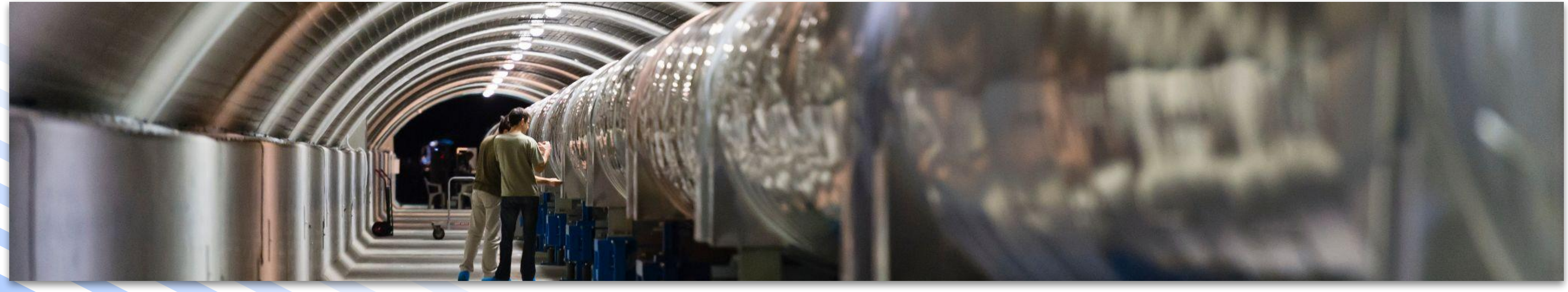
VIRGO CALIBRATION AND DATA RECONSTRUCTION

How to compute the data réconsfructiOn Uncertainty

Journée de Rencontre Jeunes Chercheurs 2023 - Cervane Grimaud



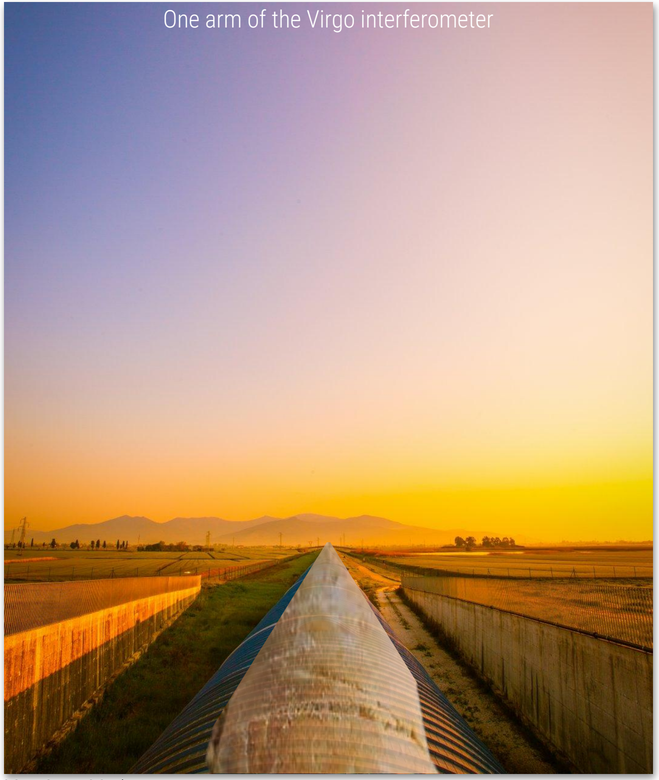
Summary

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

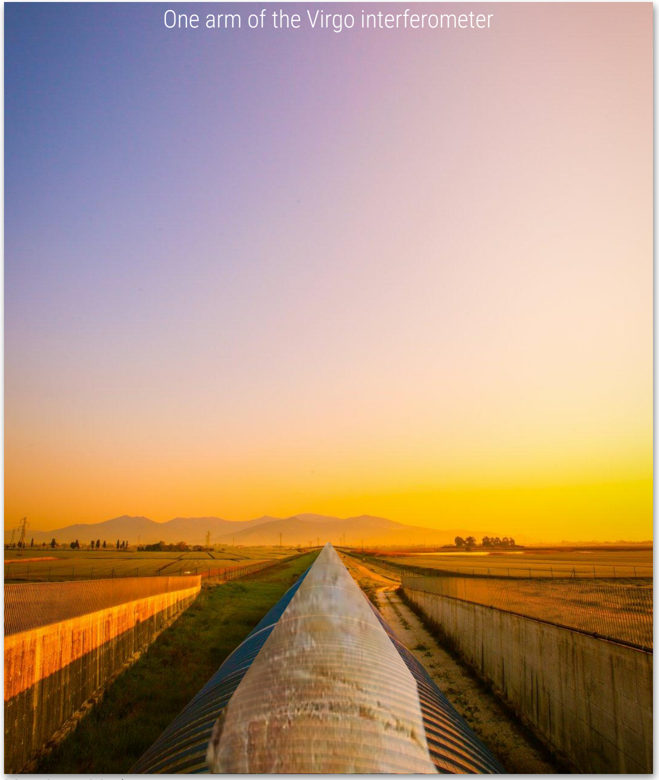


SOURCE - EGO photo

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



SOURCE - EGO photo

Gravitational waves

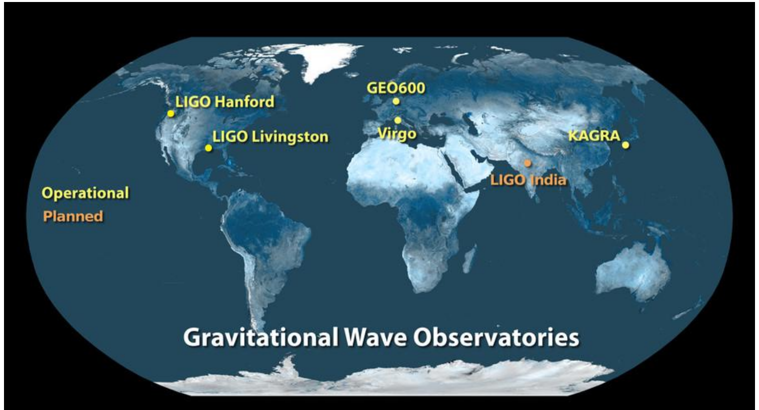
- Deformation of the space time metric
- Propagating at the speed of light
- Produced by various sources
  (**compact binary coalescences** *(detected)* , supernova, stochastic background…)

Gravitational waves

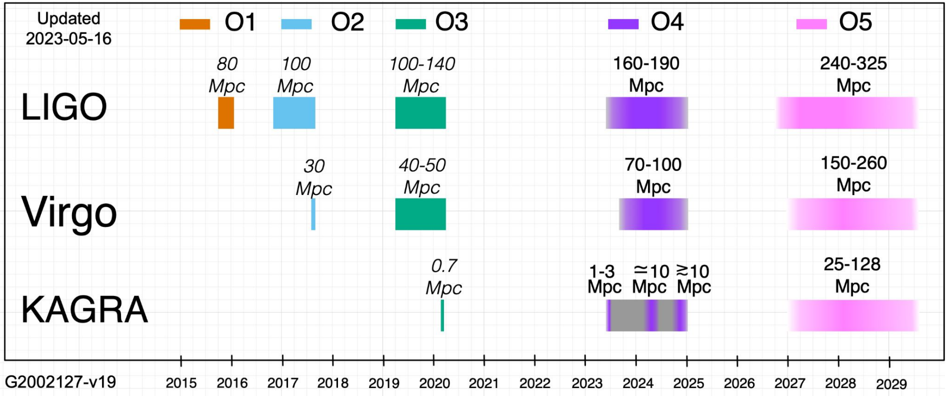
- Deformation of the space time metric
- Propagating at the speed of light
- Produced by various sources
(**compact binary coalescences** *(detected)* , supernova, stochastic background…)

LIGO-Virgo-KAGRA collaboration

- Collaboration between 4 ground interferometers
- 90 GW signal detected in O2 and O3
- Various scientific goals (Neutron Star physics, Black Hole physics, gravity studie, multi-messenger astronomy …)



SOURCE - Caltech/MIT/LIGO Lab

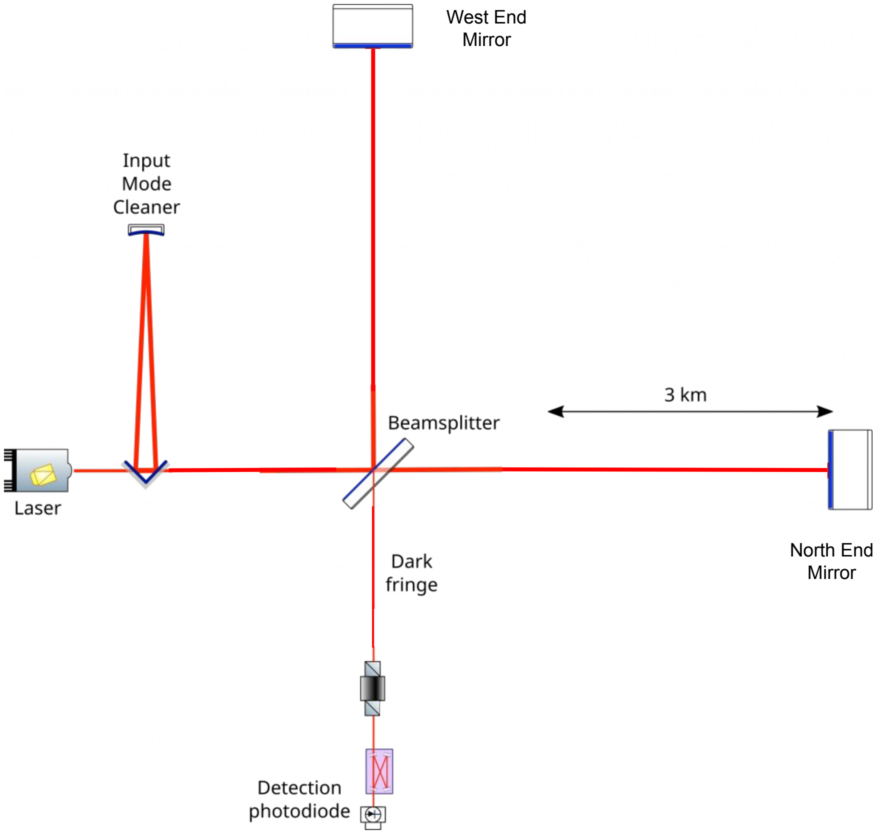


SOURCE - LVK collaboration

Detection method

3 km long arms interferometer with :

- Laser source, near-IR (1064 nm)
- Beam splitter (BS)
- End mirrors (NE, WE)

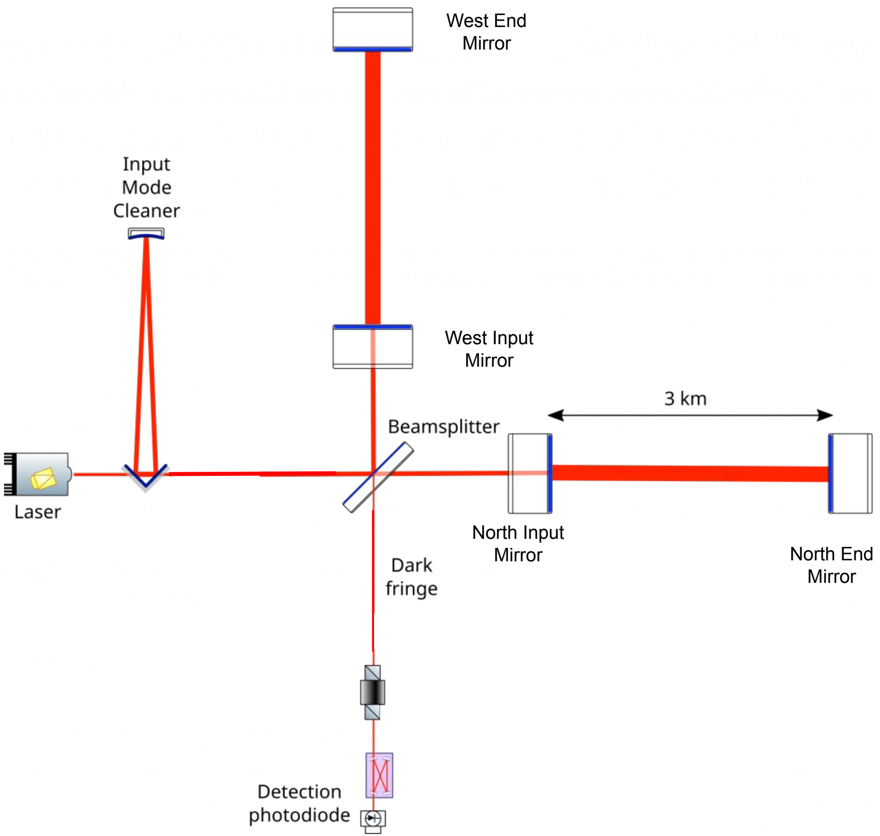


SOURCE - Virgo collaboration

Detection method

3 km long arms interferometer with :

