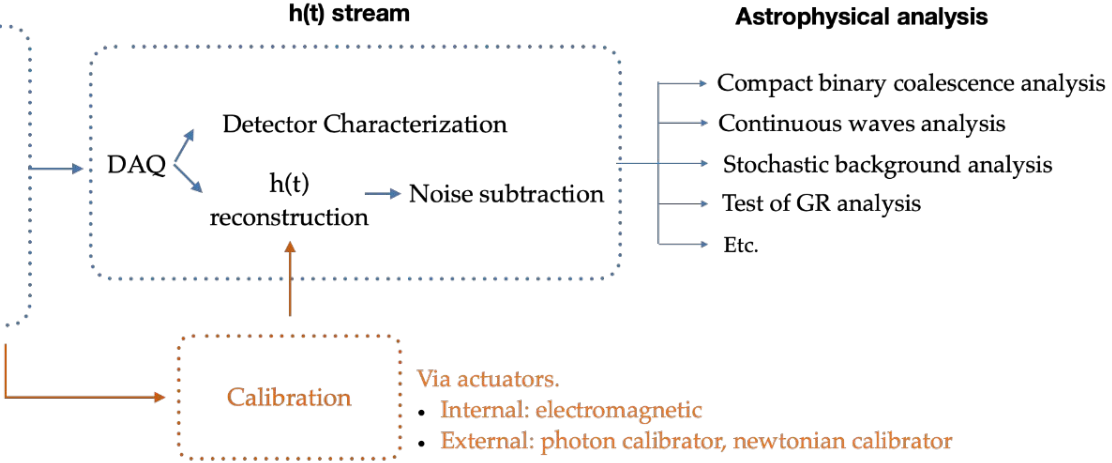
All the mirrors can be displaced by electromagnetic actuators (EM actuators).

The end mirrors (NE and WE) are in control loop with the detector signal. Because of this control loop, the GW signal is contained in both the actuator control signal and photodiodes output signal.

At frequencies [10 Hz, 2 kHz]: Free length of L_0 = 3 km, and h ~ 10^{-22} ⇒ Arm length variation δL ~ 10^{-19} m

Reconstruction of the detector strain h(t)



