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Investigation of Variations in the Absolute Calibration of the Laser Power Sensors for the LIGO Photon Calibrators

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Investigation of Variations in the Absolute Calibration of the Laser Power Sensors for the LIGO Photon Calibrators

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A photon calibrator, one method used to calibrate the LIGO interferometers, utilizes a power-modulated laser to induce displacements of a test mass via the recoil of photons. These displacements are linearly proportional to the power incident on the mass. Therefore, interferometer calibration at the 1% level requires absolute power calibration at the 1% level or better. To realize high-accuracy power measurements a *gold standard* temperature-stabilized photodetector, mounted on an integrating sphere, was calibrated at NIST. This standard is maintained in a controlled laboratory environment to preserve its calibration accuracy. To calibrate the internal photodetector that samples the light power directed to a test mass in an installed photon calibrator, the calibration of the *gold standard* must first be transferred to a similar *working standard*. The principal source of error in calibrating the *working standard* has been identified to be temporal variations in the detector outputs resulting from multi-beam interference effects within the integrating sphere (laser speckle). A procedure for transferring the calibration has been generated and tested. The uncertainty in the derived *working standard* calibration coefficient is 0.49% (1σ). The estimated uncertainty for the calculated photon calibrator photodetector calibration coefficient is 0.56% (1σ).

1 BACKGROUND

1.1 Introduction

The purpose of the Laser Interferometer Gravitational-Wave Observatory (LIGO) is to directly measure the effects of gravitational waves. Gravitational waves induce strains on the order of 10^{-20} [1]. The interferometer arm lengths are on the order of kilometers, thus producing a necessary test-mass-displacement sensitivity of around

10^{-17} m. Several innovative approaches have been employed to calibrate the interferometers to this sensitivity. The official method utilizes magnets and coils for the necessary small-scale actuation [1]. Another method, necessary for crosschecking the calibration, induces displacements by directing a power-modulated laser toward the test mass. The instruments employed for this calibration method are generally referred to as the photon calibrators.

1.2 Photon Calibrators

The photon calibrators direct a 1047nm, CrystaLaser, Model #IRCL-500-1047, Nd:YAG laser towards the test masses situated at the ends of the LIGO interferometers. As the photons impinge upon each test mass, they exert a force:

$$F = \frac{2P\cos(\theta)}{c}\ [2].$$

This force is associated with a displacement proportional to both the force and the power of the laser. Power measurement is thus integral to determining the displacement of a test mass; for this, a small fraction of the light is sampled by a New Focus, Model 2033, Large-Area IR Photoreceiver. Due to the proportionality between the power and displacement, calibration accuracy at the 1% level requires power measurement accuracy at the 1% level or better.

1.3 Absolute Calibration

To achieve the necessary accuracy in the calibration of the photon calibrators, the power meters originally utilized to calibrate the photodetectors were replaced by integrating spheres. One integrating sphere, called the *gold standard*, was calibrated by the National Institute of Standards and Technology (NIST) and is maintained in a laboratory setting to preserve this calibration. NIST determined the calibration factor and expanded 2σ uncertainty at two nominal power inputs: at 99 mW, the calibration factor was 3.1991 V/W with an expanded uncertainty of 0.88%, and at 316 mW, the calibration factor was 3.1919 V/W with an uncertainty of 0.86% [3]. For calibration of the photon calibrators, the gold standard calibration must be transferred to another integrating sphere, known as the *working standard*, which can leave the laboratory environment. Therefore, the purpose of this project was to quantify the error involved in both steps: transferring the calibration from the gold standard to the working standard, and then transferring that calibration to the photon calibrator photodetectors.

2 WORKING STANDARD CALIBRATION

2.1 Theory

A specific optical setup is used for working standard calibrations. As part of this, a photon calibrator laser is directed through an optical layout, as described in section 5.2. The beam then passes through a beamsplitter, which divides the light between the gold standard and the working standard integrating spheres. This setup, along with the placement of the optical layout breadboard, is shown in Figure 1.

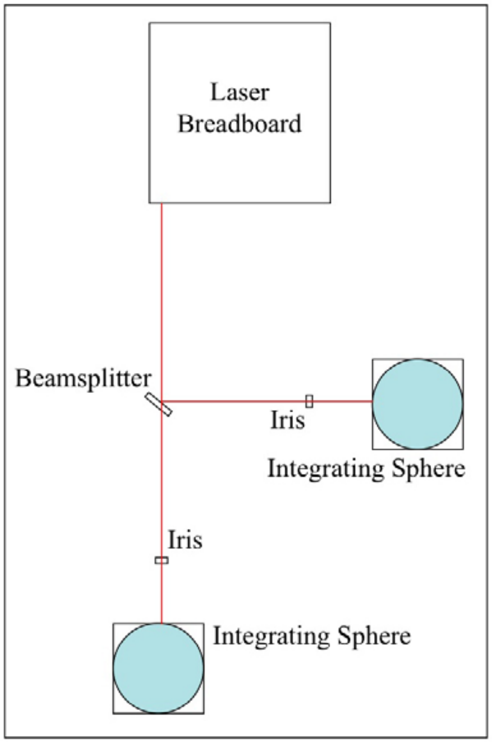

Figure 1: Working standard calibration setup

Signals from the integrating spheres are recorded and the ratio between them is taken, eliminating laser power variations. The positions of the integrating spheres are then swapped, and the process is repeated; combining the second ratio with the first eliminates the effect of the beamsplitter. Since the gold standard calibration coefficient is known, the working standard calibration coefficient can be isolated. This process is detailed in section 5.3.

