Modeling of Optical Scattering in Advanced LIGO

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LIGO-G1400923

What is Optical Scattering and Why Do We Care?

Equation 1: The Bidirectional Reflection Distribution Function

$$BRDF = \frac{P_s}{\Omega \times P_i \times \cos(\theta_s)}$$

Equation 2: The solid angle

$$\Omega = \frac{A}{L}$$

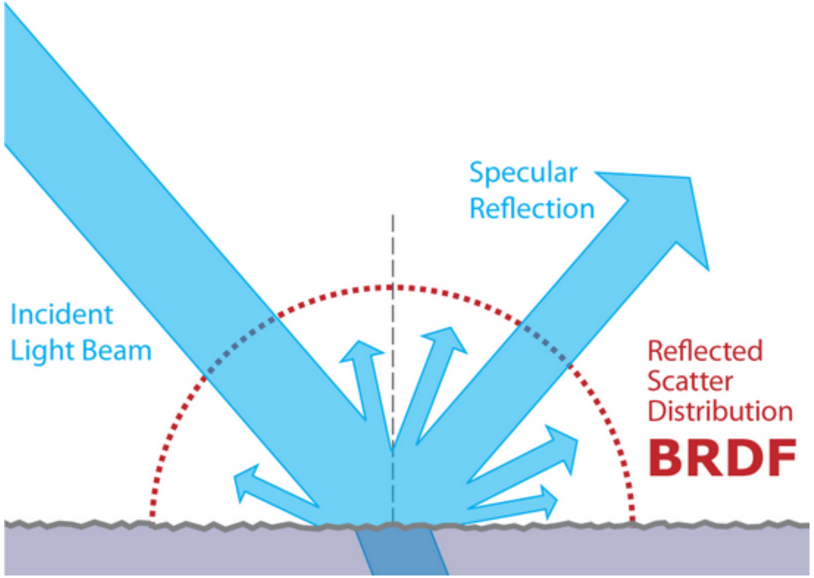


Figure 1: http://en.wikipedia.org/wiki/Bidirectional_scattering_distribution_function#mediaviewer/File:BSDF05_800.png

How Do We Measure It?

- Images with a known power incident on the camera

- Photodiodes

Project Motivation

- Large particle seen on ETMY
  - CCD calibration factor needed

- Baffle PDs provide scatter information just asking to be modeled

CCD Calibrations

- We need a method for calculating the power seen by a camera from its image
  - Measurements only existed for long exposures (low power)

$$\frac{Power(W) \times Exposure(\mu s)}{Intensity} = constant$$

Equation 3: The CCD calibration factor

Experimental Setup

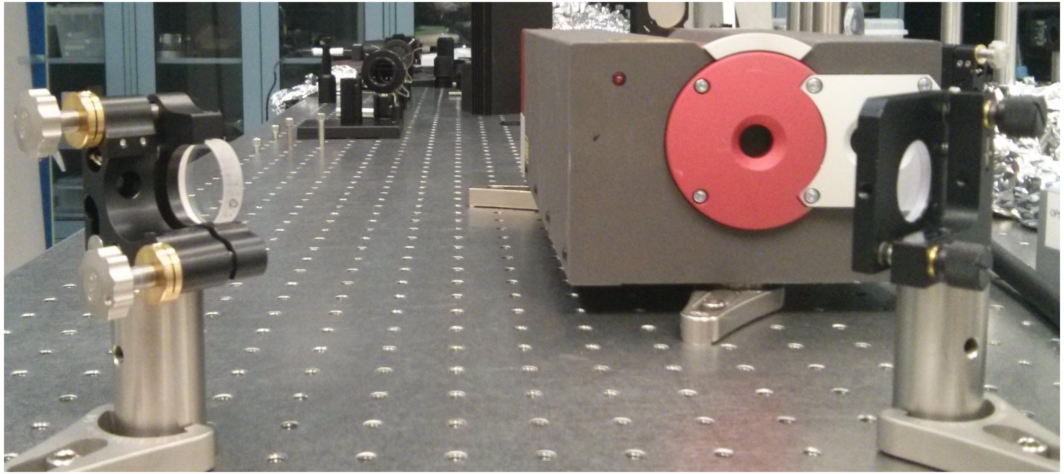


Figure 2: Experimental setup for measuring power incident on a camera

Figure 3: Back view of Figure 2

Results

8 bit Data:

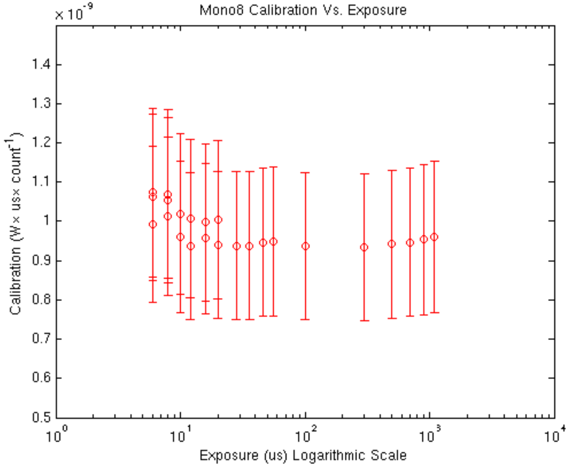
mean: 1e-9 $\pm$ 2e-8 (W)(us)/count

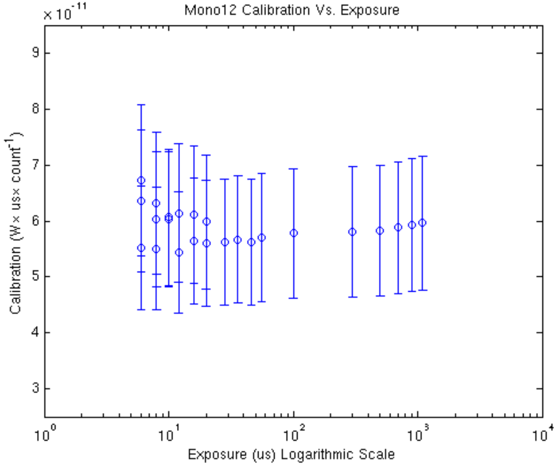
std: 4.7e-11

12 bit data:

mean: 6e-11 $\pm$ 1e-11 (W)(us)/count

std: 3.1e-12





Figures 4a (top) and 4b(bottom)

Analysis of Large Angle ETMY Scatter

The particle shown in the zoom accounts for over 50% of the scatter.

Loss from spot: 18 ± 4 ppm

Total loss: 36 ± 7 ppm

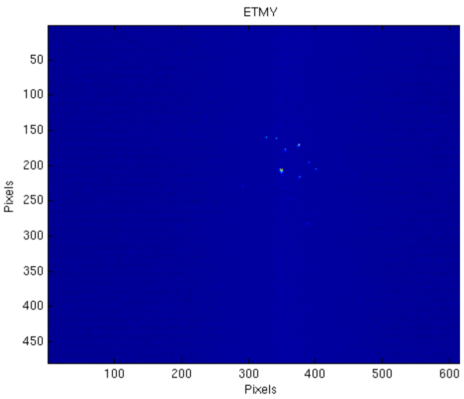


Figure 4: Raw tiff of ETMY

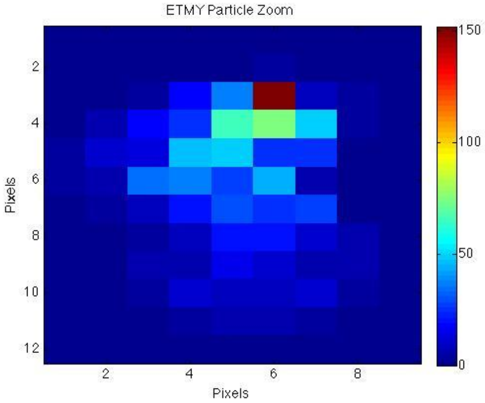


Figure 5: Zoom in of particle on ETMY with noise subtracted

Baffle PD Data Acquisition

- Gather the data from EPICS channels
  - L1:LSC-POP_A_LF_NORM_MON
    - Normalized power pick off before the beamsplitter
  - L1:LSC-POP_A_LF_OUTPUT
    - Power pick off in Watts
  - L1:AOS-*TM*_BAFFLEPD_*_VOLTS
    - PD voltage
  - L1:AOS-*TM*_BAFFLEPD_*_GAIN
    - Dimensionless PD gain
  - Subsequently crash the NDS server (repeatedly)