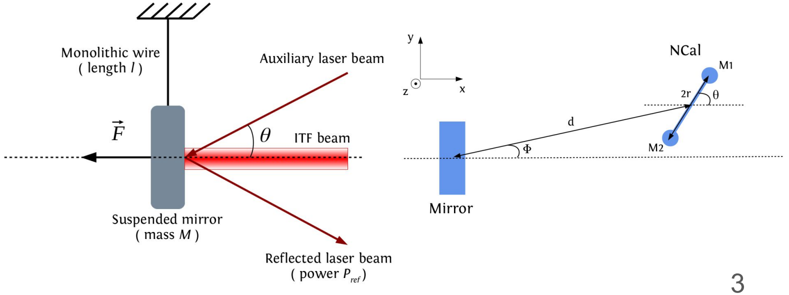


$$h = \frac{\Delta L_N - \Delta L_W}{L_0} = \frac{\Delta L}{L_0}$$

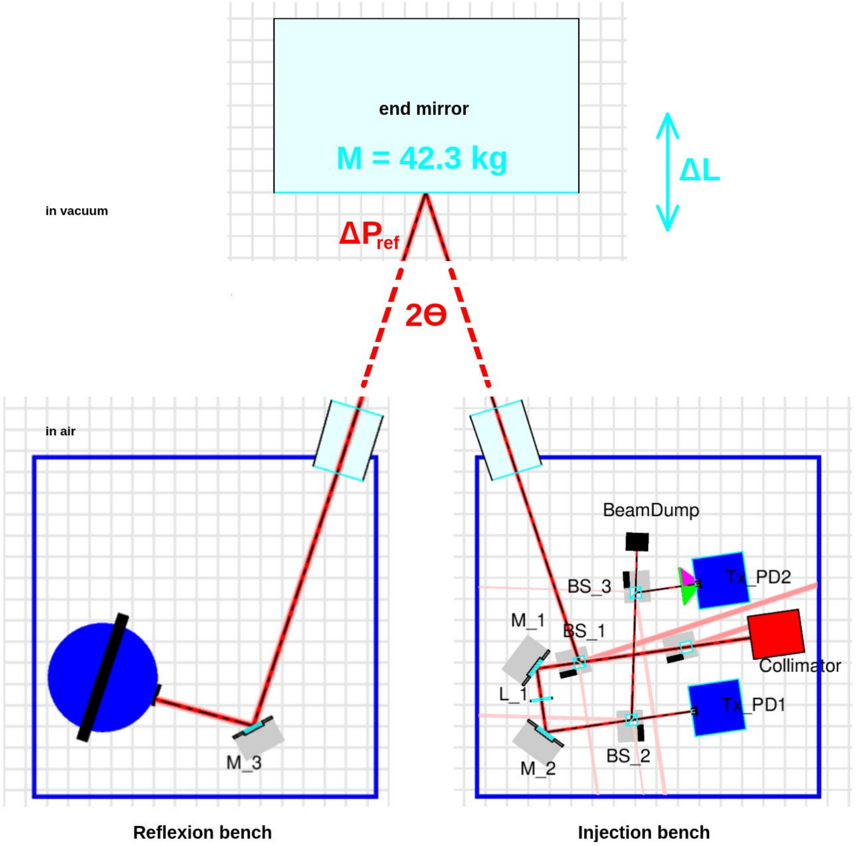
The h_{rec} signal is reconstructed by a pipeline that uses models of:

- Photodetector response
- **EM actuators**
- **Interferometer optical response**

Measured with the photon calibrator



Photon calibrator working principle



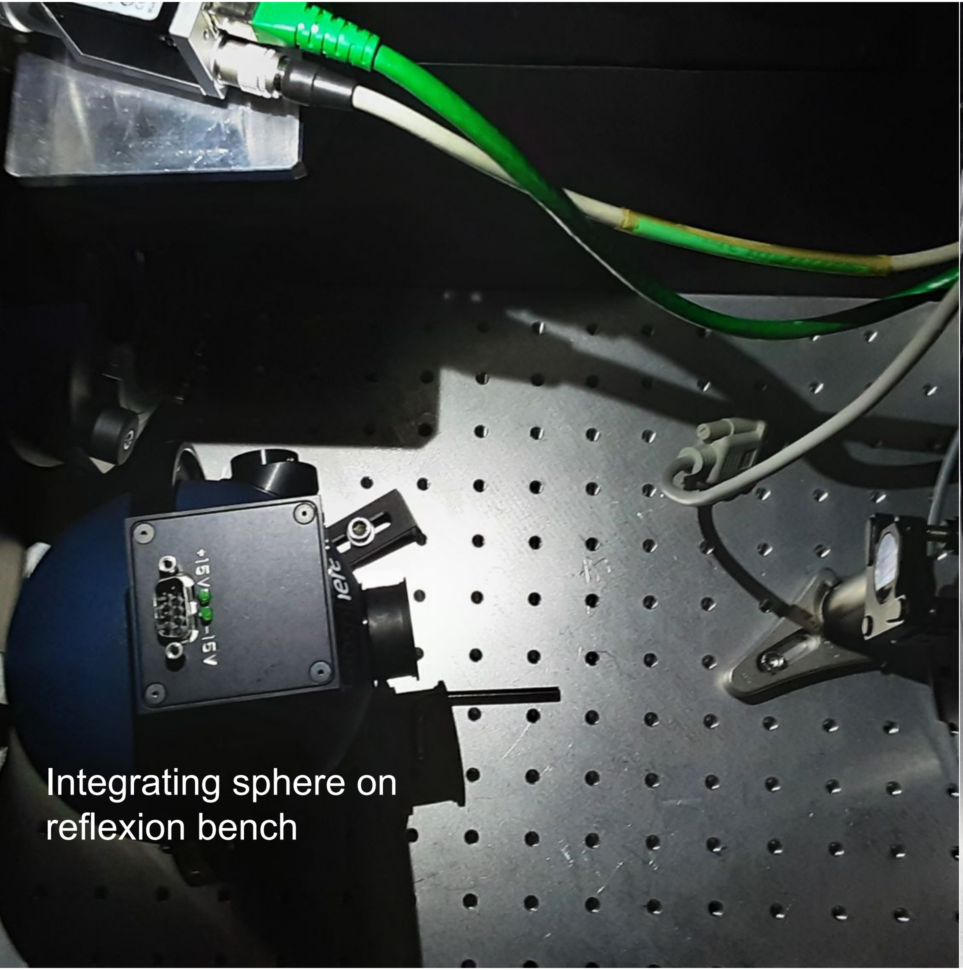
$$\Delta L(f) = \frac{-2cos(\theta)}{cM(2\pi f)^2}\Delta P_{ref}(f)$$

