LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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H1 Optical Lever Commissioning and Testing

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LIGO Scientific Collaboration

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Scope and Introduction

This document covers the methods and results of each H1 aLIGO optical levers testing and commissioning phase. All measurements to date are done with HEPI floating and ISI damping for whenever applicable, if HEPI is not yet commissioned, then it will be locked prior to the beginning of the measurement. Additionally, all available suspension damping loops will be engaged wherever applicable. These results will serve the purpose of verifying that each optical lever is passing specs outlined in E1200719-v1 as well as letting the end user know the characteristics of each lever such as the linear range and structural resonances. If an optical lever does not meet spec, changes may be made to the physical system (mechanical, electronics, software, etc) in order to comply with requirements. Those changes to the system will require changes to this document (new graphs or data).

Required attributes that will deem an optical lever commissioned and passed testing phase:

- Calibration of the optical levers into micro radians.
- Beam profiles in vertical and horizontal directions at the QPD. The beam scan used for taking this data was a THORLABS BP209-VIS.
- Calibrated spectra comparing the Optical Lever signals to OSEMS or ISI position sensors.
- Longitudinal to angular coupling coefficients (calculated via T1300130):
    - $d\theta'/dx \text{ (yaw)} = ds' \text{ (yaw)} / (2\,L) = (1 / L) \sin(\theta) \cos(\varphi)$
    - $d\varphi'/dx \text{ (pitch)} = ds' \text{ (pitch)} / (2\,L) = (1 / L) \sin(\theta) \sin(\varphi)$
- Long-term drift testing results.
- Dark current noise floor measurement.

1 ITMY

	Gaussian_Width (mm)	Calibration (Counts/uradian)	Low-Frequency Resonances (Hz)	Long-to-ang coupling coefficient (urad/m)	Peak-to-peak drift (uradians/10 minutes)
Pitch	4.2	23.4	0.4	0.56	0.007
Yaw	3.9	24.7	0.4	0.30	0.014

1.1 Calibration Parameters

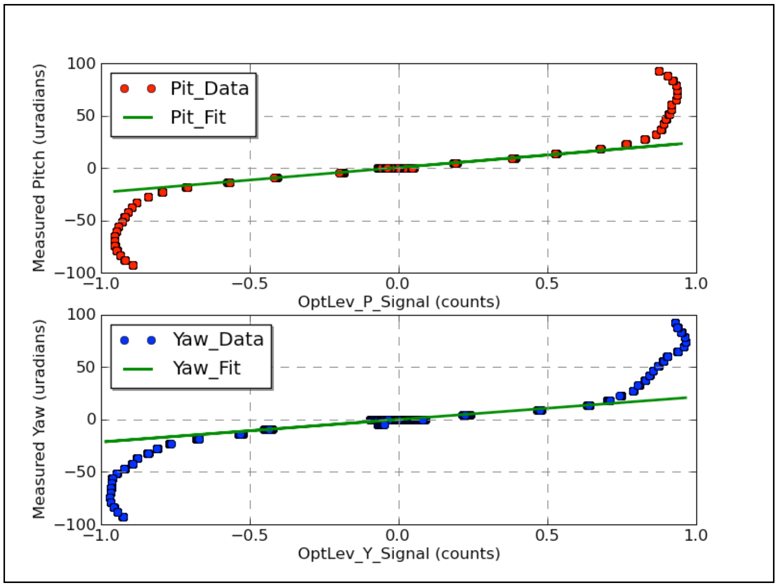

Figure 1

The slope of the linear region of the graph for pitch and yaw:

```
Pitch: 23.4 [uradians/counts]
Yaw:   24.7 [uradians/counts]
```

The geometric calculation for these parameters uses a Zeemax calculation for the path lengths of the lever arms from E1200836--v1. A DC method was used to obtain the y-axis data; we first translate the QPD a fixed amount as measured with a micrometer and use the geometry of the setup to correlate an angular deviation to the pitch or yaw signals.

These results are inputted into the SUS gain filters:

```
H1-SUS-ITMY_L3_OPLEV_PIT_GAIN
H1-SUS-ITMY_L3_OPLEV_YAW_GAIN
```

1.2 Beam Profile

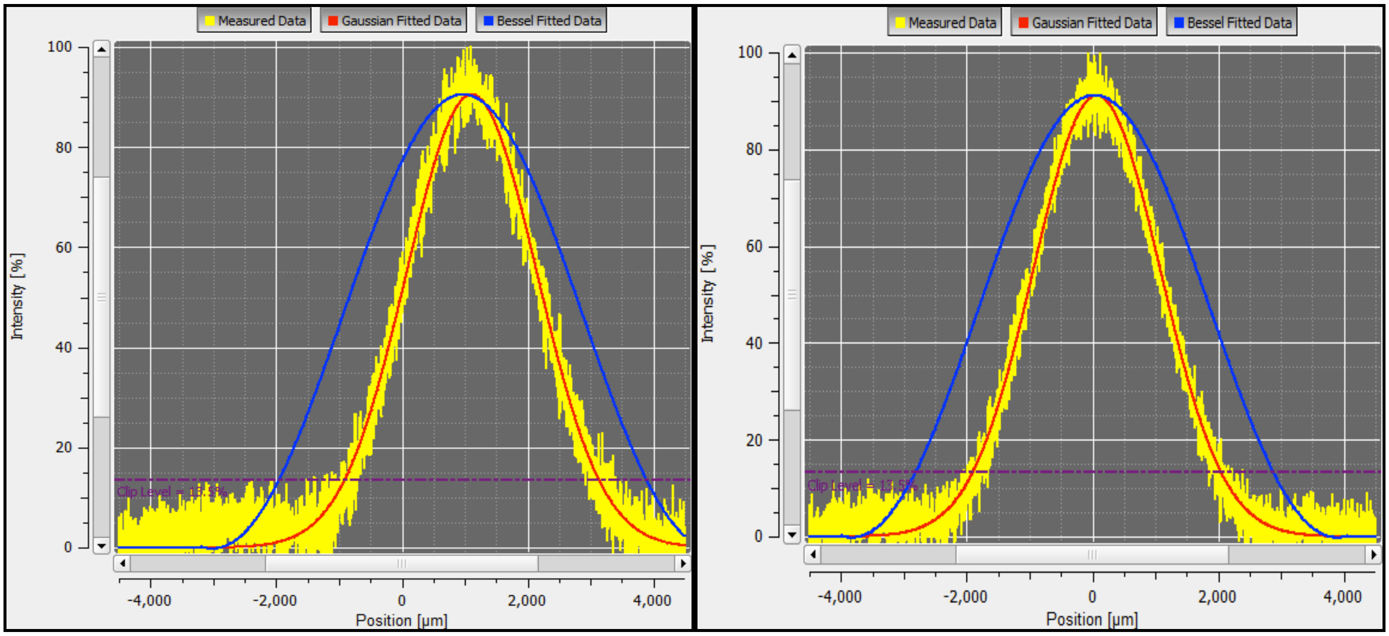

Figure 2

	Gaussian Width (mm)	Gaussianity (%)
X-Axis (left side)	4.18434	96.53
Y-Axis (right side)	3.99521	95.23

