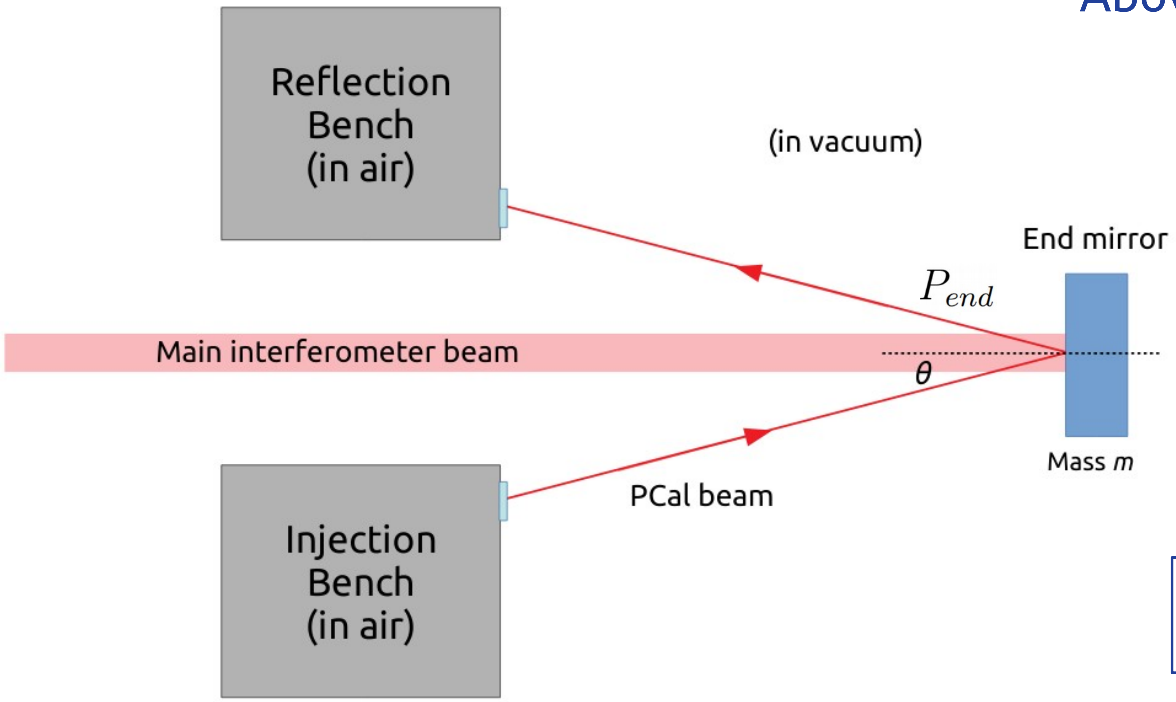
Virgo O3 PCal update

D. Estevez for the calibration team

D. Estevez et al.,The Advanced Virgo Photon Calibrators, 2020
(currently VIR-0705A-20 through PnP)

PCal setup



Above the suspension resonance frequency:

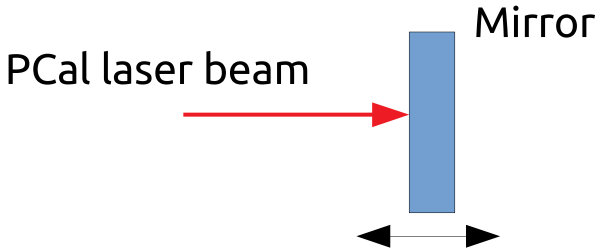
$$x_{pcal}^{free}(f) = -\frac{1}{m(2\pi f)^2}\frac{2\cos(\theta)}{c}P_{end}(f)$$

Need to be precisely measured

P_{end} estimated with photodiodes

Laser Power Noise (LPN)

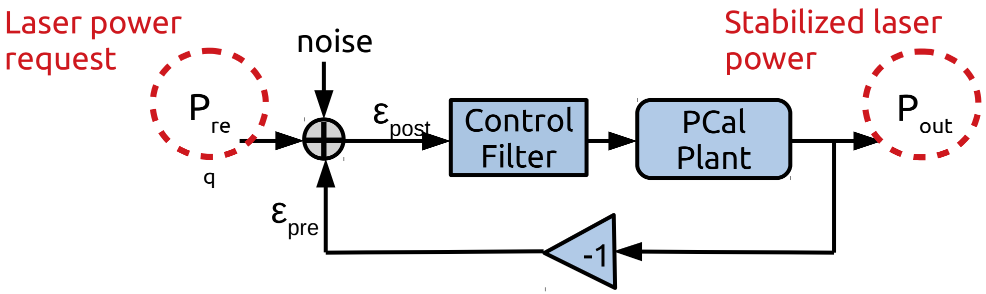
Prior to calibrate and use the PCals:



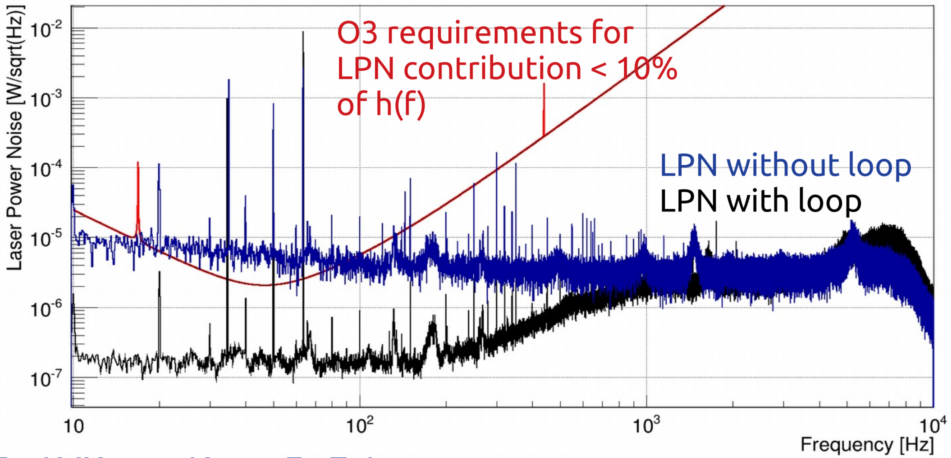
$$\Delta x(f) \propto LPN$$

PCal laser beam intrinsic noise at all frequencies:

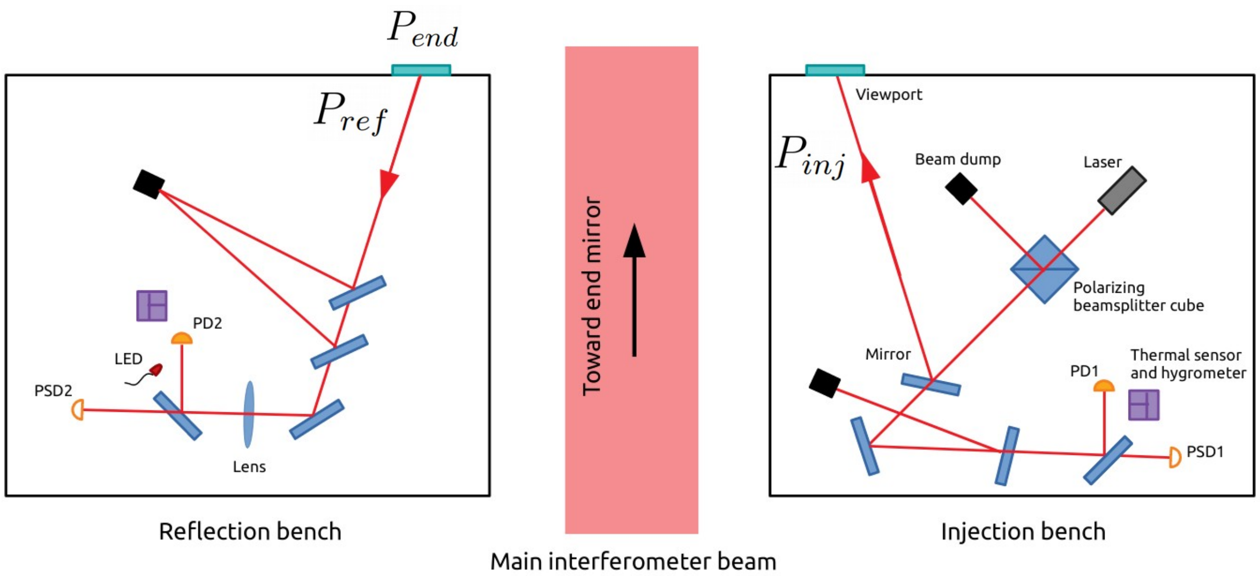
- Laser Power Noise
  - Displacement of the mirror
    - Limit the sensitivity h(f)



