Advanced LIGO Photon Calibrators

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University of Oregon

GW Metrology Workshop
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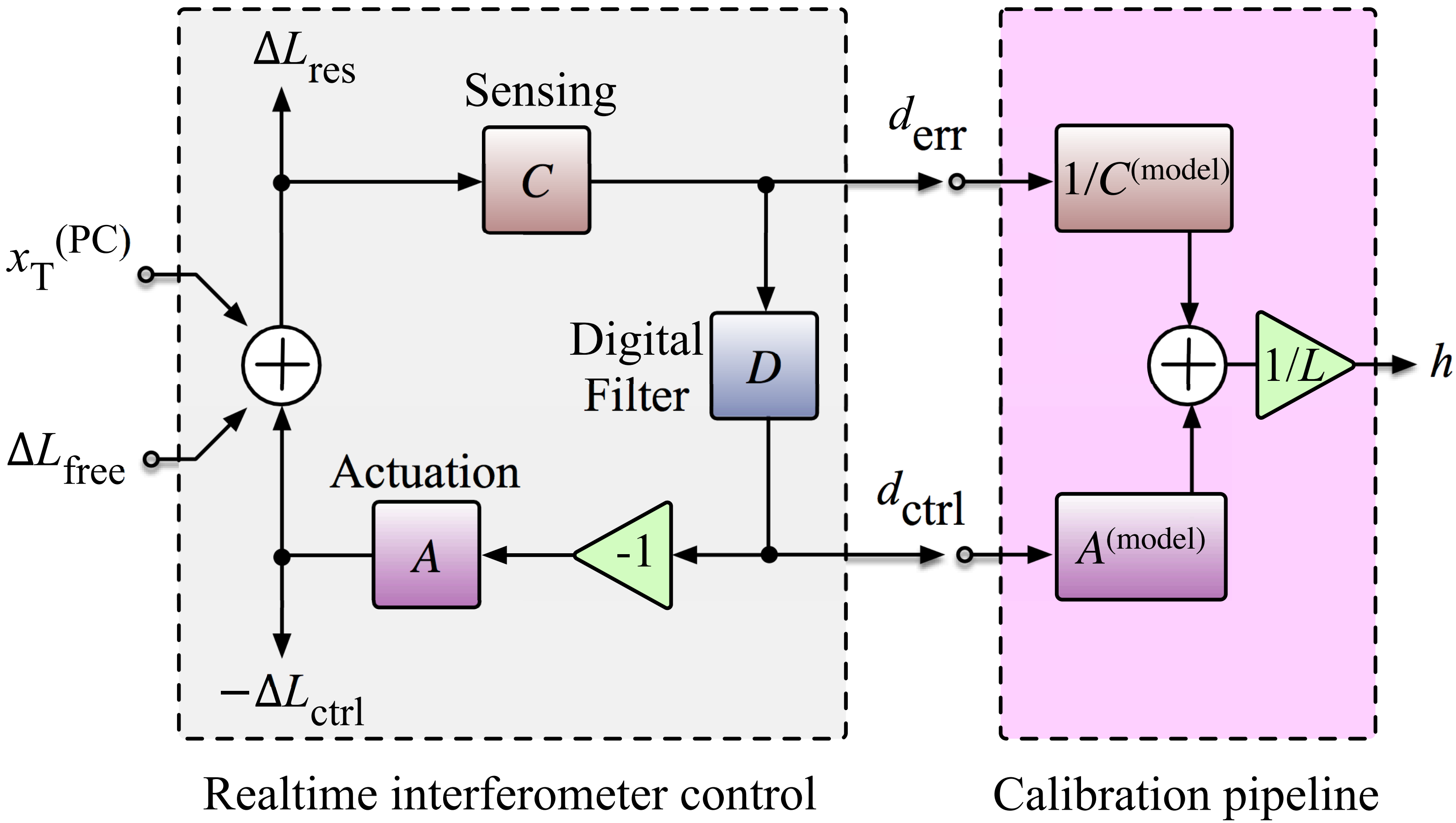
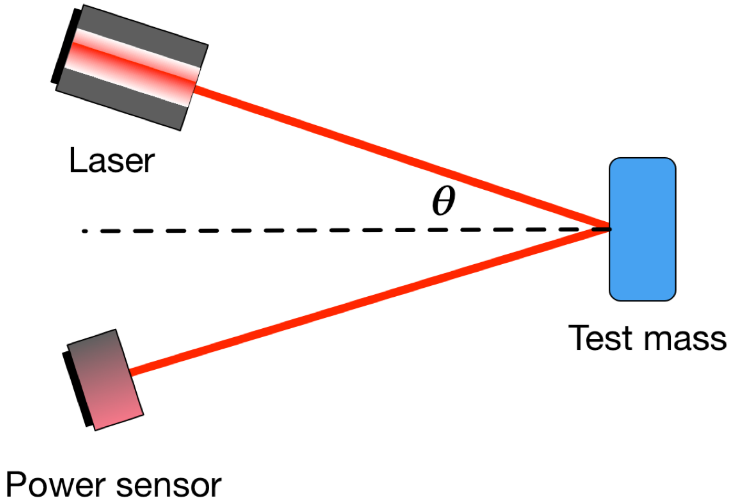
RECAP: Evan's Talk



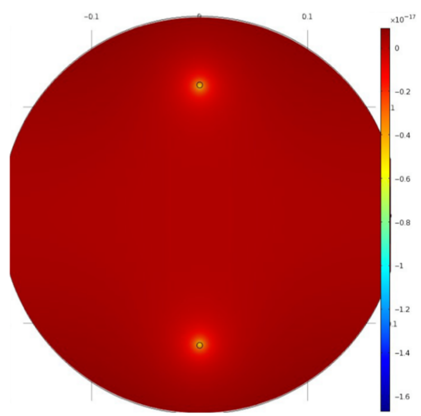
PHOTON CALIBRATOR
Principle of Operation

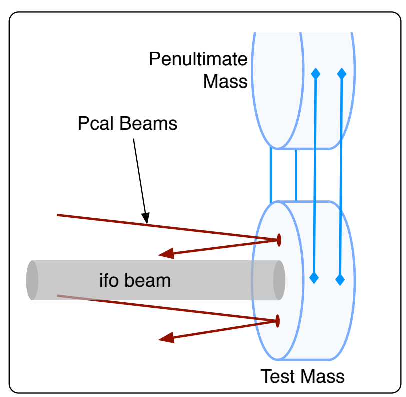


Introduce fiducial displacements

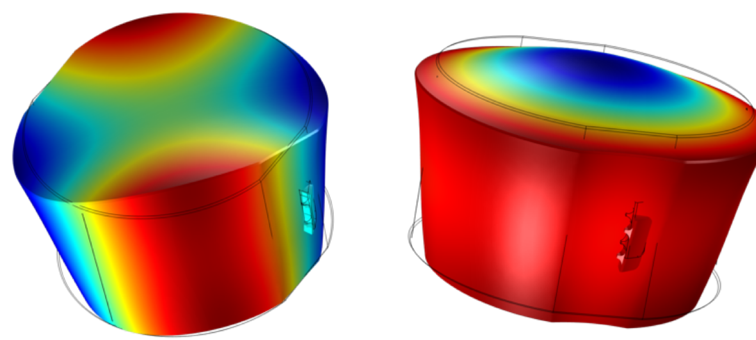
$$x(f) = \frac{2\cos(\theta)}{c} P(f) \frac{1}{M(2\pi f)^2} \;\mathcal{R}\; \mathcal{G}(f)$$

