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Calibration of Fast Channels

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Calibration of Fast Channels v.2

S.Giampanis, T. Fricke, and A.C. Melissinos
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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 centered at 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 (obviously) only in the fast channels. Thus only the fast channels can be directly calibrated. By comparing the noise level of 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.

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. The fast channel spectra for H1, H2 and L1 are shown in Figs. 1-3. Note that only diode AS3 is recorded by the fast channel while both AS3 and AS4 are recorded in the heterodyned channels. The heterodyned channel spectra for H1, H2 and L1 are shown in Figs. 4-6.

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 the calibration lines in the fast channels and the amplitude of discrete (test mass resonances) lines for the heterodyned channels. We define

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

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, at the time of the calibration and are included in Table II.

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 resulting weights $N3$ and $N4$ are listed 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 at:
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

$$\begin{aligned} \text{H1} \qquad C(0) &= (2.46 \pm 0.2) \times 10^{21} \\ \text{H2} \qquad C(0) &= (1.17 \pm 0.1) \times 10^{21} \\ \text{L1} \qquad C(0) &= (2.72 \pm 0.5) \times 10^{21} \end{aligned}$$

The quoted errors for H1, H2 are obtained from the scatter of four 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. For L1 only two measurements are available and they differ from their mean by 12%; we therefore assign a 20% error.

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 calibration (when referenced to the same GPS time 793176553) by a factor of 1.14 ± 0.07 using the three calibration lines.

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

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

Recall however that at this frequency the open loop gain is zero. Plots of the magnitude and phase of the response functions for H1, H2 and L1 are shown in Figs. 7-9.
At 37.52 kHz the resulting values are

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

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

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

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

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

We thank D. Sigg, M. Landry and B. O'Reilly for providing the relevant data and information on the calibration procedure.

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_CH1_SHORT (AS3_I)
L1:DAQ - FAST_CH2_SHORT (AS3_Q)

Table II

Rotation and Normalization parameters

H1				
	measured	$\phi = 52.6°$	posted	$\phi = 51.4°$
		$\theta = 9°$		$\theta = -17.2°$
		N3 = 1.29		
		N4 = 0.71		
H2				
		$\phi = -172°$		$\phi = 175°$
		$\theta = 23°$		$\theta = -27°$
		N3 = 1.16		
		N4 = 0.84		
L1				
		$\phi = -71°$		
		$\theta = -64°$		
		$N3 = 0.88$		
		$N4 = 1.12$		

Table IIIa

Details of Calculation of sensing function

IFO: H1 Date = 050327

f	(Hz)	393.1	1144.3
$P = \sqrt{\lvert\mathrm{AS3}\rvert^2 * BW}$	(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}
$h_{\mathrm{applied}}(\mathrm{rms})$	(strain)	0.95×10^{-21}	1.99×10^{-20}
$\lvert R(f)\rvert = h_{\mathrm{app}}(\mathrm{rms})/P$	(strain/count)	1.29×10^{-21}	4.49×10^{-21}
$G(f)$		$0.55\exp(-i2.47)$	$0.21\exp(i2.04)$
$\lvert C(f)\rvert = \lvert 1+G(f)\rvert/\lvert R(f)\rvert$	(counts/strain)	5.16×10^{20}	2.06×10^{20}
$H(f)$		0.224	0.0787
$\lvert C(0)\rvert = \lvert C(f)\rvert/\lvert H(f)\rvert$		2.31×10^{21}	2.62×10^{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 IIIb

Details of Calculation of sensing function

IFO: H2 Date = 050327

f	(Hz)	407.3	1159.7
$P = \sqrt{\lvert \text{AS3}\rvert^2 * BW}$	(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}
$h_{\text{applied}}(\text{rms})$	(strain)	2.08×10^{-21}	1.79×10^{-20}
$\lvert R(f)\rvert = h_{\text{app}}(\text{rms})/P$	(strain/count)	1.33×10^{-21}	5.64×10^{-21}
$G(f)$		$0.47\exp(-i2.98)$	$0.15\exp(i0.71)$
$\lvert C(f)\rvert = \lvert 1+G(f)\rvert/\lvert R(f)\rvert$	(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:

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

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

Table IIIc

Details of Calculation of sensing function

IFO: L1 Date = 050324

f	(Hz)	396.7	1151.5
$P = \sqrt{\lvert \text{AS3} \rvert^2 * BW}$	(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}
$h_{\text{applied}}(\text{rms})$	(strain)	1.61×10^{-21}	3.20×10^{-20}
$\lvert R(f) \rvert = h_{\text{app}}(\text{rms})/P$	(strain/count)	1.00×10^{-21}	4.91×10^{-21}
$G(f)$		$0.47\exp(-i3.12)$	$0.17\exp(-i0.17)$
$\lvert C(f) \rvert = \lvert 1 + G(f) \rvert / \lvert R(f) \rvert$	(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:

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

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

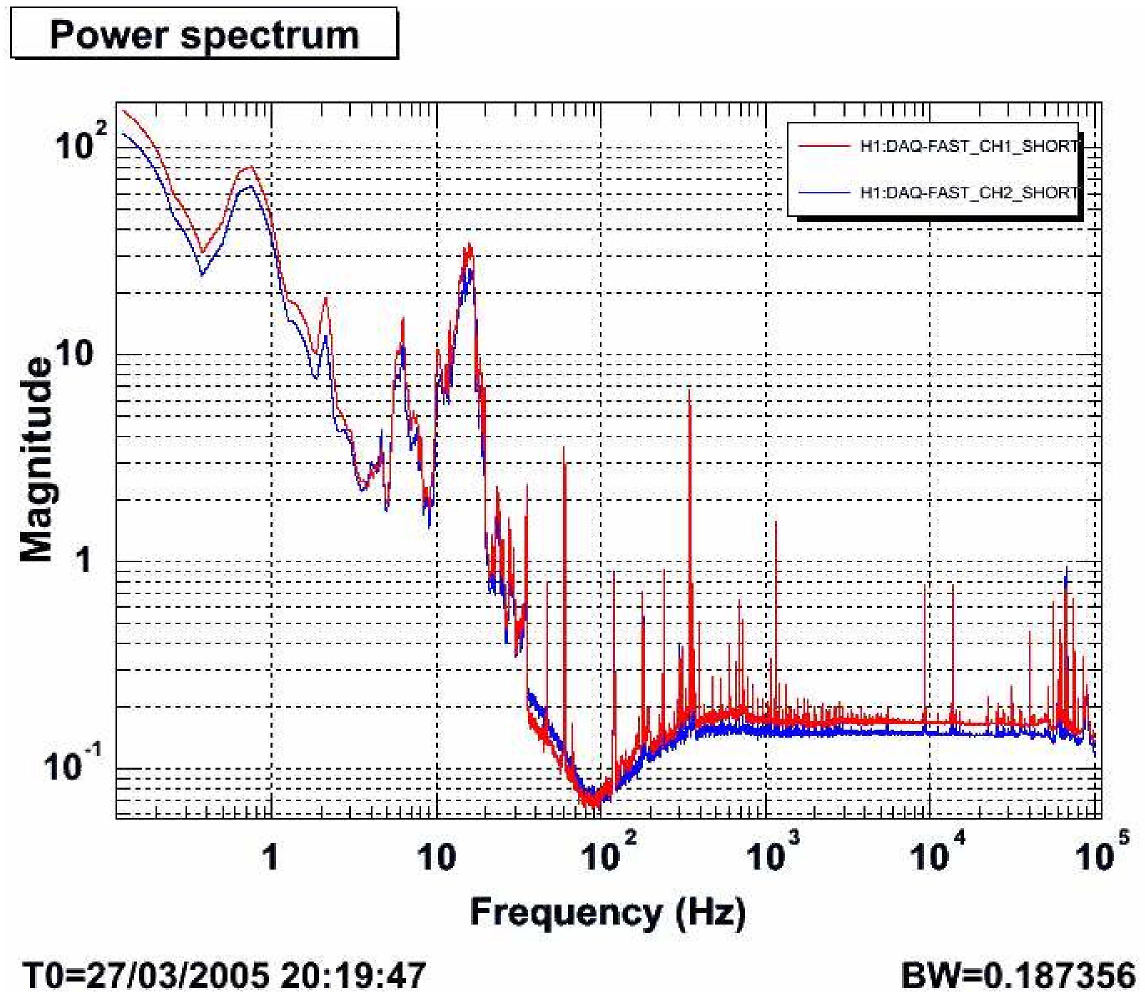

Figure 1: H1 power spectra of the fast channels.

