Characterization of O4 Pcal power sensors

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May 6, 2022

Overview

This slide stack, documents the math formalism, measurement and analysis methods. and experimental results that characterize the Pcal power standards that were updated in anticipation of LIGO's fourth oberving run, O4.
Detector spacers were added to the power standards to reduce the temperature dependence of the responsivity by limiting the field of view of the sensor. The transimpedance amplifier circuits were also updated to incorporate AD590 temperature sensors soldered in place and to adjust the overall gain to compensate for the attenuation of the detector spacers.
Measurements of the temperature dependence of both the dark voltages and the responsivity were realized by insulating one of the sensors and heating in an oven to about 15 K above the ambient laboratory temperature. Responsivity ratio measurements made in the standard fashion as the heated device cooled where then used to estimate the temperature-dependent dark voltage and the temperature dependent-responsivity ratios.

Key steps in the sensor characterization

1. Reference all measured parameters to device-specific AD590 temperatures: $T' = 300.15\,\mathrm{K}$ (27 °C)
2. Measure temperature dependence of dark voltages: $V_{dark} = V'_{dark} + m_{dark}(T - T')$
3. Measure temperature dependent responsivity ratios. Then:
   * subtract temperature-dependent dark voltages
   * divide denominator voltages by $[1 + \kappa_{dev2}(T_2 - T')]$
   * plot and fit: $\rho_{dev1}/\rho'_{dev2} = m\,(T_1 - T') + b$, where $b = \rho'_{dev1}/\rho'_{dev2}$
   * fit gives $\alpha'_{dev1,dev2} = \rho'_{dev1}/\rho'_{dev2}$ and $\kappa_{dev1} = m\,/\alpha'_{dev1,dev2}$
4. Correct voltages in normal (not heated) responsivity ratio measurements to obtain estimates of $\alpha'_{1,2} = \rho'_{dev1}/\rho'_{dev2}$
5. Use temperature-corrected primary measurements from NIST and/or PTB (ρ'_{dev2}) and temperature-corrected responsivity ratio measurements to estimate $\rho_{dev1}(T_1)$:

$$\rho_{dev1}(T_1) = \alpha'_{dev1,dev2} \times \rho'_{dev2} = \rho'_{dev1}[1 + \kappa_{dev1}(T_1 - T')]$$

Temperature-dependent dark voltages - Data

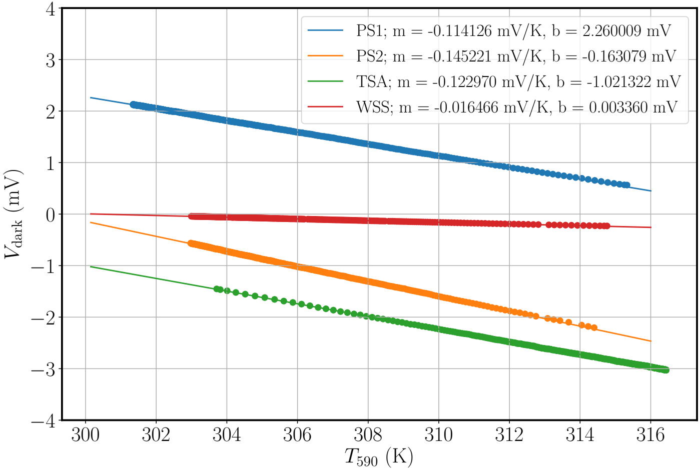
Path in SVN: /ligo/svncommon/CalSVN/aligocalibration/trunk/Projects/PhotonCalibrator/measurements/LabData/...

Device	Data directory
PS1	.../PS1_PS2/i2022-03-29T164919
PS2	.../PS2_PS1/i2022-03-25T104152
PS3	.../TSA_TSB/i2021-10-13T155703
WSS	.../WSS_PS2/i2022-04-01T165457

Table: Data directories for temperature dependence of dark voltage measurements

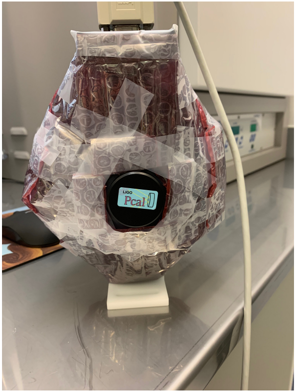
Temperature-dependent dark voltages - Results

