Diagnostic Breadboard Instruction Manual LIGO-T0900133-v2

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1 Introduction

This instruction manual describes how to use the Diagnostic Breadboard (DBB) for diagnostic laser beam measurements. The local interface and the remote interface are described and step by step instructions for performing and calibrating the measurements are provided. Reference measurements are given for comparisons.

Single frequency, linear polarized laser beams at a wavelength of 1064 nm with a high (>50%) TEM00 content can be analyzed with this breadboard. The relative intensity noise between 1 Hz and 100 kHz and between 1 MHz and 100 MHz, the frequency noise between 1 Hz and 100 kHz, the pointing between 1 Hz and 100 kHz and the beam quality of the incoming beam can be measured.

1.1 Definitions and Acronyms

AA	autoalignment / alignment loops
CCD	charge-coupled device
DBB	diagnostic breadboard
DBID	diagnostic breadboard serial number
DWS	differential wavefront sensing
FRQ	frequency noise measurement
FSR	free spectral range
HV	high voltage
Lag	Laguerre Gaussian mode
LSD	linear spectral density
MSC	modescan measurement
PMC	pre-mode-cleaner
PNT1X	pointing measurement 1X
PNT1Y	pointing measurement 1Y
PNT2X	pointing measurement 2X
PNT2Y	pointing measurement 2Y
PZT	piezo-electric transducer
QPD	quadrant photodiode
RF	radio frequency
RIN	relative intensity noise
RINRF	relative intensity noise at radio frequencies
RPD	RIN photodiode
TEM	transversal electro magnetic mode, Hermite Gaussian mode
TF	transfer function
TIA	trans-impedance amplifier
TPD	photodiode in transmission of PMC

2 Installation

Read the whole section before starting the installation of the DBB

The breadboard has a size of roughly 610 mm × 500 mm. You might need some mirrors to do the rough alignment to the breadboard, a beam power attenuator and a polarization turning component. The electronics consists of a 6HE crate and two power supplies. One power supply is a 3HE crate, the other power supply is in a table top case. The cables between the breadboard and the electronic crate have a length of 3 m.

The breadboard must be mounted on an optical table with five bases. Holes are provided in the breadboard, such that you can screw the breadboard from the top to imperial and metric optical tables with bases between the table and the breadboard. These holes are marked by blue circles in figure 3. The beam height is 65 mm above the breadboard and the breadboard is 20 mm thick. Choose appropriate bases to adapt the breadboard to your beam height. Five bases for a total beam height of 100 mm are delivered with the breadboard. They are screwed to the breadboard near component BS1.

Mount the breadboard by starting with the hole near the end of the input coupling rail and then choose the fitting hole for each of the remaining four hole pairs.

The following components are probably necessary for operating the DBB.

- Two mode matching lenses for ML1 and ML2. The focal lengths depend on the input beam. The lenses should be mounted in a mount with an outer diameter of 25 mm. They have to fit into the mount OH40-D25 from Owis (http://www.owis-staufen.de).

- CCD Monitor

- 75 Ω BNC cable for the CCD Monitor

- Standard laboratory equipment, e.g oscilloscope, function generator, multimeter, ...

The input beam must be coupled into the breadboard along the input coupling rail. It must pass both iris diaphragms. The rough alignment of the beam should be made in front of the breadboard. The fine alignment to the PMC can be done with the mirror M1 and M2. The beam should have a power of 135 mW, at least between 120 mW and 150 mW, in p-polarization (horizontal).

The two lenses ML1 and ML2 on the input coupling rail can be used for modematching the beam to the PMC. You will need to have a beam waist of 189 um radius in the middle between the PZT mirrors. This location has an optical way distance of 804 mm from the breadboard input. Change the focal length and the position of the two lenses to match the input beam to the PMC. See the sticker on the PMC tank or figure 1 for reference.

Make all electrical connections between the breadboard, the crate and the power supplies – except the connection between the hv amplifier electronic module and the breadboard. A schematic is shown in figure 2. Now turn on the power supplies and use the potentiometers ctrl1.x.ofs, ctrl1.y.ofs, ctrl1.pmc.ofs, ctrl2.x.ofs and ctrl2.y.ofs to set all five high voltage signals to 0 V. Use the five monitor signals at the hv module to check this. Now connect the hv module
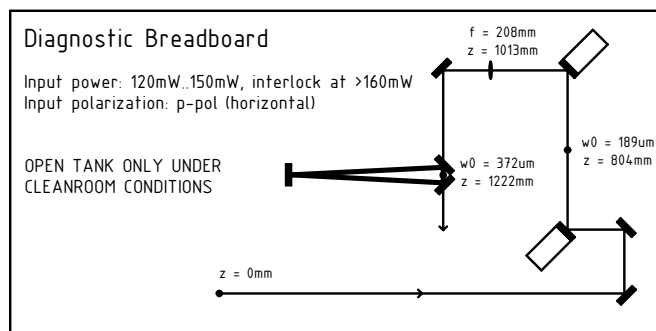
Figure 1: Modematching reference

with the breadboard and use the mentioned potentiometers to slowly increase the voltage to 150 V in about 10 seconds. This procedure is recommended after long storage of the PZTs by the manufacturer and should be repeated if the DBB is not used for a couple of weeks. In general, connect or disconnect the hv amplifier electronic module and the breadboard only if all five high voltage signals are at 0 V.

The following components are user maintainable:

- I1 and I2: open/close, slide position

- ML1 and ML2: lens, slide position

- M1 and M2: alignment

- BS2 and M9: alignment

- TPD: offset potentiometer

Never try to adjust PZT1, PZT2, L1 or BS1! If the position or alignment of these components are changed, the whole breadboard has to be rebuild component by component!

Have a look at section 4 for the adjustments which have to be made after installing the DBB.

Breadboard size	610 mm × 500 mm
Input power	135 mW (120 mW ... 150 mW)
Input polarization	p-polarization (horizontal)
Beam height above optical table	≥ 85 mm
Beam height above breadboard	65 mm
Breadboard thickness	20 mm
Waist radius	189 um
Waist position	804 mm downstream of breadboard input
Possible lens positions	60 mm ... 440 mm downstream of breadboard input

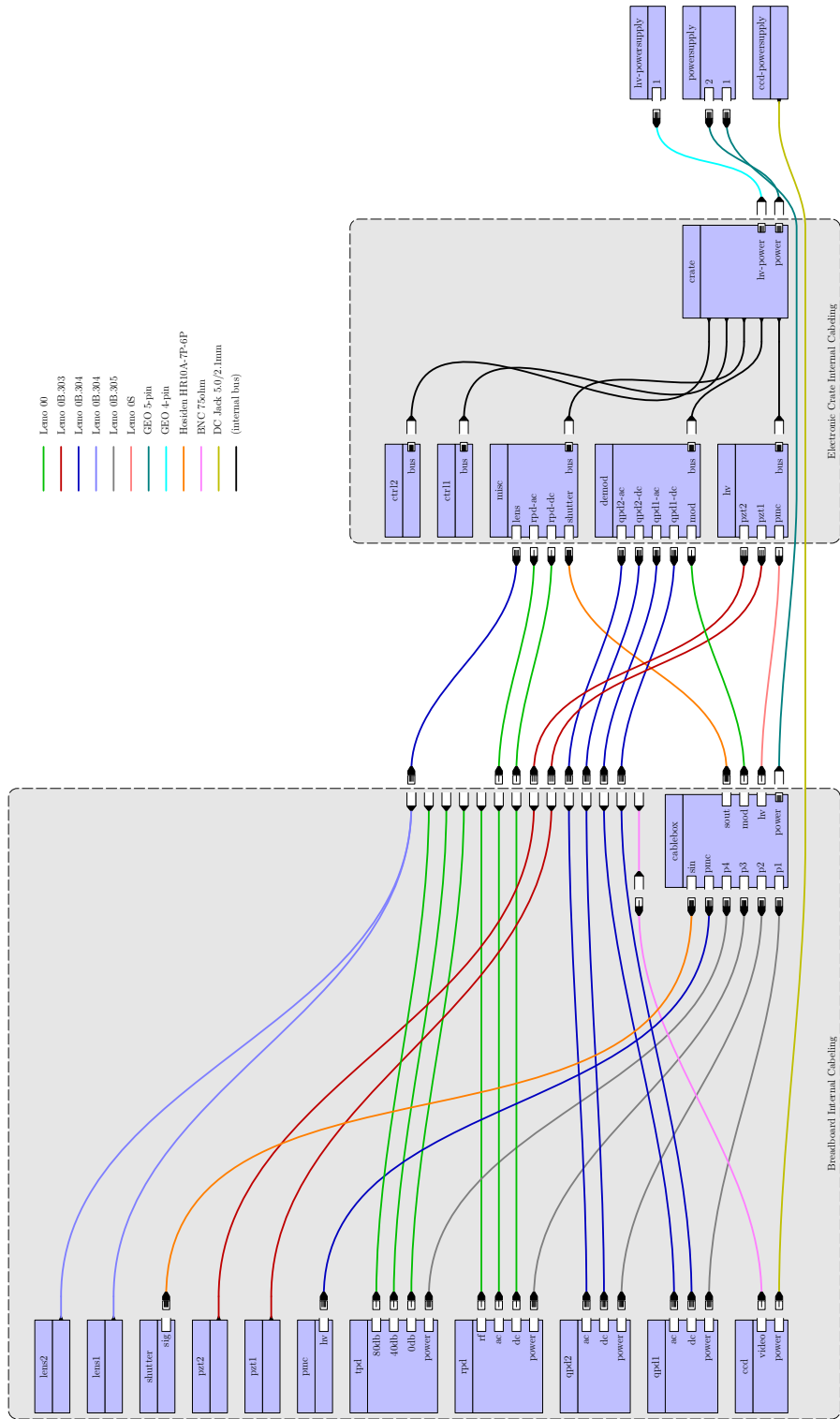Table 1: Quick installation reference

Figure 2: Cabling reference

Figure 3: Breadboard schematic

3 Interface

The DBB can be operated in two independent modes: a local and a remote mode. A digital signal at the bus of the electronic crate determines the operation mode. A yellow LED labeled with 'rmt' at the fronts of the electronic modules indicate, that this electronic module is operating in remote mode.

Both modes are completely independent, which means for example that signals which are injected using the local interface cannot change the behavior in remote operation or the other way around.

Most signals are available through both interfaces, but there are exceptions.

A simplified schematic of the whole electronics is shown in figure 4. More detailed schematics of the electronic modules are contained in the construction manual.

The following two sections describe the local and the remote interface. The step by step instructions in later sections use the connector, indicator and control names of the local interface for describing the procedures.

3.1 Local interface

The local interface to the DBB consists of five front plates of the electronic modules in the crate, one connector panel at the breadboard and an offset adjustment potentiometer at the case of the photodiode TPD.

The connector names and the voltage ranges, where applicable, are described in the figures 5, 6, 7, 8, 9 and 10 for the electronic modules and the connector panel. Each connector, indicator or control has a unique name, which are used in the step by step instructions for performing the measurements. If a signal is available also as remote signal, then the name of the remote signal is mentioned as well (upper case signal names).
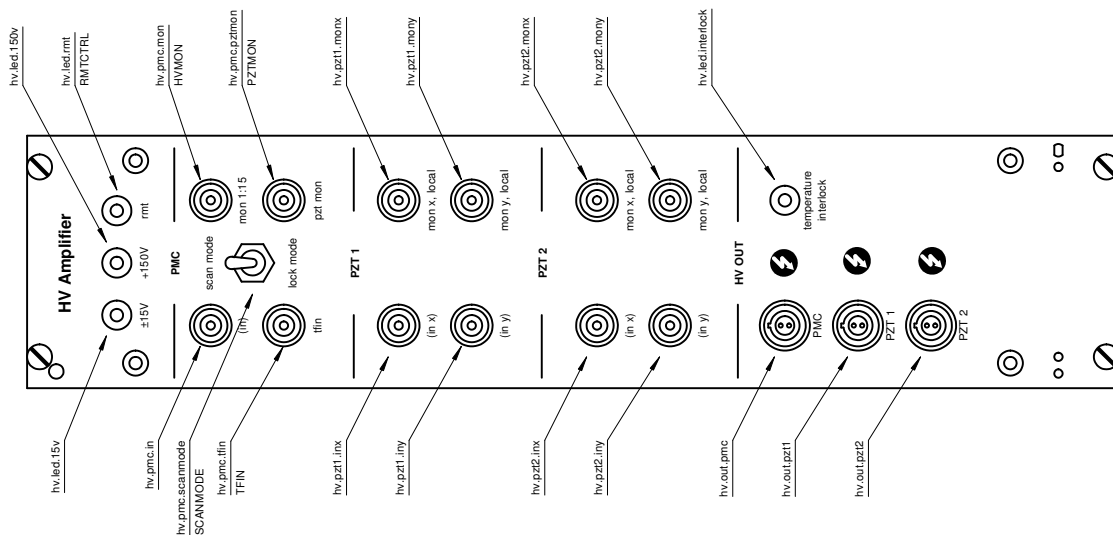
Figure 4: Simplified schematic of the whole electronics. The names of the local interface are used for the connectors, indicators and controls. (It is advisable to print this page or better only the schematic above at least on a A3 sheet)

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Connector	Range	Type	Description
hv.led.15v			Indicates a working ±15 V power supply
hv.led.150v			Indicates a working $+150$ V power supply
hv.led.rmt			Indicates remote operation mode
hv.pmc.in	-10 V...10 V	in	Optional input for HV amplifier for PMC PZT. Input must be activated first with switch on PCB.
hv.pmc.scanmode			Setting mode for scanning or locking the PMC
hv.pmc.tfin	-10 V...10 V	in	Signal is added to HV amplifier input for PMC PZT
hv.pmc.mon	0 V...10 V	out	1/15 of output voltage for PMC PZT
hv.pmc.pztmon	-15 V...-15 V	out	Output voltage for PMC PZT filtered by special TF
hv.pzt1.inx	-10 V...10 V	in	Optional input for HV amplifier for PZT1-X. Input must be activated first with switch on PCB.
hv.pzt1.monx	0 V...10 V	out	1/15 of output voltage for PZT1-X
hv.pzt1.iny	-10 V...10 V	in	Optional input for HV amplifier for PZT1-Y. Input must be activated first with switch on PCB.
hv.pzt1.mony	0 V...10 V	out	1/15 of output voltage for PZT1-Y
hv.pzt2.inx	-10 V...10 V	in	Optional input for HV amplifier for PZT2-X. Input must be activated first with switch on PCB.
hv.pzt2.monx	0 V...10 V	out	1/15 of output voltage for PZT2-X
hv.pzt2.iny	-10 V...10 V	in	Optional input for HV amplifier for PZT2-Y. Input must be activated first with switch on PCB.
hv.pzt2.mony	0 V...10 V	out	1/15 of output voltage for PZT2-Y
hv.out.pmc	0 V...150 V	out	Output voltage for PMC PZT
hv.out.pzt1	0 V...150 V	out	Output voltage for PZT1
hv.out.pzt2	0 V...150 V	out	Output voltage for PZT2
hv.led.interlock			Indicates an interlock due to overtemperature

Figure 5: HV Amplifier local interface description.
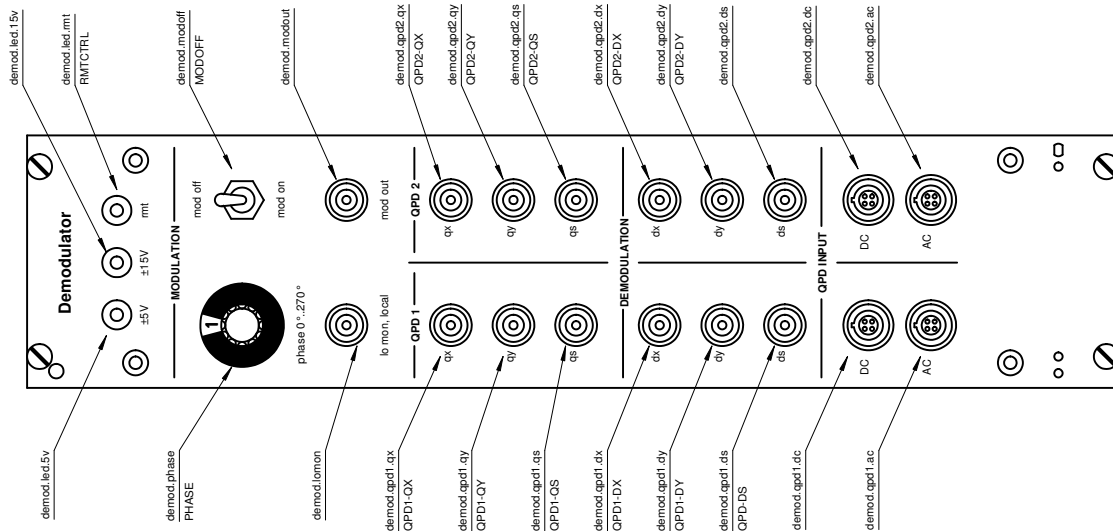
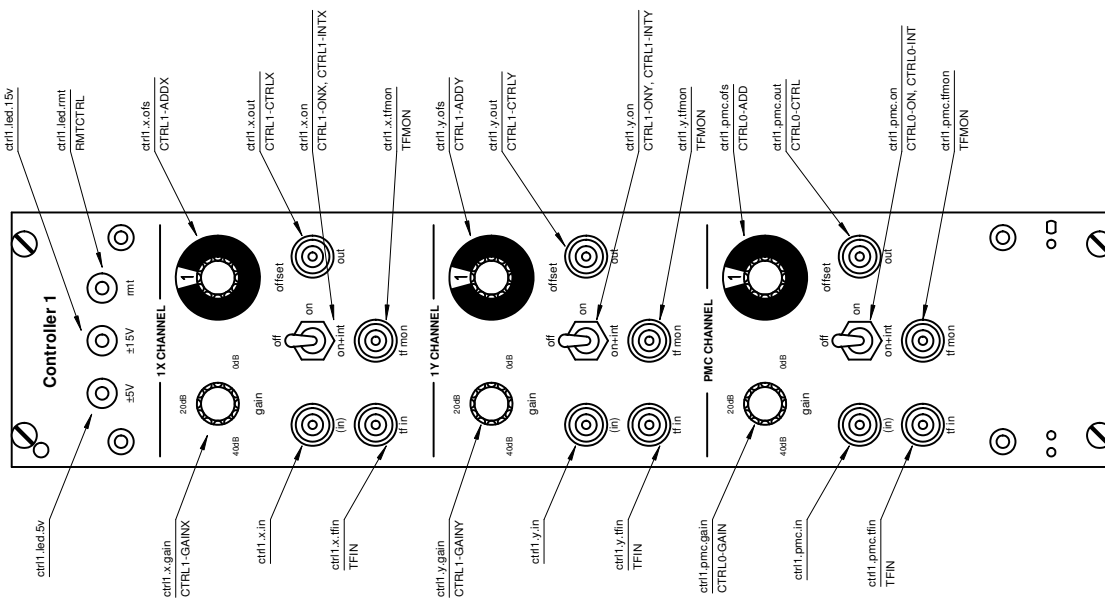| Connector	Range	Type	Description
demod.led.5v			Indicates a working ±5 V power supply
demod.led.15v			Indicates a working ±15 V power supply
demod.led.rmt			Indicates remote operation mode
demod.phase			Modulation phase. Roughly between 0° and 270°, non-linear.
demod.lomon	−10 V…10 V	out, 50Ω	Local oscillator
demod.modoff			Turn local oscillator on or off
demod.modout	−15 V…15 V	out	Phase shifted local oscillator for PMC PZT modulation
demod.qpd1.qx	−10 V…10 V	out	Power difference between left and right half of QPD1
demod.qpd1.qy	−10 V…10 V	out	Power difference between top and bottom half of QPD1
demod.qpd1.qs	−10 V…10 V	out	Power sum on QPD1
demod.qpd2.qx	−10 V…10 V	out	Power difference between left and right half of QPD2
demod.qpd2.qy	−10 V…10 V	out	Power difference between top and bottom half of QPD2
demod.qpd2.qs	−10 V…10 V	out	Power sum on QPD2
demod.qpd1.dx	−10 V…10 V	out	Demodulated difference between left and right half of QPD1
demod.qpd1.dy	−10 V…10 V	out	Demodulated difference between top and bottom half of QPD1
demod.qpd1.ds	−10 V…10 V	out	Demodulated sum signal of QPD1
demod.qpd2.dx	−10 V…10 V	out	Demodulated difference between left and right half of QPD2
demod.qpd2.dy	−10 V…10 V	out	Demodulated difference between top and bottom half of QPD2
demod.qpd2.ds	−10 V…10 V	out	Demodulated sum signal of QPD2
demod.qpd1.dc	−10 V…0 V	in	Quadrant signals of QPD1
demod.qpd1.ac	−10 V…10 V	in	Quadrant signals of QPD1, AC coupled and amplified
demod.qpd2.dc	−10 V…0 V	in	Quadrant signals of QPD2
demod.qpd2.ac	−10 V…10 V	in	Quadrant signals of QPD2, AC coupled and amplified

