LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note	**LIGO-T1100602-v2-**	2013/01/31

Beam Splitter / Folding Mirror Suspension (BSFM) Actuation Ranges

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1 Introduction

This document defines the maximum range of the actuators on an Advanced LIGO (aLIGO) Beam Splitter / Folding Mirror Suspension (BSFM), given the final design of its respective actuation chains. The range is calculated explicitly at DC in tabular form in section 3. Because the range depends on the actuator driver's frequency response which are different at each stage, the single actuator force is shown as a function of frequency in section 4. The mechanical response to longitudinal force, and pitch and yaw torques are shown in 5. Finally, the magnitude of test mass displacement as a function of frequency for high(est)-range and low(set)-noise configurations is shown in section 6.

2 Calculating the Maximum Force

The maximum (peak) differential drive voltage, V_{max}, from an aLIGO Digital-to-Analog Converter (DAC), a General Standards PCIe66-18AO8, 18-bit, DAC card, is 10 $[V_p]$ [1].

Though the BSFM is a triple suspension with optic forming the final suspended stage (M3), it only has actuators on its upper two stages (Top, Intermediate or Middle, henceforth abbreviated as M1 and M2 respectively) [3, 9]. For the those stages , the force is calculated by multiplying each component of the linear actuation chain,

$$F = \eta \, T_{CD} \, G_{AI} \, V_{DAC} \tag{1}$$

where V_{DAC} is the applied DAC voltage, G_{AI} is the gain of the anti-aliasing chassis (assumed to be unity), T_{CD} is the transconductance of the coil driver (in $[A/V]$), and η is the OSEM arrangement's coil-magnet force coefficient (in $[N/A]$). Each isolation stage's driver circuit transconductance produces frequency-dependent current, and this frequency dependence is switchable such that the driver can meet both actuation range and output noise requirements. Table 1 summarizes the frequency response of each driver configuration for each stage. The assumed-frequency-independent, force-per-current coefficient for a given OSEM arrangement is then applied to determine the force produced in the actuator basis.

For both stages, the frequency-dependent, single-actuator, maximum force is converted to the Euler basis using the number of actuators and lever arm for each degree of freedom, which is then propagated through the aLIGO production BSFM Matlab model [7] transfer functions between drive each stage's Euler degree of freedom and test mass displacement in the same degree of freedom.

Table 1: Frequency response for each state of the two actuator driver types. Maximum range states are marked with †, low-noise states are marked with ♢. TTOP is a Triple Top Coil Driver, TACQ is an (unmodified) Triple Acquisition Coil Driver.

Driver	**Drawing #**	**State Name**	**(zeros):(poles) [Hz]**
TTOP	D0902747-v4	acq †	(31):(0.9)
		lp ♢	(10, 31):(0.9, 1)
TACQ	D0901047-v4	acqOff lpOff	(9):(82)
		acqOn lpOff †	(1.05):(46)
		acqOff lpOn ♢	(9, 11, 21):(1, 82, 210)
		acqOn lpOn	(1.05, 11, 21):(1, 46, 210)

3 Maximum Displacement at DC

Beam Splitter / Fold-Mirror Suspension (BSFM)
Details of OSEMS, Magnets, Coil Drivers and maximum DC drive range at each stage
T1100602-v2
Jeff Kissel and Norna Roberston
31st January 2013

Max DAC Voltage	
[V_p]	(Differential voltage across the Plus and Minus legs)
10	

Suspension Stage	OSEM Type	Magnet Type	Magnet Size diameter x thickness	Coil Magnet Actuation Strength	Coil Magnet Actuation Strength
Units	[ ]	[ ]	[mm]	[N/A]	[N/mA]
Top (TOP, M1)	BOSEM	NdFeB	10 x 10	1.694	0.001694
Intermediate Mass (MID, M2)	BOSEM	SmCo	10 x 5	0.963	0.000963
Optic (BOT, M3)	none	none	n/a	n/a	n/a

Coil Driver	DC Transconducance	DC Max Current Output	DC Current Range	DC Current Range Requirement	Frequency Range
Units	[mA/V]	[mA_p]	[mA_pp]	[(mA_p) or (mA_rms)]	[Hz]
Triple TOP (D0902747-v4)	11.919	119.19	238.38	60 (p), 200 (rms)	f < 1 Hz, 1 Hz < f < 100 Hz
Triple Acq. (D0901047-v4)	0.32635	3.2635	6.527	M2: 2.5 (p)	f < 1 kHz
Modified Triple Acq. (L1200226-v2)	2.8284	28.284	56.568	n/a	n/a