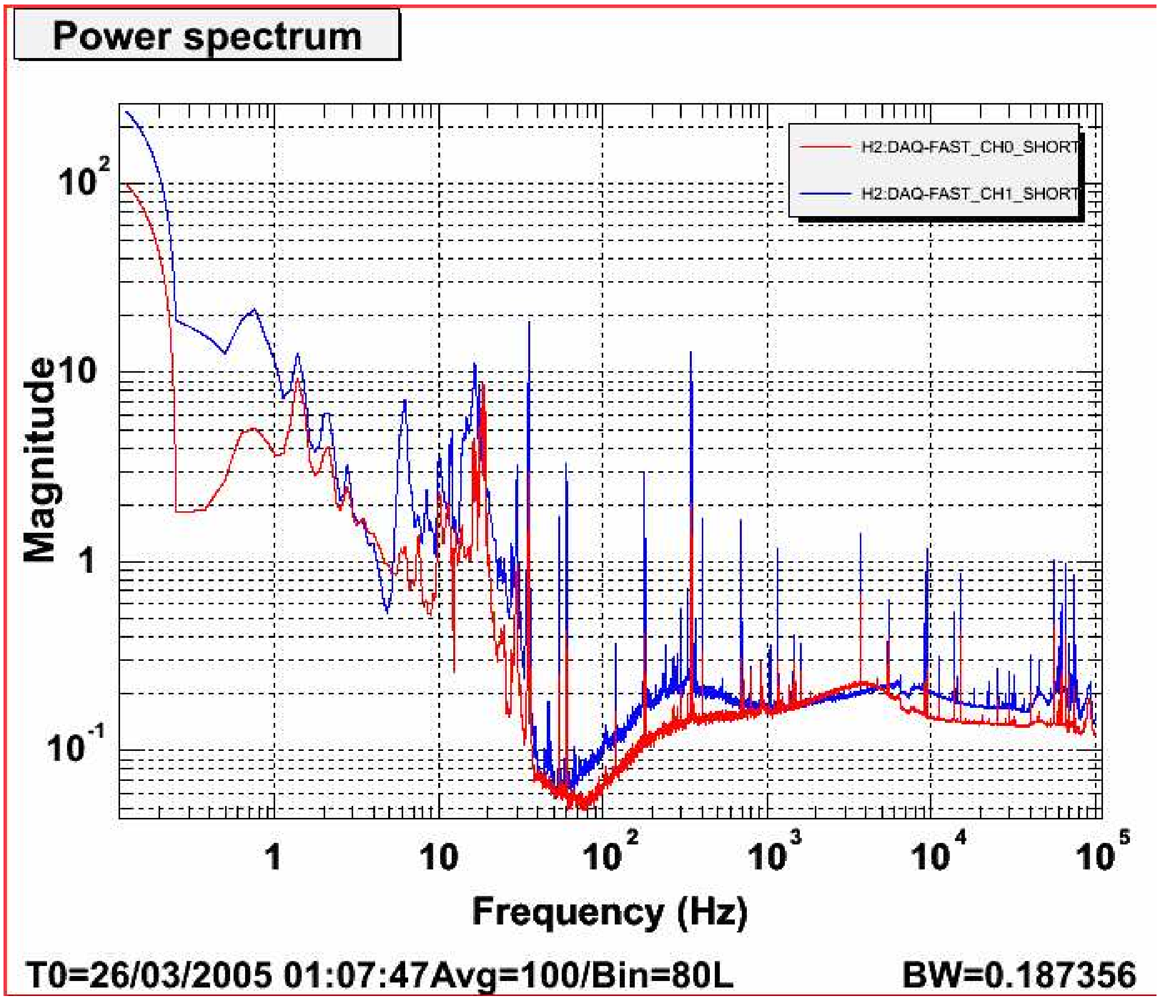

Figure 2: H2 power spectra of the fast channels.

