LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Note: O3 Pcal LHO Calibration Factors

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1 Introduction

At the beginning of each run, Pcal calibration factors are calculated using the data we have at the time. These calibration factors are used to calibrate the interferometer strain channel. However, at the end of the run, we recalculate these calibration factors in light of additional calibration measurements we have collected during the course of the run. The ratio between the new calibration factor and the one used during the run will be the known systematic error, η_{Pcal}, on our calibrated strain data. This systematic error is either corrected or ignored depending on its magnitude and impact on the data. During the process we also calculate the statistical uncertainty on the calibration factors and provide $1-\sigma$ uncertainty bound on our calibration factors.

This document is organized in following ways. Section 2 lists the Pcal calibration factor used during O3A and O3B run. Section 3 provides all the components used in estimating the calibration factor at the end of the run. Section 4 provides the final calibration factor determined by combining the calibration factors from two end stations and includes 1-σ uncertainty on the factors. Section 5 lists the ratio between the final calibration factor and the calibration factors used during the run.

2 Pcal calibration factors used during O3A and O3B

The Pcal calibration factors used during O3A and O3B run are listed in the table below. The LIGO mirrors were upgraded at the beginning of O3 but we failed to update the masses in the calibration factors (particularly in the suspension model) and it resulted in small systematic errors in the calibrated data during O3A. At the beginning of O3B, for a week, due to technical difficulties, instead of updating the mass in the suspension model we adjusted the force factor to absorb that error. Within a week, we were able to correct the mass in the suspension model and change the adjusted factors to compensate. Thus, during O3B the calibrated data did not carry any known systematic errors. However data calibrated during both O3A and O3B could still have systematic errors characterized by η_{Pcal}, which is the main focus of this document.

The amplitude (in m) of a periodic displacement induced by periodic Pcal forces at angular frequency ω is given by X/ω^2.

Table 1: Pcal calibration factors used to calibrate Pcal power sensor output channels during O3A and O3B

Date	**Force factor**	**Mass**	**Disp. Factor(X)**
	LHO X-end		
3/26/19 to 10/31/19	6.2142×10^{-13}	39.649	1.5673×10^{-14}
10/31/19 to 11/11/19	6.2333×10^{-13}	39.649	1.5721×10^{-14}
11/11/19 to 4/1/20	6.2307×10^{-13}	39.657	1.5711×10^{-14}
	LHO Y-end		
3/26/19 to 10/31/19	6.2560×10^{-13}	39.643	1.5781×10^{-14}
10/31/19 to 11/11/19	6.2795×10^{-13}	39.643	1.5840×10^{-14}
11/11/19 to 4/1/20	6.2663×10^{-13}	39.584	1.5830×10^{-14}

3 Pcal calibration factors calculated after the end of O3B

The components that are used in determining the Pcal calibration factors are listed in tables below. All the tables in the section are copied from LIGO-P2000113 and thus the details of how these numbers are calculated can be found there.

3.1 Responsivity of the receiver-side (Rx) power sensors

Table 2: Measured responsivities of the Pcal end station power sensors, ρ_R, together with contributing factors (indented) and uncertainties, for the H1 during the O3 observing run. For Type A uncertainties (see LIGO-P2000113), the number of measurements is noted in parentheses.

Param	LHO X-end		LHO Y-end		**Units**	**Type**
	Values	$\mathbf{u_{rel}}$ **(%)**	**Values**	$\mathbf{u_{rel}}$ **(%)**		
ρ_R	1.068×10^4	0.328	1.061×10^4	0.326	ct/W	C
ρ_G	-8.0985	0.315	Common with X-end		V/W	C
α_{WG}	1.1172	0.010 (38)	Common with X-end		-	A
α_{RW}	-0.7209	0.042 (8)	-0.7157	0.014 (12)	-	A
ζ_W	1636.9	0.002 (8)	1637.6	0.002 (9)	ct/V	A
ξ_{LN}	1.0020	0.070	Common with X-end		-	C
ξ_{EL}	0.9986	0.04	0.9986	0.04	-	C

3.2 Temperature correction factors

Table 3: Measured temperature correction factors, ξ_{LN} and ξ_{EL}, for the Pcal end station power sensor calibrations, together with contributing factors (indented) and uncertainties, for the LHO interferometer during the O3 observing run.

Param	LHO X-end		LHO Y-end		**Units**	**Type**
	Values	$\mathbf{u_{rel}}$ **(%)**	**Values**	$\mathbf{u_{rel}}$ **(%)**		
ξ_{LN}	1.0020	0.070	Common with X-end		-	C
κ_G	6.73×10^{-4}	1.4	Common with X-end		1/K	A
ΔT_{LN}	3.0	34	Common with X-end		K	C
ξ_{EL}	0.9986	0.040	0.9986	0.040	-	C
κ_W	4.38×10^{-4}	1.4	Common with X-end		1/K	A
ΔT_{EL}	-3.2	28	-3.3	28	K	C

3.3 Optical Efficiency

Table 4: Measured optical efficiency correction factors, η_R, for the receiver-side end station power sensors, together with contributing factors (indented) and uncertainties, for the LHO interferometer during the O3 observing run. For Type A uncertainties, the number of measurements is noted in parentheses.

Param	LHO X-end		LHO Y-end		**Type**
	Values	$\mathbf{u_{rel}}$ **(%)**	**Values**	$\mathbf{u_{rel}}$ **(%)**	
η_R	0.9942	0.04	0.9948	0.04	C
η	0.9874	0.03 (8)	0.9886	0.03 (12)	A
β	0.9989	0.08 (3)	0.9988	0.08 (3)	A

3.4 Uncertainty due to rotation

3.5 Measured displacement factors

Table 5: Estimated uncertainties due to unintended rotation of the ETM induced by Pcal forces, ϵ_{rot}, together with contributing factors (indented), for the LHO interferometer during the O3 observing run.