Degree of Freedom (DOF)	Stage	DC Compliance at Mass	Lever Arm	# of OSEMs	DC Compliance at Coil Driver Output	DC Max Disp. from Coil Drive	DC Max Disp. from Coil Drive	DC Disp. Range from Coil Drive	DC Disp. Range from Coil Drive
Units	[ ]	[(m/N) or (rad/N.m)]	[m]	[ ]	[(m/mA) or (rad/mA)	[(m_p) or (rad_p)]	[(um_p) or (urad_p)]	[(m_pp) or (rad_pp)]	[(mm_pp) or (mrad_pp)]
Longitudinal	M1	0.001528	1	2	5.177E-06	6.171E-04	617.07	1.234E-03	1234.142
Pitch	M1	0.137720	0.055	1	1.283E-05	1.529E-03	1529.37	3.059E-03	3058.743
Yaw	M1	0.152080	0.104	2	5.359E-05	6.387E-03	6386.88	1.277E-02	12773.757
Longitudinal	M2	0.003691	1	4	1.422E-05	4.640E-05	46.40	9.281E-05	92.807
Pitch	M2	0.303950	0.0707	4	8.278E-05	2.701E-04	270.14	5.403E-04	540.283
Yaw	M2	0.329090	0.0707	4	8.962E-05	2.925E-04	292.49	5.850E-04	584.971
Longitudinal	MODM2	0.003691	1	4	1.422E-05	4.022E-04	402.17	8.043E-04	804.334
Pitch	MODM2	0.303950	0.0707	4	8.278E-05	2.341E-03	2341.25	4.683E-03	4682.509
Yaw	MODM2	0.329090	0.0707	4	8.962E-05	2.535E-03	2534.90	5.070E-03	5069.804

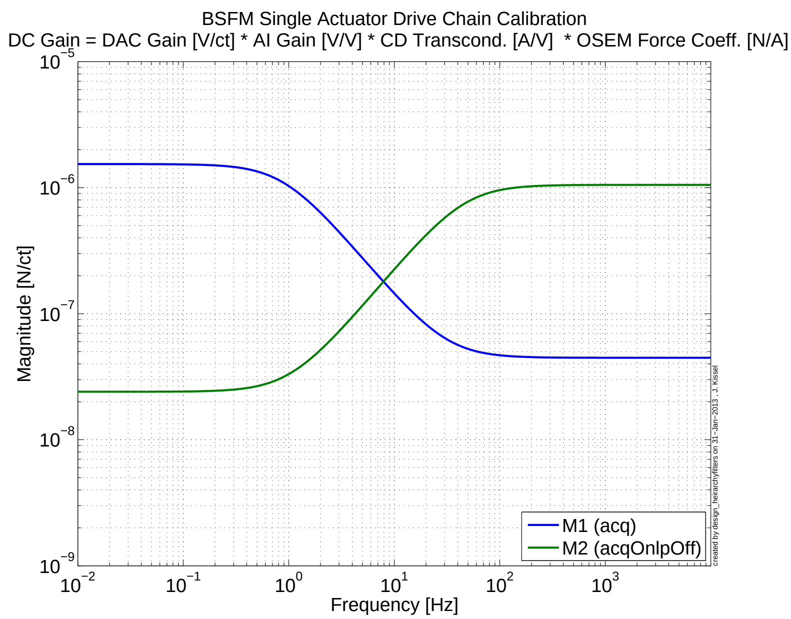
References

DAC Voltage	T1200311-v1		
OSEM and magnet details	M0900034-v4		
OSEM Coil/Magnet Actuation Strengths	T1000164-v3		
DC Compliances for long/pitch/yaw	https://redoubt.ligo-wa.caltech.edu/svn/sus/trunk/Common/MatlabTools/TripleModel_Production/		
	Model:	ssmake3MBf	rev1891
	Parameters:	bsfmopt_metal.m	rev2005
	DC compliance ==	Transfer function from given stage drive to test mass; L to L,P to P, and Y to Y	
Coil driver requirements	T080065-v1		
	Informed by	https://awiki.ligo-wa.caltech.edu/aLIGO/TripleSuspensionActuation	
Coil Driver DC Transconductance	https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=4495		
Lever Arms	D1000392-v7		