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

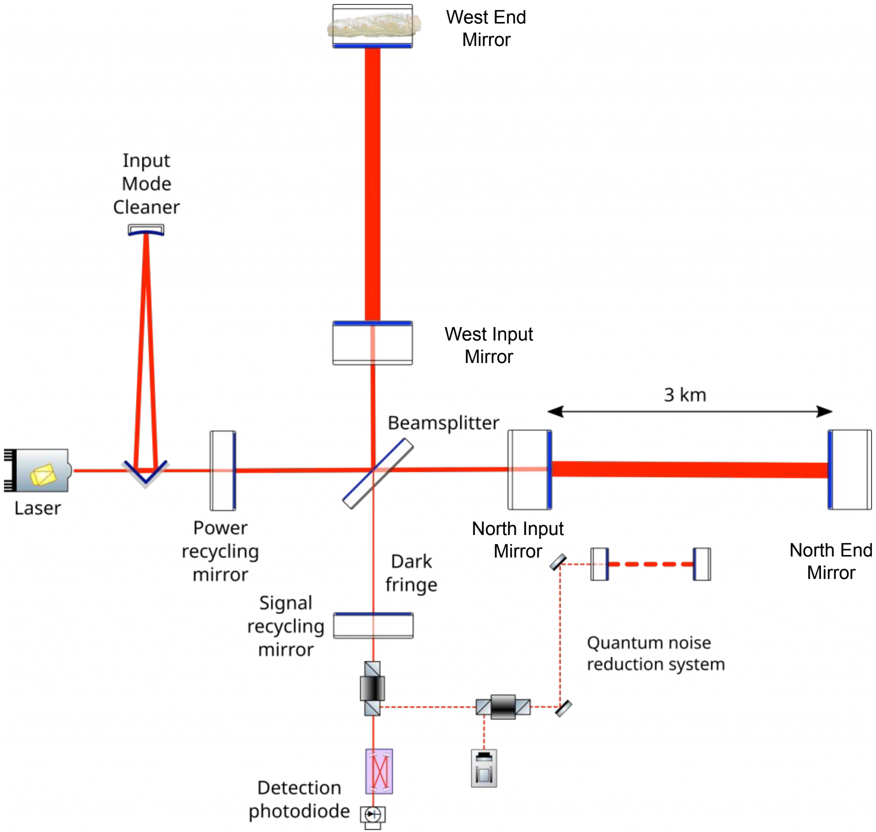


SOURCE - Virgo collaboration

Detection method

3 km long arms interferometer with :

- Laser source, near-IR (1064 nm)
- Beam splitter (BS)
- End mirrors (NE, WE)
- **Input mirrors (NI, WI)**
  Resonant optical Fabry Perot cavities
  → increase effective length travel by the beam
- Power recycling mirror (PR)
  Signal recycling mirror (SR)
  Quantum noise reduction system
- Suspended mirrors in vacuum



SOURCE - Virgo collaboration

Detection method

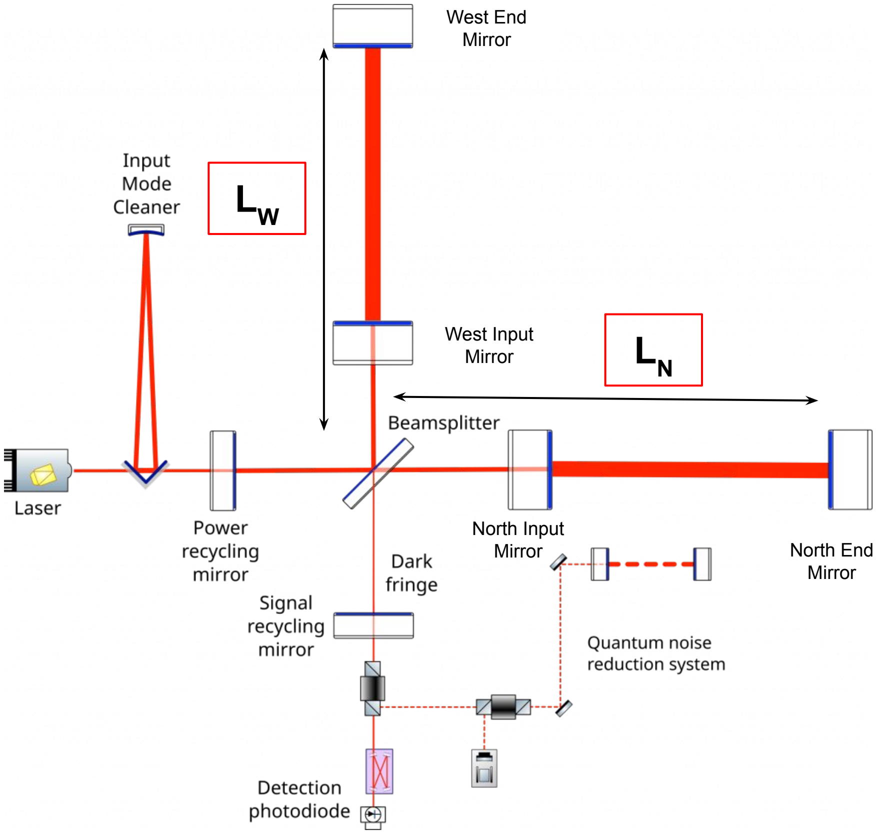
When GW goes through :

- 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

Detection method

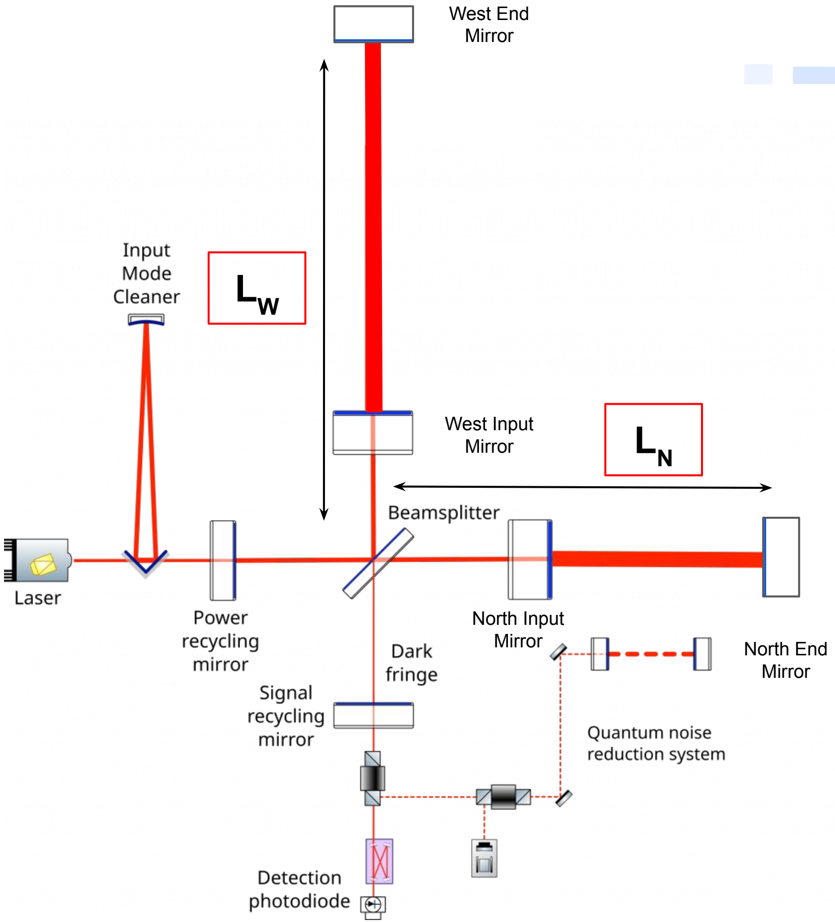
When GW goes through :

- 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

Detection method

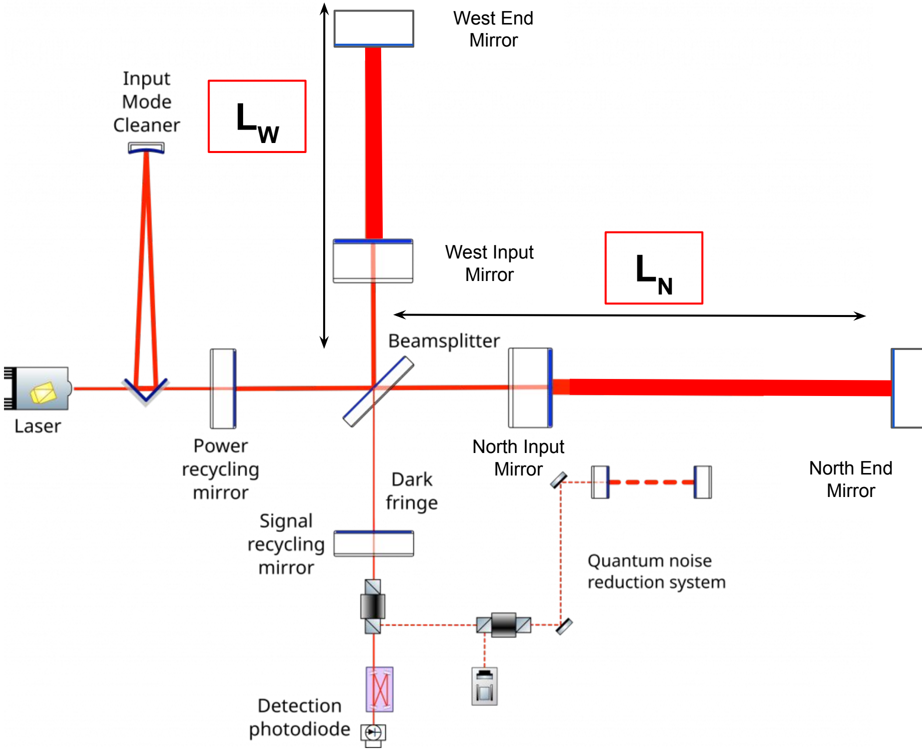
When GW goes through :