2.2 Statistical Errors

To identify the statistical errors in the working standard calibration, this procedure was repeated 55 times. In some calibrations, major systematic errors were identified; these calibrations were excluded from the statistical analysis. The calibration coefficients for the included and excluded calibrations are shown in Figure 2. Motivations behind the exclusion of specific calibrations are discussed in section 5.4.

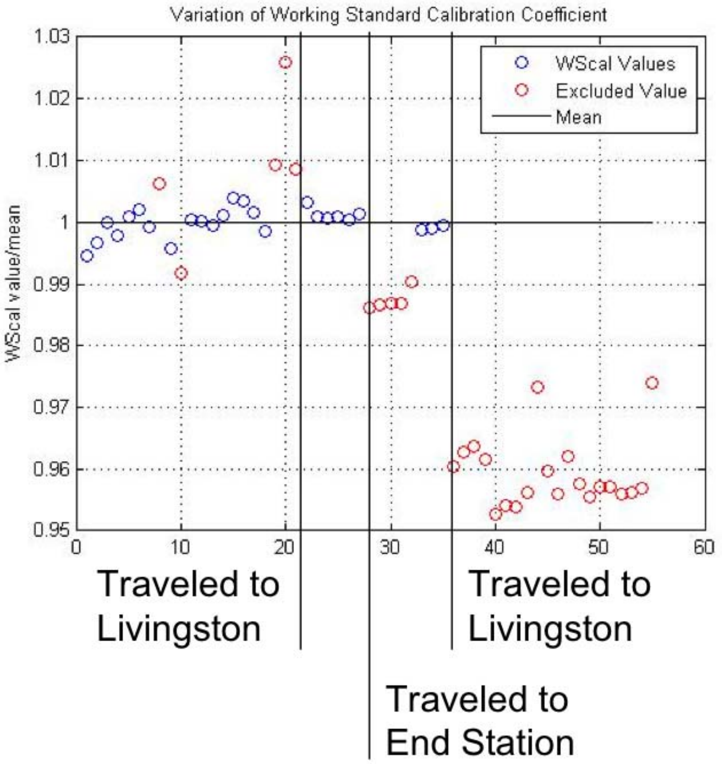

Figure 2: Included and excluded calibration coefficients shown with the mean of the included values and the timing of working standard shipments

The mean of the included values is 3.20 V/W, and the standard deviation (1σ) is 0.21%. Figure 3 shows the variations among the included calibration coefficients.

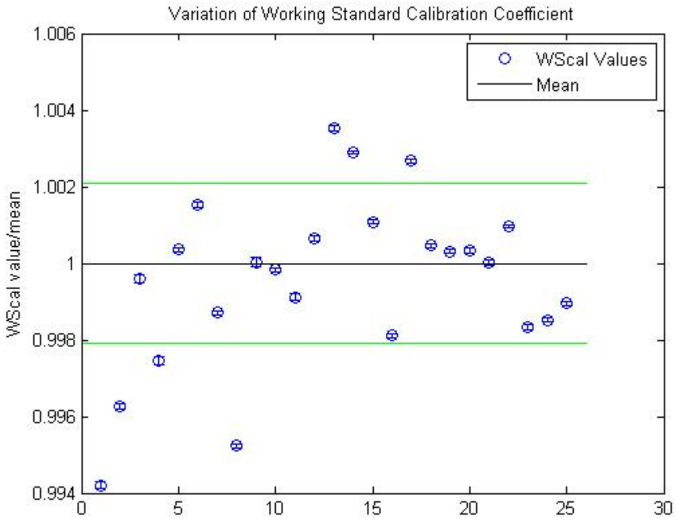

Figure 3: Included calibration coefficients normalized to the mean shown with mean and +/- 1 standard deviation

2.3 Laser Speckle

During a typical working standard calibration, slow variations in both integrating sphere signals are observed. These slow variations have an amplitude of less than 1% mean to peak and a period of 5-20s. Figure 4 shows typical variations.

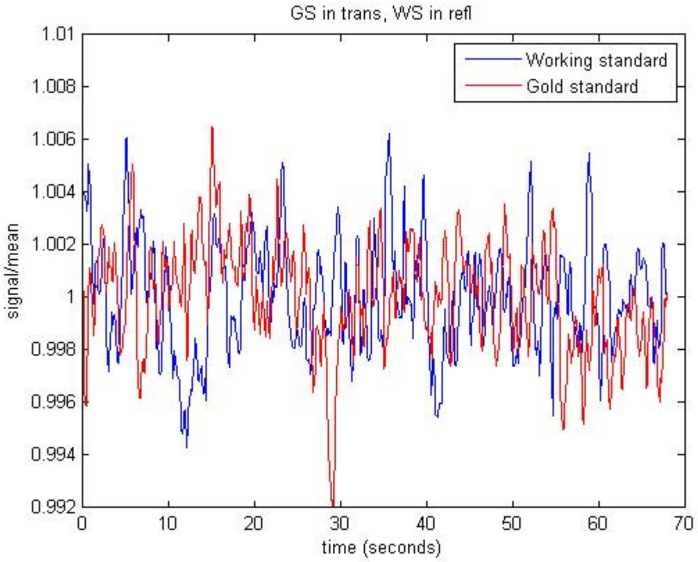

Figure 4: Gold standard and working standard signals during a calibration performed on July 1, 2008

Since these variations contribute to the error involved in the working standard calibration, their origin needed to be identified.