Figure 6: Demodulator local interface description.

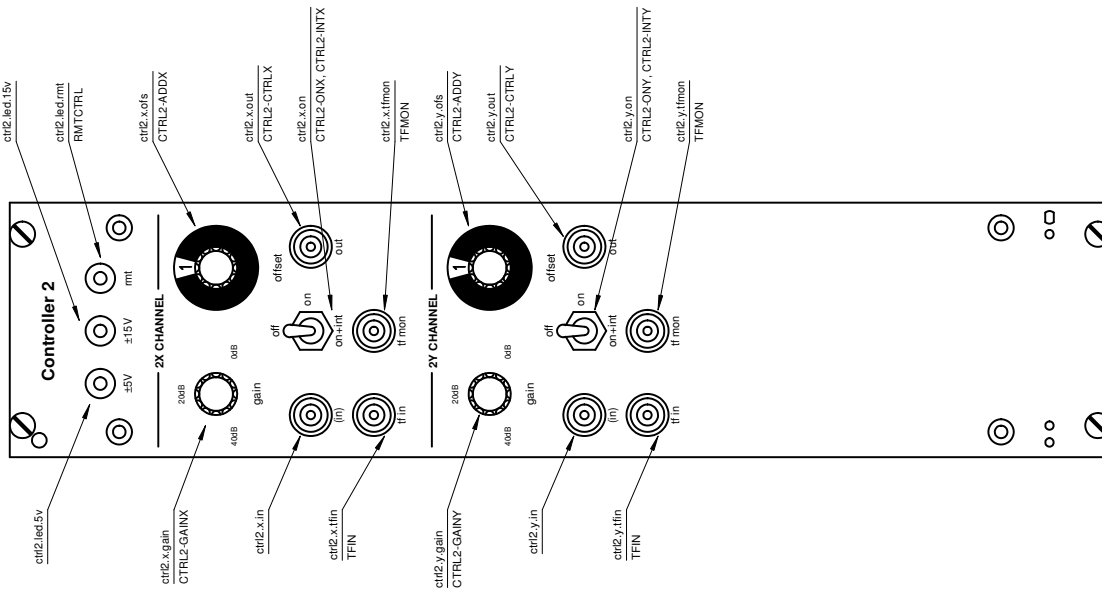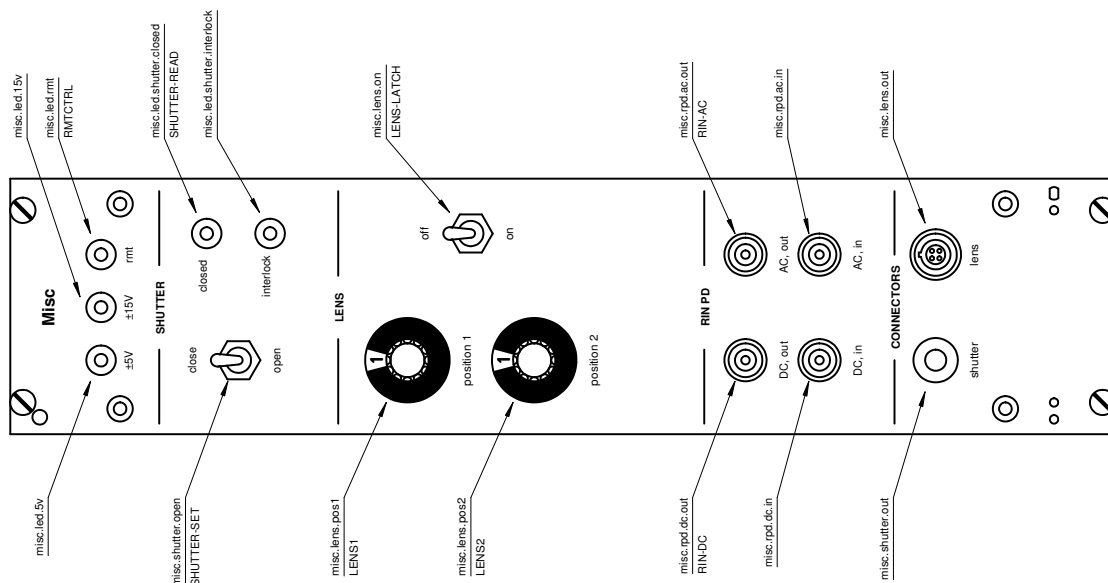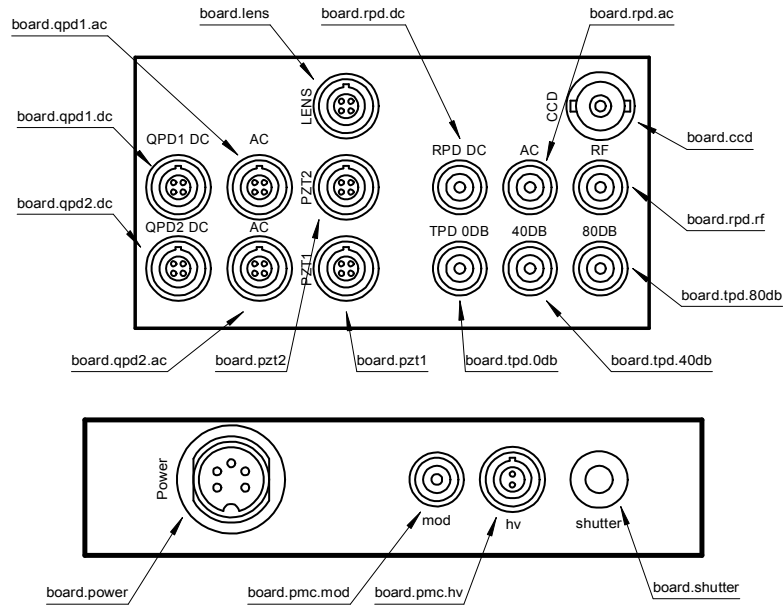| Connector	Range	Type	Description
ctrl1.led.5v			Indicates a working ±5 V power supply
ctrl1.led.15v			Indicates a working ±15 V power supply
ctrl1.led.rmt			Indicates remote operation mode
ctrl1.x.gain			Gain for PZT1-X loop, adjustment bandwidth < 1Hz
ctrl1.x.in	-10 V…10 V	in	Optional input for error signal of PZT1-X loop. Input must be activated first with switch on PCB.
ctrl1.x.tfin	-10 V…10 V	in	Signal is added to error signal of PZT1-X loop
ctrl1.x.ofs			Offset added to control signal of PZT1-X loop
ctrl1.x.out	-15 V…15 V	out	Control signal of PZT1-X loop
ctrl1.x.on			Tri-state switch for state of PZT1-X loop
ctrl1.x.tfmon	-15 V…15 V	out	Error signal of PZT1-X loop, after tfin addition
ctrl1.y.gain			Gain for PZT1/2-Y loop, adjustment bandwidth < 1Hz
ctrl1.y.in	-10 V…10 V	in	Optional input for error signal of PZT1-Y loop. Input must be activated first with switch on PCB.
ctrl1.y.tfin	-10 V…10 V	in	Signal is added to error signal of PZT1-Y loop
ctrl1.y.ofs			Offset added to control signal of PZT1-Y loop
ctrl1.y.out	-15 V…15 V	out	Control signal of PZT1-Y loop
ctrl1.y.on			Tri-state switch for state of PZT1-Y loop
ctrl1.y.tfmon	-15 V…15 V	out	Error signal of PZT1-Y loop, after tfin addition
ctrl1.pmc.gain			Gain for PMC PZT loop, adjustment bandwidth < 1Hz
ctrl1.pmc.in	-10 V…10 V	in	Optional input for error signal of PMC PZT loop. Input must be activated first with switch on PCB.
ctrl1.pmc.tfin	-10 V…10 V	in	Signal is added to error signal of PMC PZT loop
ctrl1.pmc.ofs			Offset added to control signal of PMC PZT loop
ctrl1.pmc.out	-15 V…15 V	out	Control signal of PMC PZT loop
ctrl1.pmc.on			Tri-state switch for state of PMC PZT loop
ctrl1.pmc.tfmon	-15 V…15 V	out	Error signal of PMC PZT loop, after tfin addition

Figure 7: Controller 1 local interface description.

Connector	Range	Type	Description
ctrl2.led.5v			Indicates a working ± 5 V power supply
ctrl2.led.15v			Indicates a working ± 15 V power supply
ctrl2.led.rmt			Indicates remote operation mode
ctrl2.x.gain			Gain for PZT2-X loop, adjustment bandwidth < 1Hz
ctrl2.x.in	-10 V…10 V	in	Optional input for error signal of PZT2-X loop. Input must be activated first with switch on PCB.
ctrl2.x.tfin	-10 V…10 V	in	Signal is added to error signal of PZT2-X loop
ctrl2.x.ofs			Offset added to control signal of PZT2-X loop
ctrl2.x.out	-15 V…15 V	out	Control signal of PZT2-X loop
ctrl2.x.on			Tri-state switch for state of PZT2-X loop
ctrl2.x.tfmon	-15 V…15 V	out	Error signal of PZT2-X loop, after tfin addition
ctrl2.y.gain			Gain for PZT2-Y loop, adjustment bandwidth < 1Hz
ctrl2.y.in	-10 V…10 V	in	Optional input for error signal of PZT2-Y loop. Input must be activated first with switch on PCB.
ctrl2.y.tfin	-10 V…10 V	in	Signal is added to error signal of PZT2-Y loop
ctrl2.y.ofs			Offset added to control signal of PZT2-Y loop
ctrl2.y.out	-15 V…15 V	out	Control signal of PZT2-Y loop
ctrl2.y.on			Tri-state switch for state of PZT2-Y loop
ctrl2.y.tfmon	-15 V…15 V	out	Error signal of PZT2-Y loop, after tfin addition

Figure 8: Controller 2 local interface description.

Connector	Range	Type	Description
misc.led.5v			Indicates a working ± 5 V power supply
misc.led.15v			Indicates a working ± 15 V power supply
misc.led.rmt			Indicates remote operation mode
misc.shutter.open			Switch for opening or closing the shutter
misc.led.shutter.closed			Indicates a closed shutter
misc.led.shutter.interlock			Indicates an interlock due to too much input power
misc.lens.pos1			Position of lens ML1, if lens movement is turned on
misc.lens.pos2			Position of lens ML2, if lens movement is turned on
misc.lens.on			Turn lens movement on or off
misc.rpd.dc	-13 V…13 V	in	Input for RPD.DC signal
misc.rpd.ac	-10 V…10 V	in	Input for RPD.AC signal
misc.shutter.out	0 V…6 V	in/out	Multiple input and output signals for the shutter
misc.lens.out		out	Output signals and power supply for lens servos

Figure 9: Misc local interface description.

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Connector	Range	Type	Description
board.qpd1.dc	-10 V...0 V	out	Quadrant signals of QPD1
board.qpd1.ac	-10 V...10 V	out	Quadrant signals of QPD1, AC coupled and amplified
board.qpd2.dc	-10 V...0 V	out	Quadrant signals of QPD2
board.qpd2.ac	-10 V...10 V	out	Quadrant signals of QPD2, AC coupled and amplified
board.pzt1	0 V...150 V	in	PZT1 signals
board.pzt2	0 V...150 V	in	PZT2 signals
board.lens		in	Signals and power supply for lens servos
board.tpd.0db	-12 V...0 V	out	Signal of TPD, 1 kΩ transimpedance amplifier
board.tpd.40db	0 V...12 V	out	Amplified TPD signal
board.tpd.80db	-12 V...0 V	out	Amplified TPD signal
board.rpd.dc	-12 V...0 V	out	Signal of RPD, 200 Ω transimpedance amplifier
board.rpd.ac	-12 V...12 V	out	Amplified and AC coupled signal of RPD
board.rpd.rf	-12 V...12 V	out, 50Ω	Amplified and AC coupled signal of RPD
board.ccd		out	Video signal of CCD camera
board.power		in	Power supply for the photodiodes
board.pmc.mod	-15 V...15 V	in	Input for PMC PZT modulation
board.pmc.hv	0 V...150 V	in	Input for PMC PZT HV signal
board.shutter		in/out	Multiple input and output signals for the shutter

Figure 10: Breadboard interface description.

3.2 Remote interface

The electronic modules can be controlled by signals on the analog and digital bus of the electronic crate. Furthermore all measurements can be performed with the bus signals and three further photodiode signals, except the relative intensity noise between 1 MHz and 100 MHz, which requires an RF spectrum analyzer. So it is possible to control the DBB and perform measurements using only the bus and the mentioned three photodiode signals.

The electronic crate has room for two more electronic modules, which could do the actual interfacing between the bus and for example a computer. This interface module has to inject 14 analog signals (possibly 5 analog signals more, if you want to add offset voltages at the error points of the five control loops) and has to measure 21 analog signals. 18 digital signals must be set by the interface module and 1 digital signal must be read.

The analog bus is described in table 2 and the digital bus is described in table 3. The TFIN and TFMON analog signals are multiplexed to save some lines on the analog bus. The digital signals TFSEL0, TFSEL1 and TFSEL2 are used to select the desired signal (see table 4). Beyond the signals of these two buses, the interface modules has to measure the analog photodiode signals at the connectors board.tpd.0db, board.tpd.40db, board.tpd.80db. These three signals are due to space problems not available on the analog bus.ses, the interface modules has to measure the analog photodiode signals at the connectors board.tpd.0db, board.tpd.40db, board.tpd.80db. These three signals are due to space problems not available on the analog bus.

Every analog signal which is injected to the bus, is measured with a pseudo-differential amplifier by the appropriate module to avoid ground loops. The digital signals have to be referenced to the analog ground of the electronic crate. The interface module should use (pseudo-) differential amplifiers to measure the signals to avoid ground loops.

The demodulation phase can be controlled with the PHASE signal. The range is roughly from $0°$ to $270°$, in a nonlinear way. The gain signals are coded as $G(u) = 10\,\text{V}/u$.

4 Long-term adjustments

From time to time it might be necessary to make some adjustments to compensate for long-term drifts of mounts and electronic offsets. After installing the DBB for the first time or after moving it to a new location, these adjustments should be always performed. The best time to perform these adjustments is, when the whole DBB has reached the thermal equilibrium. The following sections describe which adjustments might be necessary. Perform the adjustments in the given order, since there are some dependencies.

QPD1 alignment

Align the incoming beam to the PMC using M1 and M2 (s. Sec. 6.1). Stop scanning the PMC and make the PMC off-resonant. Now measure the demod.qpd1.qx and demod.qpd1.qy signals and use BS2 to align the beam to QPD1. Both signals should be as close as possible to 0 V.