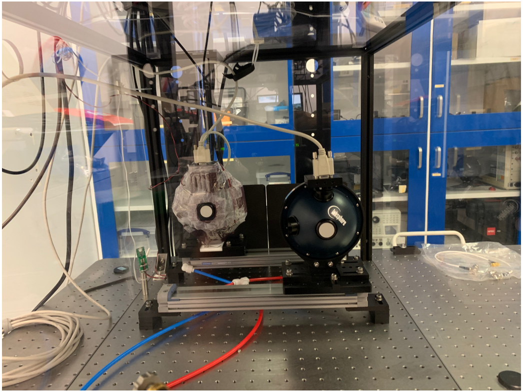
$$V_{dark}(mV) = m_{dark}\left(T_{590} - T'\right) + b_{dark}$$



Temperature-dependent responsivity ratio measurements - Setup

The relative responsivity temperature coefficients, κ, are determined by insulating, then heating, one sphere in an oven before performing responsivity ratio measurements while it cools.





Temperature-dependent responsivity ratios - Data

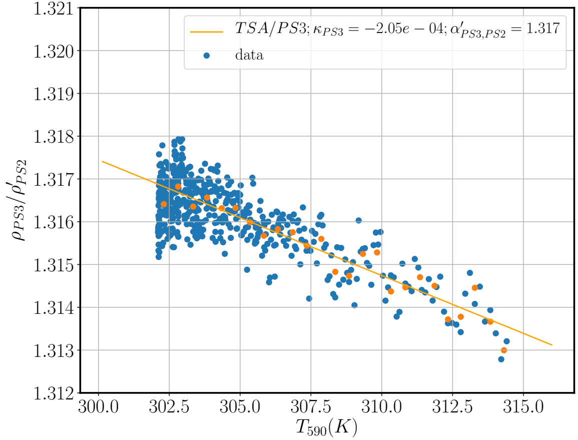
Path in SVN: /ligo/svncommon/CalSVN/aligocalibration/trunk/Projects/PhotonCalibrator/measurements/LabData/...

Ratio	Data directory
PS3/PS2	.../PS3_PS2/i2022-04-27T093520
PS2/PS3	.../PS2_PS3/i2022-03-22T083532
PS1/PS3	.../PS1_PS3/i2022-03-17T083753
PS1/PS3	.../PS1_PS3/i2022-03-18T102237
PS2/PS1	.../PS2_PS1/i2022-03-23T102428
WSS/PS2	.../WSS_PS2/i2022-04-01T094944

Table: Data directories for temperature dependence of responsivity ratios measurements

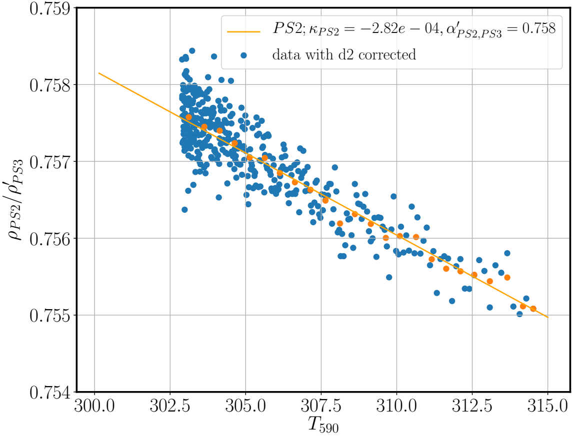
Temperature-dependent responsivity ratio - PS3/PS2

First estimate, without compensating for PS2 responsivity temperature dependence.



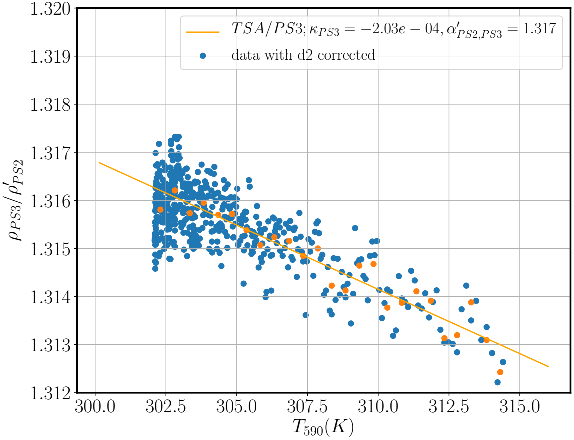
Temperature-dependent responsivity ratio - PS2/PS3