- 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



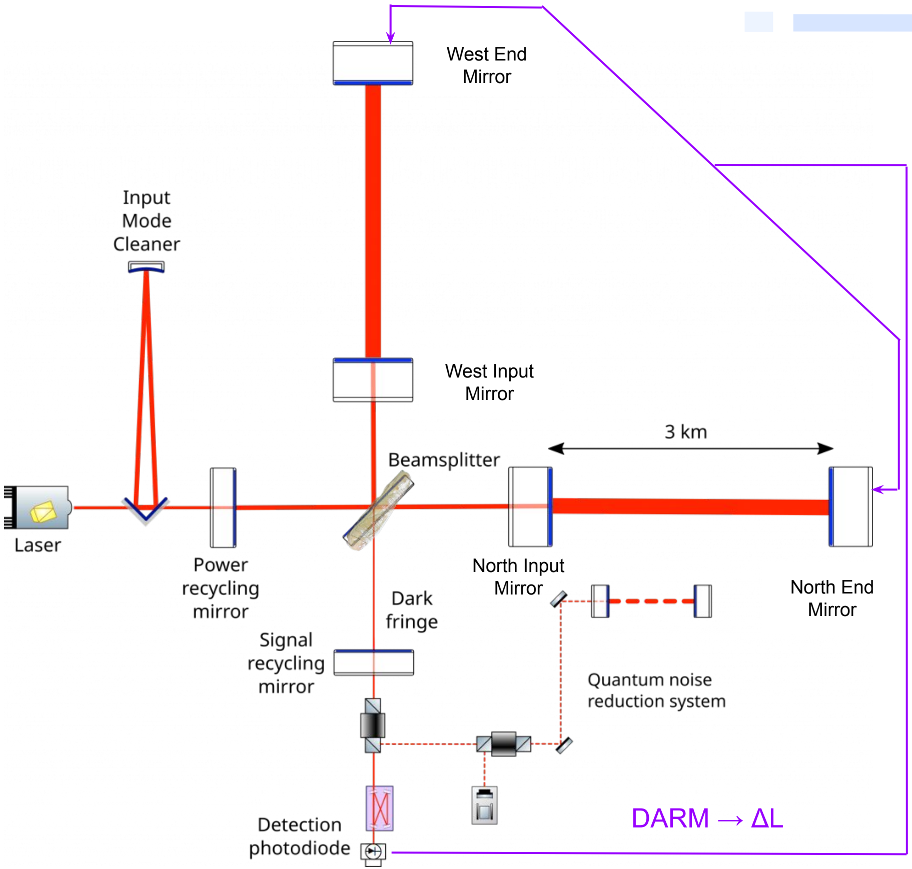
SOURCE - Virgo collaboration

Operating the interferometer

Mirror are moving at low frequency

⬇

Need to control the mirrors movement to operate the interferometer



SOURCE - Virgo collaboration

Operating the interferometer

Mirror are moving at low frequency

↓

Need to control the mirrors movement to operate the interferometer

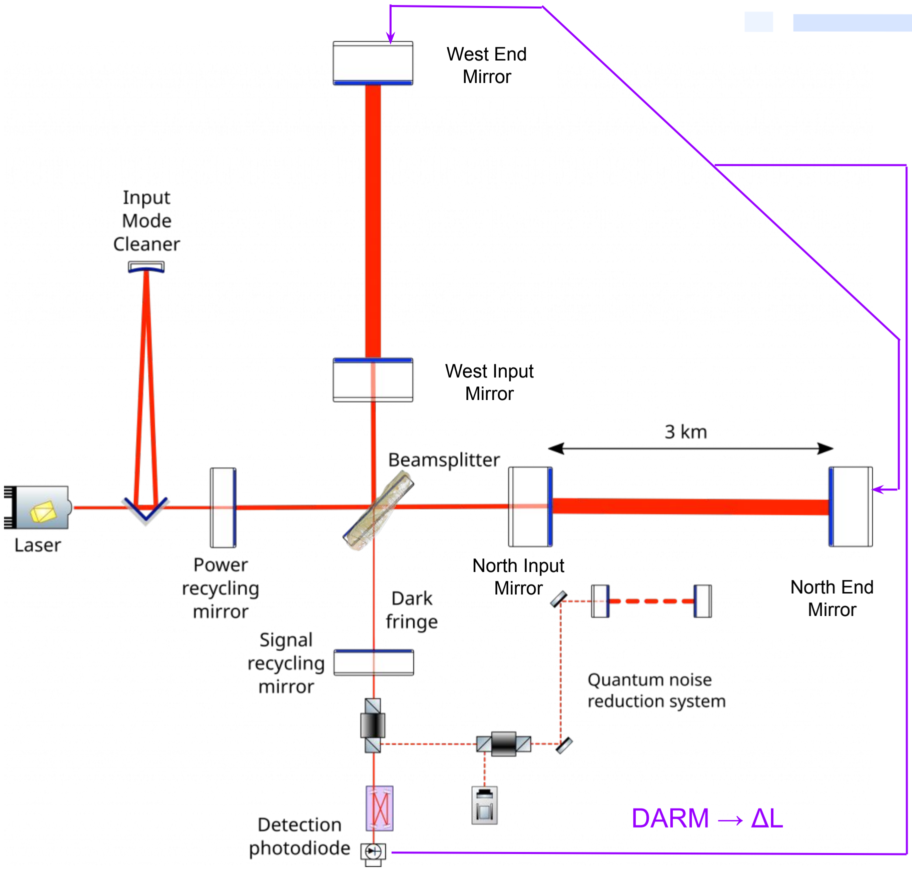
↓

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



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**

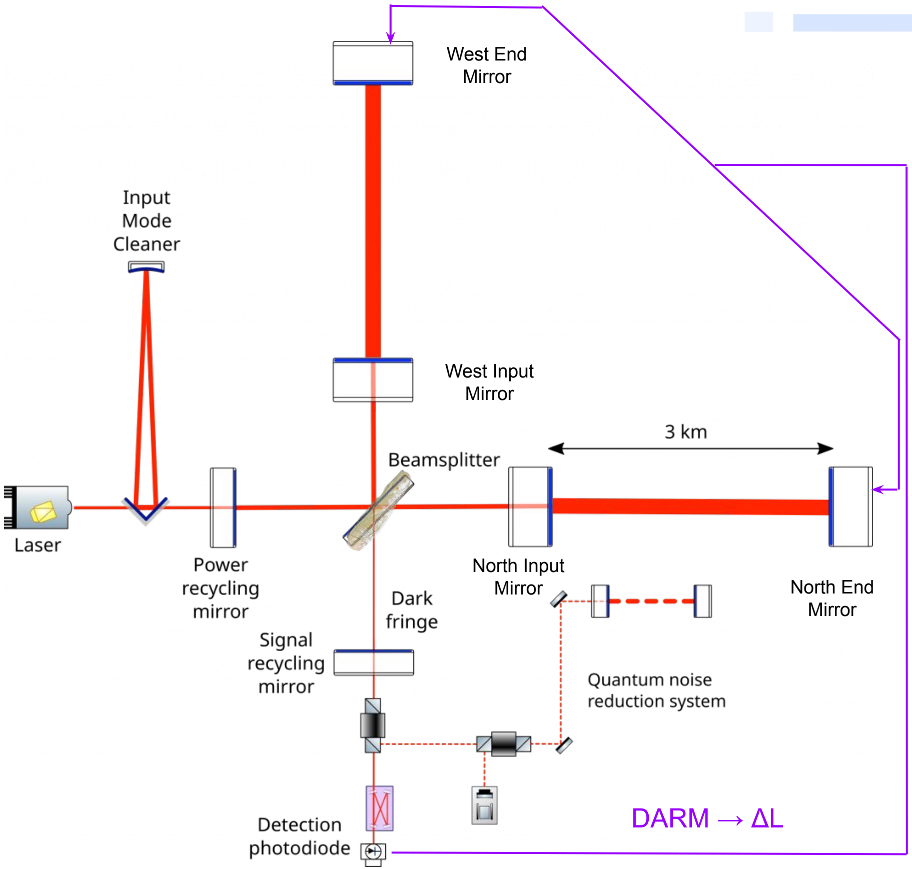
To check and control different parameters of the interferometer

↓

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**

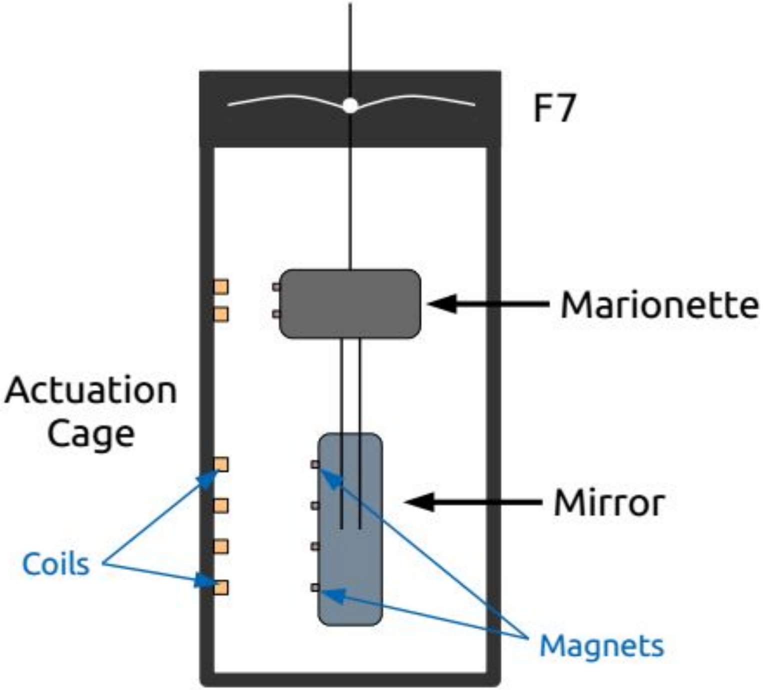


SOURCE - Virgo collaboration

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

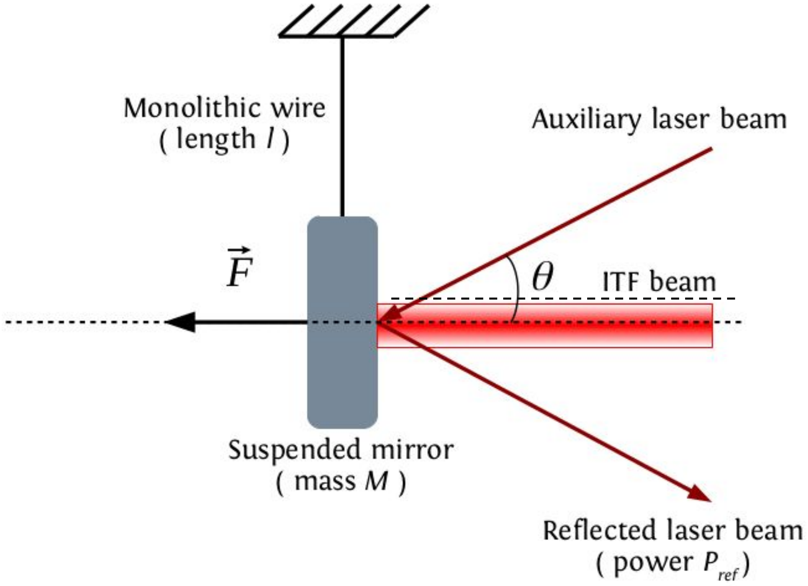
Mirrors actuation

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



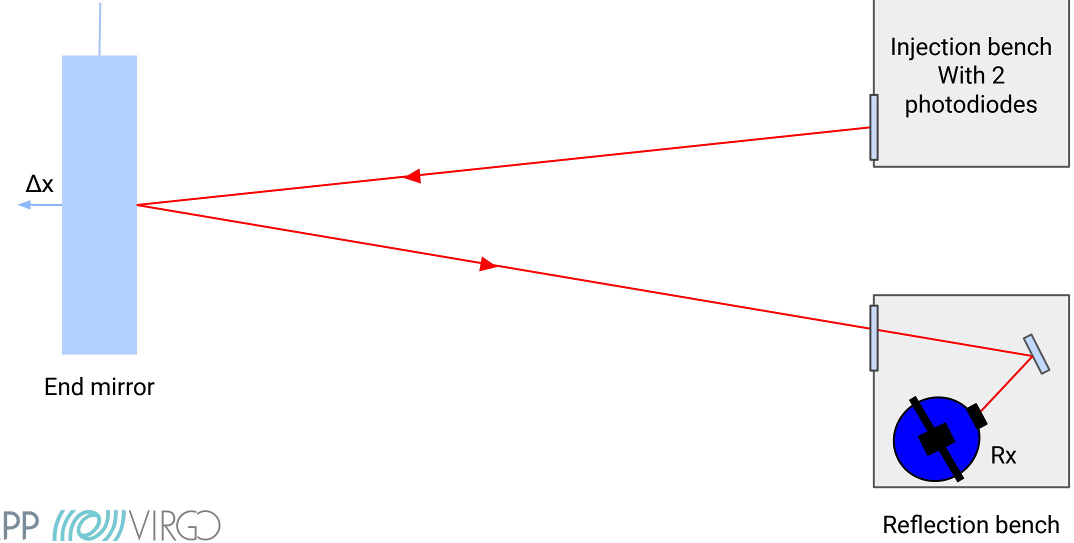
SOURCE - PhD thesis D. Estevez

Mirror motion induced by Pcal actuator

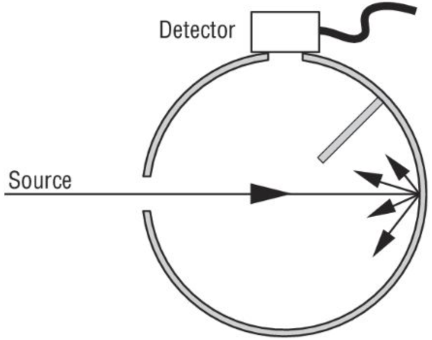
Pcal setup in **observation mode** :

