Improving the absolute calibration of the GW detectors

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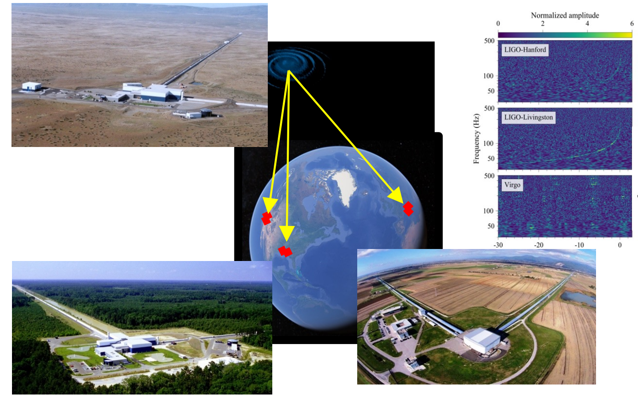
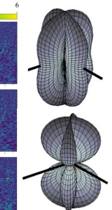
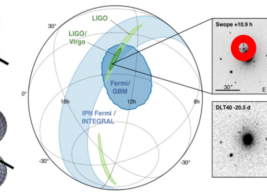
Workshop R&Ds - Développements Instrumentaux / Virgo-ET

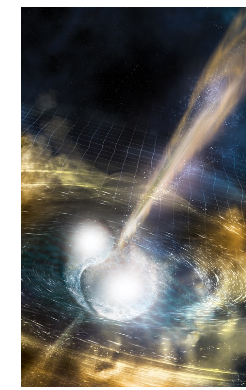
Why do we need a good calibration

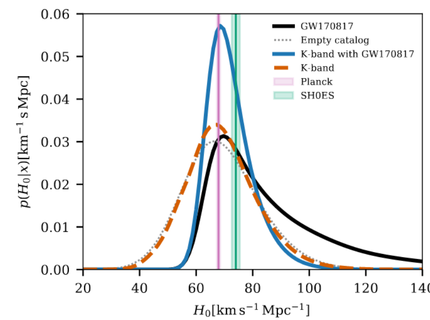
- Find the sources
  - Source position from:
    - Time of flight
    - Relative signal amplitude
- Measure the Hubble constant
  - Source distance given by GW amplitude
  - Calibration uncertainty translate to H_0 uncertainty
- Measure astrophysical source rate
  - Calibration uncertainty translate to volume uncertainties
- Testing General Relativity
  - Need a good calibration over frequency range
- …











- Needed accuracy (largest SNR observed around 40):
  - Sub-percent level for current/O5 detectors
  - Sub-per mille level for ET

Current calibration systems uncertainties

- Calibration: build an actuator which moves a mirror of a well known amount

- PCal: developed by LIGO and Virgo
  - Push the mirror with an auxiliary laser
  - Uncertainties: see LIGO-P2300412-v7
  - Virgo PCal currently at 0.6 % (VIR-0107A-24)
    - Dominated by optical losses uncertainties

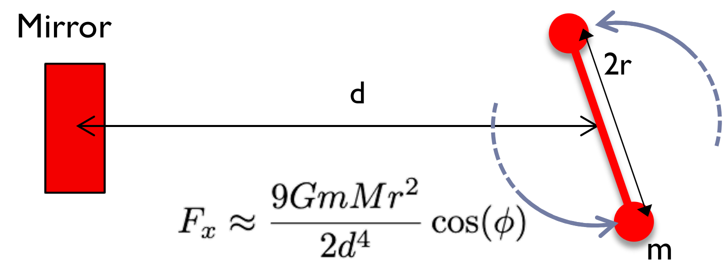
Table 3. Relative standard uncertainties (%) in displacement factors and contributing parameters (indented) the LHO and Virgo end station Rx sensor outputs. Parameters that are NOT common to both end stations are in blue text.