After testing each component of the calibration setup, it was determined that the variations were related to both the geometry of the integrating spheres and laser light. If the photodetectors were utilized without the integrating spheres, or if the integrating spheres were illuminated by lamplight, the variations did not appear. After further investigation into the possibilities, laser speckle was proposed as a cause.

Laser speckle occurs when coherent, monochromatic light, as originates from a laser, impinges upon a diffuse surface. The rough surface induces phase shifts and direction changes in the light, causing it to produce complex interference patterns, commonly referred to as laser speckle. An integrating sphere is lined with a diffuse material; it is logical that laser speckle could be produced. In fact, integrating spheres have been utilized to produce laser speckle as part of a proposed method for modulation transfer function testing of detector arrays [4].

To determine whether the working and gold standards produce laser speckle, a <5mW red laser pointer was directed towards the gold standard. As the integrating sphere was illuminated, both the input and output ports of the integrating sphere were inspected; speckle was noted at both ports. A photograph of the speckle pattern at the input port of the gold standard integrating sphere is shown in Figure 5.

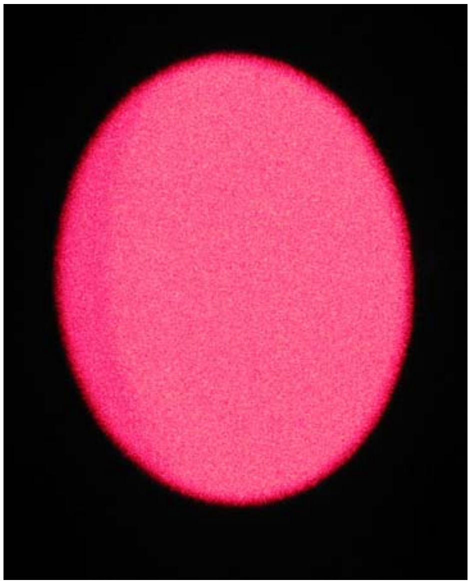

Figure 5: Laser speckle at the input port of the gold standard integrating sphere when illuminated by a laser pointer

Speckle clearly occurs when laser light illuminates the spheres. Air currents inside the sphere could cause temporal variations in the speckle pattern. As this occurs, the amount of light incident on the photodetectors will vary, causing fluctuations similar to those observed during working standard calibrations. This theory is supported by the fact that manipulating air currents affects these slow variations. The signals from the gold and working standards were recorded for

60s; 15s into the data set, compressed air (Quill Office Duster) was blown into the input port of the gold standard. This process was repeated at 45s. The results are shown in Figure 6.

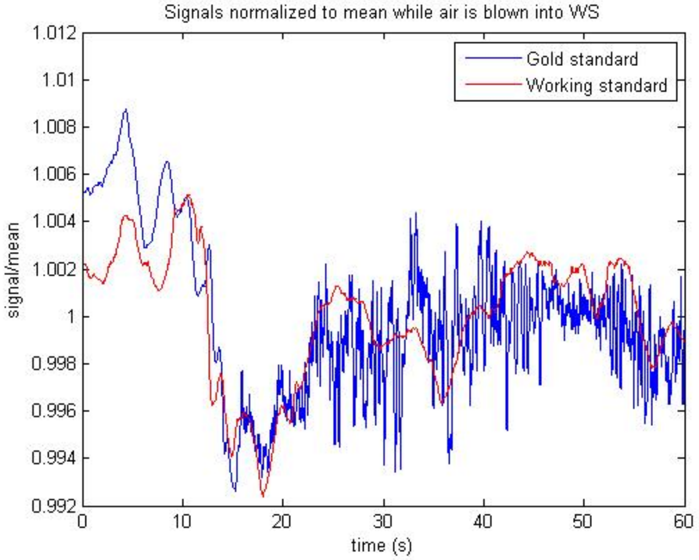

Figure 6: Signals normalized to means for gold and working standards during test where office duster was blown into input port of gold standard for 5s at times 15s and 45s into data set

The frequency of the variations in the gold standard increases dramatically at about 15s, while the working standard variations remain stable throughout the time series. This indicates that manipulating the air currents affects the frequency of the variations, supporting the theory that the variations are caused by laser speckle.

To find the error due to laser speckle, an hour-long time series of the ratio between the working and gold standard signals was recorded and divided into minute-long samples. The mean of each of these segments was taken, and the standard deviation of these means was calculated to be 0.15%. This is a representation of the variation between ratios due to laser speckle alone; no other environmental variations were introduced. Using the process described in section 5.5, the expected variation due to laser speckle among working standard calibrations is 0.11%. However, the observed standard deviation was 0.21%. This indicates a 0.18% error from other systematic sources.

2.4 Other Systematic Errors

A possible source of systematic errors was variations in the controlled temperature of the integrating-sphere photodetectors. To test this, the signals at different temperature-controller settings were recorded. The results of this test are shown in Figure 7.