First estimate, using first estimate of PS3 temperature dependence



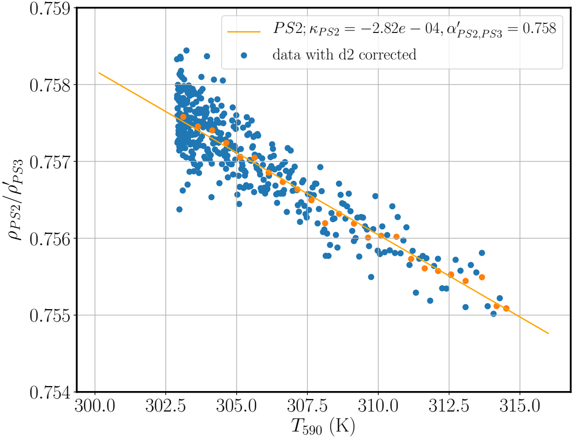
Temperature-dependent responsivity ratio - PS3/PS2

Second estimate, using first estimate of PS2 responsivity temperature dependence.



Temperature-dependent responsivity ratio - PS2/PS3

Second estimate, using second estimate of PS3 temperature dependence



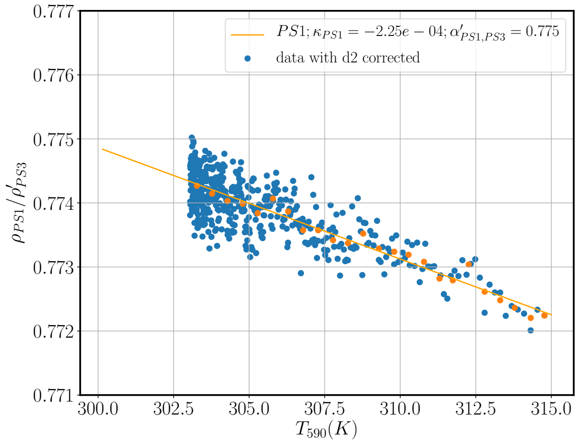
Iteration to determine κ values for PS2 and PS3

Analysis steps listed in order performed. First iteration with no temperature compensation for device 2.

Ratio	κ (hop/K)	α'	$1/\alpha'$
PS3/PS2	$\kappa_{PS3} = -2.05$	$\alpha'_{PS3,PS2} = 1.317$	$1/\alpha'_{PS3,PS2} = 0.759$
PS2/PS3	$\kappa_{PS2} = -2.82$	$\alpha'_{PS2,PS3} = 0.758$	$1/\alpha'_{PS2,PS3} = 1.319$
PS3/PS2	$\kappa_{PS3} = -2.03$	$\alpha'_{PS3,PS2} = 1.317$	$1/\alpha'_{PS1,PS3} = 0.759$
PS2/PS3	$\kappa_{PS2} = -2.82$	$\alpha'_{PS2,PS3} = 0.758$	$1/\alpha'_{PS2,PS3} = 1.319$

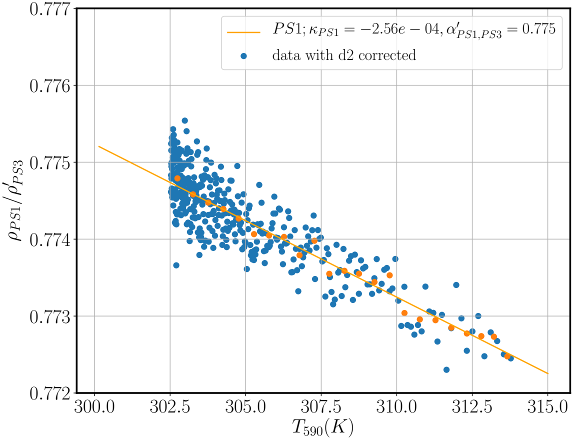
Temperature-dependent responsivity ratio - PS1/PS3