Wire	Name	Front connector	Range	BW	Source	Sink	Description
2-1	PHASE	demod.phase	0 V...10 V	0.3 Hz	*	demod	Demodulation Phase
3-1	CTRL1-GAINX	ctrl1.x.gain	0.1 V...10 V	0.3 Hz	*	ctrl1	Gain
4-1	CTRL1-GAINY	ctrl1.y.gain	0.1 V...10 V	0.3 Hz	*	ctrl1	Gain
5-1	CTRL2-GAINX	ctrl2.x.gain	0.1 V...10 V	0.3 Hz	*	ctrl2	Gain
6-1	CTRL2-GAINY	ctrl2.y.gain	0.1 V...10 V	0.3 Hz	*	ctrl2	Gain
7-1	CTRL0-GAIN	ctrl1.pmc.gain	0.1 V...10 V	0.3 Hz	*	ctrl1	Gain
8-1	CTRL1-OFSX		-12 V...12 V	100 kHz	*	ctrl1	Ctrl Offset
9-1	CTRL1-OFSY		-12 V...12 V	100 kHz	*	ctrl1	Ctrl Offset
10-1	CTRL2-OFSX		-12 V...12 V	100 kHz	*	ctrl2	Ctrl Offset
11-1	CTRL2-OFSY		-12 V...12 V	100 kHz	*	ctrl2	Ctrl Offset
12-1	CTRL0-OFS		-12 V...12 V	100 kHz	*	ctrl1	Ctrl Offset
14-13	CTRL1-ADDX	ctrl1.x.ofs	-10 V...10 V	100 kHz	*	ctrl1	Ctrl Add
16-15	CTRL1-ADDY	ctrl1.y.ofs	-10 V...10 V	100 kHz	*	ctrl1	Ctrl Add
18-17	CTRL2-ADDX	ctrl2.x.ofs	-10 V...10 V	100 kHz	*	ctrl2	Ctrl Add
20-19	CTRL2-ADDY	ctrl2.y.ofs	-10 V...10 V	100 kHz	*	ctrl2	Ctrl Add
22-21	CTRL0-ADD	ctrl1.pmc.ofs	-10 V...10 V	100 kHz	*	ctrl1	Ctrl Add
24-23	TFIN	(several)	-12 V...12 V	100 kHz	*	ctrl1/2,hv	TF Input
26-25	QPD1-QX	demod.qpd1.qx	-15 V...15 V	10 kHz	demod	*	DC Delta X Signal
27-25	QPD1-QY	demod.qpd1.qy	-15 V...15 V	10 kHz	demod	*	DC Delta Y Signal
28-25	QPD1-QS	demod.qpd1.qs	0 V...15 V	10 kHz	demod	*	DC Sumsignal
30-29	QPD2-QX	demod.qpd2.qx	-15 V...15 V	10 kHz	demod	*	DC Delta X Signal
31-29	QPD2-QY	demod.qpd2.qy	-15 V...15 V	10 kHz	demod	*	DC Delta Y Signal
32-29	QPD2-QS	demod.qpd2.qs	0 V...15 V	10 kHz	demod	*	DC Sumsignal
34-33	QPD1-DX	demod.qpd1.dx	-15 V...15 V	100 kHz	demod	ctrl1	Demodulated Delta X Signal
36-35	QPD1-DY	demod.qpd1.dy	-15 V...15 V	100 kHz	demod	ctrl1	Demodulated Delta Y Signal
38-37	QPD-DS	demod.qpd1.ds	-15 V...15 V	100 kHz	demod	ctrl1	Demodulated Sumsignal
40-39	QPD2-DX	demod.qpd2.dx	-15 V...15 V	100 kHz	demod	ctrl2	Demodulated Delta X Signal
42-41	QPD2-DY	demod.qpd2.dy	-15 V...15 V	100 kHz	demod	ctrl2	Demodulated Delta Y Signal
44-43	CTRL1-CTRLX	ctrl1.x.out	-15 V...15 V	100 kHz	ctrl1	hv	Control Signal
46-45	CTRL1-CTRLY	ctrl1.y.out	-15 V...15 V	100 kHz	ctrl1	hv	Control Signal
48-47	CTRL2-CTRLX	ctrl2.x.out	-15 V...15 V	100 kHz	ctrl2	hv	Control Signal
50-49	CTRL2-CTRLY	ctrl2.y.out	-15 V...15 V	100 kHz	ctrl2	hv	Control Signal
52-51	CTRL0-CTRL	ctrl1.pmc.out	-15 V...15 V	100 kHz	ctrl1	hv	Control Signal
54-53	PZTMON	hv.pmc.pztmon	-15 V...15 V	100 kHz	hv	*	PZT Monitor
56-55	TFMON	(several)	-15 V...15 V	100 kHz	ctrl1/2,hv	*	TF Monitor
58-57	HVMON	hv.pmc.mon	0 V...10 V	100 kHz	hv	*	HV Monitor
60-59	RIN-DC	misc.rpd.dc.out	-15 V...0 V	100 kHz	misc	*	RIN PD DC
61-59	RIN-AC	misc.rpd.ac.out	-15 V...15 V	100 kHz	misc	*	RIN PD AC
63-62	LENS1	misc.lens.pos1	-10 V...10 V	50 Hz	*	misc	Lens1 Position
64-62	LENS2	misc.lens.pos2	-10 V...10 V	50 Hz	*	misc	Lens2 Position

Table 2: Analog bus, 64 wire flatband cable. The wires are given in the format (signal wire)-(ground wire). BW = bandwidth.

Wire	Name	Front connector	Source	Sink	Low (0V)	High (5V)
13	D0		*	*	Spare	Spare
14	LENS-LATCH	misc.lens.on	*	misc	move	stay
15	SHUTTER-CLOSED	misc.led.shutter.closed	misc	*	Shutter Open	Shutter Closed
16	SHUTTER-OPEN	misc.shutter.open	*	misc	Close Shutter	Open Shutter
17	CTRL1-ONY	ctrl1.y.on	*	ctrl1	Ctrl Loop Open	Ctrl Loop Closed
18	RMTCTRL	*.led.rmt	*	(all)	Electronics in local control	Electronics in remote control
19	CTRL2-ONX	ctrl2.x.on	*	ctrl2	Ctrl Loop Open	Ctrl Loop Closed
20	MODOFF	demod.modoff	*	demod	1 MHz PZT Modulation	No RingPZT Modulation
21	CTRL2-ONY	ctrl2.y.on	*	ctrl2	Ctrl Loop Open	Ctrl Loop Closed
22	SCANMODE	hv.pmc.scanmode	*	hv	Lock Mode	Scan Mode
23	CTRL0-INT	ctrl1.pmc.on	*	ctrl1	Integrator Off	Integrator On
24	CTRL1-INTX	ctrl1.x.on	*	ctrl1	Integrator Off	Integrator On
25	CTRL0-ON	ctrl1.pmc.on	*	ctrl1	Ctrl Loop Open	Ctrl Loop Closed
26	CTRL1-INTY	ctrl1.y.on	*	ctrl1	Integrator Off	Integrator On
27	CTRL2-INTY	ctrl2.y.on	*	ctrl2	Integrator Off	Integrator On
28	CTRL2-INTX	ctrl2.x.on	*	ctrl2	Integrator Off	Integrator On
29	CTRL1-ONX	ctrl1.x.on	*	ctrl1	Ctrl Loop Open	Ctrl Loop Closed
30	TFSEL0		*	ctrl1/2,hv		
31	TFSEL1		*	ctrl1/2,hv		
32	TFSEL2		*	ctrl1/2,hv		

Table 3: Digital bus. All signals are referenced to ground at wires 7 and 8.

TFSEL	2	1	0
disabled	Low	Low	Low
ctrl1.x	Low	Low	High
ctrl1.y	Low	High	Low
ctrl1.pmc	Low	High	High
ctrl2.x	High	Low	High
ctrl2.y	High	High	Low
hv.pmc	High	High	High

Table 4: TFSEL coding.

QPD2 alignment

If you have not already aligned the incoming beam to the PMC using M1 and M2 and the Modescan technique, do it now. Stop scanning the PMC and make the PMC off-resonant. Now measure the demod.qpd2.qx and demod.qpd2.qy signals and use only M9 to align the beam to QPD2. Both signals should be as close as possible to 0 V.

TPD offset

Close the shutter and measure the offset at board.tpd80db. Use a screw driver to adjust the offset at the case of TPD to below 2 mV. Make this adjustment only after TPD has warmed up for at least 15 minutes.

5 Calibration

The following sections describe how to calibrate the DBB. These calibrations are long-term stable and hence need only be done once after building a DBB. Example calibrations are given in the appendix for comparison. For compatibility the calibration data should be stored in simple text files. The filenames and the format are described in the following sections. Table 5 shows an overview of the different calibration files.

If the DBB is controlled by RTLinux not all calibrations need to be performed. The calibrations which are only necessary for the analog controller case are marked.

Transfer functions should be saved in the following format: Three columns of numbers, decimal point is '.', line comments starts with '#' and the first column is the Fourier frequency in Hz, the second the magnitude in dB and the third the phase in degree. See an example below.

```
#   [ Freq, Hz ]      [ Mag, dB ] [ Phase, deg ]
            1          140.737         122.095
      1.02329          140.364         122.174
      1.04713          140.139         122.224
      1.07152          139.872         122.754
```

5.1 RPD calibration

5.1.1 TF from TIA output to board.rpd.ac signal

1. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V

2. Modulate the input power of the DBB or use a photodiode tester (which is assumed in the following).

3. Measure the TF from the laser diode monitor to the *rpd.ac* signal from 1 Hz to 100 kHz.

4. With the same setup and light power, measure the TF from the laser diode monitor to the *rpd.dc* signal between 1 Hz and 10 kHz

Filename	Content	Needed for
`date.dat`	Date of calibration	
`dbid.dat`	Serial number of DBB	
`pmc-cali.dat`	DC calibration of hv.pmc.mon in MHz/V	FRQ
`pmc-cali.py`	Calibration polynom of hv.pmc.mon in FSR/V for ramp signal	MSC
`pmc-fsr.dat`	FSR in MHz	MSC
`pnt1x-cali.dat`	DC calibration of ctrl1.x.out in eps/V	PNT1X
`pnt1y-cali.dat`	DC calibration of ctrl1.y.out in eps/V	PNT1Y
`pnt2x-cali.dat`	DC calibration of ctrl2.x.out in eps/V	PNT2X
`pnt2y-cali.dat`	DC calibration of ctrl2.y.out in eps/V	PNT2Y
`tf-hv-pztmon.dat`	TF from hv.pmc.pztmon to PMC resonance frequency in Hz/V	FRQ
`tf-pmc-loop.dat`	Loop TF of PMC length control loop	FRQ
`tf-pnt1x.dat`	TF from ctrl1.x.out to relative alignment in eps/V	PNT1X
`tf-pnt1x-loop.dat`	Loop TF of 1X alignment control loop	PNT1X
`tf-pnt1y.dat`	TF from ctrl1.y.out to relative alignment in eps/V	PNT1Y
`tf-pnt1y-loop.dat`	Loop TF of 1Y alignment control loop	PNT1Y
`tf-pnt2x.dat`	TF from ctrl2.x.out to relative alignment in eps/V	PNT2X
`tf-pnt2x-loop.dat`	Loop TF of 2X alignment control loop	PNT2X
`tf-pnt2y.dat`	TF from ctrl2.y.out to relative alignment in eps/V	PNT2Y
`tf-pnt2y-loop.dat`	Loop TF of 2Y alignment control loop	PNT2Y
`tf-rpd-ac.dat`	TF from RPD TIA output to board.rpd.ac	RIN
`tf-rpd-rf.dat`	TF from RPD TIA output to board.rpd.rf	RINRF

Table 5: Calibration files.

5. Calculate the TF from *rpd.dc* to *rpd.ac*. If you cannot measure below 100 Hz, extrapolate the *rpd.ac* TF down to 1 Hz and add a highpass at 10 Hz to the TF

6. Save the TF as `tf-rpd-ac.dat`

5.1.2 TF from TIA output to board.rpd.rf signal

1. Use a photodiode tester with a bandwidth of at least 100 MHz

2. Measure the TF from the laser diode monitor to the *rpd.rf* signal from 1 MHz to 100 MHz

3. With the same setup and light power, measure the TF from the laser diode monitor to the *rpd.dc* signal between 1 kHz and 10 kHz

4. Extrapolate the flat TF of the rpd.dc signal to 100 MHz and divide the TF of *rpd.rf* by this extrapolated TF.

5. If you were using a network analyzer with $50\,\Omega$ input impedance (which you should use at these frequencies), then divide the TF by 2, since the *rpd.dc* is a low impedance output and the *rpd.rf* is an $50\,\Omega$ output. This TF is now the TF from TIA output to the *board.rpd.rf* signal.

6. Save the TF as `tf-rpd-rf.dat`

5.2 PMC calibration

5.2.1 Calibration of hv.pmc.mon

1. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V

2. Turn all five control loops off

3. Switch *hv.pmc.scanmode* to scanmode

4. Switch *demod.modoff* to off

5. Adjust *ctrl1.pmc.ofs* such that *ctrl1.pmc.out* is 0 V.

6. Optimize the modematching with ML_1 and ML_2 and the alignment with M_1 and M_2. The fundamental mode must have at least twice the power of any higher order mode.

7. Inject a ramp signal with 10 V amplitude, a frequency of 1 Hz and an offset of 0 V into *hv.pmc.tfin*. Keep in mind that *hv.pmc.tfin* is a high impedance input.

8. Modulate the laser frequency with a ramp signal of about 1 GHz (corresponds to about 100 mV amplitude at NPRO temperature modulation input) with a frequency of 1 mHz. Make sure there is no mode hopping when modulating the frequency.

9. Simultaneous sample the signals *hv.pmc.mon* and *board.tpd.0db* at 250 kSamples/s for 1000 s DC coupled.

10. Determine for all 1000 rising ramps the *hv.pmc.mon* signal where a fundamental mode in the *board.tpd.0db* signal occurs. (see `pztfindpeaks.py`)

11. Calculate a function f(u), which returns the frequency tuning of the resonator in units of free spectral ranges for the given *hv.pmc.mon* signal. An overdetermined linear equation system can be solved for a polynom with the condition that the difference between this polynom applied to *hv.pmc.mon* signals of neighboring fundamental mode is one. (see `pztfit.py`)

12. Save this function as python function in `pmc-cali.py` . For example:

```
def f(x):
    return 0 + 0.446964*x**1 + 0.0131752*x**2 +
    -0.00142824*x**3 + 0.000154563*x**4 + -6.54091e-006*x**5
```

13. Calculate the FSR of the PMC. The round trip length of the PMC is $L = 420\,\text{mm}$ and hence the FSR $\nu = c/L = 714\,\text{MHz}$. Save the number in Hz in `pmc-fsr.dat` .

14. Calculate the average slope of f(u) and multiply it by the FSR in MHz. This is now the DC calibration of *hv.pmc.mon* in MHz/V (see `pztfit.py`). Save the number in `pmc-cali.dat` .

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5.2.2 TF from hv.pmc.pztmon to frequency

1. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V

2. Lock the PMC to the fundamental mode

3. Measure the TF from *hv.pmc.mon* to *demod.qpd1.ds* from 0.5 Hz to 10 Hz. Inject the source signal at *ctrl1.pmc.tfin*. This TF should look like a lowpass with a corner frequency around 3 Hz

4. Use the TF at low frequencies around 1 Hz at the flatband of the lowpass to calibrate the error signal *demod.qpd1.ds*. The DC calibration of the *hv.pmc.mon* signal is available in `pmc-cali.dat`.

5. Measure the TF from *hv.pmc.pztmon* to *demod.qpd1.ds* from 1 Hz to 100 kHz. Inject the source signal at *ctrl1.pmc.tfin*.

6. Calibrate *hv.pmc.pztmon* signal with the now known calibration of *demod.qpd1.ds*. The units of this TF should be Hz/V.

7. Save the TF as `tf-hv-pztmon.dat`

5.2.3 Loop TF

This calibration is only necessary for the analog controller case.

1. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V

2. Lock the PMC to the fundamental mode

3. Adjust the control loop gain at *ctrl1.pmc.gain*

4. Measure the TF from *demod.qpd1.ds* to *ctrl1.pmc.out* from 1 Hz to 100 kHz. Inject the source signal at *hv.pmc.tfin*.

5. Measure the TF from *ctrl1.pmc.out* to *demod.qpd1.ds* from 1 Hz to 100 kHz. Inject the source signal at *ctrl1.pmc.tfin*.

6. Multiply both TFs to get the loop TF. Since the loop TF has a very high gain at low frequencies, it is difficult to measure the TF in one go.

7. Save the TF as `tf-pmc-loop.dat` and double check the sign/phase of the loop TF.

5.3 PZT1, PZT2 calibration

The following instructions describe how to calibrate the 1X alignment loop. For calibrating the 1Y, 2X and 2Y loop you simply have to exchange the signal names in the instructions.

5.3.1 DC calibration of ctrl1.x.out

1. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V

2. Turn all five control loops off

3. Switch *hv.pmc.scanmode* to scanmode

4. Adjust *ctrl1.pmc.ofs* such that *ctrl1.pmc.out* is 0 V.

5. Adjust *ctrl1.x.ofs* such that *ctrl1.x.out* is 0 V.

6. Inject a ramp signal with 10 V amplitude, a frequency of 1 Hz and an offset of 0 V into *hv.pmc.tfin*.

7. Use a scope to measure *board.tpd.0db* and trigger on the injected ramp signal

8. Optimize the alignment to the PMC with M1 and M2

9. Measure the power ratio TEM10/TEM00 mode dependent on *ctrl1.x.out*. Adjust for example *ctrl1.x.ofs* such that *ctrl1.x.out* changes between -3 V and 3 V in 250 mV steps. You should get an almost quadratic dependence.

10. Fit the measured ratio to the model $r(\epsilon)$ to determine the DC calibration of *ctrl1.x.out* in eps/V.
$$r(\epsilon) = \epsilon^2$$

11. Save the number as `pnt1x-cali.dat`

5.3.2 TF from ctrl1.x.out to relative alignment

This calibration is only necessary for the analog controller case.

1. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V

2. Lock the PMC to the fundamental mode

3. Turn on the alignment loops

4. Measure the TF from *ctrl1.x.out* to *demod.qpd1.dx* from 1 Hz to 100 kHz. Inject the source signal at *ctrl1.x.tfin*. This TF should look like a lowpass with a corner frequency around 100 Hz

5. Use the TF at low frequencies at the flatband of the lowpass to calibrate *ctrl1.x.out*. The DC calibration of the *ctrl1.x.out* signal is saved in `pnt1x-cali.dat` . This TF should have the units eps/V.

6. Save the TF as `tf-pnt1x.dat`

5.3.3 Loop TF

This calibration is only necessary for the analog controller case.

1. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V

2. Lock the PMC to the fundamental mode

3. Turn on the alignment loops

4. Measure the TF from *ctrl1.x.tfmon* to *demod.qpd1.dx* from 1 Hz to 100 kHz. Inject the source signal at *ctrl1.x.tfin*. This TF is the loop TF of the alignment control loop.