	LHO			Virgo	
Parameter	X-End	Y-End	Type	Ends	Type
X_X^c and X_Y^c	0.29	0.29	U_{rel}	—	—
X/Y corr. fact.	0.26	0.26	$u_{rel,\,comb.}$	—	—
X_X and X_Y	0.44	0.37	U_{rel}	0.40	U_{rel}
Deform. mod.	—	—	—	0.30	$u_{rel,\,comb.}$
Inc. angle	0.03	0.03	$u_{rel,\,TypeB}$	0.16	$u_{rel,\,TypeB}$
ETM mass	0.01	0.01	$u_{rel,TypeB}$	0.05	$u_{rel,\,TypeB}$
Rotation	0.41	0.31	$u_{rel,\,TypeB}$	0.09	$u_{rel,\,TypeB}$
Optical eff.	0.03	0.10	$u_{rel,\,TypeB}$	0.10	$u_{rel,\,TypeB}$
Rx responsiv.	0.14	0.17	$u_{rel,\,comb.}$	0.15	$u_{rel,\,comb.}$

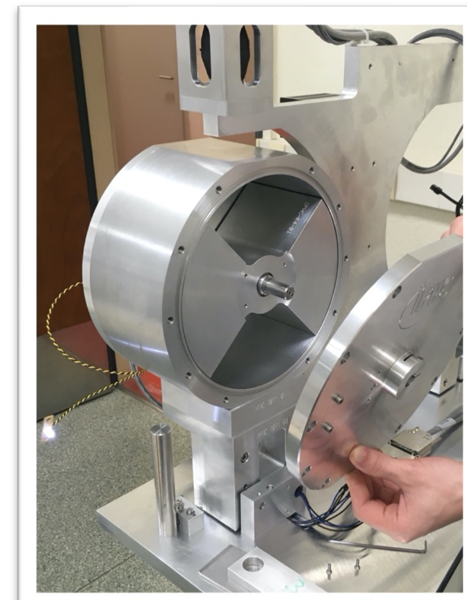
- NCal developed in Virgo since O2
  - Push the mirror with a variable gravitational field
  - Preliminary uncertainty for O4b around 0.2 % (see details later)
- → Will focus this talk on the NCal R&D

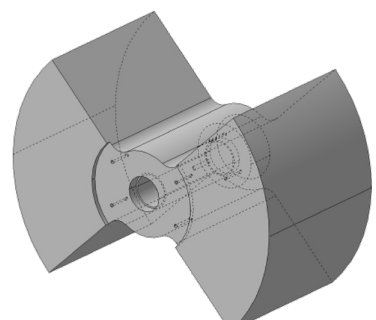
NCal principle

- Rotor made of two masses
  - Center of mass is not moving
  - The non-linear Newtonian force creates the signal
  - Signal at twice the rotor frequency
  - Signal goes as $1/d^4$ → Mirror to NCal distance is critical
- Expected benefits
  - Signal depends mainly on the rotor geometry, mass & position
    - Replace power measurements (PCal) by distance measurement (NCal)
  - Mass of the mirror cancels out
  - No aging effect of the signal
  - Simple interface with the detector (no viewports)
- Challenges:
  - Metrology
  - Fast rotation
  - Parasitic couplings
  - Reliability



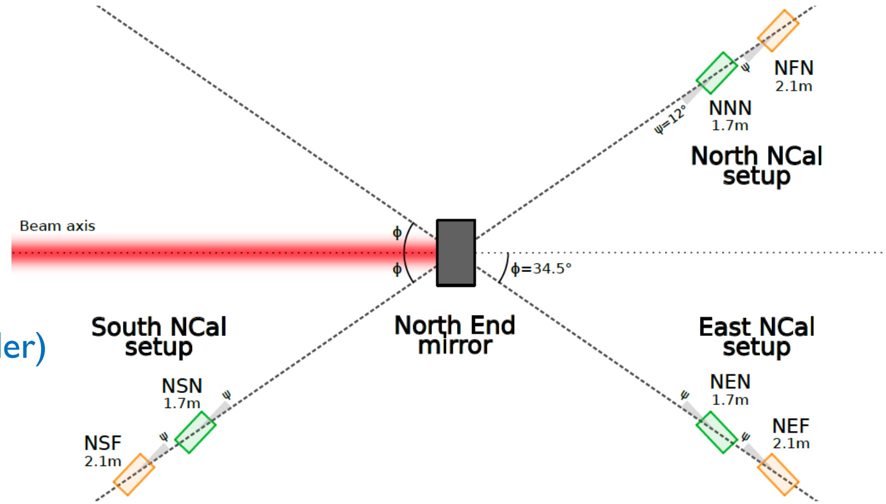
$$F_x \approx \frac{9GmMr^2}{2d^4}\cos(\phi)$$