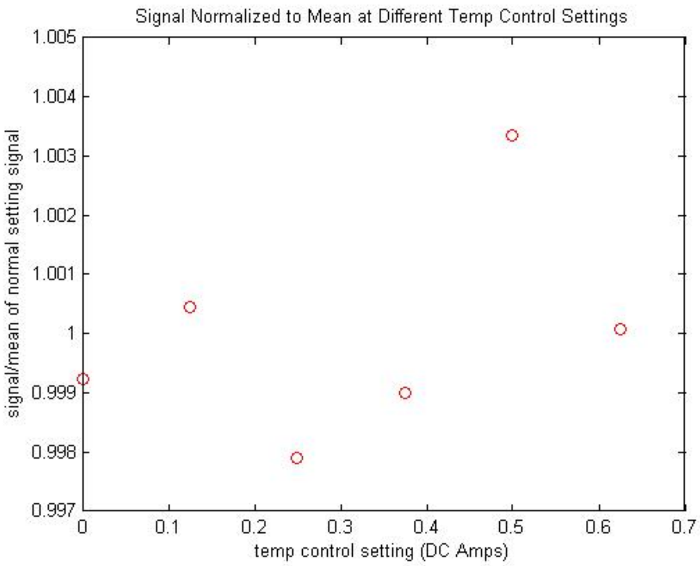

Figure 7: Signals normalized to mean depending on temperature controller setting

The maximum variation from the mean is about 0.3%. The standard deviation of these signal values is 0.19%. The variations do not appear to be related to the temperature-controller setting by a specific function.

Another possible source of systematic errors was beam placement in the input port of the integrating spheres. To determine the magnitude of this error, the signal from the working standard integrating sphere was recorded at different beam distances from the estimated center of the port. The signal remained close to the mean until the beam started clipping the edge of the port. The results are shown in Figure 8.

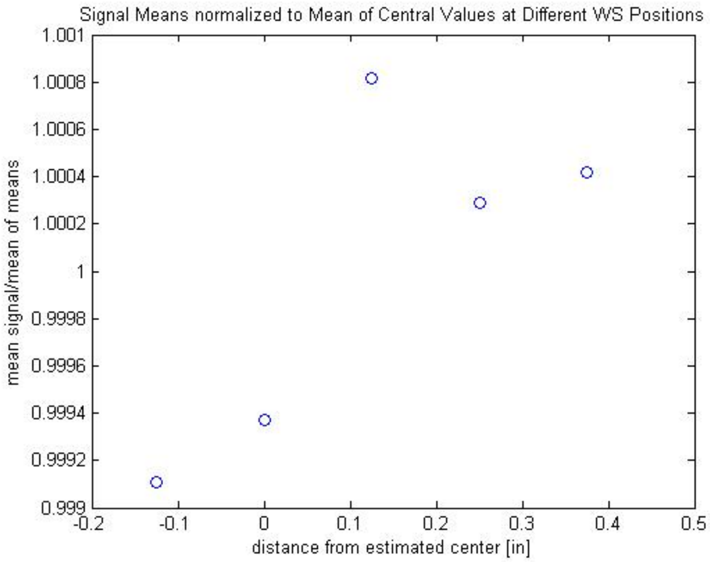

Figure 8: Signal normalized to mean as a function of distance from estimated center when beam is not clipping port edge

The signals vary less than 0.1% from the mean, and the standard deviation is 0.073%.

Angular variations were also examined. To quantify this effect, the gold standard integrating sphere was rotated, and signals were recorded at various angles of incidence.

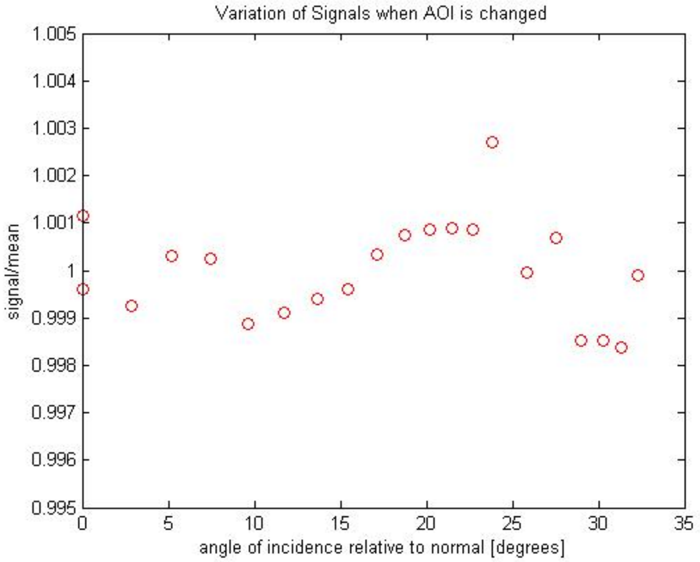

Figure 9: Signal normalized to mean depending on angle of incidence

These signals are shown in Figure 9. The maximum variation is about 0.3% from the mean. The standard deviation of the signals is 0.11%.

These values can be combined to determine the maximum expected systematic error. When added in quadrature, the resulting 1σ error is 0.23%. This is the maximum error possible from these sources; these components were varied to extreme values not expected during working standard calibrations. In fact, this value is greater than the determined value of 0.18% from unknown systematic sources.

3 OVERALL ERROR

3.1 Working Standard Calibration Error

To determine the error for absolute calibration, the error in a working standard calibration must be calculated. This involves two parts: the uncertainty in the NIST gold standard calibration, and the error introduced during the working standard calibration process. The gold standard calibration error is 0.88% (2σ) [3]. The error introduced by the calibration process is the standard deviation of the working standard calibration values: 0.21% (1σ). These values are combined using the process described in section 5.5; the overall error in a working standard calibration coefficient is 0.49% (1σ).

