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

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1 Introduction

This document provides the Pcal calibration factor for the entirety of O3 run based on the measurements made before and throughout the run. It follows the scheme described in the paper published recently in CQG and carries a DCC number of P2000113.

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 factor used during O3A and O3B

The Pcal calibration factor used during O3A and O3B run are listed in the table below.

Table 1: Pcal calibration factor used during O3A and O3B

Date	**Force factor**	**Mass**	$\mathbf{X}_Y$
	LLO X-end		
3/29/19 to 11/1/19 (O3A)	6.5144×10^{-13}	39.641	1.6433×10^{-14}
11/1/19 to 4/1/20 (O3B)	6.5339×10^{-13}	39.554	1.6519×10^{-14}
	LLO Y-end		
3/29/19 to 11/1/19 (O3A)	6.3991×10^{-13}	39.639	1.6143×10^{-14}
11/1/19 to 4/1/20 (O3B)	6.4245×10^{-13}	39.671	1.6194×10^{-14}

3 Pcal Calibration factor at the end of O3B

The components that go in determining the Pcal calibration factors are described and listed below.

3.1 Responsivity of Rx Power Sensors

Power sensor responsivity is determined by transferring the calibration of NIST calibrated Gold Standard to the Pcal power sensors via Working Standards. During O3, the Gold Standard calibration changed at the middle of the run, however we were able to determine the amount of change from routine transfer measurements we make at the lab and the Pcal systems at the end stations. To be consistent with what we did at LHO, the change in Gold standard responsivity has been absorbed in the value of α_{WG}. Details about this can be found in DCC-G2001252.

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

Param	LLO X-end		LLO Y-end		**Units**	**Type**
	Values	$\mathbf{u_{rel}}$ (%)	**Values**	$\mathbf{u_{rel}}$ (%)		
ρ_R	1.017×10^4	0.348	1.034×10^4	0.349	ct/W	C
ρ_G	-8.0985	0.315	Common with X-end		V/W	C
α_{WG} [1]	1.0750	0.144 (6)	Common with X-end		-	A
α_{RW}	-0.7129	0.012 (4)	-0.7265	0.042 (4)	-	A
ζ_W	1638.1	0.0006 (6)	1634.4	0.0026 (6)	ct/V	A
ξ_{LN}	1	0	Common with X-end		-	C
ξ_{EL}	1	0	1	0	-	C

3.2 Temperature Correction factors

In lack of reliable temperature sensors at the end stations, the power sensor responsivity were not corrected for temperature dependence.

3.3 Optical Efficiency

Optical efficiency of the system is determined using the optical loss measurement between the transmitter and receiver side made inside the vacuum, captured in β and outside the vacuum, captured in η.

Table 3: Measured optical efficiency correction factors, η_R, for the receiver-side end station power sensors, together with contributing factors (indented) and uncertainties, for the LLO interferometer during the O3 observing run. For Type A uncertainties, the number of measurements is noted in parentheses.

Param	LLO X-end		LLO Y-end		**Type**
	Values	$\mathbf{u_{rel}}$ (%)	**Values**	$\mathbf{u_{rel}}$ (%)	
η_R	0.9950	0.04	0.9943	0.05	C
η	0.9870	0.01 (6)	0.9887	0.07(6)	A
β	0.9969	0.08	0.9995	0.08	A

[1] Look at the description under 3.1

3.4 Uncertainty due to rotation

The rotation component is calculated using the estimated pcal beam offset from their optimal position and the measured interferometer beam position. This component is treated as an uncertainty in displacement since we don't know the direction of the Pcal beam offset.

Table 4: Estimated uncertainties due to unintended rotation of the ETM induced by Pcal forces, ϵ_{rot}, together with contributing factors (indented), for the LLO interferometer during the O3 observing run.