- 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

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

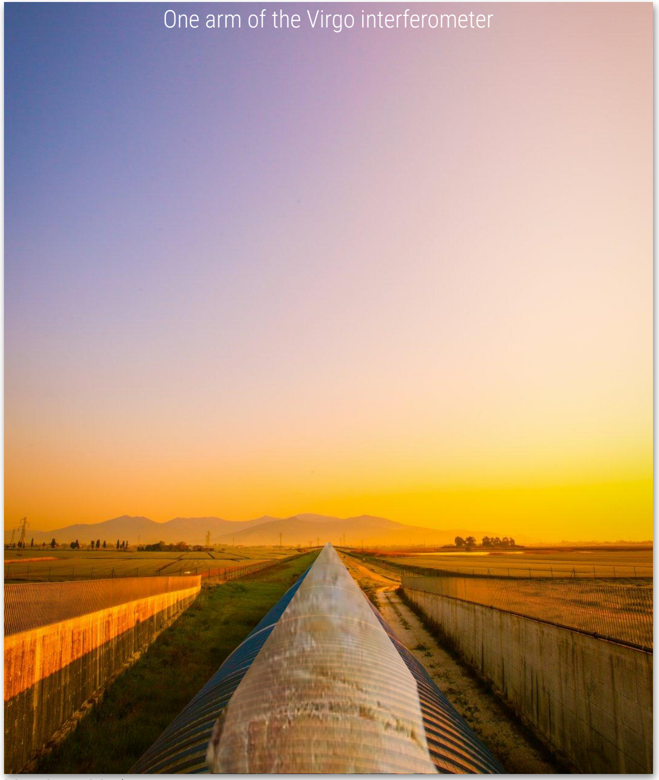


SOURCE - LIGO-G2300653-v8



SOURCE - PhD thesis D. Estevez

One arm of the Virgo interferometer

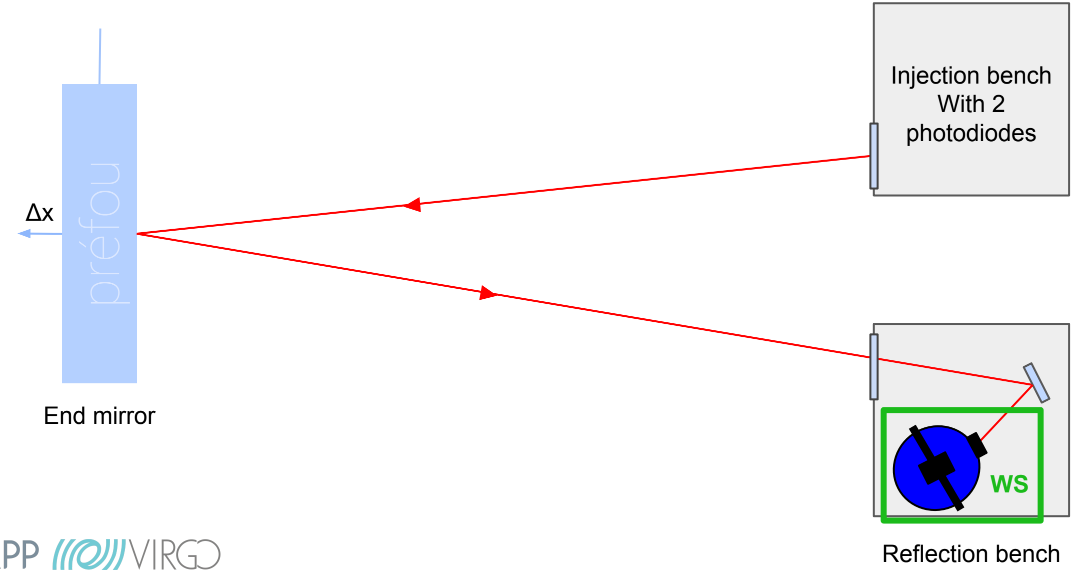


SOURCE - EGO photo

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**

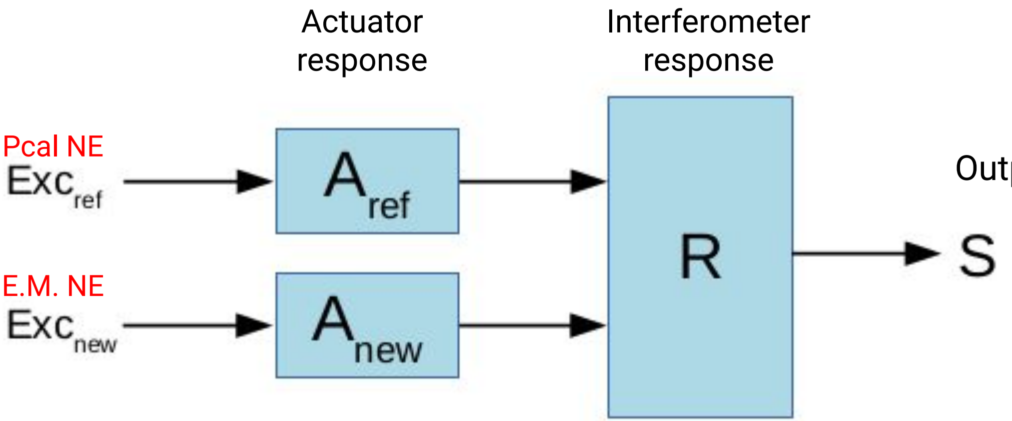


Pcal

Reference for the rest of the calibration

Calibration principle

- Series of calibration transfers
- ComPare actuator of RÉference *(ref)* to actuator to calibrate *(new)* by injecting signals inside the interFerometer with bOth actUators

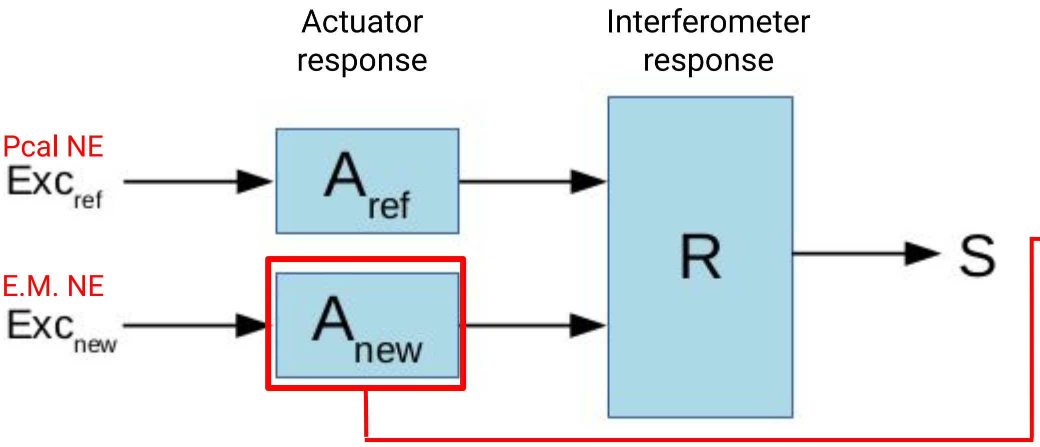


Output signal of the interferometer

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

Calibration principle

- Series of calibration transfers
- Compare actuator of reference *(ref)* to actuator to calibrate *(new)* by injecting signals inside the interferometer with both actuators
- Signals combined to to extract A_{new}

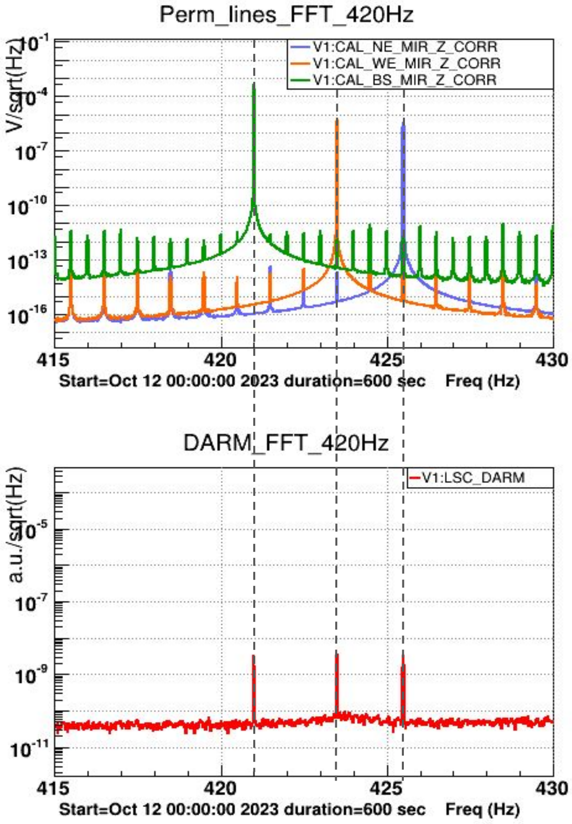


$$A_{new} = (S_{out}/Exc_{new}) \times (S_{out}/Exc_{ref})^{-1} \times A_{ref}$$

Injecting signal inside the interferometer

Lines injections

- Sinusoidal signals sent to move the mirrors using the different actuators (Pcal and Electromagnetic)
- Example of the 420Hz lines injected with E.M. actuators on NE, WE and BS mirrors
- Lines injected seen in the fourier transform of the DARM signal



Noise injections

- Broadband injections sent to move the mirrors

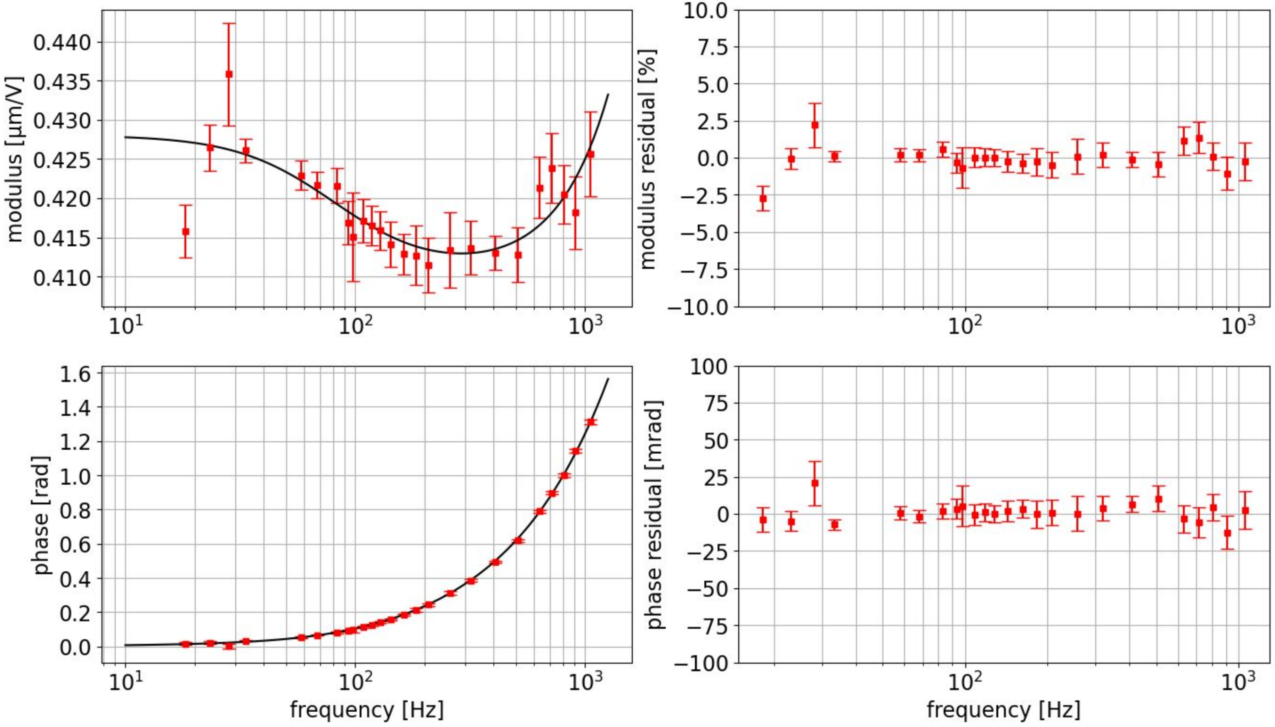
O4 Calibration models - Example

04/08/2023 results :

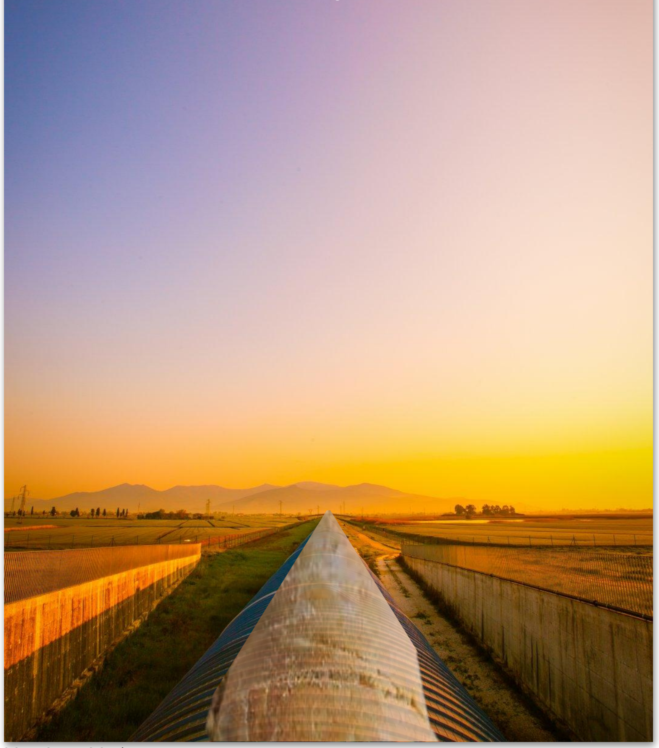
North End electromagnetic actuator response normalised by the pendulum response

