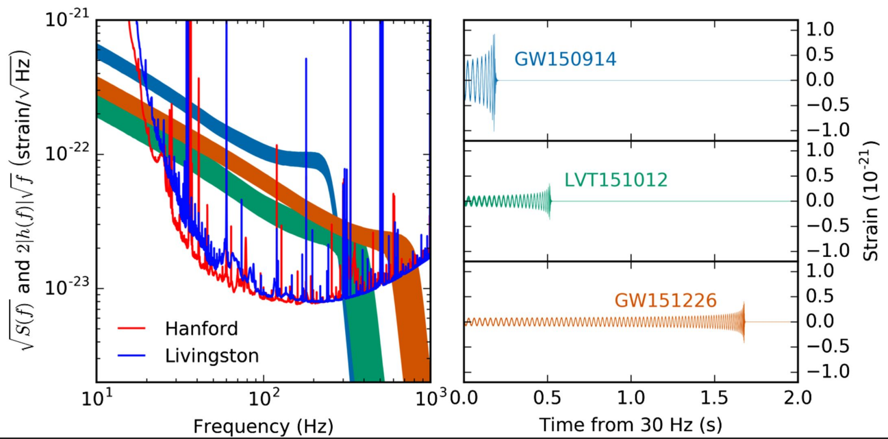
Advanced LIGO Calibration Uncertainty for Precision Astrophysics

Craig Cahillane
July 10th, 2017

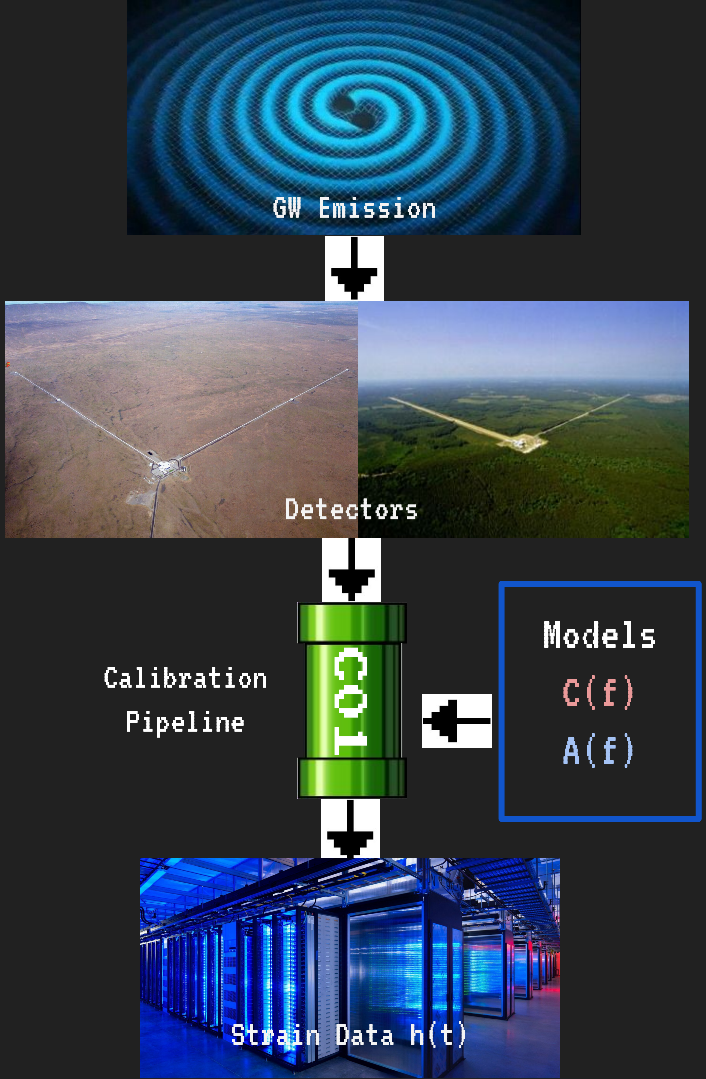
Table of Contents

O1 + O2 Calibration Uncertainty Budgets

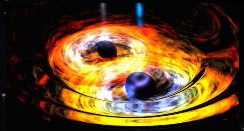
- What is calibration?
  - Production of GW strain data from our detector data
- Why calibration uncertainty?
  - It's the project I was handed when I was a first year
  - No one cared until we made a detection
  - Now everyone cares
  - Imperative for precision astrophysics



Taken from [1]



Motivation for Low Calibration Uncertainty

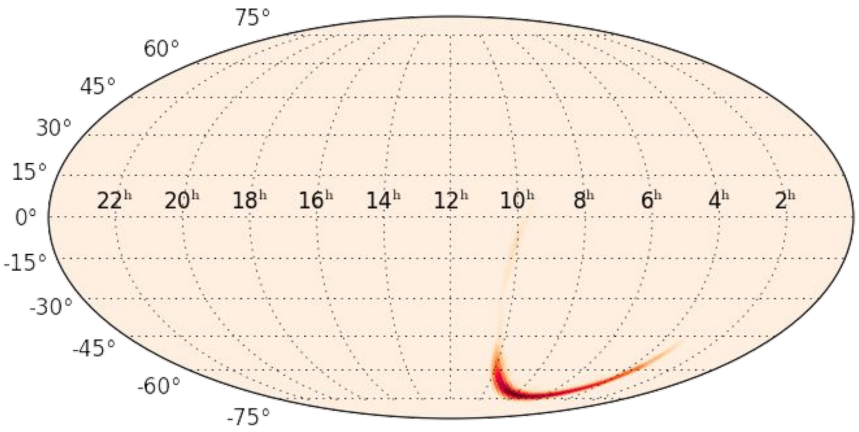


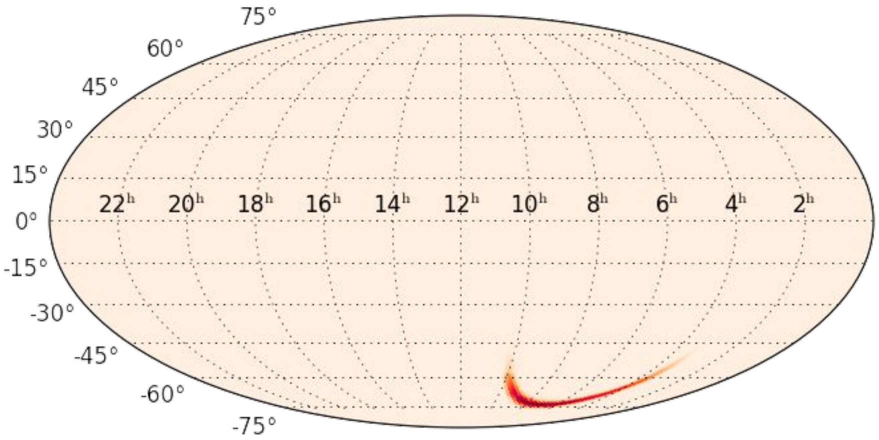
- We don’t want to just make detections, we want to do astrophysics with these detections
    - Source parameters
        - Black hole masses, spins, luminosity distance, inclination, sky location, etc
    - Merger rates
        - Event rate, universal mass distribution, binary star formation
    - Tests of general relativity
        - Strong-field non-linear regime
    - Cosmology
        - Hubble constant measurements
- The accuracy and precision to which we know GW strain data affects all of the above
- Right now we aren’t calibration uncertainty limited, we are SNR limited
    - This won’t always be the case, when we start getting SNR ~ 700 detections in Super Advanced LIGO

Impact of Cal Uncertainty on GW150914 Sky Location

GW150914 90% sky area with 10%, 10 degrees cal uncertainty = 231 square degrees

GW150914 90% sky area with NO cal uncertainty = 153 square degrees

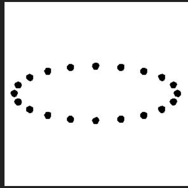




Plots from Chris Berry

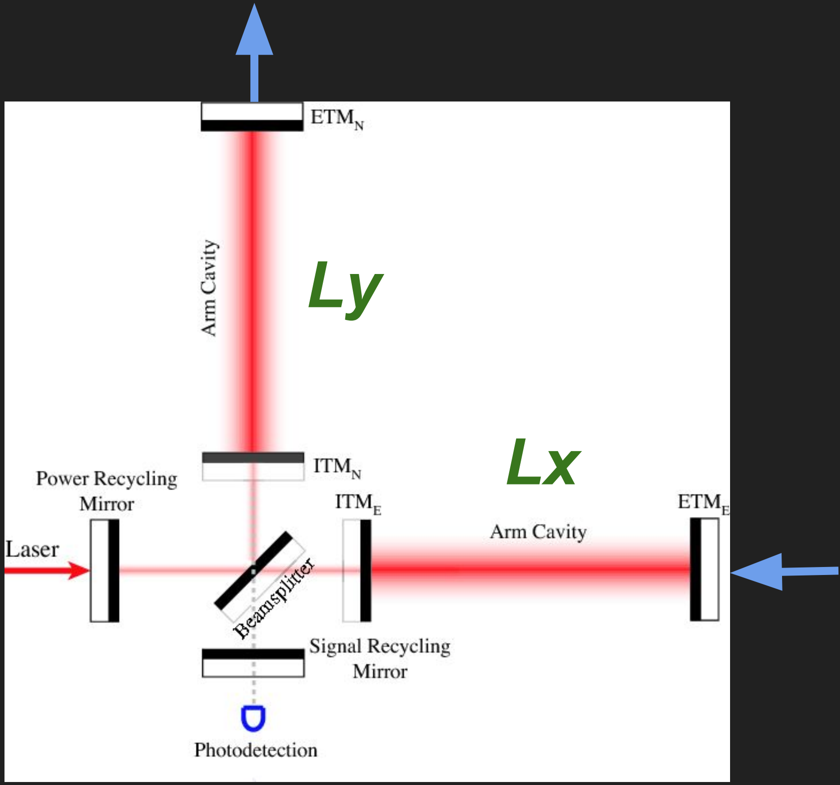
Gravitational Waves and Interferometers

- When a GW hits test particles, it stretches and squeezes them in a quadrupolar way