Fast Digital Control Loop running @200 kHz
Need to make sure the loop is stable



Injection and reflection benches

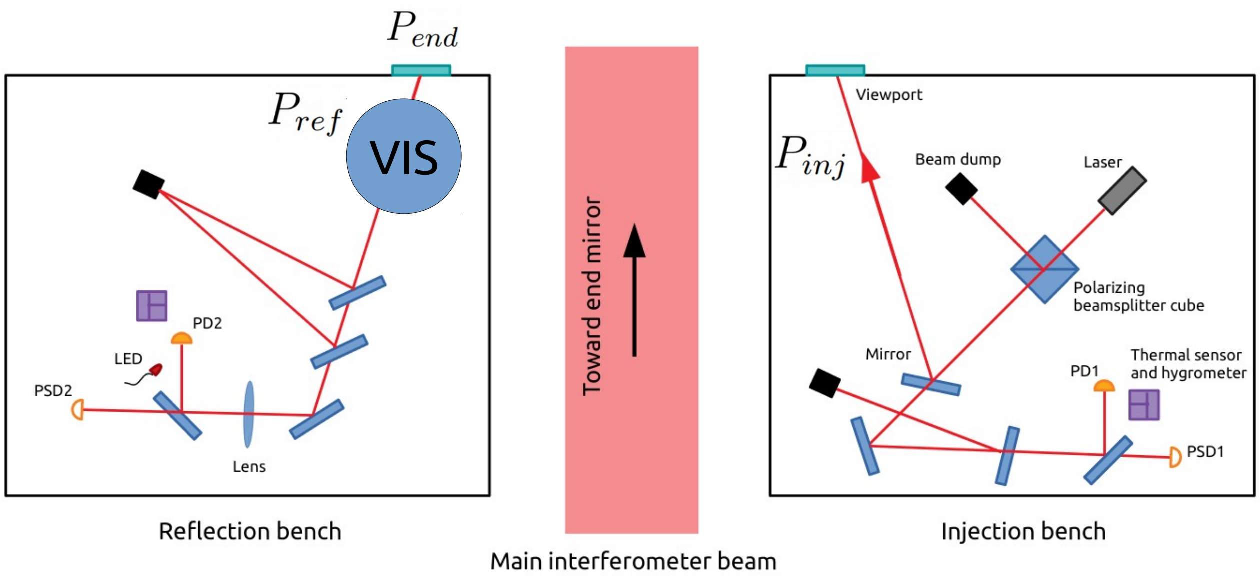


PD1 and PD2 used to estimate P_{end}

- P_{end} ~ 2 W
- ~ 3 mW onto PD1 and PD2
- Viewports losses $(1-R)^2$, $R = 0.05\%$
- $P_{end} = P_{inj}(1-R)^2 = \frac{P_{ref}}{(1-R)^2}$
- $\eta = P_{ref}/P_{inj}$ ~ 0.998 (expected)

PD1 and PD2 calibrated with Virgo Integrating Sphere (VIS)

Photodiodes calibration

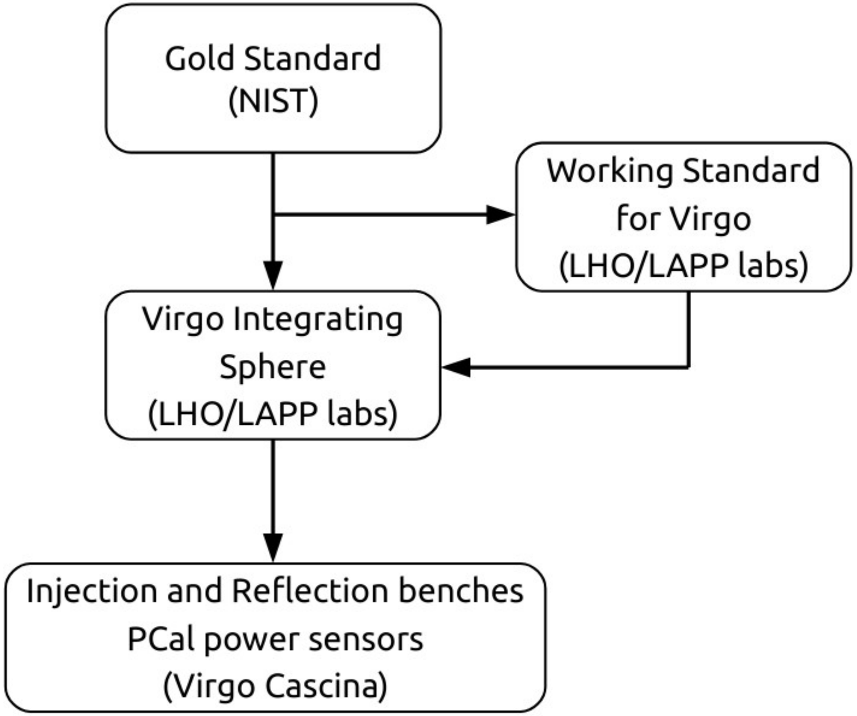


- Measuring simultaneously the laser power with the integrating sphere and the output voltage of the photodiode located on the injection bench (PD1)
- Derive a conversion factor in W/V for the photodiode (PD1)
- Calibrate PD2 using PD1
- Are we measuring the same “absolute” power as LIGO?