Calculations

$$P_s = \frac{V_s}{R \times T \times G}$$

Equation 4: Power scattered

$$(\Delta P_s)^2 = (\frac{1}{R \times T \times G})^2 (\Delta V_s)^2 + (\frac{V_s}{R^2 \times T \times G})^2 (\Delta R)^2$$

Equation 5: Uncertainty in power scattered

$$P_i = P_{ITM} \times \frac{2F}{\pi}$$

Equation 6: Power incident on the test masses

$$(\Delta BRDF)^2 = (\frac{1}{\Omega \times P_i \times \cos(\theta_s)})^2 (\Delta P_s)^2 + (\frac{P_s}{\Omega \times P_i^2 \cos(\theta_s)})^2 (\Delta P_i)^2$$

Equation 7: Uncertainty in the BRDF

Figure 6: Scatter from ETMX

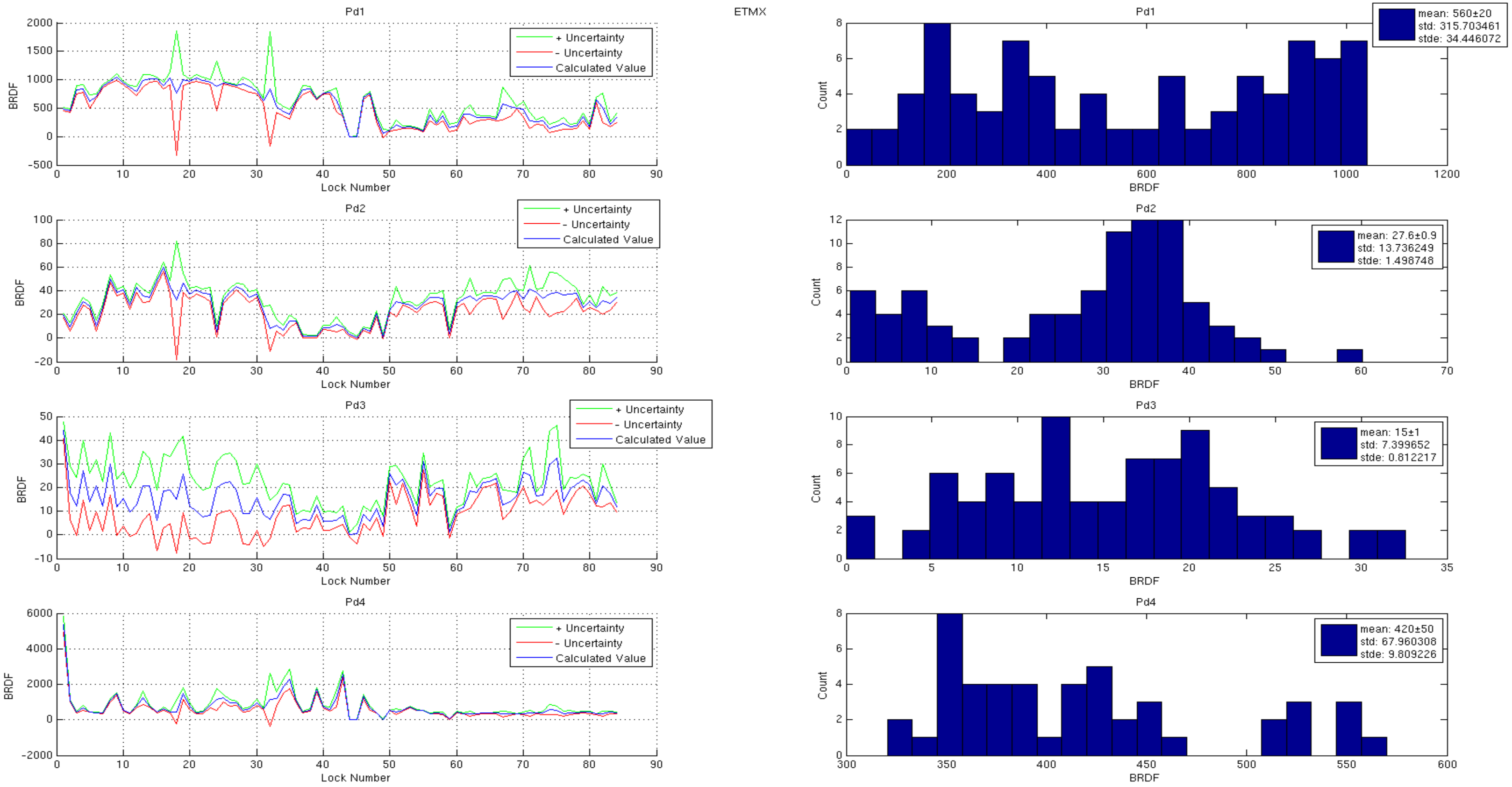


Figure 7: Scatter from ITMX

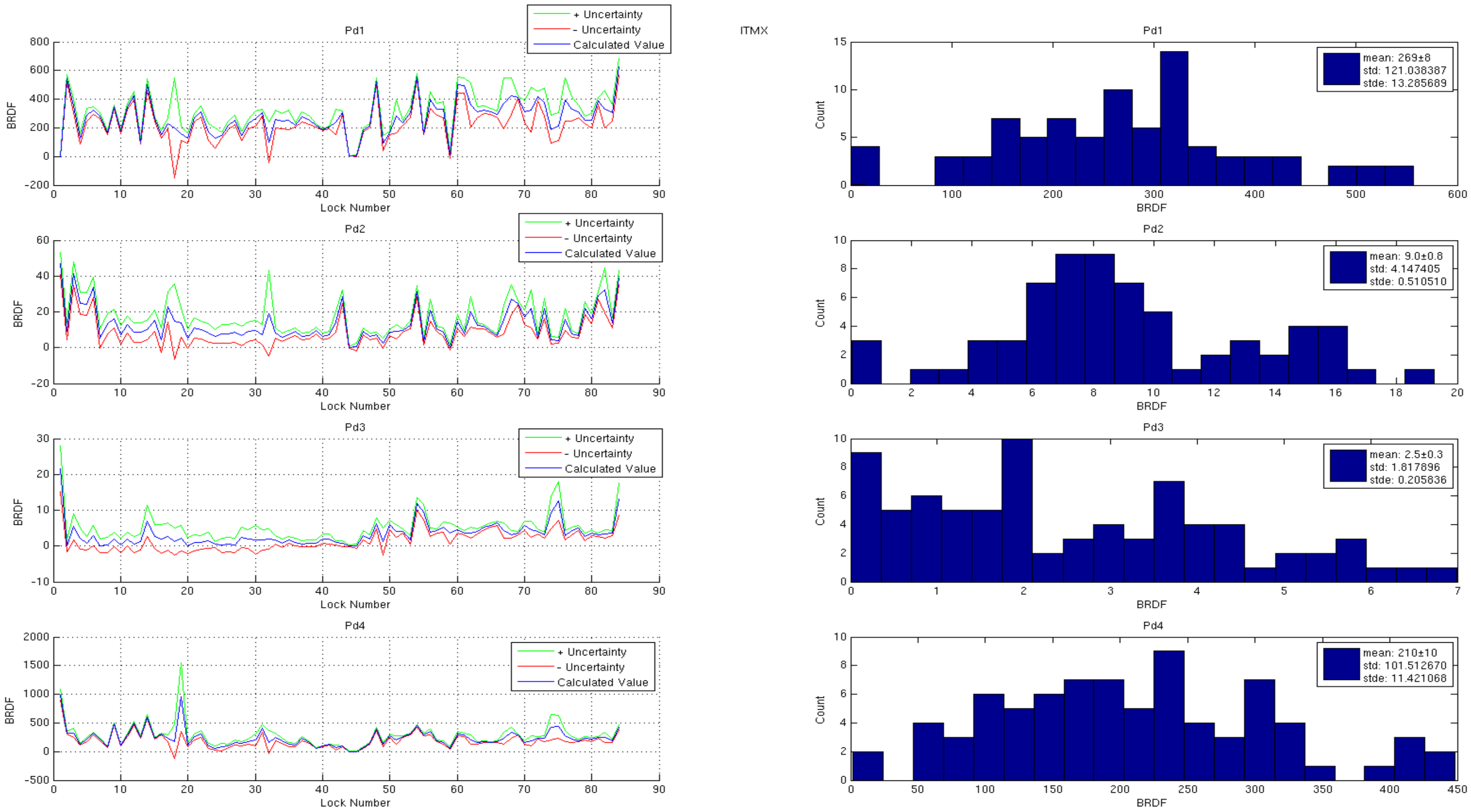