Local Elastic Deformation + Rotation

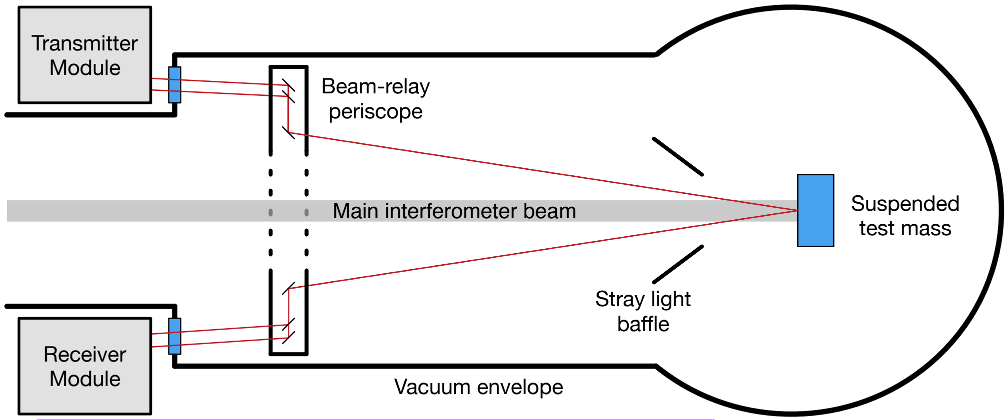




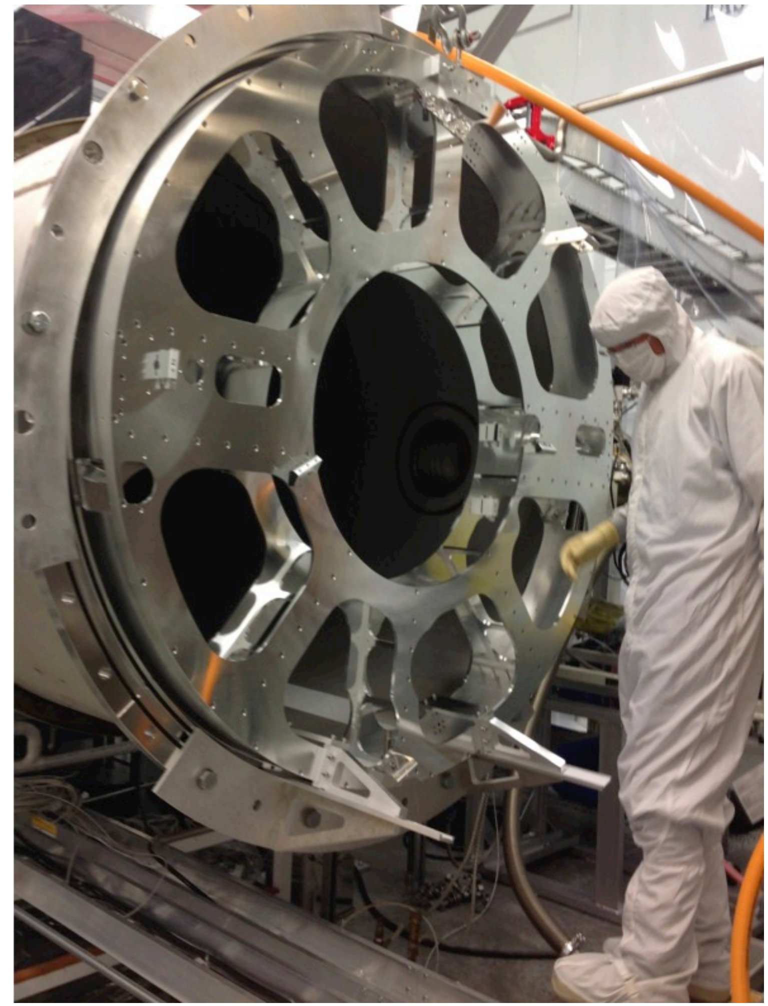
Bulk Elastic Deformation



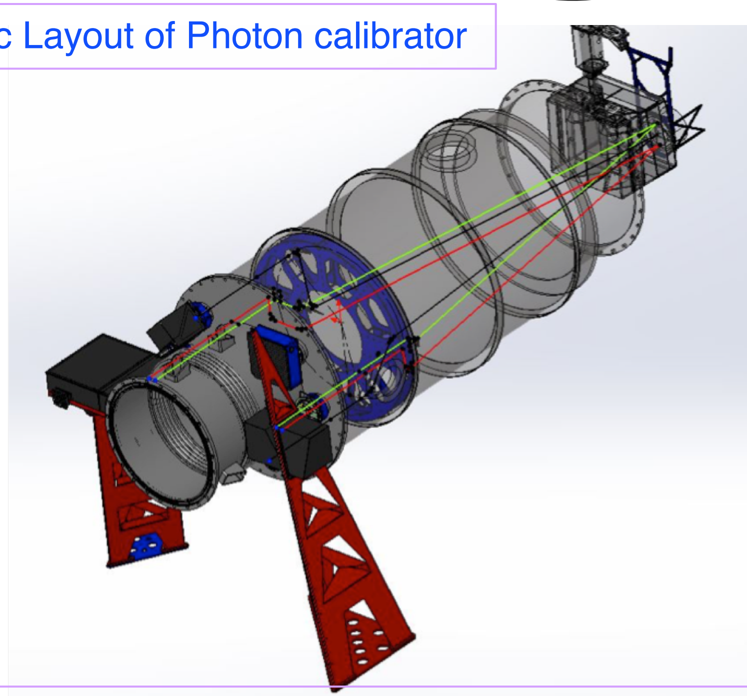
PHOTON CALIBRATOR
Hardware Overview



Schematic Layout of Photon calibrator



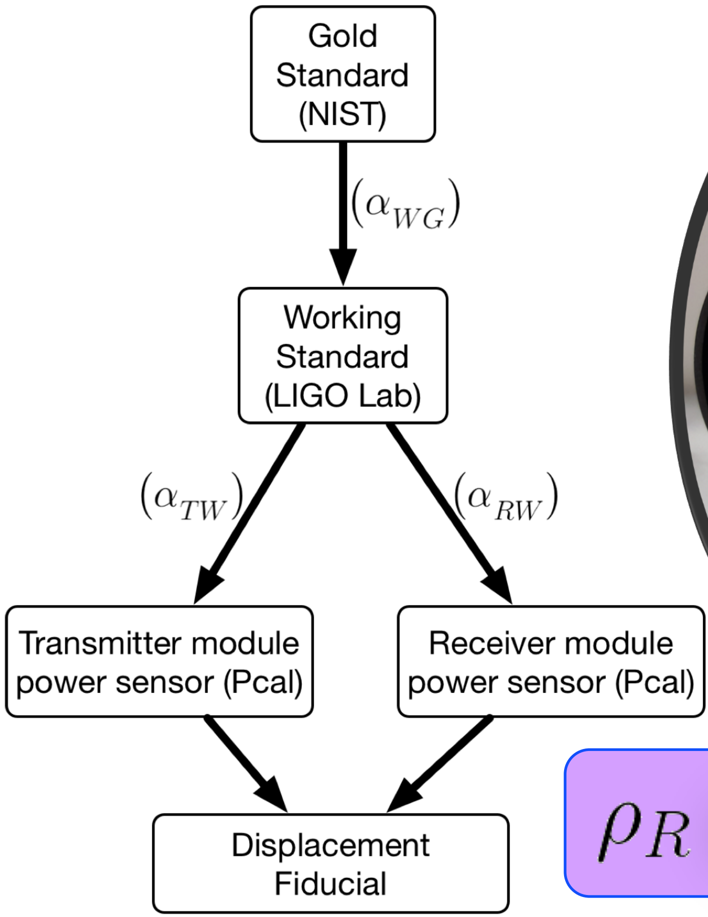
Pcal persicope structure



Bird's eye view of the layout of Photon calibrator as installed.

POWER CALIBRATION
GS/WS Strategy (J. Hadler at NIST)

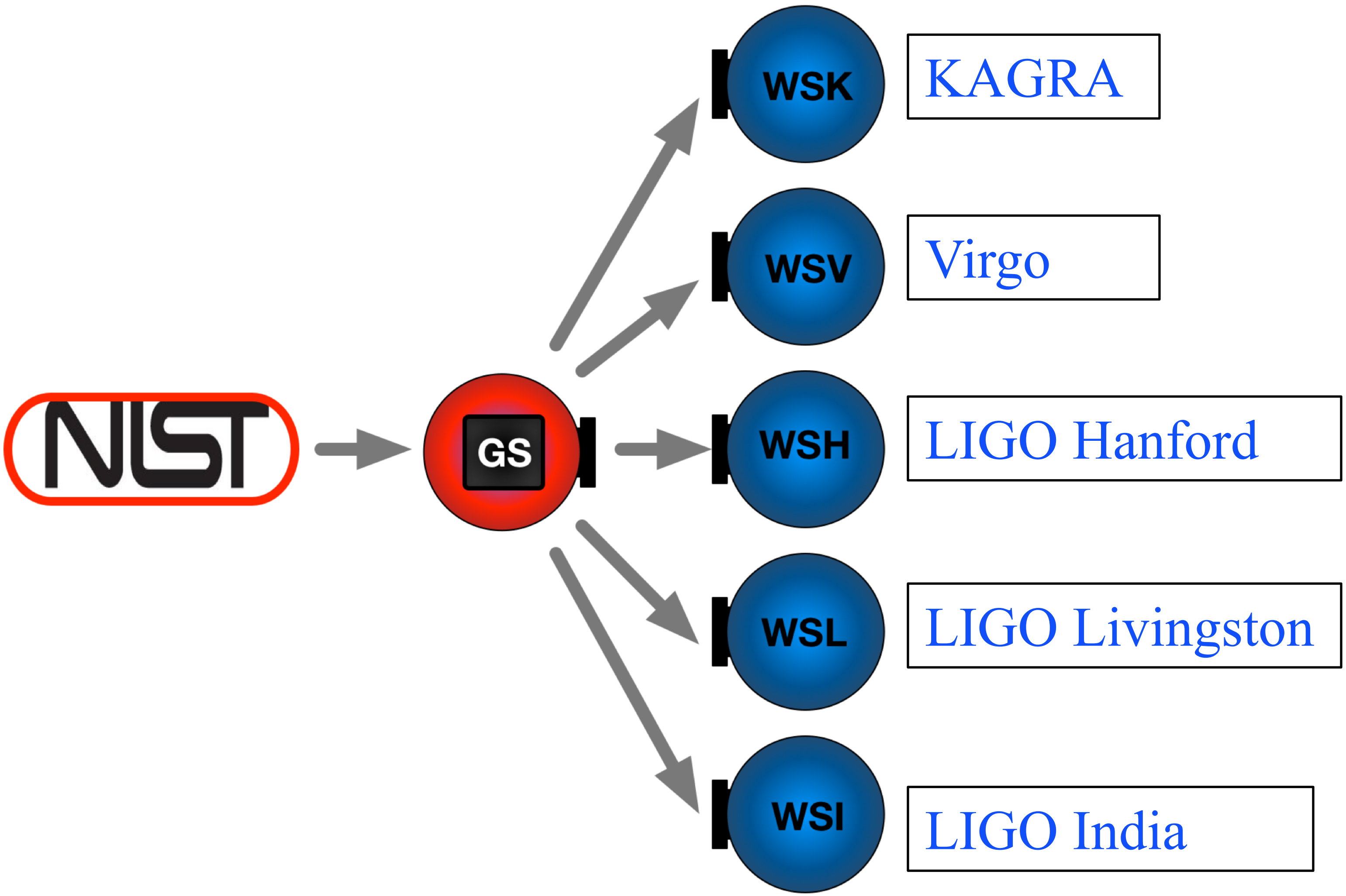
$$x(f) = \frac{2\cos(\theta)}{c} P(f) \frac{1}{M(2\pi f)^2} \mathcal{R}\,\mathcal{G}(f)$$



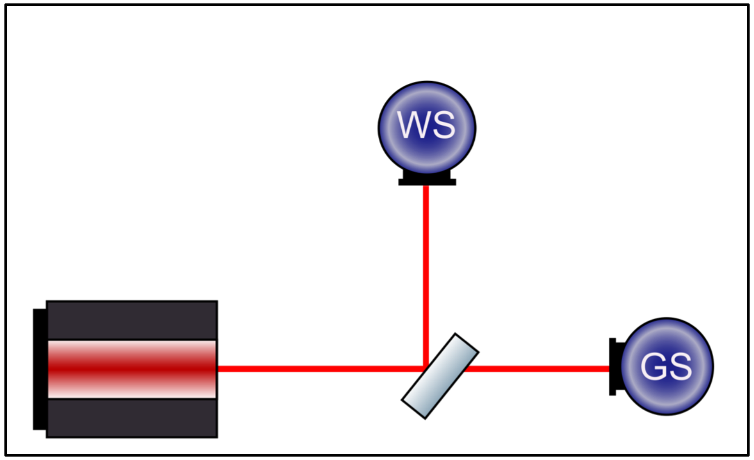
- Gold Standard (GS) calibrated at NIST
  - One single standard.
- Working Standard (WS) calibrated against GS.
  - WS -> One for each detector
- Pcal power sensors (Tx and Rx) at each end station calibrated against WS.