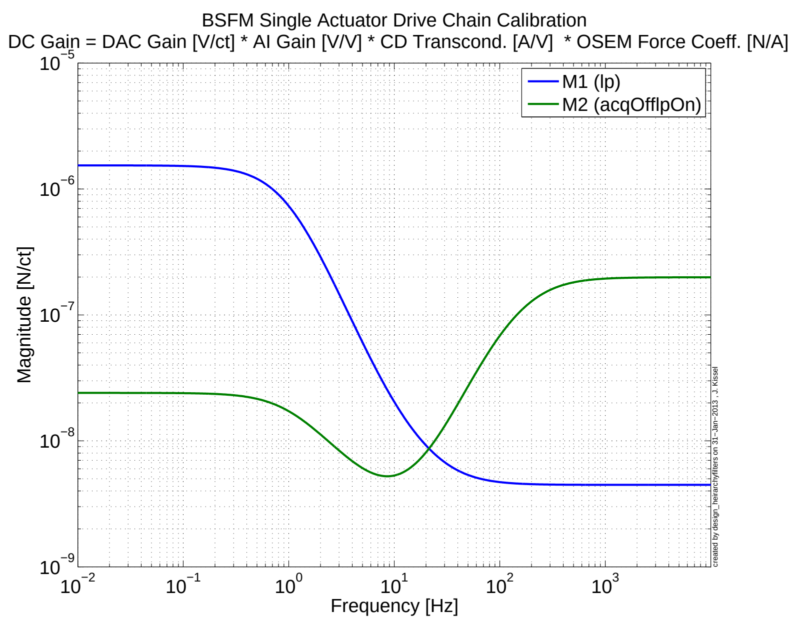
Figure 1: Explicit actuation range calculation at DC for aLIGO BSFM Suspension. As this calculation is prone to erroneous factors of two everywhere (differential vs. single ended, peak vs. peak-to-peak, etc.), the calculation is shown explicitly from both the maximum displacement (peak) and displacement range (peak-to-peak). Note that maximum, peak values are denoted with subscript "p," and range, peak-to-peak values are denoted with subscript "pp." Similar results from the previous version of this table against the peak-to-peak range.