1.3 Longitudinal to Angular Coupling

- L = 66.1207 m
- ɵ = 1.22 degrees
- φ = 59.62 degrees

dɵ'/dx = 0.56 urad/m
dφ'/dx = 0.3 urad/m

1.4 Calibrated Spectra

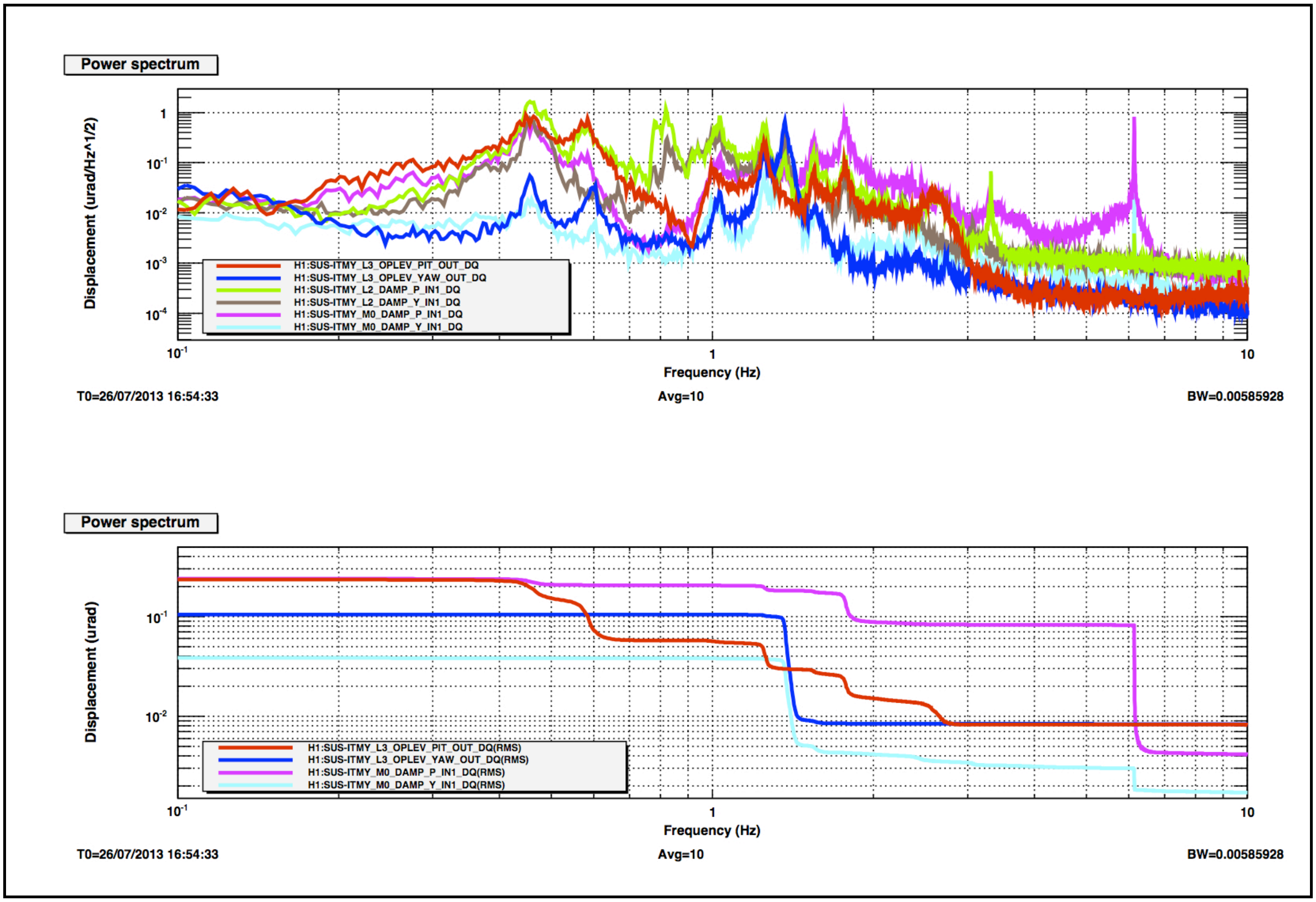

Figure 3

1.5 Calibrated Long Term Drift

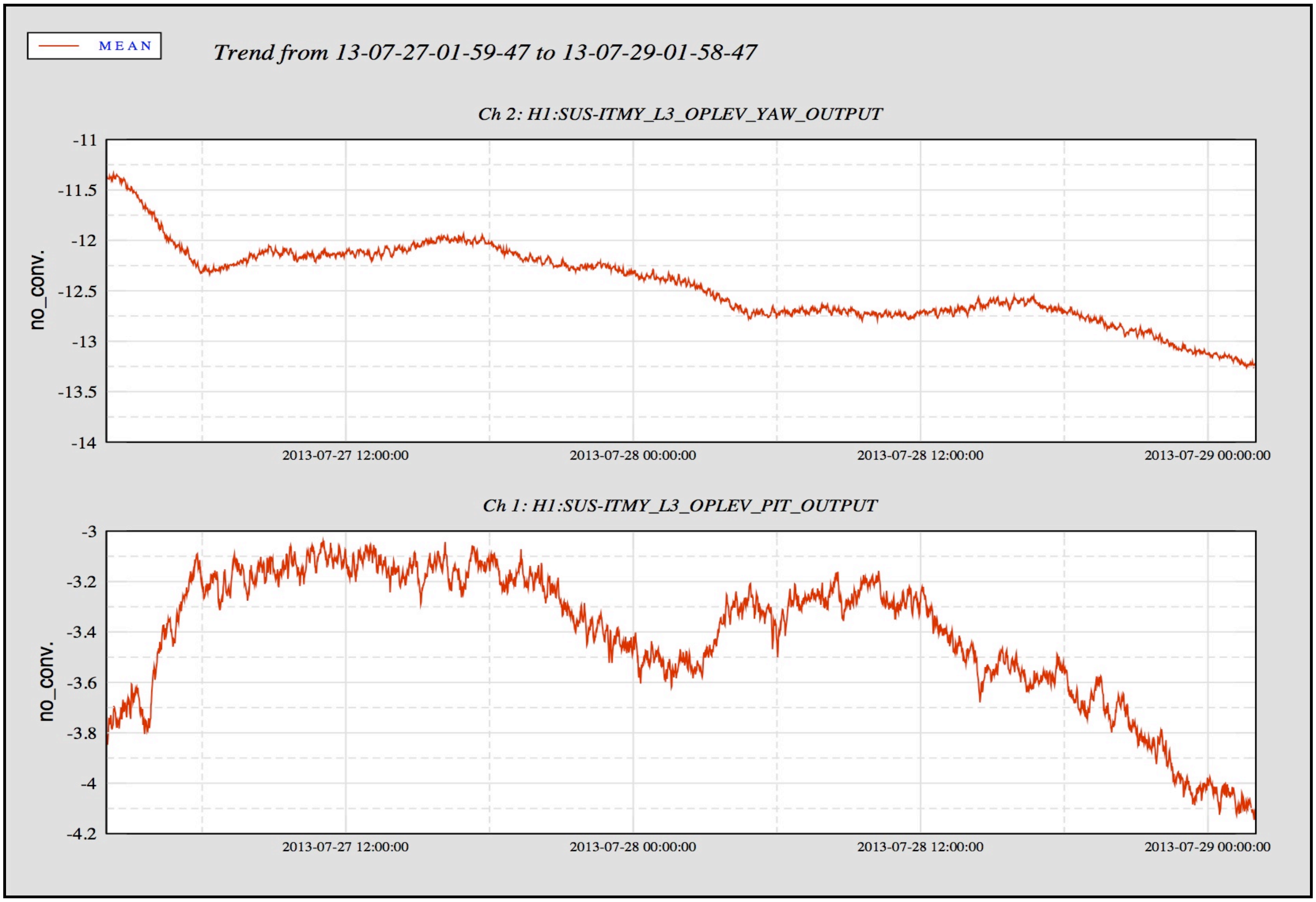

Figure 4

The Y-axis is calibrated to micro-radians and the X-axis spans over 48 hours. Over the course of this time frame, both pitch and yaw pass the spec of 1 micro-radian/10 minutes.

1.6 QPD Sensor Dark Noise

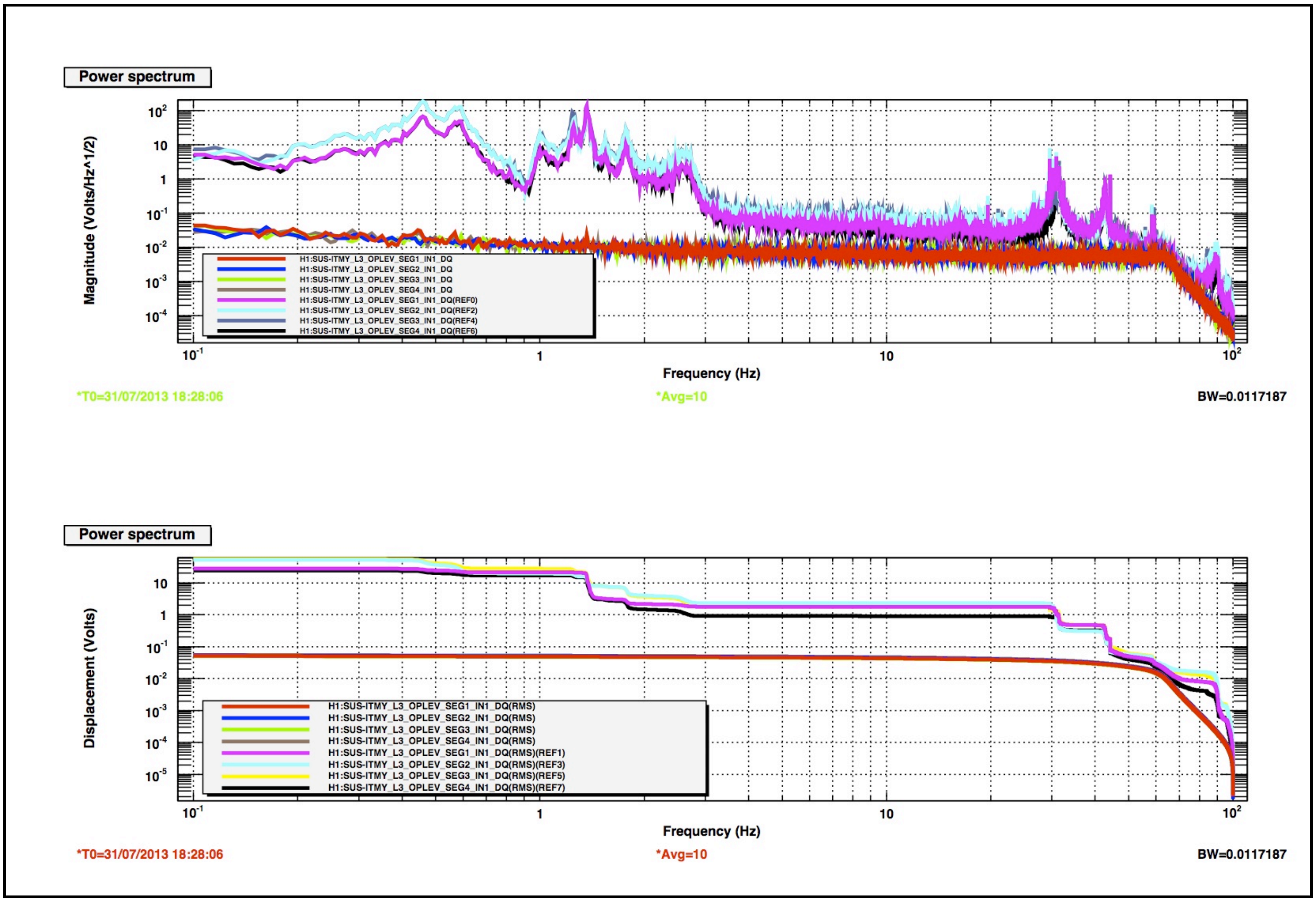

Figure 5

2 ETMY

	Gaussian Width (mm)	Calibration (Counts/uradian)	Low-Frequency Resonances (Hz)	Long-to-ang coupling coefficient (urad/m)	Peak-to-peak drift (uradians/10 minutes)
Pitch	2.0	54.5		0.76	0.004
Yaw	2.2	56.6		0.40	0.003

2.1 Calibration Parameters

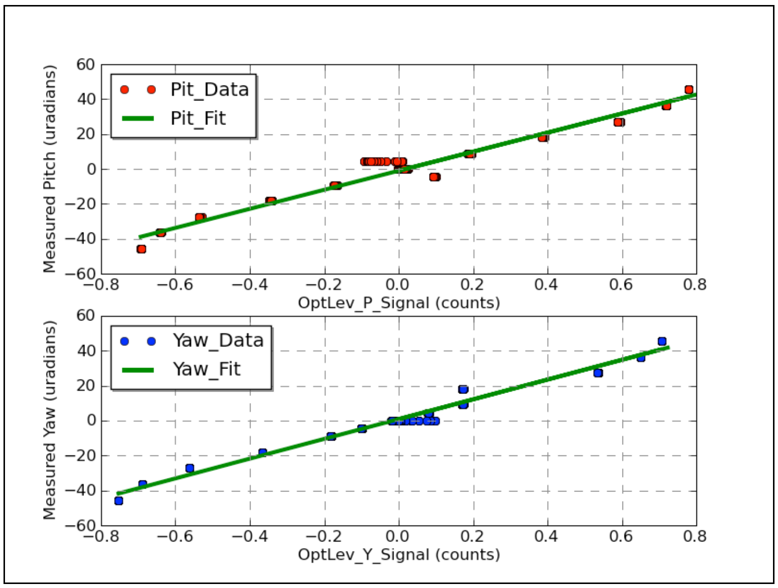

Figure 6

The slope of the linear region of the graph for pitch and yaw:

```
Pitch: 54.53 [uradians/counts]
Yaw:   56.56 [uradians/counts]
```

The geometric calculation for these parameters uses a Zeemax calculation for the path lengths of the lever arms from **E1200836--v1**.