ΔL: needed value
Fraction: geometrical and mass parameter
ΔP: reflected power to be measured absolutely

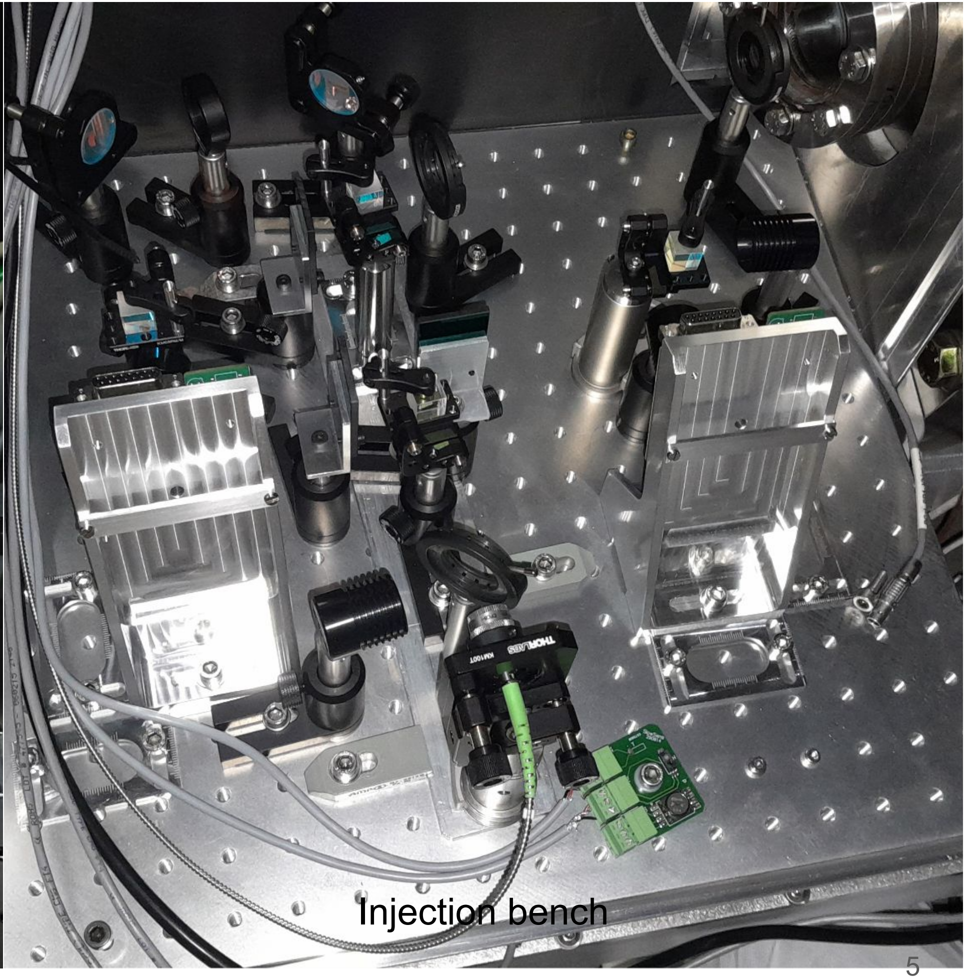
Orders of magnitude:

$<P_{ref}> = 1.3$ W

$\Delta P_{ref} = 0.1$ W -> $\Delta L = 10^{-16}$ m



Integrating sphere on reflexion bench

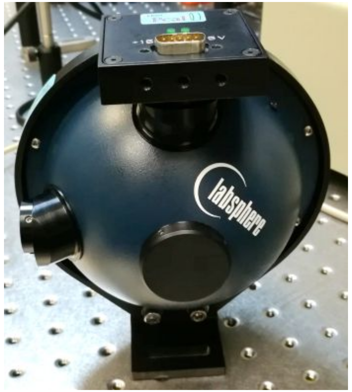


Injection bench

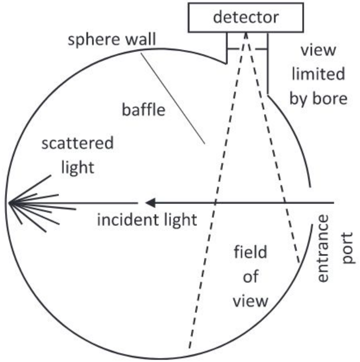
PCal absolute power sensor calibration

4 integrating spheres for Virgo:

- 2 Rx spheres, permanently installed on PCal benches
- 2 Standard spheres: GSV & WSV

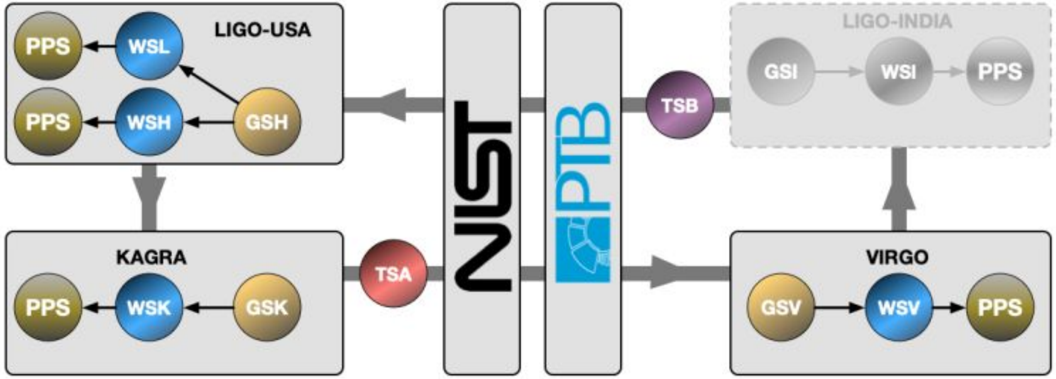


Picture of an integrating sphere



Scheme of the integrating sphere

Absolute power calibration
with 0.1 % level precision



Scheme of the O4 intercalibration procedure, with two national metrology institutes for cross-validation

Integrating spheres names:

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

Uncertainty budget: from O3 to O4

Variable	1σ Uncertainty
NIST, PTB spheres calibration	0.32%
Calibration transfers from spheres to PCal sensor	1.12%
Integrating sphere calibration stability	0.4%
Geometric parameters	0.13%
PCal power sensor stability in time	0.51%
Total	1.34%

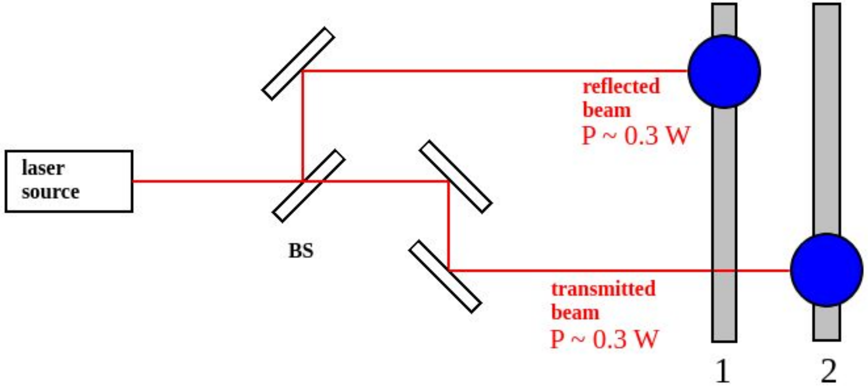
Variable	1σ Uncertainty
NIST, PTB spheres calibration	0.1%
Calibration transfers from spheres to PCal sensor	0.41%
Integrating sphere calibration stability	0.1%
Geometric parameters	0.13%
PCal power sensor stability in time	0.2%
Total	0.49%