$$\rho_R = \alpha_{RW} \times \alpha_{WG} \times \rho_G$$

POWER CALIBRATION
Sharing Gold Standard Calibration

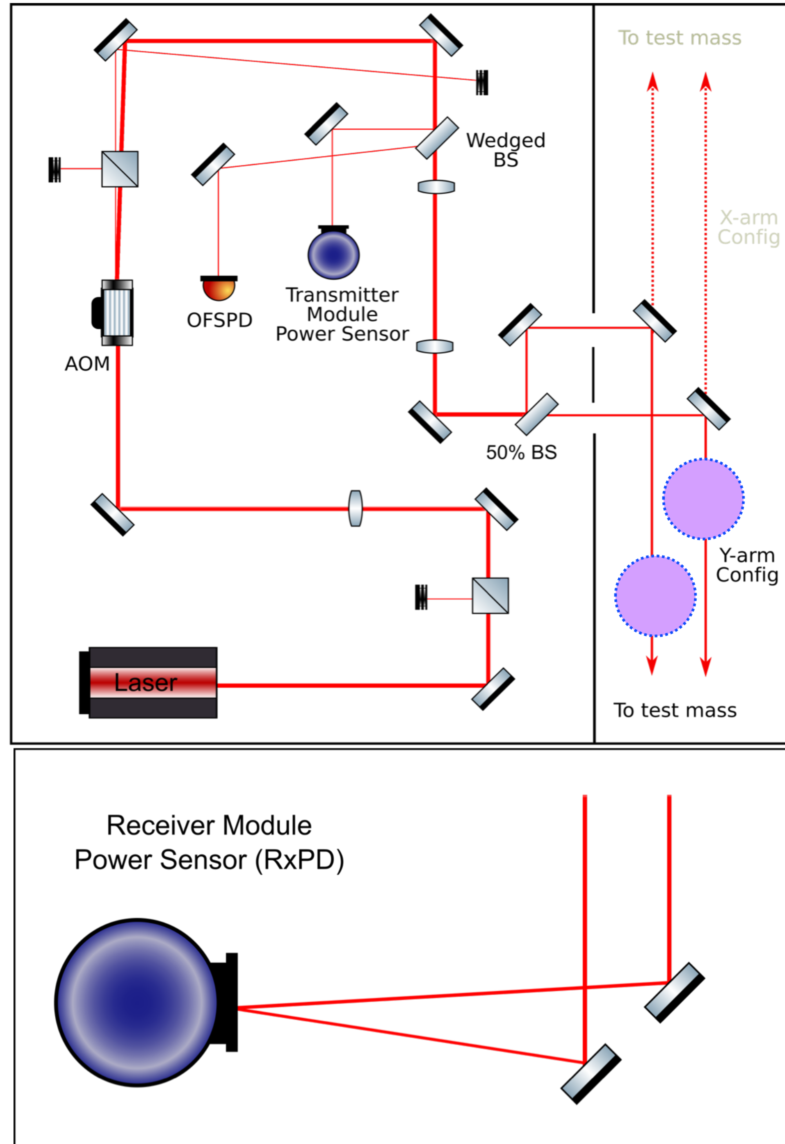


POWER CALIBRATION
Calibration Transfer



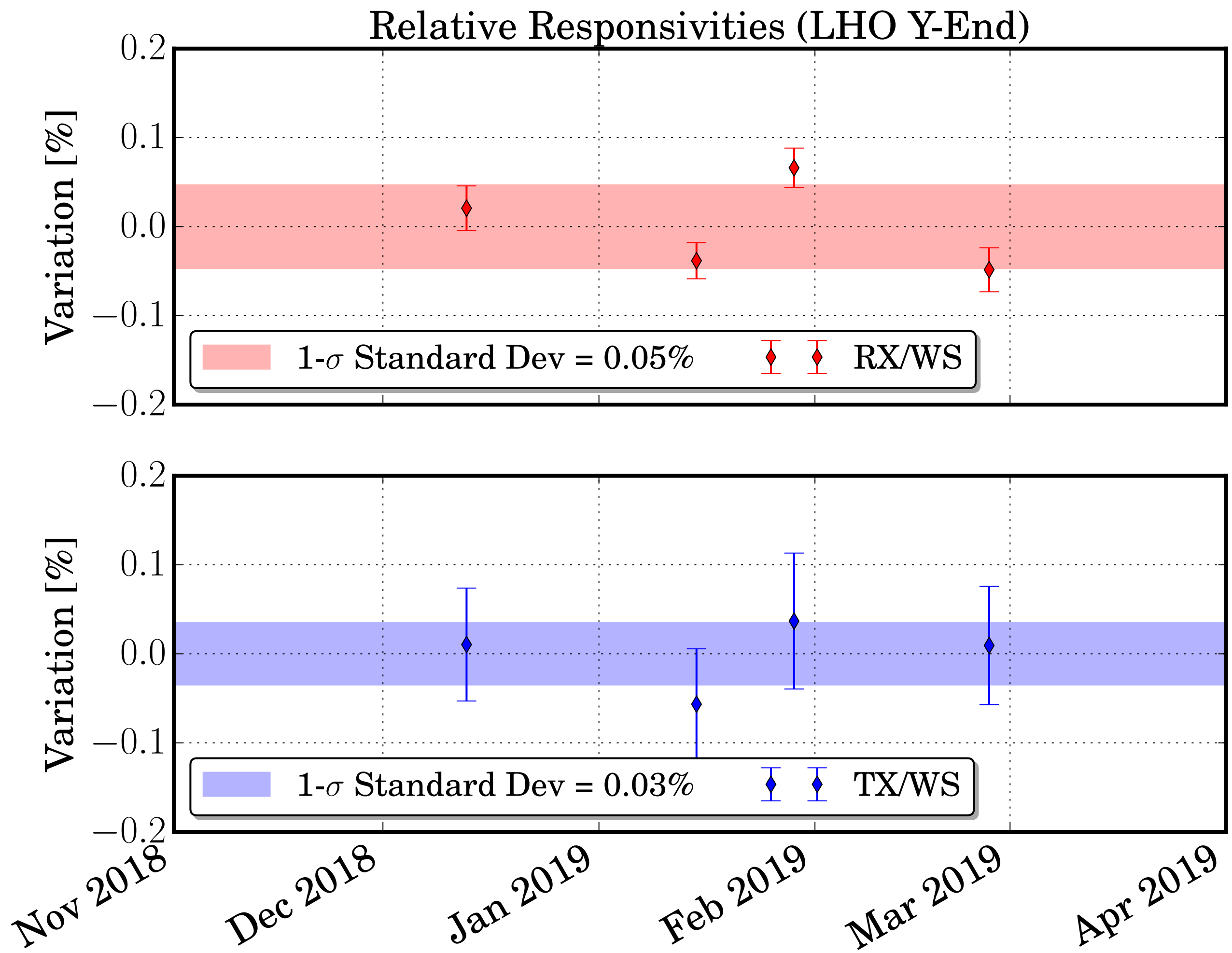
GS → WS

- Annual NIST measurement has uncertainty of ~ 0.35%.
- Uncertainties in relative responsivity measurements are approx. 0.10%.



WS → Tx / Rx

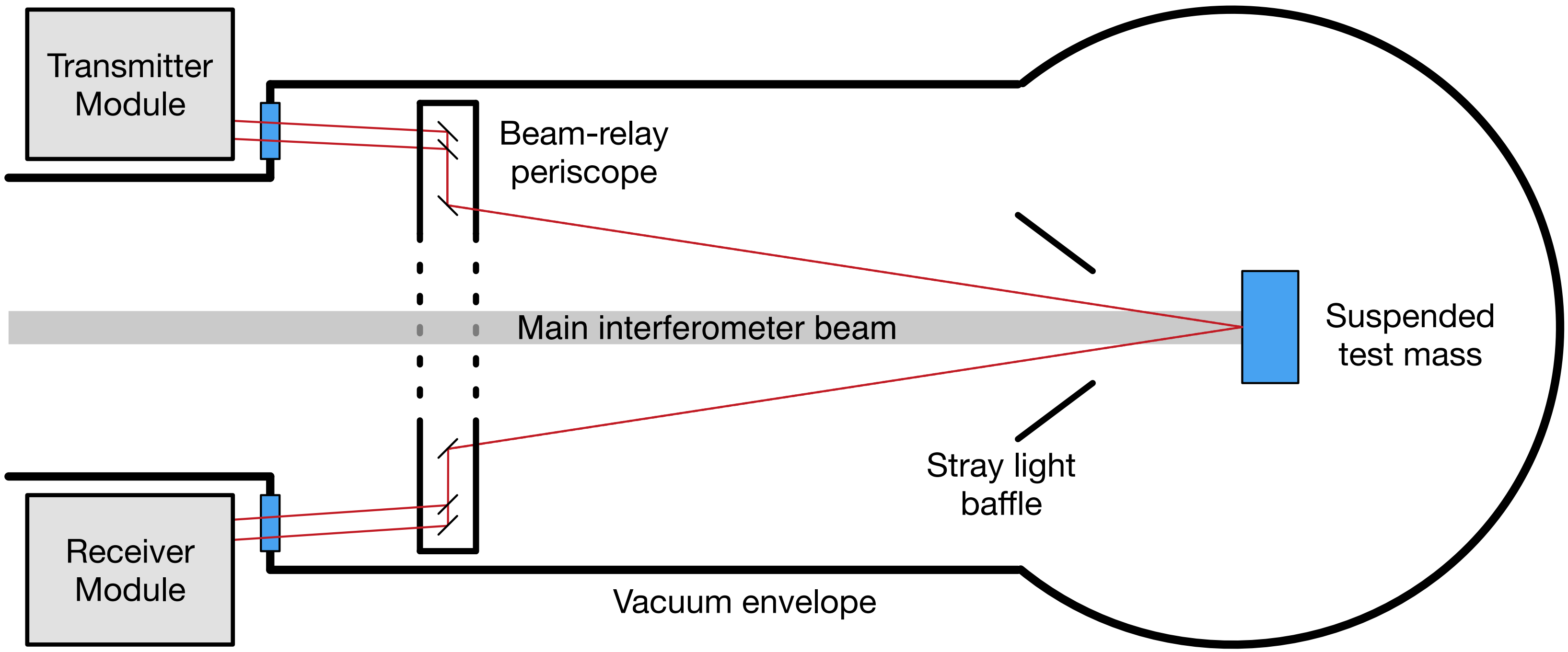
POWER CALIBRATION
Calibration Transfer (WS → Tx / Rx)



POWER CALIBRATION
Uncertainty Budget

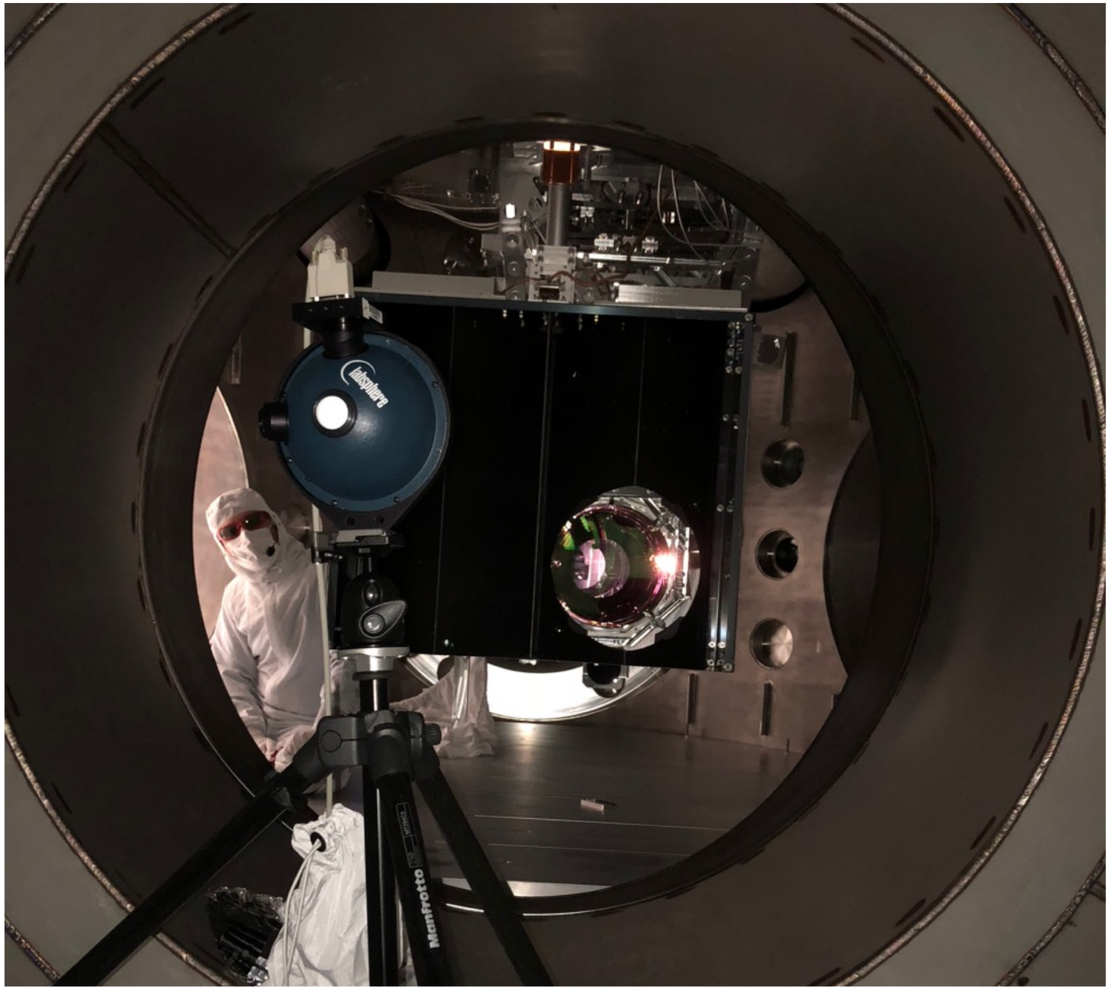
Parameter	Relative Uncertainty
NIST -> GS [ρ_{GS}]	$0.35\,\%$
WS/GS [α_{WG}]	$0.10\,\%$
Rx/WS [α_{RW}]	$0.10\,\%$
Overall	$< \mathbf{0.40\,\%}$