5. Check the sign of the flat transfer function from *demod.qpd1.dx* to *ctrl1.x.tfmon*. There is no special point for source signal injection, use the existing noise to determine the sign.

6. Save the TF as `tf-pnt1x-loop.dat` and double check the sign/phase of the loop TF.

6 General Procedures

6.1 Manual input beam alignment

The following steps describe how to align a laser beam to the DBB.

1. Remove ML1 and ML2 from the rail

2. Use mirrors in front of the DBB to align the beam such, that it passes both almost closed iris diaphragms I1 and I2 on the rail

3. Calculate a modematching to the PMC

4. Eventually change the lenses of ML1 and ML2 to do the modematching

5. Mount ML1 and ML2 onto the rail at the calculated positions

6. Use the potentiometers ctrl1.x.ofs, ctrl1.y.ofs, ctrl1.pmc.ofs, ctrl2.x.ofs and ctrl2.y.ofs to set the high voltage roughly to 75V (5V at the high voltage monitors).

7. Set hv.pmc.scanmode to scan mode.

8. Scan the PMC by injecting a ramp signal (e.g. 10V, 12Hz) at hv.pmc.tfin

9. You should now see higher modes with the CCD camera. Use M1 and M2 to improve the alignment using the CCD camera signal

10. Use a scope to measure board.tpd.0db and trigger on the injected ramp signal

11. Use M1 and M2 to reduce the power of the TEM10 and TEM01 modes

12. Stop scanning the PMC by disconnecting the ramp signal.

6.2 PMC lock

The following steps describe how to lock one PMC resonance to the input beam. Figure 11 shows an overview of the different control loops.
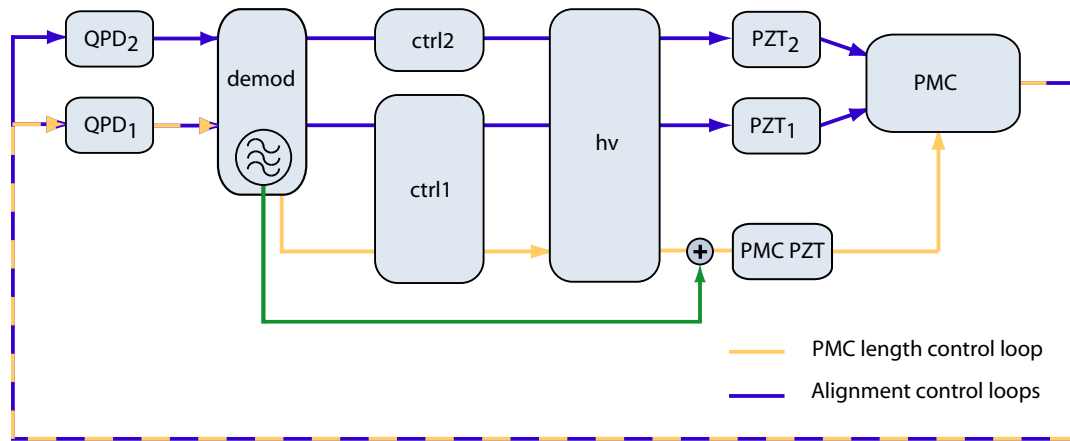
Figure 11: Control loops

1. Align the input beam to the PMC (s. Sec. 6.1)

2. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V.

3. Set hv.pmc.scanmode to lock mode.

4. Verify that the *demod.modoff* is turned on and no ramp signal is injected at *hv.pmc.tfin*.

5. Adjust *ctrl1.pmc.ofs* until a TEM00 mode is resonant. Use the CCD camera, *board.tpd.0db* or *demod.qpd1.qs* to check for the resonance condition.

6. Use *ctrl1.pmc.on* to turn on the control loop and the same switch to turn the integrator as well on.

7. Adjust the gain of the control loop with *ctrl1.pmc.gain*, such that the *demod.qpd1.ds* is not oscillating. Be aware of the low (<1Hz) adjustment bandwidth of *ctrl1.pmc.gain*.

6.3 Alignment locks

The following steps describe how to lock the alignment loops. Figure 11 shows an overview of the different control loops.

1. Lock the PMC (s. Sec. 6.2)

2. Turn on all alignment loops with *ctrl1.x.on*, *ctrl1.y.on*, *ctrl2.x.on* and *ctrl2.y.on*. Turn the integrators as well on.

3. Adjust the gains of the control loops with *ctrl1.x.gain*, *ctrl1.y.gain*, *ctrl2.x.gain* and *ctrl2.y.gain*. The error signals *demod.qpd1.dx*, *demod.qpd1.dy*, *demod.qpd2.dx*, *demod.qpd2.dy* must not oscillate.

4. To optimize the range of PZT1 and PZT2, use a scope to monitor the signals *ctrl1.x.out*, *ctrl1.y.out*, *ctrl2.x.out* and *ctrl2.y.out*. Use M1 and M2 to adjust the input beam alignment until all four monitored signals are $\approx 0\,\mathrm{V}$ (<1 V).

6.4 Modematching optimization

The following steps describe how to optimize the modematching to the PMC.

1. Lock the alignment loops (s. Sec. 6.3)

2. Measure the signal *demod.qpd1.qs* or *demod.qpd2.qs*. This is the reflected light power, which must be minimized.

3. While optimizing, monitor the signals *ctrl1.x.out*, *ctrl1.y.out*, *ctrl2.x.out* and *ctrl2.y.out*. These signals might saturate. If this is the case, use M1 and M2 to realign the input beam to the PMC. For the largest dynamic range these signals should be near 0V.

4. Either move ML1 and ML2 along the rail manually or use *misc.lens.pos1* and *misc.lens.pos2* to move the lenses. You have to turn the lens movement on using *misc.lens.on* beforehand. After optimizing the lens positions turn the lens movement off since otherwise the servo motors might overheat.

5. To find the global minimum of *demod.qpd1.qs* both lenses must be moved in general. Optimizing each lens on its own is often not sufficient.

6. To finally check, if the modematching is optimized, set *ctrl1.x.out*, *ctrl1.y.out*, *ctrl2.x.out* and *ctrl2.y.out* to 0V and then turn all control loops off and use *ctrl1.pmc.ofs* to make the TEM20 and TEM02 modes resonant. Use the CCD camera to check the actual mode structure. Lag10 mode fractions can be completely matched to the PMC. However Lag02 mode fractions cannot be matched to PMC using only two spherical lenses. So the modematching is optimized when only a Lag02 mode is visible.

7 Relative Intensity Noise

The power of the input beam is measured with the photodiode RPD. The photocurrent is converted to a voltage with a TIA and some signal conditioning is done inside of RPD. The AC output has a gain of about 40 dB and a high pass at around 10 Hz.

7.1 Measurement

Preparations

1. Align the input beam to the PMC

2. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V.

Sampling

1. Simultaneous sample the *board.rpd.dc* and *board.rpd.ac* signals at 250 kSamples/s. Measure these signals with differential inputs. Use DC coupling for *board.rpd.dc* and keep in mind, that this signal may be larger than 10 V. Use AC coupling for *board.rpd.ac*.

7.2 Calibration and Presentation

Long-term power fluctuations

1. Downsample the *board.rpd.dc* signal to 1 Sample/s

2. Calculate the average signal, the min/max signal and the standard deviation of the signal

3. Plot the normalized signal for the measurement duration over the time

Noise in measurement band

1. Calculate the LSD of the *board.rpd.ac* signal from 1 Hz to 100 kHz

2. Divide by AC coupling TF

3. Divide by the TF `tf-rpd-ac.dat`

4. Normalize the LSD by the average signal U_{avg} obtained from the *board.rpd.dc* measurement to get RIN

5. Plot this LSD

6. Include the shotnoise level, which should be around $2.5 \cdot 10^{-9}/\sqrt{Hz}$

$$N_{sn} = \sqrt{2 \cdot 1.602 \cdot 10^{-19}\,\text{C} \cdot 200\,\Omega/U_{avg}}$$

8 Relative Intensity Noise in RF Band

The power of the input beam is measured with the photodiode RPD. The photocurrent is converted to a voltage with a TIA and some signal conditioning is done inside of RPD. The RF output has a gain of about 34 dB and a high pass at around 1 MHz. This output is a 50 Ω output.

8.1 Measurement

Preparations

1. Align the input beam to the PMC

2. Turn the PMC modulation at *demod.modoff* off.

3. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V.

Sampling

1. Connect the *board.rpd.rf* signal to an spectrum analyzer with 50 Ω input impedance.

2. Measure the LSD (not the spectrum!) of the signal in three frequency bands: 1 MHz to 10 MHz, 10 MHz to 30 MHz and 30 MHz to 100 MHz. Use about 32 averages.

3. Measure the DC value of the *board.rpd.dc* signal

Electronic noise

To correct for electronic noise of the photodiode, do the following measurement. It is advisable to correct for electronic noise for measurements above about 60 MHz.

1. Close the shutter

2. Connect the *board.rpd.rf* signal to the spectrum analyser with 50 Ω input impedance.

3. Measure the LSD of the signal in three frequency bands: 1 MHz to 10 MHz, 10 MHz to 30 MHz and 30 MHz to 100 MHz. Use about 32 averages.

8.2 Calibration and Presentation

Steps 3 to 5 are optional.

1. Merge the LSD of the three frequency bands

2. Divide this LSD by the transfer function `tf-rpd-rf.dat`

3. Merge the LSD of the three frequency bands of the electronic noise (opt.)

4. Divide this electronic noise LSD by the transfer function `tf-rpd-rf.dat` (opt.)

5. Subtract the electronic noise from the merged signal LSD (opt.)

6. Divide this LSD by the DC value U_{avg} of the *board.rpd.dc* signal

7. Plot this LSD

8. Include the shot noise level, which should be around $2.5 \cdot 10^{-9}/\sqrt{Hz}$

$$N_{sn} = \sqrt{2 \cdot 1.602 \cdot 10^{-19}\,\text{C} \cdot 200\,\Omega/U_{avg}}$$

9 Frequency Noise

The frequency noise of the input beam is measured with the PMC. To be able to measure the frequency noise, the round-trip length of the PMC must be more stable than the laser frequency. One resonance of the PMC is locked to the laser frequency by changing the length of the PMC with a PZT. This control loop has a bandwidth of about 1 kHz. The deviation between the resonance frequency of the PMC and the laser frequency can be measured at *demod.qpd1.ds*. This signal contains the frequency fluctuations of the laser above unity gain. The signal at the PZT can measured at *hv.pmc.pztmon*. The signal *hv.pmc.pztmon* is AC coupled and reflects frequency fluctuations below the unity gain frequency. For long-term frequency fluctuations you have to use the DC coupled signal *hv.pmc.mon*.

9.1 Measurement

Preparations

1. Align the input beam to the PMC

2. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V.

3. Lock the PMC including the AA, to reduce pointing effects

4. For the rest of the measurement do not adjust the gain of the PMC length control loop or the input power.

Sampling

1. Simultaneous sample the three signals *demod.qpd1.ds*, *hv.pmc.pztmon* and *hv.pmc.mon* at 250 kSamples/s. Use AC coupling and differential inputs to measure the signals *demod.qpd1.ds*, *hv.pmc.pztmon*. Use DC coupling and differential inputs for *hv.pmc.hvmon*.

Short-term calibration measurements

1. Measure the TF from *hv.pmc.pztmon* to *demod.qpd1.ds* from 100 Hz to 1 kHz. Inject the source signal at *hv.pmc.tfin*. This TF is used to calibrate the errorsignal. It is enough to note the level of the TF, since it should be a flat TF.

2. Measure the TF from *demod.qpd1.ds* to *ctrl1.pmc.out* around 500 Hz to 600 Hz at one Fourier frequency. Inject the source signal at *hv.pmc.tfin*. This TF is used to calculate the loop TF.

3. Measure the TF from *ctrl1.pmc.out* to *demod.qpd1.ds* at the same Fourier frequency. Inject the source signal at *ctrl1.pmc.tfin*. This TF is used to calculate the loop TF.

9.2 Calibration and Presentation

Long-term frequency fluctuations

1. Downsample the *hv.pmc.hvmon* signal to 1 Sample/s

2. Calibrate the signal by `pmc-cali.dat` to frequency fluctuations in MHz.

3. Calculate the average signal

4. Subtract the average from the signal

5. Calculate the min/max signal

6. Calculate the standard deviation of the signal

7. Plot the signal for the measurement duration over the time

Noise in measurement band

1. Calculate the LSD of the *demod.qpd1.ds* and *hv.pmc.pztmon* signal from 1 Hz to 100 kHz

2. Divide by AC coupling TF

3. Multiply the inverse of TF `tf-hv-pztmon.dat` with the measured TF from *hv.pmc.pztmon* to *demod.qpd1.ds*. This is now a TF from frequency fluctuations to the *demod.qpd1.ds* signal. Since this TF is flat, it is enough to evaluate this formula at one Fourier frequency.

4. Calibrate the LSD of *demod.qpd1.ds* to frequency fluctuations by dividing by the TF from frequency fluctuations to the *demod.qpd1.ds* signal.

5. Calibrate the LSD of *hv.pmc.pztmon* to frequency fluctuations by multiplying by the TF `tf-hv-pztmon.dat`.

6. Calculate the loop TF of the PMC length control loop by adjusting the p-gain of `tf-pmc-loop.dat`, such that it matches the measured loop TF at the one Fourier frequency.

7. Merge the calibrated signals *demod.qpd1.ds* and *hv.pmc.pztmon* to one LSD of frequency fluctuations with the loop TF.

8. Plot this LSD

10 Pointing

Pointing is measured in respect to the fundamental mode of the PMC. One resonance of the PMC is locked to the input beam. The beam which is reflected from the PMC is a superposition of a phase modulated beam from the inside of the PMC and the input beam. The quadrant photodiodes QPD1 and QPD2 are used to measure the beat between both beams to determine the relative alignment between them (DWS). The PZTs PZT1 and PZT2 are used to align the beam

to the PMC using four control loops 1X, 1Y, 2X and 2Y. The bandwidth of the control loops is about 100 Hz. Pointing fluctuations below unity gain can be measured using the control signals *ctrl1.x.out*, *ctrl1.y.out*, *ctrl2.x.out* and *ctrl2.y.out*. Above unity gain the alignment deviation can be measured using the error signals *demod.qpd1.dx*, *demod.qpd1.dy*, *demod.qpd2.dx* and *demod.qpd2.dy*.

10.1 Measurement

Preparations

1. Align the input beam to the PMC

2. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V.

3. Lock the PMC including the AA

4. For the rest of the measurement do not adjust the gain of the alignment control loops or the input power.

Sampling

1. Simultaneous sample the two signals *demod.qpd1.dx* and *ctrl1.x.out* at 250 kSamples/s. Use AC coupling and differential inputs for both signals. Additionally sample the signal *ctrl1.x.out* using DC coupling.

Repeat these steps for the alignment loops 2X, 1Y and 2Y.

Short-term calibration measurements

1. Measure the TF from *ctrl1.x.out* to *demod.qpd1.dx* from 1 Hz to 30 Hz. Inject the source signal at *ctrl1.x.tfin*. This TF is used to calibrate the errorsignal. It is enough to note the level of the TF, since it should be a flat TF.

2. Measure the TF from *ctrl1.x.tfmon* to *demod.qpd1.dx* around 500 Hz to 600 Hz at one Fourier frequency. Inject the source signal at *ctrl1.x.tfin*. This TF is the loop TF of the alignment control loop.

Repeat these steps for the alignment loops 2X, 1Y and 2Y.

10.2 Calibration and Presentation

Long-term pointing fluctuations

1. Downsample the *ctrl1.x.out* signal, which was DC coupled, to 1 Sample/s

2. Calibrate the signal by `pnt1x-cali.dat` to relative alignment fluctuations

3. Calculate the average signal

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4. Subtract the average from the signal

5. Calculate the min/max signal

6. Calculate the standard deviation of the signal

7. Plot the signal for the measurement duration over the time

Noise in measurement band

1. Calculate the LSD of the *demod.qpd1.dx* and *ctrl1.x.out* signal from 1 Hz to 100 kHz

2. Divide by AC coupling TF

3. Multiply the inverse of TF `tf-pnt1x.dat` with the measured TF from *ctrl1.x.out* to *demod.qpd1.dx*. This is now a TF from tilt fluctuations to the *demod.qpd1.dx* signal. Since this TF is flat below about 30 Hz, it is enough to evaluate this formula at one Fourier frequency.

4. Calibrate the LSD of *demod.qpd1.dx* to tilt fluctuations by dividing by the TF from tilt fluctuations to the *demod.qpd1.dx* signal.

5. Calibrate the LSD of *ctrl1.x.out* to tilt fluctuations by multiplying by the TF `tf-pnt1x.dat` .

6. The TF from *ctrl1.x.tfmon* to *demod.qpd1.dx* is the loop TF, except for the sign. Adjust the p-gain of `tf-pnt1x-loop.dat` to match the magnitude of the measured loop TF. This TF is now the loop TF.

7. Merge the calibrated signals *demod.qpd1.dx* and *ctrl1.x.out* to one LSD of pointing fluctuations with the loop TF.

8. Plot this LSD

Repeat these steps for the alignment loops 2X, 1Y and 2Y.

11 Beam Quality

The beam quality of the input beam is measured by scanning the PMC over one FSR. By scanning the PMC and measuring the transmitted power with the photodiode TPD, the input beam can be decomposed into TEM modes. The photocurrent is converted to a voltage using a TIA. The power in the TEM00 modes compared to the total power is used to characterize the beam quality. The photodiode TPD contains two low offset DC coupled 40 dB amplifiers for signal conditioning. TPD generates the signals *board.tpd.0db*, *board.tpd.40db* and *board.tpd.80db*.

11.1 Measurement

Preparations

1. Optimize the modematching and the alignment to the PMC

2. Adjust the input power, such that *board.rpd.dc* is between 9 V and 11 V.

3. Turn all five control loops off

4. Switch the *hv.pmc.scanmode* to scanmode.

5. Turn the *demod.modoff* off.

6. Adjust *ctrl1.pmc.ofs* such that *ctrl1.pmc.out* is 0 V.

7. Inject a ramp signal with 10 V amplitude, a frequency of 1 Hz and an offset of 0 V into *hv.pmc.tfin*. Keep in mind, that *hv.pmc.tfin* is a high impedance input.