Figure 8: Scatter from ETMY

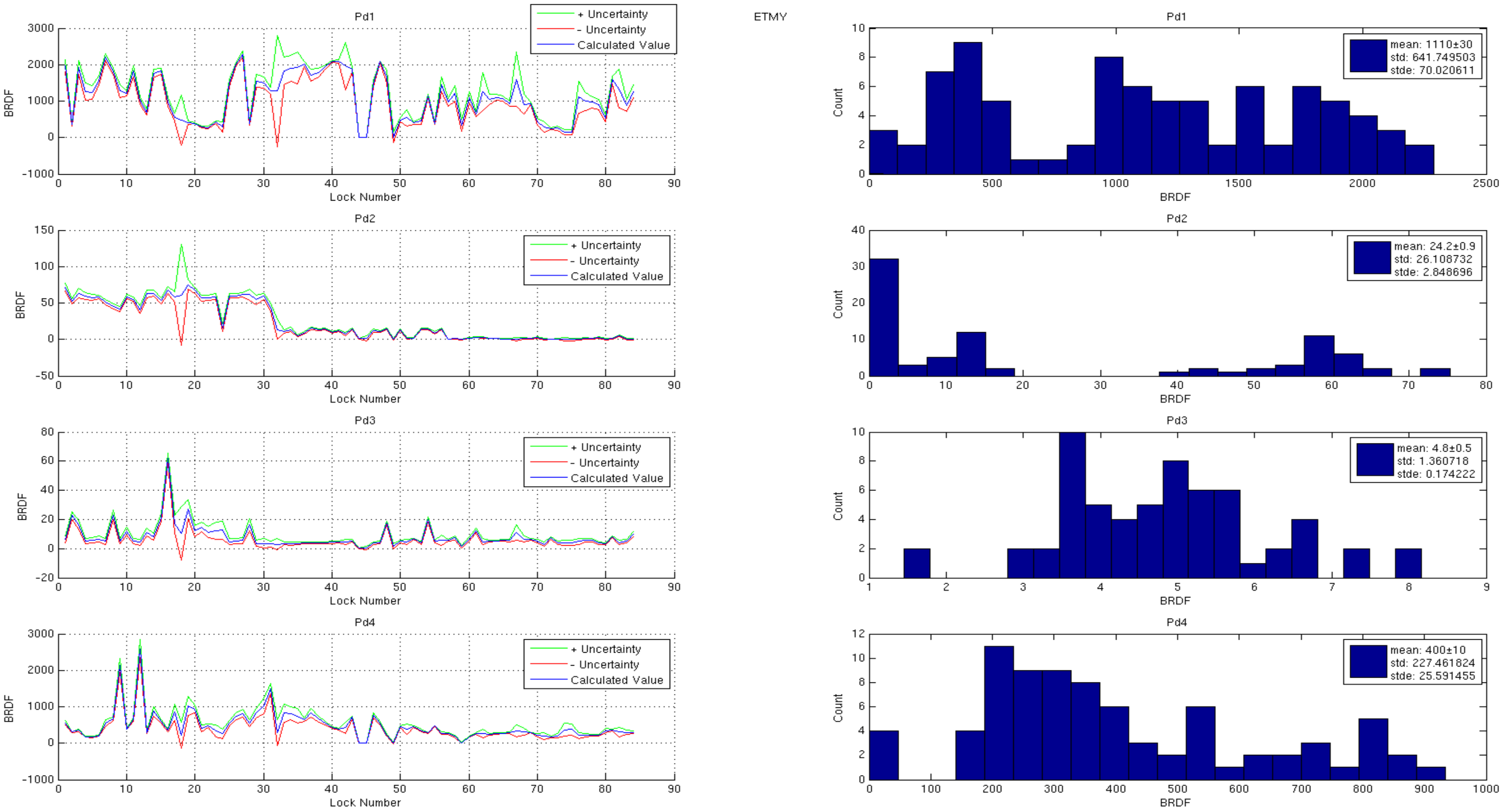


Figure 9: Scatter from ITMY

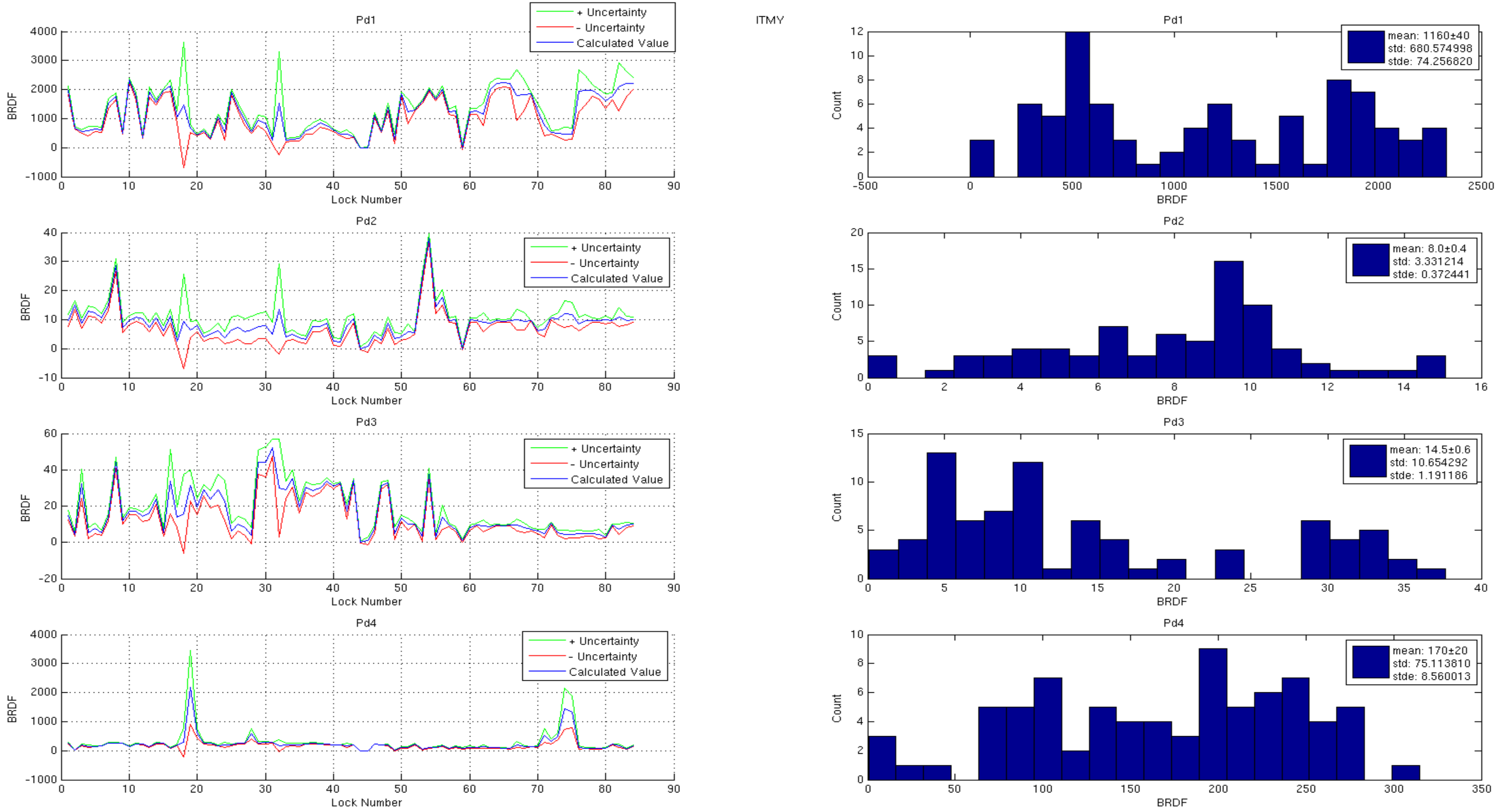
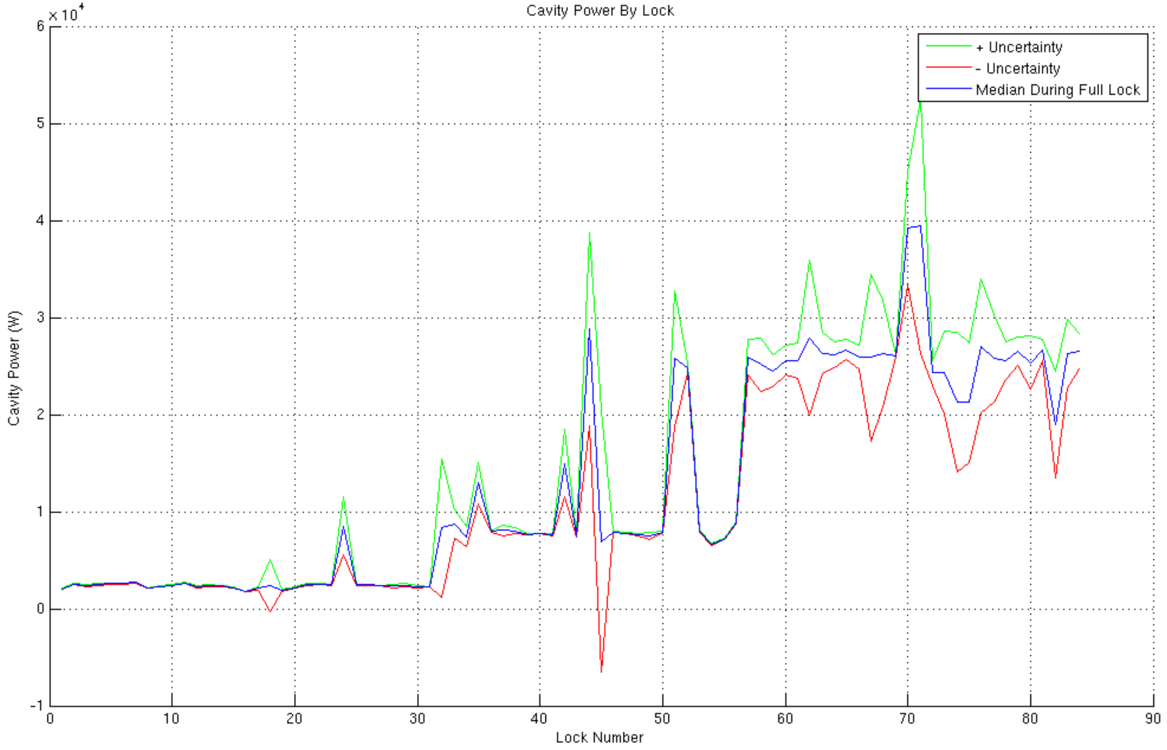