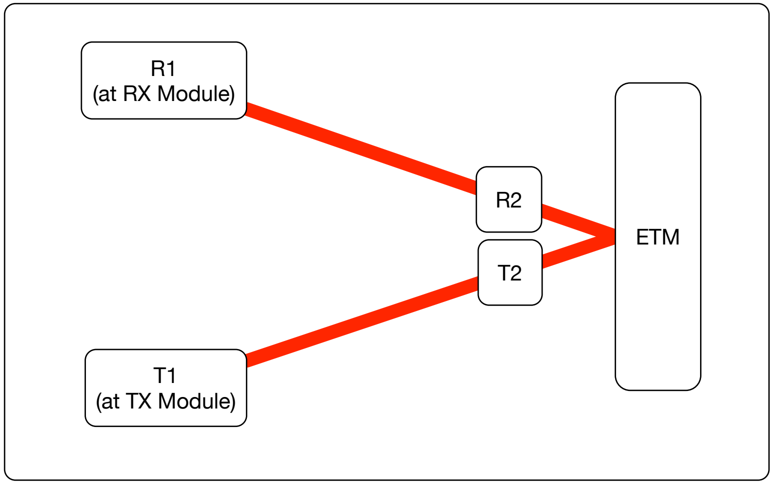
POWER CALIBRATION
Optical Efficiency



$$\frac{1.3\%}{2\sqrt{3}} \approx 0.37\%$$

POWER CALIBRATION
Optical Efficiency Improvements





In vacuum measurements at all 4 end stations

» Allows us to apportion the losses between the input and output paths

0.37% → 0.10%

DISPLACEMENT CALIBRATION
Uncertainty in "M" and "θ"

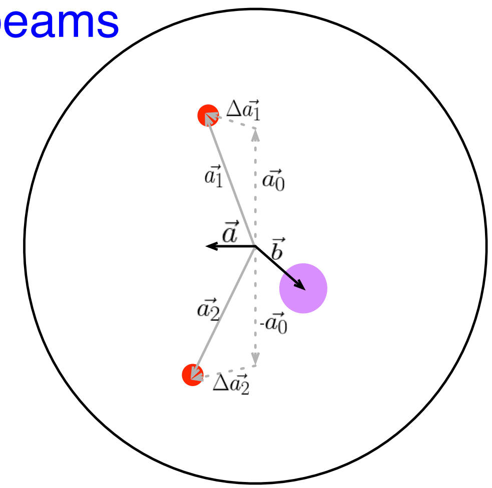
$$x(f) = \frac{2\cos(\theta)}{c} P(f) \frac{1}{M(2\pi f)^2} \mathcal{R}\, \mathcal{G}(f)$$

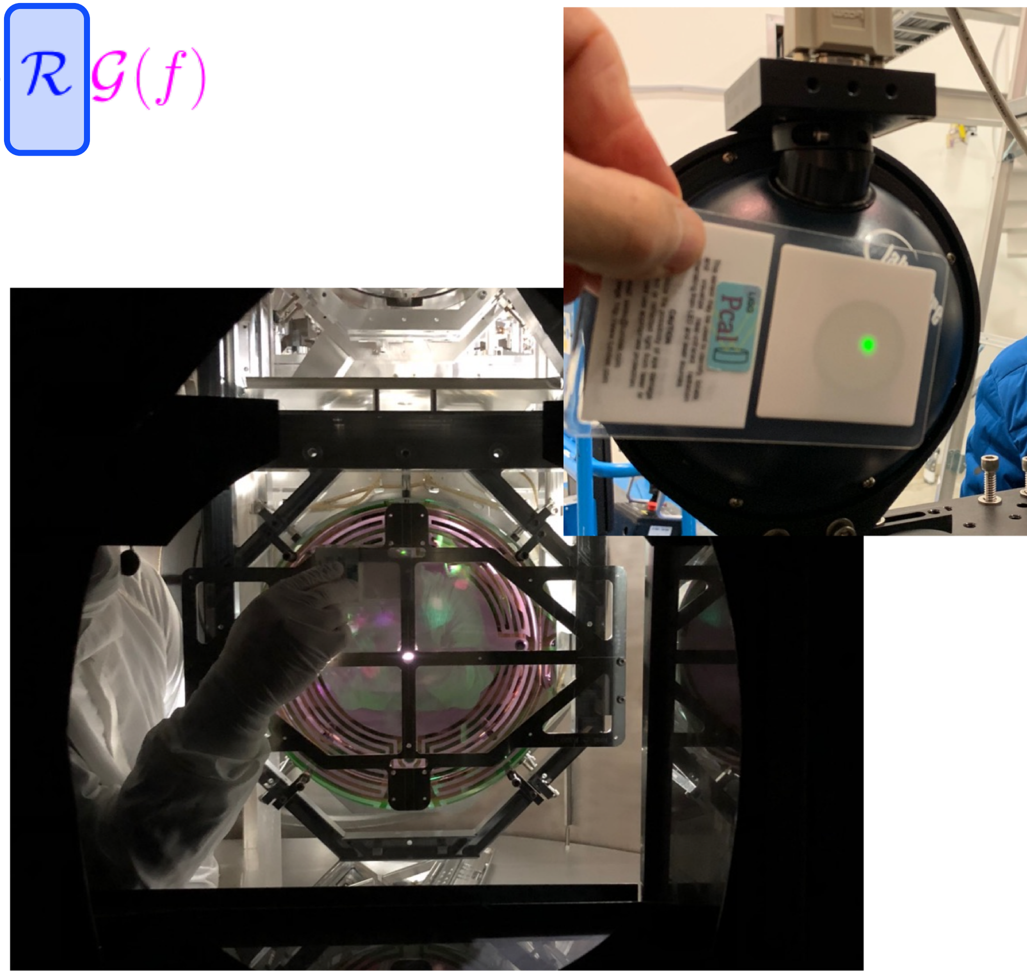
Parameter	Rel. Uncertainty
Mass (M)	0.005 %
Cos θ	0.07 %

DISPLACEMENT CALIBRATION
Error due to Rotation

$$x(f) = \frac{2\cos(\theta)}{c} P(f) \frac{1}{M(2\pi f)^2} \mathcal{R} \mathcal{G}(f)$$

- Unintended Rotational effect
  - Poor localization of the beams
  - Power imbalance between the beams





$$\mathcal{R}(a,b) = \left[1 + \frac{M}{I}\vec{a}\cdot\vec{b}\right]$$

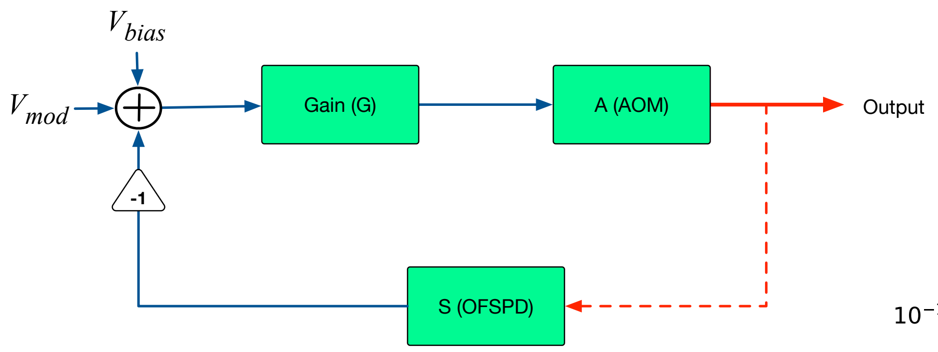
$\sim 0.20\ \%$

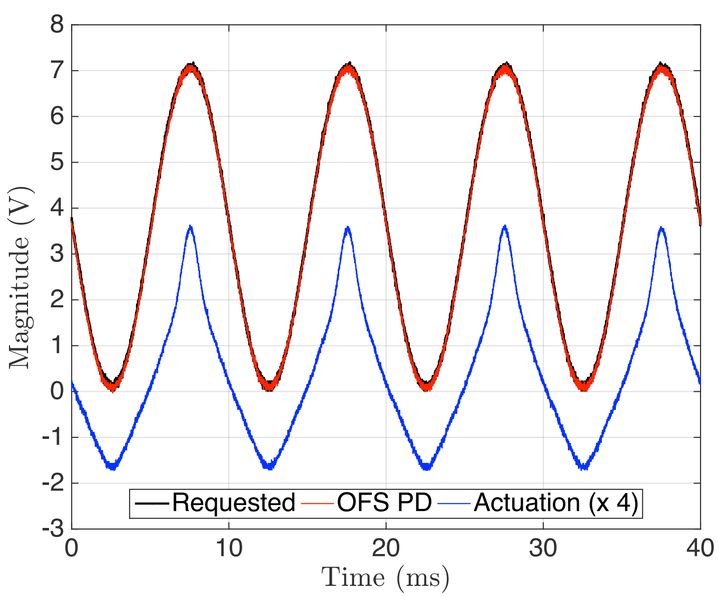
DISPLACEMENT CALIBRATION
Expected Uncertainty

Parameter	Relative Uncertainty
NIST -> GS [ρ_{GS}]	0.35 %
WS/GS [α_{WG}]	0.10 %
Rx/WS [α_{RW}]	0.10 %
Optical efficiency [$\mathcal{E}_T$]	0.10 %
Angle of incidence [$\cos\theta$]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$\mathcal{R}$]	0.20 %
Overall	**$<$ 0.50 %**

This is the accuracy of calibration on the displacement fiducials.

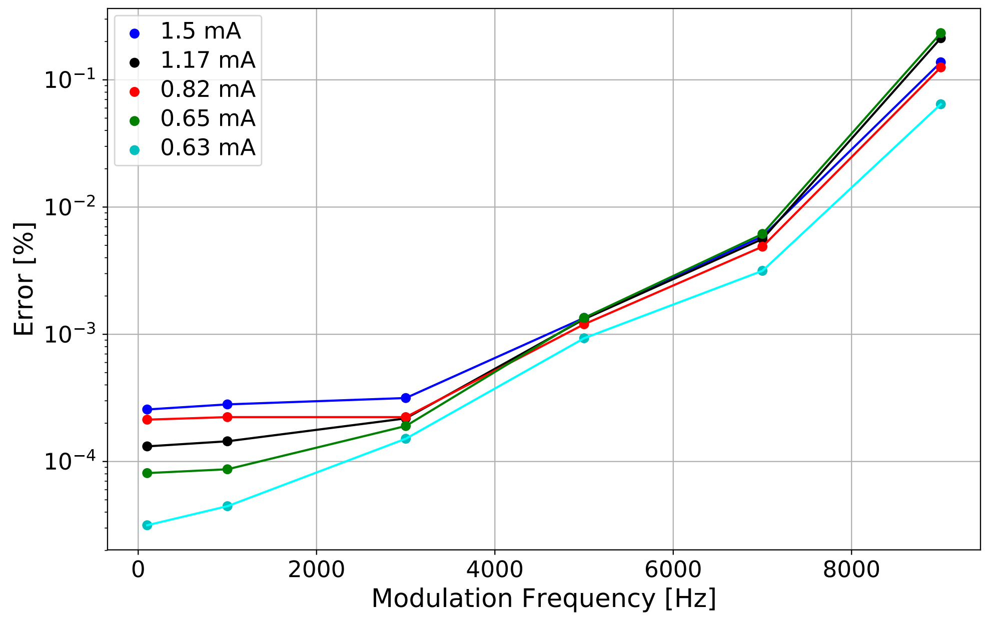
OPTICAL FOLLOWER SERVO
Frequency Response of WS





