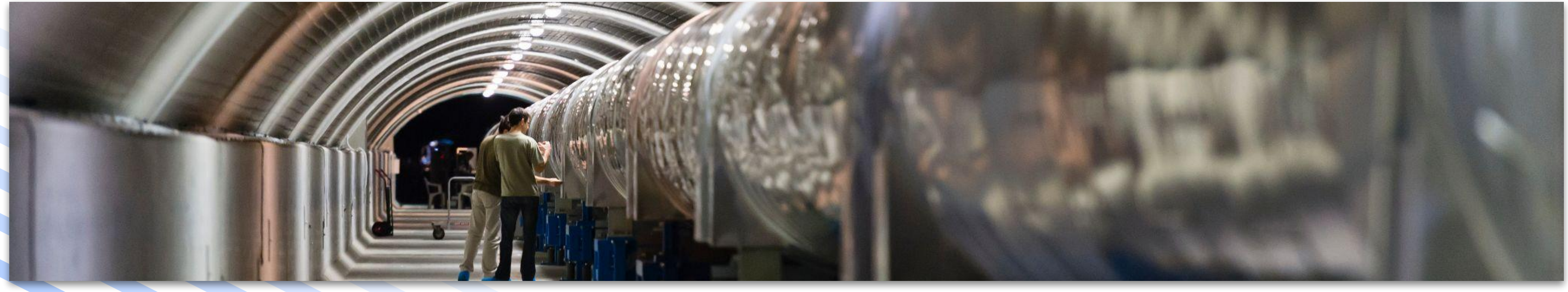
VIRGO CALIBRATION AND DATA RECONSTRUCTION

How to compute the data reconstruction uncertainty

1st year CSI Seminar - Cervane Grimaud

PhD advisors : Loic Rolland & Didier Verkindt



Summary

1 - Virgo Interferometer
- Gravitational waves
- Detection Method
- Mirrors actuation

2 - Virgo Calibration
- Pcal calibration
- Calibration principle
- O4 calibration models

3 - Uncertainty computation
- Data reconstruction algorithm
- Reconstruction bias monitoring
- Uncertainty estimation
- Preliminary result for O4


One arm of the Virgo interferometer

SOURCE - EGO photo

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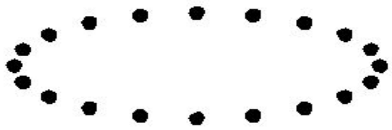
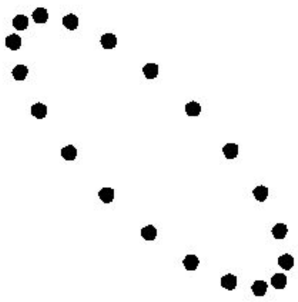
SOURCE - EGO photo

Gravitational waves

- Deformation of the space time metric
- Propagating at the speed of light
- Produced by various sources
(**compact binary coalescences** *(detected)* , supernova, stochastic background…)



+ polarisation

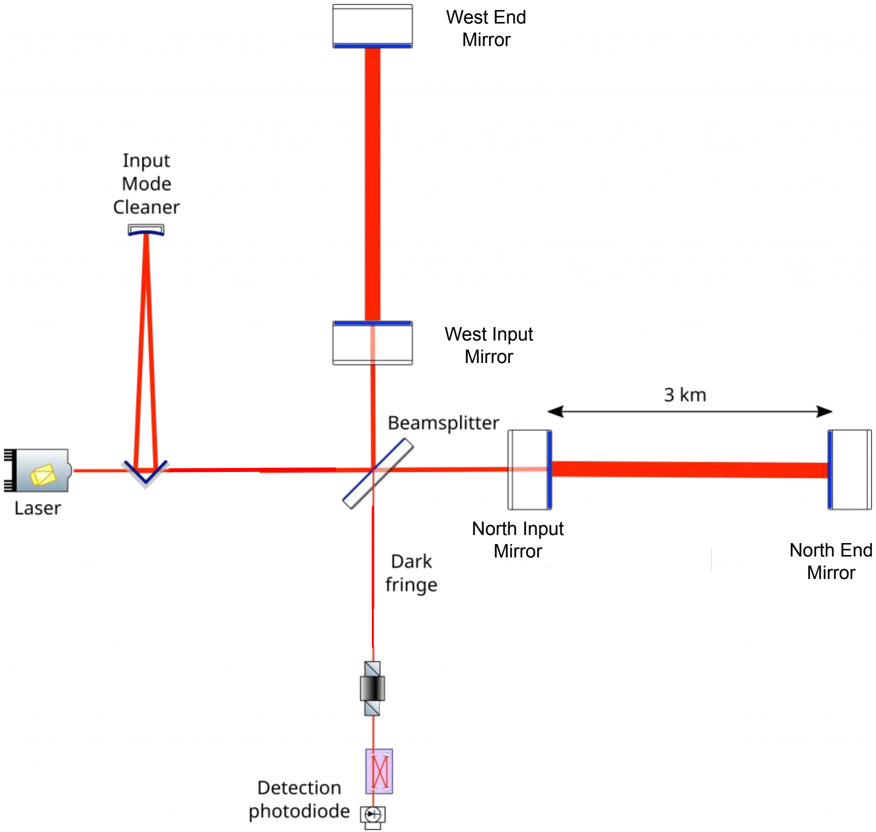


x polarisation

Detection method

3 km long arms interferometer with :

- Laser source, near-IR (1064 nm)
- Beam splitter (BS)
- End mirrors (NE, WE) and Input mirrors (NI, WI)
- Resonant optical Fabry Perot cavities
  → increase effective length travel by the beam



SOURCE - Virgo collaboration

Detection method

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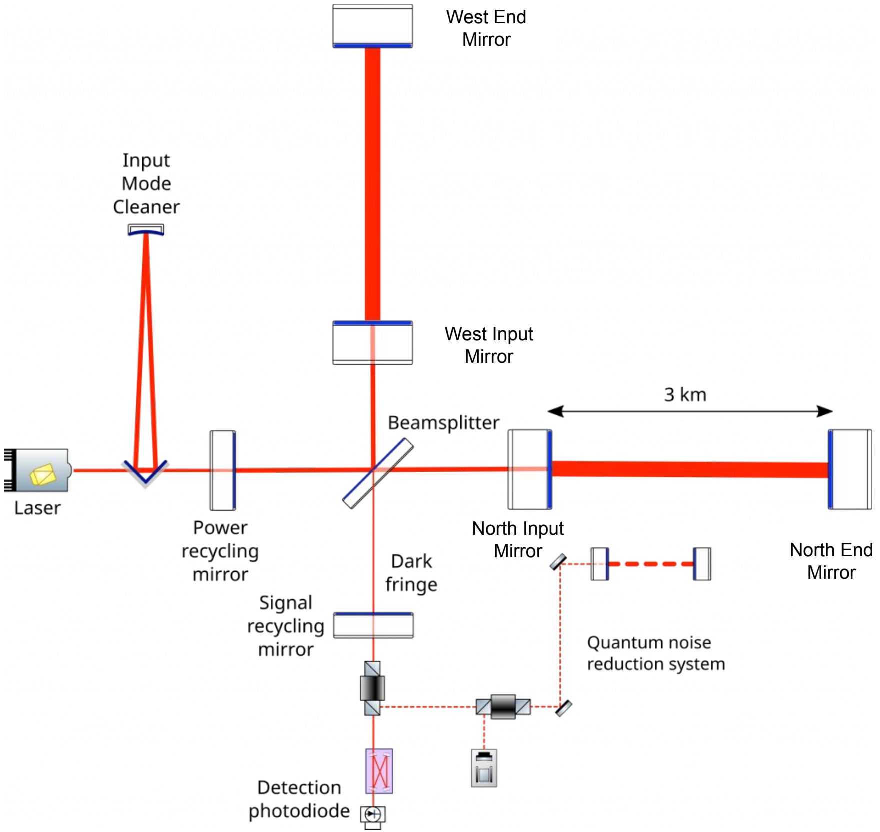
- End mirrors (NE, WE) and Input mirrors (NI, WI)
- Resonant optical Fabry Perot cavities
  → increase effective length travel by the beam
- Power recycling mirror (PR)
- Signal recycling mirror (SR)
- Suspended mirrors in vacuum



SOURCE - Virgo collaboration

Detection method

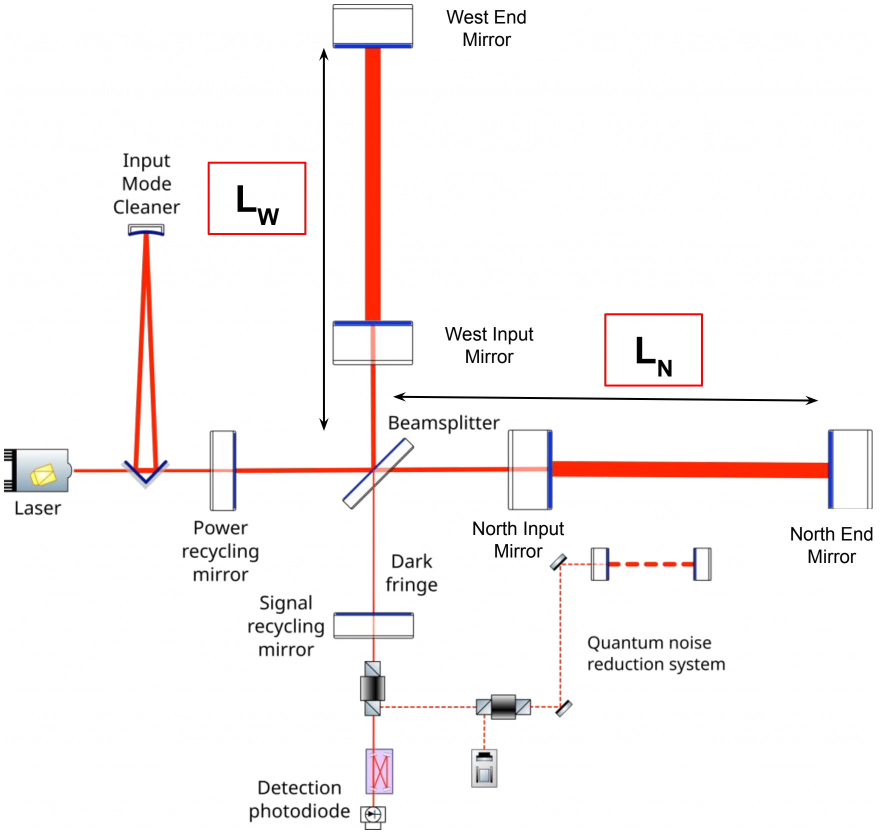
When GW goes through :