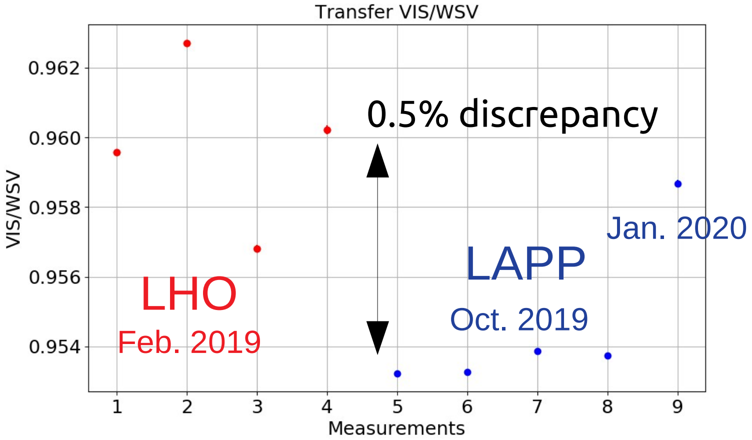
LIGO-Virgo intercalibration

Idea: calibrate the GW detectors network on the same "absolute" reference

D. Bhattacharjee et al., 2020, arXiv:2006.00130v1



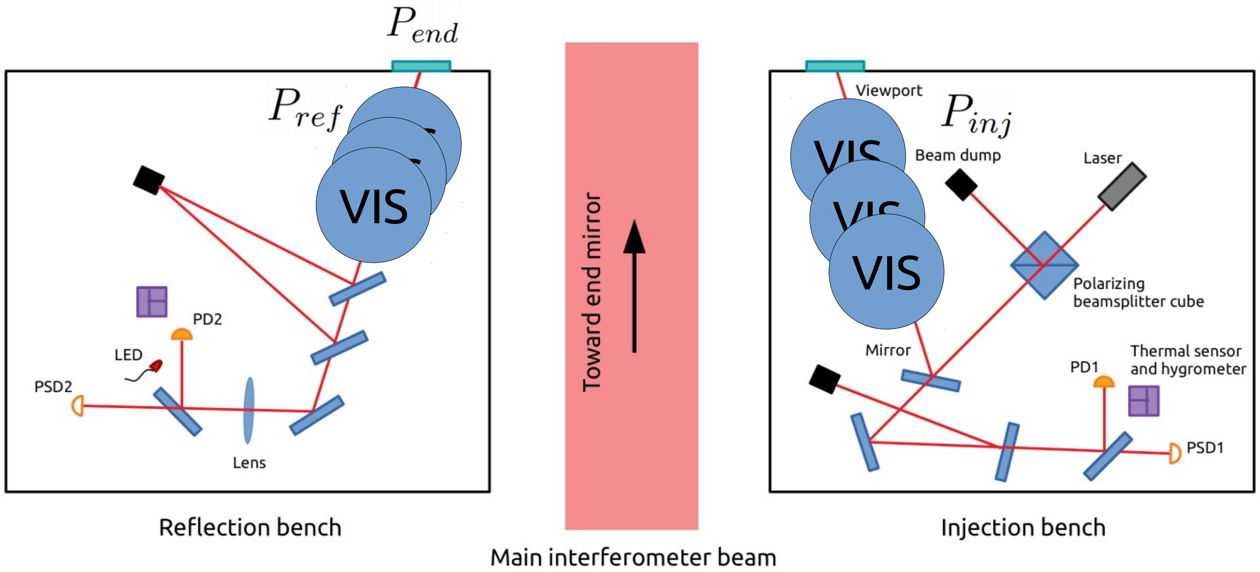
- Gold Standard (GS) calibrated by NIST → 0.32%
- VIS calibrated at LHO (2019):
  - Laser power corrected by 3.92% ± 0.34%
- Working Standard Virgo (WSV) (2019):
  - Check the stability of VIS calibration → 0.5%



Only stat. errors

VIS position issue

Investigations on the dependency of the measured laser power with VIS position on the benches



P_{ref} value stable (large laser beam)

P_{inj} value → 0.8% variations depending on VIS position (small laser beam)

- from (1-0.5%) P_{ref} to (1+0.3%) P_{ref}

$P_{ref} > P_{inj}$ Unphysical

$P_{ref} < P_{inj}$ Reasonable

Keep a conservative uncertainty of 0.8%+0.2% (expected optical efficiency) to estimate P_{end}

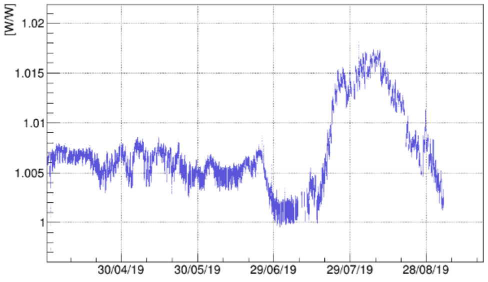
- Need to be addressed for O4 → measurements at different laser beam sizes