A DC method was used to obtain the y-axis data; we first translate the QPD a fixed amount as measured with a micrometer and use the geometry of the setup to correlate an angular deviation to the pitch or yaw signals.

These results are inputted into the SUS gain filters:

```
H1-SUS-ETMY_L3_OPLEV_PIT_GAIN
H1-SUS-ETMY_L3_OPLEV_YAW_GAIN
```

2.2 Beam Profile

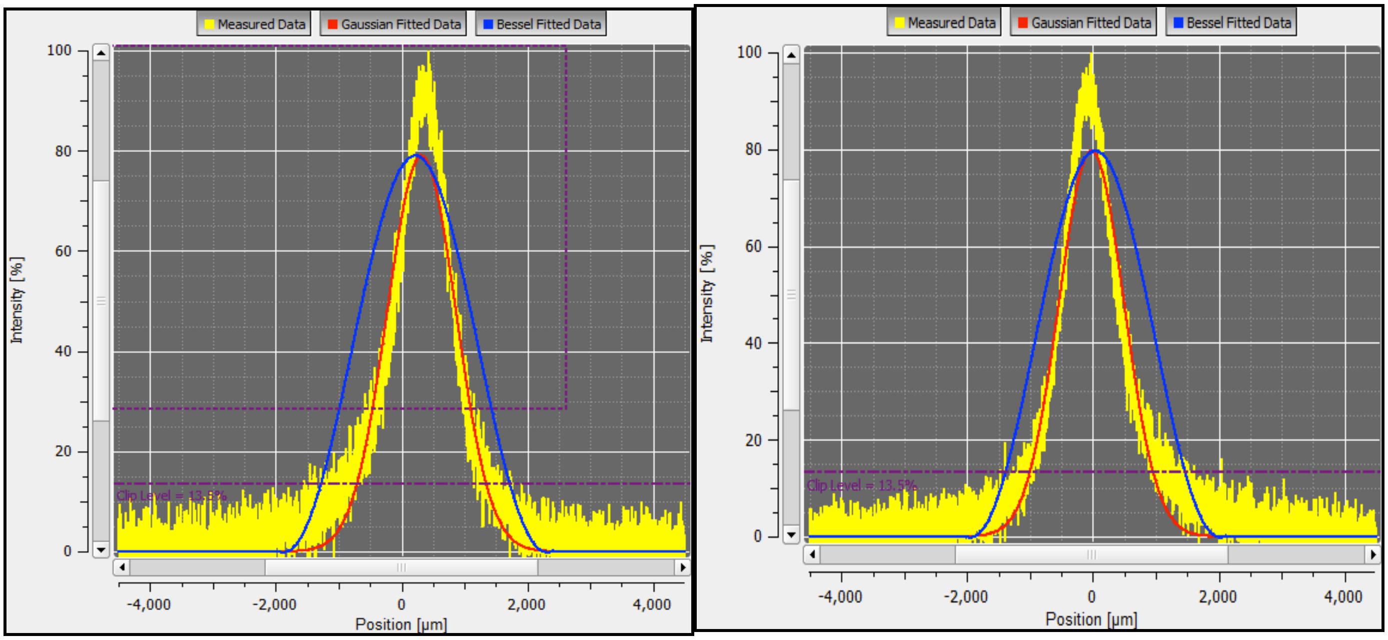

Figure 7

	Gaussian Width (mm)	Gaussianity (%)
X-Axis (left side)	2.31248	94.12
Y-Axis (right side)	2.02837	94.28

2.3 Longitudinal to angular coupling

- L = 11.16 m
- ɵ = 7.65 degrees
- φ = 60.25 degrees

dɵ'/dx = 20.91 urad/m

dφ'/dx = 11.90 urad/m

2.4 Calibrated Spectra

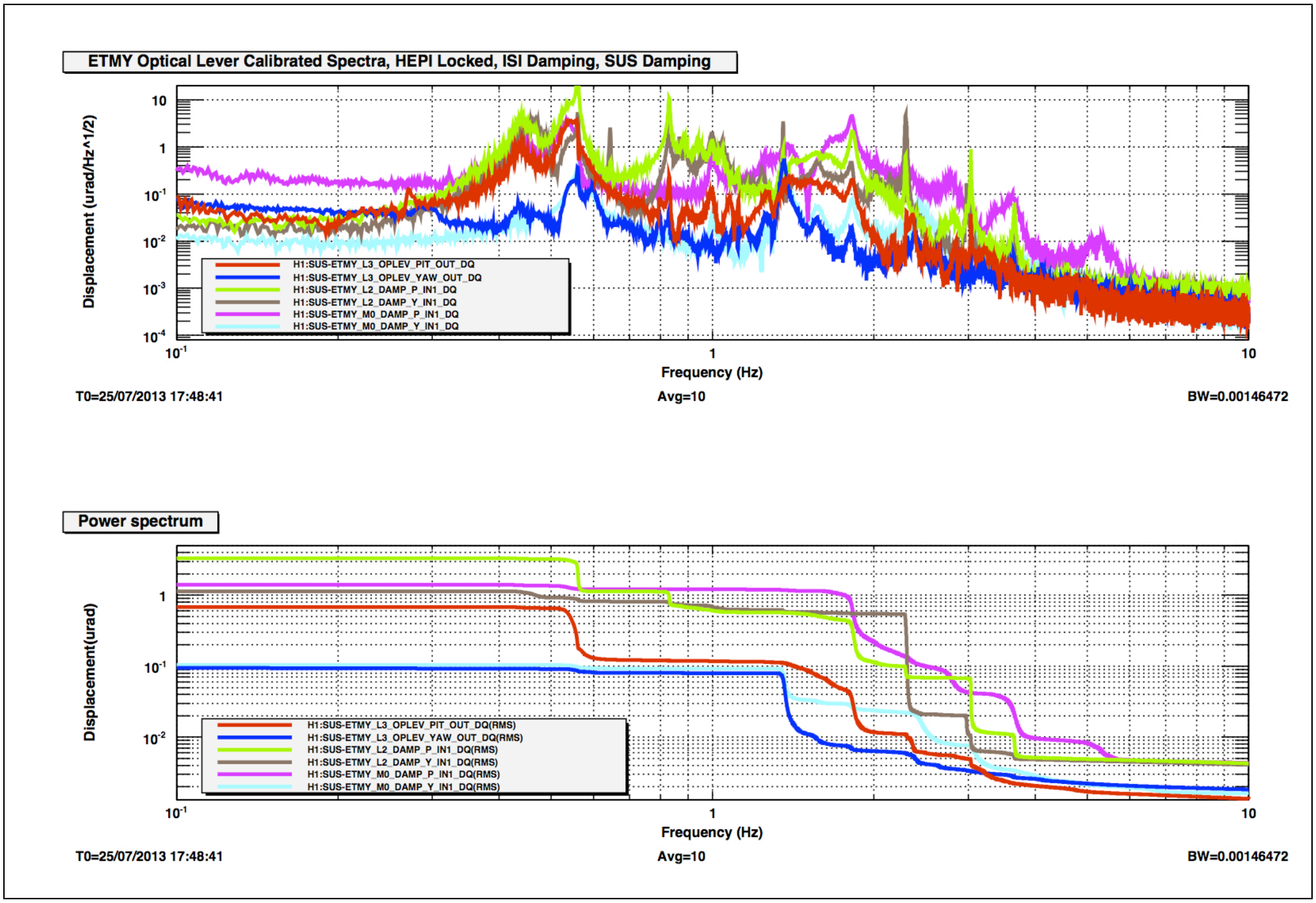

Figure 8

2.5 Calibrated Long Term Drift

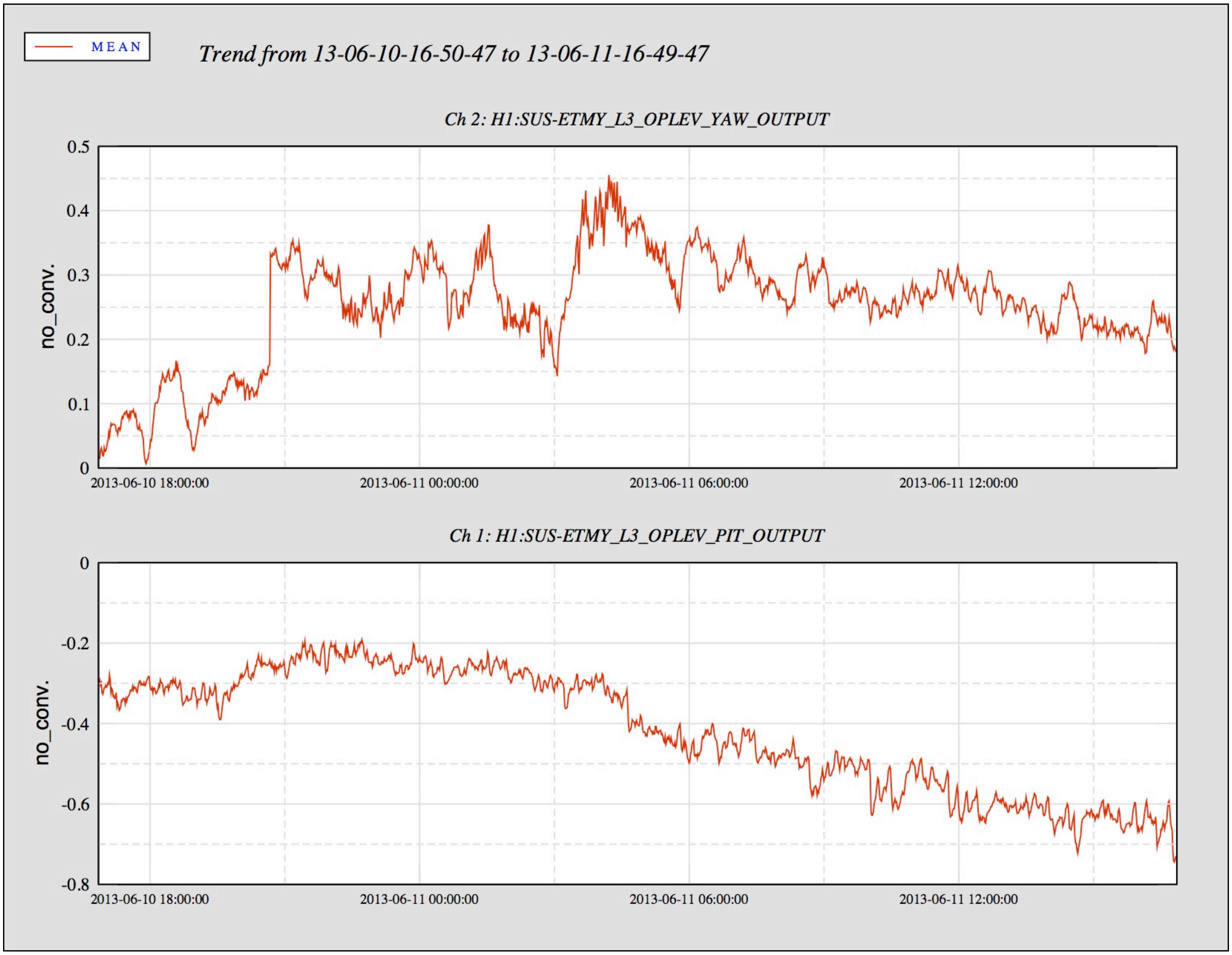

Figure 9

The Y-axis is calibrated to micro-radians and the X-axis spans over 24 hours. Over the course of this time frame, both pitch and yaw pass the spec of 1 micro-radian/10 minutes.