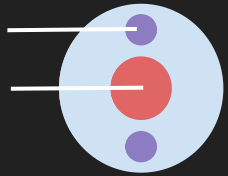
Ring of test particles hit by plus polarized GW

- An interferometer's End Test Masses (ETMs) are like the above test particles
    - A GW changes the distances L_x and L_y
- When on resonance, or "locked", an interferometer is hyper-sensitive to differential arm motion
    - DARM = Differential Arm Motion
    - $L_{DARM} = L_x - L_y$
- We control this motion with the DARM control loop

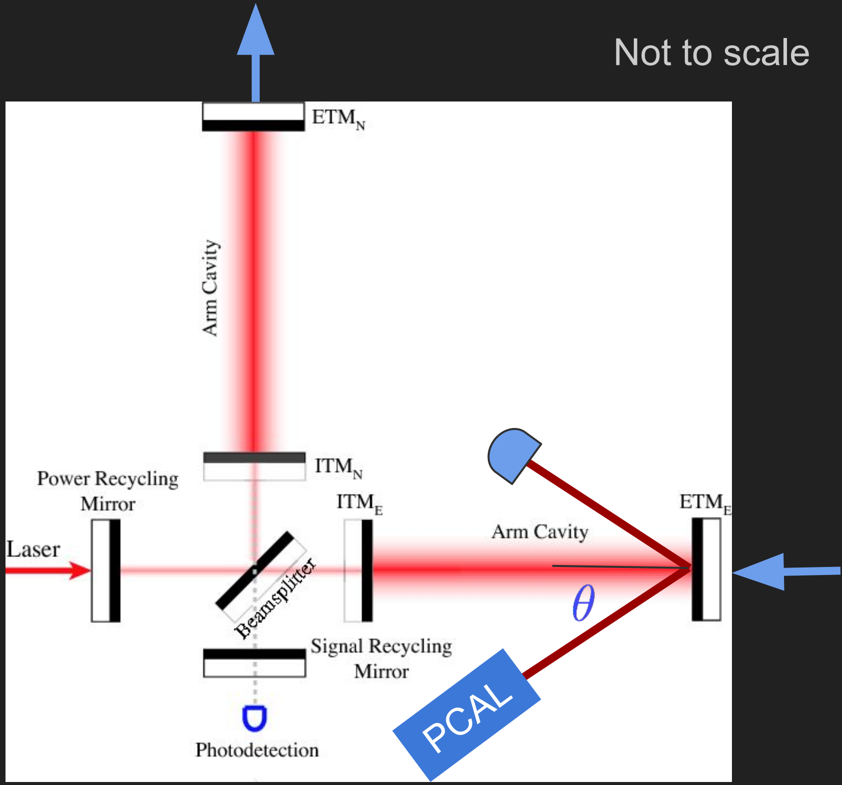


What is Calibration?

- Push on end mirrors by known amount with the photon calibrator laser (PCAL) [8]
  - This laser's power is extremely well known (~2 Watts)
  - Imposes a fundamental limit on our test mass motion uncertainty of ~0.8%
- When we push on one end test mass, it simulates a gravitational wave incident on our detector
  - Light in the cavity is phase shifted into the antisymmetric port onto our photodetector
- This photodetector readout gives us our calibration from meters of test mass motion to arbitrary counts

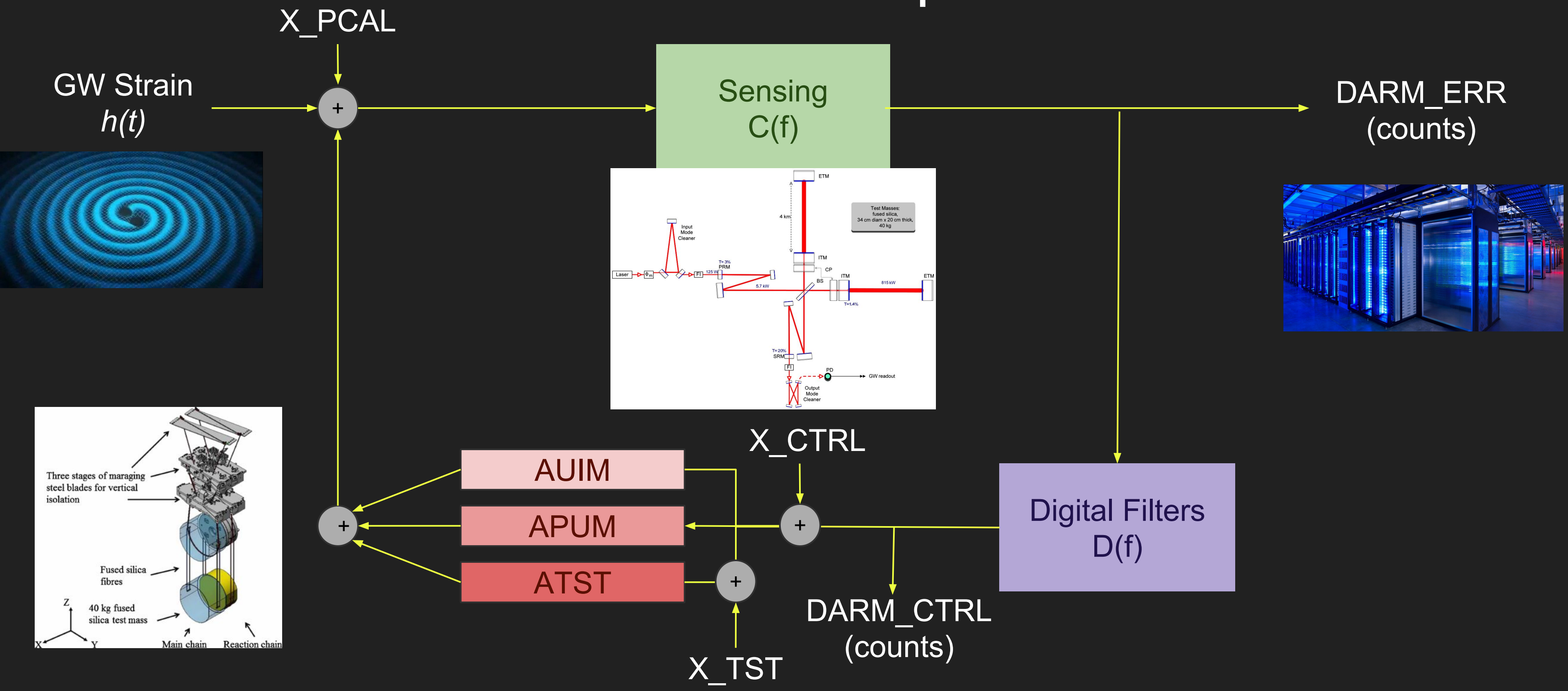


Not to scale



$$\theta = 8.75^\circ$$
$$\lambda = 1047 \text{ nm}$$

DARM Loop



$$G(f) = C(f)\,D(f)\,A(f)$$

$$R^{-1}(f) = \frac{1 + G(f)}{C(f)}$$

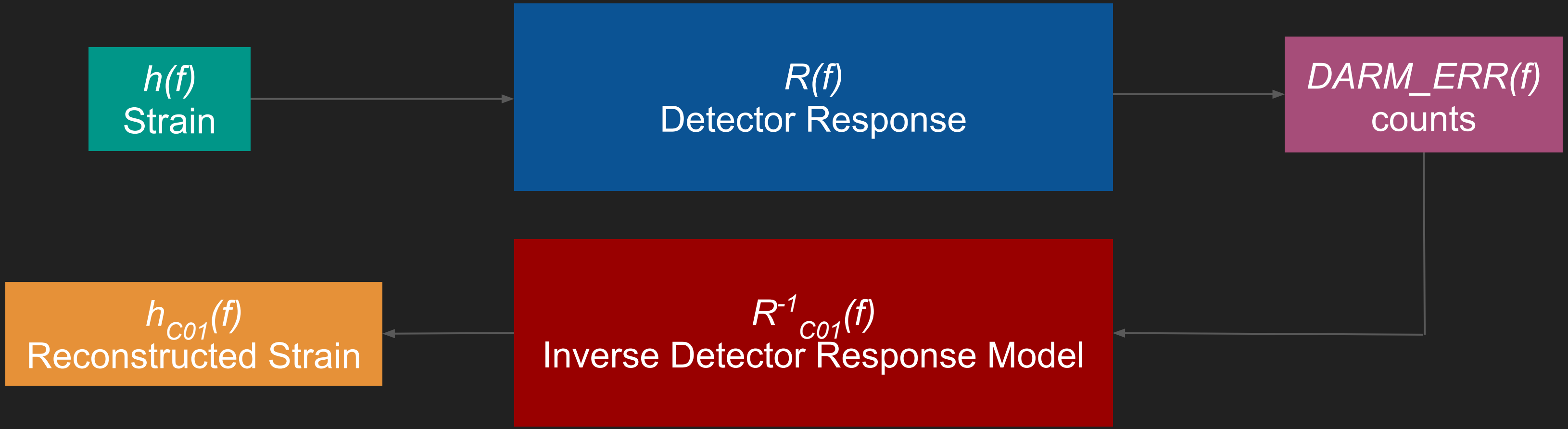
DARM Response

- The inverse detector response function $R^{-1}(f)$ is the transfer function from GW strain to DARM_ERR counts:

$$h(f) = R^{-1}(f)\, d_{err}(f)$$

- This means that uncertainty in strain is equivalent to uncertainty in the response:

$$\sigma_h(f) = \sigma_{R^{-1}}(f)$$



Sensing Function *C(f)* Model

- Through the work of Buonanno and Chen, Robert Ward, Evan Hall, and Kiwamu and myself, the calibration group has a physical model for our interferometer
  - Buonanno and Chen modeled a signal-recycled interferometer using quantum optics [2].
  - Robert Ward converted the above into dual-recycled Fabry-Perot interferometer model [3].
  - Evan Hall showed the above model described detuning of the interferometer [4].
  - Kiwamu and I simplified the model down to the simple pole and optical spring we have today.

Calibration Sensing Model C(f)

$$\frac{f^2}{f^2 + f_S^2 - i f f_S Q^{-1}} \frac{\kappa_C(t) H_C}{1 + i f / f_{CC}(t)}$$

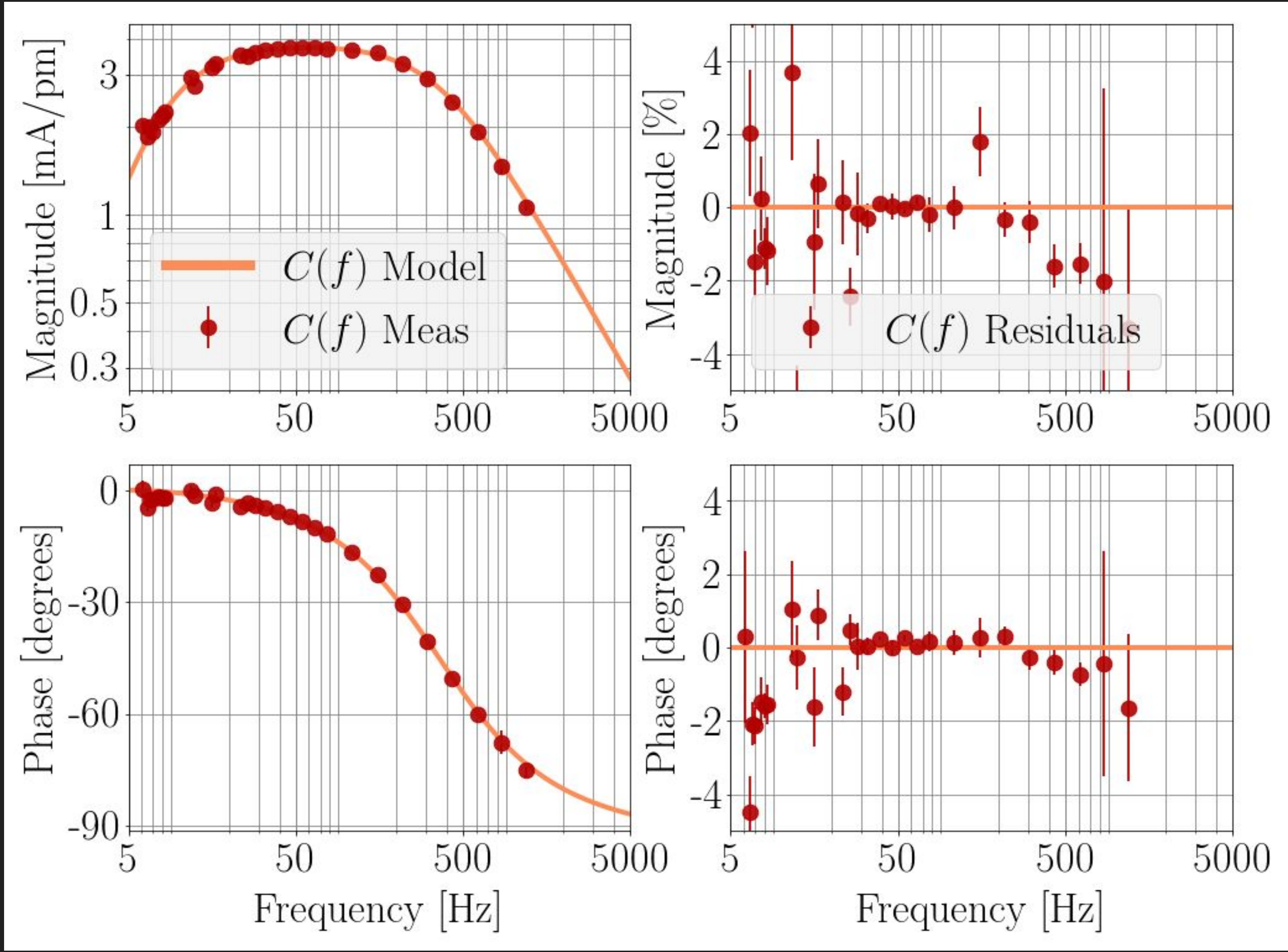
$$H_c = \text{Optical Gain}$$

$$\kappa_C(t) = \text{Gain Time-Dependent Scalar}$$

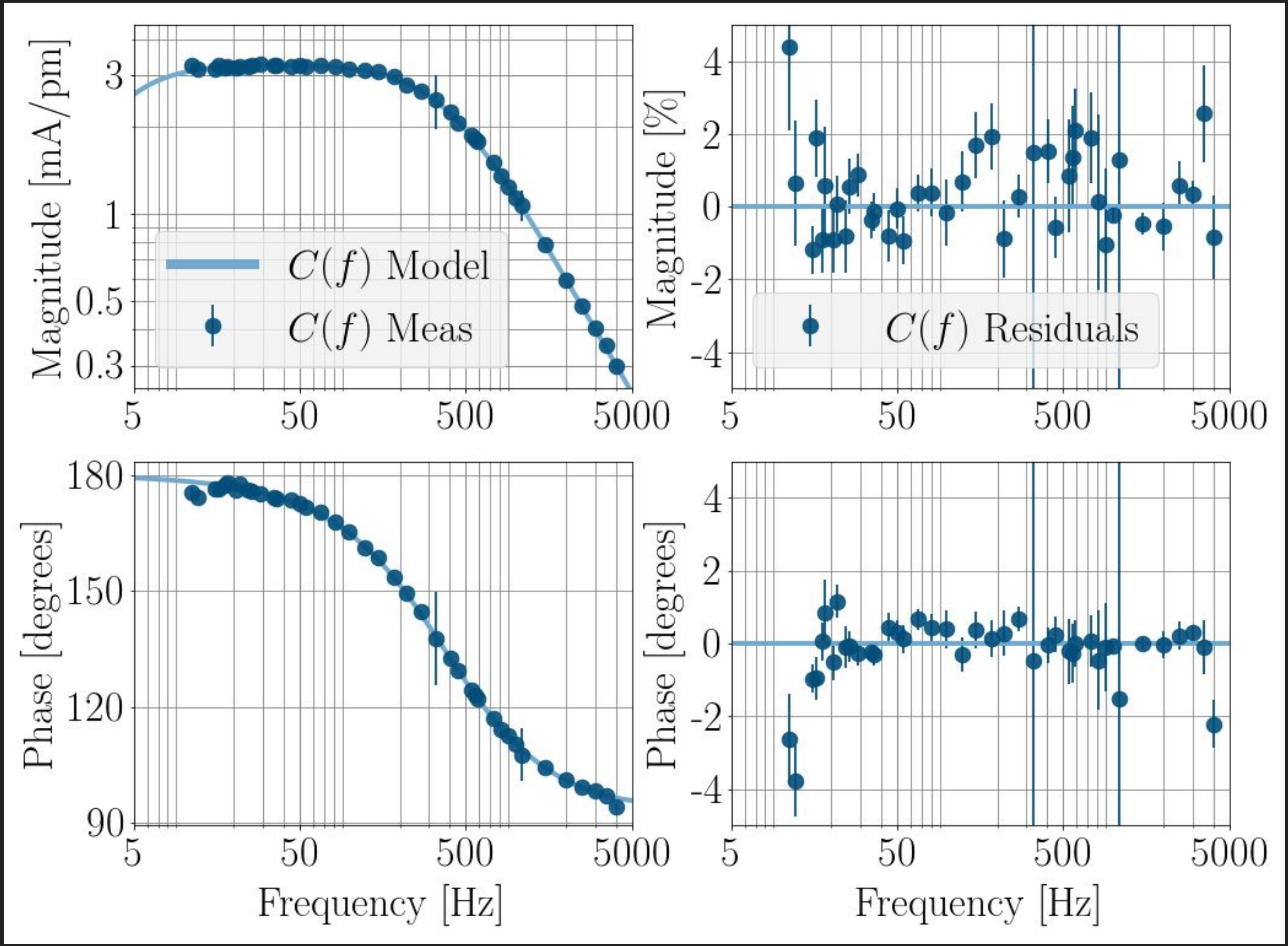
$$f_{cc}(t) = \text{Coupled Cavity Pole}$$