Param	**LHO-X**	**LHO-Y**	**Units**
ϵ_{rot}	0.41 %	0.31 %	-
$\lvert\vec{a}\rvert$	2×10^{-3}	2×10^{-3}	m
$\lvert\vec{b}\rvert$	29×10^{-3}	22×10^{-3}	m
I_p	0.419	0.419	$\mathrm{kg\,m^2}$
I_y	0.410	0.410	$\mathrm{kg\,m^2}$
M/I_p	94.65	94.47	$1/\mathrm{m}^2$
M/I_y	96.68	96.50	$1/\mathrm{m}^2$

Table 6: Measured Pcal displacement factors, together with contributing factors (indented) and uncertainties, for the LHO interferometer during the O3 observing run.

Param	LHO X-end		LHO Y-end		**Units**	**Type**
	Values	$\mathbf{u_{rel}}$ (%)	**Values**	$\mathbf{u_{rel}}$ (%)		
X_X, X_Y	1.565×10^{-14}	0.53	1.578×10^{-14}	0.45	$\mathrm{m/s^2ct}$	C
$\cos\theta$	0.9884	0.03	0.9884	0.03	-	B
M	39.657	0.01	39.584	0.01	kg	B
ϵ_{rot}	-	0.41	-	0.31	-	B
ρ_R	1.068×10^4	0.33	1.061×10^4	0.33	ct/W	C
η_R	0.9942	0.04	0.9948	0.04	-	C

3.6 Combined displacement correction factors

Table 7: Calculated X-end and Y-end combined displacement correction factors, C_X and C_Y, together with χ_{XY}, μ_g, and the non-common factors contributing to end station displacement factor uncertainty (indented), and their uncertainties, for the LHO interferometer during the O3 observing run. For Type A uncertainties, the number of measurements is noted in parentheses.

Param	LHO X-end		LHO Y-end		**Unit**	**Type**
	Values	$\mathbf{u_{rel}}$ **(%)**	**Values**	$\mathbf{u_{rel}}$ **(%)**		
C_X, C_Y	1.0029	0.25	1.0017	0.25	-	C
χ_{XY}	1.0046	0.01 (148)	1.0046	0.01 (142)	-	A
μ_g	1.003	0.25	Common with X-end		-	C
$\cos\theta$	0.9884	0.03	0.9884	0.03	-	B
M	39.657	0.01	39.584	0.01	kg	B
ϵ_{rot}	-	0.41	-	0.31	-	B
α_{RW}	-0.7209	0.042 (8)	-0.7157	0.014 (12)	-	A
ζ_W	1636.9	0.002 (8)	1637.6	0.002 (9)	ct/V	A
η_R	0.9942	0.04	0.9948	0.04	-	C
ξ_{EL}	0.9986	0.040	0.9986	0.040	-	C

4 Combined displacement factors

This is the final calibration factors determined using the uncertainty information from both end stations. The 1-σ uncertainty on this displacement factor is highlighted in red.

Table 8: Measured *combined* displacement factors, X^c, together with contributing factors (indented) and uncertainties, for the LHO interferometer during the O3 observing run. For Type A uncertainties, the number of measurements is noted in parentheses.

Param	LHO X-end		LHO Y-end		**Unit**	**Type**
	Values	$\mathbf{u_{rel}}$ **(%)**	**Values**	$\mathbf{u_{rel}}$ **(%)**		
X^c_X, X^c_Y	1.561×10^{-14}	0.41	1.581×10^{-14}	0.41	m/s^{2}ct	C
ρ_G	-8.0985	0.315	Common with X-end		V/W	C
α_{WG}	1.1172	0.01 (38)	Common with X-end		-	A
ξ_{LN}	1.0020	0.070	Common with X-end		-	C
C_X, C_Y	1.0029	0.25	1.0017	0.25	-	C

5 Pcal Correction Factor η_{Pcal}

The ratio between the "final" displacement factors and the ones used during the run, η_{Pcal}, results from known systematic errors in Pcal calibration factors and thus in the calibrated strain data. Correcting strain data that was calibrated during the observing run epochs requires multiplying the data by η_{Pcal} for the relevant epoch.

Table 9: Pcal calibration factors used during the O3 observing run, including the "Final" factors, calculated after the the end of the run, taking into account all collected data and improvements in analysis methods. The final column lists η_{Pcal}, the ratio of the final displacement factor to the displacement factors used during the run.

Date	**Force factor (N/ct)**	**Mass (kg)**	**Disp. factor, X (m/s^2ct)**	η_{Pcal}
		LHO X-end		
3/26/19 to 10/31/19	6.2142×10^{-13}	39.649	1.5673×10^{-14}	**0.9960**
10/31/19 to 11/11/19	6.2333×10^{-13}	39.649	1.5721×10^{-14}	**0.9929**
11/11/19 to 4/1/20	6.2307×10^{-13}	39.657	1.5711×10^{-14}	**0.9935**
Final (end of O3)	6.1904×10^{-13}	39.657	1.5610×10^{-14}	-

		LHO Y-end		
3/26/19 to 10/31/19	6.2560×10^{-13}	39.643	1.5781×10^{-14}	**1.0018**
10/31/19 to 11/11/19	6.2795×10^{-13}	39.643	1.5840×10^{-14}	**0.9980**
11/11/19 to 4/1/20	6.2663×10^{-13}	39.584	1.5830×10^{-14}	**0.9986**
Final (end of O3)	6.2576×10^{-13}	39.584	1.5808×10^{-14}	-