- Modification of the L_W and L_N alternatively
  → Changes the interference pattern

- What we measure is the differential length of the arms $\Delta L = L_N - L_W$

- Gravitational wave strain $h = \Delta L / L_0$ (L_0 = 3km)

ΔL of GW ~ 10^{-19} m



SOURCE - Virgo collaboration

Operating the interferometer

Mirror are moving at low frequency

⬇

Need to control the mirrors movement to operate the interferometer

⬇

Use **control loops**

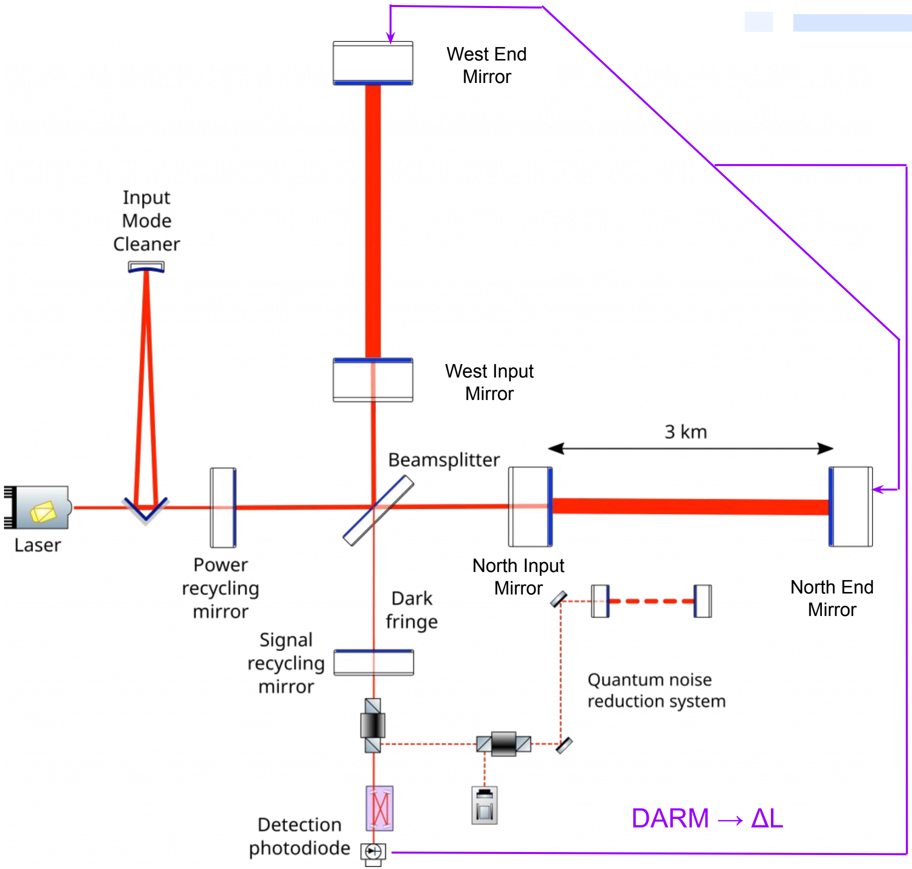
To check and control different parameters of the interferometer

⬇

Example : DARM → to keep the interferometer in the same position on the interference pattern, counteract the ΔL

⬇

Consequence : Part of the GW information goes in the control signals → need to **reconstruct the GW signal**

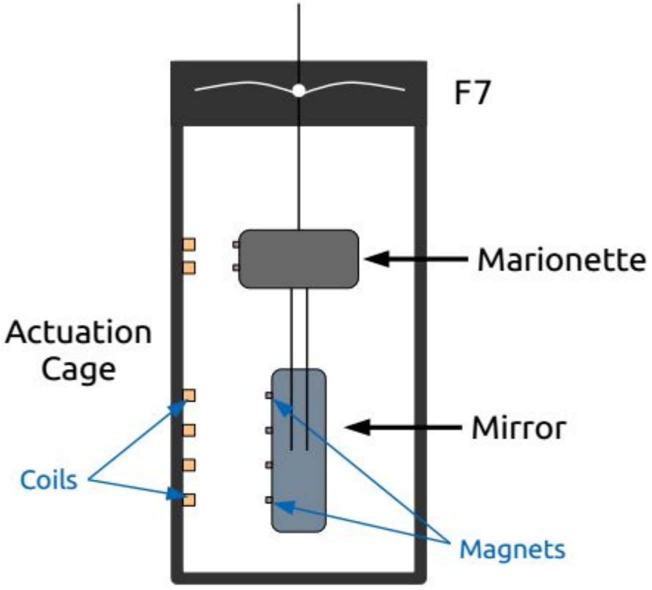


SOURCE - Virgo collaboration

Mirrors actuation

Electromagnetic actuators :

- 4 magnets in the back of the mirrors
- 4 coil to create magnetic field
- Used for the control loops



SOURCE - PhD thesis D. Estevez

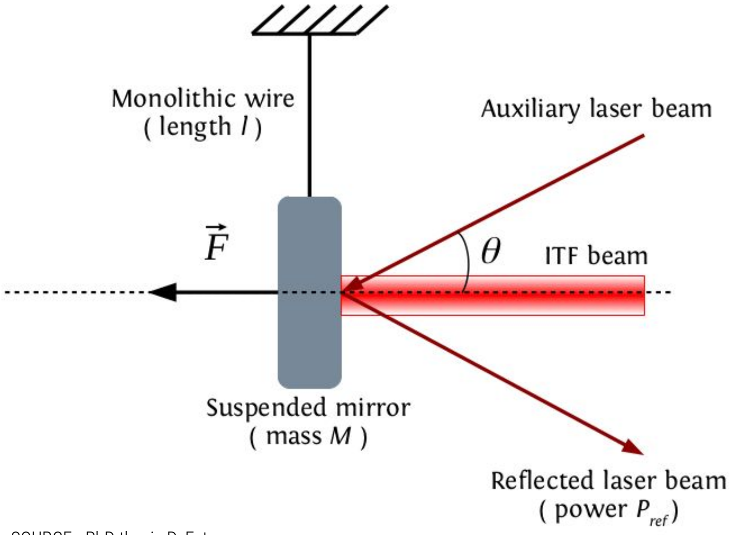
Mirrors actuation

Electromagnetic actuators :

- 4 magnets in the back of the mirrors
- 4 coil to create magnetic field
- Used for the control loops

Pcal actuators :

- Only at the end mirrors
- Laser beam sent to the mirror center
- Mirror moves thanks to radiation pressure
- Used as reference for the Virgo calibration



SOURCE - PhD thesis D. Estevez

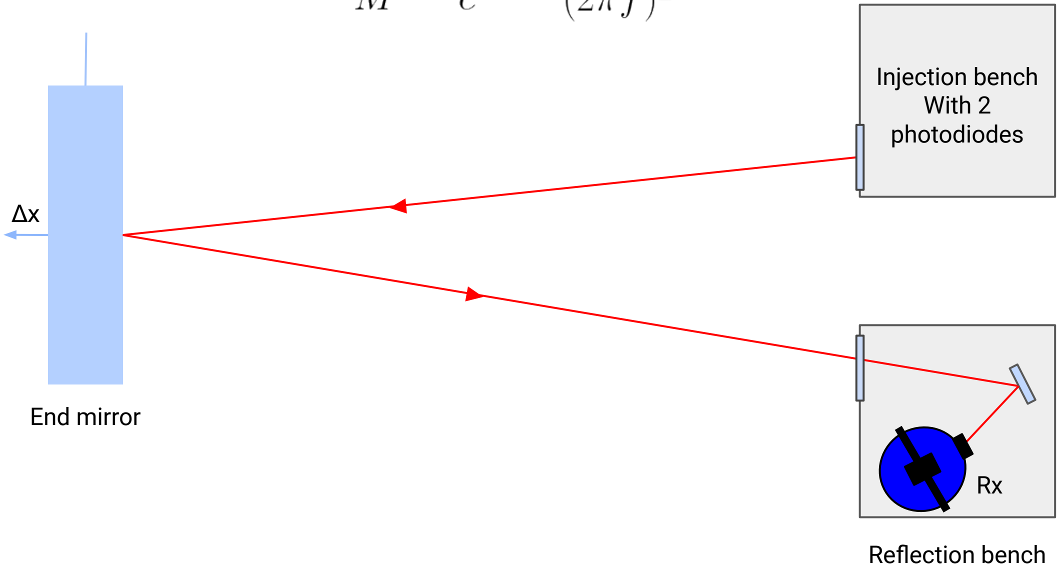
Mirror motion induced by Pcal actuator

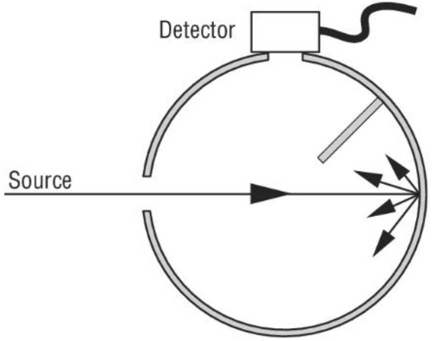
Pcal setup in **observation mode** :

- Need to precisely measure the reflected laser beam power to know the mirror motion
- Use Integrating sphere (Rx) as power meter on the reception bench

SOURCE - LIGO-G2300653-v8

$$\Delta x_{pend}(f) = -\frac{1}{M}\frac{2\,cos(\theta)}{c}\frac{\Delta P_{ref}(f)}{(2\pi f)^2}$$