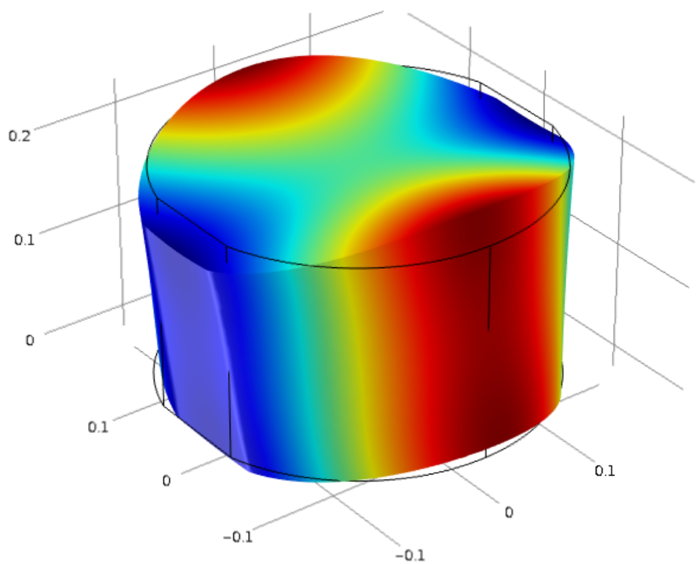
Frequency Response of Working Standard

Total Harmonic Distortion (14 harmonics)

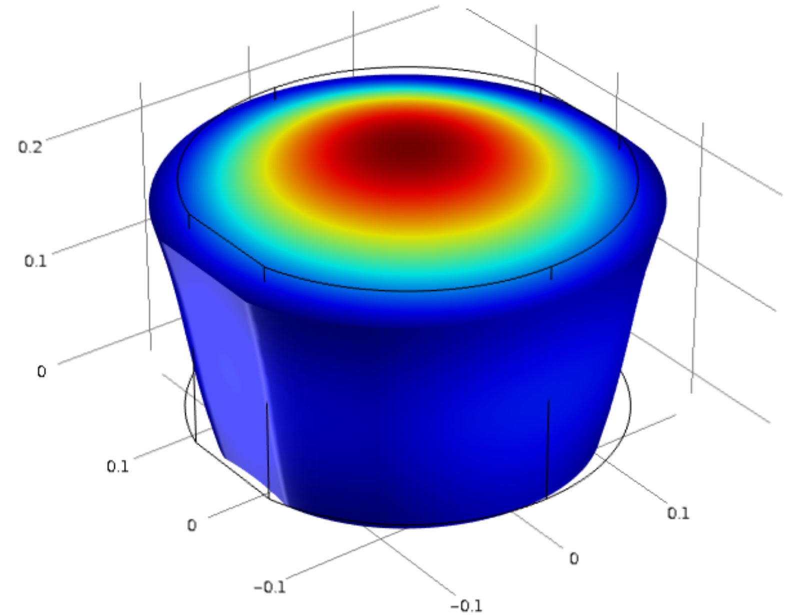


Error less than 0.01% up to 7 kHz

CALIBRATION AT HIGHER FREQUENCIES
Bulk Elastic Deformation



Butterfly Mode
5953 Hz

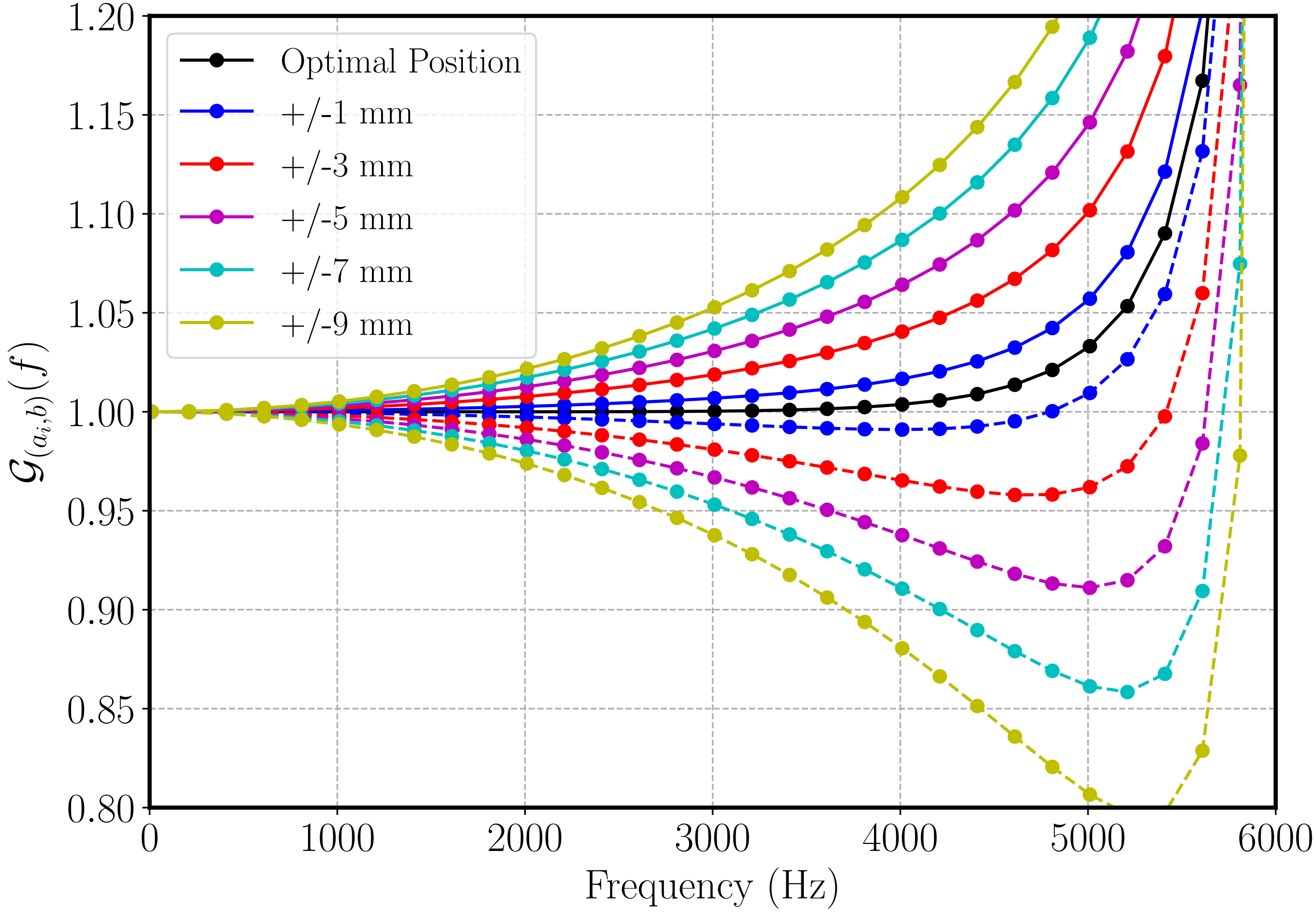


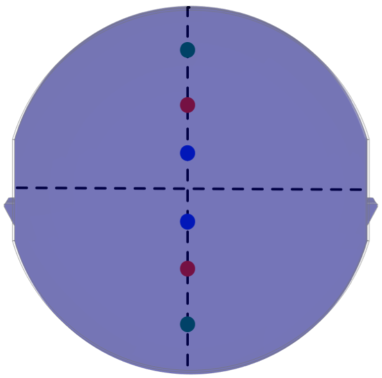
Drumhead Mode
8151 Hz

ETM motion deviates from their rigid body approximation due to the excitation of the natural modes by applied forces

$$x(f) = \frac{2\cos(\theta)}{c} P(f) \frac{1}{M(2\pi f)^2} \mathcal{R} \boxed{\mathcal{G}(f)}$$

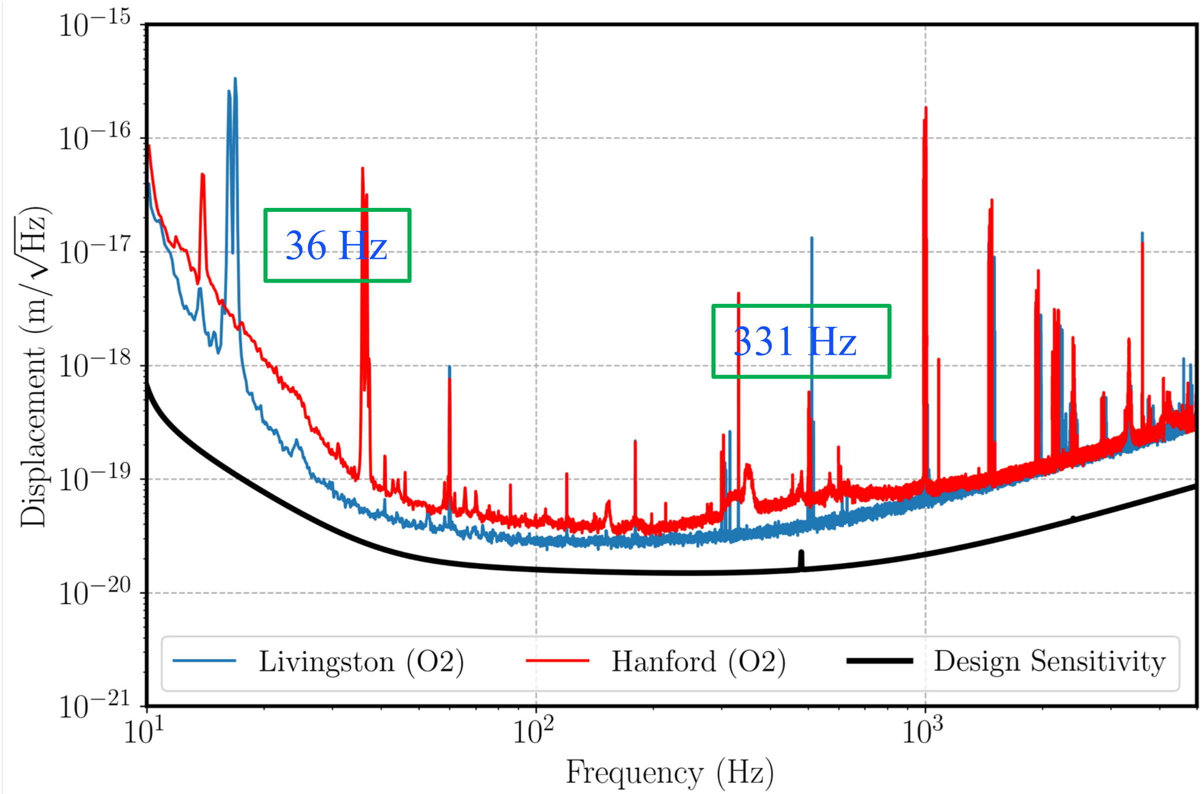
CALIBRATION AT HIGHER FREQUENCIES
FEA (COMSOL) Results





Front face of the test mass

CONTINUOUS CALIBRATION via Pcal Lines



Photon calibrators, that rely on absolute laser power calibration from NIST, are providing fiducial displacements with sub-1% accuracy.