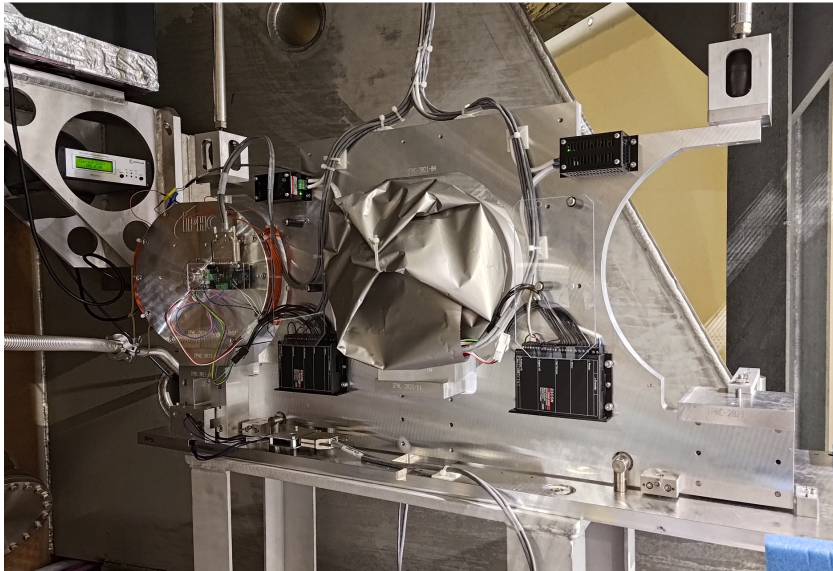




O4b NCal system

- 6 NCals around the NE mirror
- 2 couples of NCals along the north-south axis
  - Remove mirror-NCal distance uncertainty (at first order)
  - Near NCal at 1.7 m with PVC rotors
  - Far NCal at 2.1 m with Aluminum rotors
- Est setup dedicated to:
  - Parasitic coupling studies
  - Frequency scan
- Maximum operating frequency:
  - 120-150 Hz in h(t) for Al rotors
- Permanent operation since last August
  - PVC rotors installed in February

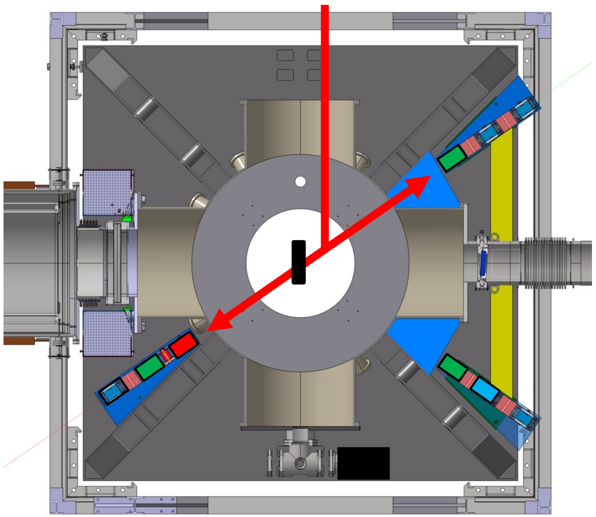


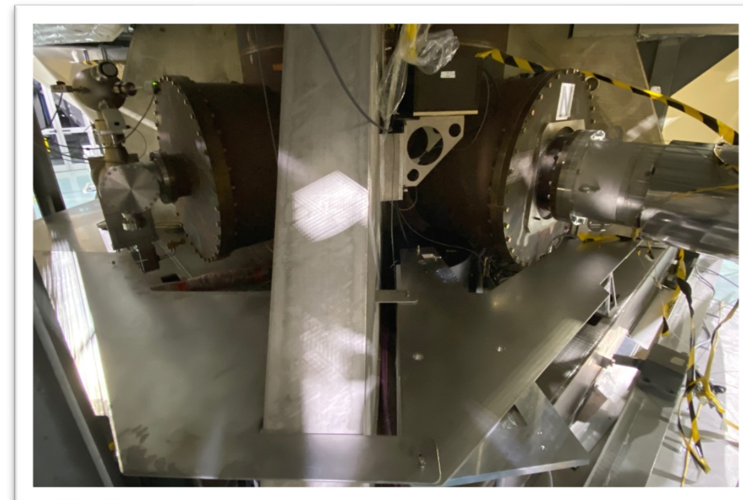


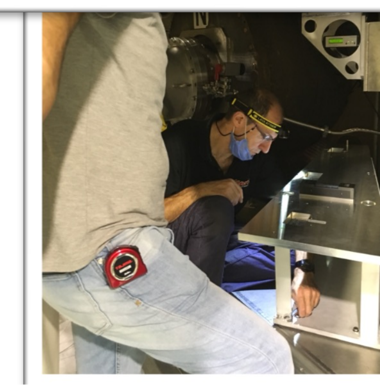
Knowing the NCal relative distance

- Use a mechanical template to install the NCal supports
- Get positions from geometrical survey