3 ITMX

3.1 Calibration Parameters

3.2 Beam Profile

3.3 Longitudinal to angular coupling

3.4 Calibrated Spectra

3.5 Calibrated Long Term Drift

4 Beamsplitter

	Gaussian Width (mm)	Calibration (Counts/uradian)	Low-Frequency Resonances (Hz)	Long-to-ang coupling coefficient (urad/m)	Peak-to-peak drift (uradians/10 minutes)
Pitch	2.0	268.03		0.00	
Yaw	2.3	265.76		26.3	

4.1 Calibration Parameters

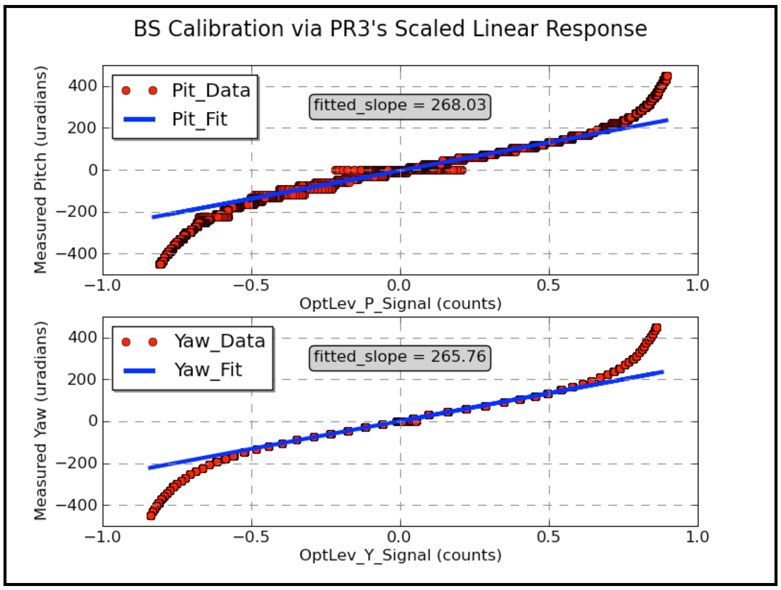

Figure 10

The slope of the linear region of the graph for pitch and yaw:

Pitch: 268.03 [uradians/counts]

Yaw: 265.76 [uradians/counts]

Since the Beamsplitter optical lever is a transceiver unit that does not have a translation stage with a micrometer attached to the QPD, the standard DC calibration does not work for this unit. Also, there are no OSEMS on the last stage of the Beamsplitter suspension

4.2 Beam Profile

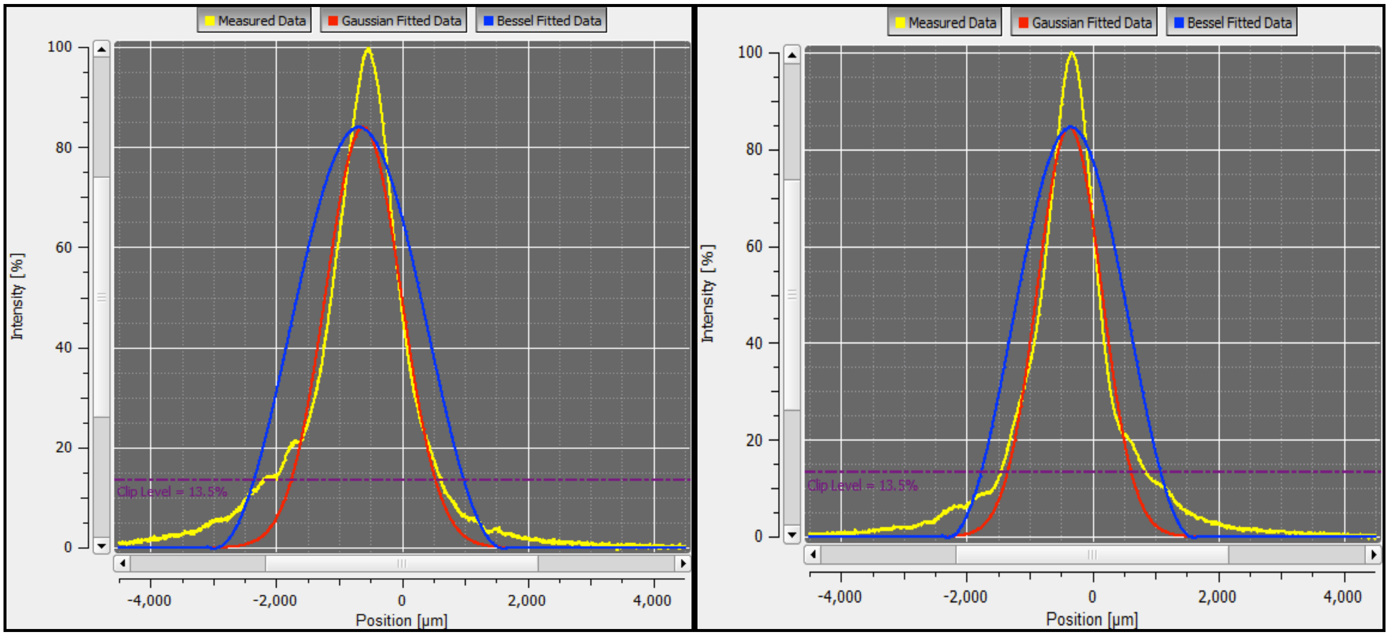

Figure 11

	Gaussian Width (mm)	Gaussianity (%)
X-Axis (left side)	2.31248	94.12
Y-Axis (right side)	2.02837	94.28