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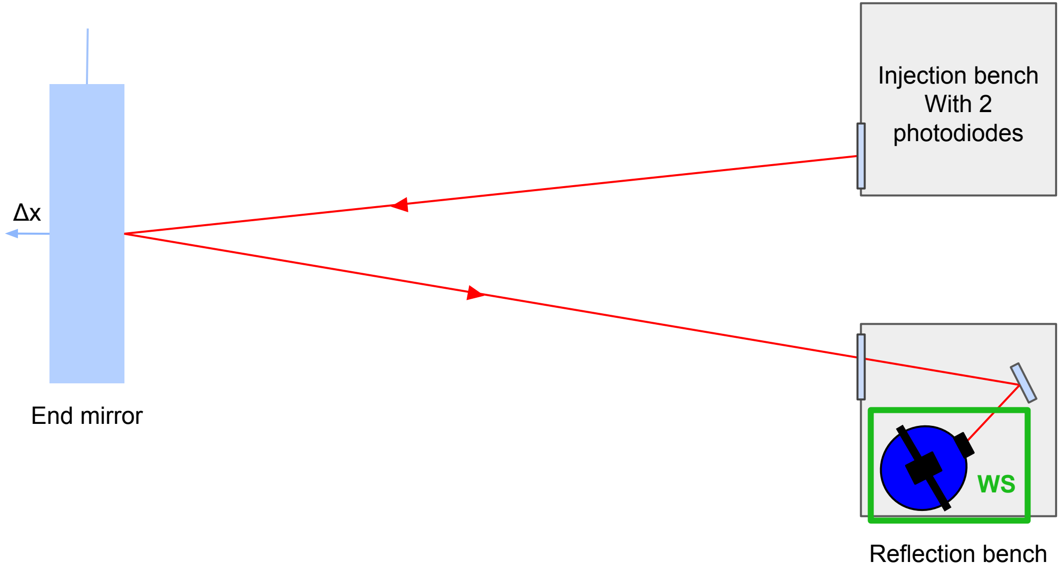
Power calibration of Pcal actuator

Pcal setup **during calibration** :

- Replace the Rx sphere by the Working Standard (WS) which is calibrated here at LAPP w.r.t. a reference sphere given by NIST/PTB
- **Photodiodes** calibration w.r.t. **WS**
- **Rx** calibration w.r.t. **Photodiode**



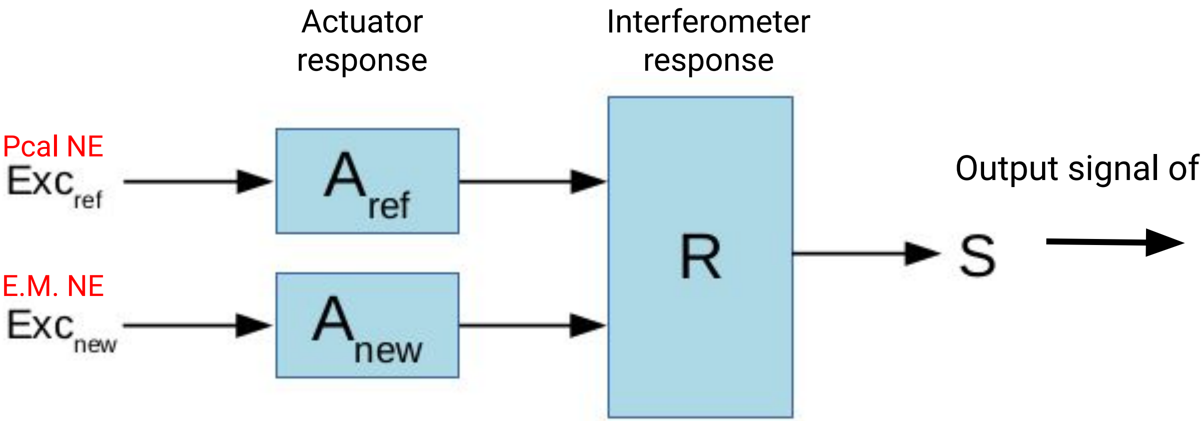
Pcal

⬇

Reference for the rest of the calibration

Calibration principle

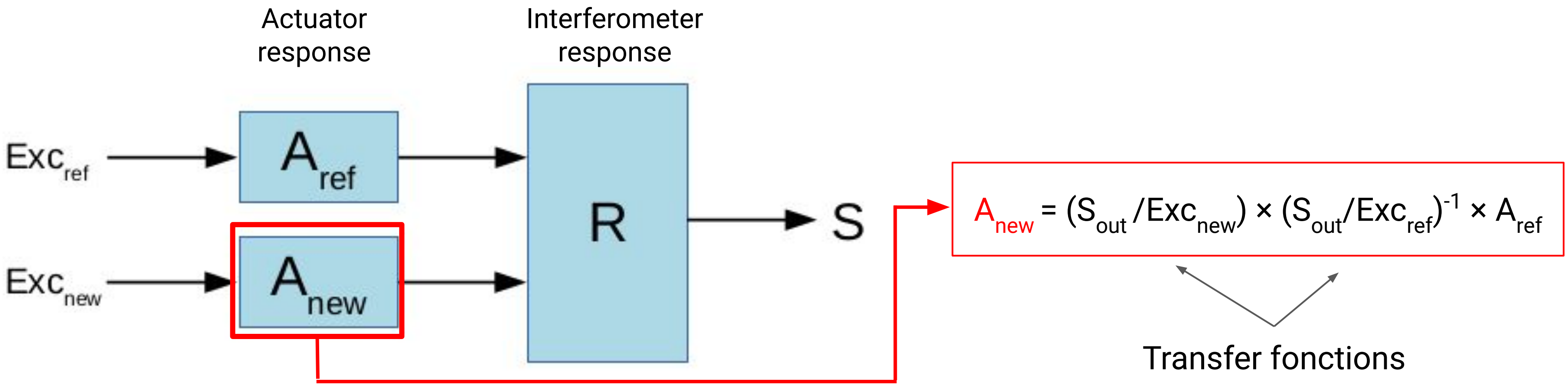
- Series of calibration transfers
- Compare actuator of reference *(ref)* to actuator to calibrate *(new)*



$$S_{out} = Exc_i \times A_i \times R$$

Calibration principle

- Series of calibration transfers
- Compare actuator of reference *(ref)* to actuator to calibrate *(new)*
- Signals combined to to extract A_{new}

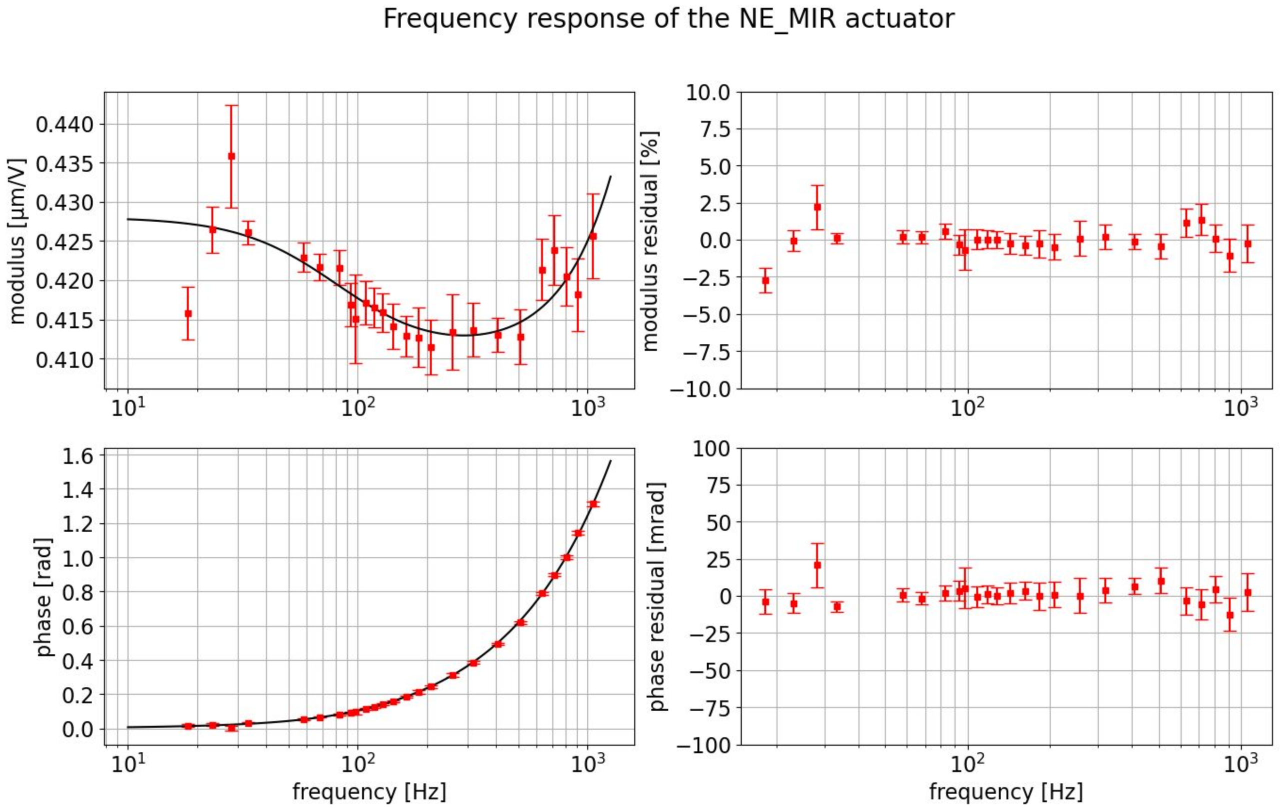


O4 Calibration models - Example

04/08/2023 results :

North End electromagnetic actuator response normalised by the pendulum response

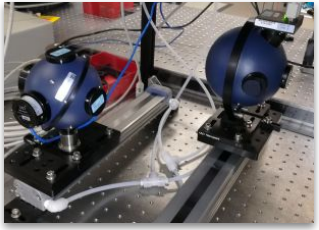
Gain	Pole	Zeros		Delay
G [µm/V]	fp [Hz]	fz1 [Hz]	fz2 [Hz]	τ [µs]
0.428 ± 0.002	82 ± 18	85 ± 19	3728 ± 370	-158 ± 4