$$f_S = \text{Optical Spring Frequency}$$

$$Q = \text{Optical Spring Q}$$



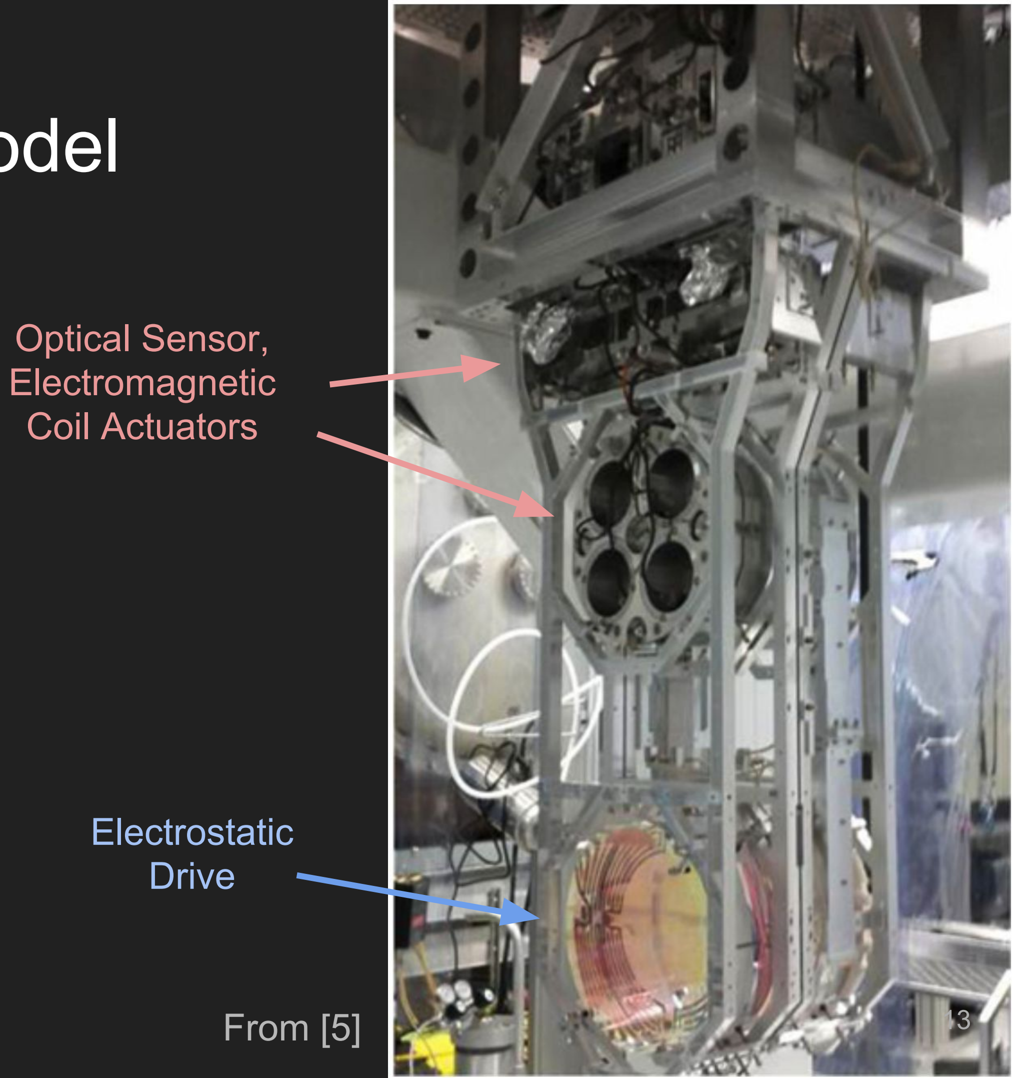
Meas Date:
Jan 4, 2017



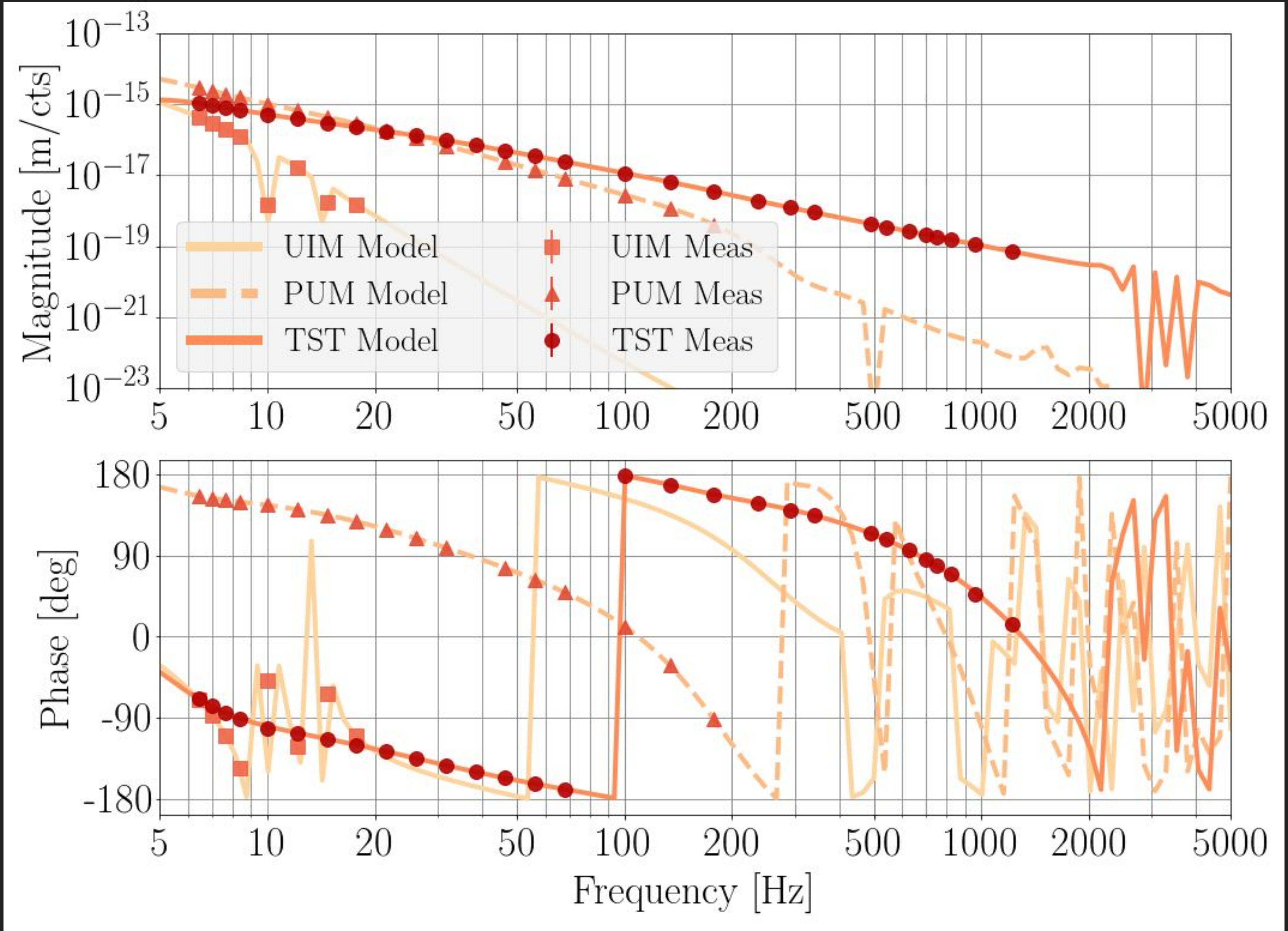
Meas Date:
Nov 26, 2016

Actuation Function *A(f)* Model

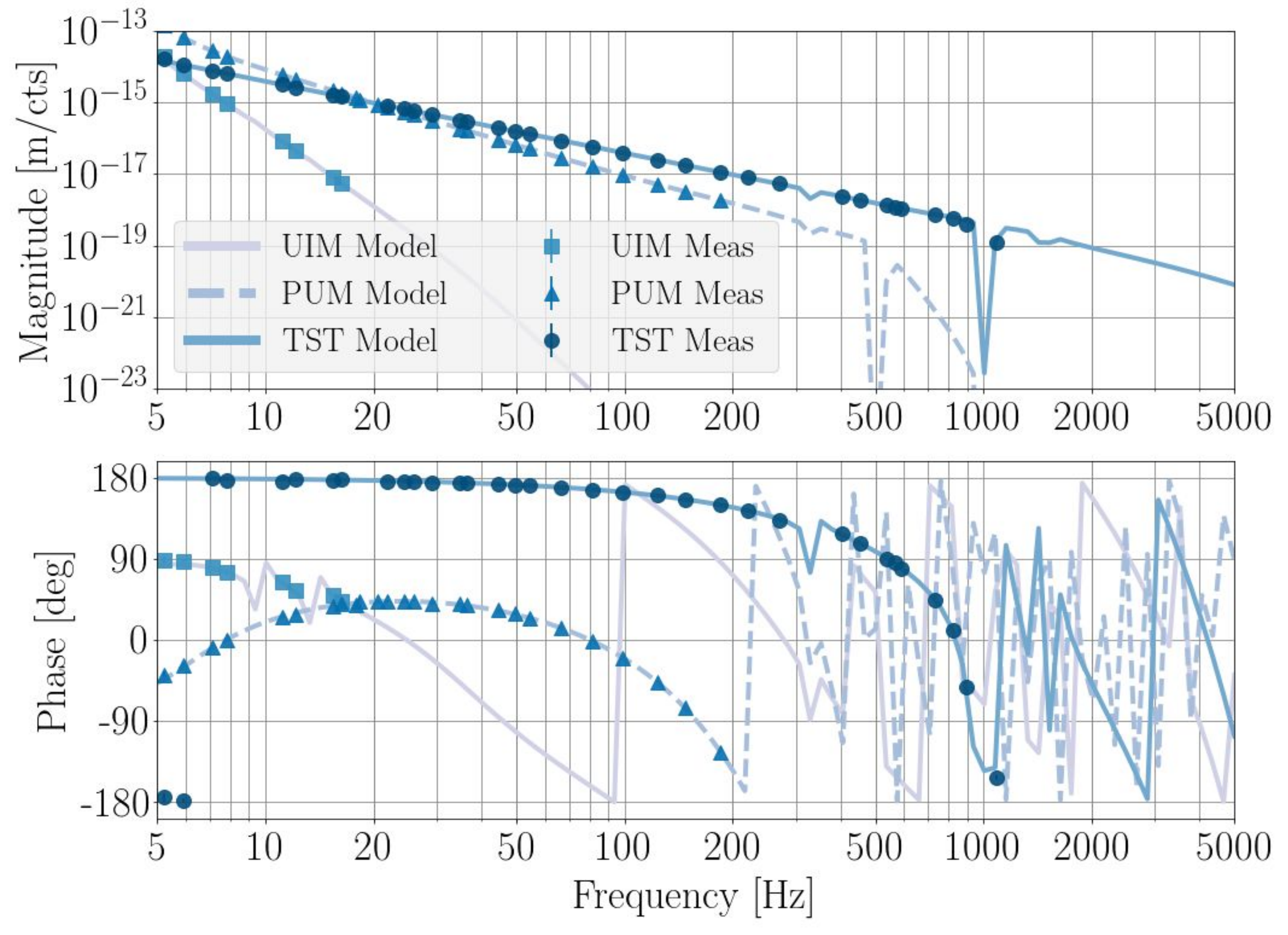
- We also have a complete model of our suspensions.
    - This is important because we actuate on our suspensions to keep the interferometer locked
    - The photon calibrator (PCAL), actuates on end optics using radiation pressure
        - This laser is our fundamental limit on calibration uncertainty