4.3 Longitudinal to angular coupling

- L = 0.43 m
- ϴ = 3.03 degrees
- φ = 59.62 degrees

dϴ'/dx = 0.00 mrad/m

dφ'/dx = 26.3 mrad/m

4.4 Calibrated Spectra

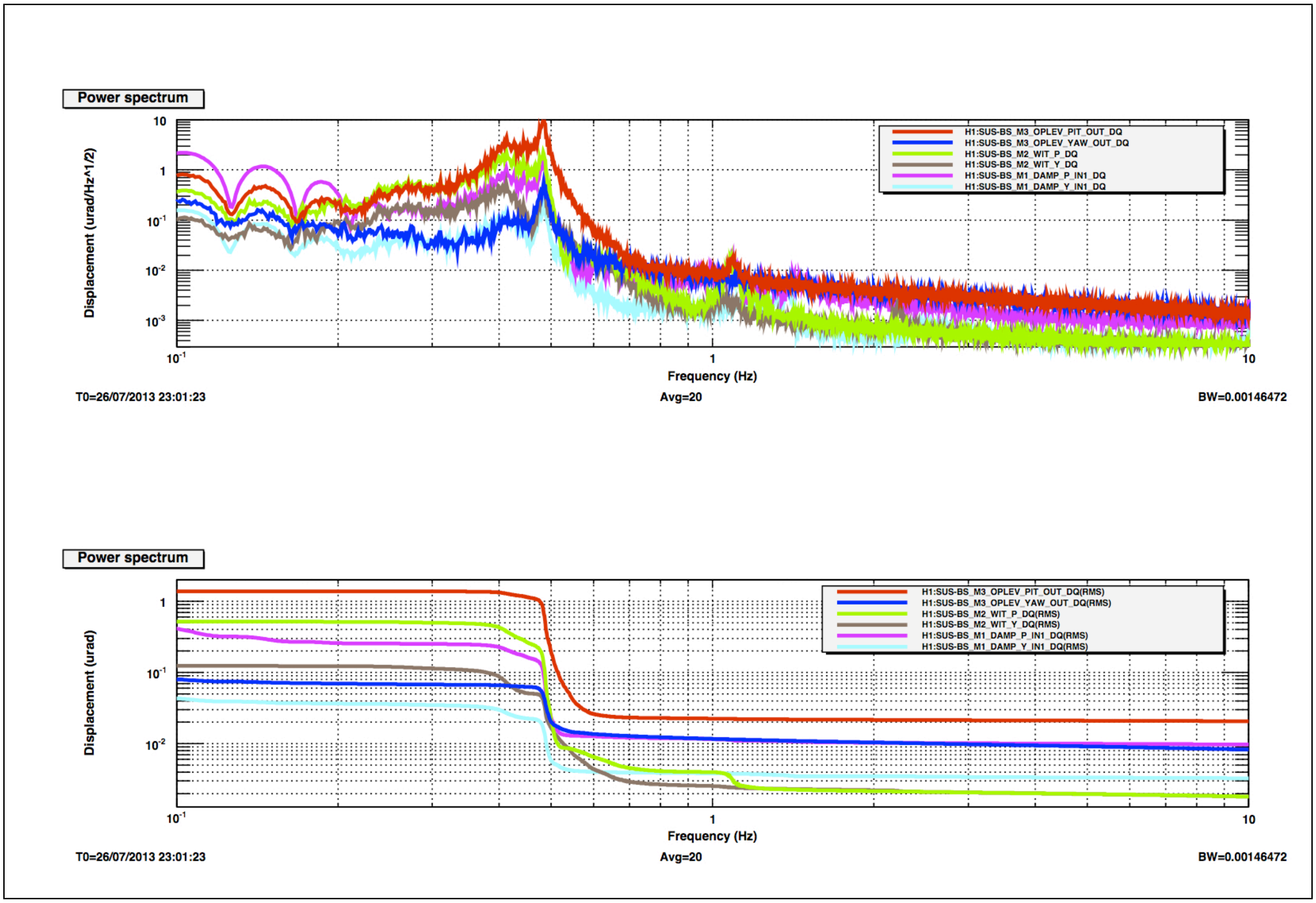

Figure 12

4.5 Calibrated Long Term Drift

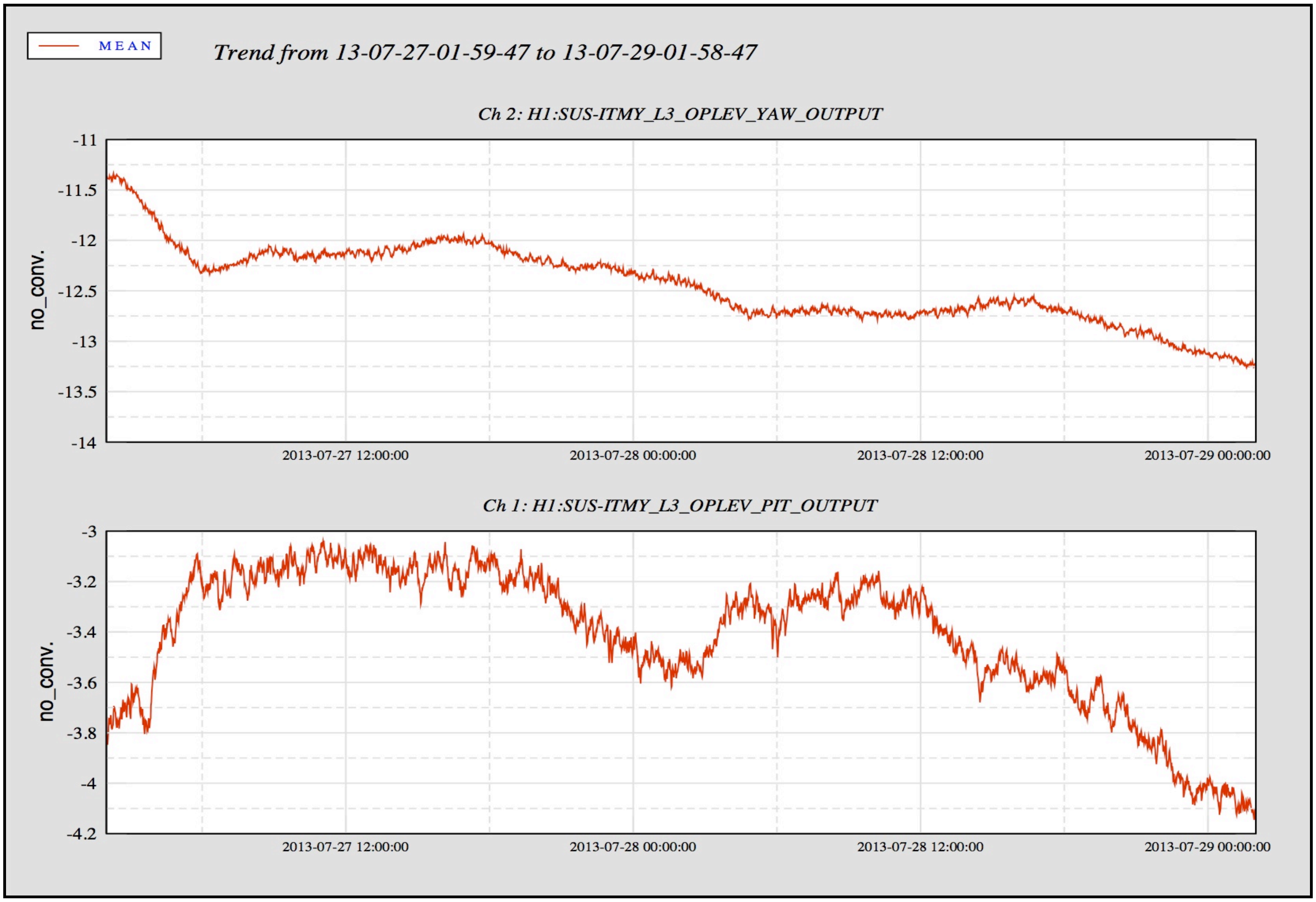

Figure 13

The Y-axis is calibrated to micro-radians and the X-axis spans over 48 hours. Over the course of this time frame, both pitch and yaw pass the spec of 1 micro-radian/10 minutes.

5 PR3

	Gaussian_Width (mm)	Calibration (Counts/uradian)	Low-Frequency Resonances (Hz)	Long-to-ang coupling coefficient (urad/m)	Peak-to-peak drift (uradians/10 minutes)
Pitch	2.04	38.86		4.59	0.055
Yaw	1.98	38.53		0.00	0.277

5.1 Calibration Parameters

The calibration procedure for the PR3 Optical Lever is similar to the test masses since there is a translation stage to which the QPD mounts to and we can use a DC method of actuating the translation stage and measure the displacement using a micrometer. However, the PR3 suspension also has OSEMs on the bottom stage where the main optic is sitting. This means we can correlate the optical lever signal to the OSEM sensors to sanity check our DC method as well as look at the error of the shadow sensors.

The OSEMs are calibrated by SUS to be read out in micro-radians these channels:

`H1-SUS-PR3_M3_WIT_P_MON`

`H1-SUS-PR3_M3_WIT_Y_MON`

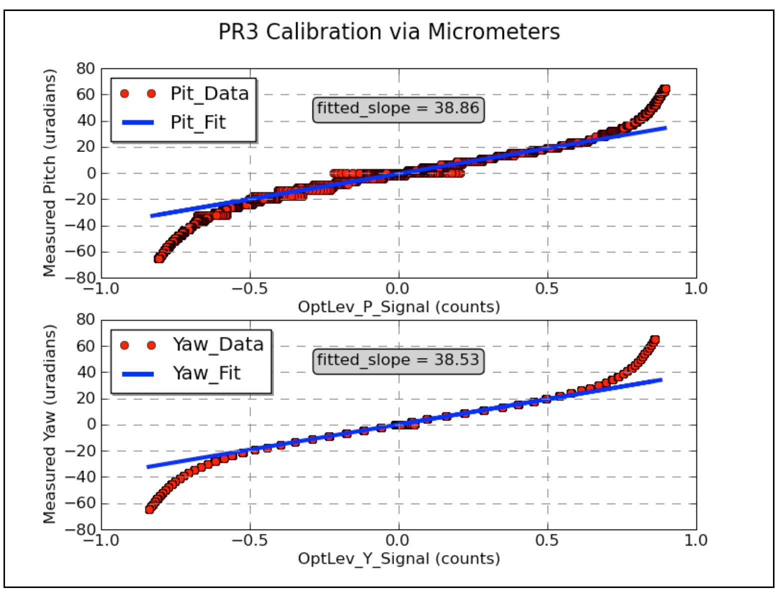

Figure 14

The slope of the linear region of the graph for pitch and yaw:

```
Pitch: 38.86 [uradians/counts]
Yaw:   38.53 [uradians/counts]
```

The geometric calculation for these parameters uses a Zeemax calculation for the path lengths of the lever arms from **E1200836--v1**. A DC method was used to obtain the y-axis data; we first translate the QPD a fixed amount as measured with a micrometer and use the geometry of the setup to correlate an angular deviation to the pitch or yaw signals.

These results are inputted into the SUS gain filters:

H1-SUS-PR3_M3_OPLEV_PIT_GAIN

H1-SUS-PR3_M3_OPLEV_YAW_GAIN

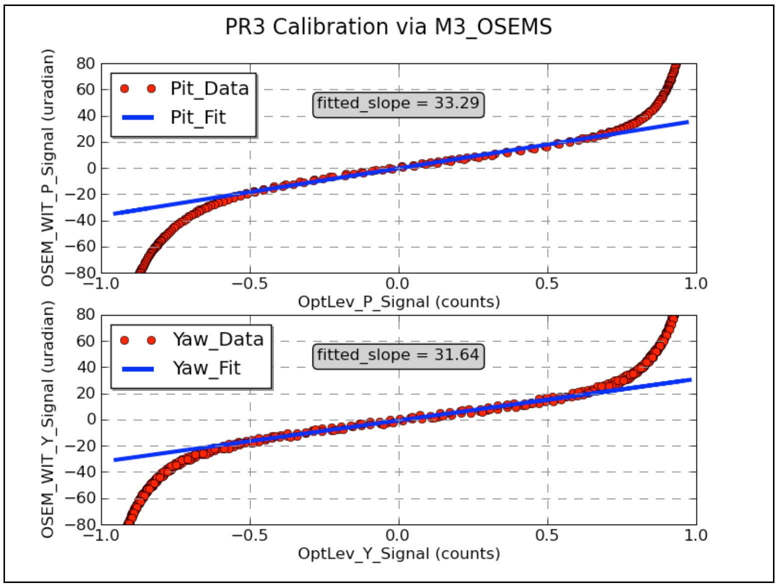

Figure 15

5.2 Beam Profile

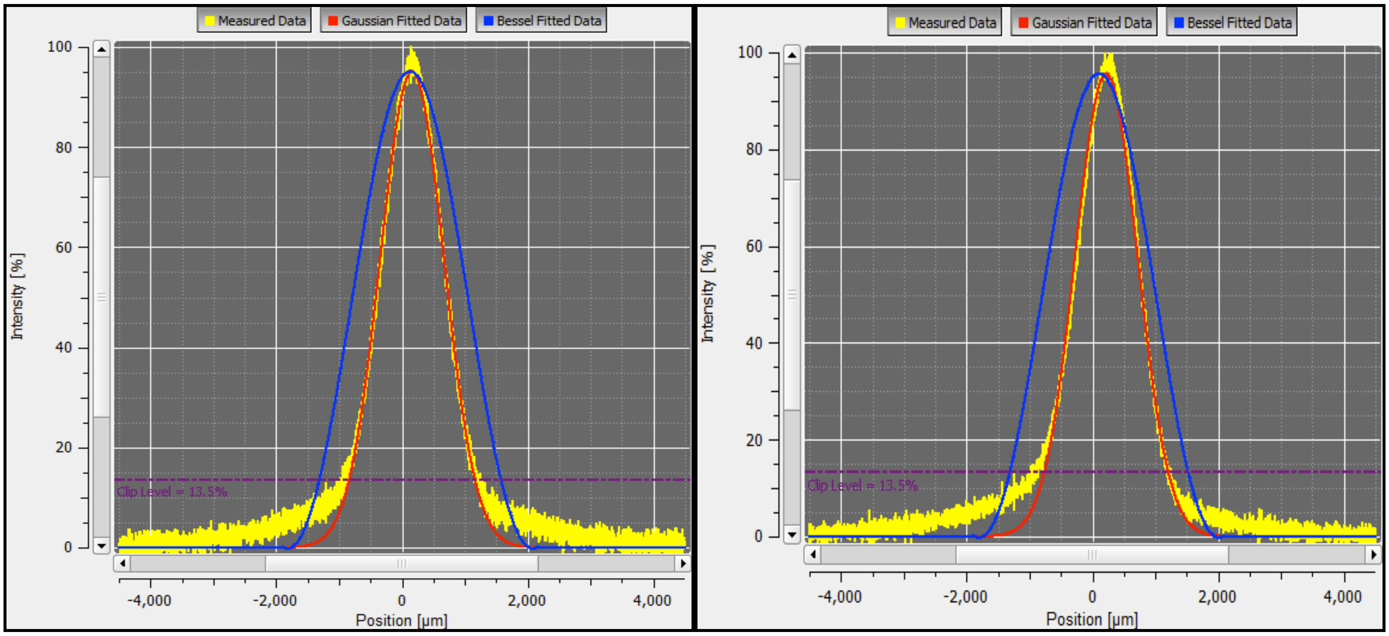

Figure 16

	Gaussian Width (mm)	Gaussianity (%)
X-Axis (left side)	2.04159	96.61
Y-Axis (right side)	1.98533	96.56