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

Frequency response of the NE_MIR actuator

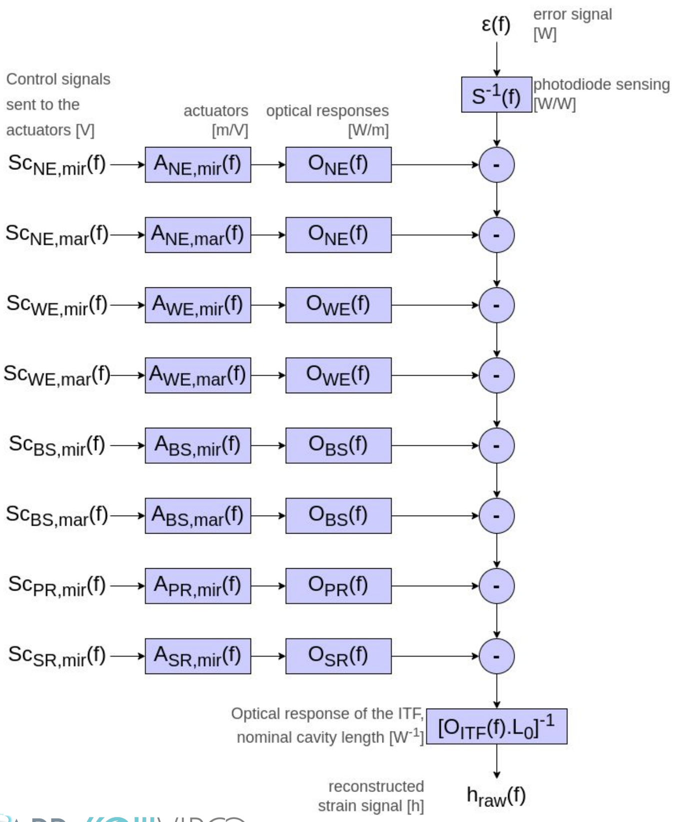


One arm of the Virgo interferometer



SOURCE - EGO photo

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

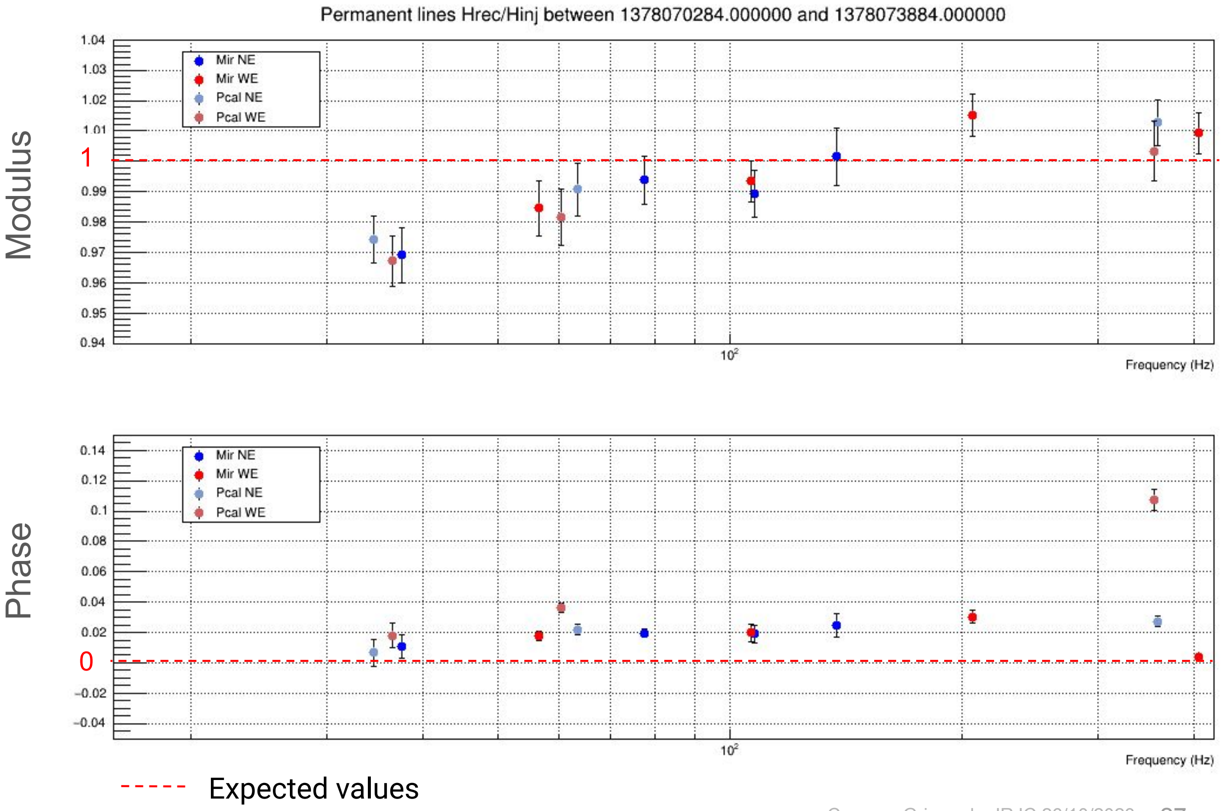
Hrec/hinj : modulus = 1 and phase =0

Calibration measurements

Permanent Lines

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

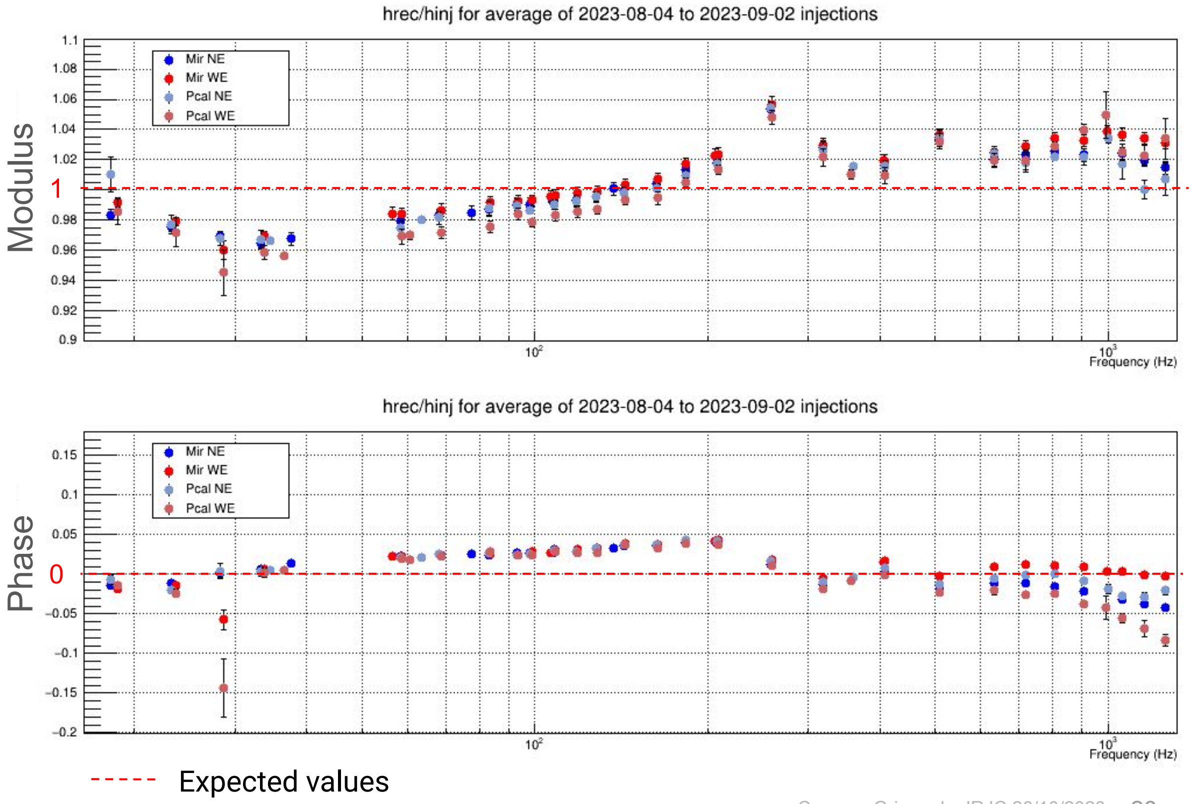
This plot shows a 1h average of h(t)/hinj modulus and phase from the 6 sep 2023 at 21h UTC



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,...

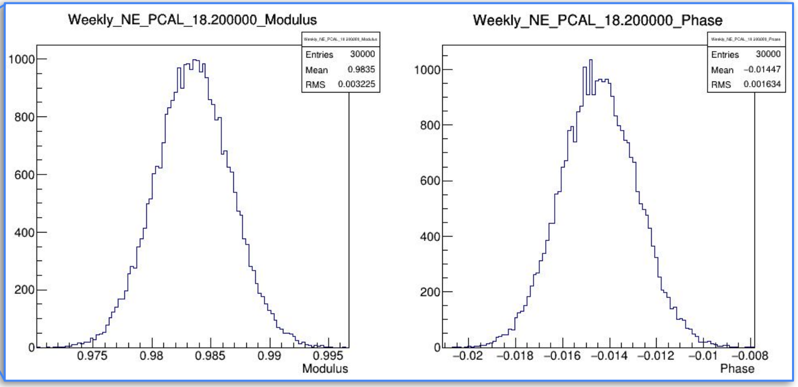
Uncertainty computation method

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



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

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

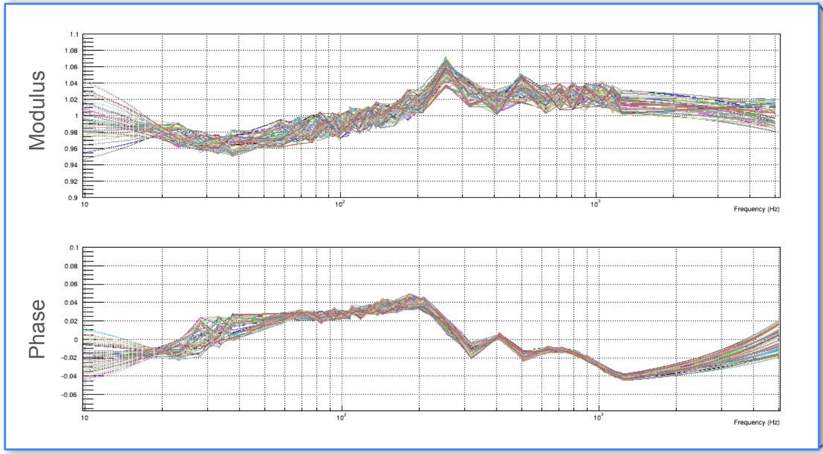
→ Random selection inside the distributions →

N sets of data

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

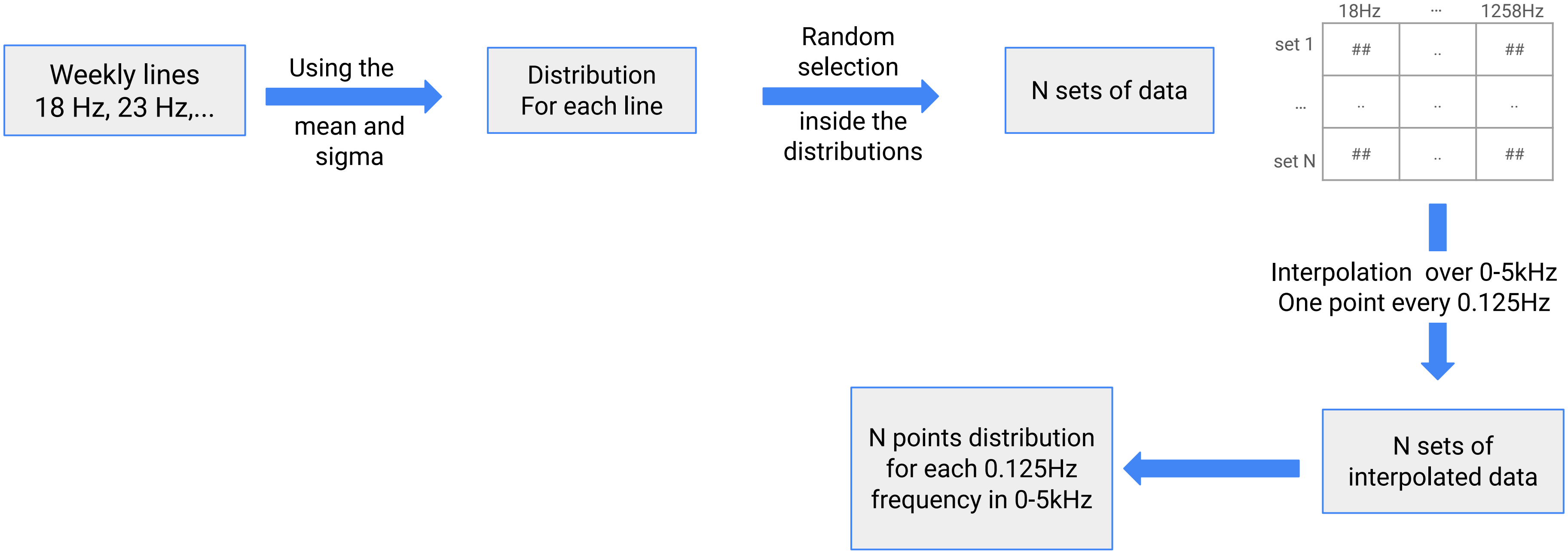
↓ Interpolation over 0-5kHz
One point every 0.125Hz ↓