Sampling

1. Simultaneous sample all four signals *hv.pmc.mon*, *board.tpd.0db*, *board.tpd.40db* and *board.tpd.80db* at 250 kSamples/s. Use DC coupling. For each second sampled, one modescan will be extracted. Sample at least two seconds.

11.2 Calibration and Presentation

For each sampled rising ramp do the following:

1. Merge the signals *board.tpd.0db*, *board.tpd.40db* and *board.tpd.80db* into one signal with increased dynamic range and normalize the signal to be between 0 and 1.

2. Fit the ramp of the *hv.pmc.mon* signal to a linear function.

3. Use `pmc-cali.py` to calibrate this linear function to frequency tuning of the resonator.

4. Trim the signal to the middle FSR.

5. Determine the power of each higher mode and identify the mode by its frequency tuning. If phase or amplitude sidebands are present on the input beam, identify them by the sideband frequency (`pmc-fsr.dat`) and the power ratio.

6. Sum all modes to determine the overall power and the calculate the power fraction in higher modes compared to the fundamental mode.

7. Plot the merged and frequency-tuning calibrated signal with a fit to the fundamental mode and a fit to the overall signal. Use a logarithmic y axis.

A Example Calibration

The following pages contain the calibration data for one DBB. Section 5 explains in detail how to measure this calibration data.

Advanced LIGO PSL DBB
Calibration Data

March 13, 2007

Serial number (DBID): DBID3000

Date of calibration: Fri Mar 9 12:32:51 2007

Serial number (DBID)	DBID3000	`dbid.dat`
Date of calibration	Fri Mar 9 12:32:51 2007	`date.dat`
hv.pmc.mon calibration	319.57926 MHz/V	`pmc-cali.dat`
FSR	716e6 Hz	`pmc-fsr.dat`
PMC PZT nonlinearity (hv.pmc.mon)	$0 \quad +0.446964 \quad \cdot \quad x^1$	`pmc-cali.py`
	$+0.0131752 \quad \cdot \quad x^2$	
	$+ \quad - \quad 0.00142824 \quad \cdot \quad x^3$	
	$+0.000154563 \quad \cdot \quad x^4$	
	$+ - 6.54091e - 006 \cdot x^5$	
	FSR/V	

Table 1: Calibration values.
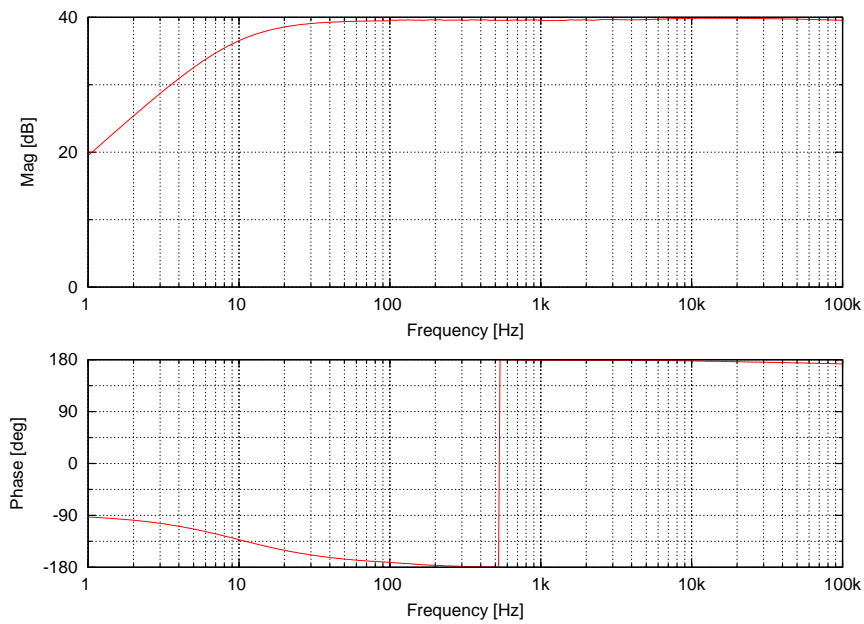
Figure 1: Transfer function from board.rpd.dc to board.rpd.ac (`tf-rpd-ac.dat`).
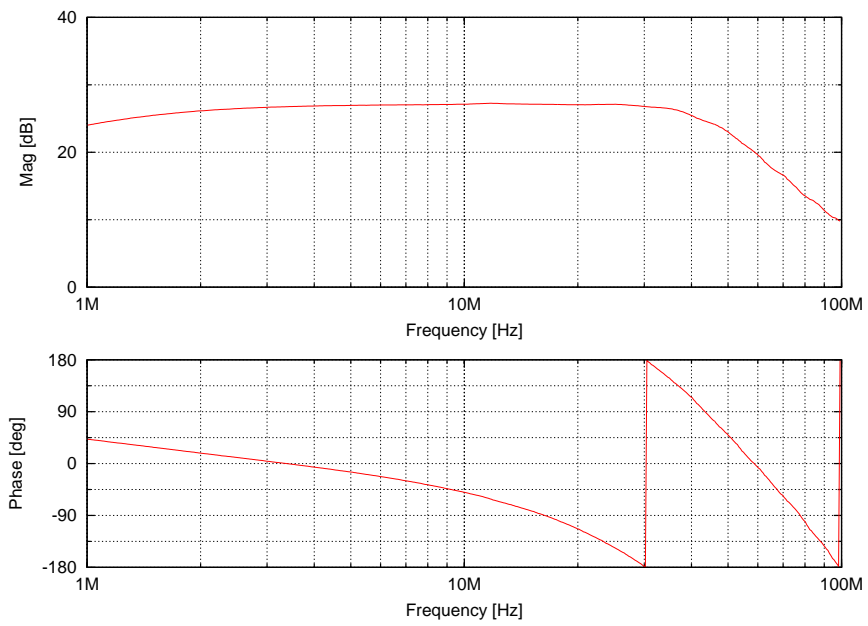
Figure 2: Transfer function from board.rpd.dc to board.rpd.rf (`tf-rpd-rf.dat`).
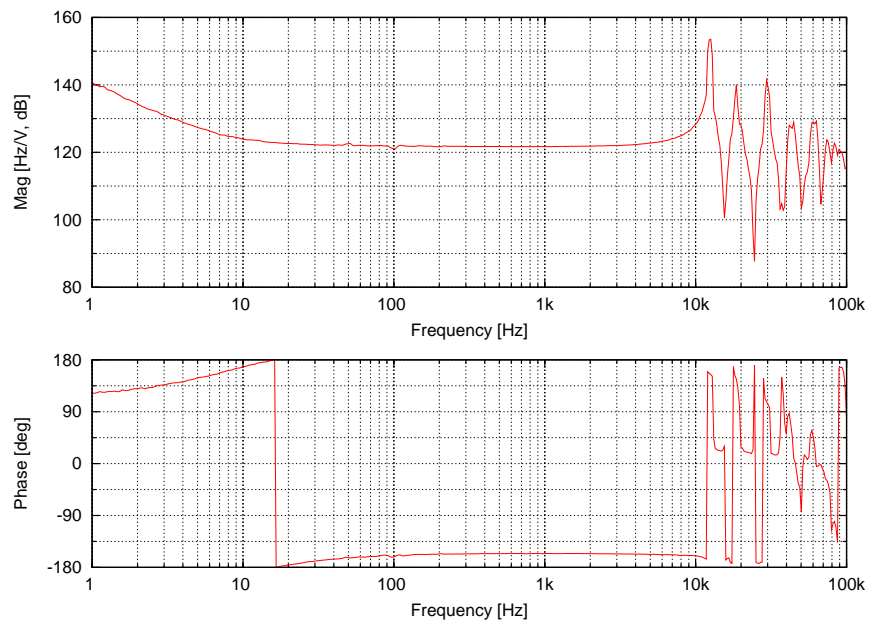
Figure 3: Transfer function from hv.pmc.pztmon to PMC resonance frequency (`tf-hv-pztmon.dat`).
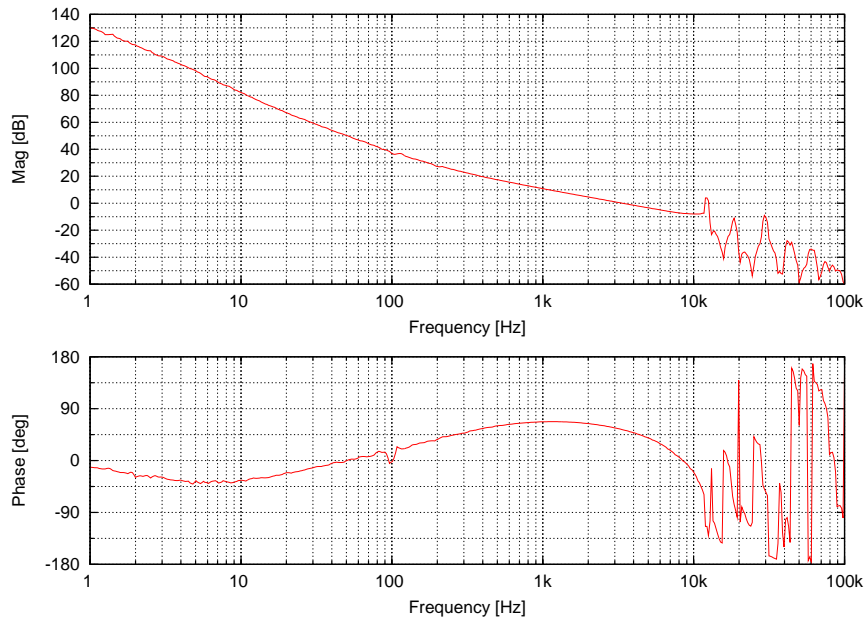
Figure 4: Loop transfer function of PMC length control loop (`tf-pmc-loop.dat`).
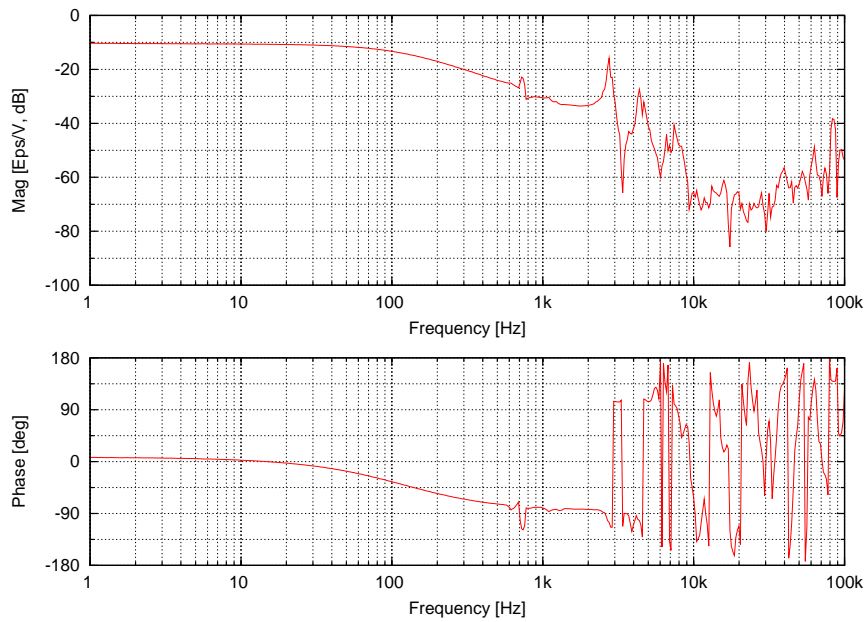
Figure 5: Transfer function from ctrl1.x.out to relative alignment to the PMC (`tf-pnt1x.dat`).
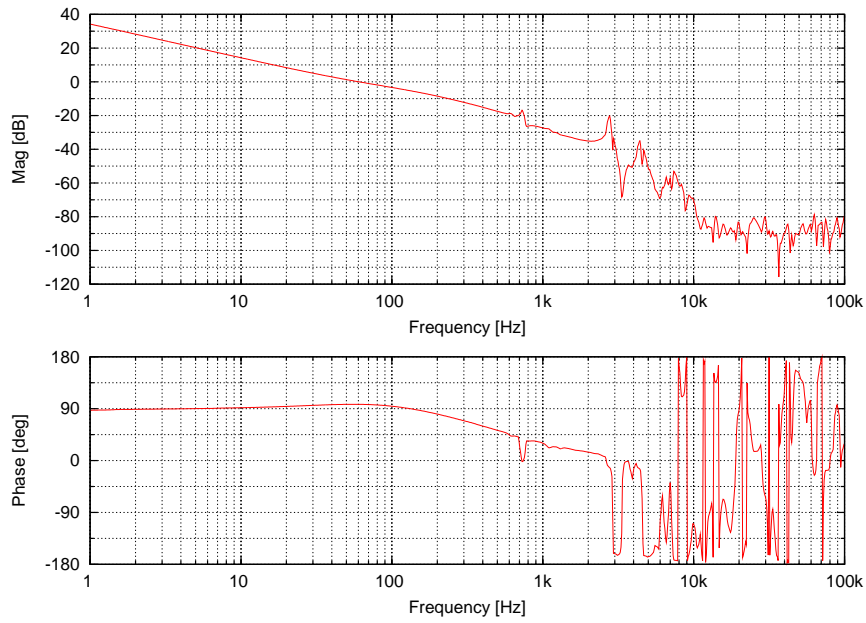
Figure 6: Loop transfer function of alignment loop 1X (`tf-pnt1x-loop.dat`).
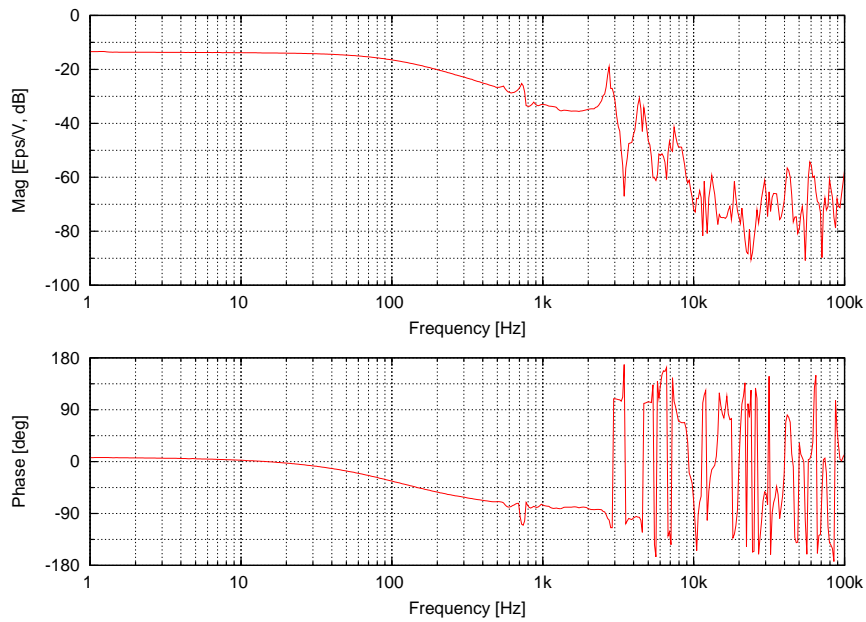
Figure 7: Transfer function from ctrl1.y.out to relative alignment to the PMC (`tf-pnt1y.dat`).
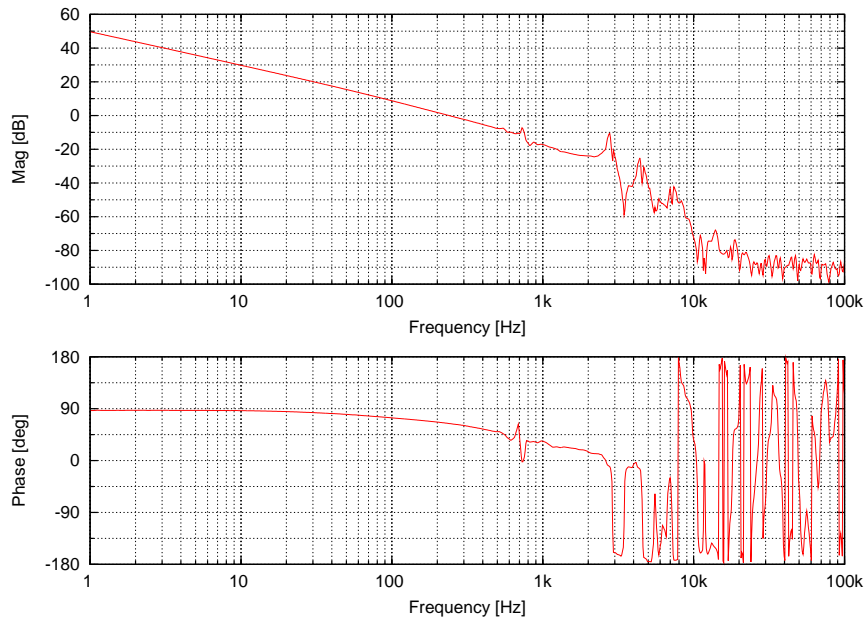
Figure 8: Loop transfer function of alignment loop 1Y (`tf-pnt1y-loop.dat`).
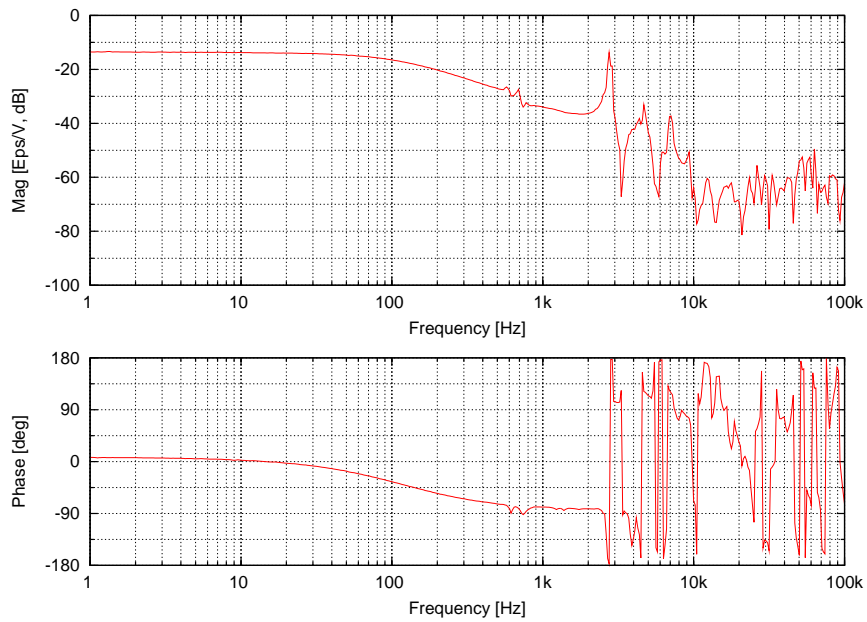
Figure 9: Transfer function from ctrl2.x.out to relative alignment to the PMC (`tf-pnt2x.dat`).
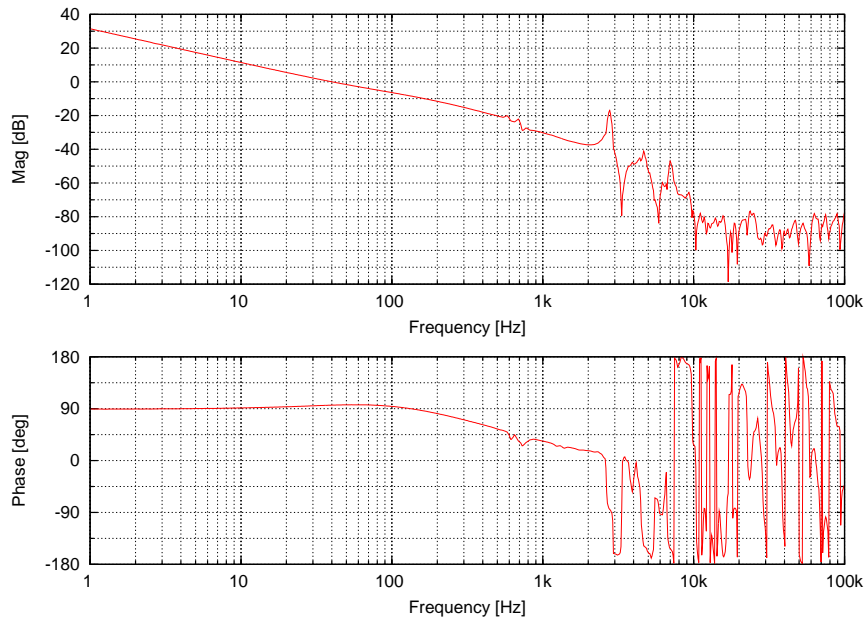
Figure 10: Loop transfer function of alignment loop 2X (`tf-pnt2x-loop.dat`).
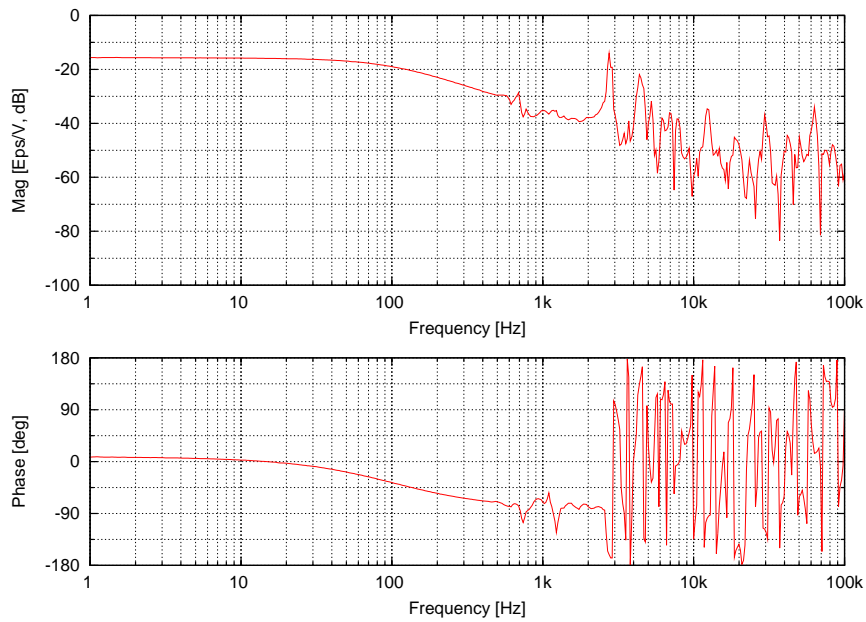
Figure 11: Transfer function from ctrl2.y.out to relative alignment to the PMC (`tf-pnt2y.dat`).
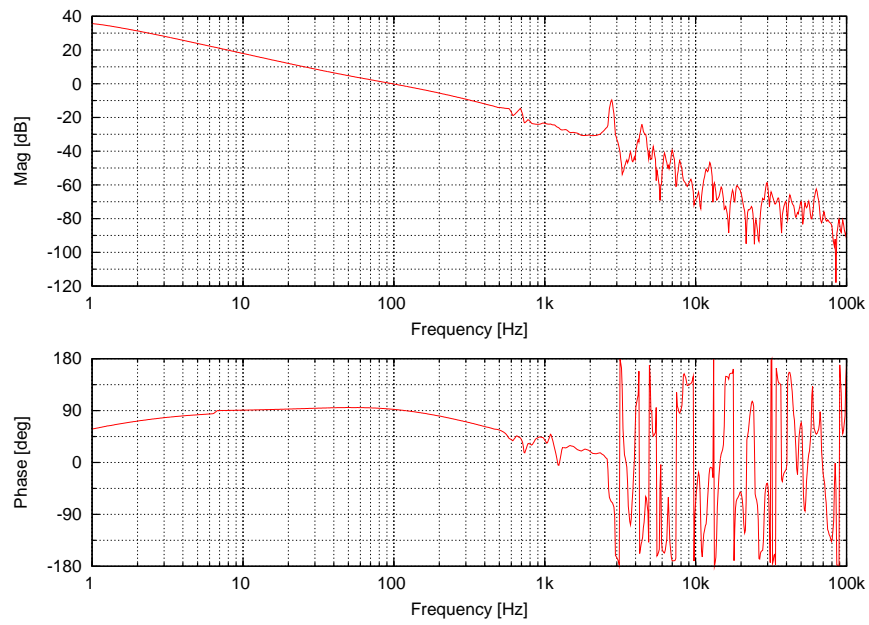
Figure 12: Loop transfer function of alignment loop 2Y (`tf-pnt2y-loop.dat`).