First of two measurements

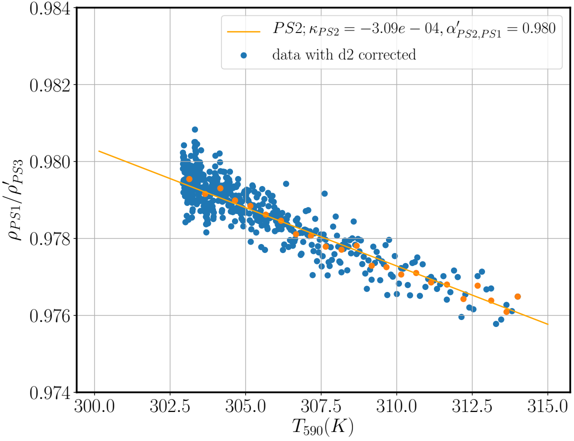


Temperature-dependent responsivity ratio - PS1/PS3

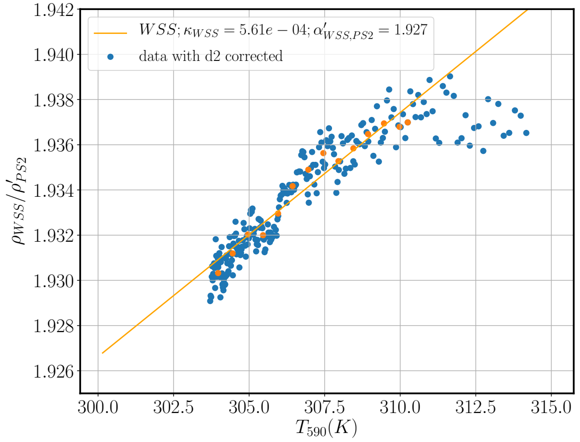
Second of two measurements



Temperature-dependent responsivity ratio - PS2/PS1



Temperature-dependent responsivity ratio - WSS/PS2



Summary of temperature-dependent responsivity ratio results

Ratio	κ (hop/K)	$\alpha^{'}$	$1/\alpha^{'}$
PS3/PS2	$\kappa_{PS3} = -2.03$	$\alpha^{'}_{PS3,PS2} = 1.317$	$1/\alpha^{'}_{PS3,PS2} = 0.7593$
PS2/PS3	$\kappa_{PS2} = -2.82$	$\alpha^{'}_{PS2,PS3} = 0.758$	$1/\alpha^{'}_{PS2,PS3} = 1.319$
PS1/PS3	$\kappa_{PS1} = -2.25$	$\alpha^{'}_{PS1,PS3} = 0.775$	$1/\alpha^{'}_{PS1,PS3} = 1.290$
PS1/PS3	$\kappa_{PS1} = -2.56$	$\alpha^{'}_{PS1,PS3} = .775$	$1/\alpha^{'}_{PS1,PS3} = 1.290$
PS2/PS1	$\kappa_{PS2} = -3.09$	$\alpha^{'}_{PS2,PS1} = 0.980$	$1/\alpha^{'}_{PS2,PS1} = 1.020$
WSS/PS2	$\kappa_{WSS} = +5.61$	$\alpha^{'}_{WSS,PS2} = 1.930$	$1/\alpha^{'}_{WSS,PS2} = 0.518$

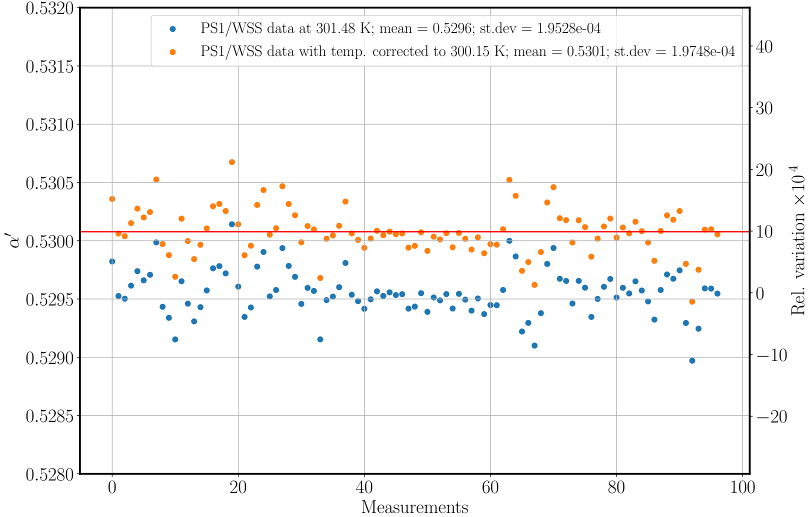
Responsivity ratio measurements - Data

Path in SVN: /ligo/svncommon/CalSVN/aligocalibration/trunk/Projects/PhotonCalibrator/measurements/LabData/...