5.3 Longitudinal to angular coupling

- L = 27.72 m
- θ = 3.64 degrees
- φ = 89.99 degrees

dθ'/dx = 4.59 mrad/m
dφ'/dx = 0.00 mrad/m

5.4 Calibrated Spectra

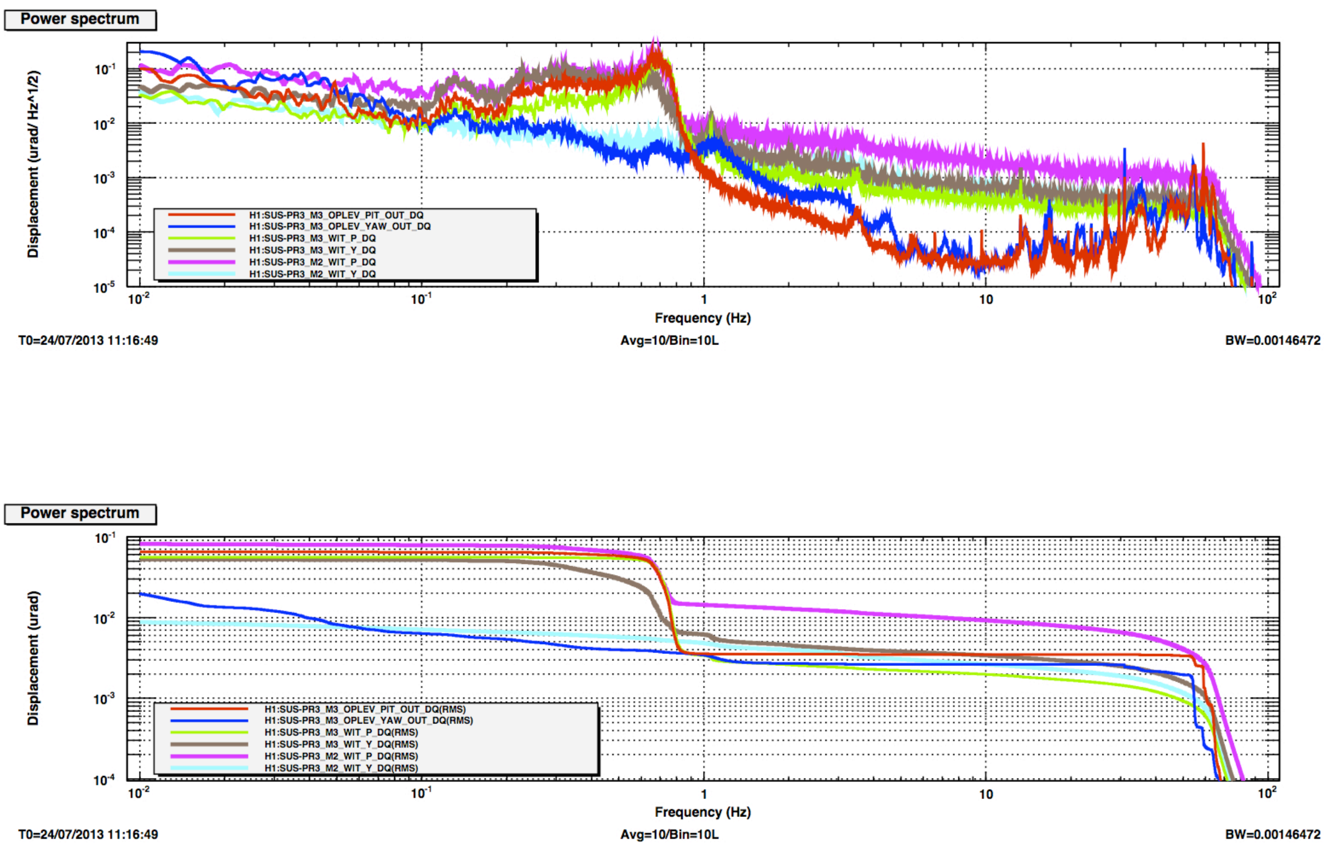

Figure 17

5.5 Calibrated Long Term Drift

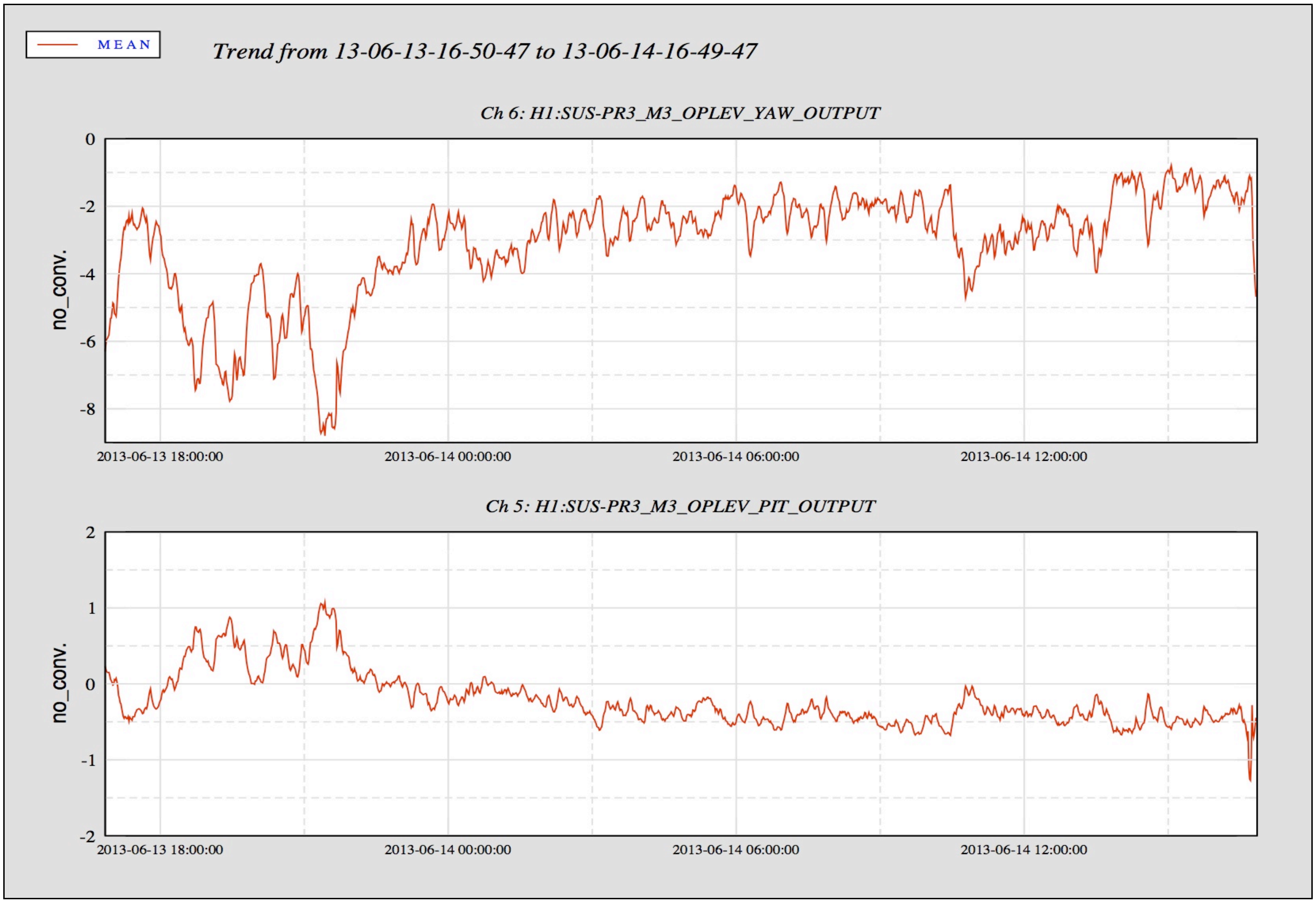

Figure 18

5.6 QPD Sensor Dark Noise

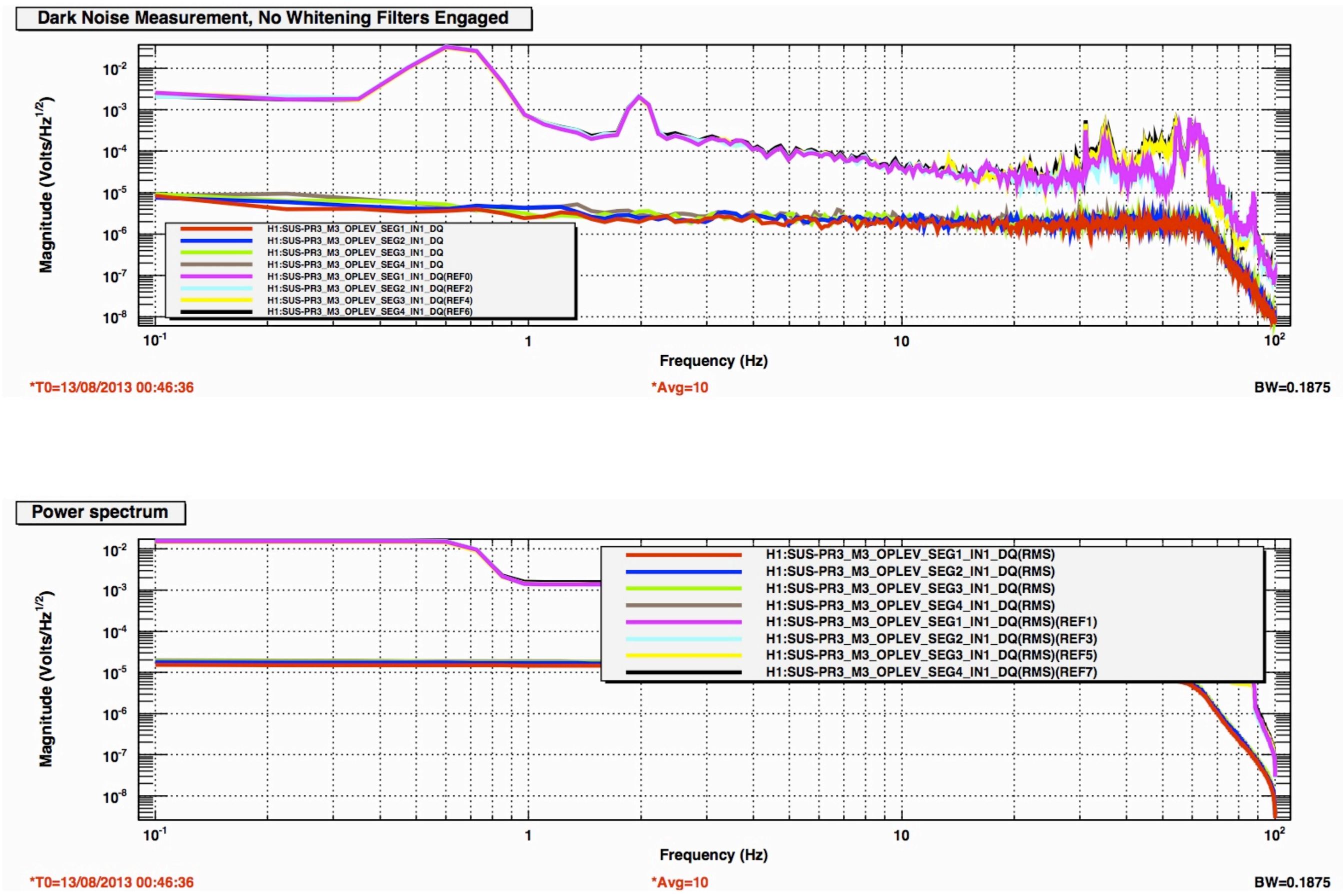

Figure 19

6 SR3

6.1 Calibration Parameters

6.2 Beam Profile

6.3 Longitudinal to angular coupling

6.4 Calibrated Spectra

6.5 Calibrated Long Term Drift

7 HAM 2

	Gaussian_Width (mm)	Calibration (Counts/uradian)	Low-Frequency Resonances (Hz)	Long-to-ang coupling coefficient (urad/m)	Peak-to-peak drift (uradians/10 minutes)
Pitch					
Yaw					

7.1 Calibration Parameters

Since the HAM optical levers do not have a translation stage with a micrometer, we need to find a separate method to measure the linear response curve.

The process for calibration will have two varieties:

The first way we can take the calibration data from another optical lever and scale the geometry, beam power, and beam width so that it matches HAM2. The geometry scaling can be derived from the Zeemax layouts and the lever arm is directly proportional to the sensitivity of the optical lever. The beam power for the optical levers can be found by looking at a time average of the sum of counts. The beam widths can be found by looking at the