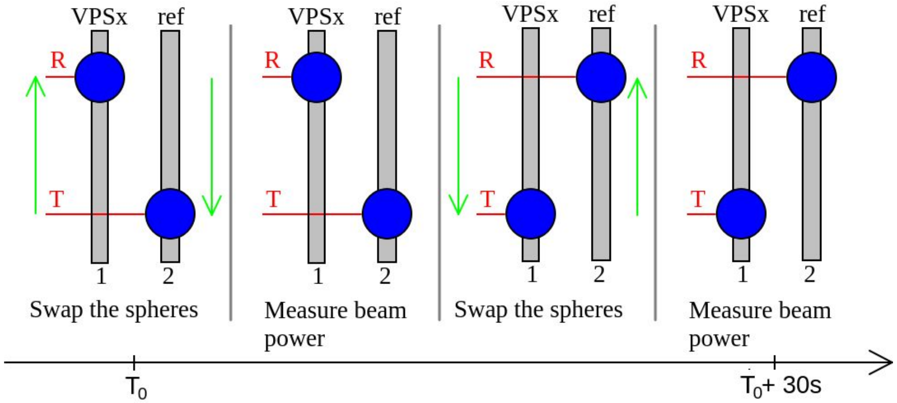
O3 uncertainties (2019/2020) ---> goal for O4 (2023/2024)

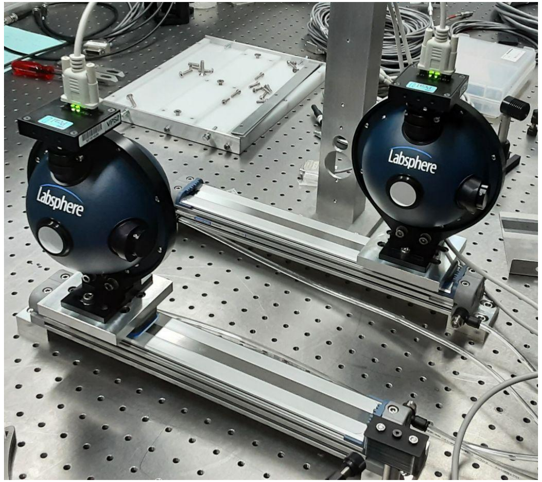
Main improvements from O3 to O4:

- More stable power sensors and standardisation of sphere power calibration
- Improvements of PCal optics to reduce variations with environment (humidity)