- With the model of the suspensions and the model of the interferometer, we have a complete physical model of our detector DARM control loop.



From [5]



Meas Date:
Jan 4, 2017



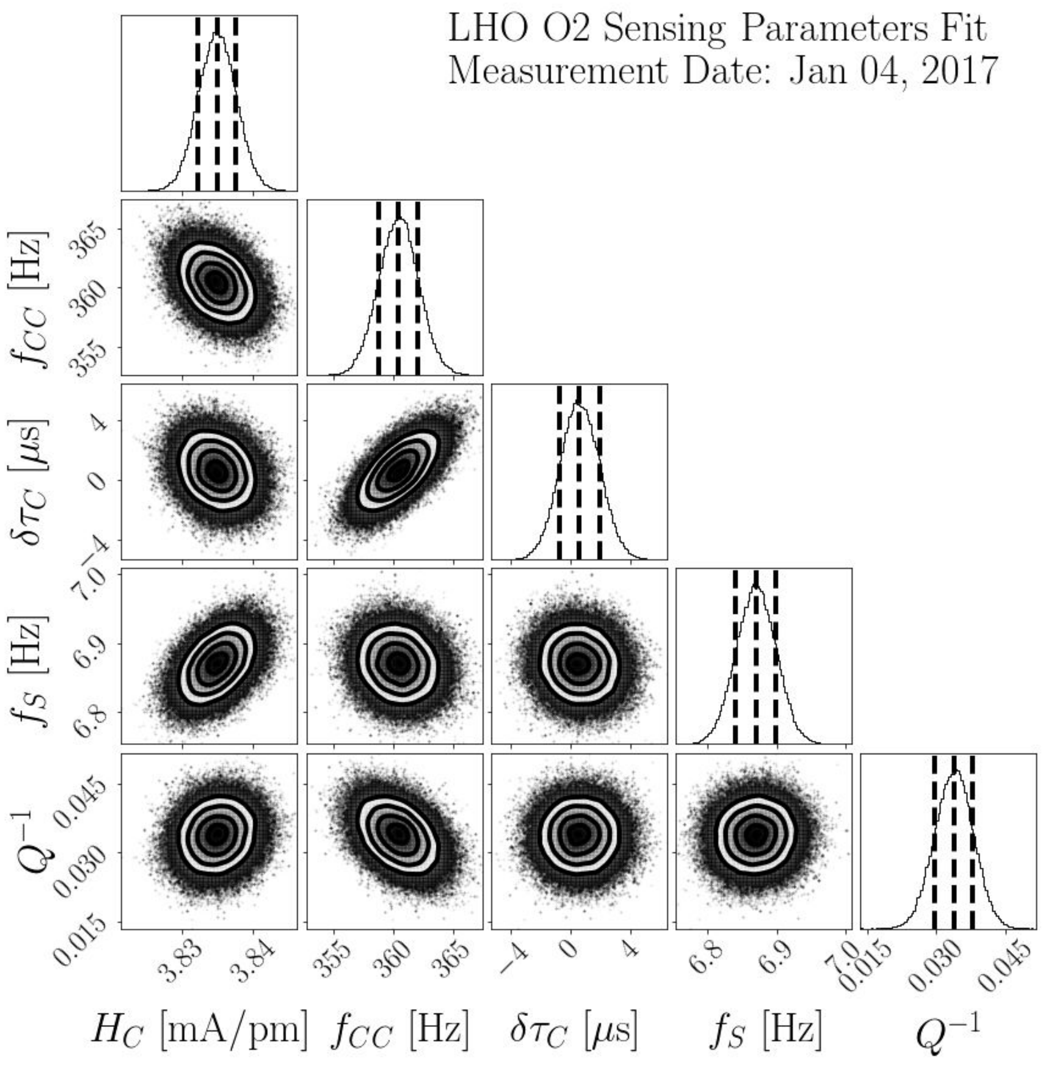
Meas Date:
Nov 26, 2016

Sensing Model Parameter Estimation

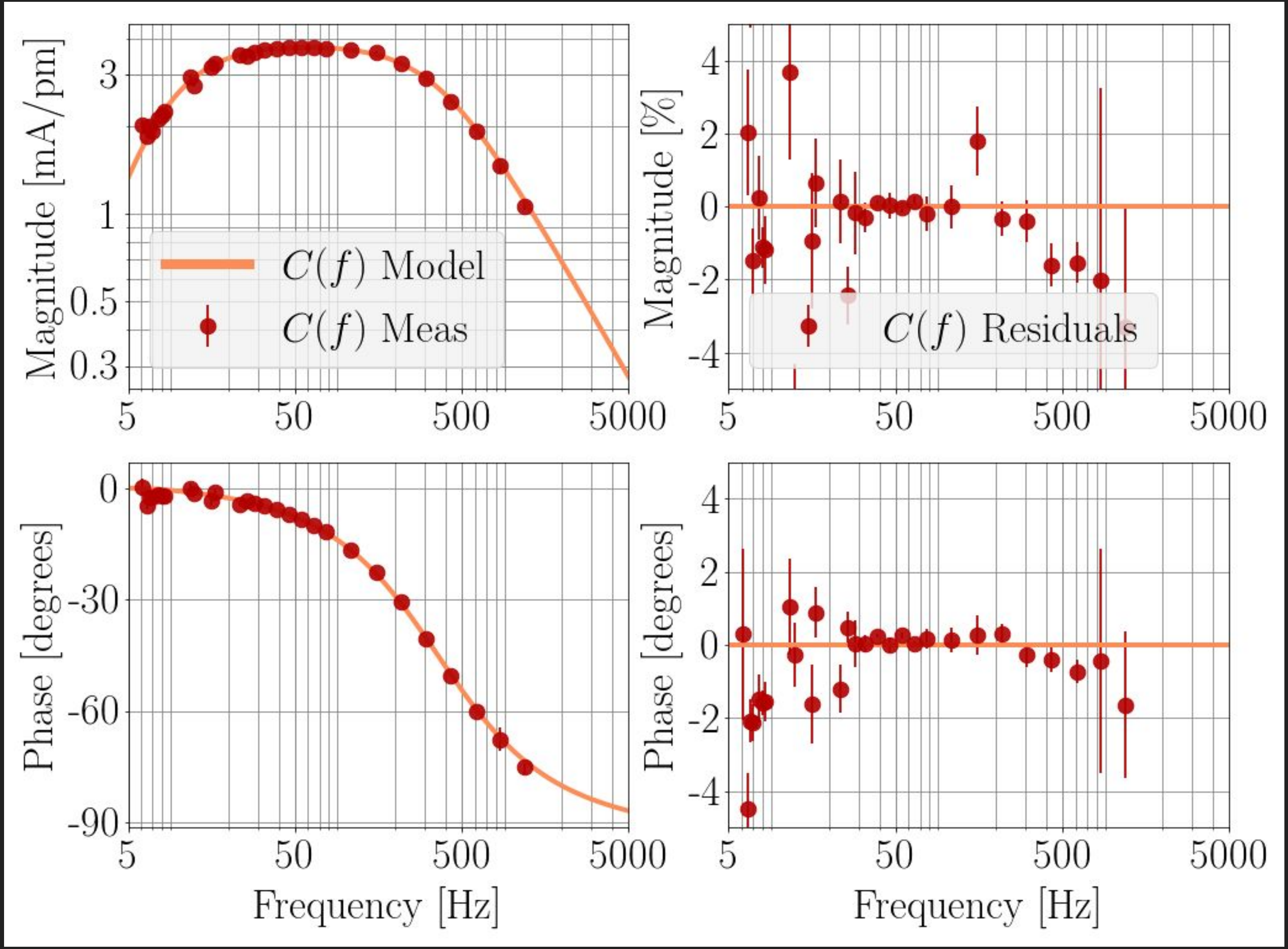
- We have calibration parameters $\vec{\lambda}$ which describe the state of our detector.
  - Optical gain
  - Coupled cavity pole
  - Time delay
  - Optical spring frequency
  - Optical spring inverse Q

