Calibration of Fast Channels

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1. Introduction

We present results for the combination of the eight (complex) heterodyned channels read out from each IFO and for their calibration during the S4 run (March 2005). Data are archived at a sampling frequency $f_s = 2048$ Hz after being down-shifted by heterodyne frequencies of 37.504 and 75.008 kHz. The four channels at each frequency correspond to the two quadratures of the photodiodes AS3 and AS4 located at the antisymmetric port. In addition there are two fast channels sampled at 262.144 kHz which are the two quadratures of AS3. The fast channels are not archived and can be read out only in real time.

The calibration lines appear only in the fast channels (at $\sim 50, 400, 1000$ Hz). Thus only the fast channels can be directly calibrated. By comparing the noise level as measured on the fast and heterodyned channels, and observing that they are comparable in the high frequency region, we adopt the same calibration for the heterodyned channels. Since at high frequency there is no gain, the response function, $R(f)$, is simply the inverse of the sensing function, $C(f)$. The time evolution of the sensing function is given by the $\alpha(t)$ coefficients.

Finally, because the whitening board has low gain below 100 Hz we are using only the two higher calibration lines. For the details of the hardware see [1]. The names of the channels are given in Table I.

2. Rotation and averaging of the time series

We rotate the I and Q channels for each diode according to

$$\mathrm{ASQ3} = \mathrm{AS3\_I} \sin\phi + \mathrm{AS3\_Q} \cos\phi$$

$$\mathrm{ASQ4} = \mathrm{AS4\_I} \sin\theta + \mathrm{AS4\_Q} \cos\theta$$

The angles θ, ϕ are given in Table II and were obtained by comparing the amplitude of discrete lines in the power spectra. For the fast channels we used calibration lines

LIGO-T050180-00-Z

whereas for the heterodyned channels we used resonance lines, and

$$|\tan\phi| = \frac{h(f)_{\mathrm{AS3\_I}}}{h(f)_{\mathrm{AS3\_Q}}}$$

The sign of the angle was obtained by assuming that all the signal (at the AS port) appears in the Q-quadrature. The resulting demodulation angles agree with those recorded on the IFO display.

Finally we wish to average the signal from the two photodiodes. We do this by weighing them inversely to their relative gain.

$$\mathrm{ASQ} = \frac{1}{(N3 + N4)}[N3 * \mathrm{ASQ3} + N4 * \mathrm{ASQ4}]$$

The weights $N3$ and $N4$ (where $N3 + N4 = 2$) are included in Table II.

3. Calibration

The calibration of the fast channels can be found for H1 at
http:/blue.ligo-wa.caltech.edu/hanford1/d/scirun/S4/Calib/4k/050327/
H1_DAQ_FAST_FSR_Channels_b.xml
and associated 37kHz and 74kHz channels from the exact same epoch:
http://blue.ligo-wa.caltech.edu/hanford1/d/scirun/S4/Calib/4k/050327/
H1_1FSR.xml
http://blue.ligo-wa.caltech.edu/hanford1/d/scirun/S4/Calib/4k/050327/
H1_2FSR.xml
For H2, the similar information is available in:
http://blue.ligo-wa.caltech.edu/hanford1/d/scirun/S4/Calib/2k/050325/

These spectra were taken by M. Landry. In addition we took spectra of the fast channels on 3/10-11/05 and the results are consistent within 10%.

The data for L1 were taken by B. O'Reilly and can be found at
/data/dtt/Calibration/S4/Mar242005/
on the LLO CDS machines and are called "1FSR.xml", "2FSR.xml" and "DAQ_FAST_FSR_Channels.xml".

To obtain the driving strain at a given frequency we calculate

$$h_{\text{applied}}(\text{rms}) = (\text{D.C. calibration}) * (\text{Excitation}) * (1/\sqrt{2})(f_p/f)^2/L_{\text{arm}}$$

D.C. Calibration = DC $*$ (output matrix)$_{\text{ETMX}}$ − DC $*$ (output matrix)$_{\text{ETMY}}$ and $f_p = 0.764$ Hz is the pendulum pole, and we use the rms value of the strain.

The signal power, P, in counts is calculated from the peak value of the PSD

$$P = \sqrt{(h/\sqrt{\text{Hz}})^2_{\text{peak}} \cdot \text{BW}}$$

where BW is the resolution bandwidth.