Setup for integrating sphere power calibration



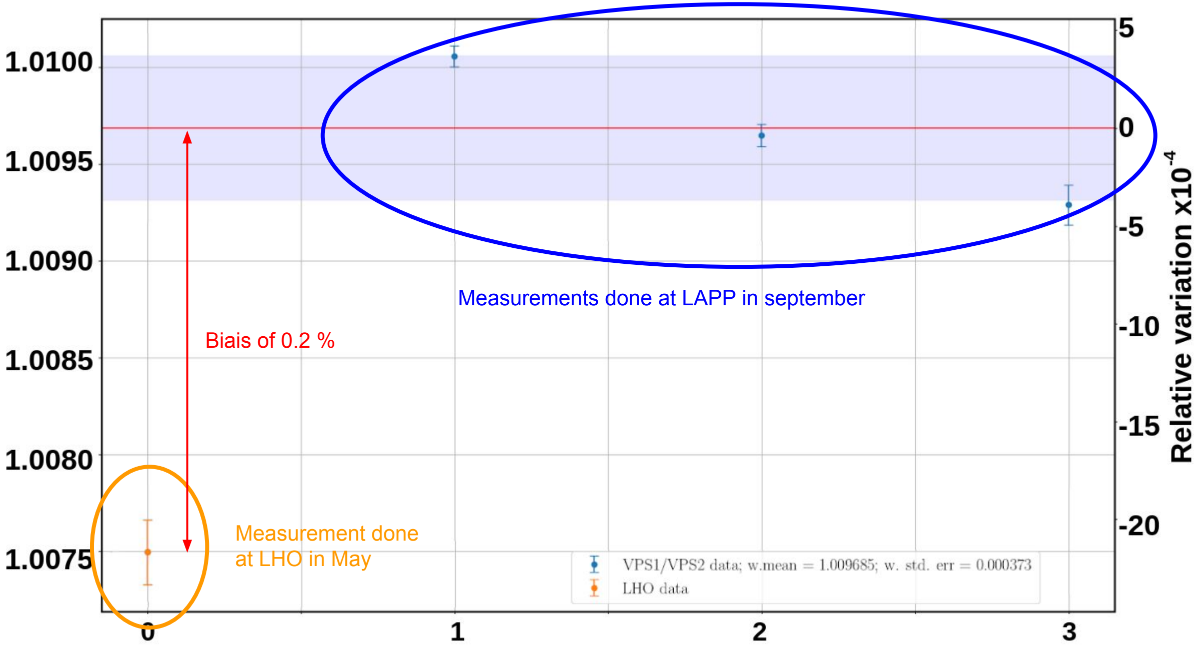




- The spheres are mounted on pneumatic rails, and can be swapped automatically.
- Four values of output voltage are recorded, one for each beam seen by each spheres
- The responsivity ratio between the two spheres is computed.

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

First power calibration measurements at LAPP



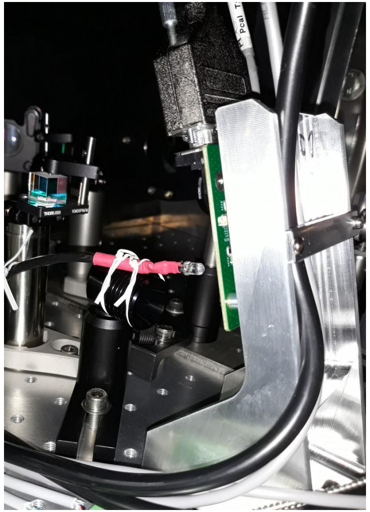
Calibration done with an input power of 0.3 W

Possible explanations to be investigated:

- Biais in sphere output voltage measurement (impedance adaptation): likely, under investigation.
- Ghost beams/scattered light entering into the spheres: rejected
- Optical effects (beam size, angle of incidence, ...)

Photodiode timing measurement

- The exact time when the mirror is pushed by the PCal is needed
    - The photodiode readout timing has to be measured, with respect to the GPS time.
    - A LED has been installed in front of the PCal photodiodes and pulse a signal synchronized with the GPS time.



LED in front of a PCal photodiode

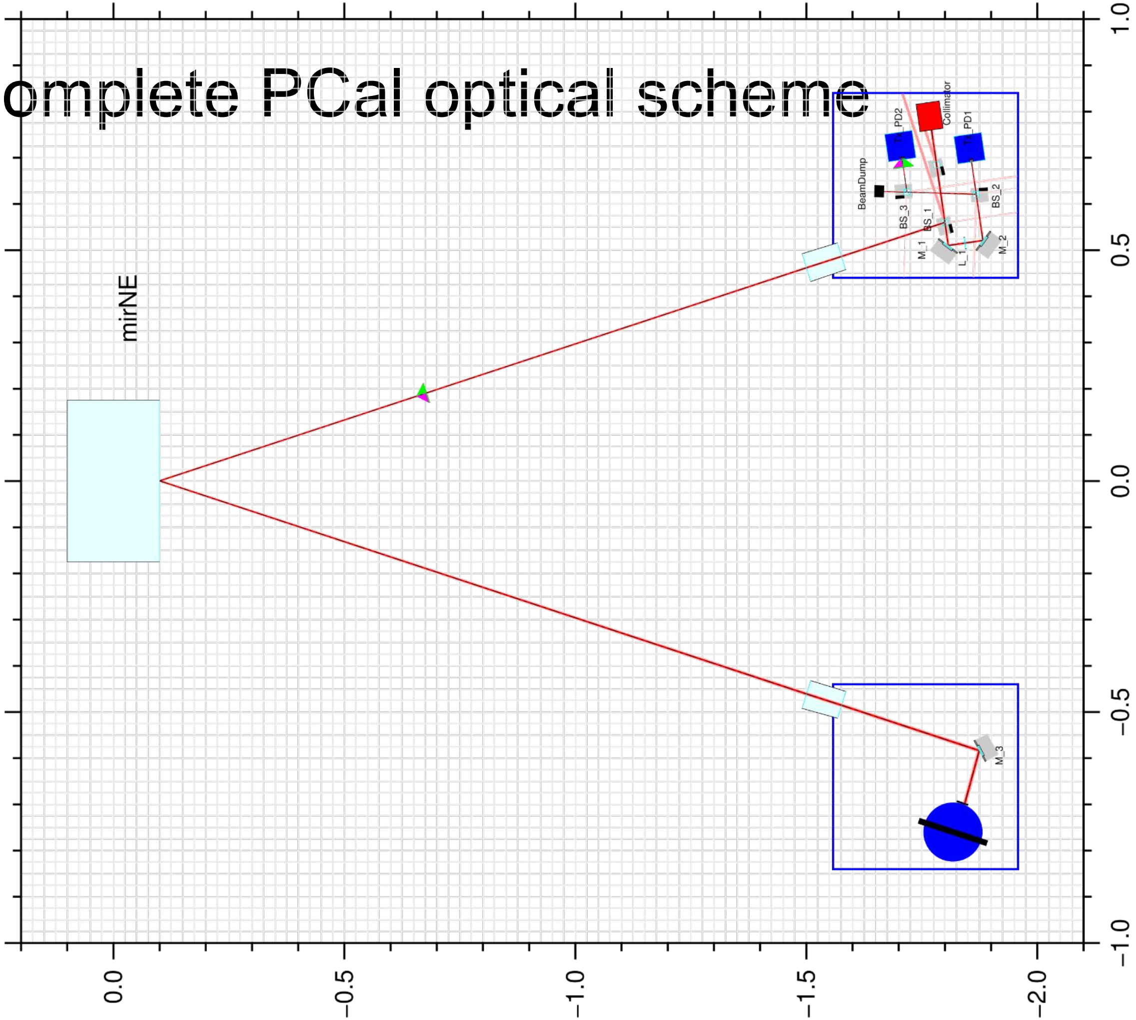
Objective: Measure the photodiode timing with an uncertainty < 1 μs

