Progress Report 2: Measurements of Optical Scatter from Advanced LIGO Test Masses

Hunter Rew, Mentor: Joseph Betzwieser

August 20, 2014

Abstract

We've measured scatter during each full lock from each test mass since May 26 2014 00:00:00 UTC using data from the baffle photodiode EPICS channels. There is significant fluctuation in the measurements from lock to lock, with standard deviations as large as 108%. The data acquisition and analysis has been bundled into a program which runs in MATLAB with external calls to Python.

1 Introduction

Advanced LIGO contains 16 photodetectors(PDs) within its beam tube baffles in order to aid in the initial alignment of the interferometer(IFO) as well as measure light scattered from test masses(TMs) during alignment. The PDs are located around each baffle hole, directly in front of each TM within the Fabry-Perot cavity. When light reflects from one TM to the other, a small portion of the light is scattered in all directions. Some of the scattered light which travels in the direction of the opposing TM reaches the PDs, allowing the scattered power, P_s to be calculated as:

$$P_s = \frac{V_s}{R \times T \times G} \tag{1}$$

where V_s is the voltage induced on the PD, R is the responsivity of the PD in A/W, T is the transimpedance of the PD in Ohms, and G is the dimensionless gain of the PD. By knowing the scattered power, the solid angle of the surface which the power is measured on, Ω, its angle relative to the incident beam, θ_s, as well as the power of the incident beam, P_i, one can calculate the bidirectional reflectance distribution function (BRDF) as [3]:

$$BRDF = \frac{P_s}{\Omega \times P_i \times \cos(\theta_s)} \tag{2}$$

It is a measure of the ratio of power which is scattered per steradian to power incident on the reflecting surface. Steradians in the solid angle are calculated as:

$$\Omega = \frac{A}{L} \tag{3}$$

Where A is the area of the surface and L is the distance from the point of scatter.

2 Data Acquisition

2.1 Power Scattered to Photodiodes

PD voltages are taken from channels of the form $L1 : AOS - *TM * \_BAFFLEPD\_*\_VOLTS$, qhere $*TM*$ is the optic the baffle is attached to, including ITMX, ETMX, ITMY, and ETMY. The second $*$ can have a value of 1,2,3, or 4, indicating the PD. These channels output Volts. The power scattered to the PD, P_s, is calculated from the median voltage scattered to the PD as shown in Equation 1. Gain is taken from channels of the form $L1 : AOS - *TM * \_BAFFLEPD\_*\_GAIN$. Transimpedance is 20 k$\Omega$, and responsivity is 0.25 ± 0.05 (A/W) [1]. Uncertainty in voltage for each lock is defined as the standard deviation of voltages throughout the lock. Uncertainty in the power scattered to each PD is calculated as a function of the uncertainties in responsivity and voltage as

$$(\Delta P_s)^2 = (\frac{1}{R \times T \times G})^2 (\Delta V_s)^2 + (\frac{V_s}{R^2 \times T \times G})^2 (\Delta R)^2 \quad (4)$$

The voltage offset is taken as the channel value at least 8 minutes before each lock.

2.2 Power Build Up in the Fabry-Perot Cavities

Power incident on each optic is calculated from the median value from the $L1 : LSC - POP\_A\_LF\_OUTPUT$ channel during each lock. This channel is the pick off from the power recycling cavity before the beam splitter and outputs Watts. After the laser passes through the beamsplitter, 50% of this power reaches each ITM. Power build up in each fabry-perot cavity is calculated as

$$P_i = P_{ITM} \times \frac{2F}{\pi} \quad (5)$$

where P_{ITM} is the power entering through the ITM and $F = 416$ is the cavity finesse. The offset is taken as the value of $L1 : LSC - POP\_A\_LF\_OFFSET$, about 3.129 W. The uncertainty in cavity power for a lock is defined as the standard deviation of values during the lock.

2.3 When Data is Taken

We've defined the IFO to be in lock (more or less arbitrarily) when the normalized output of the power recycling cavity, taken from the $L1 : LSC - POP\_A\_LF\_NORM\_MON$ channel, surpasses 20 for a duration of at least 30 minutes. This provides 84 locks. Reducing this duration to 15 minutes results in 155 locks with larger standard deviations.