3.2 Photon Calibrator Photodetector Calibration Error

In a previous measurement, the standard deviation of one-minute samples of the ratio between the working standard signal and the signal from a photon calibrator photodetector was determined to be 0.22% [5]. The experimental setup was not changed between these one-minute samples; the variations in these measurements are due to laser speckle. Among the working standard calibration coefficients the actual standard deviation was higher than the expected value due to speckle; a systematic effect of 0.18% was observed. If the same effect is assumed in photon calibrator calibrations, the overall error for these calibrations is 0.56%. As a 2σ value, which corresponds to a 95.4% [6] confidence interval, the error is 1.12%.

4 CONCLUSIONS AND SUGGESTIONS

4.1 Conclusions

The statistical uncertainty in transferring the gold standard calibration to the working standard was determined; in combination with the uncertainty in the gold standard absolute power calibration provided by NIST, this gives an overall uncertainty in the working standard calibration coefficient of 0.49% (1σ).

Investigations into the sources of error have shown that laser speckle accounts for approximately 0.11% (1σ) of the error stated above; the remaining 0.18% (1σ) results from other systematic sources such as beam position, orientation, and detector temperature variations.

The overall uncertainty in the photon calibrator photodetector calibration coefficient is estimated to be 0.56% (1σ). This gives a 95% confidence interval (2σ) of ±1.12%.

4.2 Suggestions

The accuracy of the expected error in the photon calibrator calibration should be evaluated by performing several calibrations. The working standard calibration procedure should also be evaluated; its accuracy was investigated through multiple calibrations, but many were performed before a set procedure was developed. Although values involving systematic errors were excluded to better estimate the error for this calibration process, more calibrations should be performed to ensure the accuracy of this error value.

5 METHODS

5.1 Photon Calibrator Box

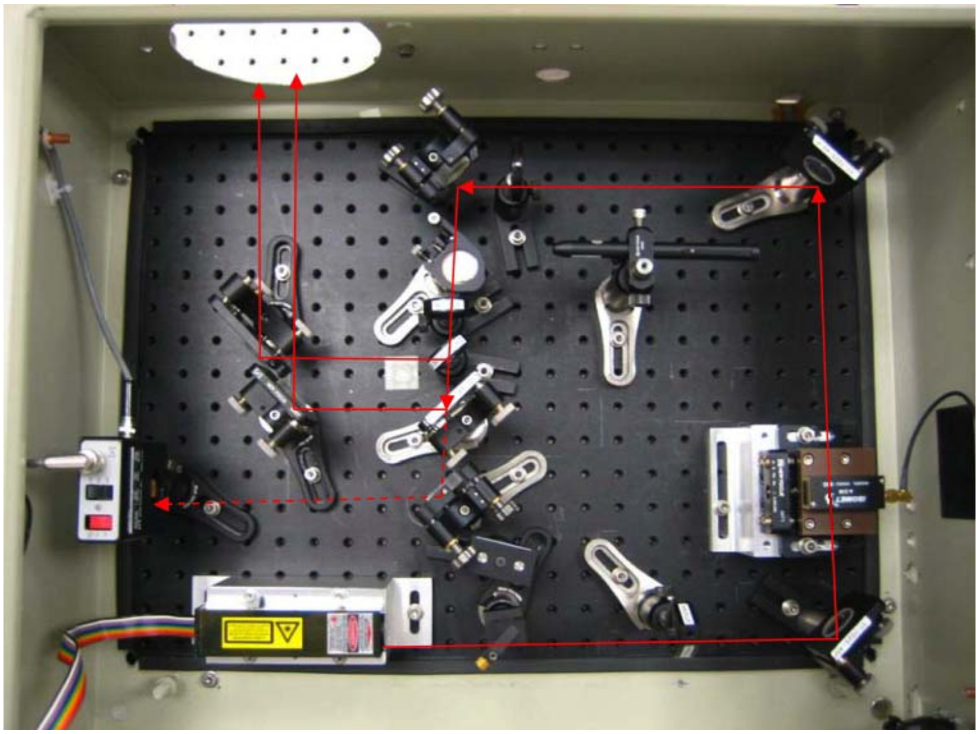

Figure 10: Photon calibrator box optical layout [7]

The optical layout of the photon calibrators is shown in Figure 10. A 1047nm, CrystaLaser, Model #IRCL-500-1047, Nd:YAG is first directed through a polarizing beamsplitter cube, thus ensuring that the light is P-polarized. The beam is then focused onto an acousto-optic modulator, which modulates the power of the beam. The beam is then focused using a spherical lens and directed onto a 50% beamsplitter. This beamsplitter divides the light into two calibration beams to control yaw motion of the test mass. A small portion of one beam is sampled and directed onto a New Focus, Model 2033, Large-Area IR Photoreceiver. The sampled light is utilized to determine the power of each beam. This figure also shows a flipper mirror and a laser pointer that provide a method of visual alignment.