4 Single-Actuator Actuation Strength

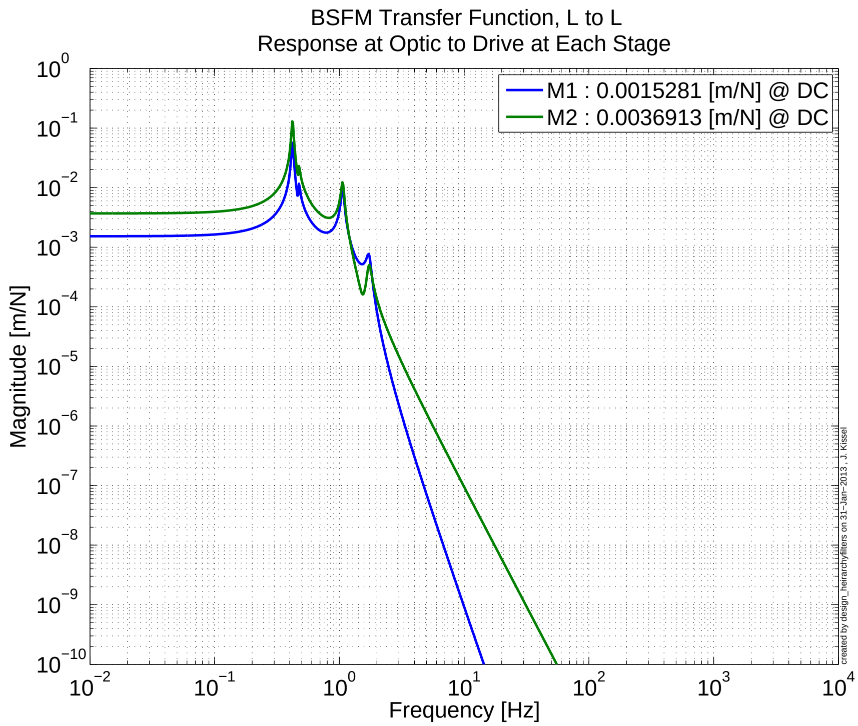
4.1 High-Range Configuration

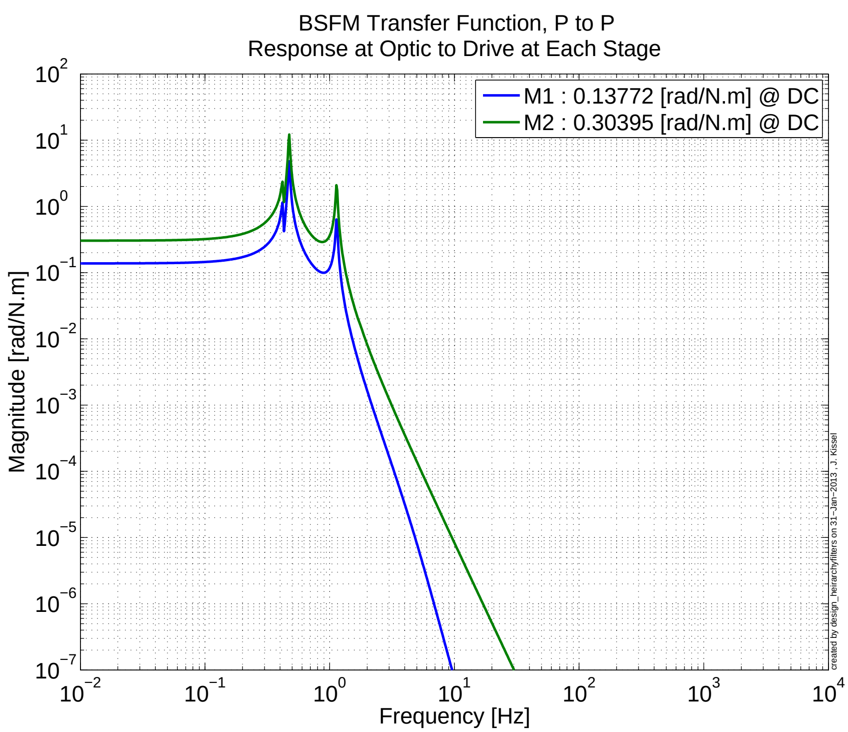


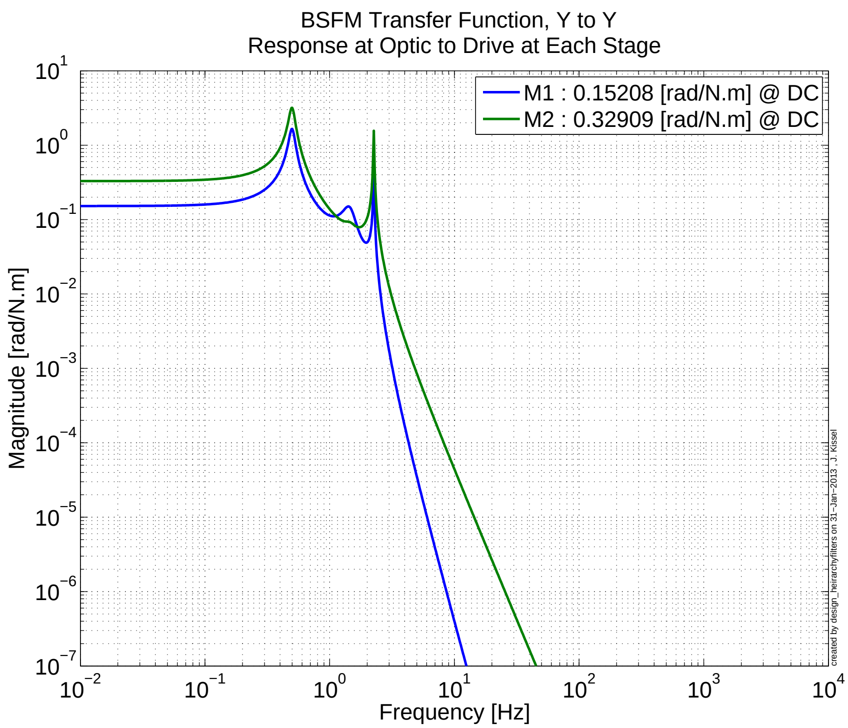