N sets of interpolated data



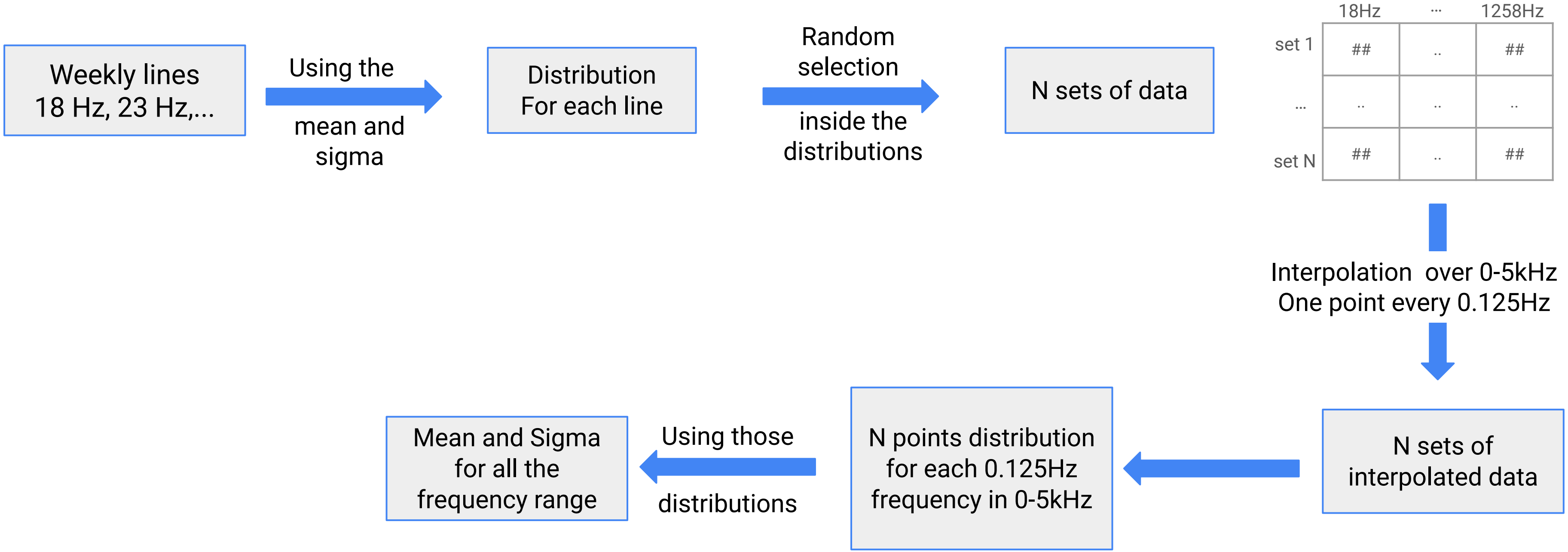
Uncertainty computation method

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



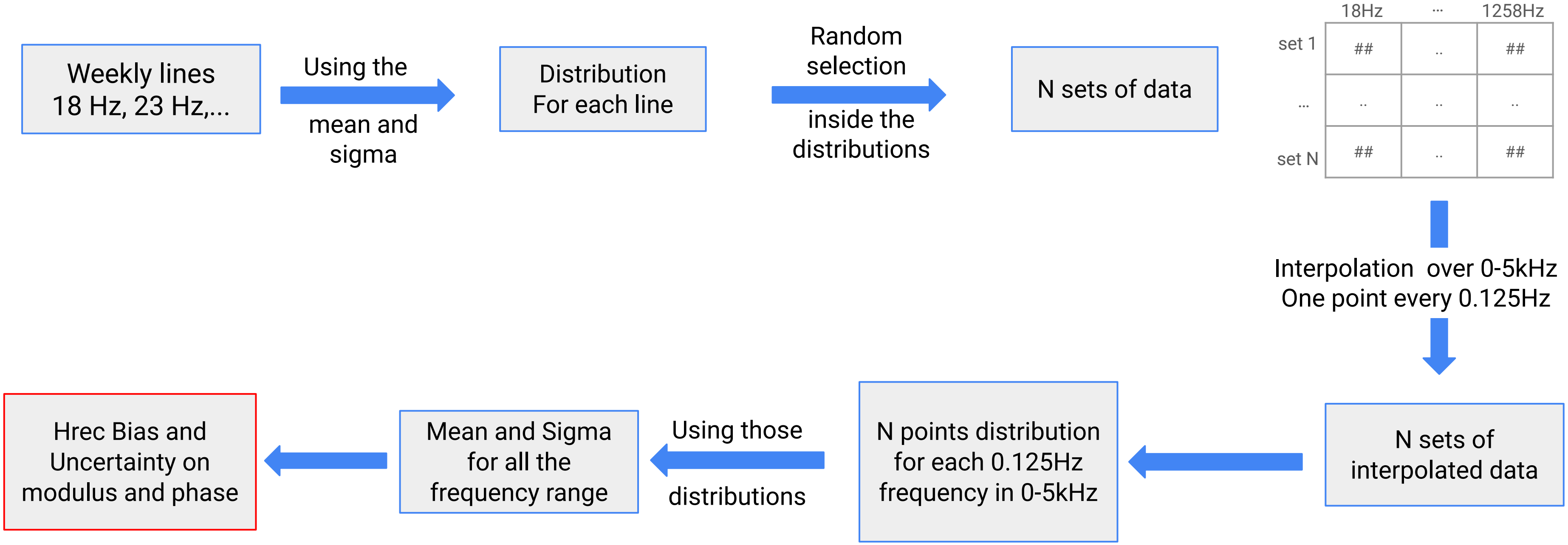
Uncertainty computation method

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



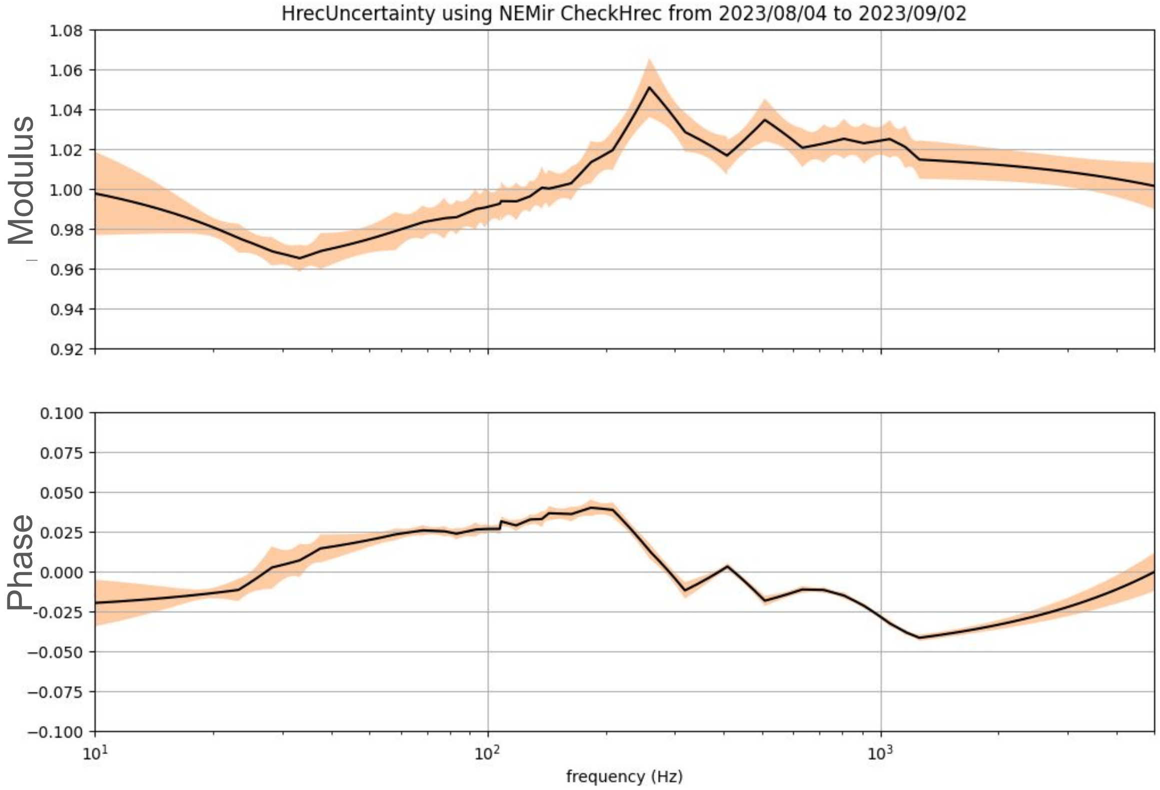
Uncertainty computation method

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



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

In this presentation we have seen that :

- To control the interferometer → we need control loops → so we need actuators
- To reconstruct the GW strain signal h(t) → we need to calibrate those actuators responses
- The reconstruction algorithm needs to be monitored → We need to implement a bias and Uncertainty computation method

Next steps are :

- Improvement of the Uncertainty computation method (adding permanent lines, correlations …)
- Taking more Hrec/Hinj data to monitor the bias and uncertainty over time
- Automatized the uncertainty computation procedure

Thank you !

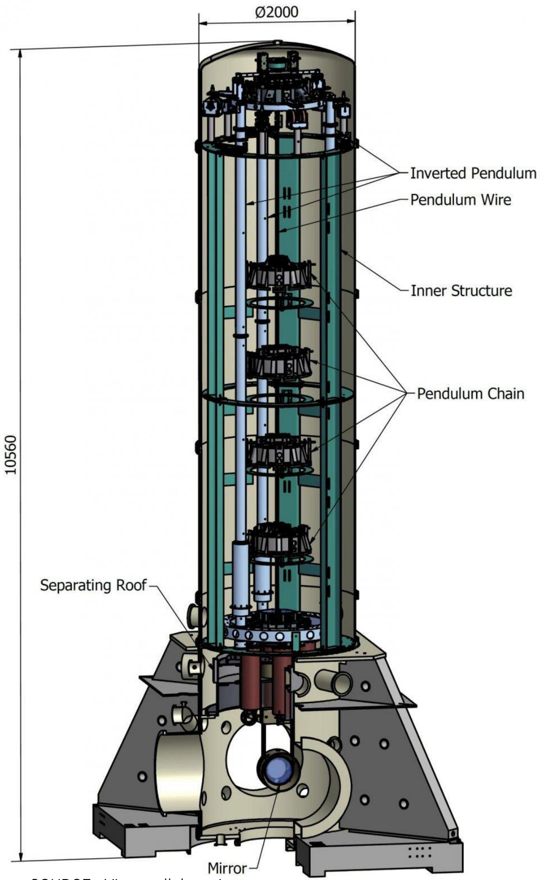
Thank you !

Did you see all of the 21 préfou references in my slides ?