5.2 Working Standard Calibration Setup

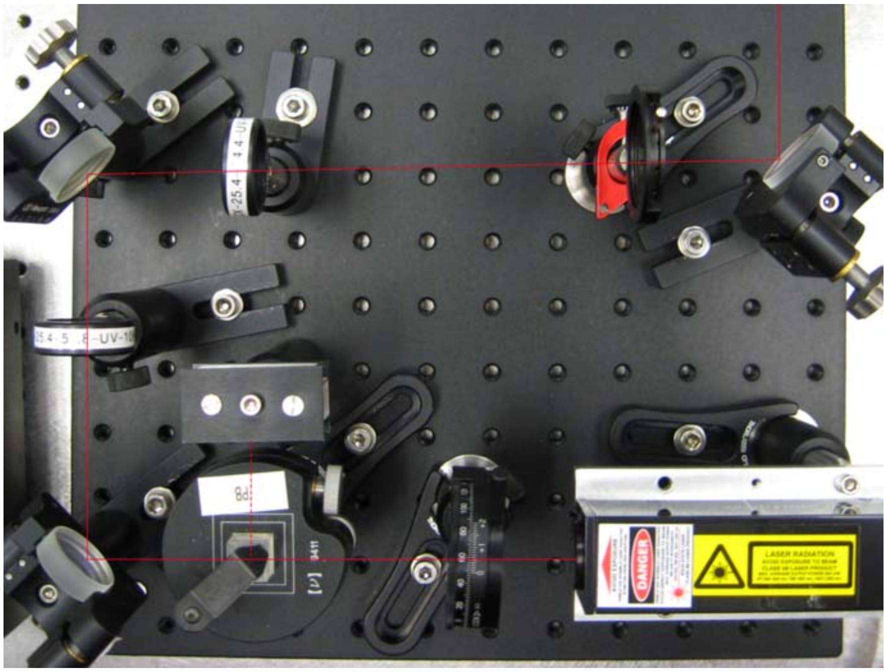

Figure 11: Laser breadboard for working standard calibration setup

Figure 11 shows the laser breadboard for the working standard calibration setup. Light from a 1047nm, CrystaLaser, Model #IRCL-500-1047, Nd:YAG laser passes through a zero-order half-wave plate and a polarizing beamsplitter cube, allowing for power output control. As the half-wave plate is adjusted, the direction of linear polarization is rotated; since only the P-polarized component of the light is transmitted, the power is changed by the rotation. The beam is then directed through two lenses; these adjust the spot size of the beam. From here, the beam passes into the larger working standard calibration setup, which is shown in Figure 1. In this setup, the beam passes through a beamsplitter, which divides the light between the two integrating spheres. The gold standard integrating sphere is shown in Figure 12.

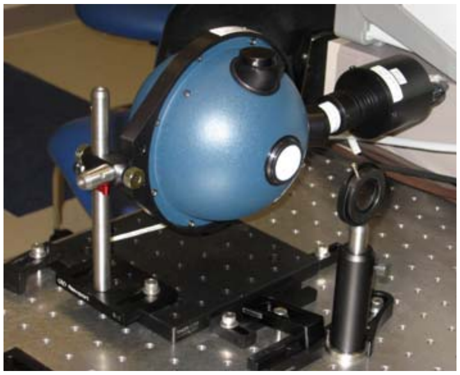

Figure 12: Gold standard integrating sphere with temperature-controlled InGaAs photodetector mounted on output port at side

Light enters each integrating sphere through an input port on the front. Spectralon, which coats the interior of the sphere, diffuses the beam. This diffuse light is then sampled by a temperature-controlled InGaAs photodetector, which produces a current output. This current is amplified by a Keithley Instruments, Model 428, Current Amplifier, which is set to a gain of 10^6 V/A during working standard calibrations. A Keithley Instruments, Model 2100, Digital Multimeter reads the voltage output from the amplifier; the data are then sent to a computer to be recorded. The gold standard amplifier and digital multimeter are shown in Figure 13, along with the Electro-Optical Systems, Inc, PS/TC-1 Temperature Controller, which regulates the temperature of the integrating sphere's photodetector.

Figure 13: Gold standard current amplifier, digital multimeter, and photodetector temperature controller

5.3 Working Standard Calibration Theory

The outputs of the integrating-sphere setups are voltages read by a Keithley, Model 2100, Digital Multimeter. These voltages can be expressed as the product of the power of the laser, P, the fraction of light reflected or transmitted, R or T, and the calibration coefficient of the integrating sphere, C_g or C_W; if the gold standard is in the reflected-light position, and the working standard receives transmitted light, the voltages, V_g and V_w, are as follows:

$$V_g = PRC_g$$

$$V_w = PTC_w.$$

By taking the ratio of the two signals, the power of the laser is eliminated. The calibration coefficient of the gold standard is known, so only the effect of the beamsplitter must be eliminated. To do this, the positions of the integrating spheres are swapped, and voltages are record. These are described as follows:

$$V_g' = P'TC_g$$

$$V_w' = P'RC_w.$$

The ratio of the two signals is then taken; this ratio is combined with the first to eliminate the effect of the beamsplitter and to determine the working standard calibration coefficient. The final product is the following equation:

$$C_w = C_g\sqrt{\frac{V_w V_w'}{V_g V_g'}} = C_g\sqrt{r_1 r_2} \qquad (1).$$

$$\text{where } r_1 = \frac{V_w}{V_g} \text{ and } r_2 = \frac{V_w'}{V_g'}$$

The ratios can be manipulated differently to isolate the ratio between the amount of reflected and transmitted light. This equation is as follows:

$$\frac{R}{T} = \sqrt{\frac{V_g V_w'}{V_w V_g'}} = \sqrt{\frac{r_2}{r_1}}.$$

The voltage signals are recorded every 25ms for about 60s, thus, time series are produced. Since the two signals are taken roughly simultaneously, it is possible to find the ratio between the two signals at each point in time. This produces a time series for the ratio, eliminating laser power. The mean of this ratio is then taken; this process is repeated to find the second ratio. These ratios are then manipulated to calculate the working standard calibration coefficient using the equation above.