4.2 Low-Noise Configuration



5 Mechanical Transfer Functions

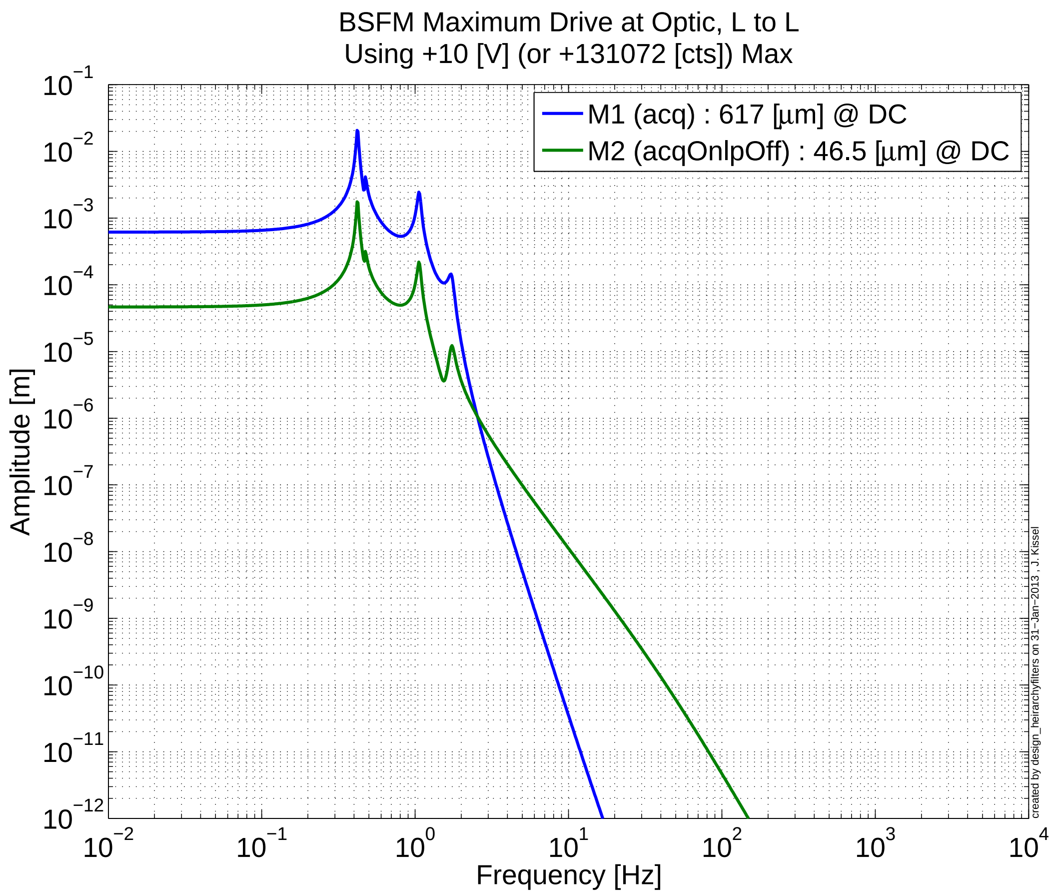


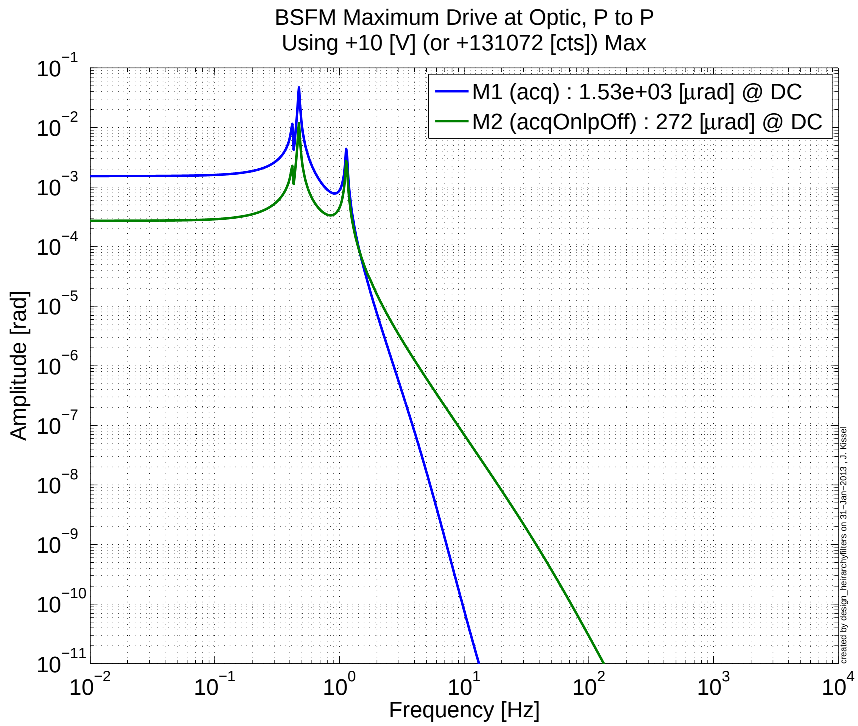


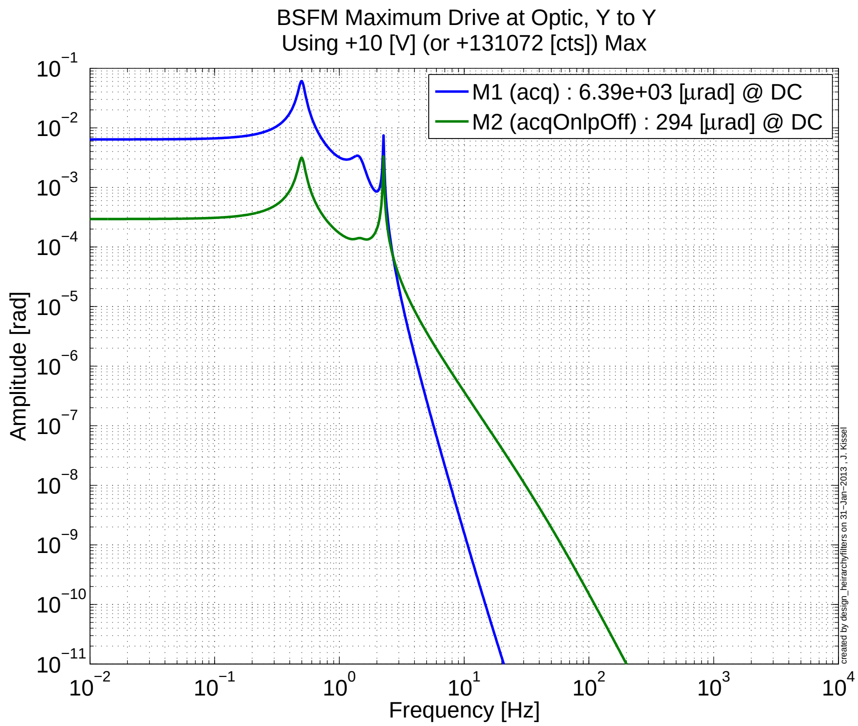

BSFM Transfer Function, Y to Y
Response at Optic to Drive at Each Stage
M1 : 0.15208 [rad/N.m] @ DC
M2 : 0.32909 [rad/N.m] @ DC
Magnitude [rad/N.m]
Frequency [Hz]
created by design_heirarchyfilters on 31−Jan−2013 , J. Kissel