Uncertainty on P_{end}

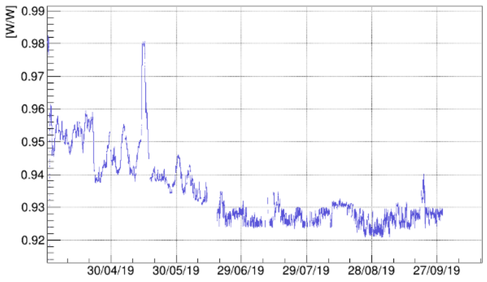
Parameter	1σ Uncertainty
GS responsivity (2018)	0.32%
VIS linearity	0.4%
VIS/GS responsivity ratio	0.1%
VIS/WSV responsivity ratio	0.5%
Voltage calibrator	0.007%
VIS position and optical efficiency	1%
Power reflected by the end mirror	1.24%

Calibration stability during O3a

O3a ratio PD1/PD2

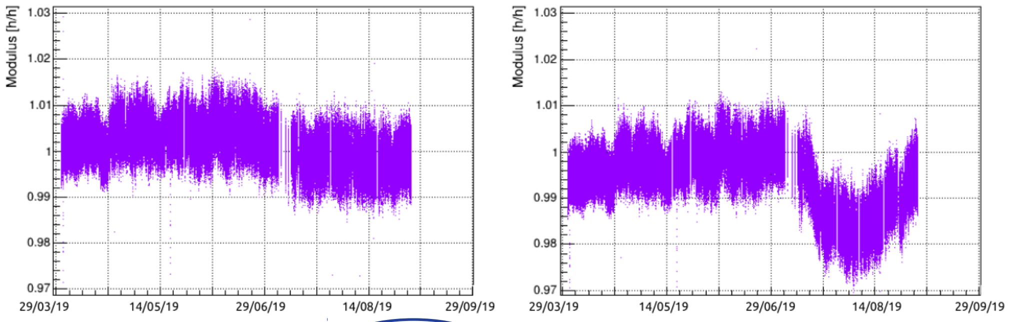


(a) WE

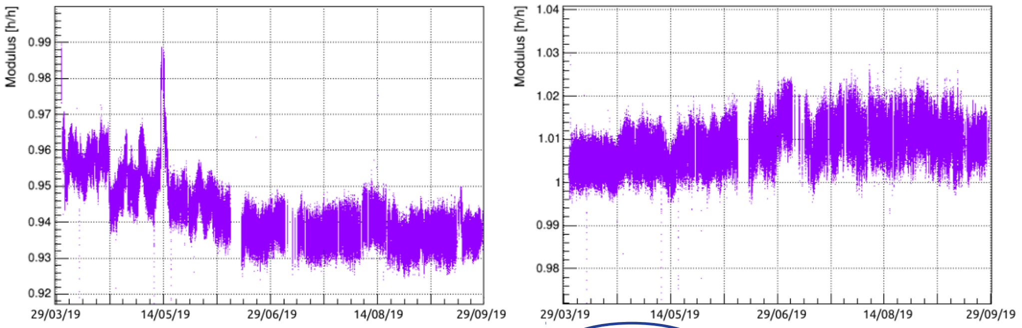


(b) NE

O3a ratio hrec/hpcal



(a) WE PD1 (left) and WE PD2 (right).



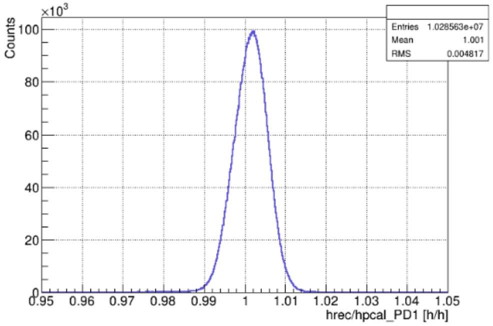
(b) NE PD1 (left) and NE PD2 (right).

Can we trust at least one photodiode on each PCal?