Param	**LLO-X**	**LLO-Y**	**Units**
ϵ_{rot}	0.30 %	0.43 %	-
$\lvert\vec{a}\rvert$	2×10^{-3}	2×10^{-3}	m
$\lvert\vec{b}\rvert$	20.8×10^{-3}	30.2×10^{-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	94.40	94.68	$1/\mathrm{m}^2$
M/I_y	96.43	96.71	$1/\mathrm{m}^2$

3.5 Measured displacement factors

Table 5: Measured Pcal displacement factors, together with contributing factors (indented) and uncertainties, for the LLO interferometer during the O3 observing run.

Param	LLO X-end		LLO Y-end		**Units**	**Type**
	Values	$\mathbf{u_{rel}}$ **(%)**	**Values**	$\mathbf{u_{rel}}$ **(%)**		
X_X, X_Y	1.646×10^{-14}	0.46	1.619×10^{-14}	0.56	$\mathrm{m/s^2}\,ct$	C
$\cos\theta$	0.9884	0.03	0.9884	0.03	-	B
M	39.554	0.01	39.671	0.01	kg	B
ϵ_{rot}	-	0.30	-	0.43	-	B
ρ_R	1.017×10^4	0.348	1.034×10^4	0.349	ct/W	C
η_R	0.9950	0.04	0.9943	0.05	-	C

3.6 Combined displacement correction factors

Table 6: 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 LLO interferometer during the O3 observing run. For Type A uncertainties, the number of measurements is noted in parentheses.

Param	LLO X-end		LLO Y-end		**Unit**	**Type**
	Values	$\mathbf{u_{rel}}$ (%)	**Values**	$\mathbf{u_{rel}}$ (%)		
C_X, C_Y	1.001	0.25	1.002	0.25	-	C
χ_{XY}	1.0032	0.03	1.0032	0.03	-	A
μ_g	1.001	0.25	Common with X-end		-	C
$\cos\theta$	0.9884	0.03	0.9884	0.03	-	B
M	39.554	0.01	39.671	0.01	kg	B
ϵ_{rot}	-	0.30	-	0.43	-	B
α_{RW}	-0.7129	0.012 (4)	-0.7265	0.042 (4)	-	A
ζ_W	1638.1	0.0006 (6)	1634.4	0.0026 (6)	ct/V	A
η_R	0.9950	0.04	0.9943	0.05	-	C
ξ_{EL}	1	0	1	0	-	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 7: 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	LLO X-end		LLO Y-end		**Unit**	**Type**
	Values	$\mathbf{u_{rel}}$ (%)	**Values**	$\mathbf{u_{rel}}$ (%)		
X^c_X, X^c_Y	1.646×10^{-14}	**0.44**	1.620×10^{-14}	**0.44**	m/s^2*ct*	C
ρ_G	-8.0985	0.315	Common with X-end		V/W	C
α_{WG}	1.0750	0.144 (19)	Common with X-end		-	A
ξ_{LN}	1	0	Common with X-end		-	C
C_X, C_Y	1.0010	0.25	1.0020	0.25	-	C

5 Pcal Correction Factor η_{Pcal}

The ratio between the final calibration factor and the one used during the run, (η_{Pcal}), is the known systematic error on Pcal calibration factor and thus in our calibrated strain data. This systematic error is either corrected or ignored depending on its magnitude and impact on the data.

Table 8: 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^{2}ct)**	η_{Pcal}
		LLO X-end		
3/29/19 to 11/1/19 (O3A)	6.5144×10^{-13}	39.641	1.6433×10^{-14}	**1.0018**
11/1/19 to 4/1/20 (O3B)	6.5339×10^{-13}	39.554	1.6519×10^{-14}	**0.9966**
Final (End of O3)	6.5118×10^{-13}	39.554	1.6463×10^{-14}	-

		LLO Y-end		
3/29/19 to 11/1/19 (O3A)	6.3991×10^{-13}	39.639	1.6143×10^{-14}	**1.0037**
11/1/19 to 4/1/20 (O3B)	6.4245×10^{-13}	39.671	1.6194×10^{-14}	**1.0005**
Final (End of O3)	6.4277×10^{-13}	39.671	1.6203×10^{-14}	-