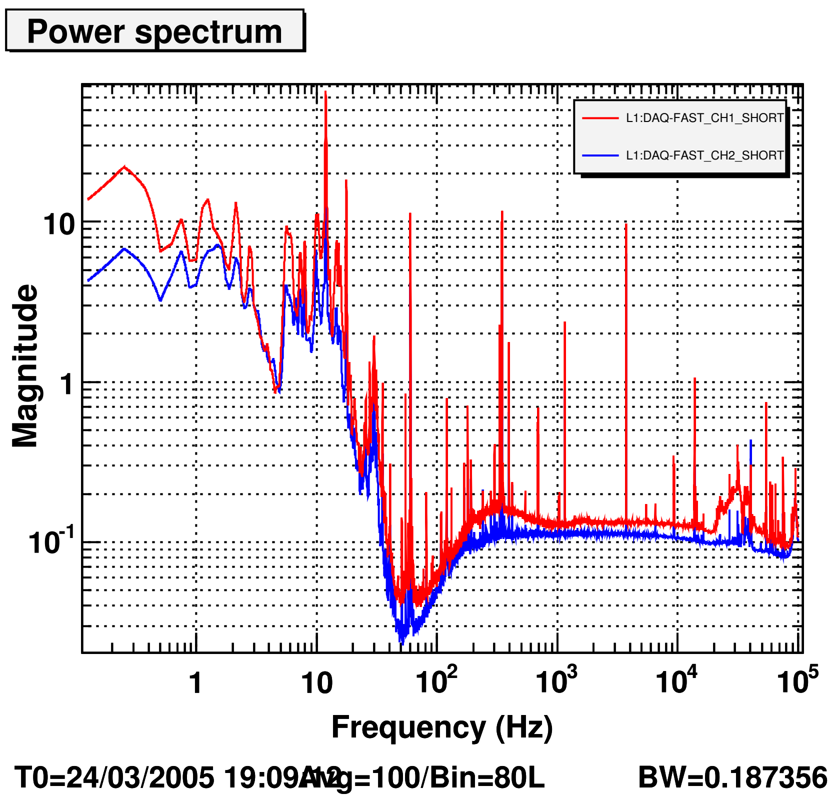

Figure 3: L1 power spectra of the fast channels.