- We have a calibration model $M(\vec{\lambda})$ and measurements $\vec{d}$.
- We use a Markov Chain Monte Carlo (MCMC) method to find the most likely parameter values $\vec{\lambda}$ given our data $\vec{d}$ and model $M(\vec{\lambda})$:

$$\log \mathcal{L}(\vec{d}|M, \vec{\lambda})$$



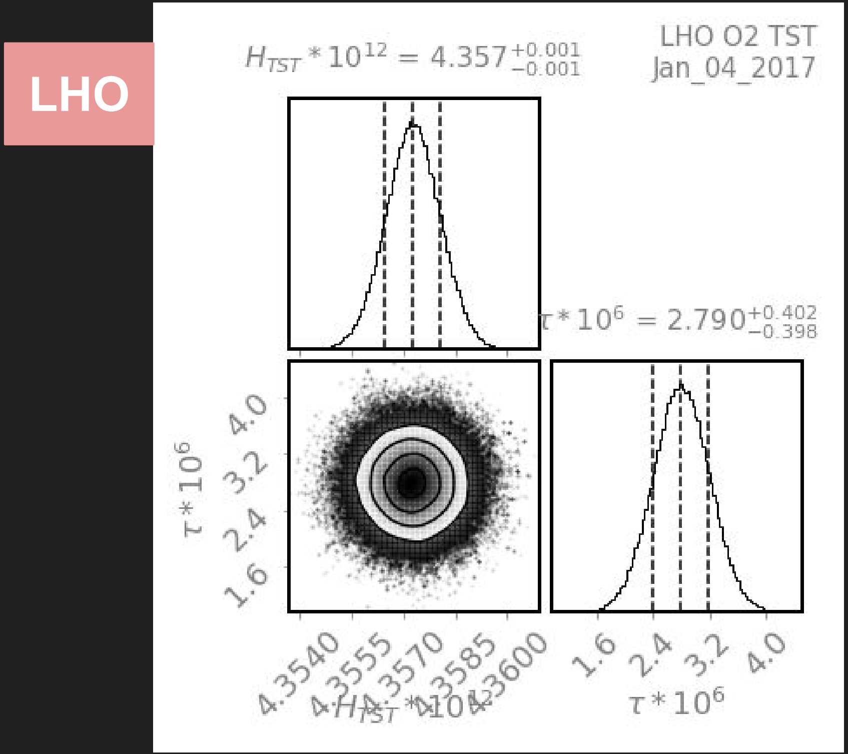
LHO

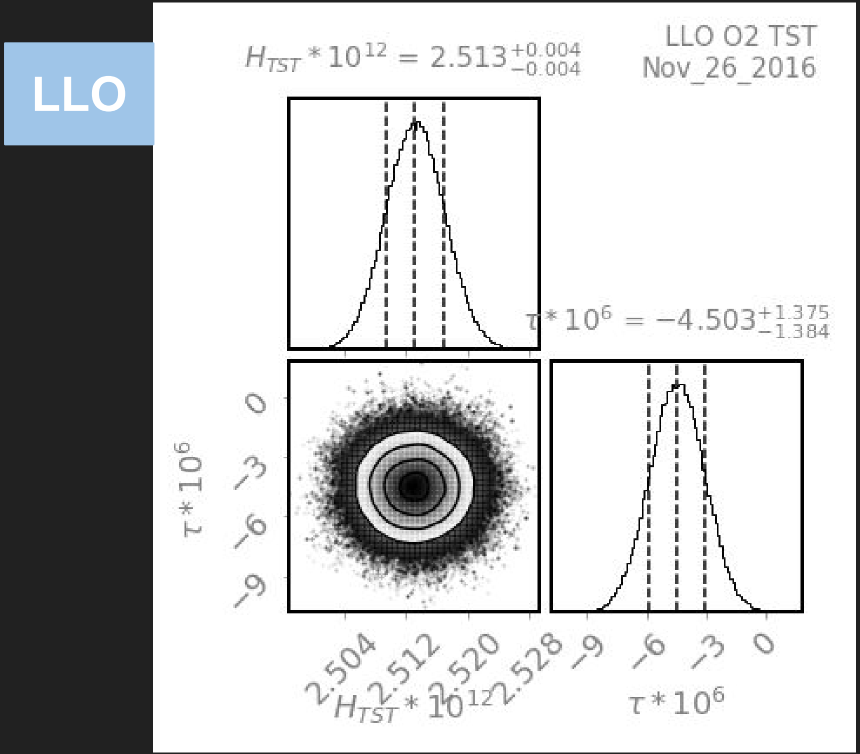


Magnitude [mA/pm]
3
1
0.5
0.3
C(f) Model
C(f) Meas
Magnitude [%]
4
2
0
-2
-4
C(f) Residuals
Phase [degrees]
0
-30
-60
-90
Phase [degrees]
4
2
0
-2
-4
5
50
500
5000
Frequency [Hz]
Frequency [Hz]

Actuation Model Parameter Estimation

- Just two parameters here: Gain and Delay
- Do this for all three stages of actuation: A_{UIM}, A_{PUM}, and A_{TST}.





Estimating Unmodeled Deviations from Measurement

- Want to find deviations from the calibration model for the sensing and actuation functions.
  - Known as systematic biases, or systematic errors
- Also need rigorous uncertainty estimation in this systematic bias

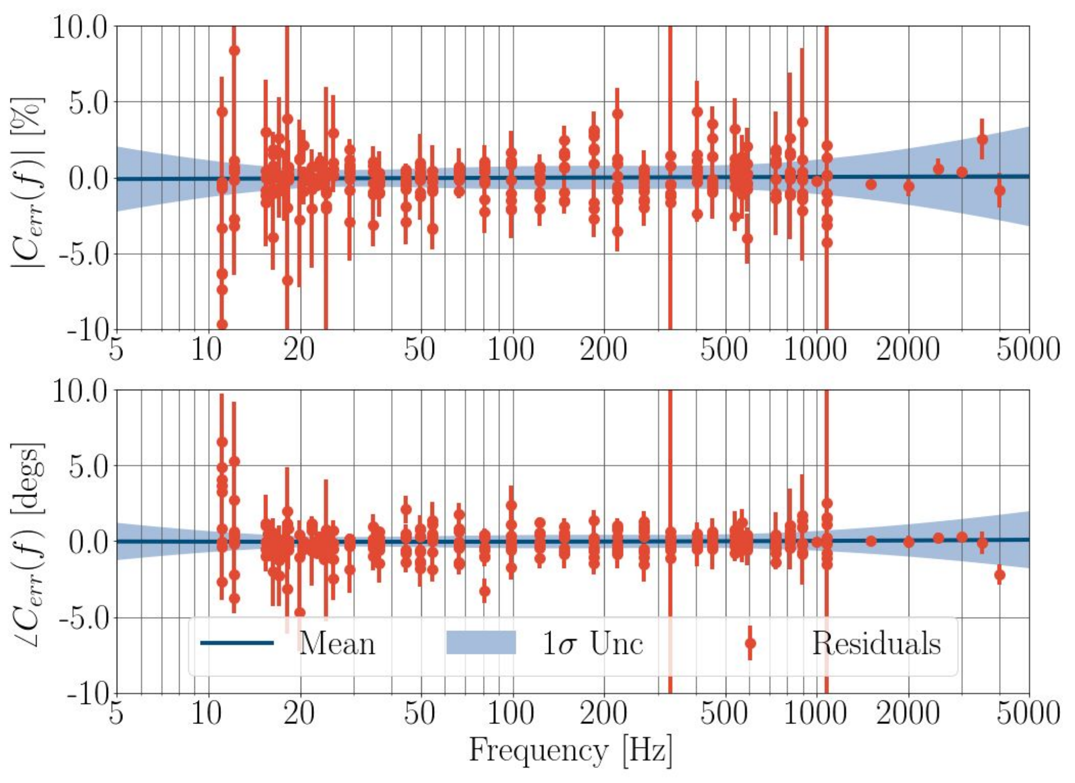
$$f(\vec{x}) = \mathcal{GP}(m(\vec{x}), k(\vec{x}, \vec{x}'))$$