5.4 Motivations Behind Excluding Certain Calibrations

Certain calibrations had to be excluded from the statistical analysis due to systematic errors. The included and excluded values are shown in Figure 2. Calibrations #8 and #10 were performed during a test to determine the effect of varying the laser power during calibration. As the power approached zero, the ratio between the signals increased dramatically; this significantly affected the values of the calibration coefficients. Calibrations #19-21 vary about 1-2.5% from the mean. Although no specific systematic errors have been identified, systematic errors are suspected. These three calibrations were performed on the same day, and the variations are likely related to swapping cables or powering off various components. Calibrations #28-32 occurred after the working standard had been transported to an end station. Later, it was discovered that the photodetector attachment to the integrating sphere had loosened. After the connection was tightened, calibrations #33-35 were executed, and the values derived from these were much closer to the mean. Before calibration #36, the working standard was transported to the LIGO Livingston Observatory (LLO) in Louisiana. After many investigations into the cause of the 4% change in the calibration coefficient after this trip, it was finally discovered that the seal of the photodetector container was broken. A picture of this photodetector can, containing both the photodetector and the thermoelectric cooler assemblies, is shown in Figure 14.

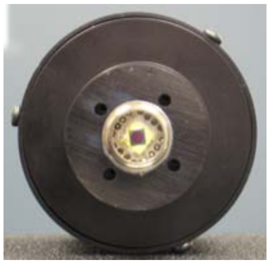

Figure 14: Vacuum can containing photodetector and thermoelectric cooler assemblies

5.5 Overall Error Analysis

When a value depends on several parameters according to a predictable function, the function and the error in the parameters can be used to predict the error of the dependent value. If the value is described by a function, f, the parameters are x_i, and the errors in each are σ_f and σ_i respectively, then the error in the value is as follows:

$$\sigma_f = \sqrt{\sum\left[\left(\frac{\partial f}{\partial x_i}\sigma_i\right)^2\right]} \quad [6] \qquad (2).$$

The calibration coefficient for the working standard is given by Equation 1, as expressed in section 5.3. The uncertainties in the ratios, r_1 and r_2, are given by the standard deviation of the group of means found as 60s samples from an hour-long time series, as described in section 2.3. The standard deviation of these means is 0.15%. When the function for the working standard calibration coefficient, given by Equation 1, is plugged into Equation 2, the following expression is produced:

$$\sigma_{C_w} = \sqrt{\left(\sqrt{r_1 r_2}\cdot\sigma_{C_g}\right)^2 + \left(\frac{C_g\sqrt{r_2}}{2\sqrt{r_1}}\sigma_1\right)^2 + \left(\frac{C_g\sqrt{r_1}}{2\sqrt{r_2}}\sigma_2\right)^2} \qquad (3).$$

To get the percent uncertainty, Equation 3 is divided by Equation 1. This gives the following equation, expressed in terms of percent uncertainties:

$$\sigma_{\%,C_w} = \sqrt{\left(\sigma_{\%,C_g}\right)^2 + \left(\frac{\sigma_{\%,1}}{2}\right)^2 + \left(\frac{\sigma_{\%,2}}{2}\right)^2} \qquad (4).$$

This error is composed of two parts: the first term is the uncertainty in the gold standard calibration by NIST, and the last two terms are the error due to laser speckle. Initially, only the expected error due to laser speckle will be evaluated; the uncertainty in the gold standard calibration coefficient will be neglected. It will also be assumed that the percent uncertainty for both ratios will equal 0.15%. This gives the following simplified expression for the error due to laser speckle:

$$\sigma_{\%,C_w} = \frac{\sqrt{2}}{2} \cdot \sigma_{\%,r} \qquad (5).$$

Using this equation, the expected standard deviation due to laser speckle is calculated to be 0.11%.

However, the observed standard deviation in the working standard calibration coefficient is 0.21%. This means that some unknown systematic effect must be present. This effect should add in quadrature to the error due to laser speckle to give the overall systematic error; this is described by the following equation:

$$\sigma_{\text{systematic}}{}^2 = \sigma_{\text{speckle}}{}^2 + \sigma_{\text{unknown}}{}^2 \qquad (6).$$

From this expression, the magnitude of the error due to the unknown effect is 0.18%

Since it has been determined that laser speckle is not the only systematic effect present in the working standard calibration process, it would not be accurate to use only the error due to laser speckle in determining the overall error in the working standard calibration coefficient. Instead, the observed standard deviation of these values is used, along with the uncertainty in the gold standard calibration coefficient, given by NIST. This value is 0.88% (2σ) [3]. To perform these operations, the function describing the working standard calibration coefficient is first viewed in the following manner:

$$C_w = C_g R,$$

where the uncertainty in R is the standard deviation in the values obtained through multiple working standard calibrations. This gives the following equation for combining the percent error:

$$\sigma_{\%,C_w} = \sqrt{\left(\sigma_{\%,C_g}\right)^2 + \left(\sigma_{\%,R}\right)^2} \qquad (7).$$

Using this equation, the overall error in the working standard calibration coefficient is calculated to be 0.49%.