November 2016
Volume 87 Number 11
Part 1 of 2
AIP
Review of Scientific Instruments
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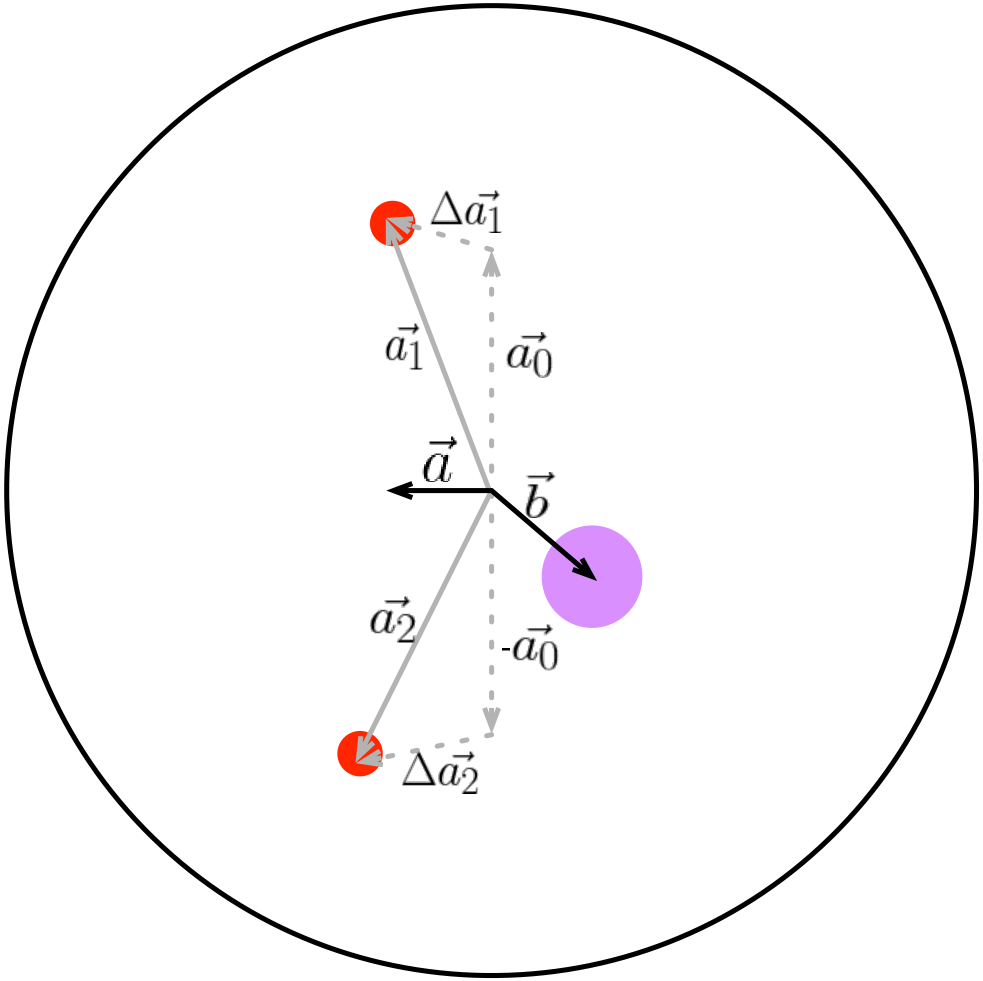
The Advanced LIGO photon calibrators
by S. Karki, D. Tuyenbayev, S. Kandhasamy et al.
rsi.aip.org

EXTRA SLIDES



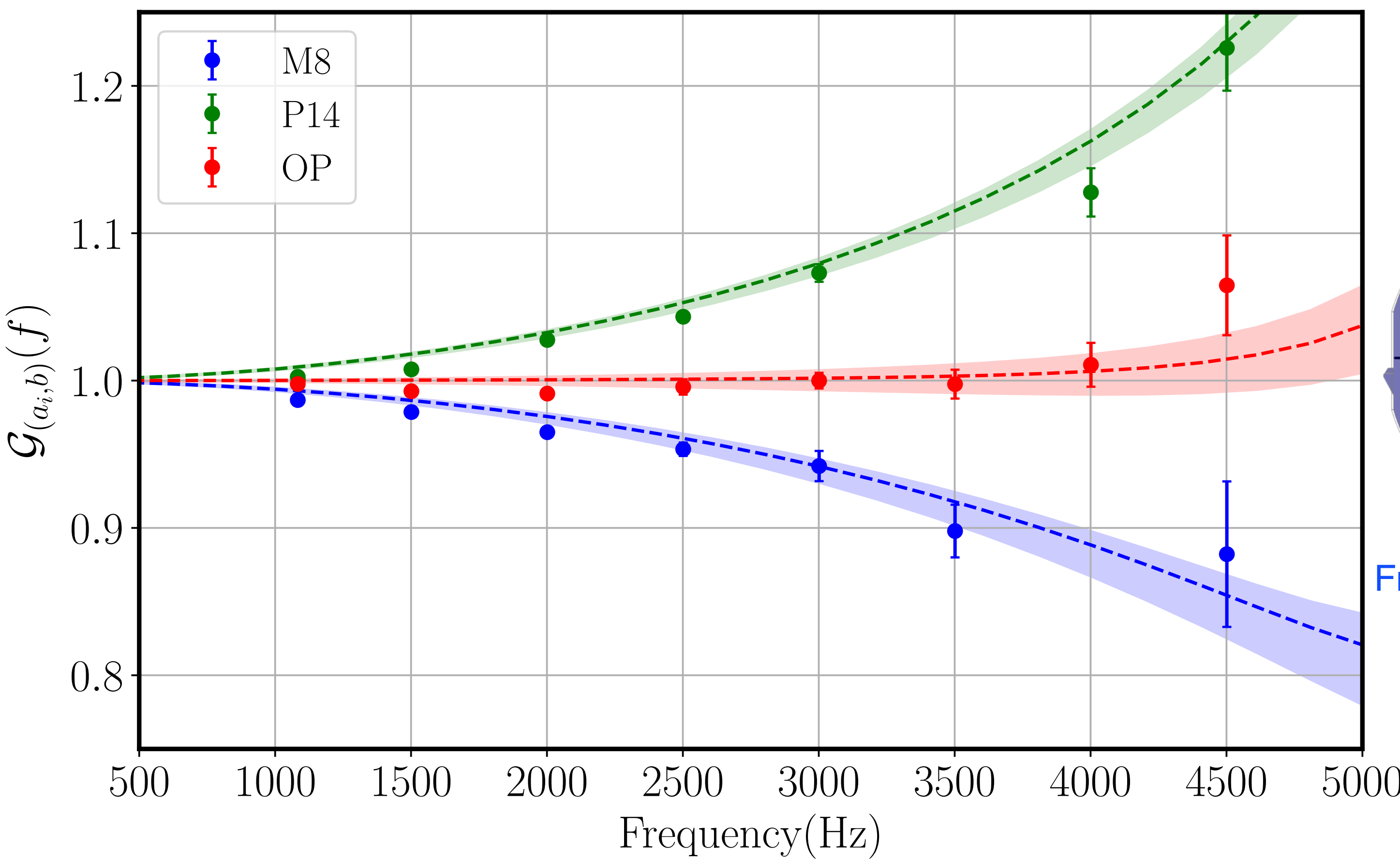
$$\vec{a} = \frac{\beta\vec{a}_1 + \bar{a}}{\beta + 1}$$

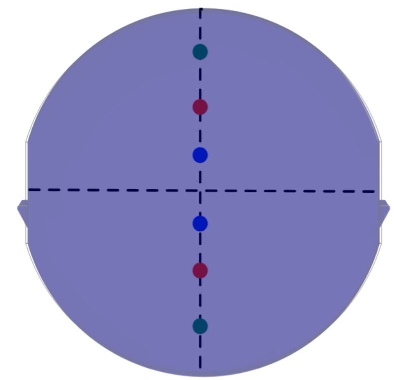
OUTLINE

- Principle of Operation
- Hardware Overview
- Laser Power and Displacement Calibration
  - Uncertainty
- Frequency Dependence
- Summary

CALIBRATION AT HIGHER FREQUENCIES
Experimental Results

Experimental confirmation of the results estimated from FEA.