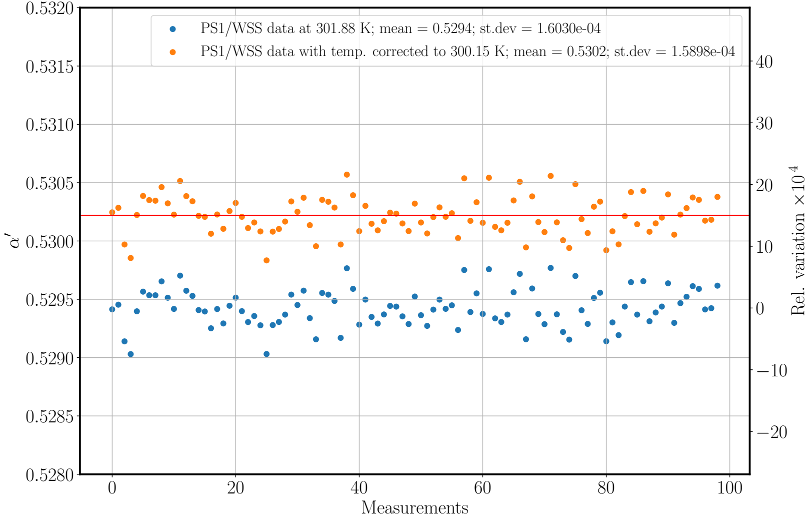
Ratio	**Data directory**
PS1/PS3	.../PS1_PS3/t2022-03-15T121600
PS1/WSS	.../PS2_WSS/t2022-04-07T091947
PS1/WSS	.../PS1_WSS/t2022-04-12T121905
PS1/WSS	.../PS1_WSS/t2022-04-14T085422
PS2/PS3	.../PS2_PS3/t2022-03-16T125012
PS2/WSS	.../PS2_WSS/t2022-04-07T131950
PS2/WSS	.../PS2_WSS/t2022-04-12T145800
PS3/WSS	.../PS3_WSS/t2022-02-17T095321
PS3/WSS	.../PS3_WSS/t2022-02-22T103612

Table: Data directories for responsivity ratio measurements

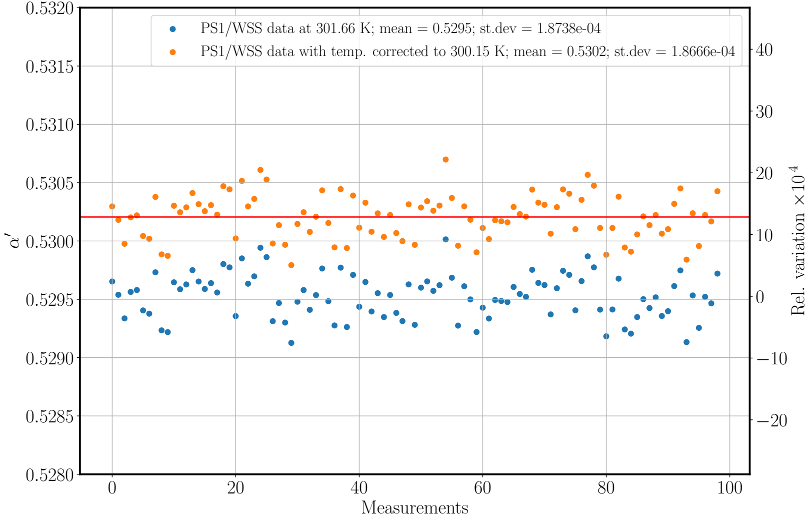
PS1/WSS responsivity ratio t2022-04-07T091947



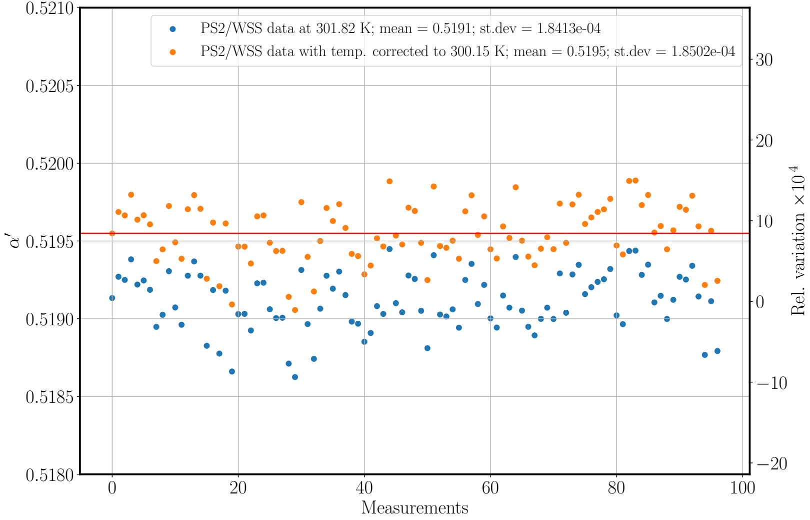
PS1/WSS responsivity ratio t2022-04-12T121905