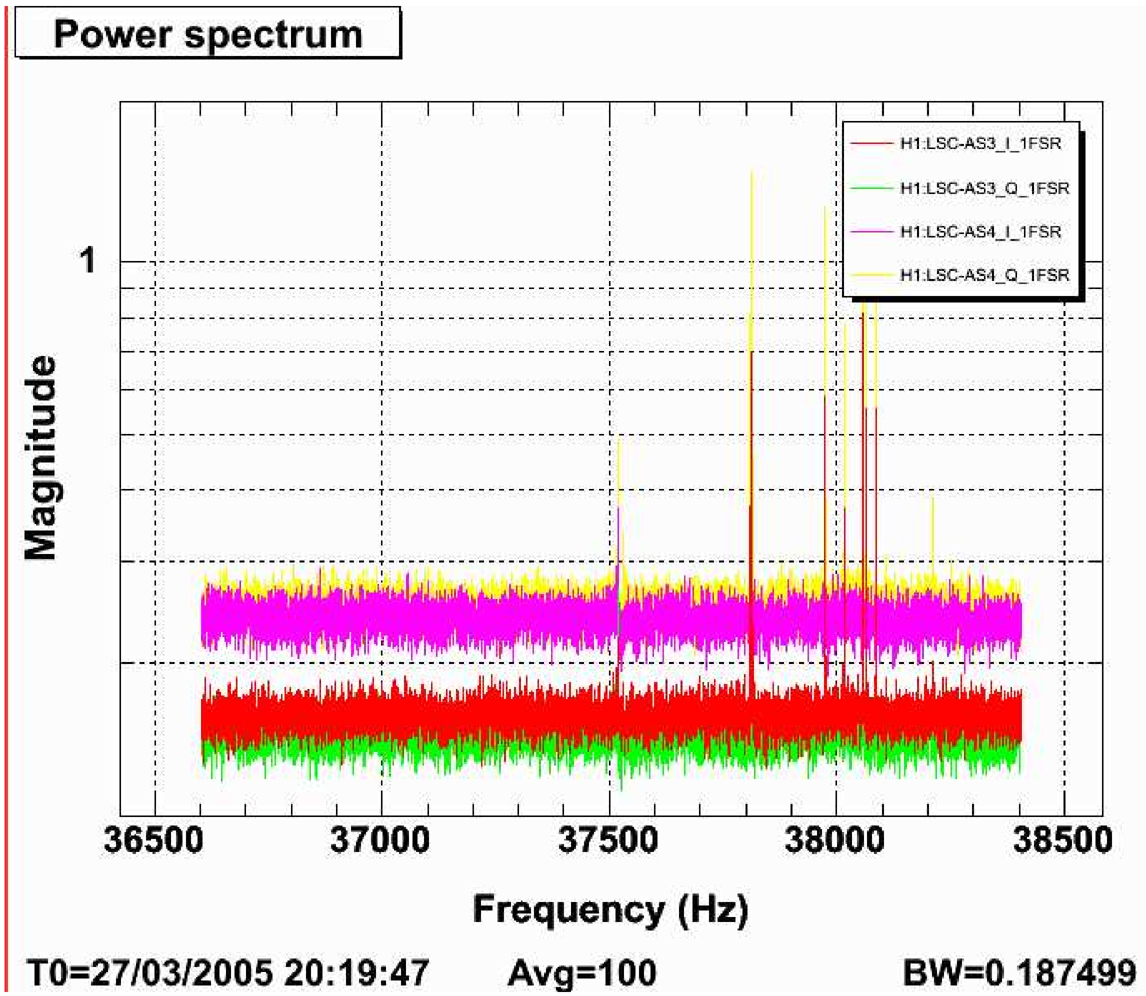

Figure 4: H1 power spectra of the heterodyned channels.

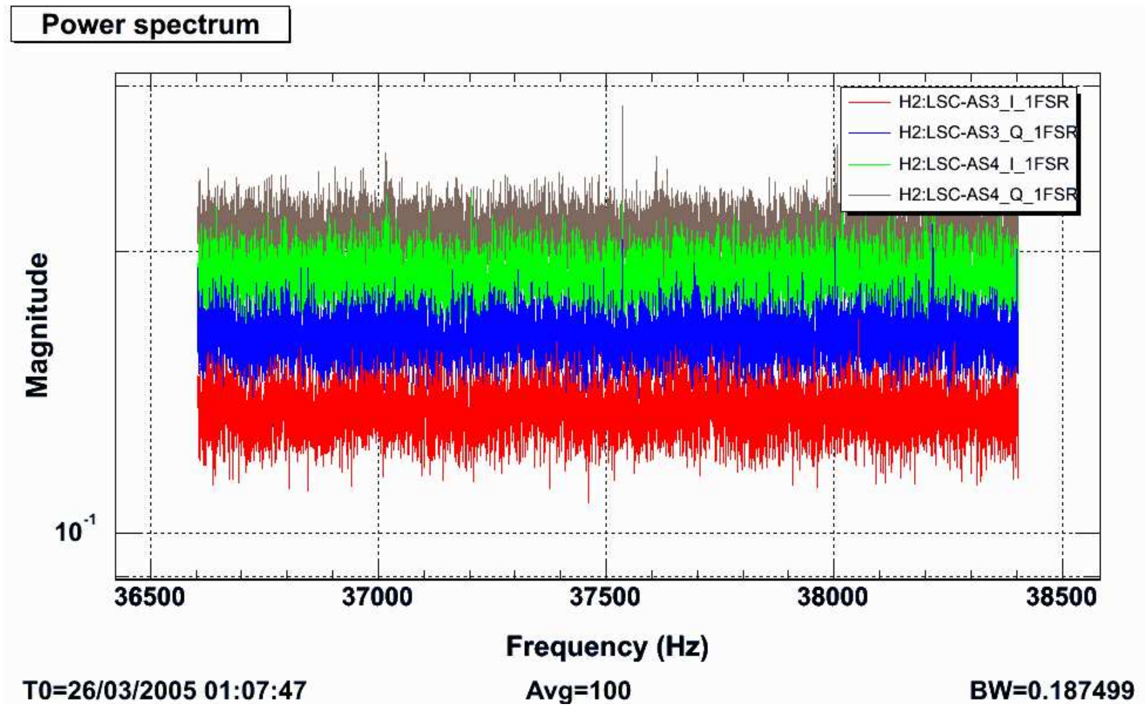

Figure 5: H2 power spectra of the heterodyned channels.