Super attenuator system

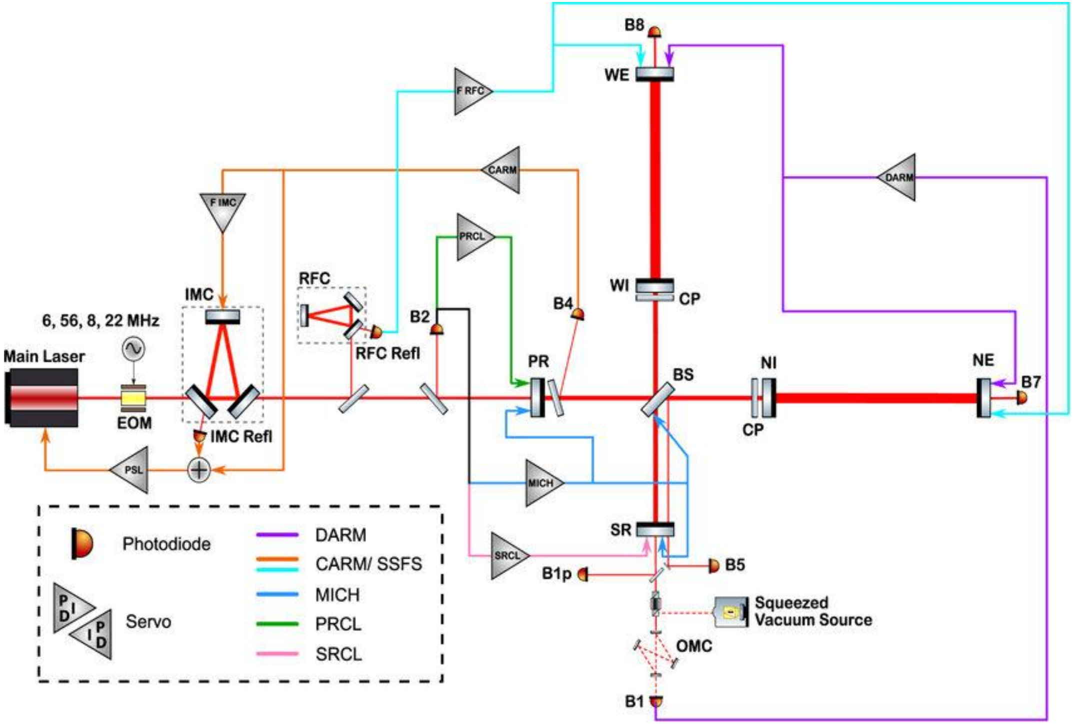
- Pendulum : longitudinal displacement
- Blade springs : vertical displacement
- Torsion threads : rotation

Resonant frequency < 1Hz



SOURCE - Virgo collaboration

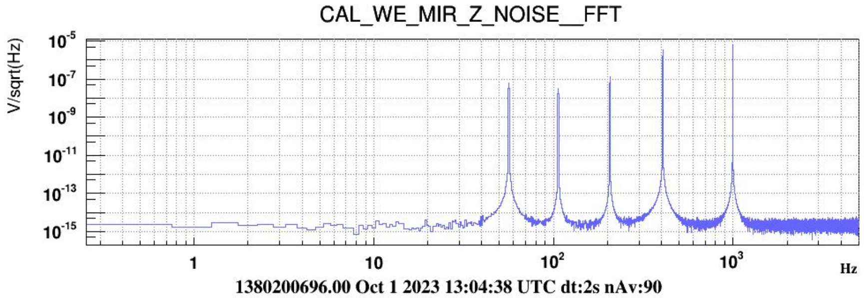
VIRGO CONTROL SIGNALS

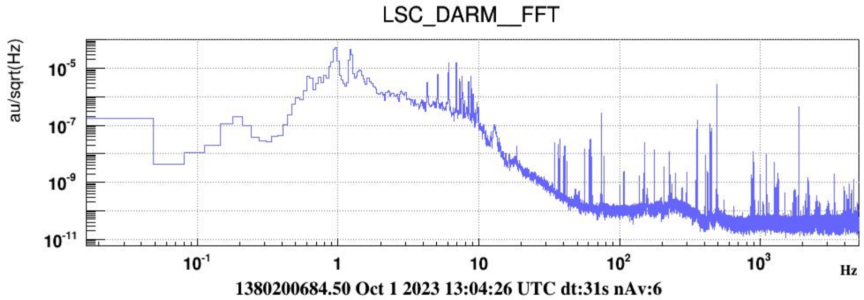


Injecting signal inside the interferometer

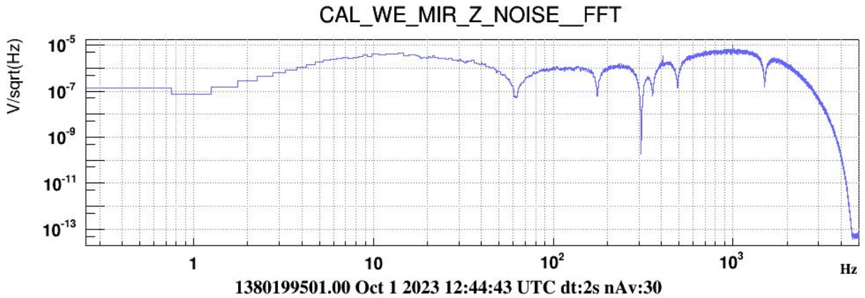
Noise injections on WE mirrors with E.M. actuator