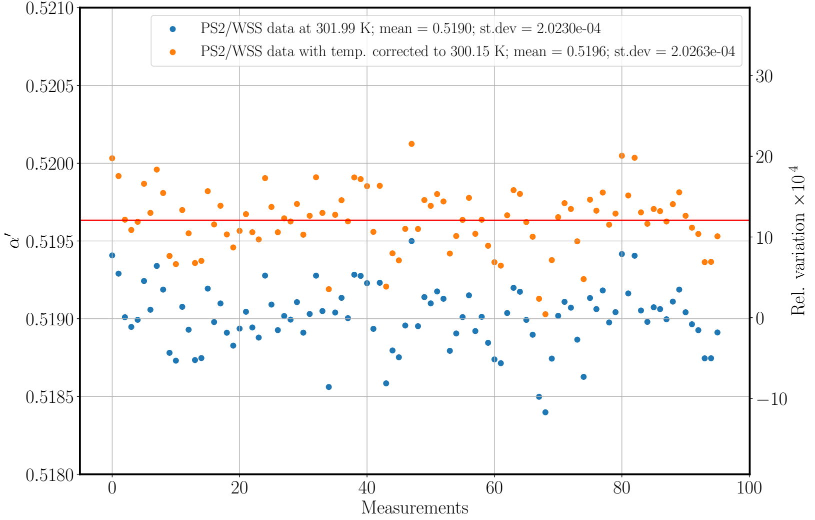
PS1/WSS responsivity ratio t2022-04-14T085422



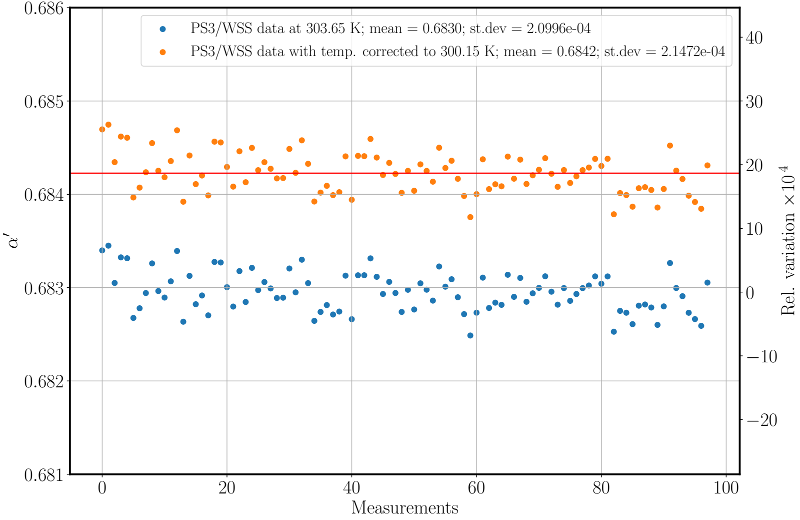
PS2/WSS responsivity ratio t2022-04-07T131950



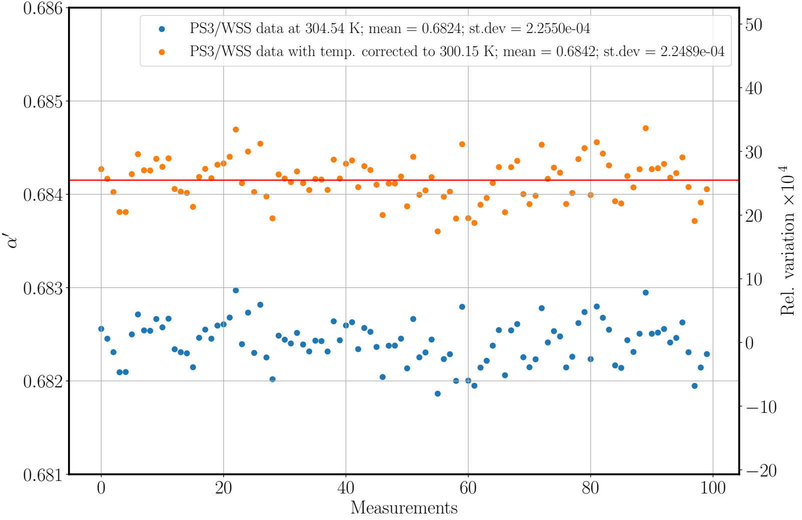
PS2/WSS responsivity ratio t2022-04-12T145800