Next, the error involved in the photon calibrator photodetector calibration must be determined. First, the expected standard deviation among the values obtained by a photon calibrator calibration will need to be predicted. The ratio between the photodetector and the working standard signals was collected and divided into minute-long intervals. The mean was taken for each of these samples, and the standard deviation of the group of samples was calculated. This standard deviation was calculated to be 0.22% [5]. Since the instruments were not moved between samples, it should be expected that the actual standard deviation between the photon calibrator calibrations will be larger than this value. If it is assumed that the same percentage of unknown systematic effects is present in this stage of the process as was present during working standard calibrations, then the value 0.18% should be added in quadrature to this value. This will give the expected standard deviation between photon calibrator calibrations if it is assumed that the working standard calibration does not vary. If the variation in the working standard calibration coefficient is also taken into account by adding the standard deviation for these measurements in quadrature with the other variation values, the expected standard deviation between photon calibrator calibrations is 0.35%.

To find the overall error of the photon calibrator photodetector calibration, the error in the working standard calibration coefficient must also be considered. These two values are combined in quadrature, resulting in an overall expected error of 0.56%.

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8 APPENDICES

8.1 Working Standard Calibration Procedure

1) Turn on Laser (make sure shuttered)
2) Put working standard (WS) together: put rod on breadboard, put sphere on rod
3) Place gold standard (GS) in reflection position and WS in transmission

4) Make sure that no part of the photodetectors are wobbly, if they are, tighten the screws; the spacer may need to be removed for this (there are screws inside)
5) Plug Temperature Controller, Amplifier (amp), and Digital Multimeter (DMM) into power
6) Attach WS photodetector to Temperature Controller using grey cable
7) Turn on Temp Control: Switch Temperature Controller on, wait 5 minutes and make sure that the meter on the front panel reads 0.625 DC Amps
8) Connect the photodetector to the amp and the amp to the DMM using BNC cables; the connector between the amp and DMM should be plugged into the back of the DMM in the spot that says 1000 V max
9) Turn on both the amp and DMM
10) Set the amp to 1E6, set the filter to 100ms (using the filter button on the "Setup" side and the dial) and turn it on (using the filter button on the "Enable" side, the light should turn on); turn zero check off (the light will turn off) and press shift, then zero check to perform a zero correct, then press zero check again so that the light turns on
11) Make sure the word "REAR" appears on the display panel of the DMM, if not, toggle the circular button on the right front panel
12) Connect computer to both DMMs using USB cables
13) Open 2100 KI Tool
14) Change Device Settings: Setting-Setting Mode… Select "Multiple Devices", then check "Save" and Select "Record 1"; Press the >> button and check "Save" and Select "Record 2"; press "OK". This causes the GS data to be saved to Record 1 and the WS data to be saved to Record 2.
15) Set Range to 10VDC: Press the button to the right of the triangle and square buttons, it has a picture of the front of a DMM on it; Select "MODEL 2100-USBTMC-1148559::I", Select Function "DC Voltage", Select Range "10 Vdc", Leave Resolution as is, and press Submit, then Select "MODEL 2100-USBTMC-1148750::I" and repeat, then press "Exit"; check to see that both "DMMs say 10 VDC" on the front displays (if they don't repeat this process)
16) Check to see that records are clear: Record-View Record… If there are any records, select them and press "Delete Record" and then "Yes", then press "Exit"
17) Check to see that the Reading Speed is 25 ms in main window. If it is not change it to 25 ms (using a slower reading speed will probably not affect the results of the calibration)
18) Make sure all irises are completely open
19) Make sure half-wave plate is rotated so that the 0 lines up with 50 and the handle roughly lines up with +2 (this ensures that the power is the same for each calibration, making comparisons for different types of analysis easier)
20) Check to see that temp controller reads 0.625 DC Amps, if it reads something else, adjust the dial and wait 5 min
21) Undo zero check on both amps (press zero check until light is off)
22) Perform zero correct on both amps
23) Remove covers of both integrating spheres
24) Unshutter Laser
25) Check to see that the beam is centered in both integrating sphere input ports using a card
26) Take 60s of data: open computer clock to keep time, press button with blue triangle to start, press button with blue square to stop
27) Save data: Record-View Record… Select "Record 1", press "Output to CSV", create folder that all data from this calibration will be stored in, save Record 1 in this folder as "GSRefl",

press “Save” and then “OK”; Make sure “Record 1” is still selected and press “Delete Record” then press “Yes”; Do the same for Record 2, but name it “WSTran”

28) Shutter the Laser
29) Take 60s of data
30) Save Record 1 as “GSRbg” and Record 2 as “WSTbg”
31) Swap the positions of the two integrating spheres
32) Unshutter the Laser
33) Check to see that beams are centered
34) Take 60s of data
35) Save Record 1 as “GSTran” and Record 2 as “WSRefl”
36) Shutter the Laser
37) Take 60s of data
38) Save Record 1 as “GSTbg” and Record 2 as “WSRbg”
39) Turn on zero check on both amps
40) Cover both integrating spheres
41) Open MATLAB
42) Save WScal.m, prop.m, and readData.m to the folder where the data was saved
43) Make sure the folder where the data was saved is open in the MATLAB “Current Folder” area
44) Run WScal.m
45) Will output WScal and R/T by Mean, Proportional, and Linear Method, will also output resnorm and standard deviations for each ratio for prop and lin methods, will also generate several plots