Conclusions

- PCal system installed and ready for commissioning.
- Preliminary power and timing calibration done.
- Expected accuracy of the injected PCal signal at the 0.5% level during O4 (1.34% during O3)
    - improve Virgo actuator calibration
    - reduce uncertainties on Virgo h(t) strain reconstruction
- Results to be compared with the Newtonian calibrator

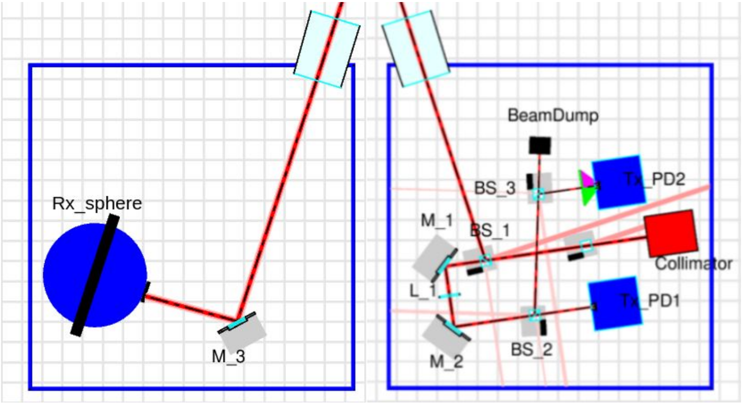
Thank you for your attention!

Backup: Complete PCal optical scheme



Backup: Photon calibrator: current status

- There are two PCals, one in front of each end mirror
- Injection bench installed on both PCal
- Rx sphere installed only on NE
- All Tx photodiodes calibrated with respect to O3 WSV on PCal bench
  - Biais of 4 mW between two photodiodes of the same bench
- NE Rx sphere calibrated with respect to O4 WSV at LAPP
  - Biais of 60 mW between the sphere and the photodiodes

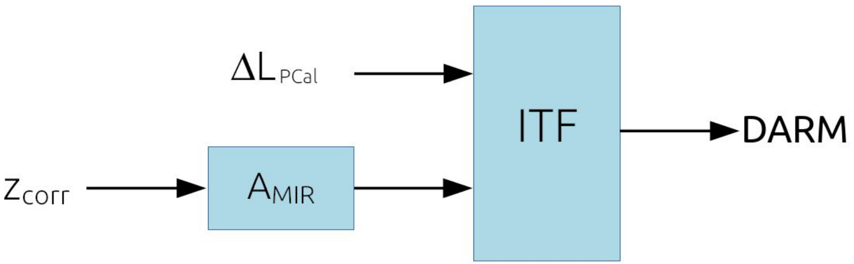


PCal optical layout:
Reflection bench *Injection bench*

Future tasks:

- Install Rx sphere on WE PCal
- Investigate biais on power measurement
- Calibrate all sensors with respect to O4 WSV

Backup: 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 A_{MIR} 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

Backup: Interferometer optical response measurement

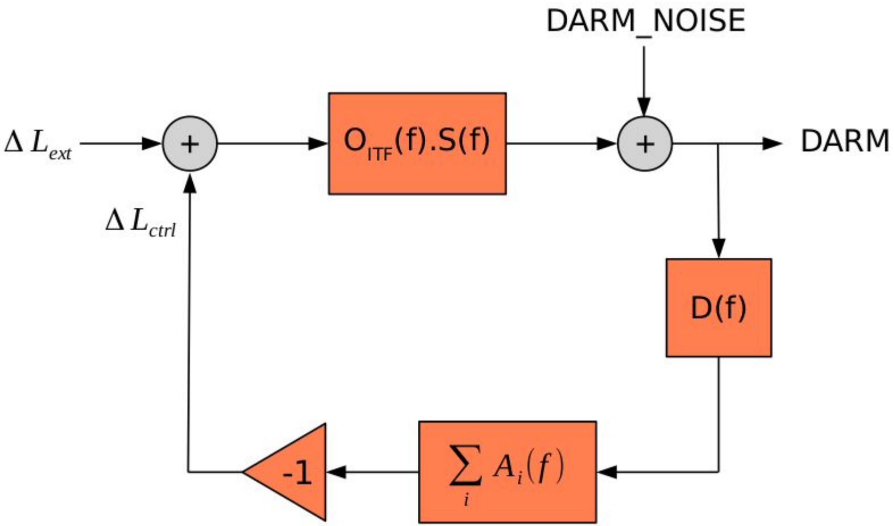


Diagram of the DARM control loop

Method:
With the DARM loop closed,

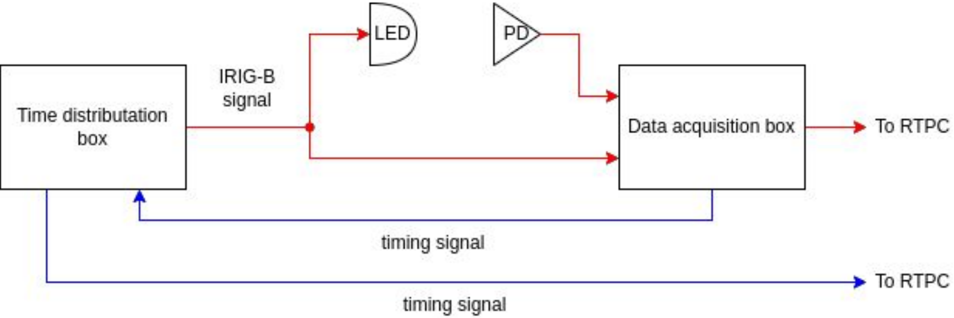
1. Make the mirror move by a known motion ΔL_{ext} in [m] with the photon calibrator (PCal), and observe the output of the interferometer DARM(PCal) in [W].
2. Add a digital signal DARM_NOISE to the loop and observe the output of the interferometer DARM(noise) in [W].
3. Compute O_{ITF} with the formula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

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

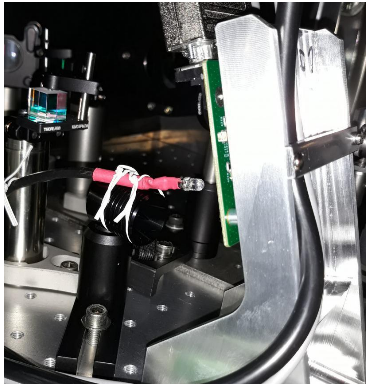
▸ This measurement will be done once the PCal is calibrated, and when the interferometer is stable

Backup: 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



LED in front of a PCal photodiode

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

-> The delay between the time axis and the rising edges of the photodiode signal is measured.

Current status:

- Method tested at LAPP
- LED installed in front of Tx_PD1 photodiode on both PCal
- PCal photodiode timing measured: ~60 μs of delay
- This measurement has to be repeated regularly