B Example Measurements

The following pages show example measurements. The output beam of an NPRO was characterized. Sections 7 to 11 explain in detail how these measurements were performed.

Relative Intensity Noise
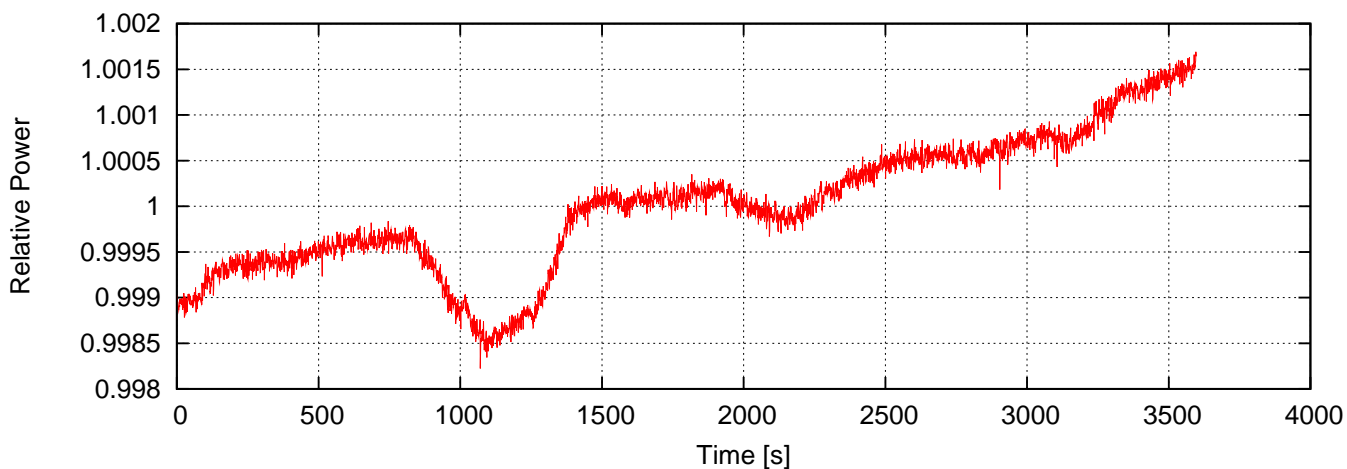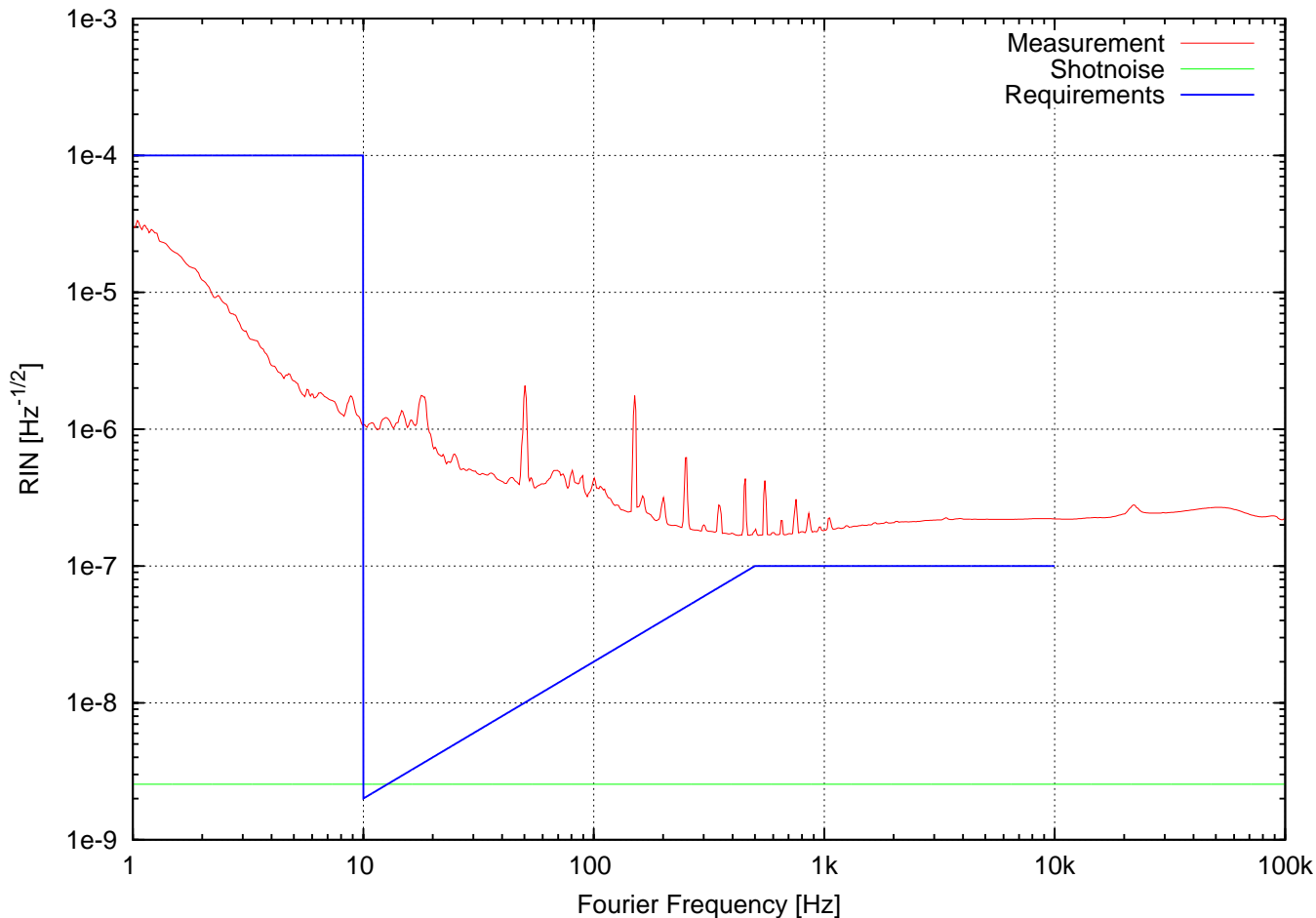
Measurement duration:	3600 s = 60 min
Measurement start:	Tue Mar 13 09:06:24 2007
Average DC signal:	9.88626 V
DC signal range (full data rate):	9.83704 V . . . 9.95362 V
Photocurrent:	49 mA
Relative shotnoise level:	2.55e-09 Hz$^{-1/2}$

Notes:

Advanced LIGO NPRO, Spare #2, I=2300mA, Noise Eater, Flowbox 2%

Relative Intensity Noise RF
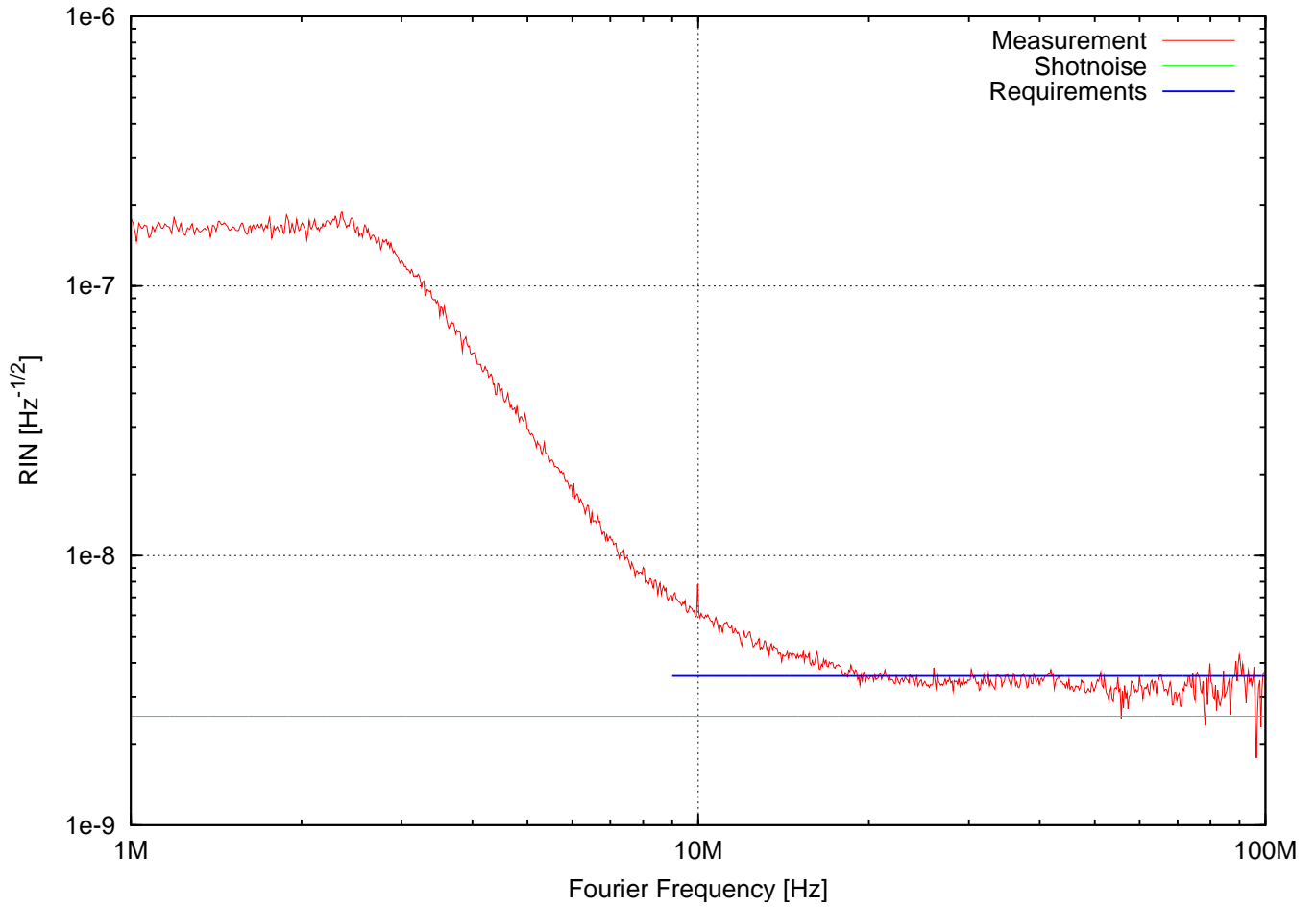
DC signal:	10 V
Photocurrent:	50 mA
Relative shotnoise level:	2.53e-09 Hz$^{-1/2}$