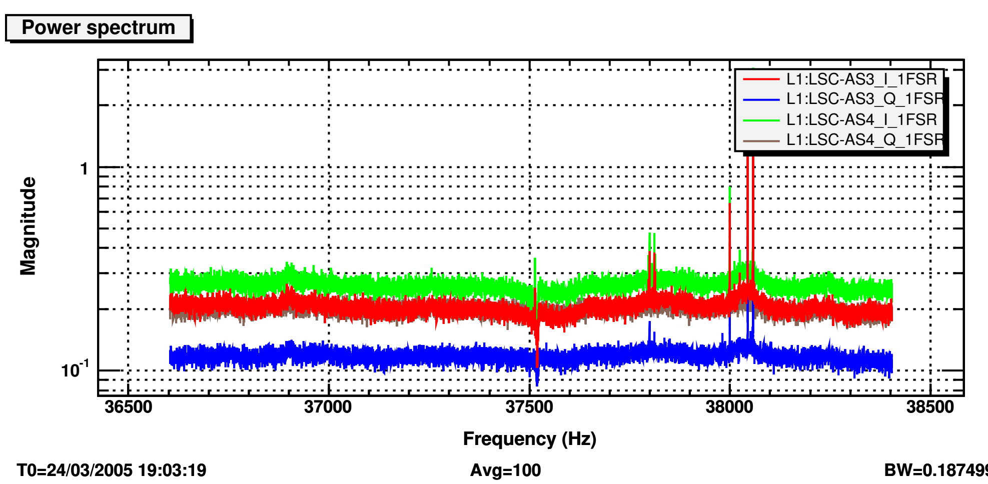

Figure 6: L1 power spectra of the heterodyned channels.