It then follows that

$$|R(f)| = h_{\text{applied}}(\text{rms})/P, \quad |C(f)| = \frac{|1+G(f)|}{|R(f)|}, \quad |C(0)| = C(f)/H(f)$$

Here $G(f)$ is the open loop gain which we read from the calibration files, and $R(f)$ is the response function and $C(f)$ the sensing function. $H(f)$ is the IFO transfer function for which we have used the simple analytic form

$$H(f) = [1 + F' \sin^2(2\pi f L/c)]^{-1/2}$$

with

$$F' = 4r_3r_4/(1 - r_3r_4)^2 = 1.75 \times 10^4$$

assuming $r_3 = \sqrt{0.97}$ and $r_4 = 1$.

The details of the calculation of the sensing function are given in Tables III. Here we summarize the result

$$\begin{aligned} &\text{H1} \qquad C(0) &=& \ (2.46 \pm 0.2) \times 10^{21} \\ &\text{H2} \qquad C(0) &=& \ (1.17 \pm 0.1) \times 10^{21} \\ &\text{L1} \qquad C(0) &=& \ (2.72 \pm 0.2) \times 10^{21} \end{aligned}$$

The quoted errors are obtained from the scatter of the different measurements and are typically 10%. The sensing function for H2 is approximately half that of H1 (or L1) as expected from the shorter length.

4. Discussion

To check our procedure we applied it to the regular AS_Q channel for H1 and compared our result with the posted calibration. We find a response function that exceeds the posted one by a factor of 1.12, including the correction for time trends.

The sensitivity at the fsr varies rapidly with frequency. Instead we prefer to give the corresponding response function

$$R(f) = \frac{1}{C(f)} = \frac{1}{C(0)} \frac{1}{H(f)}$$

At 37.52 kHz we have

$$|R_{\rm H1}| = 4.07 \times 10^{-22} \qquad \text{strain/count}$$

$$|R_{\rm H2}| = 1.13 \times 10^{-19} \qquad \text{strain/count}$$

For the cross-correlation of H1 and H2 at this frequency we will use

$$R^2_{\rm H1-H2} = 4.6 \times 10^{-41}\ (\text{strain})^2/(\text{count})^2$$

The typical noise level of the heterodyned channels is 0.10 counts/$\sqrt{\rm Hz}$ and therefore the sensitivity of H1 at 37.52 kHz is of order

$$h = 5 \times 10^{-23}/\sqrt{\rm Hz}$$

This result is compatible with that of ref. [2].

Of course one has also to correct for the geometric acceptance of a randomly oriented signal at the fsr frequency.

Acknowledgement

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References

[1] D. Sigg G040432-00-D

[2] J. Buttcane T040194-00-D

Table I

Archived heterodyned channels for S4

L1:LSC-AS3_Q_1FSR
L1:LSC-AS3_I_1FSR
L1:LSC-AS4_Q_1FSR
L1:LSC-AS4_I_1FSR

L1:LSC-AS3_Q_2FSR
L1:LSC-AS3_I_2FSR
L1:LSC-AS4_Q_2FSR
L1:LSC-AS4_I_2FSR

H1:LSC-AS3_Q_1FSR
H1:LSC-AS3_I_1FSR
H1:LSC-AS4_Q_1FSR
H1:LSC-AS4_I_1FSR

H1:LSC-AS3_Q_2FSR
H1:LSC-AS3_I_2FSR
H1:LSC-AS4_Q_2FSR
H1:LSC-AS4_I_2FSR

H2:LSC-AS3_Q_1FSR
H2:LSC-AS3_I_1FSR
H2:LSC-AS4_Q_1FSR
H2:LSC-AS4_I_1FSR

H2:LSC-AS3_Q_2FSR
H2:LSC-AS3_I_2FSR
H2:LSC-AS4_Q_2FSR
H2:LSC-AS4_I_2FSR

Names of fast (test point) channels

H1:DAQ - FAST_CH1_SHORT (AS3_I)
H1:DAQ - FAST_CH2_SHORT (AS3_Q)

H2:DAQ - FAST_CH0_SHORT (AS3_I)
H2:DAQ - FAST_CH1_SHORT (AS3_Q)

L1:DAQ - FAST_ ?
L1:DAQ - FAST_ ?