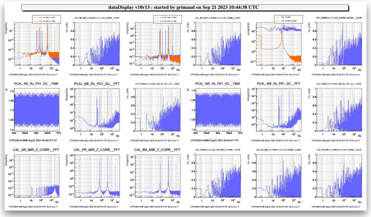
Contribution to the calibration work

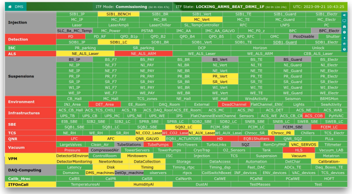
Pcal calibration at Virgo in june

Pcal intercalibration at LAPP in september



Calibration shift since october 2022





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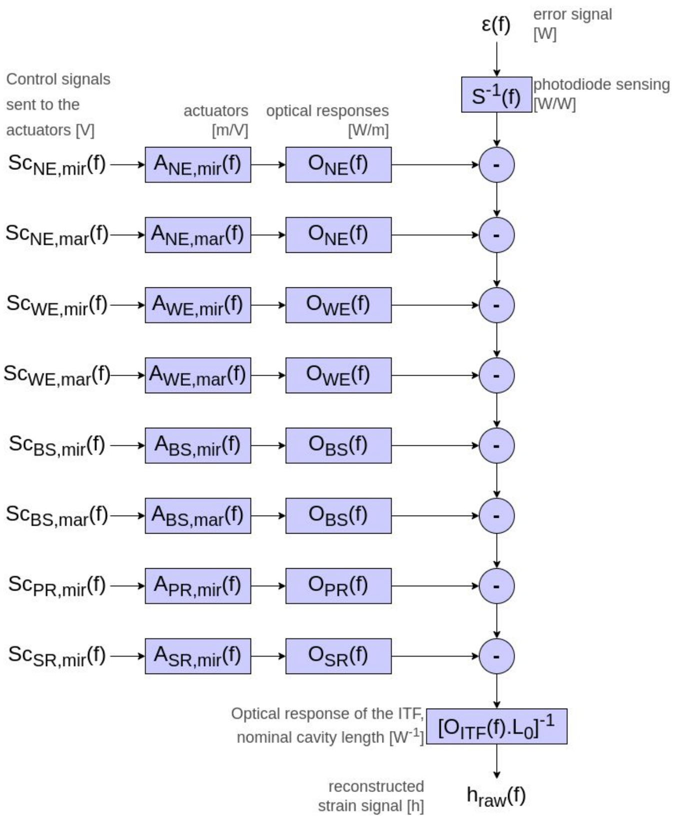
h(t) reconstruction algorithm



h_{rec}

Compute the reconstructed strain by :

- Subtracting the contribution of each longitudinal control signal (using the actuator models and optical responses models)
- Subtracting linearly calibration lines and various noises

h_{inj} → used to monitor the h_{rec} bias

- Signal injected inside the interferometer by an actuator
- h_{inj} → computed from the injected signal and from the actuator's model of the mirror on which is done the injection

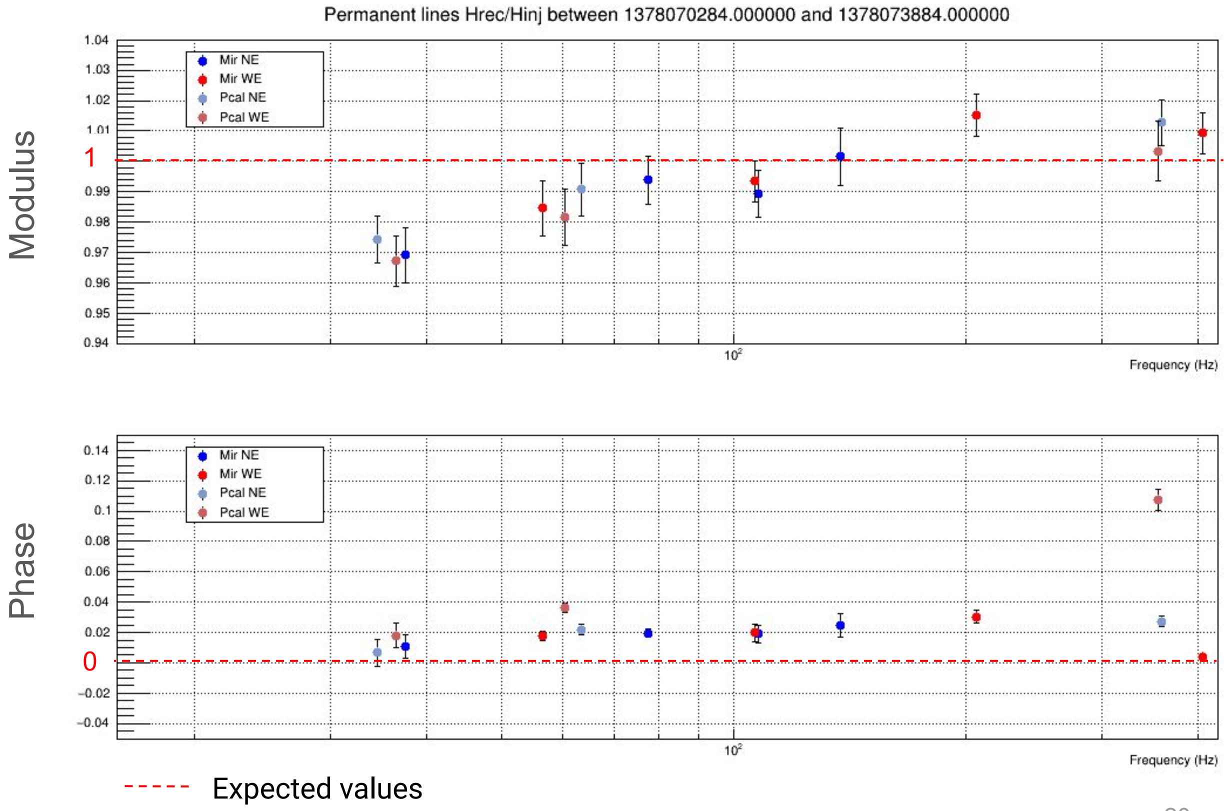
Hrec/hinj : modulus = 1 and phase =0

Calibration measurements

Permanent Lines

- 14 lines distributed between NE and WE
- These lines are permanently injected to check $h(t)/h_{inj}$

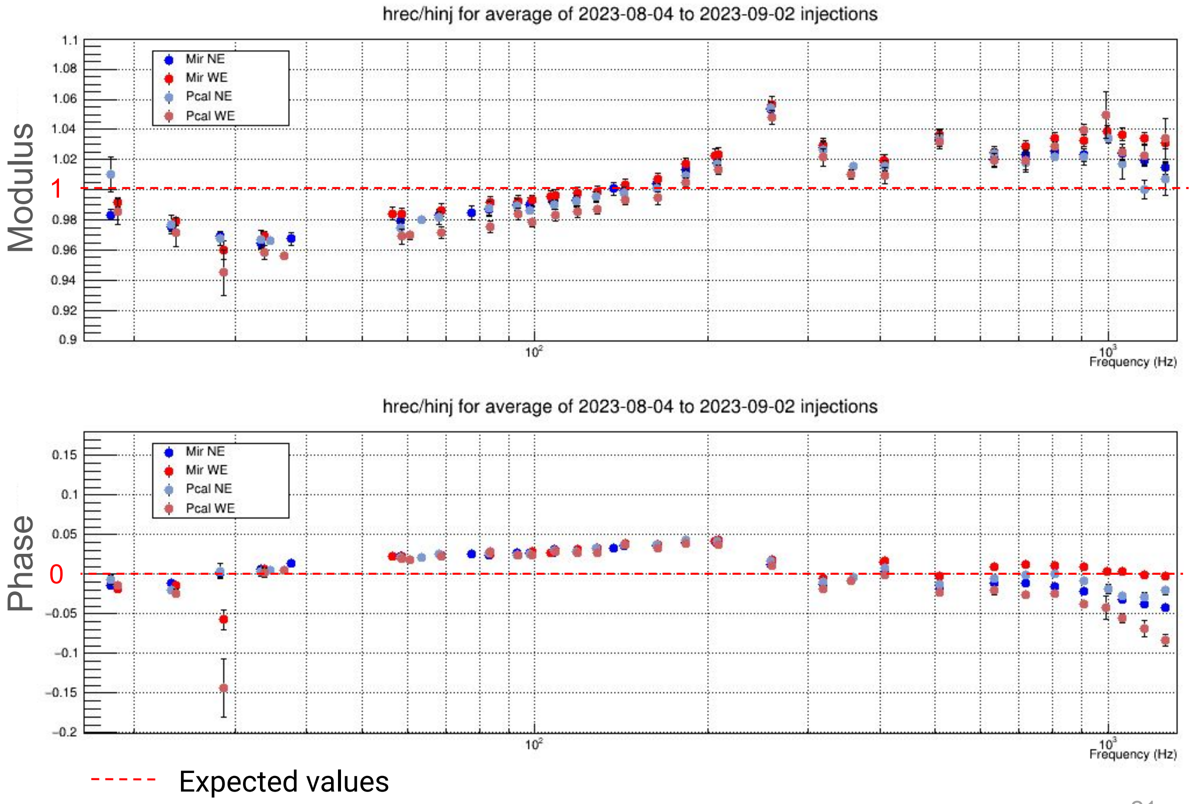
This plot shows a 1h average of h(t)/hinj modulus and phase from the 6 sep 2023 at 21h UTC



Calibration measurements

Weekly Lines

- 32 lines from 18Hz to 1238Hz
- Injected during a few minutes every week on NE and WE with both actuators (EM and PCal)
- Allows to check h(t) reconstruction more thoroughly



Uncertainty computation method

GOAL : Estimate the level of uncertainty of the h(t) reconstruction process over the full frequency range

Weekly lines
18 Hz, 23 Hz,...

Uncertainty computation method

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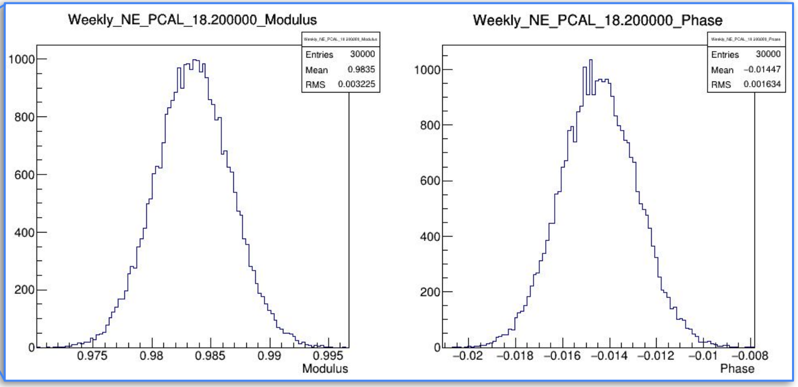
Weekly lines
18 Hz, 23 Hz,...

Using the mean and sigma

Distribution
For each line



Uncertainty computation method

GOAL : Estimate the level of uncertainty of the h(t) reconstruction process over the full frequency range

Weekly lines
18 Hz, 23 Hz,...

→ Using the mean and sigma →

Distribution
For each line

→ Random selection inside the distributions →

N sets of data

	18Hz	...	1258Hz
set 1	##	..	##
...	..	..	..
set N	##	..	##

Uncertainty computation method

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Weekly lines
18 Hz, 23 Hz,...