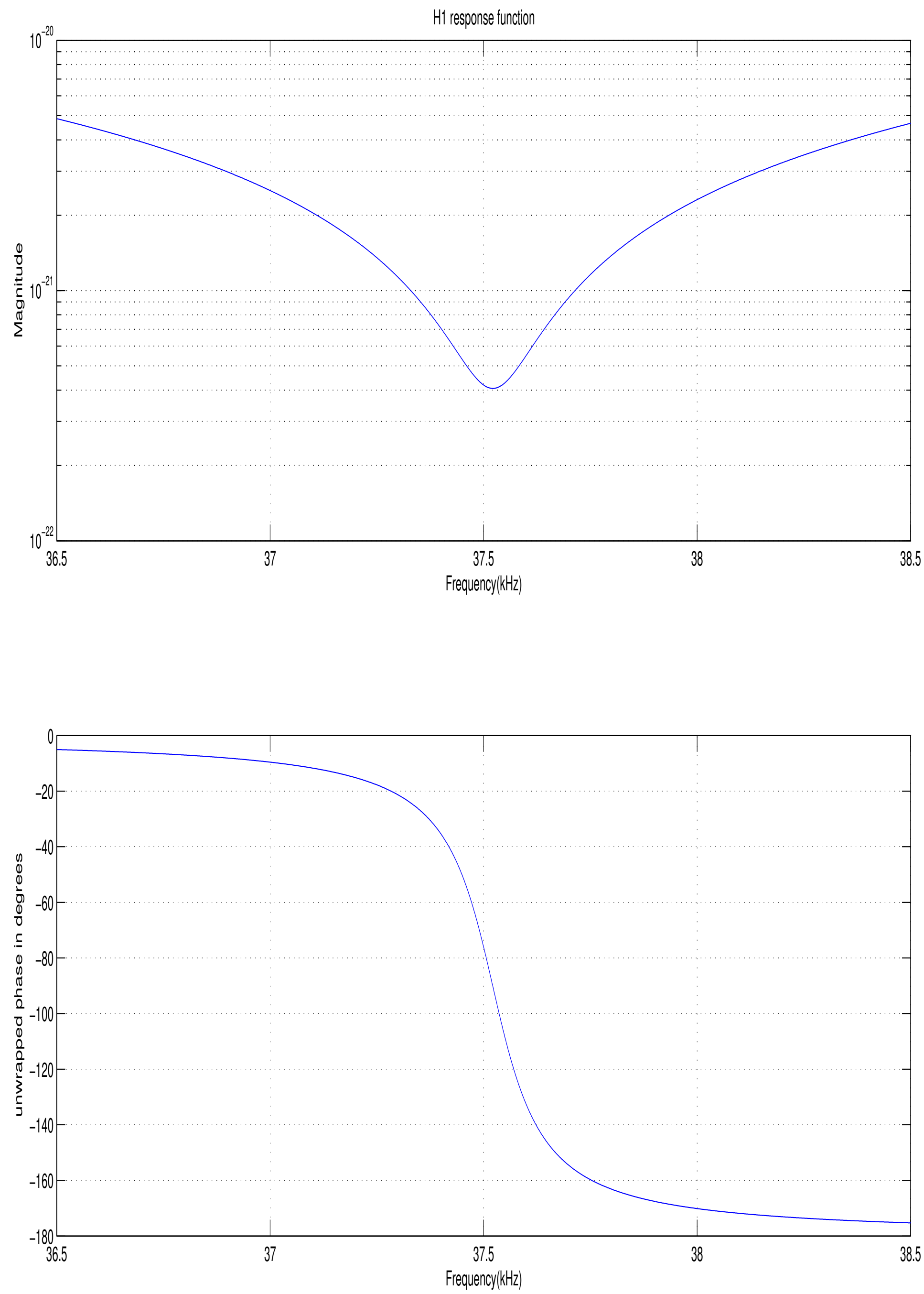

Figure 7: H1 response function

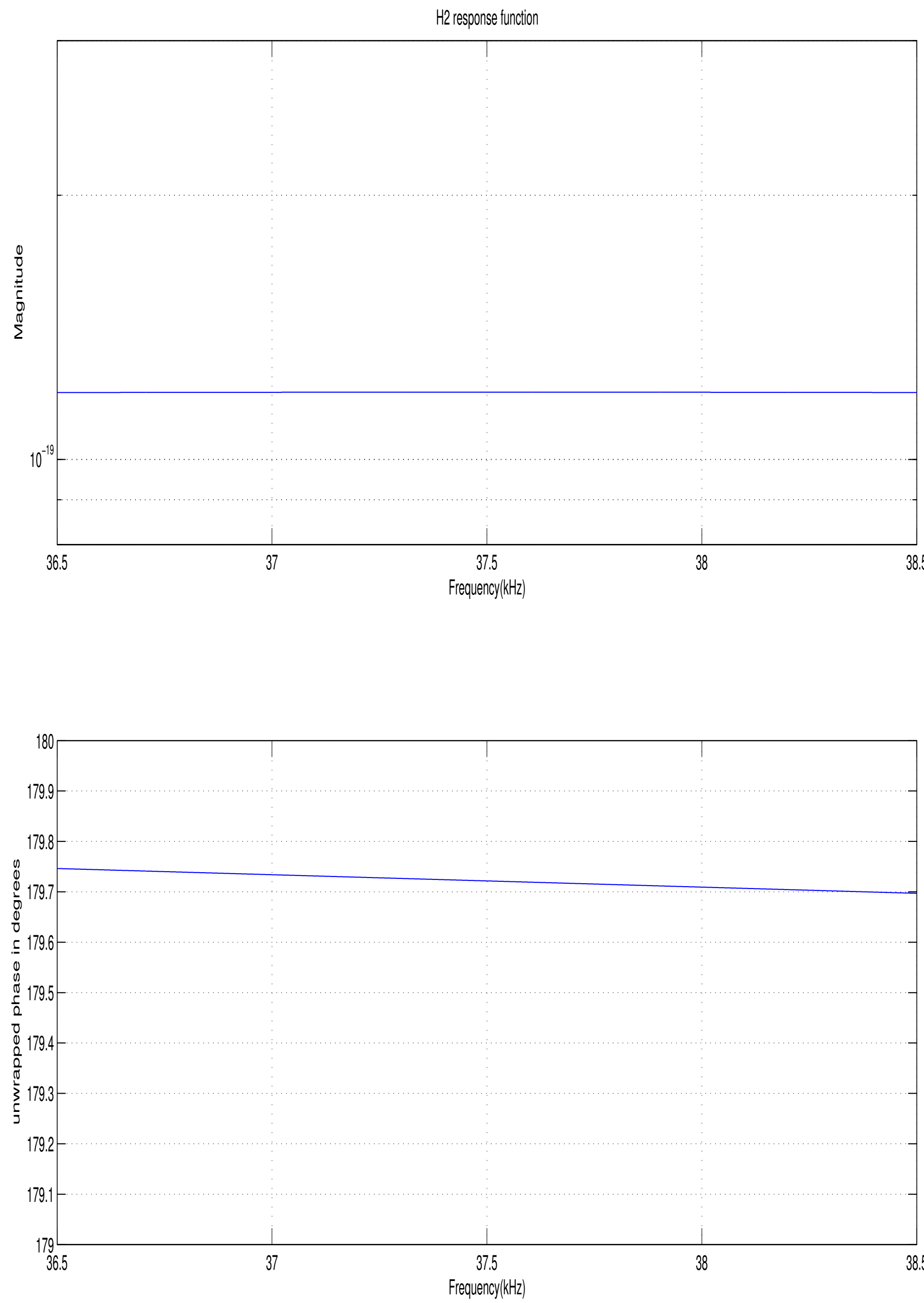