2.4 Calculation of the BRDF

Solid angle is calculated from Equation 3 with $A = 100mm^2$ [1] as the area of the PD and $L = 4000mm$ as the approximate distance from the PD to the optic it is facing. Scatter angles are calculated from the measurements given in DCC document D1200296-v5 [2]. Uncertainty in the BRDF values is calculated as a function of the uncertainties in scattered power and incident power as:

$$(\Delta BRDF)^2 = (\frac{1}{\Omega \times P_i \times \cos(\theta_s)})^2(\Delta P_s)^2 + (\frac{P_s}{\Omega \times P_i^2 \cos(\theta_s)})^2(\Delta P_i)^2 \quad (6)$$

3 Data and Analysis

Figures 2 through 5 show the BRDF values with uncertainty, as calculated from Equation 5, for each of the 84 locks in the left columns, and the distribution of values across all locks in the right columns. Standard deviations reach as high as 108% (Figure 4: ETMY PD2), while uncertainties in nearly all measurements remain below 20%. This could indicate systematic error or an unknown noise source. Figure 1 shows the cavity power for each arm during lock, along with uncertainties. Sudden peaks and trophs in this data tends to correlate with major fluctuations in the BRDFs, indicating that the PD voltages did not change with the power as expected. This could mean that these changes in power are not actually occurring.

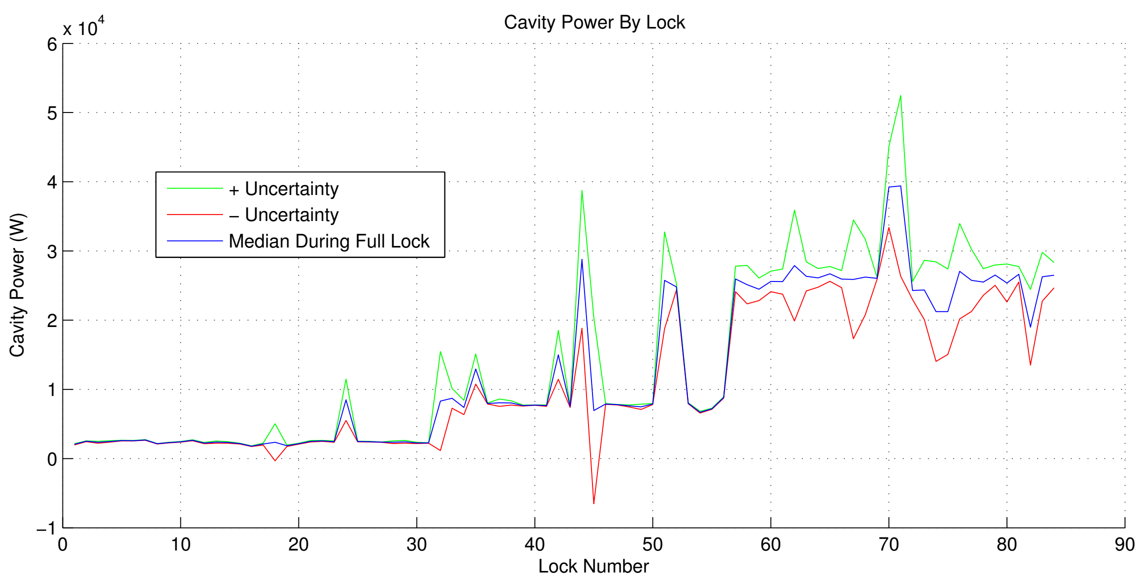

Figure 1: Cavity power for each lock as calculated from the power recycling pick off.