Using the mean and sigma →

Distribution
For each line

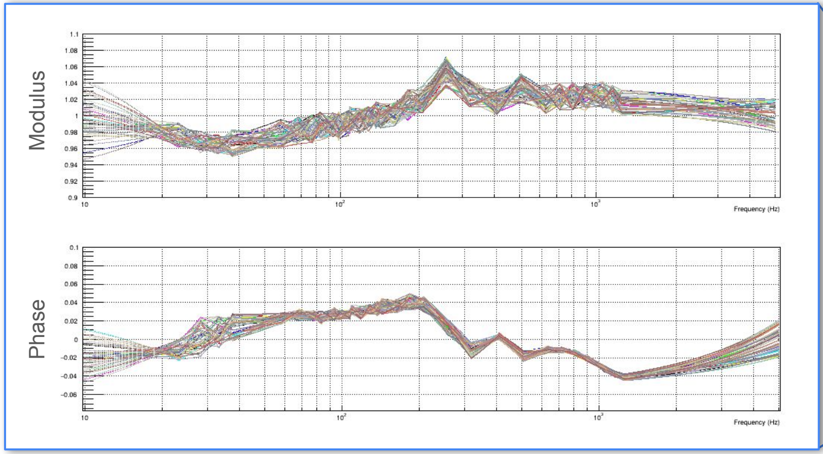
Random selection inside the distributions →

N sets of data

	18Hz	...	1258Hz
set 1	##	..	##
...	..	..	..
set N	##	..	##

↓ Interpolation over 0-5kHz
One point every 0.125Hz ↓

N sets of interpolated data



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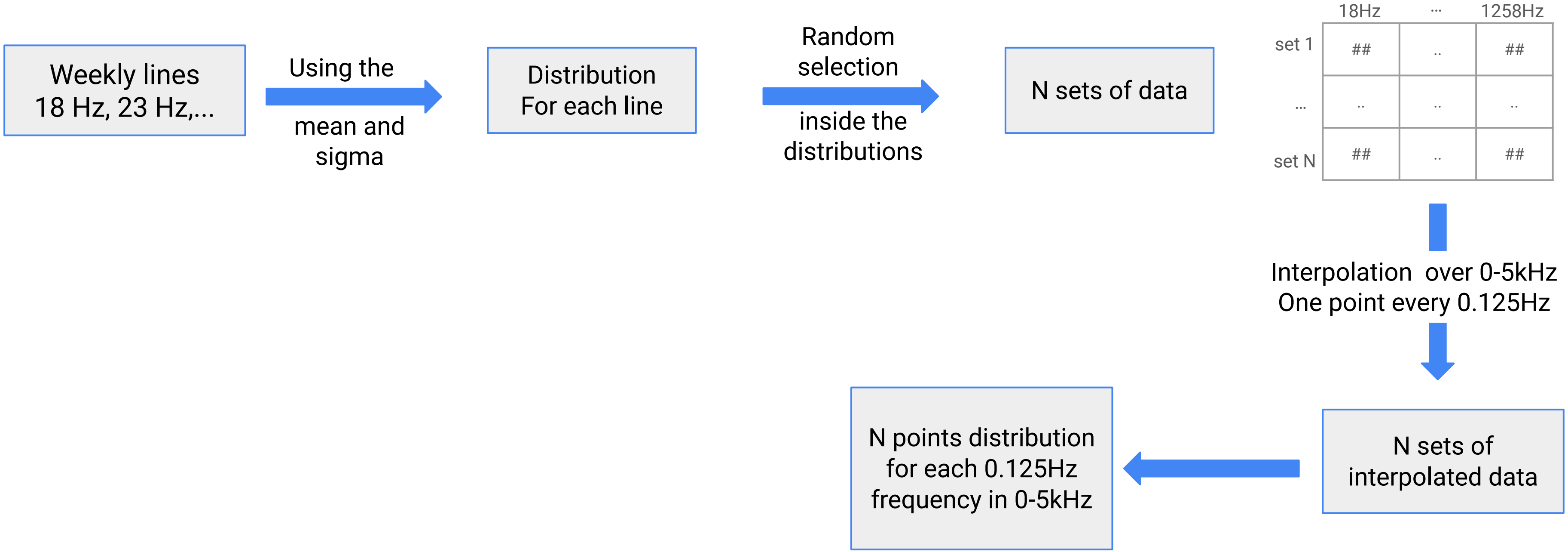

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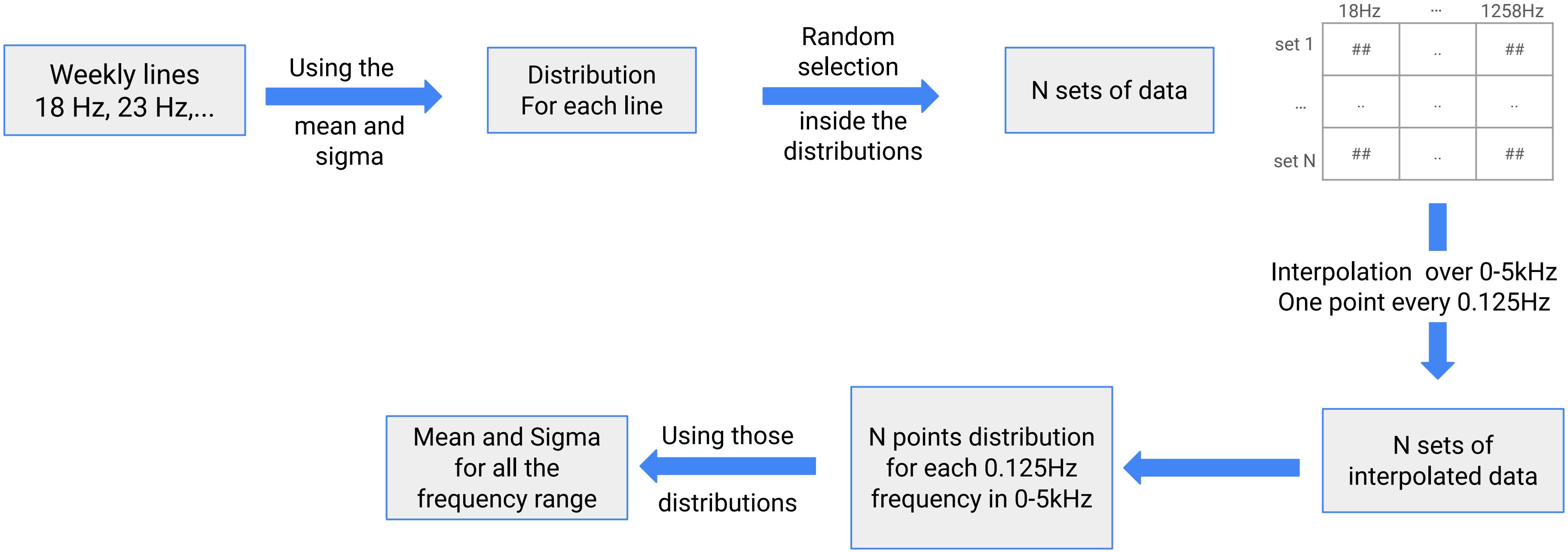

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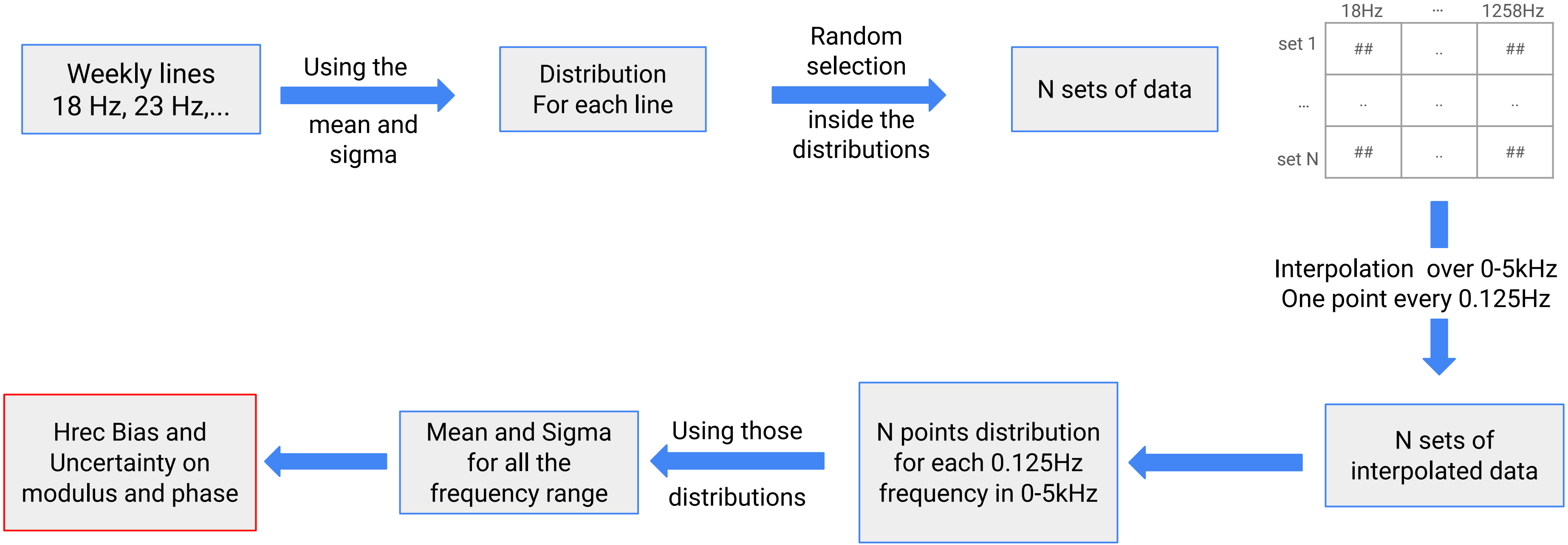
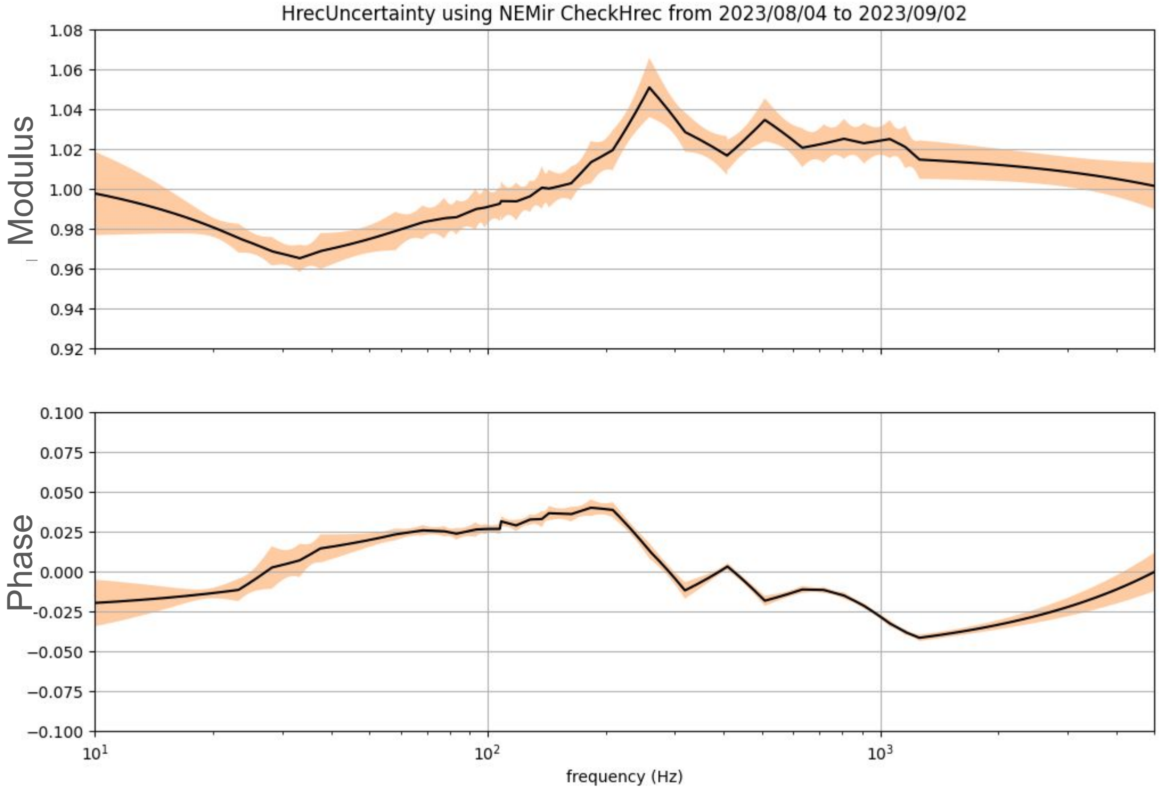