Notes:
Advanced LIGO NPRO, Spare #2, I=2300mA, Noise Eater, Flowbox 2%

Frequency Noise
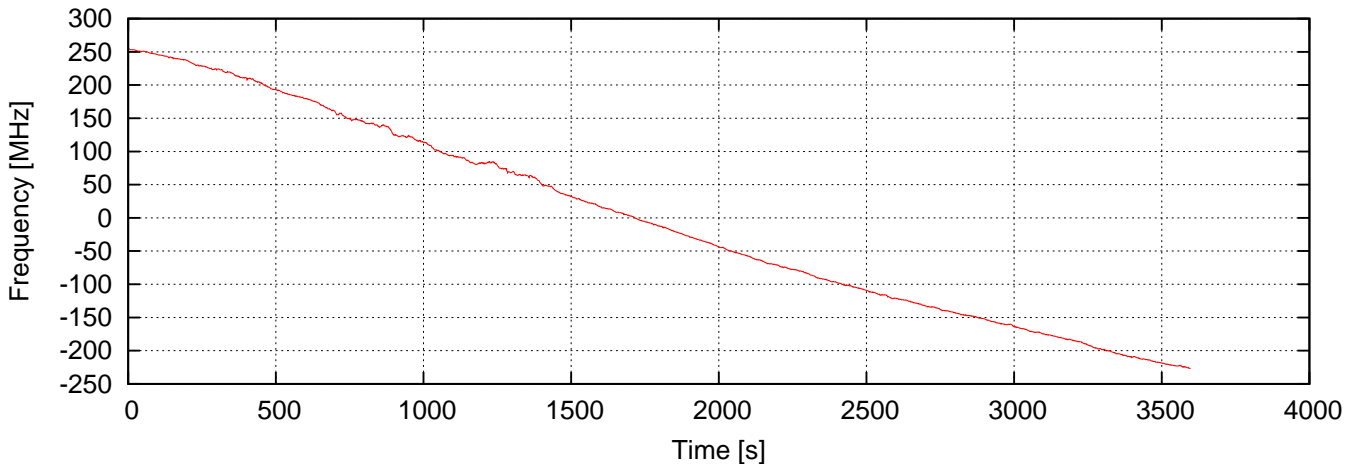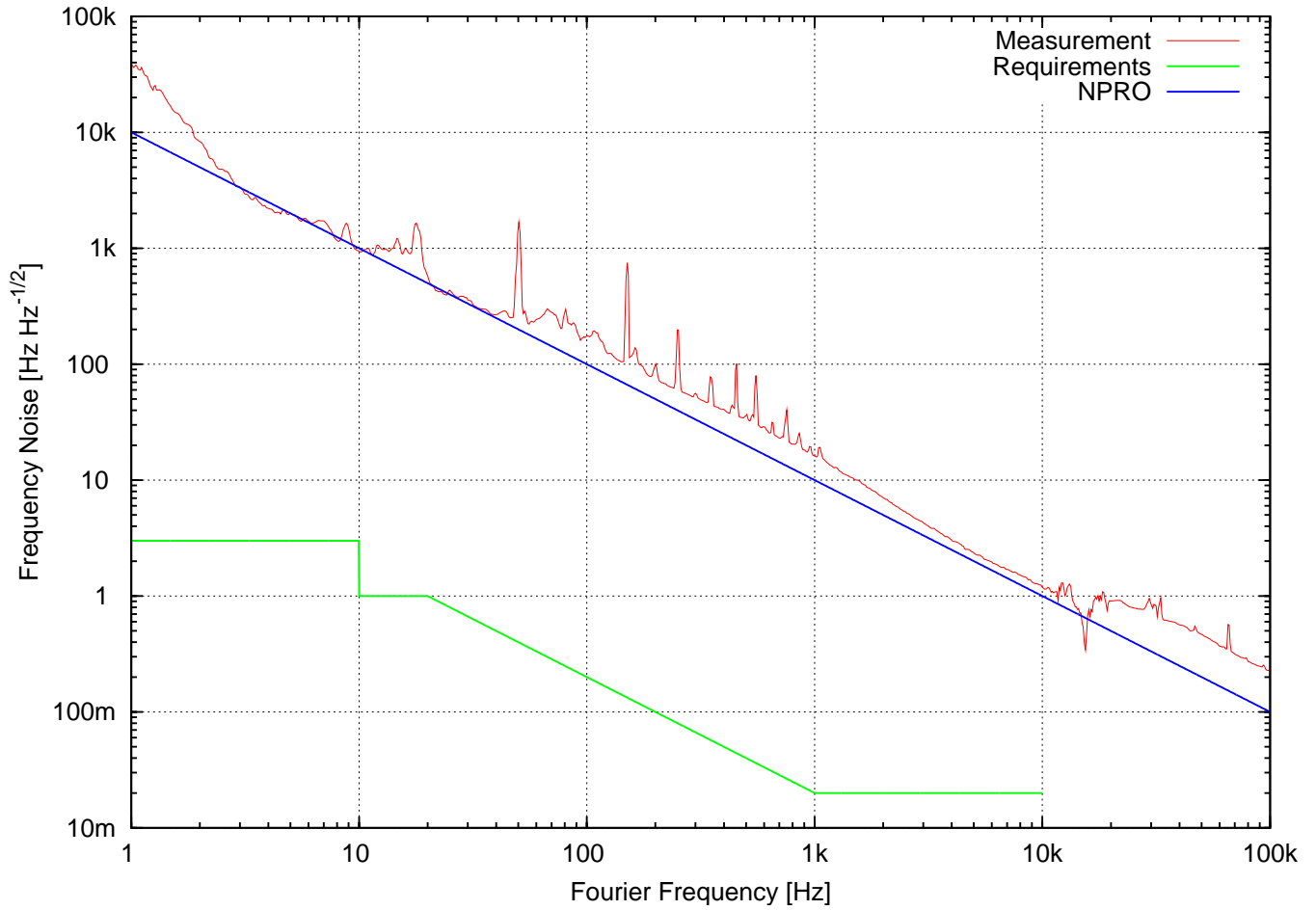
Measurement duration:	3600 s = 60 min
Measurement start:	Tue Mar 13 12:00:40 2007
Uncalibrated error signal:	0.592096 V rms, -4.21021 V … 4.24591 V
Uncalibrated PZT monitor signal:	0.40622 V rms, -7.40784 V … 7.47833 V
PZT position: 43.3 % … 58.4 %	

Notes:
Advanced LIGO NPRO, Spare #2, I=2300mA, Noise Eater, Flowbox 2%

Pointing 1X
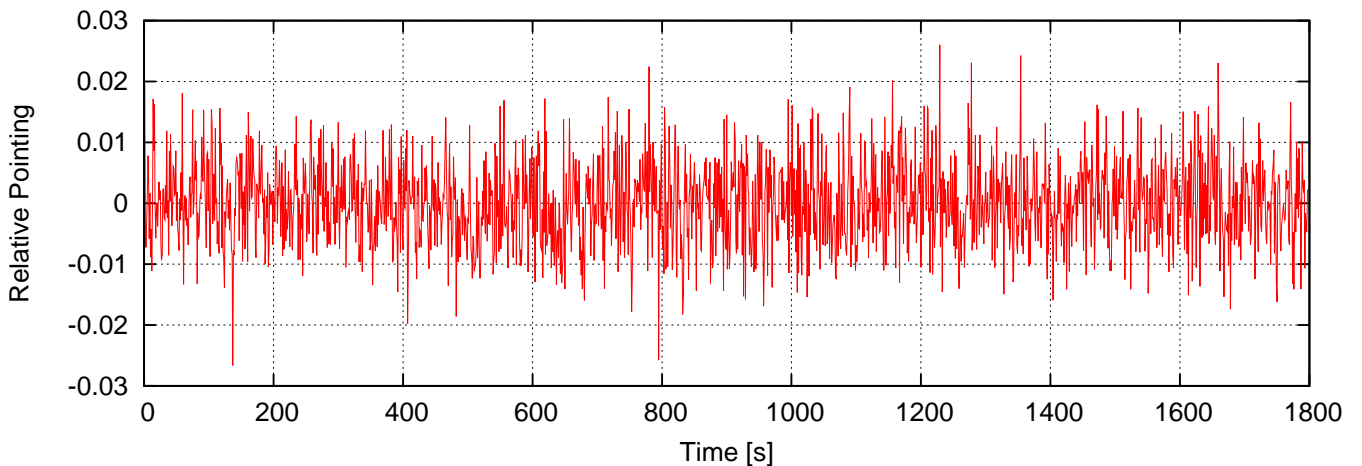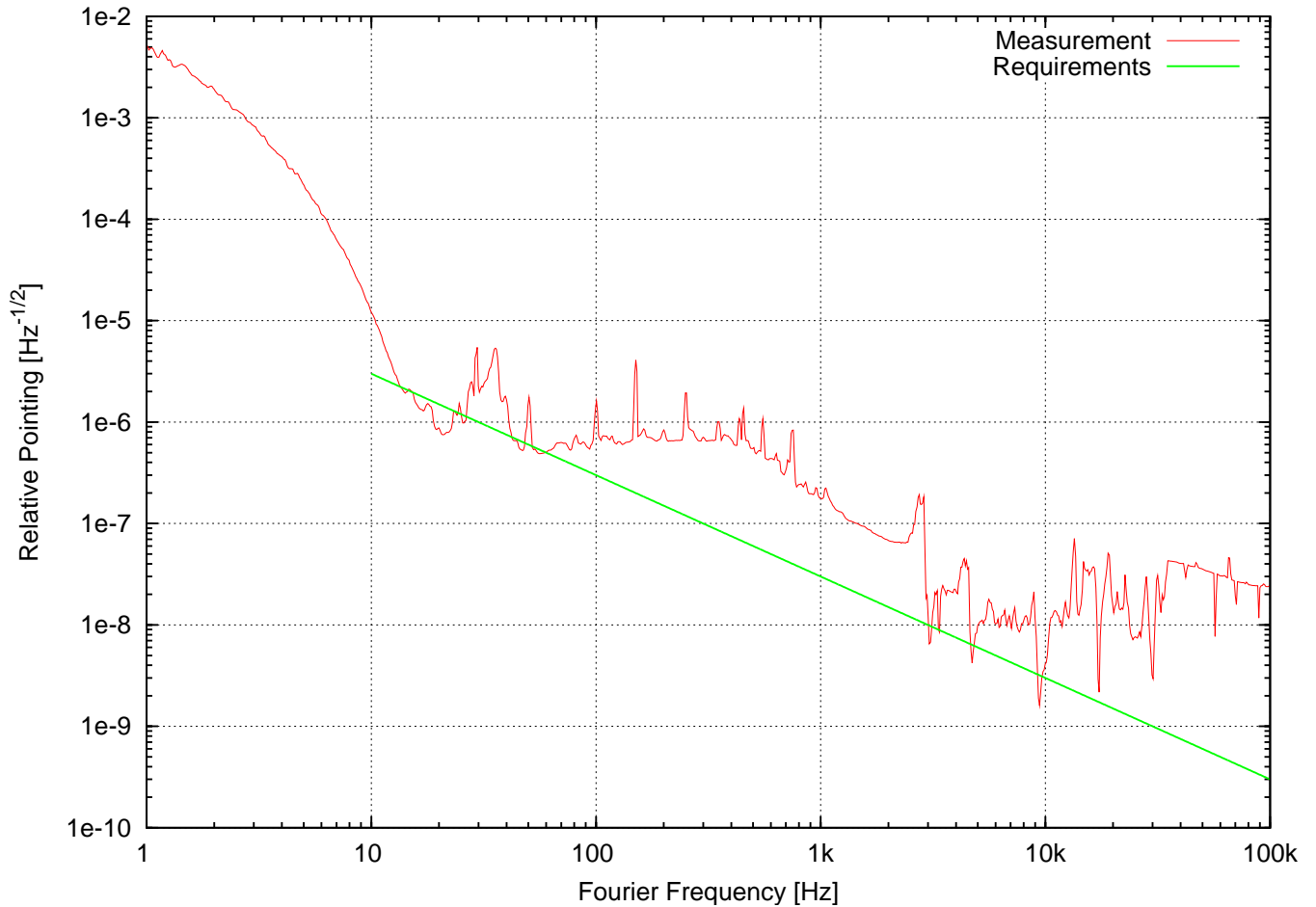
Measurement duration:	1800 s = 30 min
Measurement start:	Tue Mar 13 13:38:02 2007
Uncalibrated error signal:	0.121764 V rms, -1.12335 V . . . 0.946045 V
Uncalibrated control signal:	0.385374 V rms, -2.32971 V . . . 1.97662 V
PZT position: 53.4 % . . . 54.7 %	

Notes:
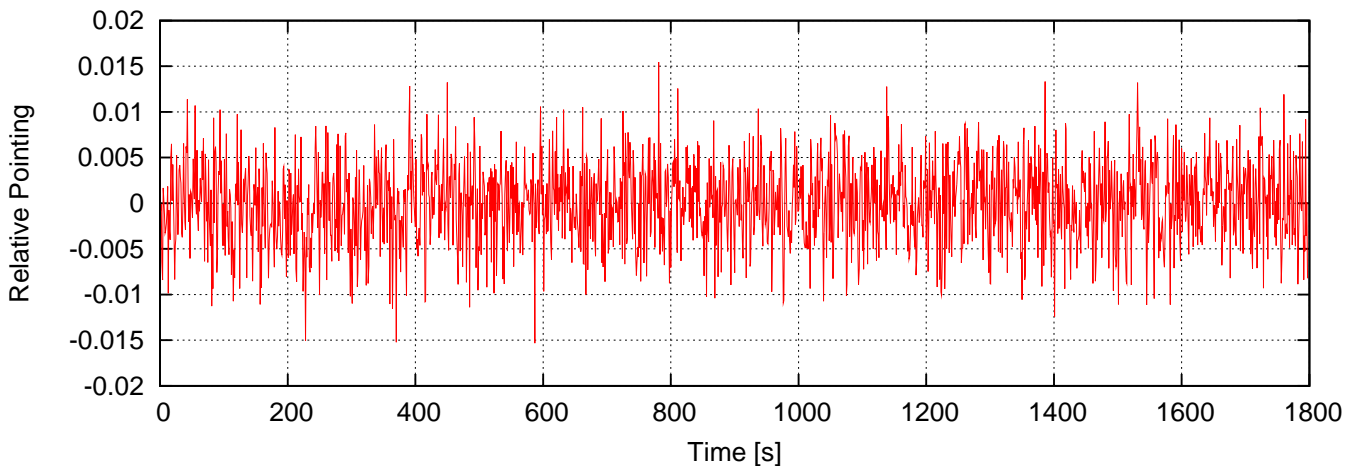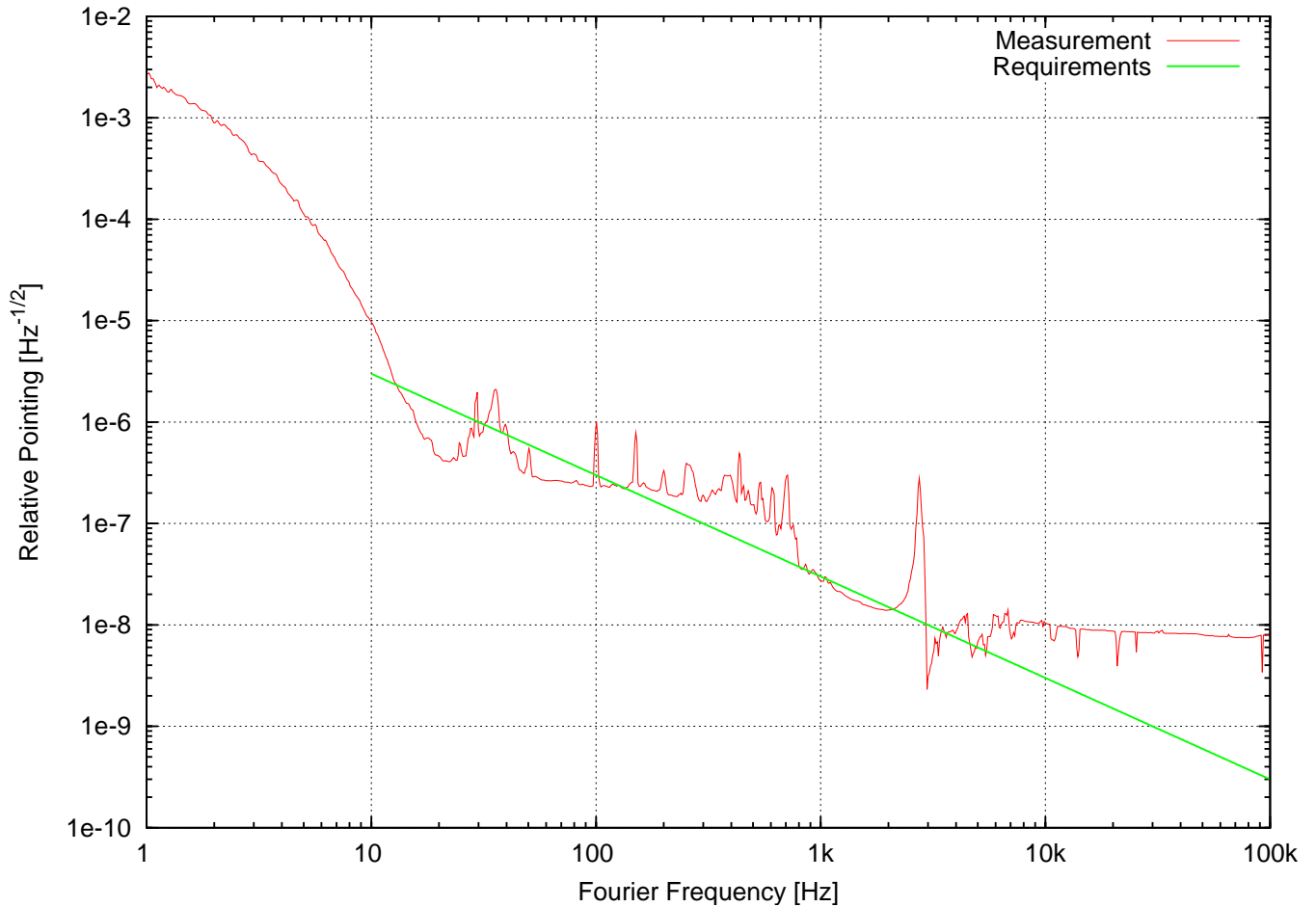Advanced LIGO NPRO, Spare #2, I=2300mA, Noise Eater, Flowbox 2%