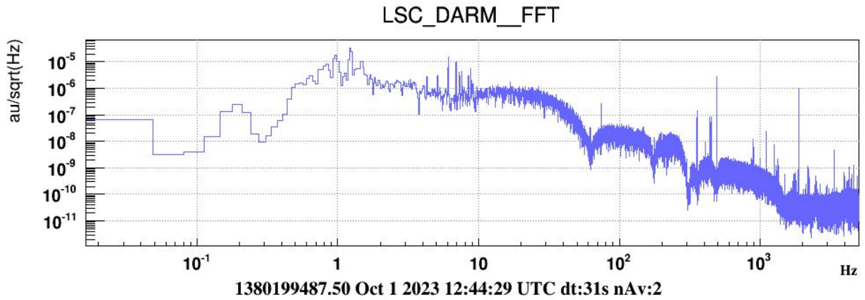
No noise injection



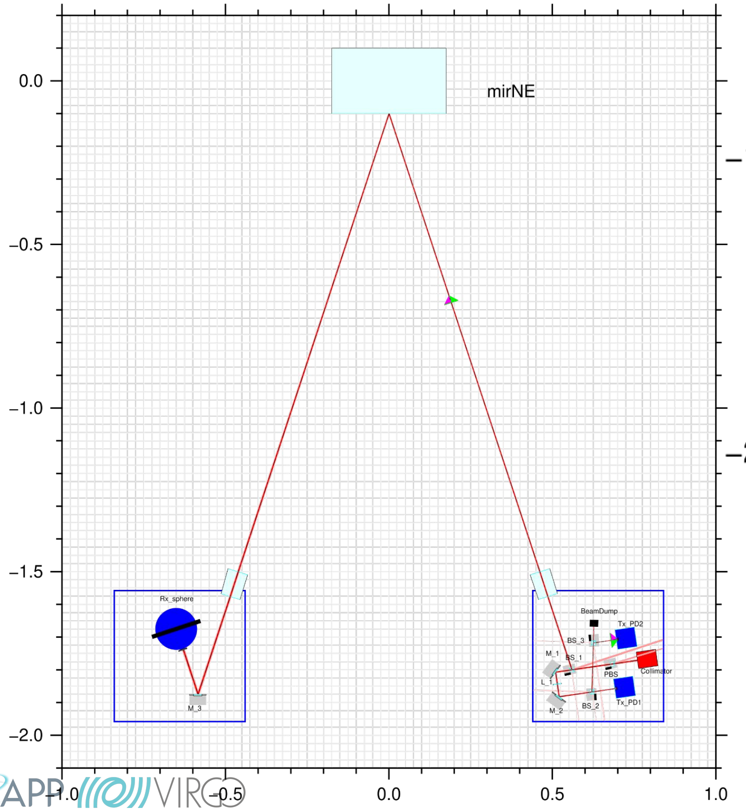


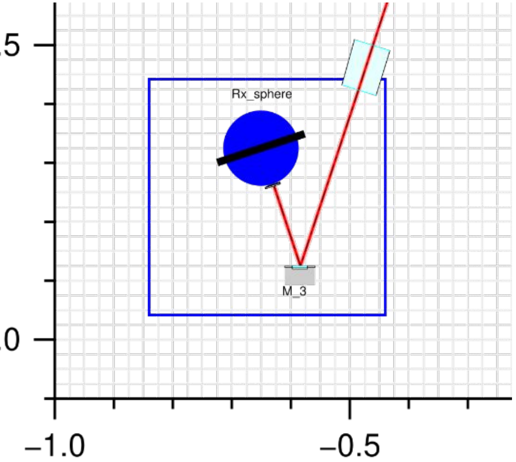
With noise injection

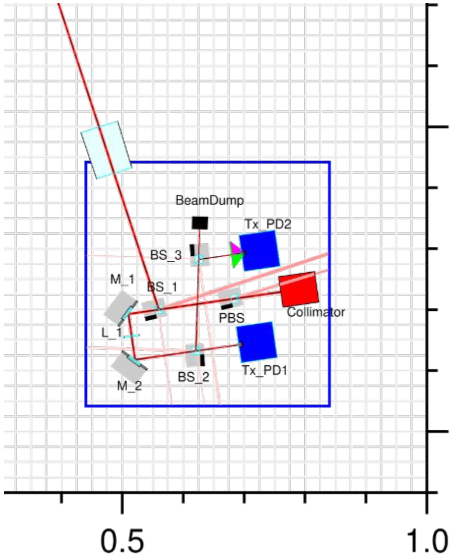




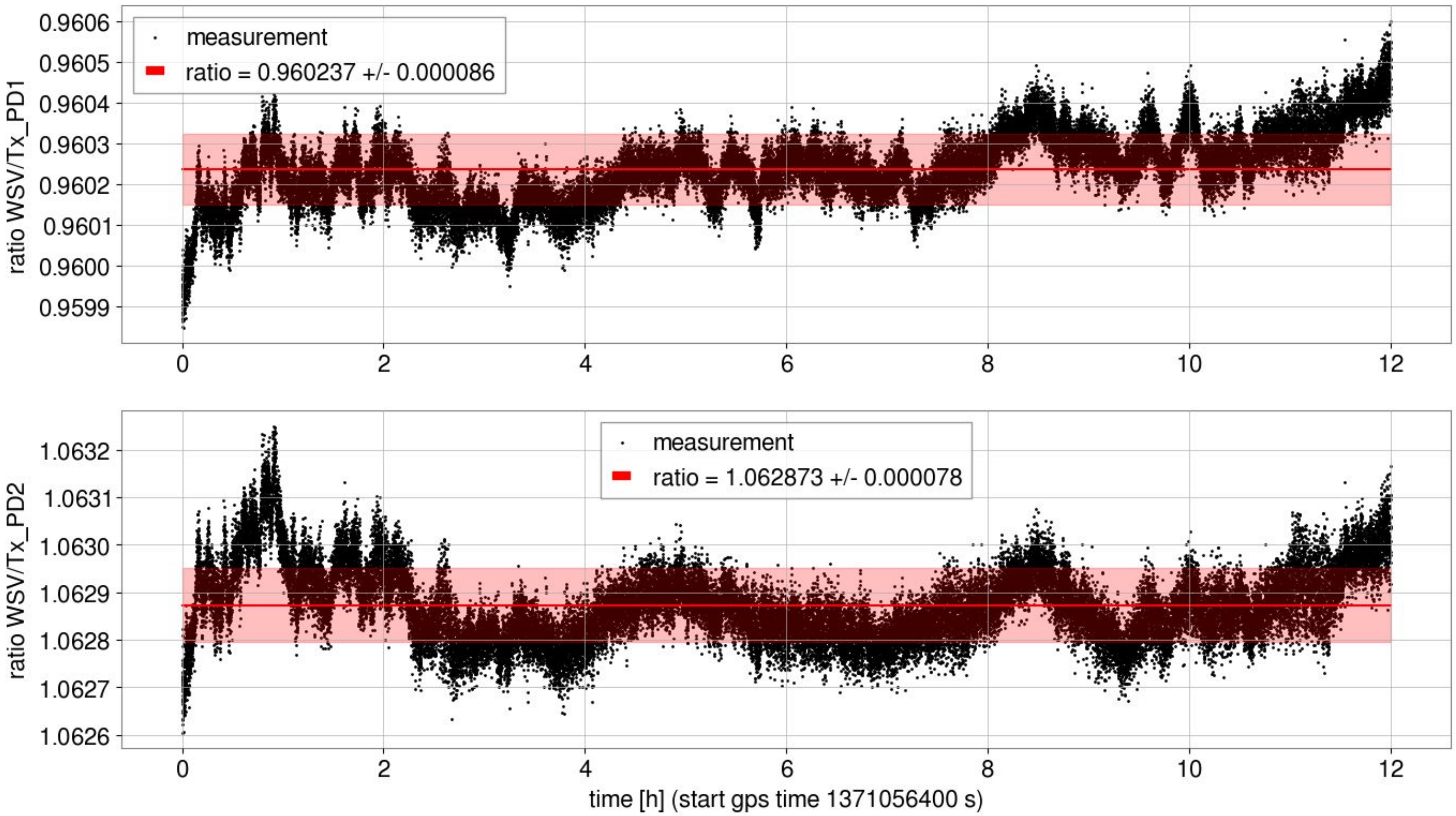
PCal optical layout







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

$m = -0.1656\ mV/K,$

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

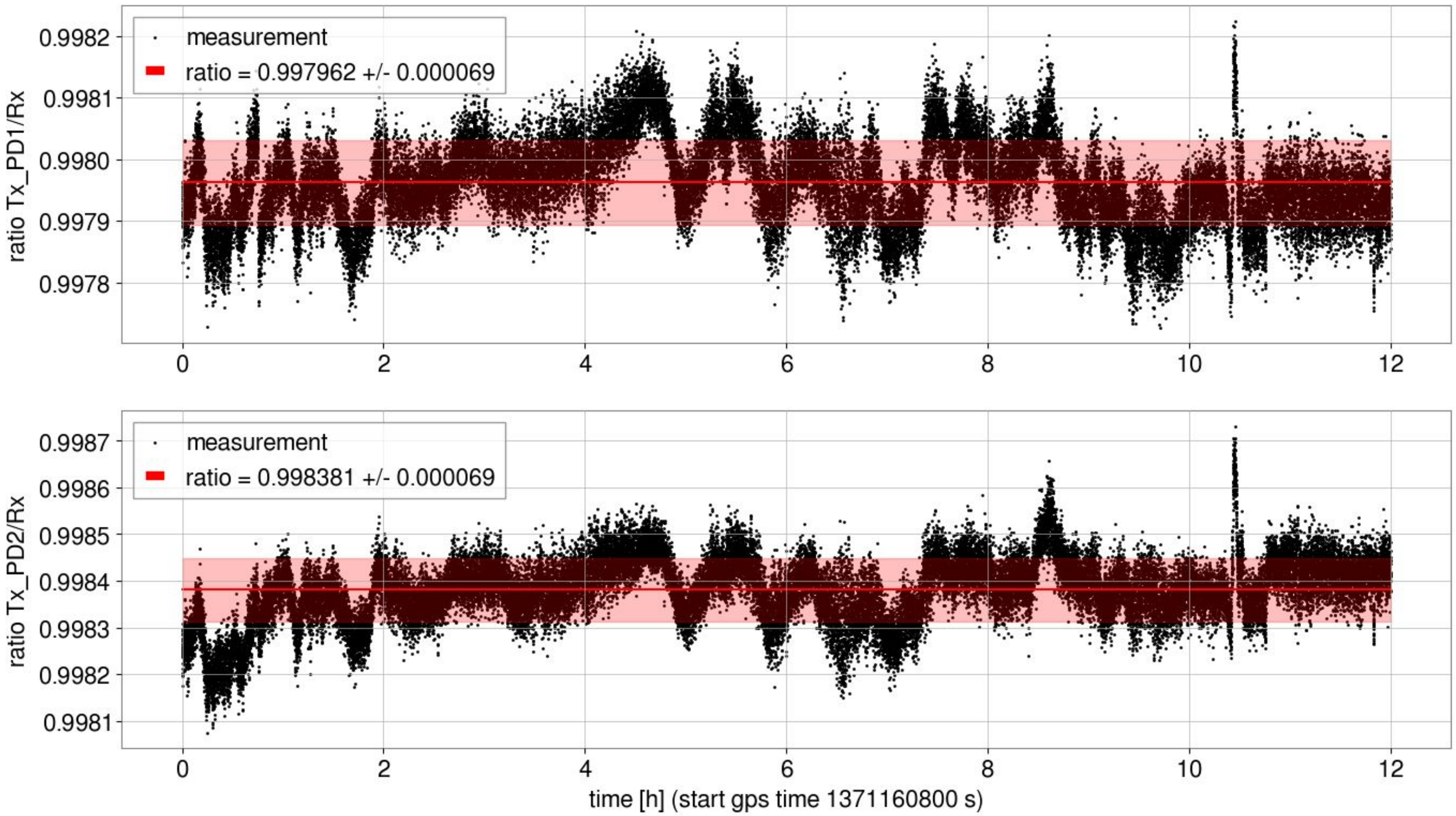
New gain and offset

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

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

Ligo coefficient

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



Calibration of Rx spheres - formulas

Corrected power for photodiodes

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

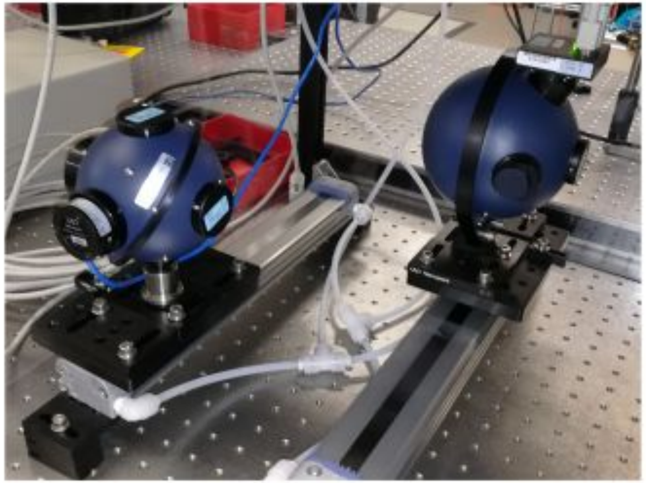
New gain and offset

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

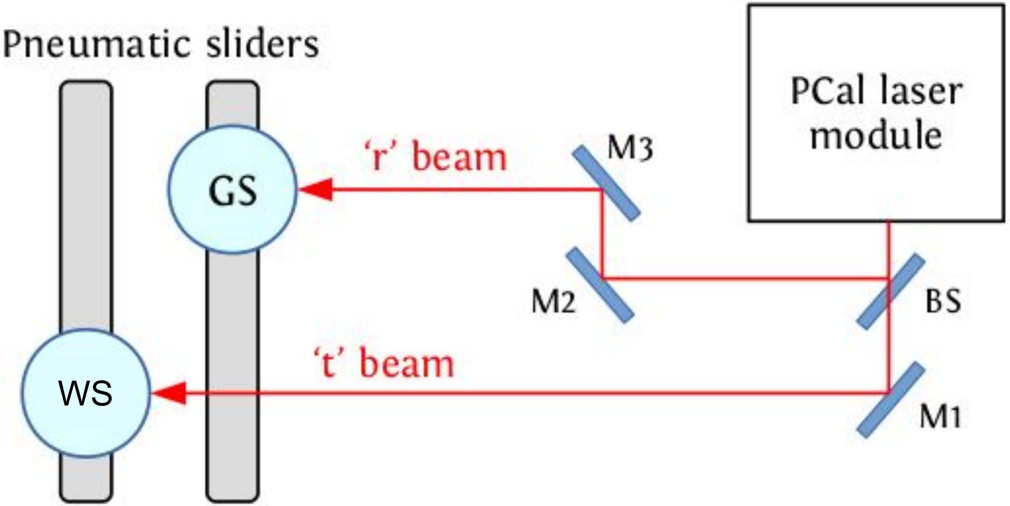
$$O_{Rx}^{new} = (O_{Rx}^{old} - P_{Rx}^{bg}) \cdot mean\left(\frac{P_{Tx\_PD1}^{corr}}{P_{Rx}^{corr}}\right)$$

PCAL intercalibration

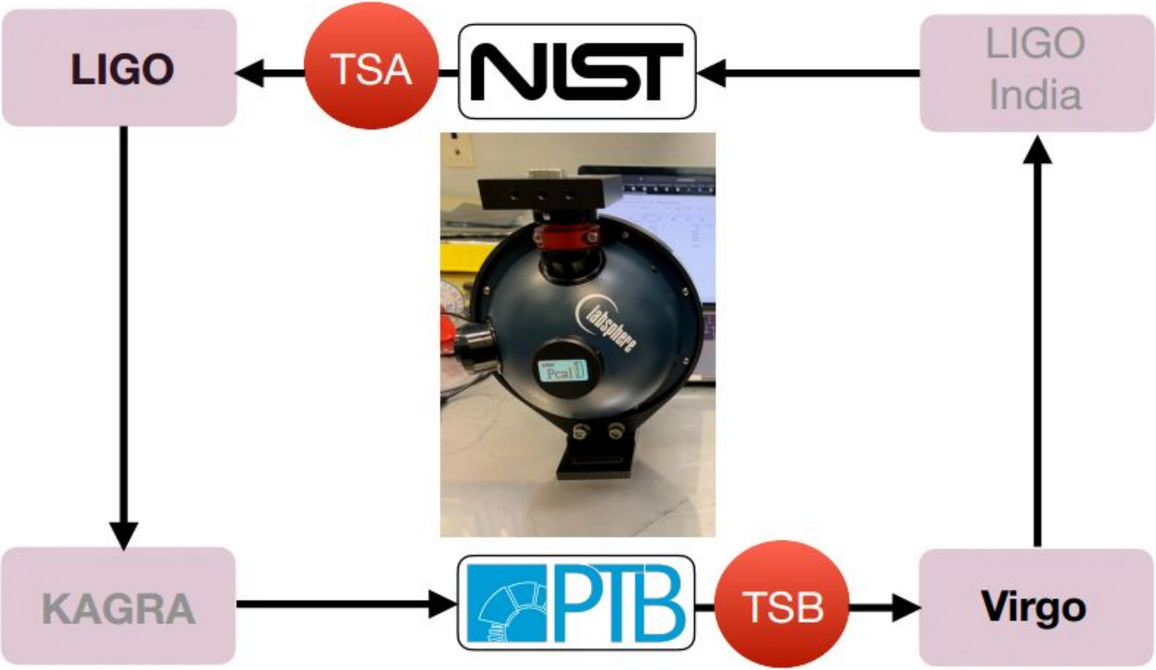
- Intercalibration method using pneumatic rail to slide the two spheres



SOURCE - PhD thesis D. Estevez



Pcal intercalibration



SOURCE - LIGO-G2300653-v8

Calibration transfers

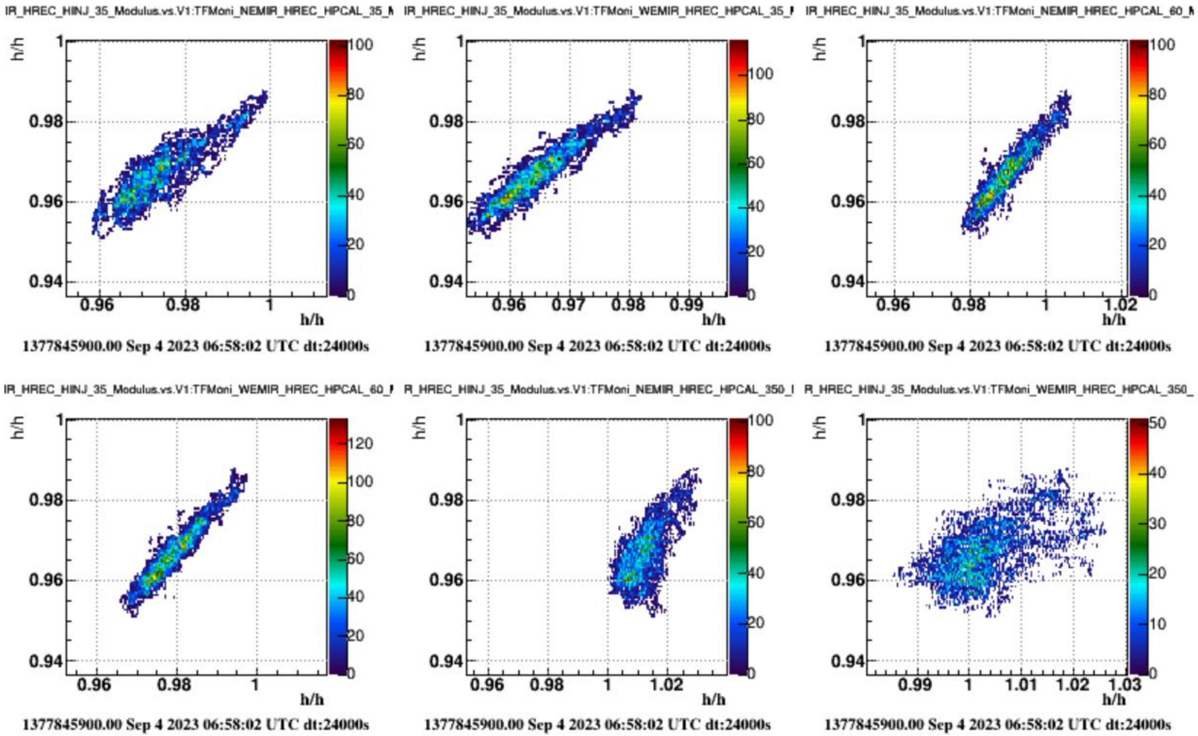
1		2		3	
REF	**NEW**	**REF**	**NEW**	**REF**	**NEW**
Pcal	E.M.	Pcal	E.M	E.M.	E.M.
↓	↓	↓	↓	↓	↓
End Mirrors	End Mirrors	End Mirrors	Input Mirrors	Input Mirrors	BS, PR, SR

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