Preliminary result

- Result computed using 3 injection sets of weekly calibration data
  From 4 Aug 2023 to 2 Sep 2023

Improvements to do :

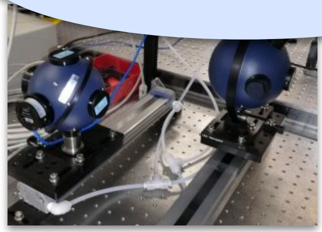
- Add actuator uncertainty
- Add correlation between frequencies in the random selections
- Add permanent lines



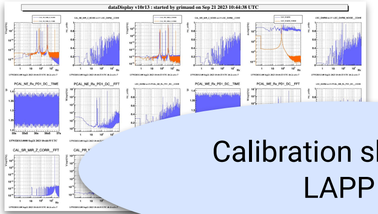
Conclusion

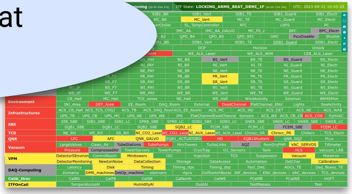
During this first year of PhD :

Pcal calibration on Virgo site and and at LAPP

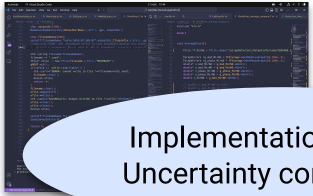


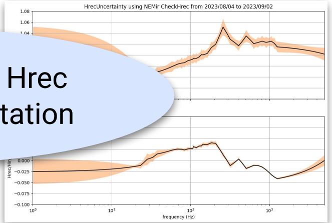
Calibration shifts at LAPP



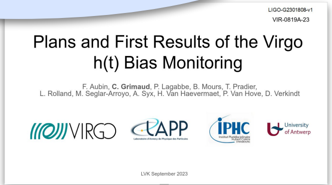


Implementation of Hrec Uncertainty computation





Presented my work on several talks

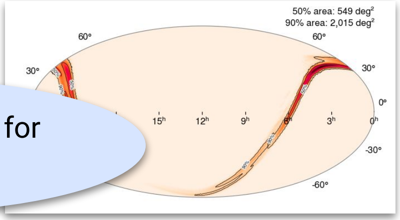

LIGO-G2301808-v1
VIR-0819A-23

Plans and First Results of the Virgo h(t) Bias Monitoring

F. Aubin, **C. Grimaud**, P. Lagabbe, B. Mours, T. Pradier, L. Rolland, M. Seglar-Arroyo, A. Syx, H. Van Haevermaet, P. Van Hove, D. Verkindt

LVK September 2023

Rapid response shift for O4



Conclusion

Perspective for the rest of the PhD :

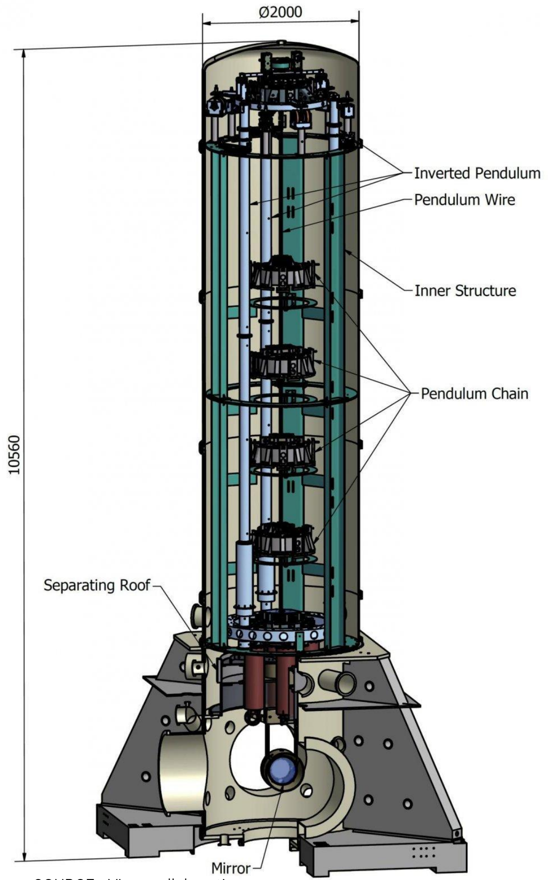
- Following on the Virgo calibration work during the O4 run (calibration shift and data analysis from those weekly shifts)
- Following on the Pcal intercalibration measurements between LVK-NIST-PTB
- Design and test of the Pcal upgrade for Virgo O5 run (2026)
- Visit of 2-3 weeks to LIGO (Hanford and maybe others) to work on calibration and uncertainty with the LIGO team
- Possibility of an analysis project to be discussed

Thank you !

Super attenuator system

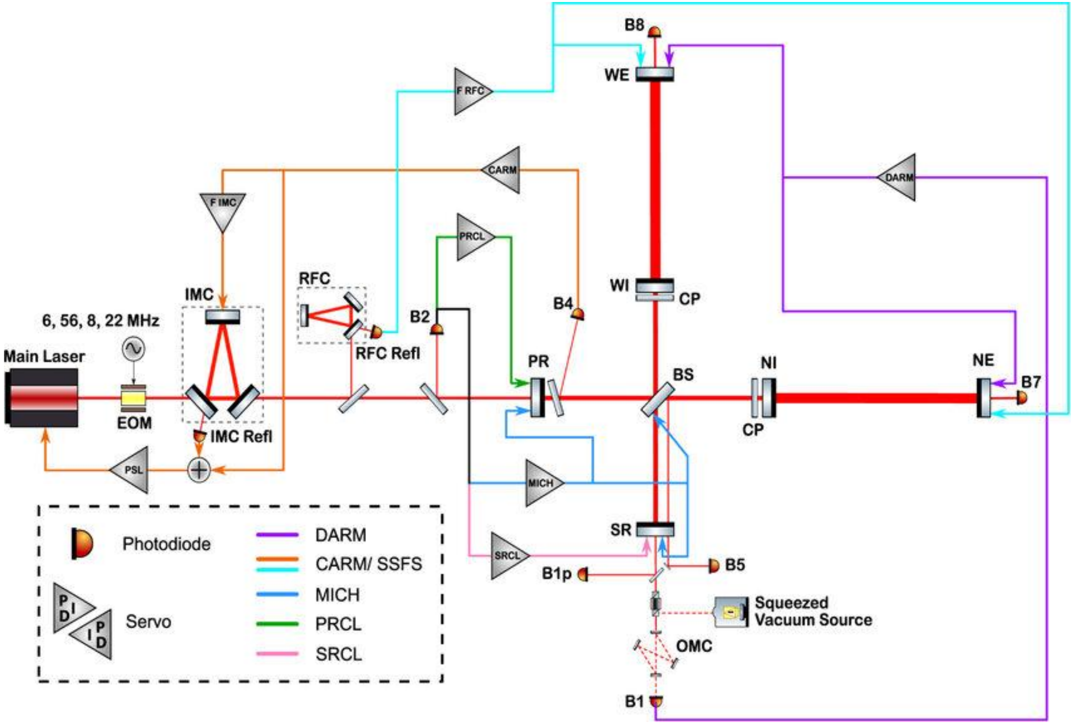
- Pendulum : longitudinal displacement
- Blade springs : vertical displacement
- Torsion threads : rotation