North-South distance
known to ± 0.58 mm

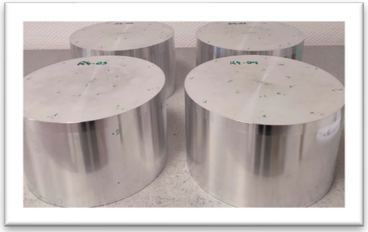


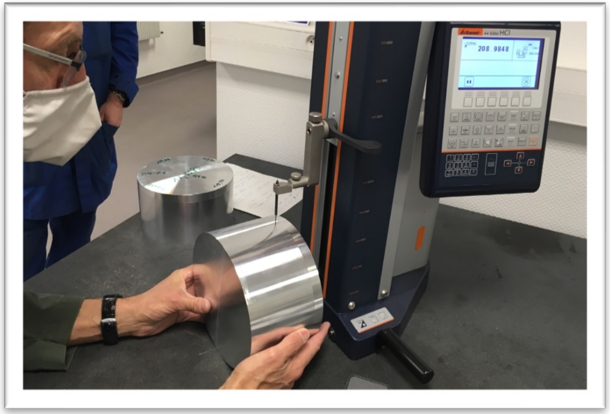




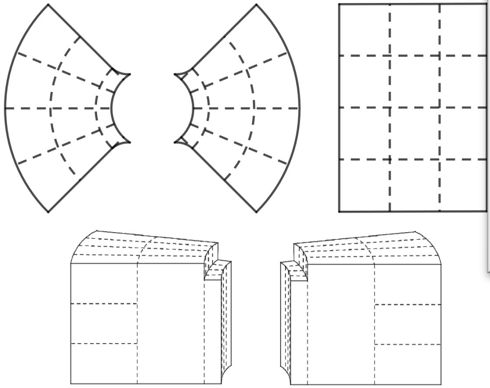
Rotor uncertainties

- Careful in-house machining
  - Tracking the material used
- Accurate
  - Density measurement
  - Rotor metrology
  - Specific FEM modelling code
- A lot of technical reports by Antoine Syx