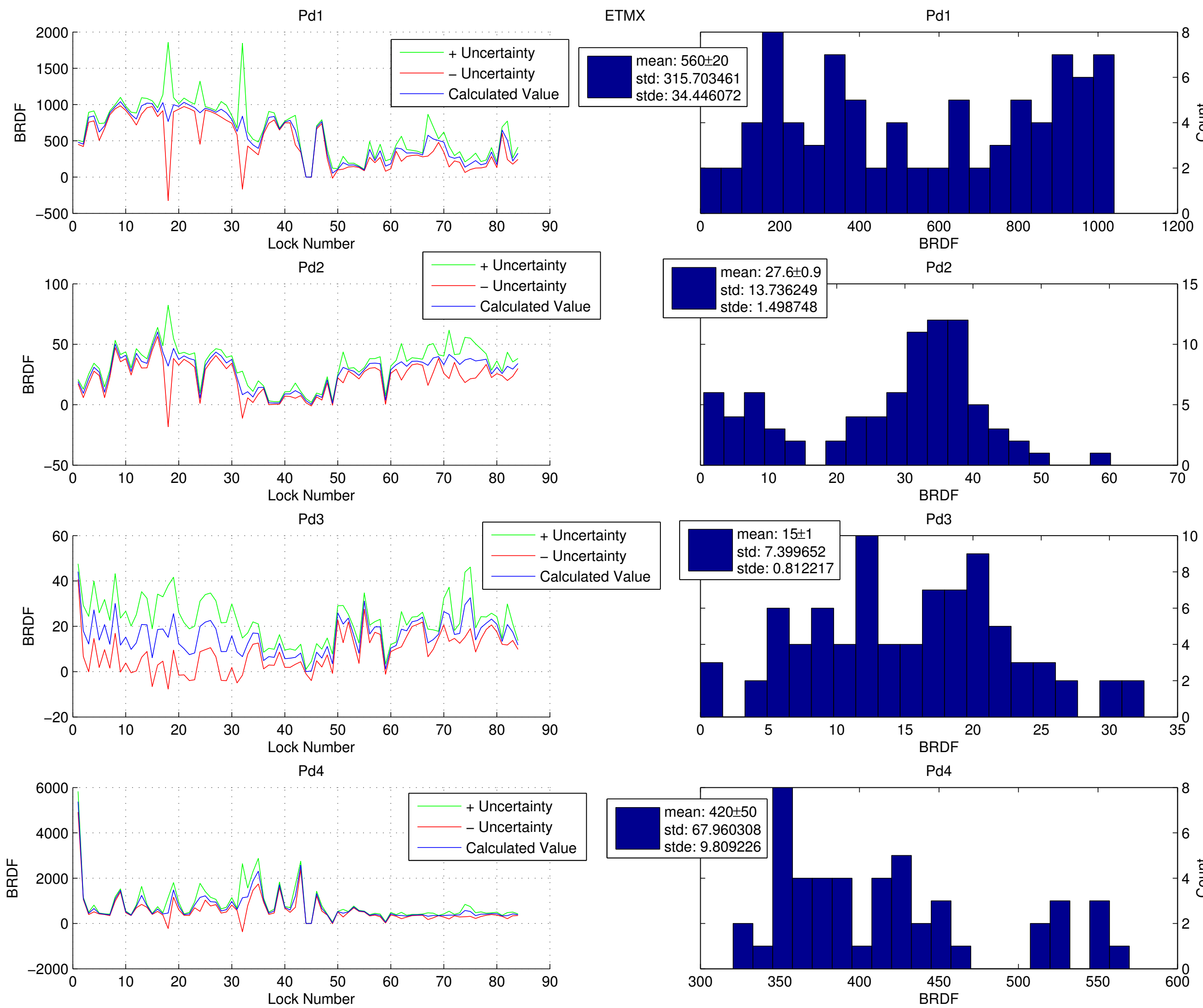

Figure 2: ETMX BRDFs and distribution by lock

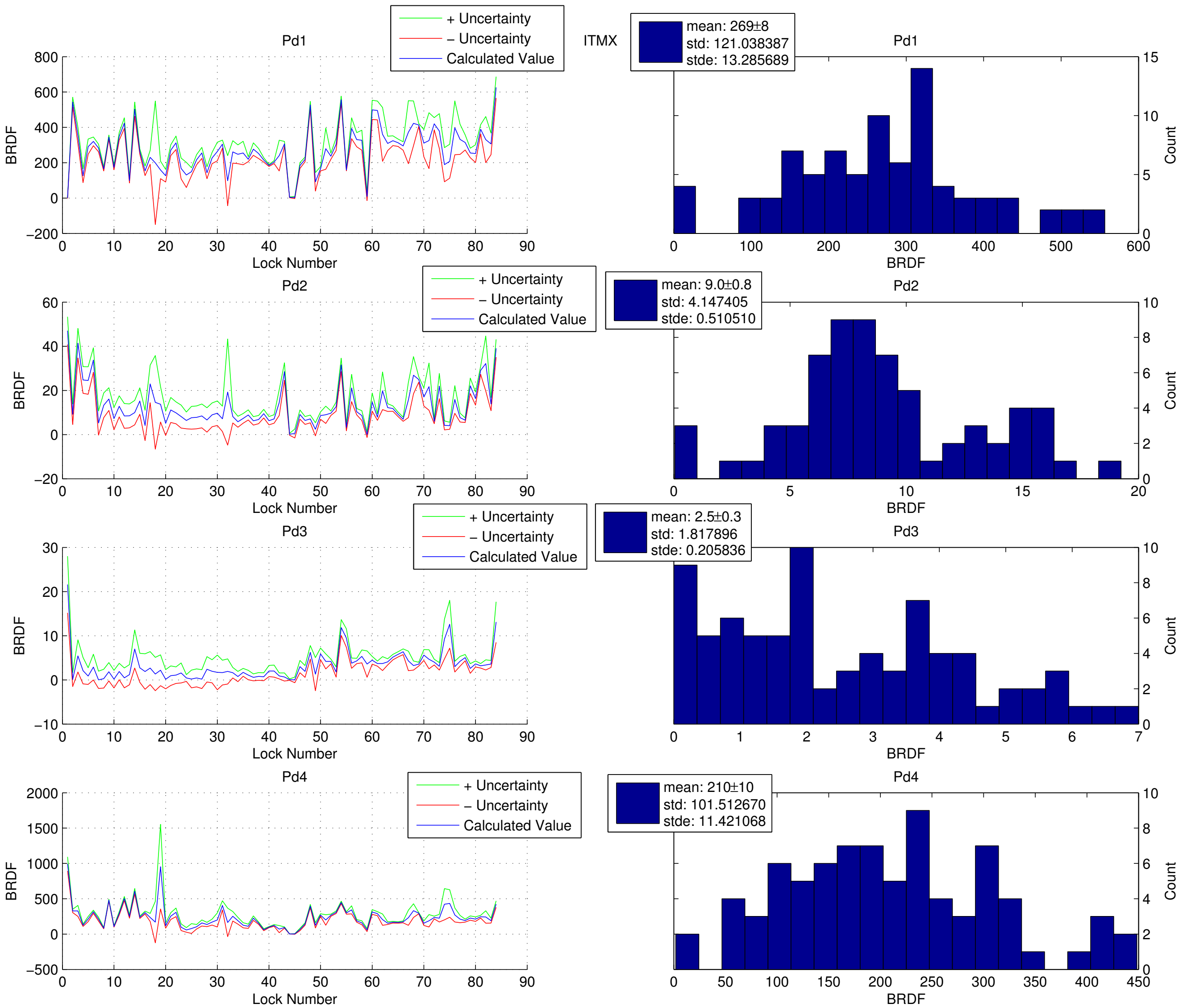

Figure 3: ITMX BRDFs and distribution by lock

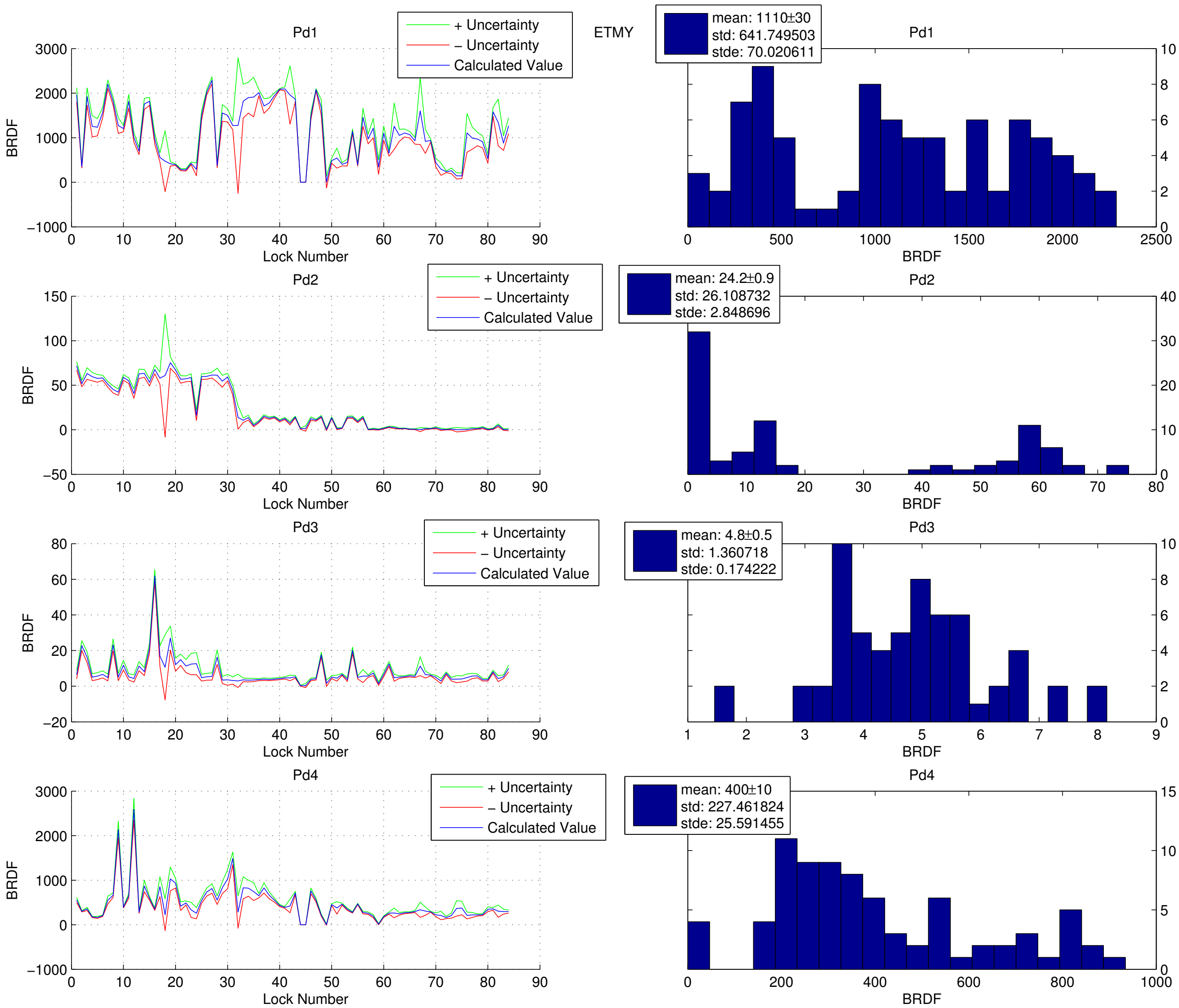

Figure 4: ETMY BRDFs and distribution by lock

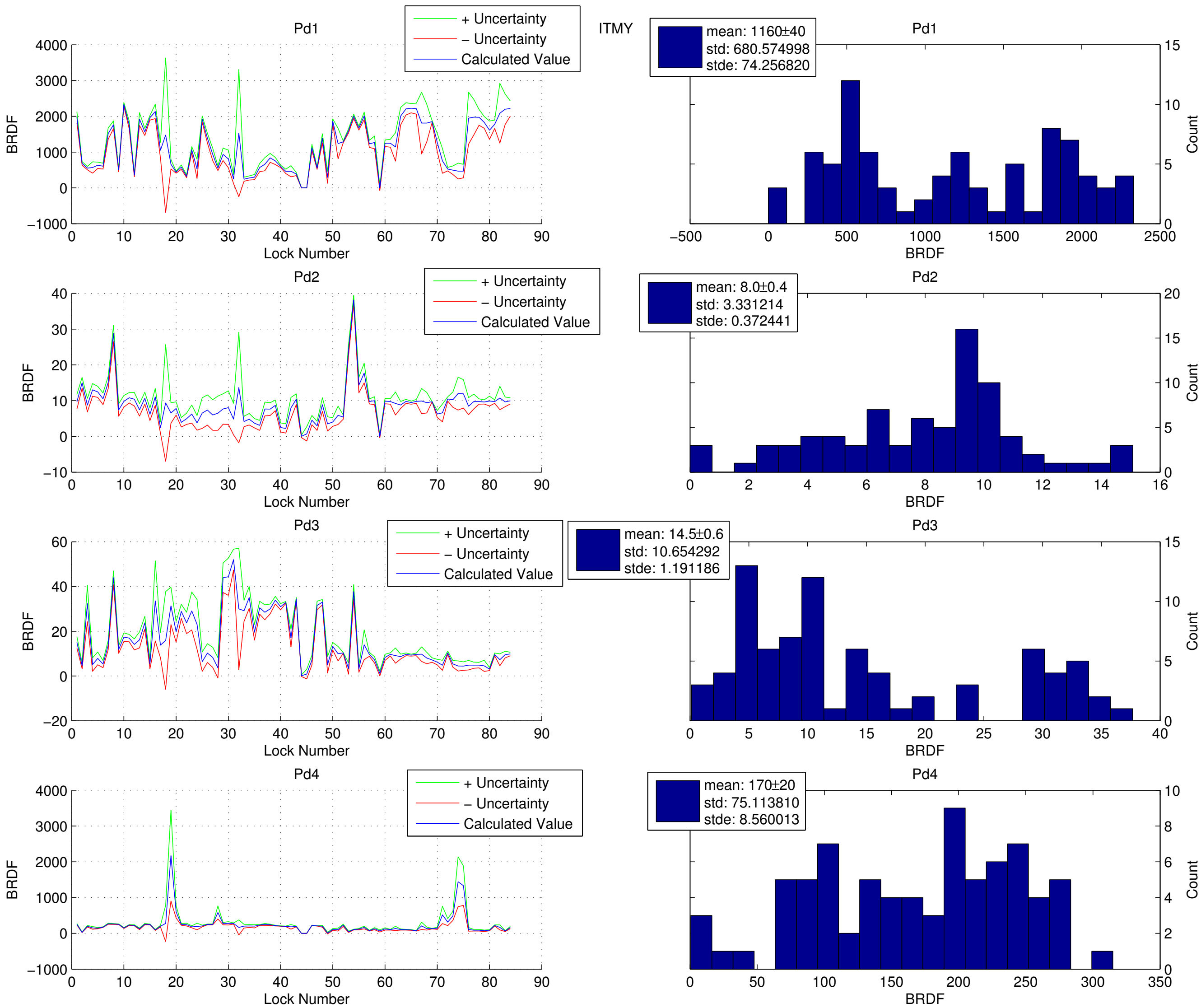

Figure 5: ITMY BRDFs and distribution by lock

4 Conclusions and Future Work

Due to the sheer amount of samples and low uncertainties in measurements, we are confident that our findings do reflect the true mean BRDFs for each PD. We are currently in the process of comparing these measurements to models of optical scatter in the Fabry-Perot cavities based on phase maps of the clean TMs, using Hiro Yamamoto's SIS program. Our goal is to add modifications to these phase maps in an attempt to duplicate the particles that have accumulated on the TMs since installation. This will provide a model for the scattering as it is today.

References

[1] EG&G Photon Devices. *YAG Series*.

[2] Manuel Ruiz and Tim Nguyen. *ACB 1 HOLE RIGHT QPD SKIN (w PD)*. LIGO DCC, October 2012.

[3] John C. Stover. *Optical Scattering: Measurement and Analysis*. The International Society for Optical Engineering, second edition, 1995.