beam profile at the QPD. Both the power and the widths are linearly related to the sensitivity so they can be scaled simply as well. A potential source of error would associated with the performance of the QPDs on an individual basis, these will be tested to look at the variance of power and sensitivity in order to create and error via this method.

A second way to map the linear response curve is to drive the ISI and correlate the optical lever pitch and yaw signals to the position sensors (RX, RY, and RZ). This requires a set actuation at a few different amplitudes to prove linearity in the actuators as well as a coherence function to show that we see good correlation. For HAM2, the RY sensors will correspond to the pitch OptLev signals and the RZ sensors will correspond to the yaw OptLev signals.

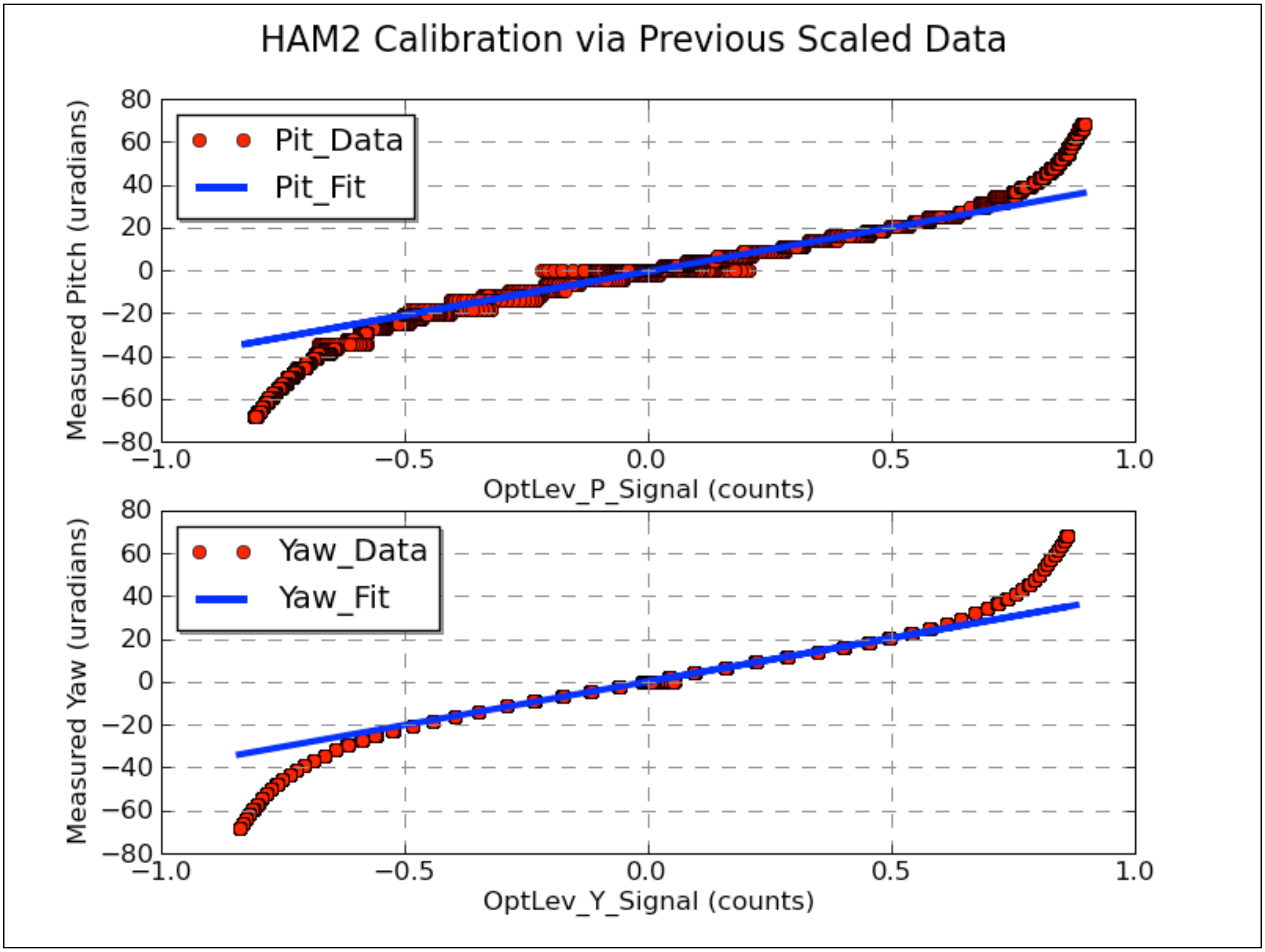

Figure 20

```
40.91 [uradians/counts]
40.56 [uradians/counts]
```

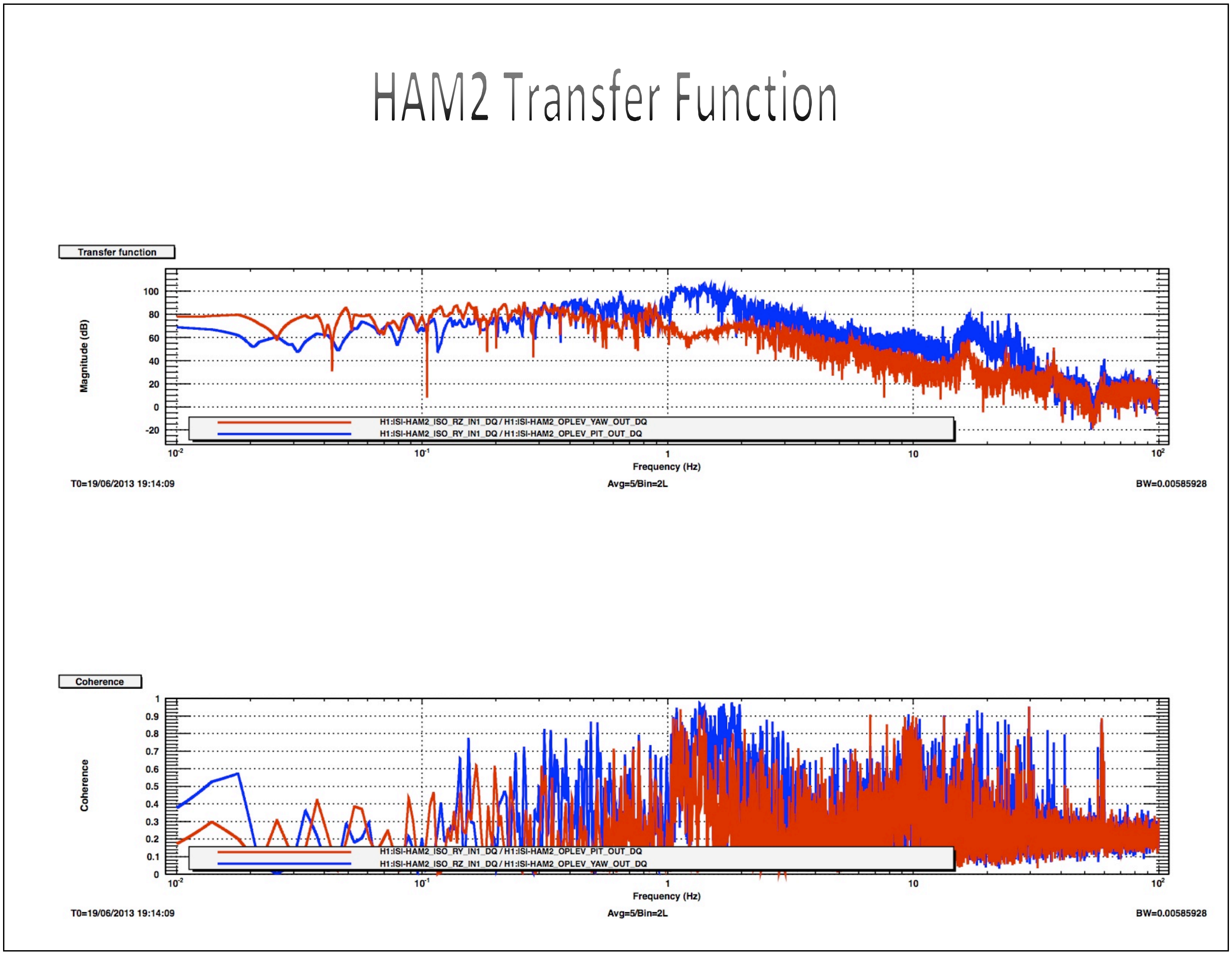
HAM2 Transfer Function
Transfer function
Magnitude (dB)
H1:ISI-HAM2_ISO_RZ_IN1_DQ / H1:ISI-HAM2_OPLEV_YAW_OUT_DQ
H1:ISI-HAM2_ISO_RY_IN1_DQ / H1:ISI-HAM2_OPLEV_PIT_OUT_DQ
Frequency (Hz)
T0=19/06/2013 19:14:09
Avg=5/Bin=2L
BW=0.00585928
Coherence
Coherence
H1:ISI-HAM2_ISO_RY_IN1_DQ / H1:ISI-HAM2_OPLEV_PIT_OUT_DQ
H1:ISI-HAM2_ISO_RZ_IN1_DQ / H1:ISI-HAM2_OPLEV_YAW_OUT_DQ
Frequency (Hz)
T0=19/06/2013 19:14:09
Avg=5/Bin=2L
BW=0.00585928