Figure 8: H2 response function

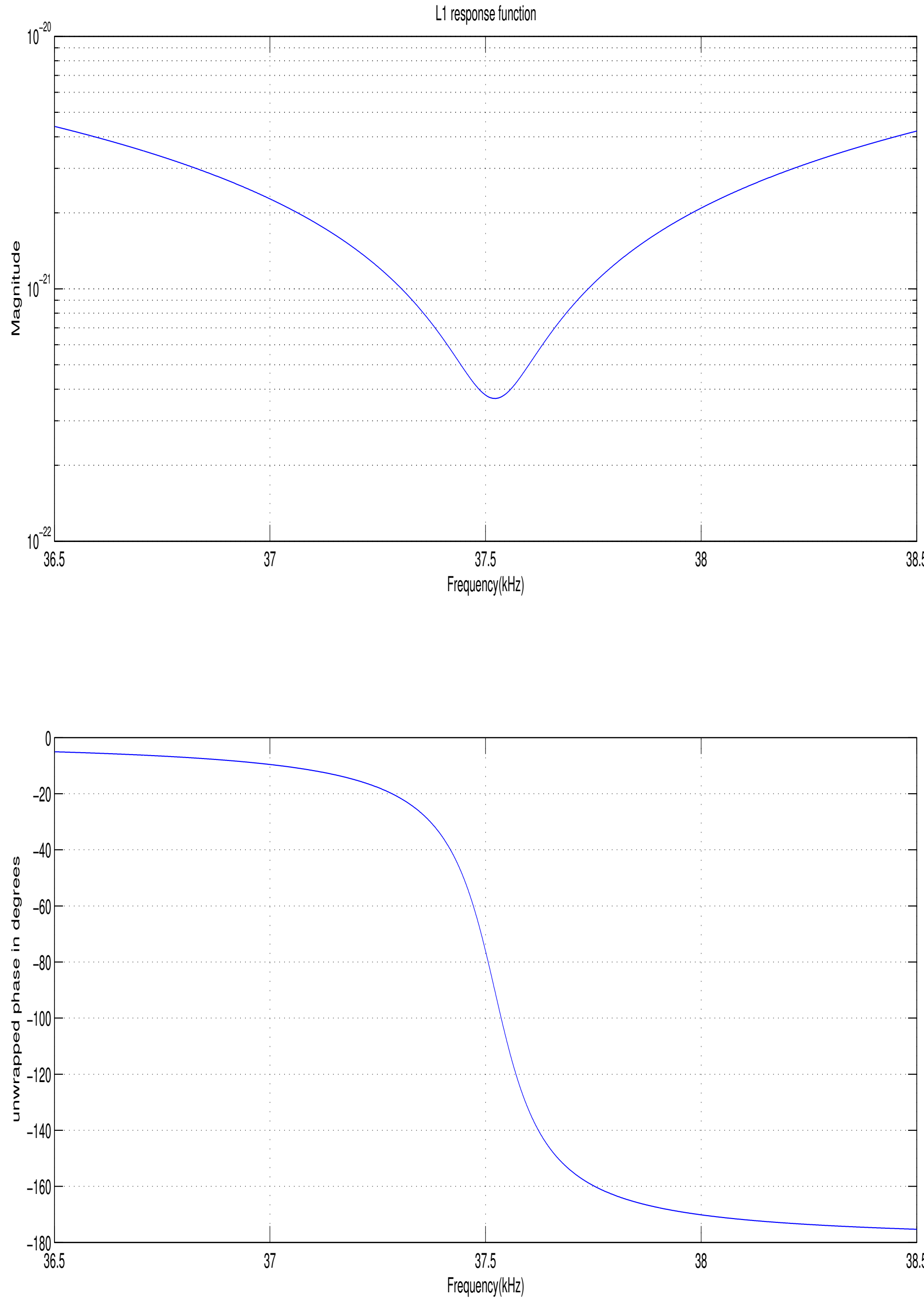

Figure 9: L1 response function