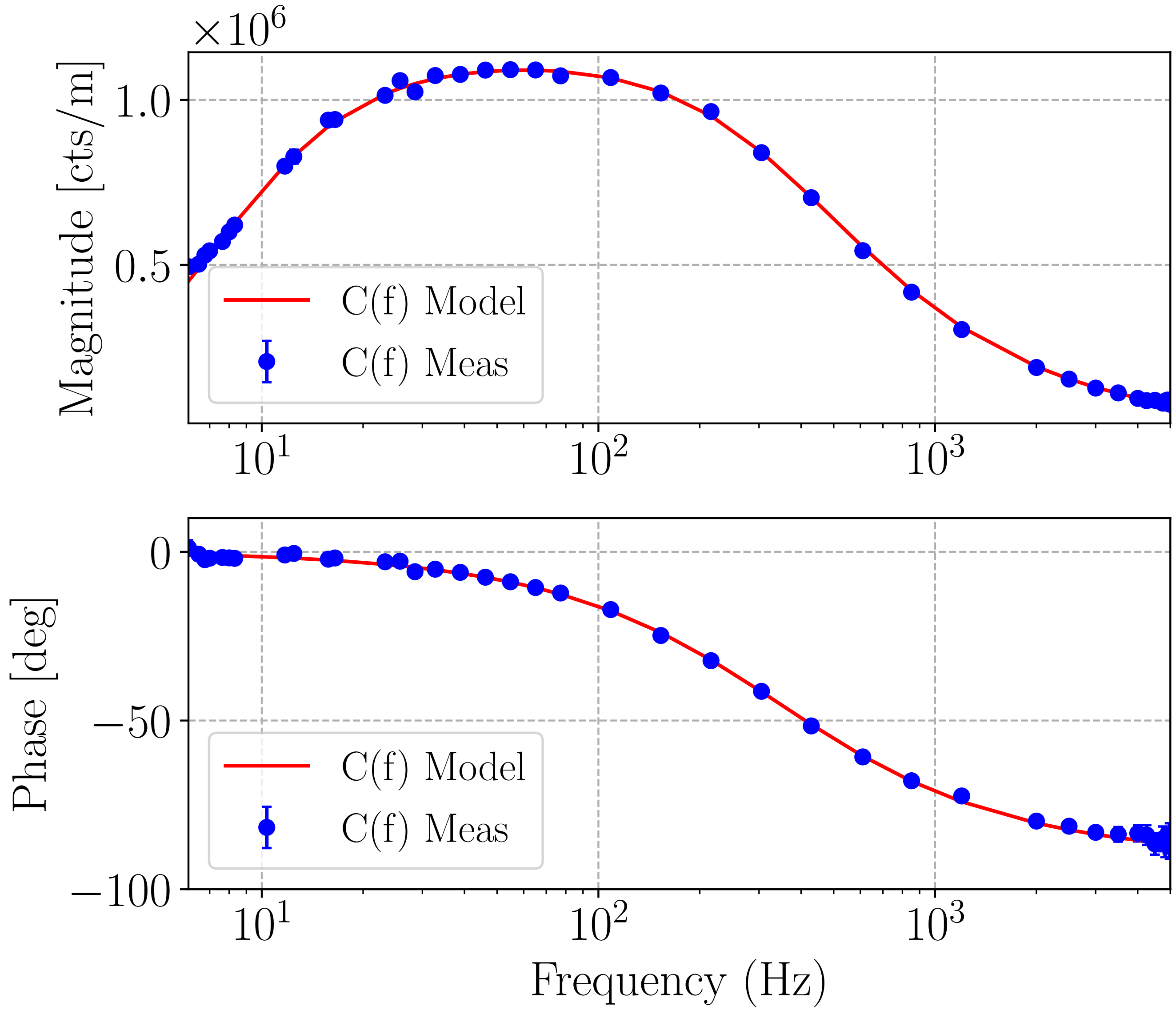




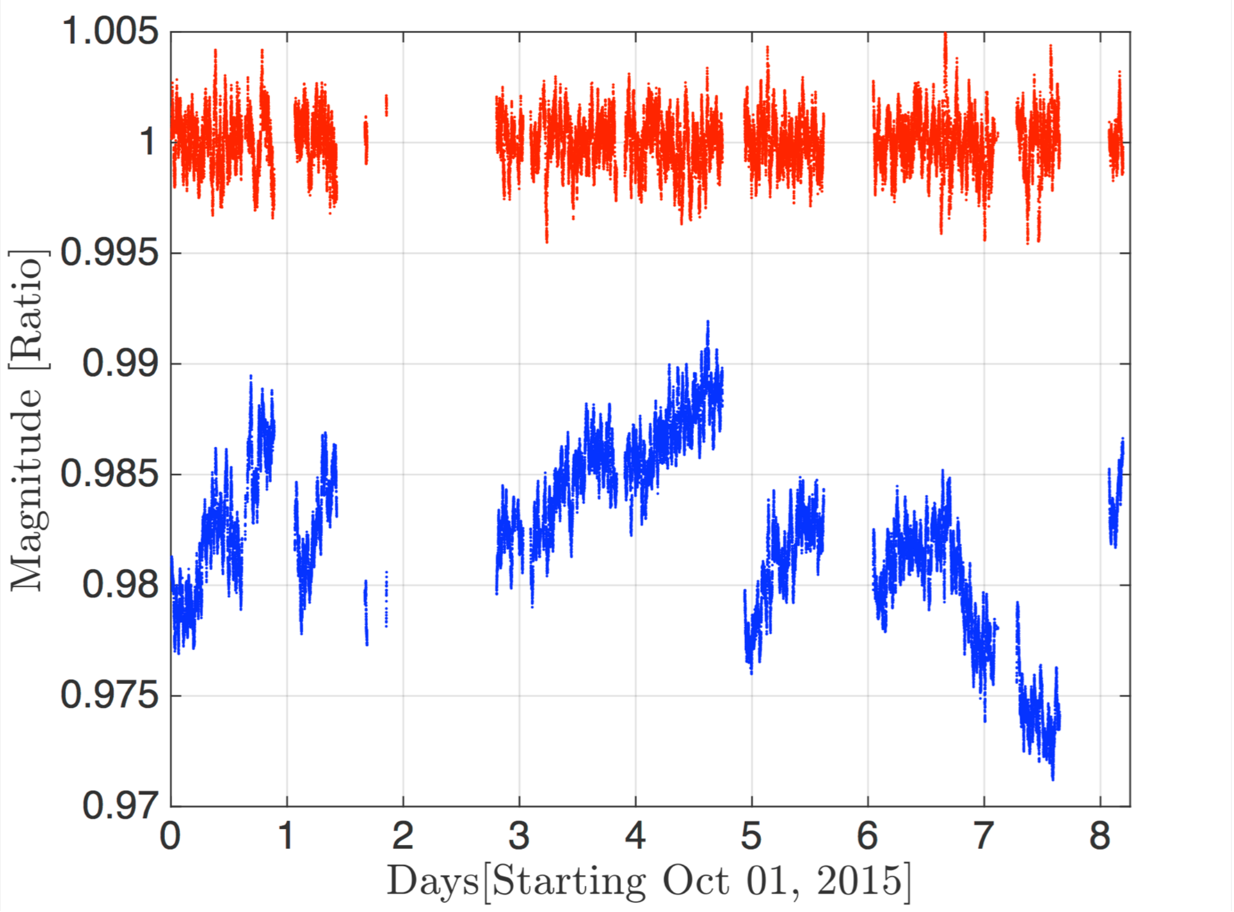
Front face of the test mass

Enable better calibration at high frequencies.

APPLICATION
Swept-Sine Measurements

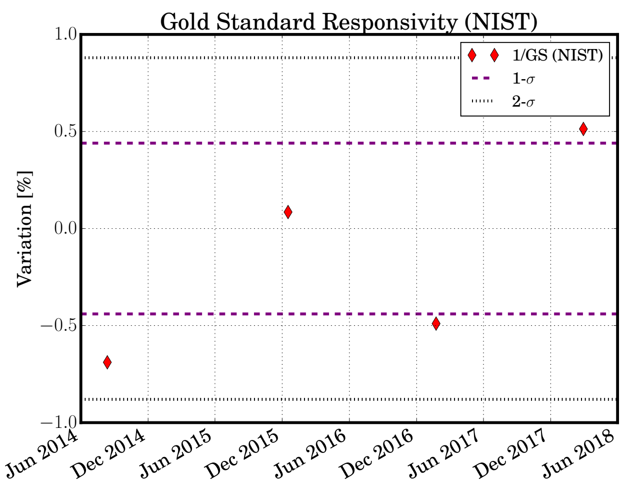


APPLICATION
Temporal Variations

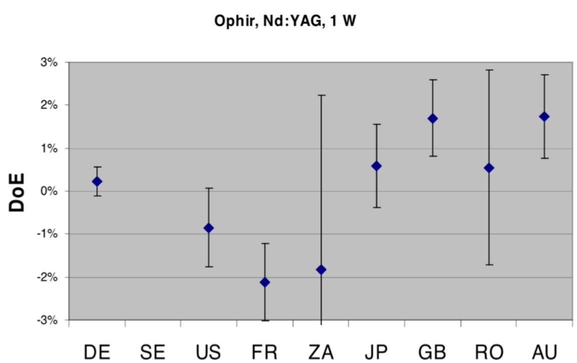


Improvement in calibrated signal after applying the time-varying calibration parameters

UNCERTAINTY BUDGET
Meeting at NIST Boulder (May 9,2018)



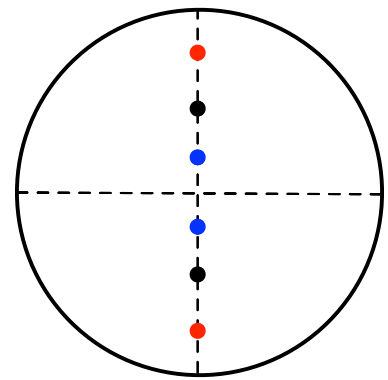
Unusually large variations in NIST calibration



Comparison of Global Power Standard.

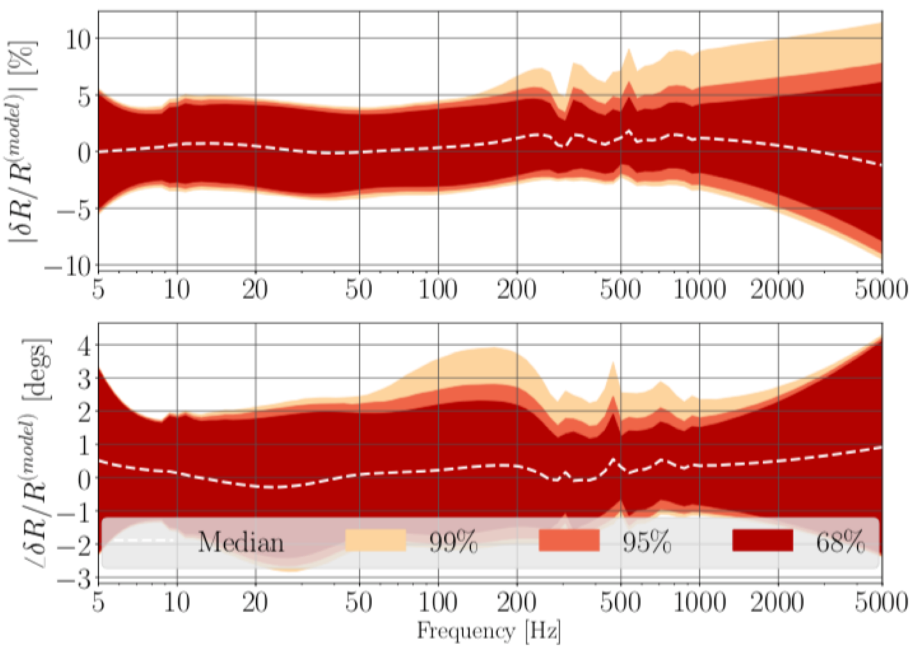
- The larger variations in NIST measurement was due to the light reflecting back from the nearby aperture into the power sensor.
  - » Confirmed this through an experiment conducted at NIST during the visit.
  - » Will start new measurements of Gold Standard and collect at least two data points before O3.
- Calibration provided by NIST are traceable to fundamental units.
  - » They are the only institute that calibrate at 1 W level.
  - » Rest of the countries extrapolate from microwatt level

CALIBRATION AT HIGHER FREQUENCIES
Measurement Setup

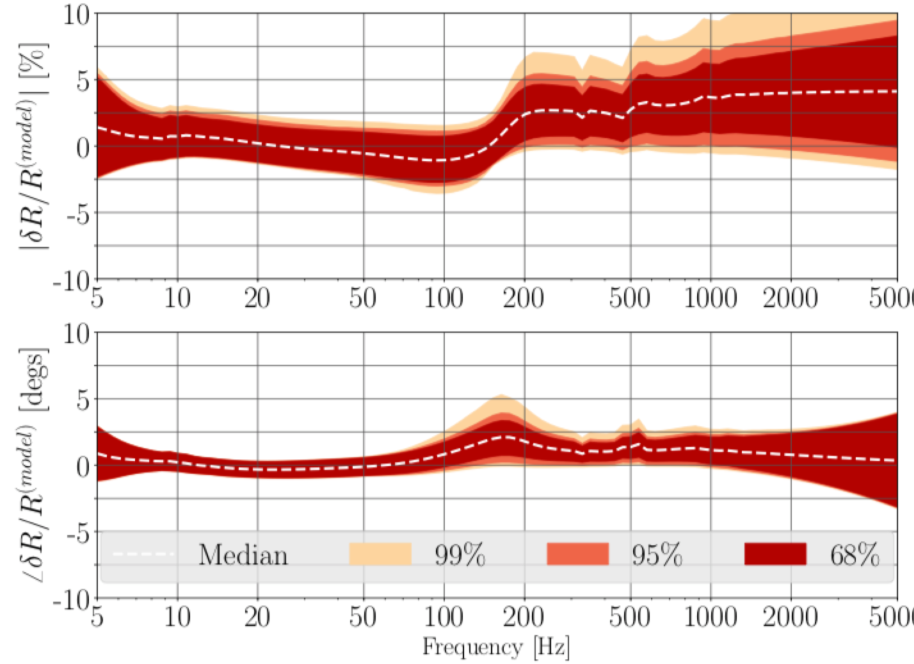
Config.	Pcal Beam Position			Beam Config.
	Beam	Target (mm)	Actual (mm)	
OP	Upper	[0, 111.6]	[0.8, 112.2]	
	Lower	[0,-111.6]	[-0.8, -111.8]	
P14	Upper	[0, 127.6]	[1.2, 126.1]	
	Lower	[0, -127.6]	[-0.5, -125.7]	
M8	Upper	[0, 103.6]	[2.5, 103.2]	
	Lower	[0, -103.6]	[-1.3, -103.0]	