- Gaussian Process Regression
  - Mean Function: $m(\vec{x})$
  - Covariance Kernel: $k(\vec{x}, \vec{x}')$
  - "A Gaussian Process is a collection of random variables, any finite number of which have a joint Gaussian distribution." [6]
  - Uses training data $\vec{x}$ and covariance kernel $k(\vec{x}, \vec{x}')$ to create a distribution over functions $f(\vec{x})$
  - With this function distribution, we may rigorously sample to get potential fits to our training data

Gaussian Process Regression

- Fit to residuals (meas/model) for our four functions C(f), A_U(f), A_P(f), A_T(f)
- Shown: LLO Sensing Gaussian Process Regression Results

- Assumptions
  - Functions are smooth
    - Can be described by simple lines
  - Uncertainty is gaussian
  - Time dependence of measurements is removed
    - Can stack measurements

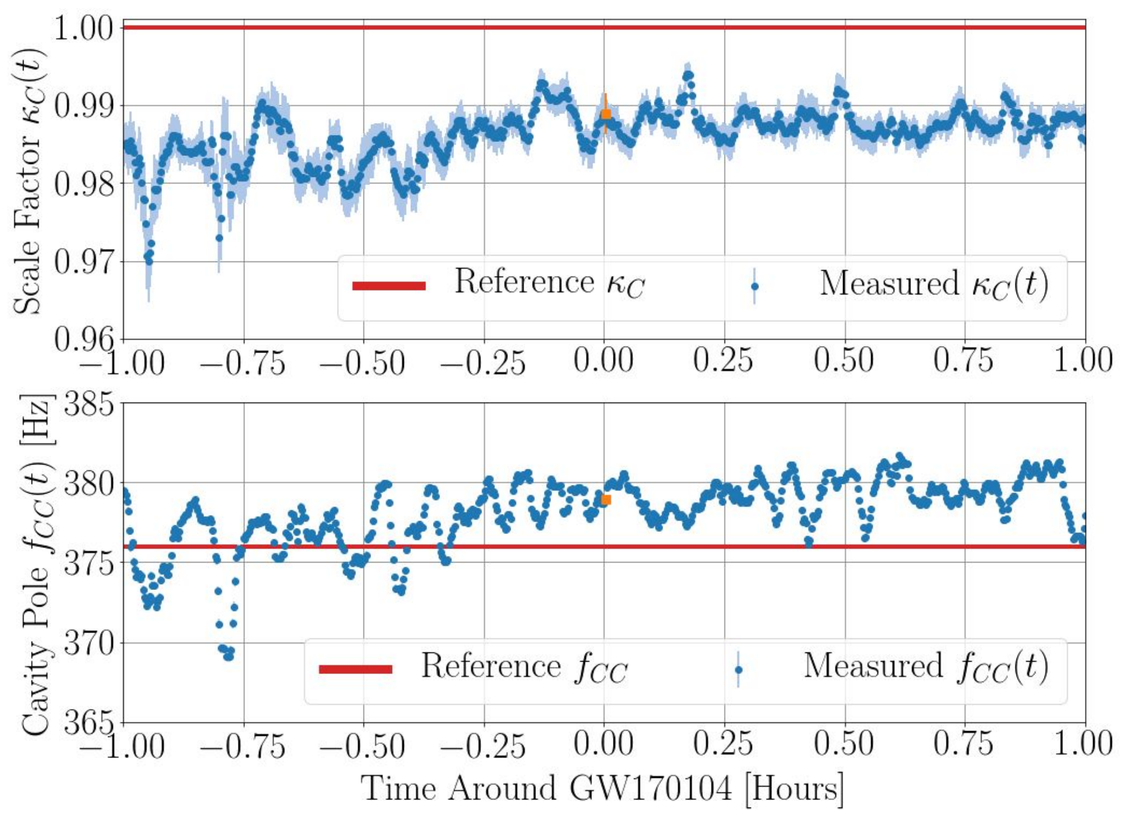


Time Dependent Parameter Uncertainty

We track changes in the interferometer in real time using calibration lines.

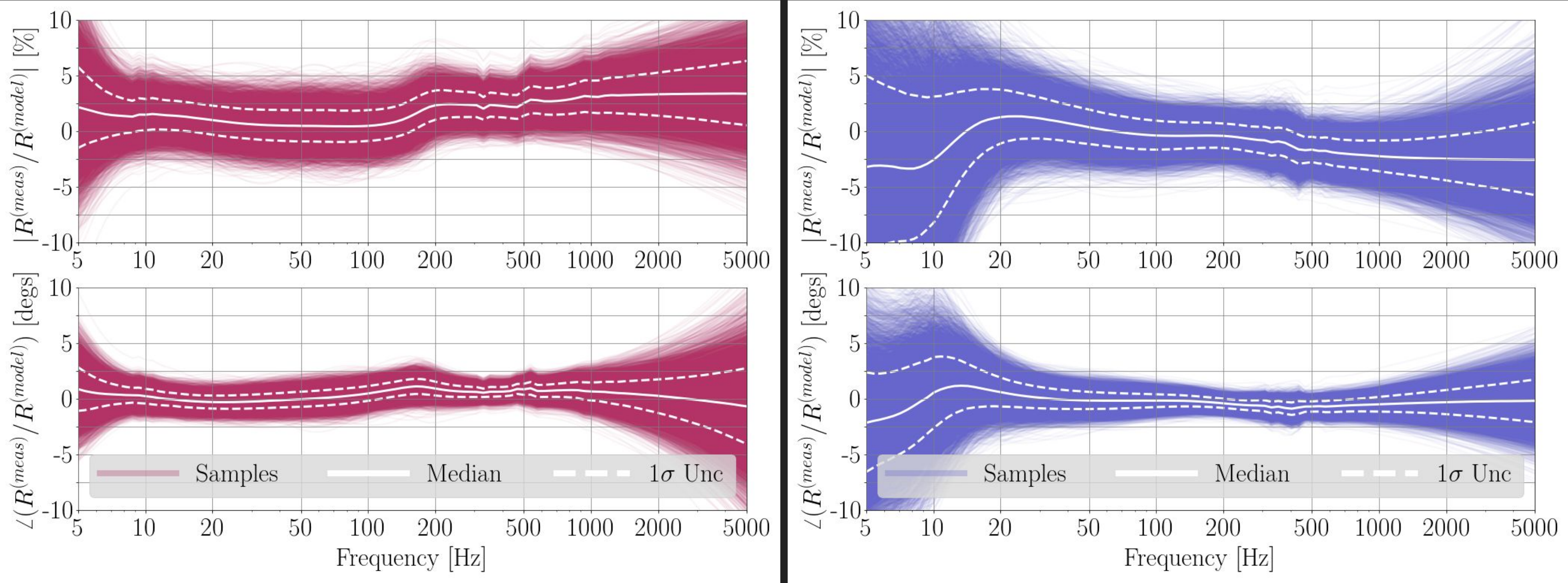
- Optical Gain
- Coupled Cavity Pole
- Electrostatic Drive Strength
- Electromagnetic Coil Drive Strength

Using the coherence of our calibration lines, we can calculate uncertainty in the lines themselves, and propagate forward to the time-dependent detector parameters.