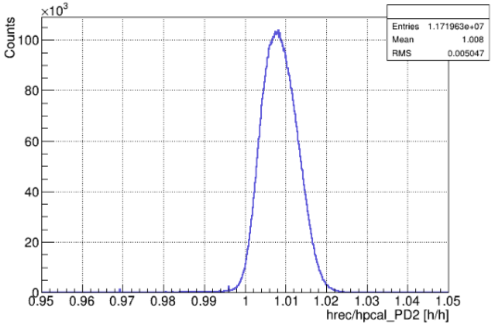
→ WE PD1 and NE PD2

Calibration stability during O3

O3a and O3b distribution of hrec/hpcal

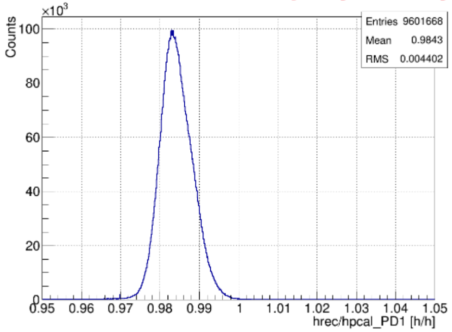


(a) WE PD1 O3a

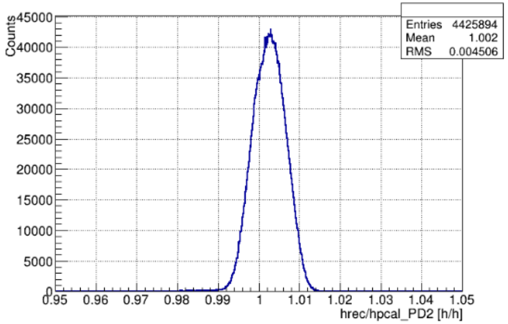


(b) NE PD2 O3a

WE and NE driver laser failure



(c) WE PD1 O3b

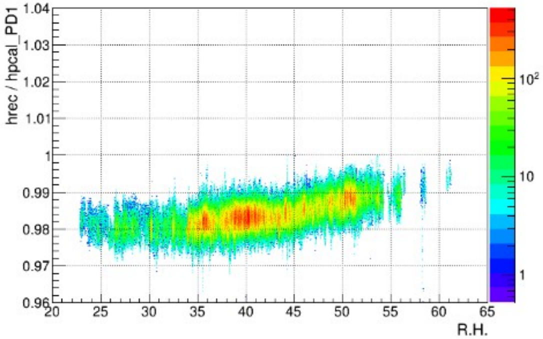


(d) NE PD2 O3b

Stability separately assessed for O3a and O3b

Parameter	1σ uncertainty O3a		1σ uncertainty O3b	
	NE	WE	NE	WE
Responsivity (temperature)	±0.1%	±0.1%	±0.1%	±0.1%
Other sources	±0.5%	±0.5%	±0.6%	±1.2%
Total	0.51%	0.51%	±0.61%	±1.2%

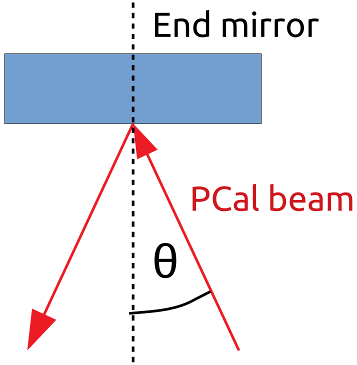
- Significant discrepancy for WE PD1 calibration between O3a and O3b
  - ➔ Relative humidity variations affect calibration



(c) WE PD1 O3b

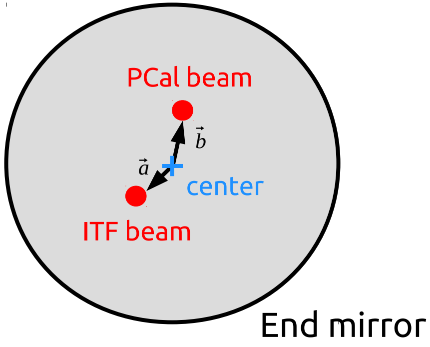
Geometrical parameters

- Angle of incidence
  → ± 0.12%



- End mirror induced rotation
  → ± 0.001%

$$x_{new} = x . \left[1 + \frac{\vec{a} . \vec{b}}{I} m \right]$$



- Mass of the mirror
  → ± 0.05%

Parameter	1σ uncertainty
Mass of the end mirror	0.05%
Angle of incidence (cosine)	0.12%
Rotation of the optic	0.001%
Total	0.13%