PS3/WSS responsivity ratio t2022-02-17T095321



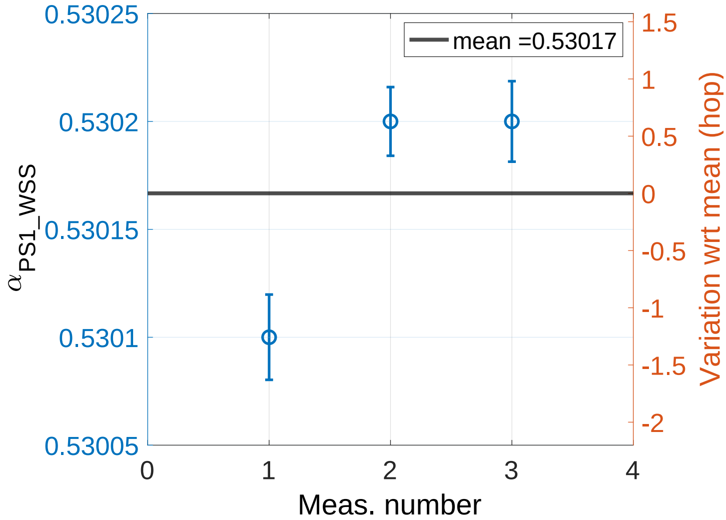
PS3/WSS responsivity ratio t2022-02-22T103612



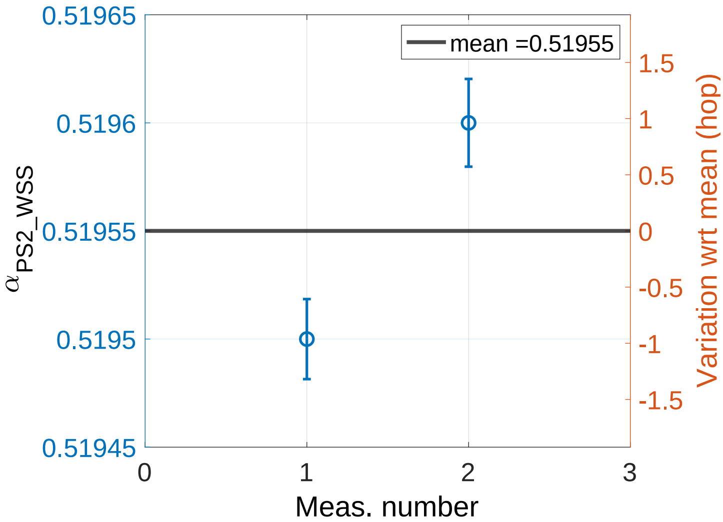
Summary of standard responsivity ratio measurement results

Ratio	Directory	α'	std. dev.
PS1/WSS	t2022-04-07T091947	$\alpha'_{PS1,WSS} = 0.5301$	1.9748e-4
PS1/WSS	t2022-04-12T121905	$\alpha'_{PS1,WSS} = 0.5302$	1.5898e-4
PS1/WSS	t2022-04-14T085422	$\alpha'_{PS1,WSS} = 0.5302$	1.8666e-4
PS2/WSS	t2022-04-07T131950	$\alpha'_{PS2,WSS} = 0.5195$	1.8502e-4
PS2/WSS	t2022-04-12T145800	$\alpha'_{PS2,WSS} = 0.5196$	2.0263e-4
PS3/WSS	t2022-02-17T095321	$\alpha'_{PS3,WSS} = 0.6842$	1.1472e-4
PS3/WSS	t2022-02-22T103612	$\alpha'_{PS3,WSS} = 0.6842$	2.2489e-4