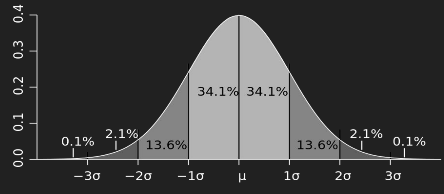


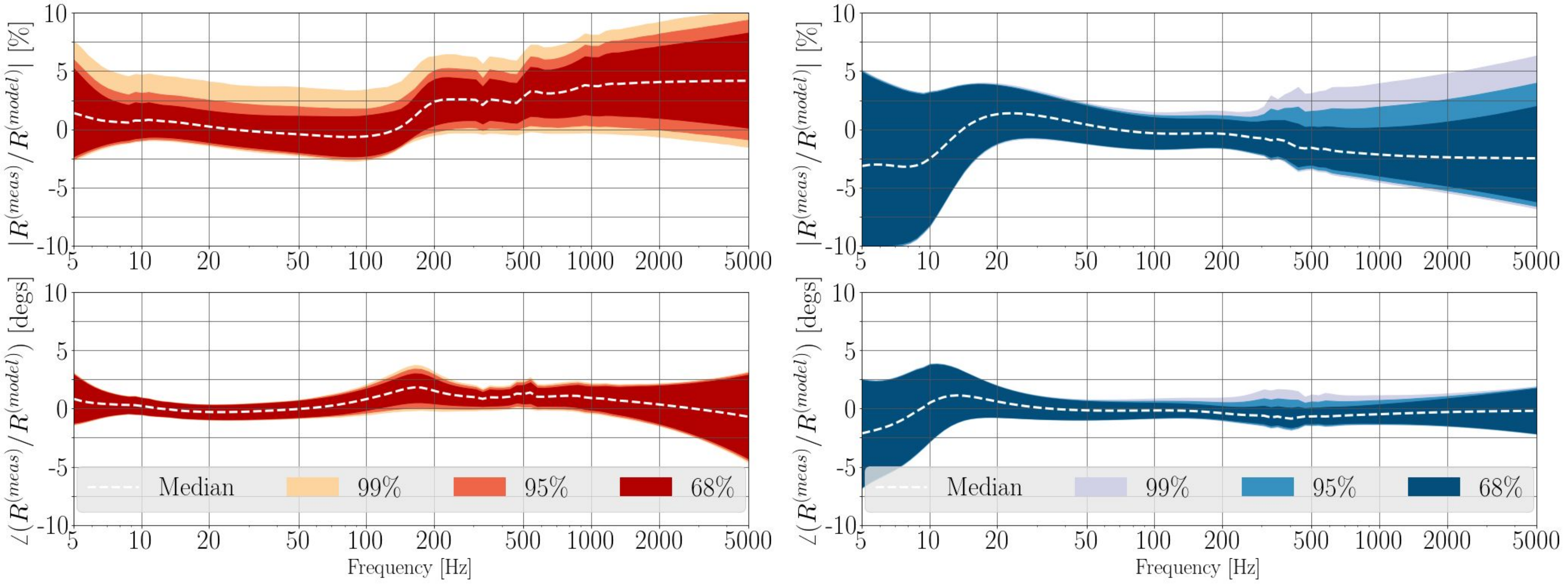
GW170104 Uncertainty Budgets

Extreme Uncertainties	Hanford	Livingston
1σ Magnitude [%]	-1.0 to +4.6	-3.7 to +3.7
1σ Phase [degrees]	-0.9 to +1.8	-1.5 to +1.9

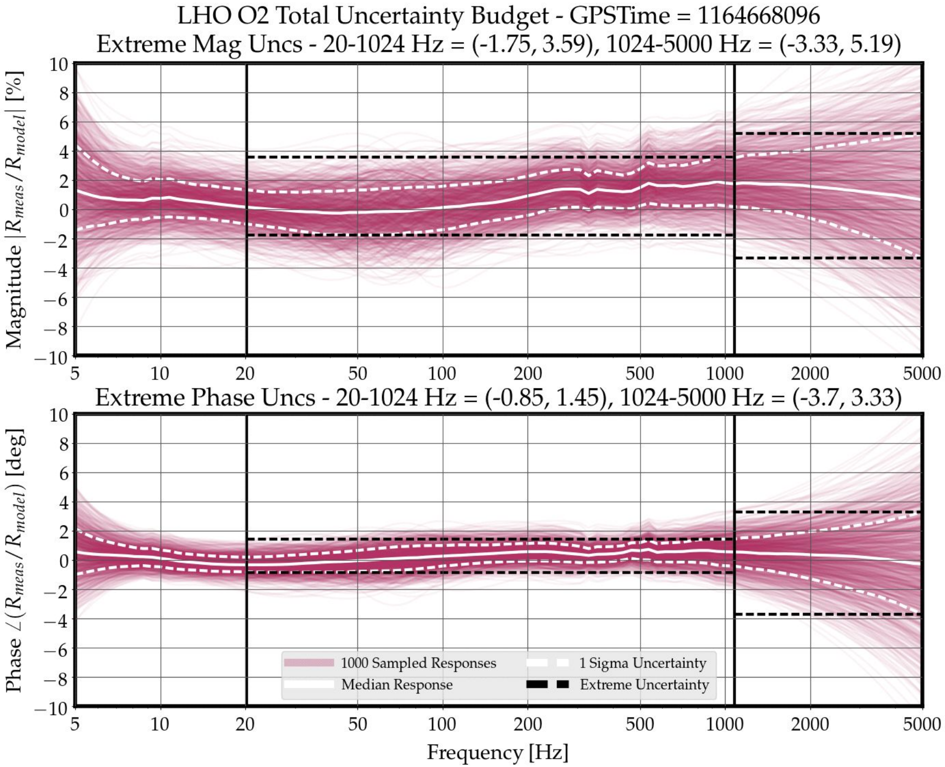


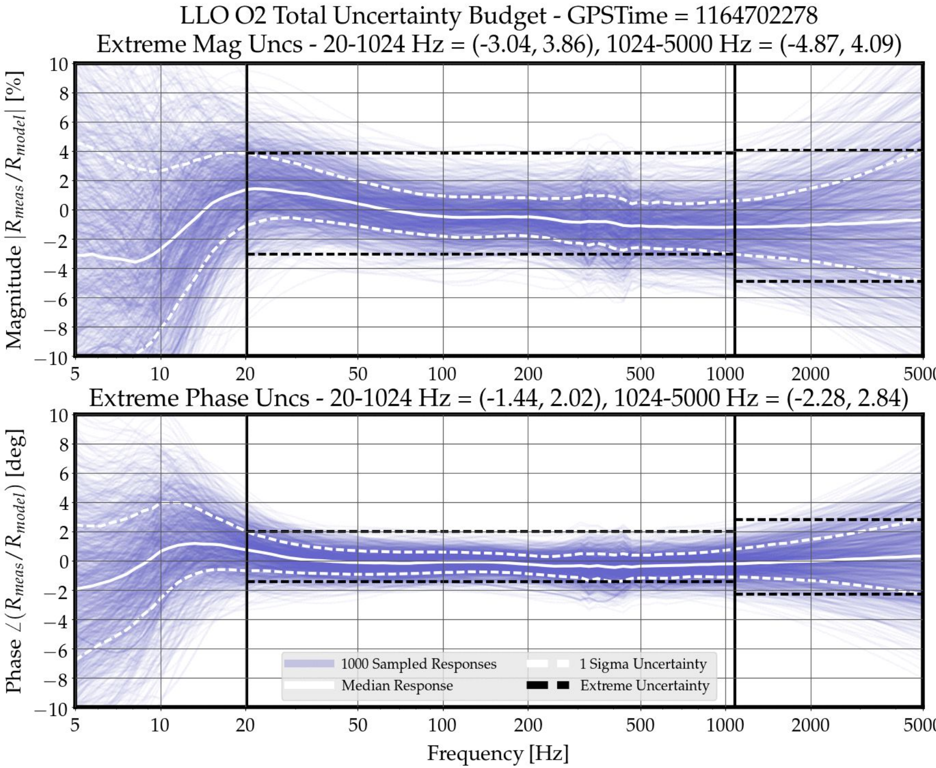
Nov - Jun O2 Uncertainty Budget Percentiles





Nov - Jun O2 Uncertainty Budget Movie





Conclusion

- The uncertainty in gravitational wave strain data is improved from 10% and 10 degrees to ~ 7.4% and 3.4 degrees from 20 to 1024 Hz for both detectors.
- The uncertainty budget is frequency dependent and quantifies known systematic biases
- This information from the uncertainty pipeline is getting incorporated into astrophysical parameter estimation pipelines
- Future work to further push down calibration uncertainty is underway

Bibliography

[1] All O1 Detections paper, B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), https://dcc.ligo.org/LIGO-P1600088/public

[2] A. Buonanno and Y. Chen, *Quantum noise in second generation, signal-recycled laser interferometric gravitational-wave detectors,* http://journals.aps.org/prd/abstract/10.1103/PhysRevD.65.042001Phys. Rev. D \textbf{65}, 042001 (2002).

[3] Robert Ward, *Length Sensing and Control of a Prototype Advanced Interferometric Gravitational Wave Detector*, PhD Thesis. California Institute of Technology, 2010.

[4] Evan Hall, *Long-baseline laser interferometry for the detection of binary black-hole mergers*, PhD Thesis. California Institute of Technology, 2017.

[5] S. M. Aston et al. *Update on quadruple suspension design for Advanced LIGO,* Classical Quant. Grav. \textbf{29}, 235004 (2012).

[6] C. E. Rasmussen and C. K. I. Williams, *Gaussian Processes for Machine Learning.*

[7] Tara Chalermsongsak, *High Fidelity Probe and Mitigation of Mirror Thermal Fluctuations*, PhD Thesis. California Institute of Technology, 2014.

[8] Sudarshan Karki, et al. *The Advanced LIGO Photon Calibrators*, Review of Scientific Instruments **87**, 114503 (2016); doi: http://dx.doi.org/10.1063/1.4967303

[9] Darkhan Tuyenbayev, et al. *Improving LIGO calibration accuracy by tracking and compensating for slow temporal variations,* CQG, Vol 34, Number 1

Bibliography

[10] M. Rakhmanov, J. D. Romano, J. T. Whelan. *High frequency corrections to the detector response and their effect on searches for gravitational waves*. CQG 25:184017, 2008

[11] R. Savage, M. Rakhmanov and H. Elliott. *LIGO high-frequency response to length- and GW-induced optical path length variations.* DCC: LIGO-G060667