Figure 10: Cavity power for each full lock



Results

ETMX			
PD	Mean BRDF	SD	SEM
1	560±20	315.70	34.45
2	27.6±0.9	13.74	1.50
3	15±1	7.40	0.81
4	420±50	67.96	9.81

ITMX			
PD	Mean BRDF	SD	SEM
1	269±8	121.04	13.29
2	9.0±0.8	4.15	0.51
3	2.5±0.3	1.82	0.21
4	210±10	101.51	11.42

ETMY			
PD	Mean BRDF	SD	SEM
1	1110±30	641.75	70.02
2	24.2±0.9	26.11	2.85
3	4.8±0.5	1.36	0.17
4	400±10	227.46	25.59

ITMY			
PD	Mean BRDF	SD	SEM
1	1160±40	680.57	74.26
2	8.0±0.4	3.33	0.37
3	14.5±0.6	10.65	1.19
4	170±20	75.11	8.56

A Hiro to Save Us

- Static Interferometer Simulation (SIS) is the best thing since sliced bread
- Models optical scatter in the arm cavities

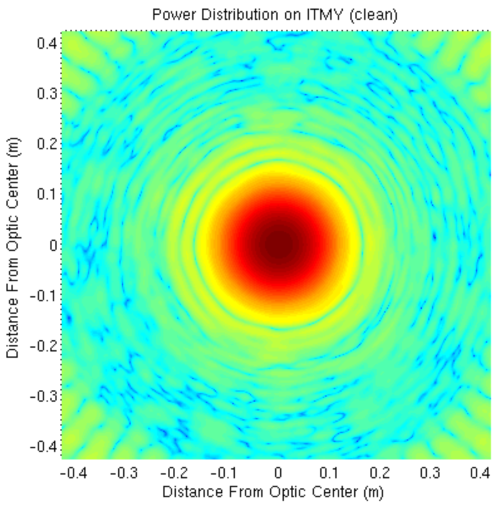


Figure 11: Top view of modeled power on ITMY

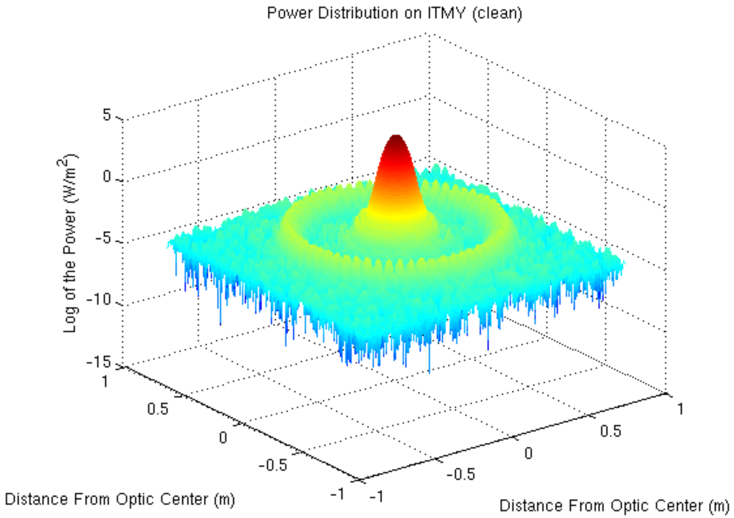


Figure 12: 3D view of the log10 of the modeled power on ITMY

Ongoing Work

3 bumps placed on the phase map

<u>Bump size</u>

waist: 1e-3 m

height: 1e-6 m

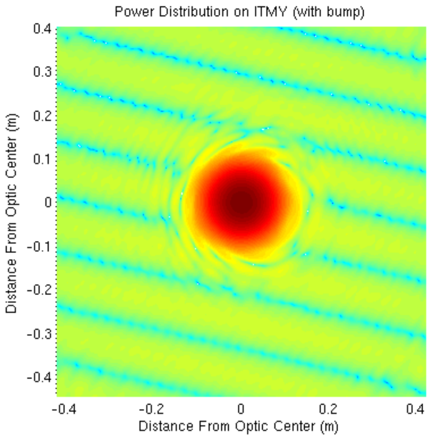


Figure 13: Top view of power distribution with bumps placed on ETMY phase map in approximate positions seen on ETMY image.

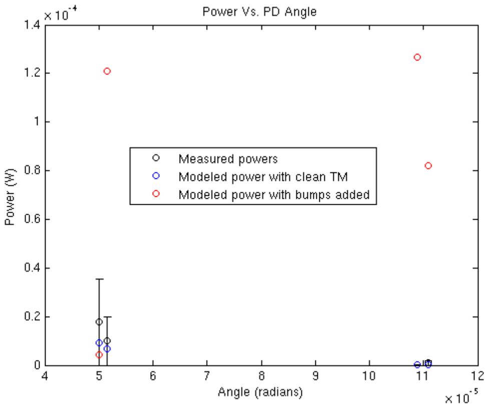


Figure 14: Comparison of measured power and modeled power

Future Work

- Modeling scatter as it is today
- Accounting for alignment changes
- Calculating power losses

Acknowledgements

- Joseph Betzwieser
- David Feldbaum
- Hiro Yamamoto
- Eugeniy Mikhailov
- CalTech
- NSF