Pointing 1Y
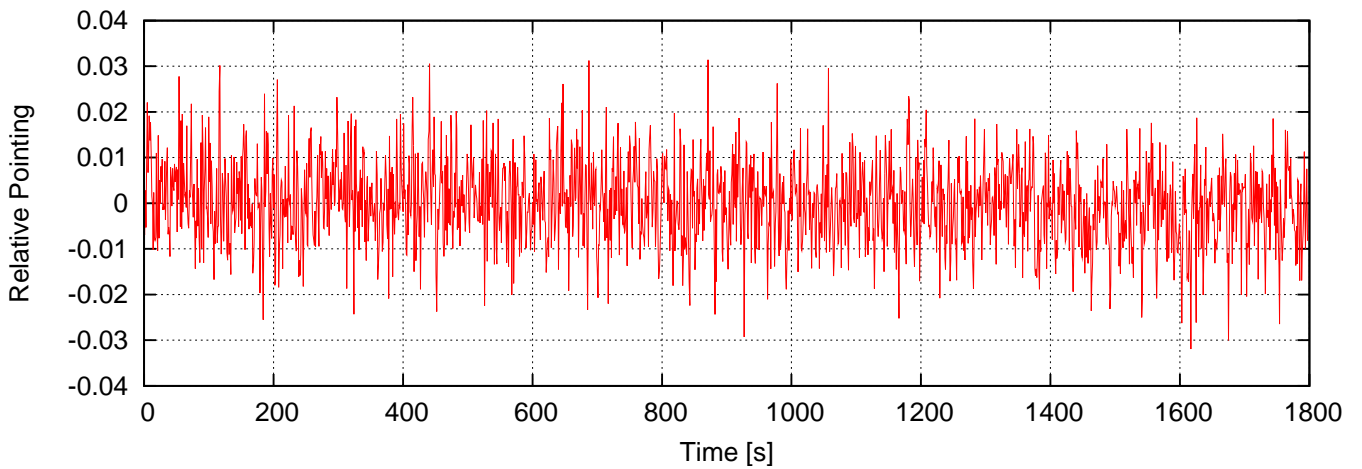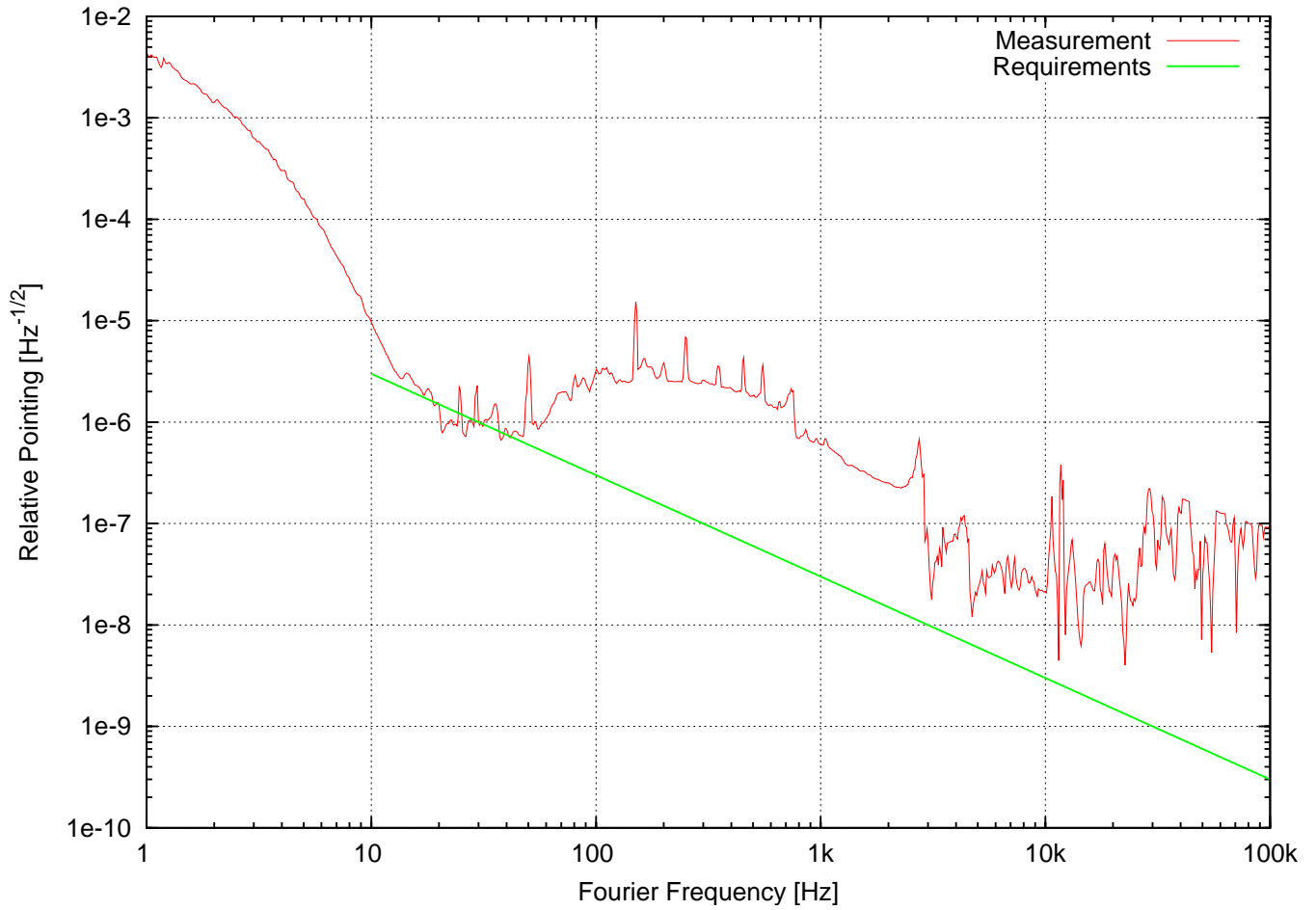
Measurement duration:	1800 s = 30 min
Measurement start:	Tue Mar 13 14:46:37 2007
Uncalibrated error signal:	0.339363 V rms, -4.37744 V ... 4.27338 V
Uncalibrated control signal:	0.470664 V rms, -2.17712 V ... 3.45337 V
PZT position: 49.7 % ... 51.2 %	

Notes:
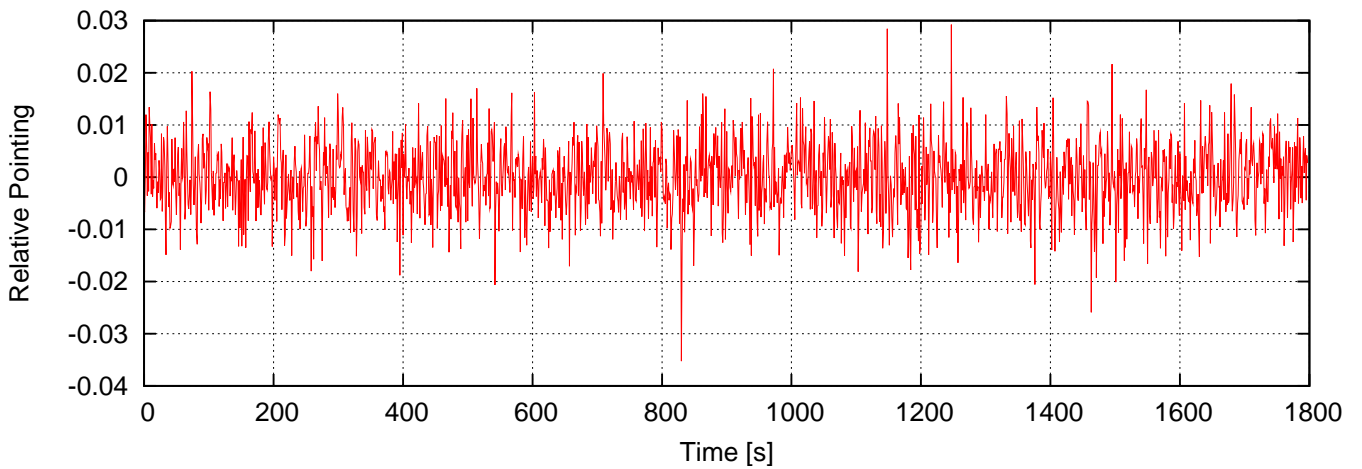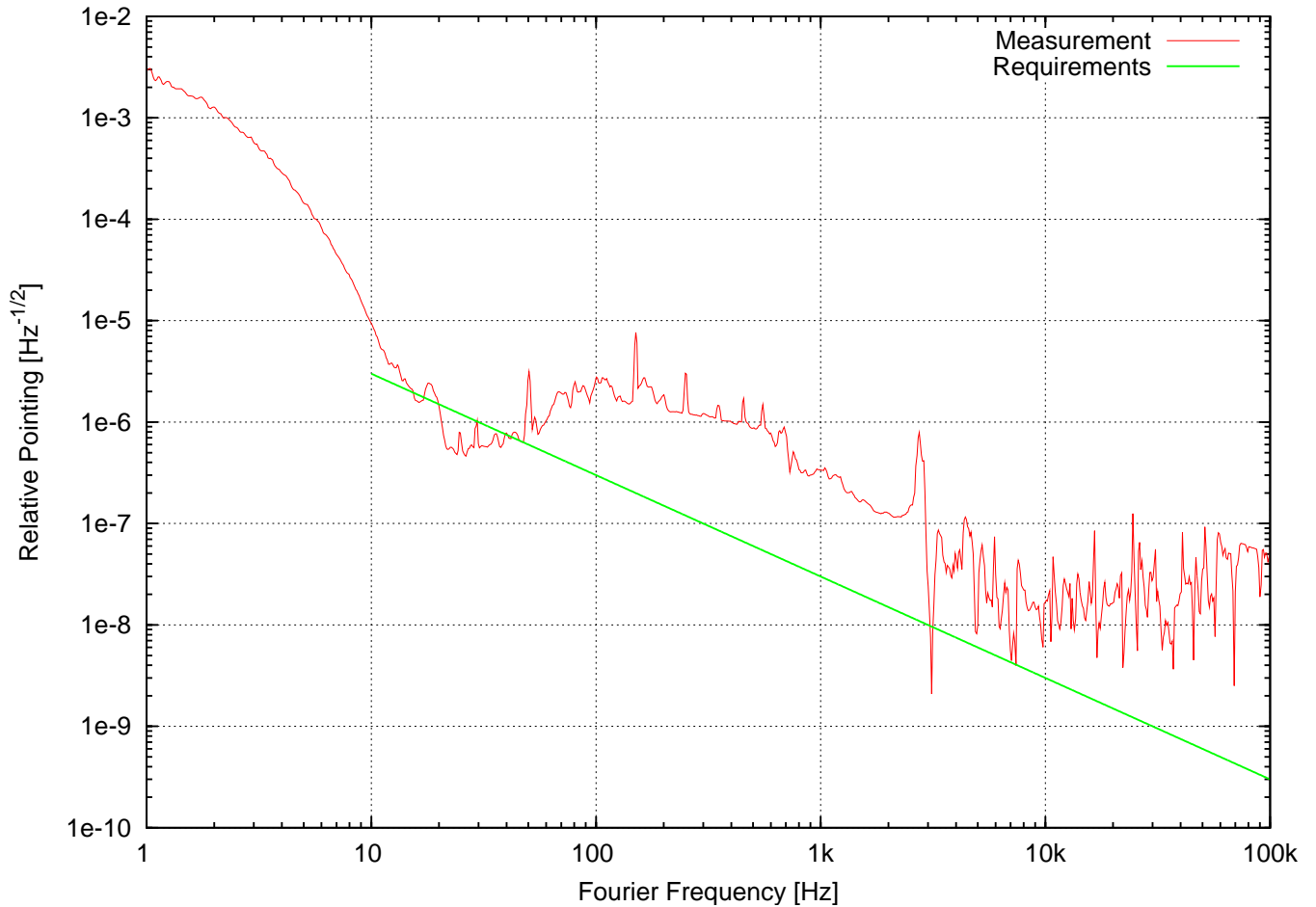Advanced LIGO NPRO, Spare #2, I=2300mA, Noise Eater, Flowbox 2%

Pointing 2X

Measurement duration:	1800 s = 30 min
Measurement start:	Tue Mar 13 15:34:52 2007
Uncalibrated error signal:	0.0672226 V rms, -1.02997 V . . . 0.857849 V
Uncalibrated control signal:	0.259174 V rms, -1.35742 V . . . 1.37085 V
PZT position: 49.7 % . . . 50.5 %	

Notes:
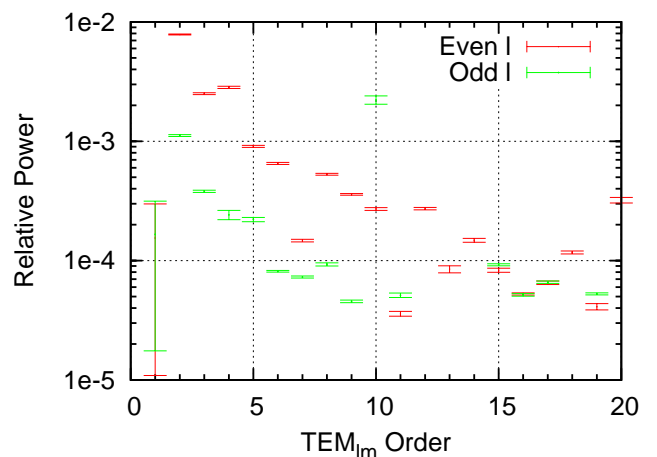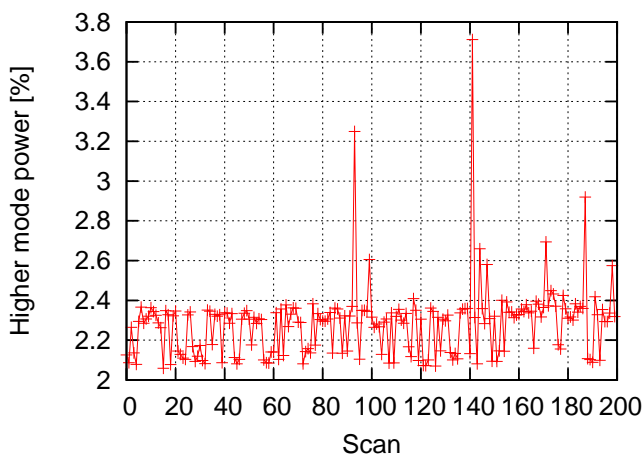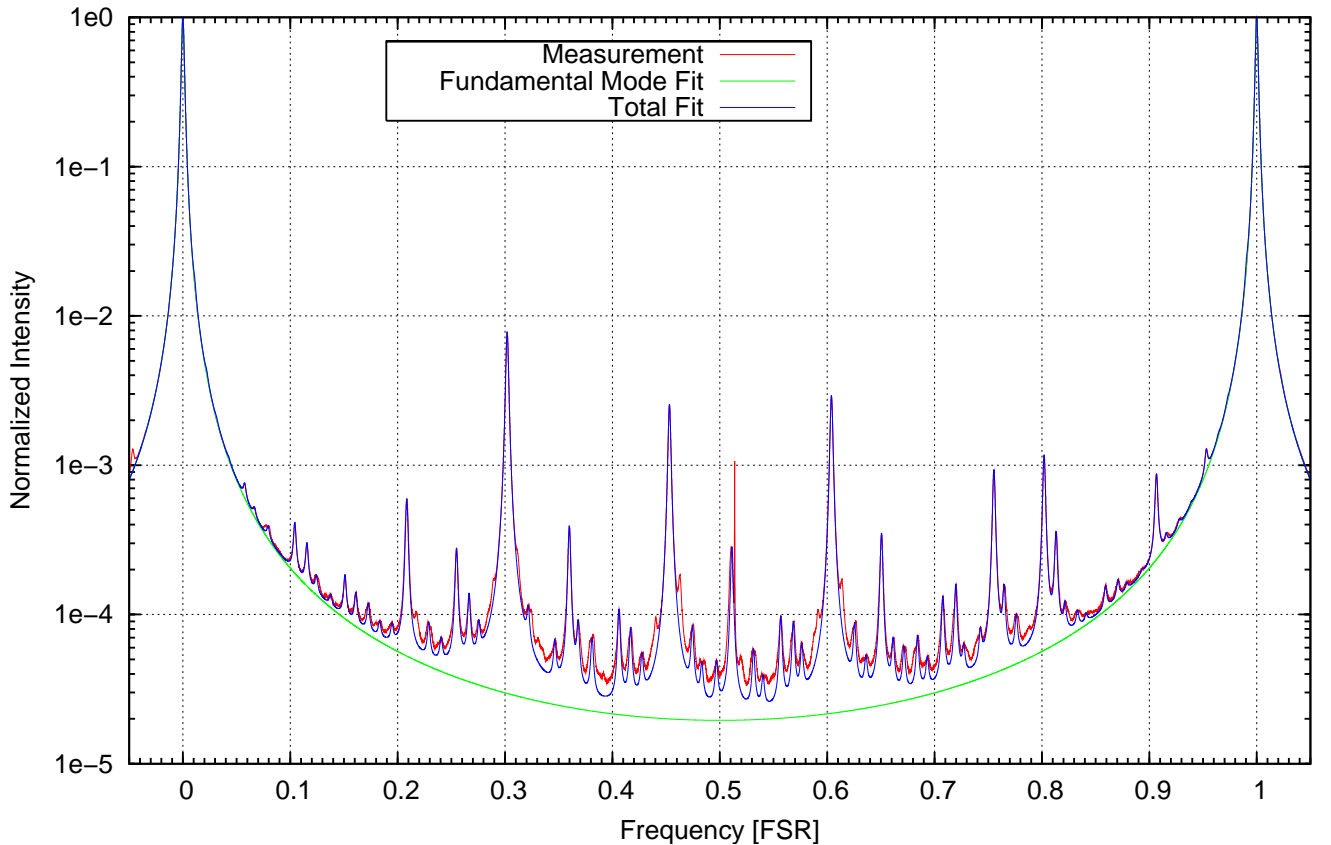Advanced LIGO NPRO, Spare #2, I=2300mA, Noise Eater, Flowbox 2%

Pointing 2Y

Measurement duration:	1800 s = 30 min
Measurement start:	Tue Mar 13 16:20:41 2007
Uncalibrated error signal:	0.541421 V rms, -6.28357 V … 6.01929 V
Uncalibrated control signal:	0.389647 V rms, -2.51038 V … 2.4176 V
PZT position: 49.4 % … 51 %	

Notes:
Advanced LIGO NPRO, Spare #2, I=2300mA, Noise Eater, Flowbox 2%

Modescan

Number of scans:	200	Relative power of one sideband:	-1 ± 0
Measurement duration:	200 s	Significant modes:	57.35 ± 2.07786
Measurement start:	Tue Mar 13 17:18:57 2007	Average deviation:	-0.000385801 FSR
PD signal:	0.000275423 V . . . 8.28579 V	Relative horizontal (X) misalignment:	0.0119504 ± 0.00482634
Samples per FSR:	23435.8 ± 23.5697	Relative vertical (Y) misalignment:	0.0115132 ± 0.0047008
Calibration deviation:	$0.17318\% \pm 0.0177406\%$	Relative mismodematching:	$0.0885816 \pm 0.000416498$
Finesse:	355.557 ± 0.215921	Roundtrip Gouy phase:	0.151031 FSR ± 1.23381e-05 FSR
Higher mode count:	71.065 ± 1.09123		
Higher mode power:	$2.2834\% \pm 0.177956\%$		

Notes:
Advanced LIGO NPRO, Spare #2, I=2300mA, Noise Eater, Flowbox 2%