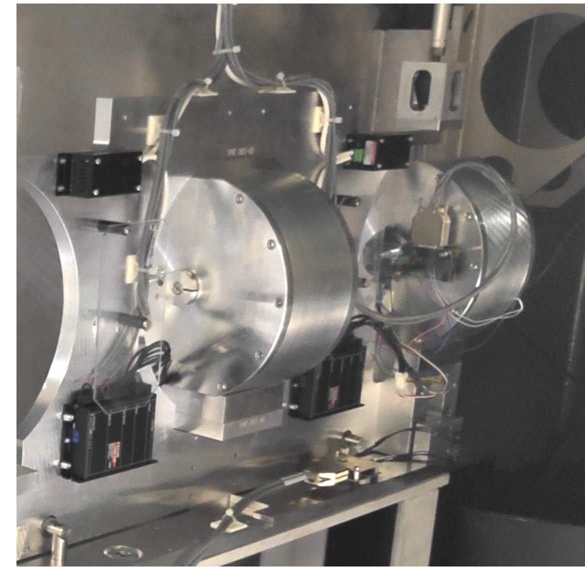


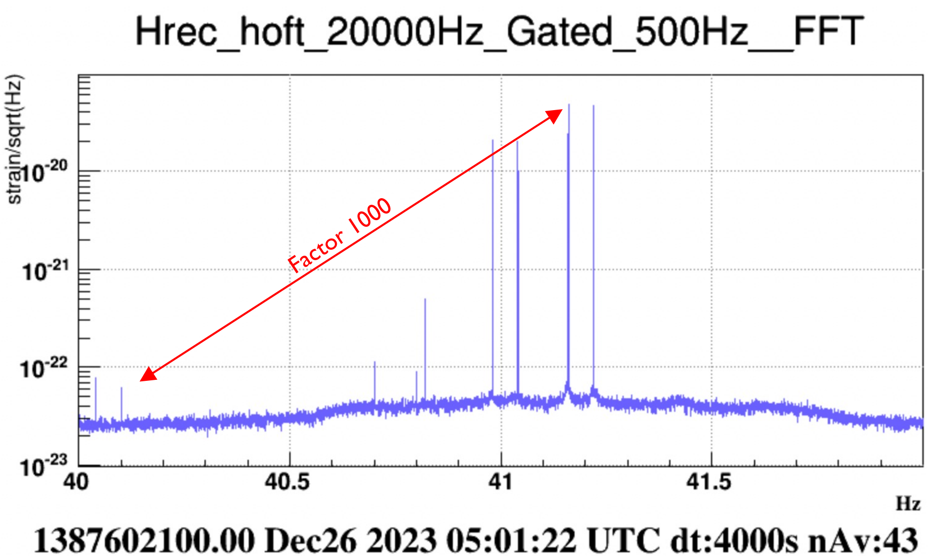
Code		Title	Date	Author(s)
VIR-0203A-24	PUBLIC	Characteristics of the rotor R4-10 for the O4 NCal system RESTRICTED ACCESS	28/02/24	Florian Aubin, Eddy Dangelser, Benoit Mours, Antoine Syx, Pierre Van Hove
VIR-0193A-24	PUBLIC	Density of the PVC used for the O4 NCal rotors RESTRICTED ACCESS	23/02/24	Florian Aubin, Eddy Dangelser, Benoit Mours, Antoine Syx, Dominique Thomas, Pierre Van Hove
VIR-0948A-23	PUBLIC	Characteristics of the rotor R4-08 for the O4 NCal system	26/10/23	Florian Aubin, Eddy Dangelser, Benoit Mours, Antoine Syx, Pierre Van Hove
VIR-0861B-22	PUBLIC	Characteristics of the rotor R4-07 for the O4 NCal system	16/06/23	Eddy Dangelser, Dimitri Estevez, Benoit Mours, Mehmet Ozturk, Antoine Syx
VIR-0670C-22	PUBLIC	Characteristics of the rotor R4-04 for the O4 NCal system	16/06/23	Eddy Dangelser, Dimitri Estevez, Hubert Kocher, Benoit Mours, Mehmet Ozturk, Antoine Syx
VIR-0530A-23	PUBLIC	Effect of a rotor misalignment (twist) on the O4 NCal signal	05/06/23	Dimitri Estevez, Benoit Mours, Antoine Syx
VIR-0860B-22	PUBLIC	Characteristics of the rotor R4-06 for the O4 NCal system	29/11/22	Eddy Dangelser, Dimitri Estevez, Benoit Mours, Mehmet Ozturk, Antoine Syx
VIR-0895A-22	PUBLIC	Characteristics of the rotor R4-31 for the O4 NCal system	19/09/22	Eddy Dangelser, Dimitri Estevez, Benoit Mours, Mehmet Ozturk, Antoine Syx
VIR-0859A-22	PUBLIC	Characteristics of the rotor R4-05 for the O4 NCal system	08/09/22	Eddy Dangelser, Dimitri Estevez, Benoit Mours, Mehmet Ozturk, Antoine Syx
VIR-0664B-22	PUBLIC	Characteristics of the rotor R4-03 for the O4 NCal system	08/09/22	Eddy Dangelser, Dimitri Estevez, Hubert Kocher, Benoit Mours, Mehmet Ozturk, Antoine Syx
VIR-0661B-22	PUBLIC	Characteristics of the rotor R4-02 for the O4 NCal system	08/09/22	Eddy Dangelser, Dimitri Estevez, Hubert Kocher, Benoit Mours, Mehmet Ozturk, Antoine Syx
VIR-0591C-22	PUBLIC	Characteristics of the rotor R4-01 for the O4 NCal system	08/09/22	Eddy Dangelser, Dimitri Estevez, Hubert Kocher, Benoit Mours, Mehmet Ozturk, Antoine Syx
VIR-0160A-22	PUBLIC	Density of the material used for the first O4 NCal rotors	07/02/22	Eddy Dangelser, Dimitri Estevez, Hubert Kocher, Benoit Mours, Mehmet Ozturk, Antoine Syx



Checking parasitic coupling

- Rotate the rotor by about 90°
  - Actually 89.7°due to rotor/mirror size
- Expect cancelation of the NCal signal
- Measured residual signal: 0.1 %
  - Aluminum rotor with magnetic shielding
  - Part is due to alignment uncertainty
  - Other part from parasitic coupling: residual magnetic field