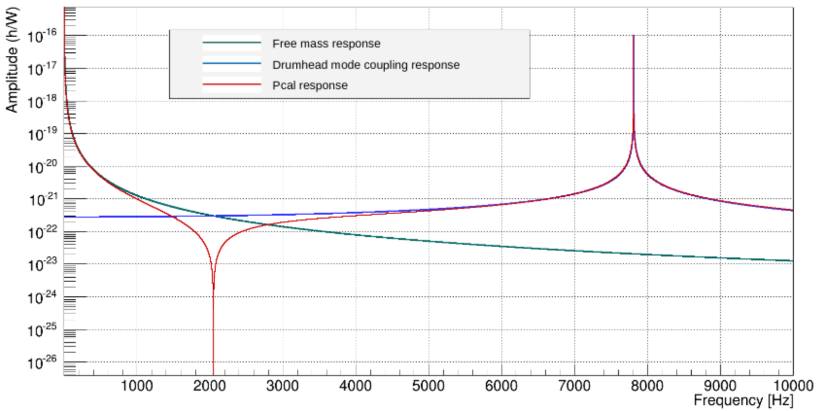
Uncertainty on x_{pcal}

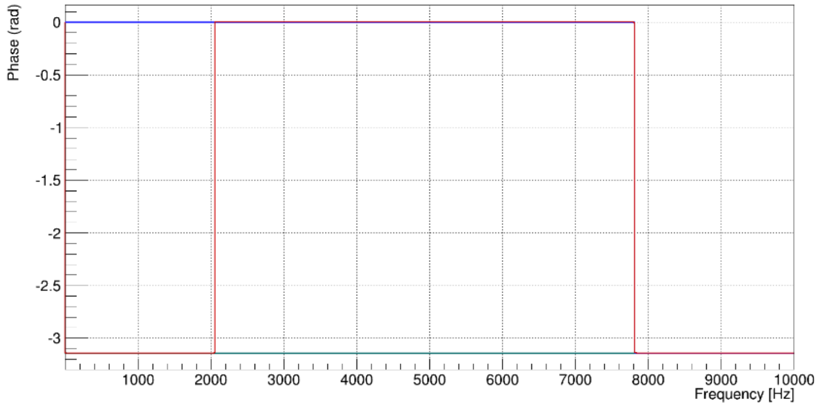
Parameter	1σ uncertainty O3a		1σ uncertainty O3b	
	NE	WE	NE	WE
Reflected laser power (P)	1.24%	1.24%	1.24%	1.24%
Geometrical parameters	0.13%	0.13%	0.13%	0.13%
Calibration stability (O3)	0.51%	0.51%	0.61%	1.2%
Total	1.35%	1.35%	1.39%	1.73%

$$x_{pcal}^{free}(f) = -\frac{1}{m(2\pi f)^2}\frac{2\cos(\theta)}{c}P_{end}(f)$$

only valid up to ~400Hz

PCal mechanical response

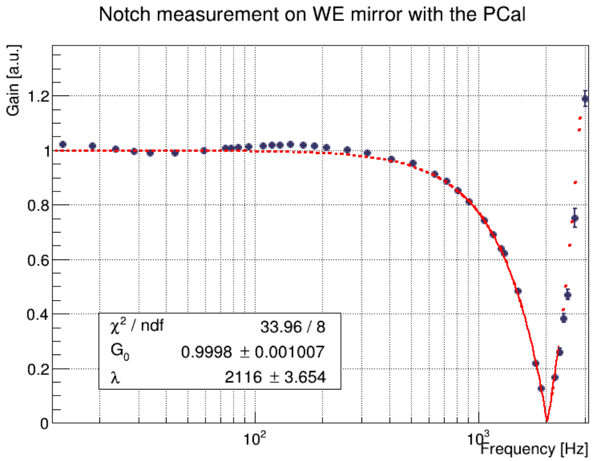




Above ~400 Hz:

$$x_{pcal}(f) = \left[-\frac{1}{m(2\pi f)^2} + H_d(f) \right] \frac{2\cos(\theta)}{c} P_{end}(f)$$

With drumhead mode coupling $H_d(f) = \dfrac{G_d}{1 + \frac{j}{Q_d}\frac{f}{f_d} - \left(\frac{f}{f_d}\right)^2}$



PCal	ΔG_d	Δf_d
WE	$\pm 0.35\%$	$\pm 0.014\%$
NE	$\pm 0.37\%$	$\pm 0.006\%$

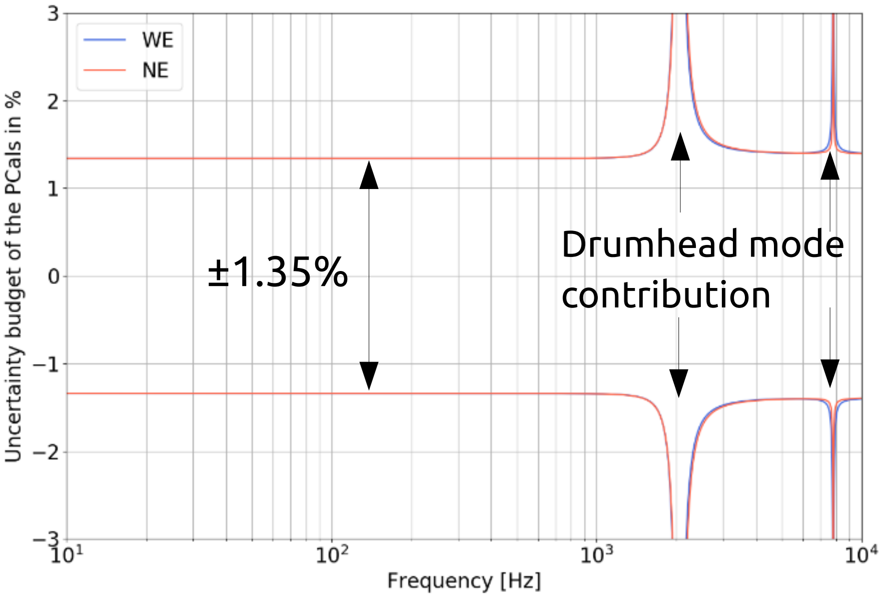
→ Only a frequency dependent feature

Total uncertainty on x_{pcal}

Valid up to 1.5 kHz

Parameter	1σ uncertainty O3a		1σ uncertainty O3b	
	NE	WE	NE	WE
Reflected laser power (P)	1.24%	1.24%	1.24%	1.24%
Geometrical parameters	0.13%	0.13%	0.13%	0.13%
Calibration stability (O3)	0.51%	0.51%	0.61%	1.2%
Total	1.35%	1.35%	1.39%	1.73%