OVERALL CALIBRATION UNCERTAINTY For O1 and O2

Cahillane et al., Phys Rev D 96, 102001



Observing Run 1



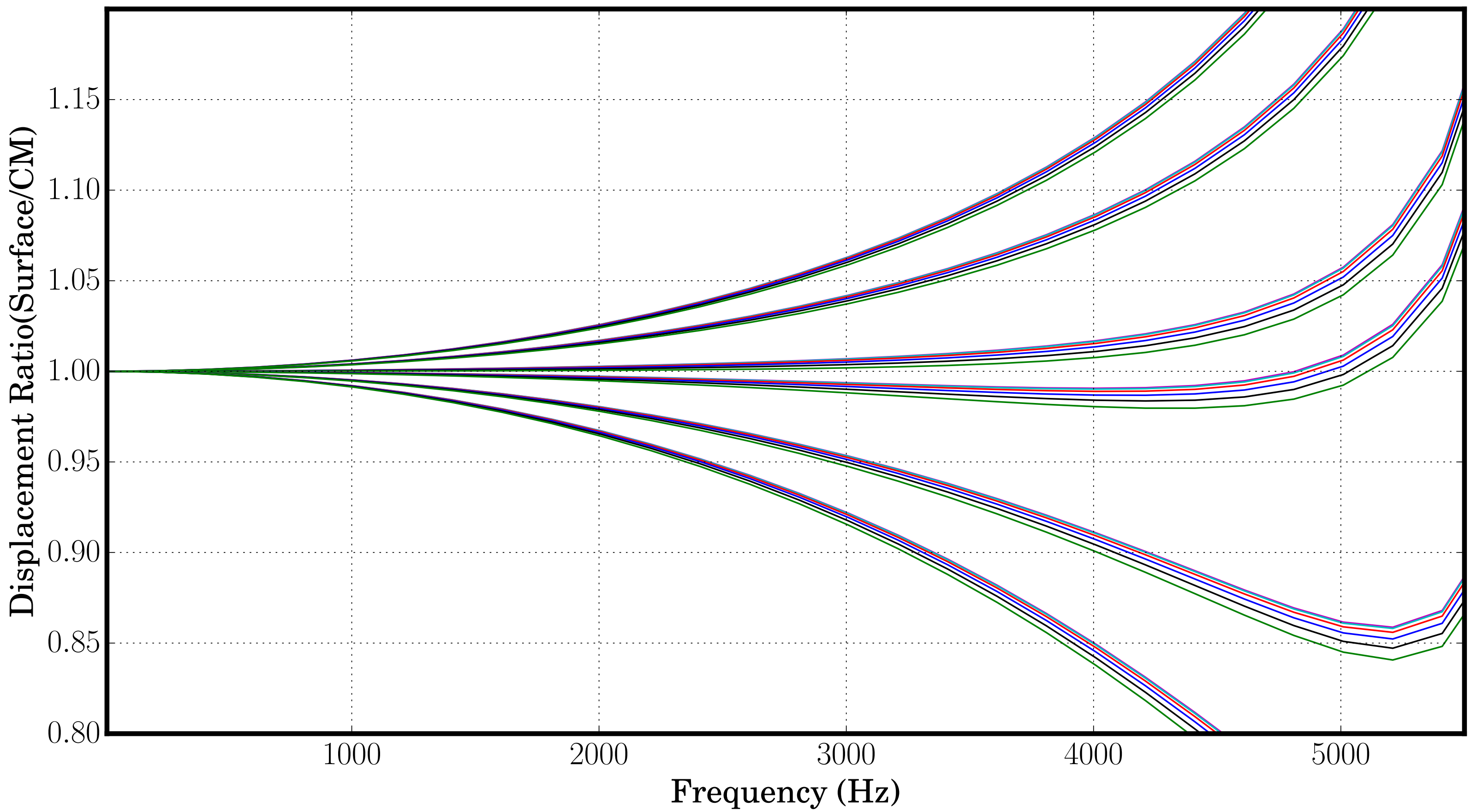
Observing Run 2

IN-VACUUM OPTICAL EFFICIENCY MEASUREMENTS

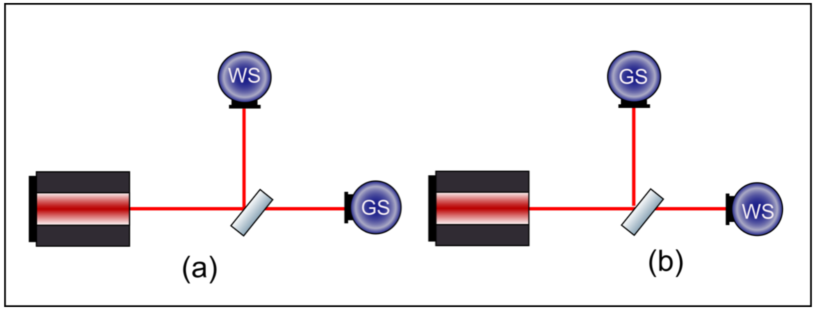
Path	Tx $\rightarrow$ ETM	ETM refl.	ETM $\rightarrow$ Rx	Total (Tx $\rightarrow$ Rx)
Inner Beam	0.9947	1.0007	0.9957	0.9911
Outer Beam	0.9920	1.0009	0.9933	0.9862
Average	0.9933	1.0008	0.9945	0.9887
			Total optical loss	1.13 %
			Fraction of optical Loss on Input side	0.56
			Fraction of optical Loss on Output side	0.44

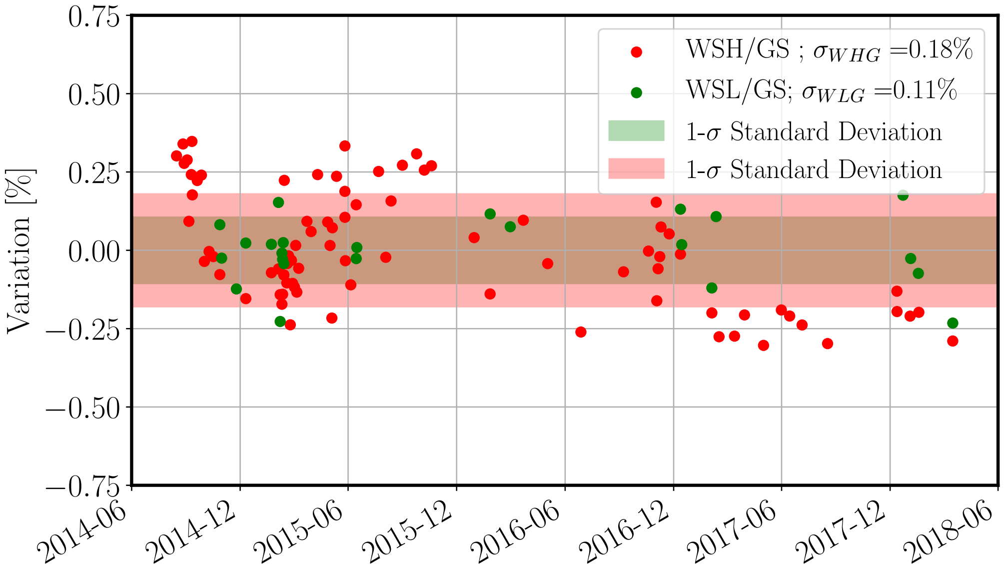
With 55% to 45% loss on two sides and

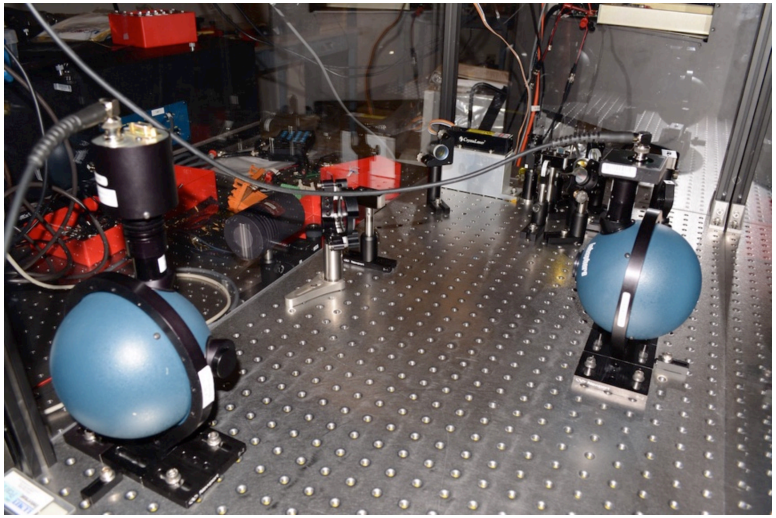
CALIBARTION AT HIGHER FREQUENCIES
Effect of IFO beam position



POWER CALIBRATION
Calibration Transfer (WS/GS)

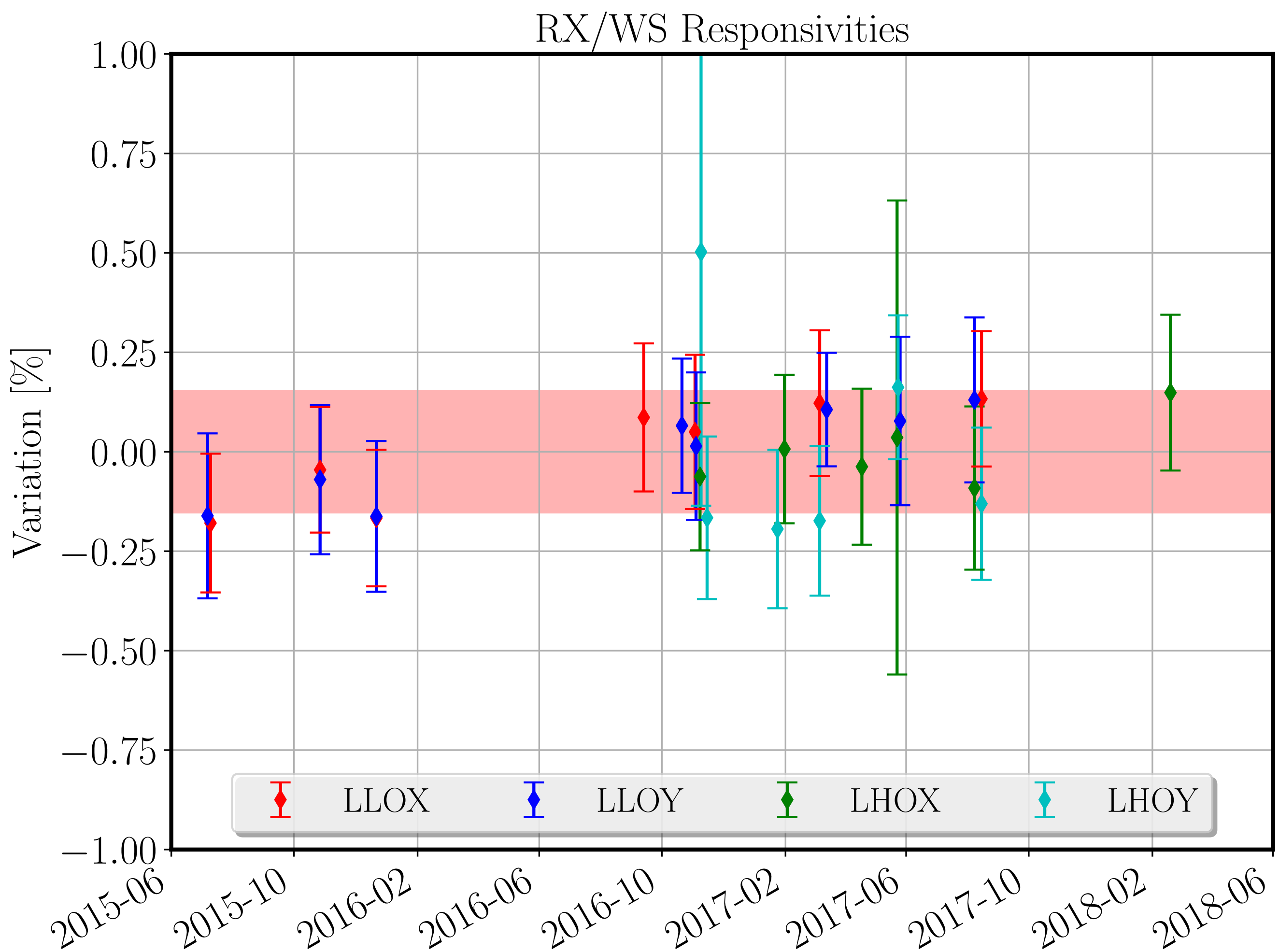






WS/GS➔ 0.03%

POWER CALIBRATION
Calibration Transfer (Rx/WS)



RX/WS➔ 0.05%