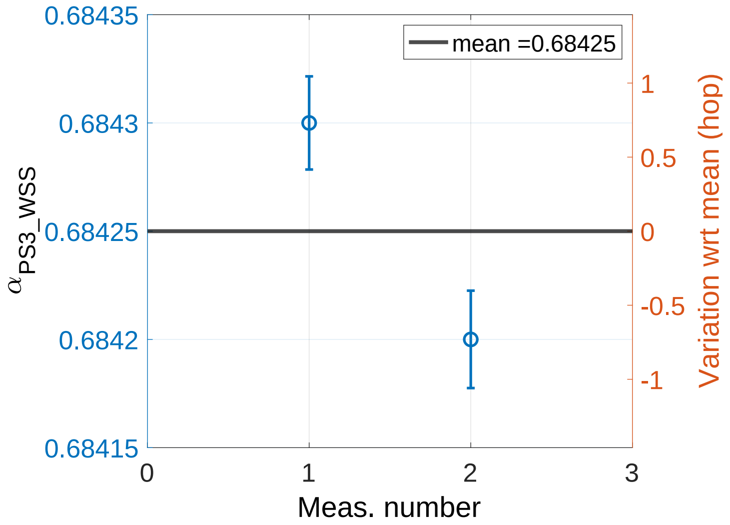
Trend of $\alpha'_{PS1/WSS}$ results.



Trend of $\alpha'_{PS2/WSS}$ results.



Trend of $\alpha'_{PS3/WSS}$ results.



Calculation of power sensor responsivities based on ρ'_{WSS}

date/timestamp	rho_WS	alpha1/WSS	alpha1/WSSstd	rhoPS1	rhoPS1std	alpha2/WSS	alpha2/WSSstd	rhoPS2	rhoPS2std	alpha3/WSS	alpha3/WSSstd	rhoPS3	rhoPS3std
20210913	8.189												
t2022-04-07T091947		0.5301	1.9748E-04	4.3410	1.6172E-03								
t2022-04-12T121905		0.5302	1.5898E-04	4.3418	1.3019E-03								
t2022-04-14T085422		0.5302	1.8666E-04	4.3418	1.5286E-03								
t2022-04-07T131950						0.5195	1.85E-04	0.27538695	9.81E-05				
t2022-04-12T145800						0.5196	2.03E-04	0.27543996	1.07E-04				
t2022-02-17T095321										0.6843	1.15E-04	0.36274743	6.08E-05
t2022-02-22T103612										0.6842	2.25E-04	0.36269442	1.19E-04

Proposed method (mostly based on discussions between Francisco and Rick)

Richard Savage <rsavage@caltech.edu>
Characterization of Pcal O4 power sensors
To: Dripta Bhattacharjee <bhattacharjee1@kenyon.edu>

Sent - Exchange 1:33 PM

1. Temperature dependent dark voltages
    a. Average Vi_trans and Vi_refl values for each measurement
    b. Fit line to V1 vs (Ti-300.15)
    c. Output: Vi_dark(Ti=300.15); slope of Vi_dark vs. temperature
2. Temperature dependence of responsivity ratios
    a. Note: start process using data from two standards that both have spacers, e.g. PS2 and PS3
        i. Subtract temperature-corrected dark voltages from all voltages
        ii. For first measurement(dev1/dev2), don't temperature compensate for the denominator
            1. Decimate to get data equally spaced in temperature
            2. Fit straight line to data: rho1/rho2 = rho1prime/rho2 + Kappa1 *(T-Tprime)
            3. Outputs: rho1prime/rho2 (first estimate); Kappa1
        iii. For second measurement (dev2/dev1)
            1. Subtract temperature-corrected dark voltages from all voltages
            2. Use Kapp1 from the first measurement to compensate the denominators in these measurements, taking all denominator voltages to T=300.15
            3. Calculate rho2/rho1prime(T) and fit a straight line to the decimated data
            4. Outputs: Kappa2, rho2prime/rho1prime (and the second estimate of rho1prime/rho2prime)
        iv. Third measurement, repeat analysis of data from first measurement, but this time using Kappa2 from second measurement to get better estimates of Kappa1 and rho1prime/rho2prime (third estimate)
        v. Iterate until values of kappas and responsivity ratios at 300.15 converge
    b. Analyze temperate dependence data for all devices,
        i. always using Kappa values for the denominator devices to correct denominator voltages to "equivalent" 300.15 K voltages
        ii. Outputs: Kappas for each device and rhoDev1prime/rhoDev2prime for all measurements
3. Responsivity ratios
    a. Subtract temperature dependent dark levels from all voltages
    b. Compensate numerator and denominator voltages to values they would have been if devices were at 300.15 deg.
    c. Calculate rhoDev1prime/rhoDev2prime for each of the 100 measurements in the suite, average and calculate studs
    d. Outputs: rhoDev1prime/rhoDev2prime, mean and std for each measurement