Table II

Rotation and Normalization parameters

H1

$$\phi = 52.6^\circ$$
$$\theta = 9^\circ$$
$$N3 = 1.29$$
$$N4 = 0.71$$

H2

$$\phi = -172^\circ$$
$$\theta = 23^\circ$$
$$N3 = 1.16$$
$$N4 = 0.84$$

L1

$$\phi = -71^\circ$$
$$\theta = -64^\circ$$
$$N3 = 0.88$$
$$N4 = 1.12$$

Table IIIa

Details of Calculation of sensing function

IFO: H1 Date = 050327

f	(Hz)	393.1	1144.3
$P = \sqrt{\|\text{AS3}\|^2 * BW}$	(counts)	0.74	4.44
D.C. calibration	(m/count)	1.58×10^{-9}	1.58×10^{-9}
Excitation	(counts)	9×10^{-4}	0.16
$(f_p/f)^2$		3.78×10^{-6}	4.46×10^{-7}
$h_{\text{applied}}(\text{rms})$	(strain)	0.95×10^{-21}	1.99×10^{-20}
$\|R(f)\| = h_{\text{app}}(\text{rms})/P$	(strain/count)	1.29×10^{-21}	4.49×10^{-21}
$G(f)$		$0.55\exp(-i2.47)$	$0.21\exp(i2.04)$
$\|C(f)\| = \|1+G(f)\|/\|R(f)\|$	(counts/strain)	5.16×10^{20}	2.06×10^{20}
$H(f)$		0.224	0.0787
$\|C(0)\| = \|C(f)\|/\|H(f)\|$		2.31×10^{21}	2.62×10^{21}

Notes:

$h_{\text{applied}}(\text{rms}) = (\text{D.C. calibr}) * (\text{Excitation}) * (1/\sqrt{2}) * (f_p/f)^2/L_{arm}$

$H(f) = [1 + F' \sin^2(2\pi f L/c)]^{-1/2}$ $F' = 1.75 \times 10^4$

Table IIIb

Details of Calculation of sensing function

IFO: H2   Date = 050327

f	(Hz)	407.3	1159.7
$P = \sqrt{\lvert \mathrm{AS3}\rvert^2 * BW}$	(counts)	1.56	3.17
D.C. calibration	(m/count)	0.97×10^{-9}	0.97×10^{-9}
Excitation	(counts)	1.72×10^{-3}	0.12
$(f_p/f)^2$		3.52×10^{-6}	4.34×10^{-7}
$h_{\mathrm{applied}}(\mathrm{rms})$	(strain)	2.08×10^{-21}	1.79×10^{-20}
$\lvert R(f)\rvert = h_{\mathrm{app}}(\mathrm{rms})/P$	(strain/count)	1.33×10^{-21}	5.64×10^{-21}
$G(f)$		$0.47\exp(-2.98)$	$0.15\exp(0.71)$
$\lvert C(f)\rvert = \lvert 1 + G(f)\rvert / \lvert R(f)\rvert$	(counts/strain)	4.07×10^{20}	1.99×10^{20}
$H(f)$		0.405	0.154
$\lvert C(0)\rvert = \lvert C(f)\rvert / \lvert H(f)\rvert$		1.01×10^{21}	1.30×10^{21}

Notes:

$h_{\mathrm{applied}}(\mathrm{rms}) = (\mathrm{D.C.\ calibr}) * (\mathrm{Excitation}) * (1/\sqrt{2}) * (f_p/f)^2/L_{arm}$

$H(f) = [1 + F' \sin^2(2\pi f L/c)]^{-1/2}$ $F' = 1.75 \times 10^4$

Table IIIc

Details of Calculation of sensing function

IFO: L1 Date = 050324

f	(Hz)	396.7	1151.5
$P = \sqrt{\lvert \mathrm{AS3} \rvert^2 * BW}$	(counts)	1.61	6.50
D.C. calibration	(m/count)	0.82×10^{-9}	0.82×10^{-9}
Excitation	(counts)	3×10^{-3}	0.5
$(f_p/f)^2$		3.71×10^{-6}	4.41×10^{-7}
$h_{\mathrm{applied}}(\mathrm{rms})$	(strain)	1.61×10^{-21}	3.20×10^{-20}
$\lvert R(f) \rvert = h_{\mathrm{app}}(\mathrm{rms})/P$	(strain/count)	1.00×10^{-21}	4.91×10^{-21}
$G(f)$		$0.47\exp(-i3.12)$	$0.17\exp(-0.17)$
$\lvert C(f) \rvert = \lvert 1 + G(f) \rvert / \lvert R(f) \rvert$	(counts/strain)	5.28×10^{20}	2.38×10^{20}
$H(f)$		0.222	0.0782
$\lvert C(0) \rvert = \lvert C(f) \rvert / \lvert H(f) \rvert$		2.38×10^{21}	3.04×10^{21}

Notes:

$h_{\mathrm{applied}}(\mathrm{rms}) = (\mathrm{D.C.\ calibr}) * (\mathrm{Excitation}) * (1/\sqrt{2}) * (f_p/f)^2/L_{arm}$

$H(f) = [1 + F' \sin^2(2\pi f L/c)]^{-1/2}$ $F' = 1.75 \times 10^4$