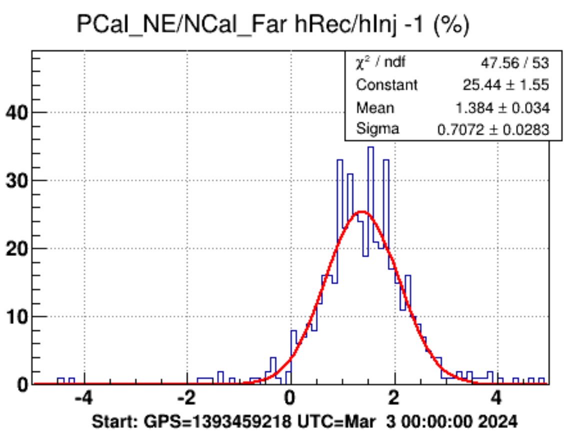
Current NCal uncertainties

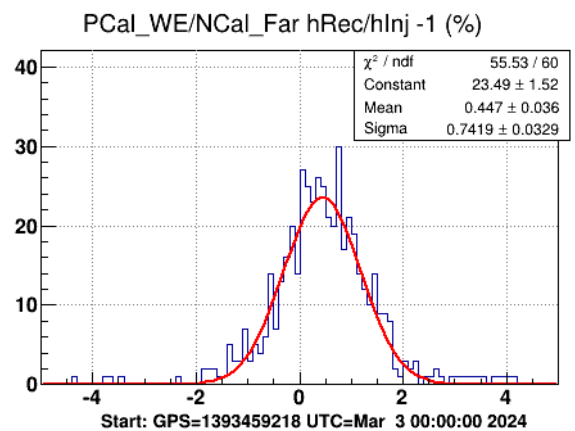
- Preliminary

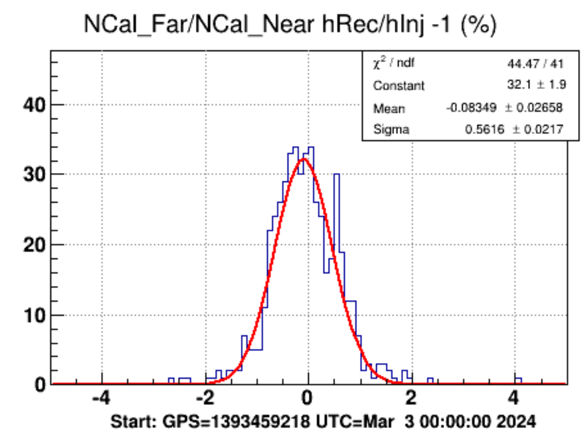
Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi\sin(\phi)$	0.08	0.08
	NCal to mirror distance (d)	numerical	0.01	0.01
	NCal twist (ψ)	numerical	$\leq 10^{-3}$	$\leq 3 \times 10^{-3}$
	NCal vertical position (z)	$5/2(z/d)^2$	8×10^{-3}	5×10^{-3}
Rotor induced strain		see end of section 4	0.057	0.061
Rotor deformation at 21 Hz		numerical	0.03	$\leq 10^{-2}$
Residual coupling (including magnetic)		see section 5	≤ 0.1	0.2
Total		quadratic sum	0.20	0.25

Comparing Virgo PCal and NCal (Preliminary)

- Typical ratios: (VIM plots, only statistical uncertainties):
  - PCal_NE/NCal : ~1.3 %
  - PCal_WE/NCal : ~ 0.4 %
  - NCal: Far/Near: ~ 0.1 %







Current R&D effort

- Mostly funded by ANR grant (2021-2025): ACALCO
  - IPHC (PI) and LAPP
  - Funding of two PhD: Antoine Syx(NCal) and Cervane Grimaud (PCal)
  - + some budget for hardware and travels
- Great for Virgo:
  - Calibration deployment and operation funded by ANR (not just the R&D)
- Must continue the R&D for the NCal system:
  - Improve NCal accuracy:
    - New rotors materials, improve rotor machining, metrology
  - Improve NCal frequency range
    - Mechanical improvements
    - Study small rotor deformations to correct them
  - Study/improve NCal reliability
  - Improve NCal positioning system for better NCal-NCal distance knowledge

→ Need person-power and funding for R&D

Summary

- Calibration is going to be more and more challenging
- NCal is the most accurate system
- PCal is versatile and could be calibrated using the NCal
- Need both systems
- The ANR ACALCO is ending in 2025, need follow-up funding