O3a budget



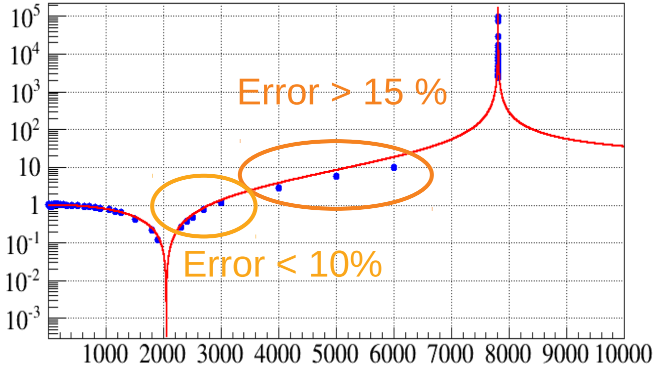
Plan for O4

- Ship Virgo Integrating Sphere (and WSV) to LHO more often to compare their calibration against the Gold Standard
- Characterize the dependency of VIS responsivity on the incoming laser beam size
- Address the humidity variations inside the PCal benches (actions TBD)
- Change Si photodiodes to InGaAs photodiodes (less sensitive to temperature changes)
- Extend the range of laser power modulation up to a few tens of kHz (currently ~8kHz maximum)

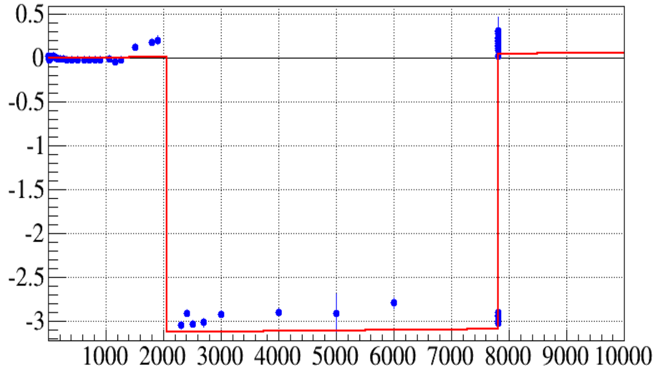
BACK-UP

Verification of h(t) at high frequency

Amplitude [hrec/hpcal]



Phase [rad]

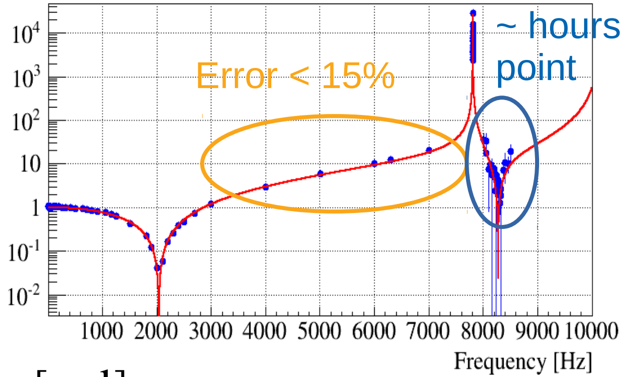


Including:

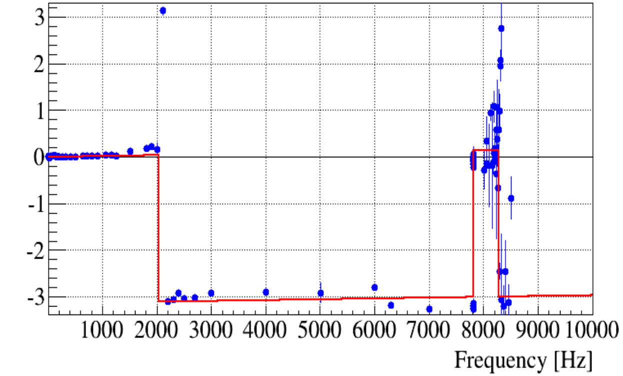
- higher order axisymmetric modes ~10 kHz and ~12 kHz
- True FP optical response

Amplitude [hrec/hpcal]

Hard to measure ~ hours for each point



Phase [rad]



→ Need a higher bandwidth of power modulation (> 10 kHz) and a higher sampling of channels