Resonant frequency < 1Hz

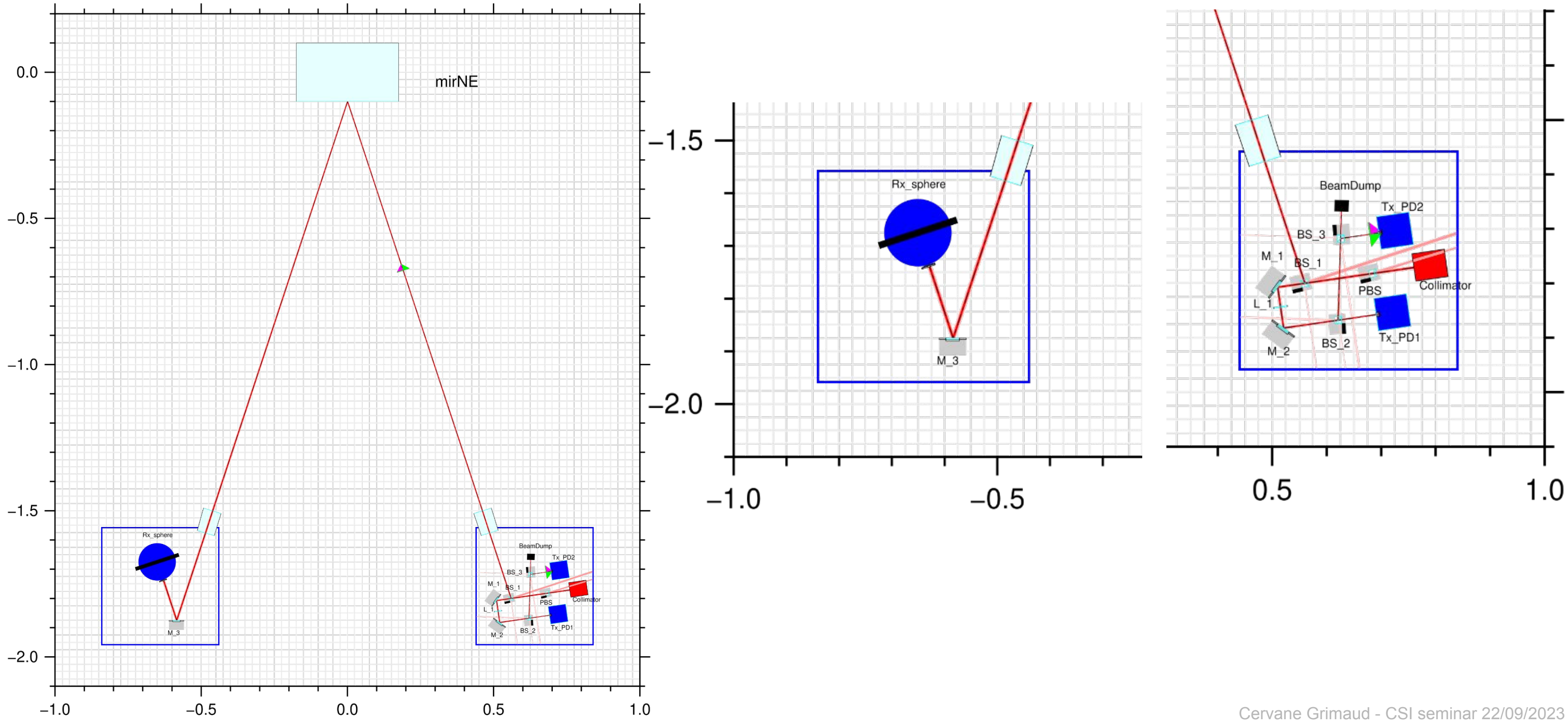


SOURCE - Virgo collaboration

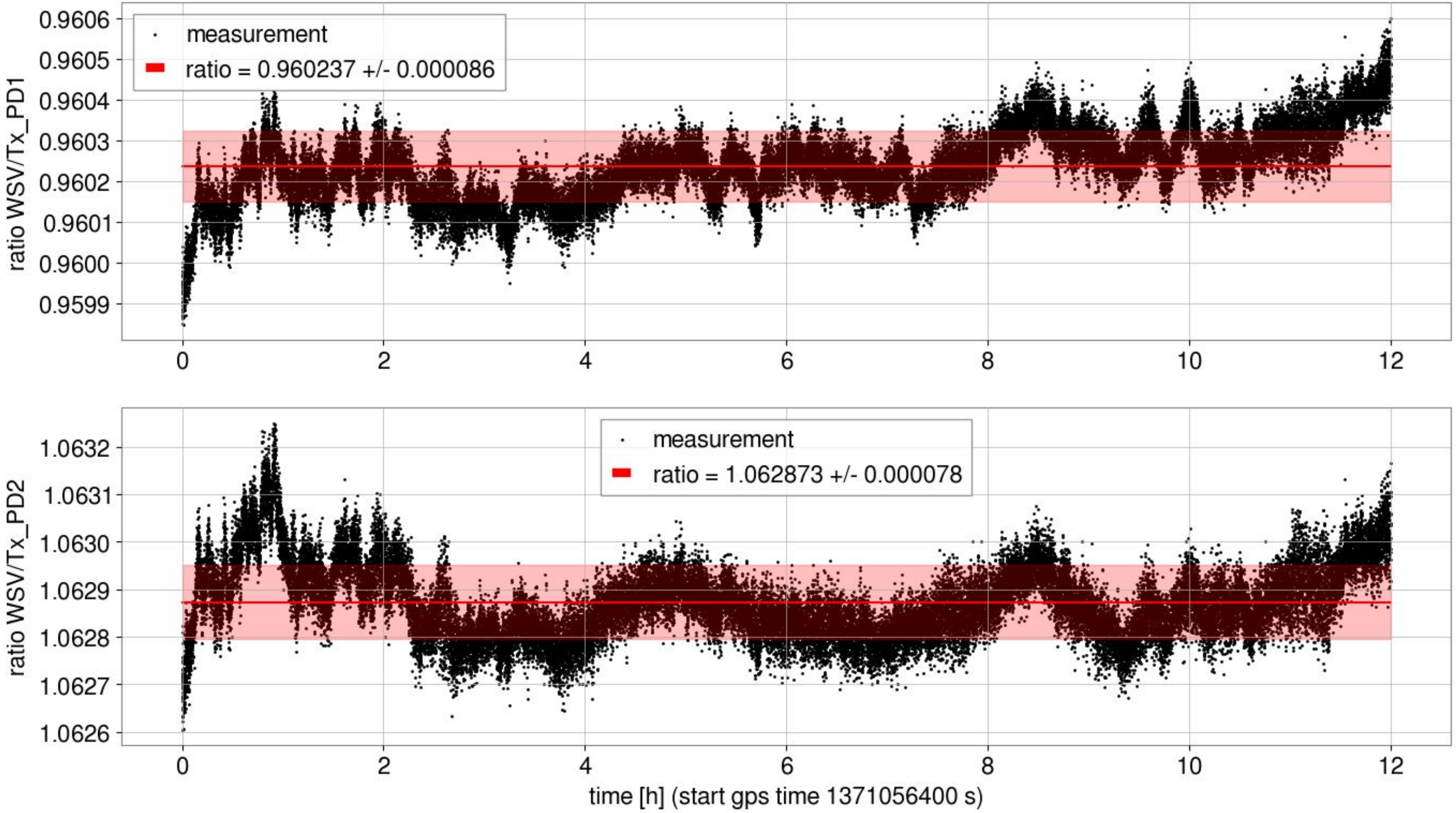
VIRGO CONTROL SIGNALS



PCal optical layout



Pcal calibration : Photodiodes calibration w.r.t. WS



PCal sensors calibration - formulas

Corrected power for photodiodes

$$P^{corr}_{TxPD1} = P^{raw}_{TxPD1} - P^{bg}_{TxPD1}$$

Corrected voltage for WSV

$$V^{corr}_{WSV} = \frac{V^{raw}_{WSV} - m \cdot (T_{WSV} - T^{bg}_{WSV}) - V^{bg}_{WSV}}{1 + \kappa \cdot (T_{WSV} - 300.15K)}$$

T_{WSV} the temperature

V^{raw}_{WSV} the raw voltage

$m = -0.1656\ mV/K,$

$\kappa = -1.486 \times 10^{-4} K^{-1}$

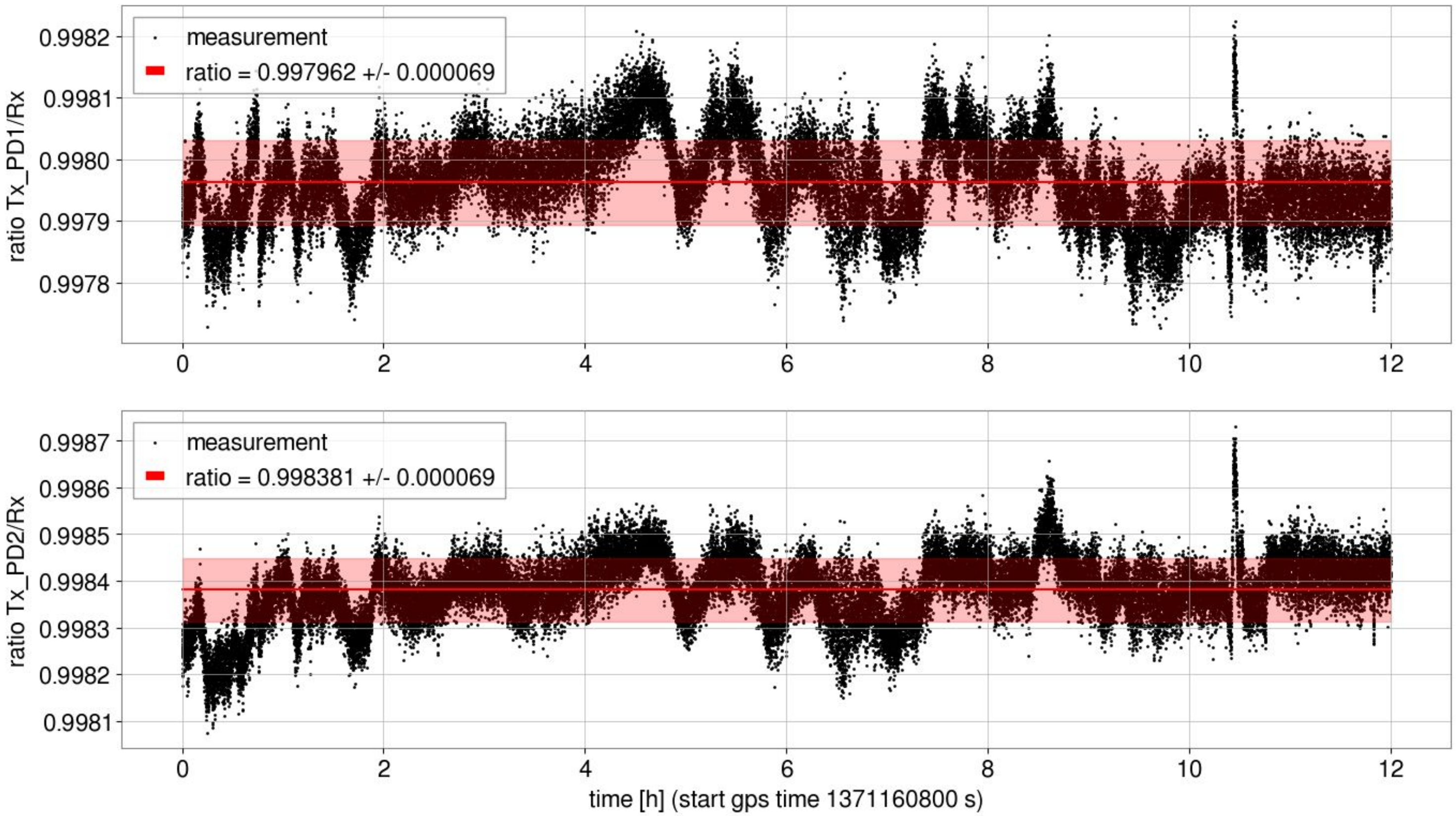
New gain and offset

$$C^{new}_{TxPD1} = C^{old}_{TxPD1} \cdot mean\left(\frac{V^{corr}_{WSV}}{P^{corr}_{TxPD1}}\right)\frac{1}{\rho_{WSV}}$$