Figure 21

7.2 Beam Profile

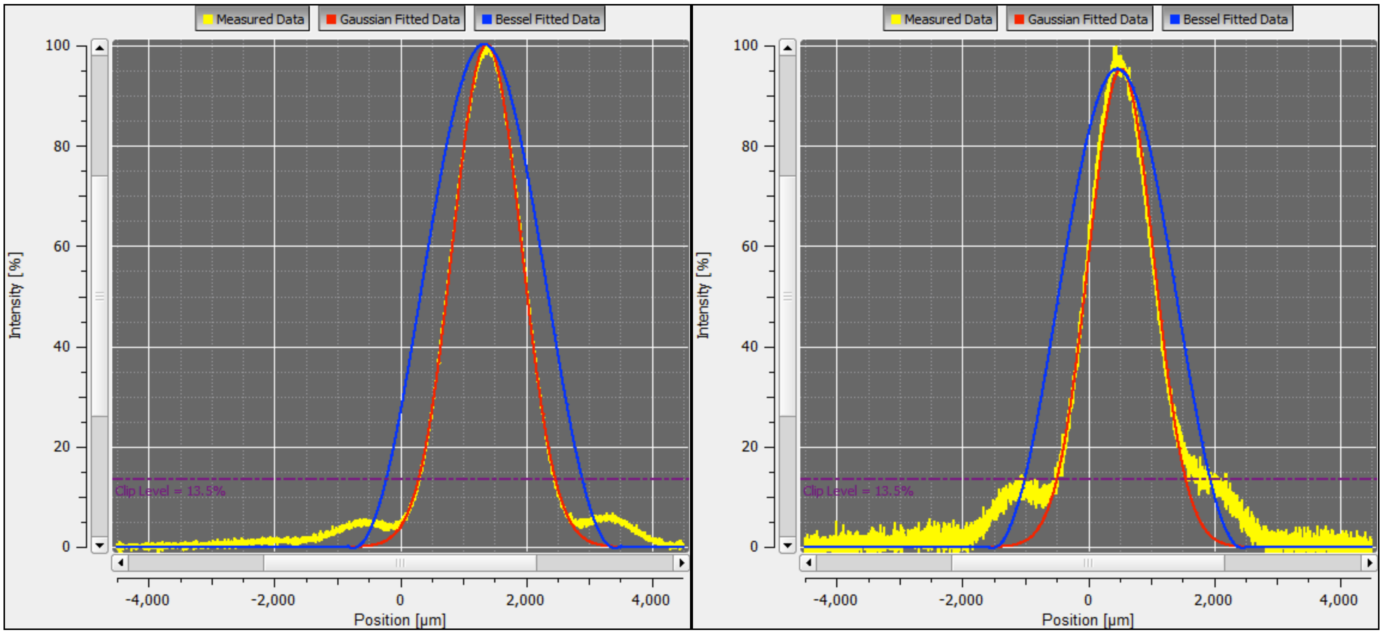

Figure 22

	Gaussian Width (mm)	Gaussianity (%)
X-Axis (left side)	2.07343	95.27
Y-Axis (right side)	1.98035	96.12

7.3 Longitudinal to angular coupling

7.4 Calibrated Spectra

7.5 Calibrated Long Term Drift

8 HAM 3

	Gaussian_Width (mm)	Calibration (Counts/uradian)	Low-Frequency Resonances (Hz)	Long-to-ang coupling coefficient (urad/m)	Peak-to-peak drift (uradians/10 minutes)
Pitch					
Yaw					

8.1 Calibration Parameters

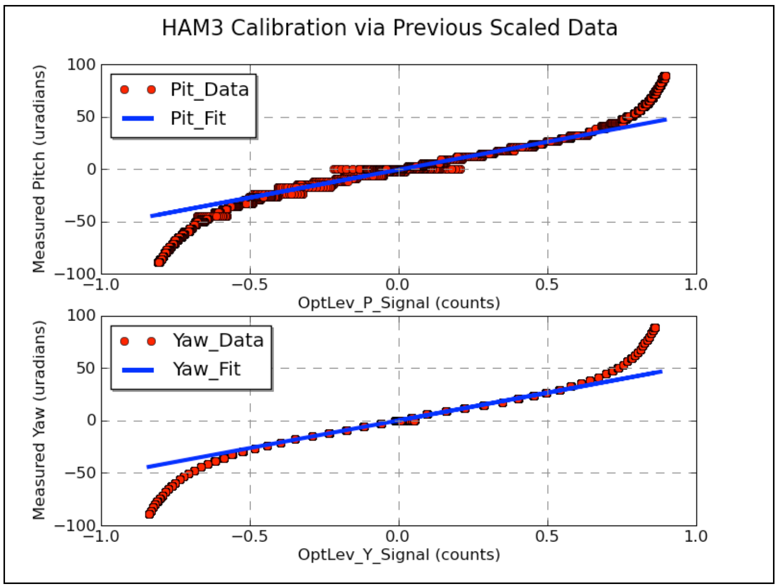

Figure 23

65.63

65.07

8.2 Beam Profile

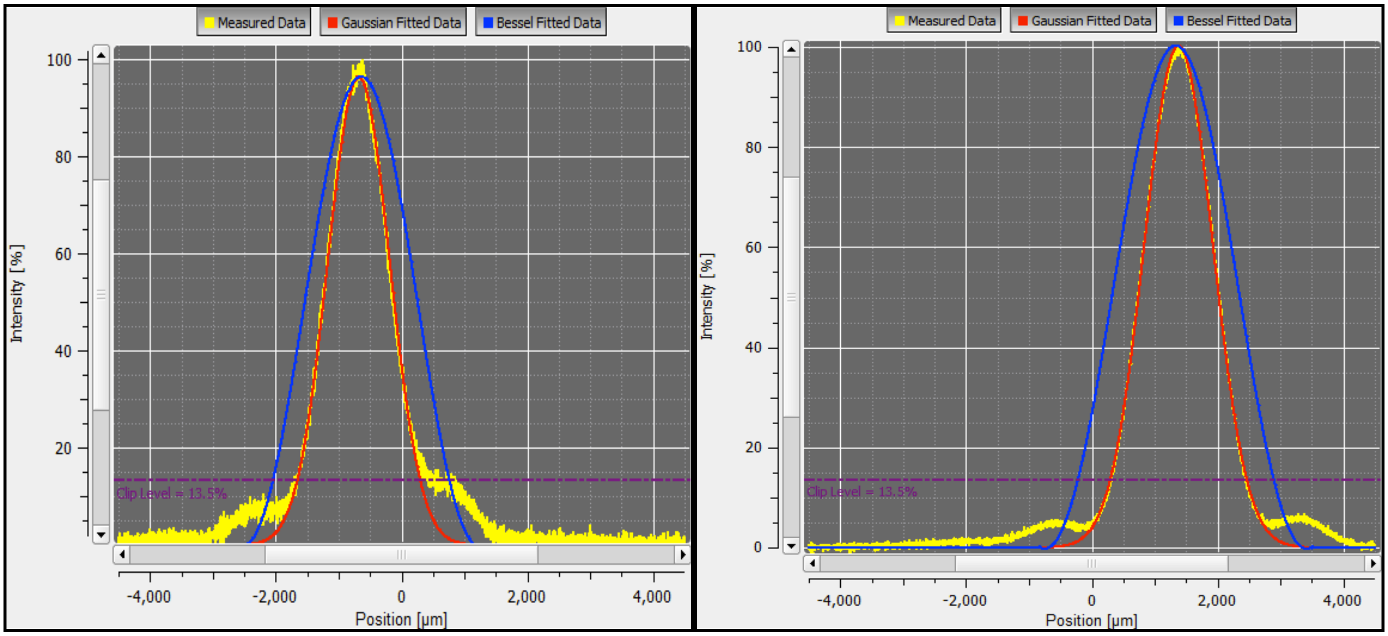

Figure 24

	Gaussian Width (mm)	Gaussianity (%)
X-Axis (left side)	2.12093	97.84
Y-Axis (right side)	2.07638	98.14

8.3 Calibrated Spectra

8.4 Longitudinal to angular coupling

8.5 Calibrated Long Term Drift

9 HAM 4

9.1 Calibration Parameters

9.2 Beam Profile

9.3 Longitudinal to angular coupling

9.4 Calibrated Spectra

9.5 Calibrated Long Term Drift

10 HAM 5

10.1 Calibration Parameters

10.2 Beam Profile

10.3 Longitudinal to angular coupling

10.4 Calibrated Spectra

10.5 Calibrated Long Term Drift