$\rho_{WSV} = -2.611683V/W$

Ligo coefficient

Pcal calibration : Rx calibration w.r.t. Tx_PD1



Calibration of Rx spheres - formulas

Corrected power for photodiodes

$$P_X^{corr} = P_X^{raw} - P_X^{bg}$$

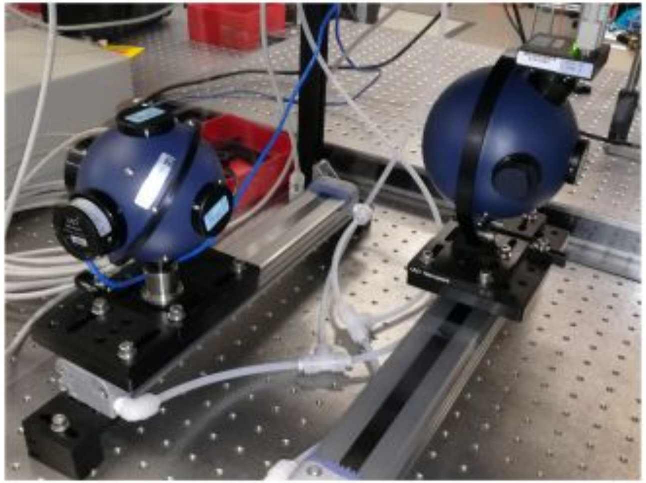
New gain and offset

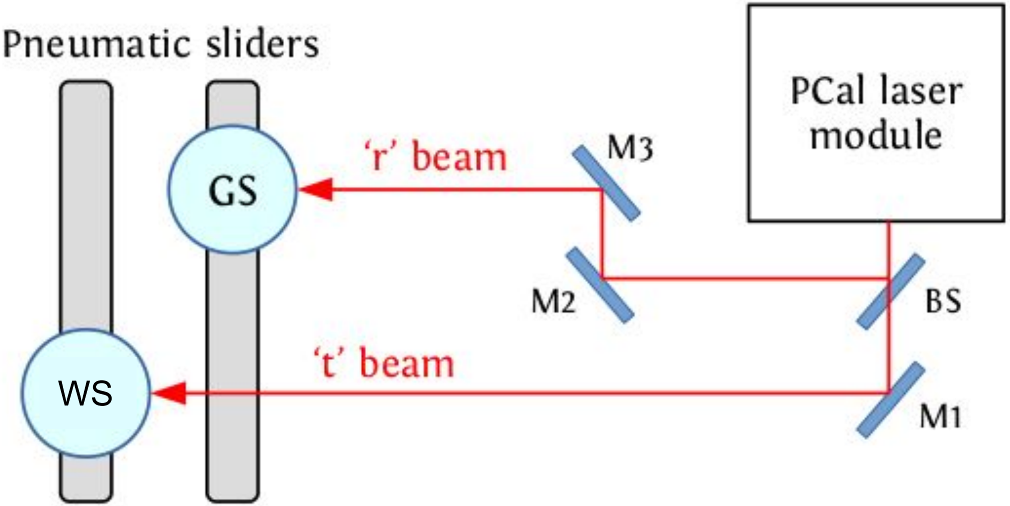
$$C_{Rx}^{new} = C_{Rx}^{old} \cdot mean\left(\frac{P_{Tx\_PD1}^{corr}}{P_{Rx}^{corr}}\right)$$

$$O_{Rx}^{new} = (O_{Rx}^{old} - P_{Rx}^{bg}) \cdot mean\left(\frac{P_{Tx\_PD1}^{corr}}{P_{Rx}^{corr}}\right)$$

PCAL intercalibration

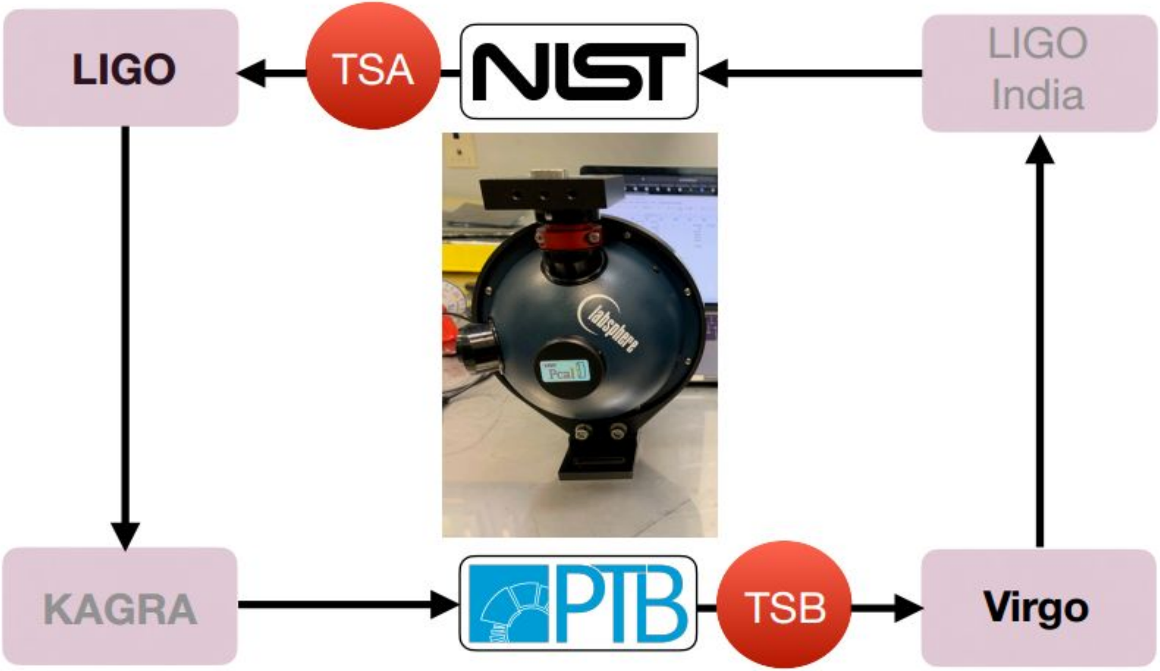
- Intercalibration method using pneumatic rail to slide the two spheres





SOURCE - PhD thesis D. Estevez

Pcal intercalibration



SOURCE - LIGO-G2300653-v8

Calibration transfers

1

REF	NEW
Pcal → End Mirrors	E.M. → End Mirrors

→

2

REF	NEW
Pcal → End Mirrors	E.M → Input Mirrors

→

3

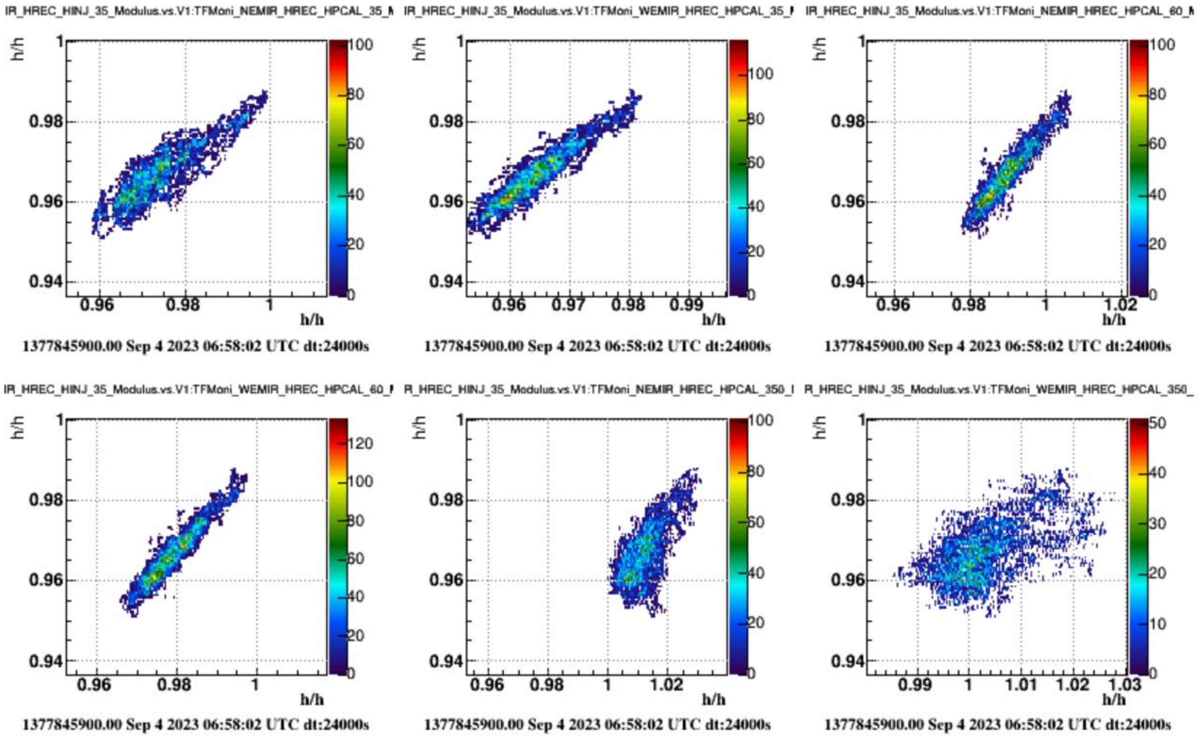
REF	NEW
E.M. → Input Mirrors	E.M. → BS, PR, SR

Take correlation into account

- Correlation plot → trying to take into account frequency correlation in the random selection

Example of modulus correlation between the NEMir 37.5Hz line and other permanent lines

Not yet taken into account in uncertainty computation



CheckHrec result for the 11th of May 2023