6 Frequency-dependent Maximum Displacement

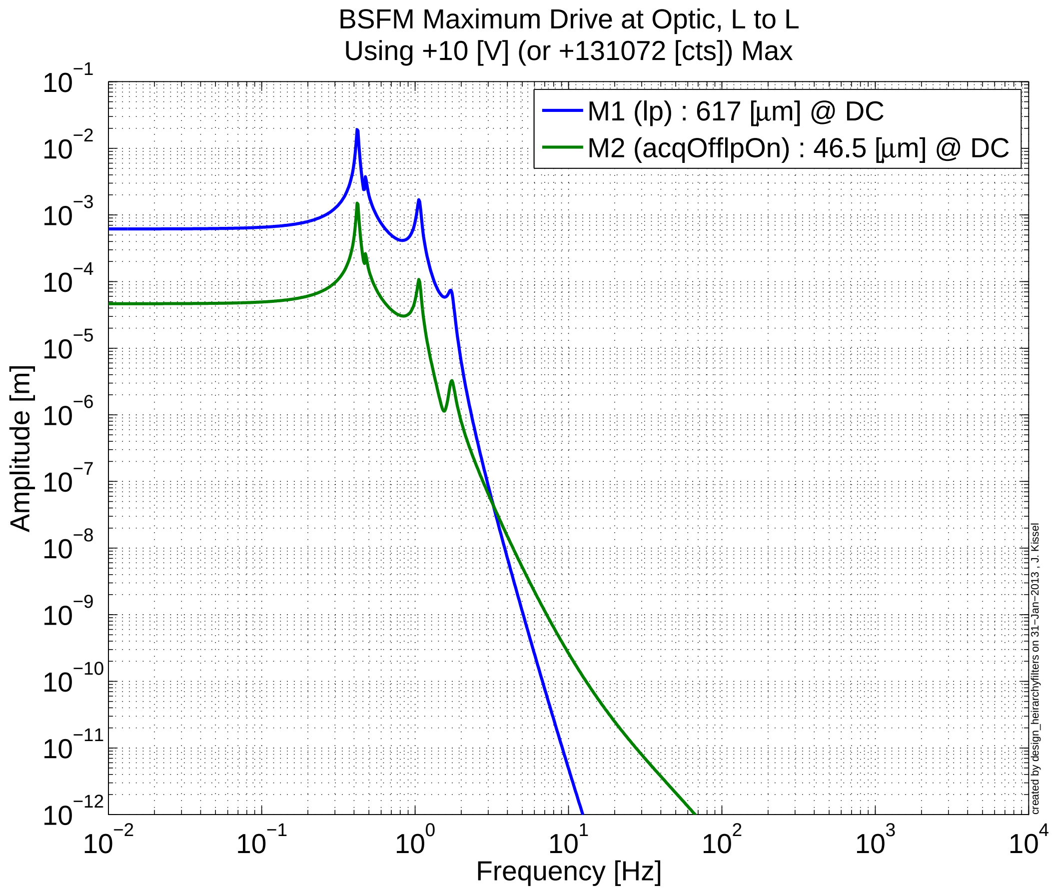
6.1 High-Range Configuration

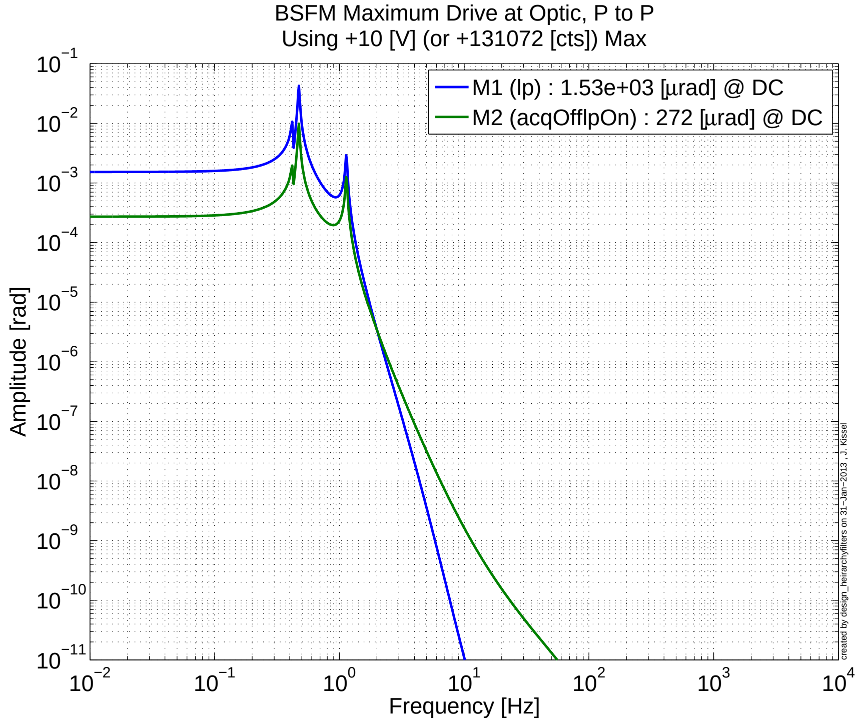


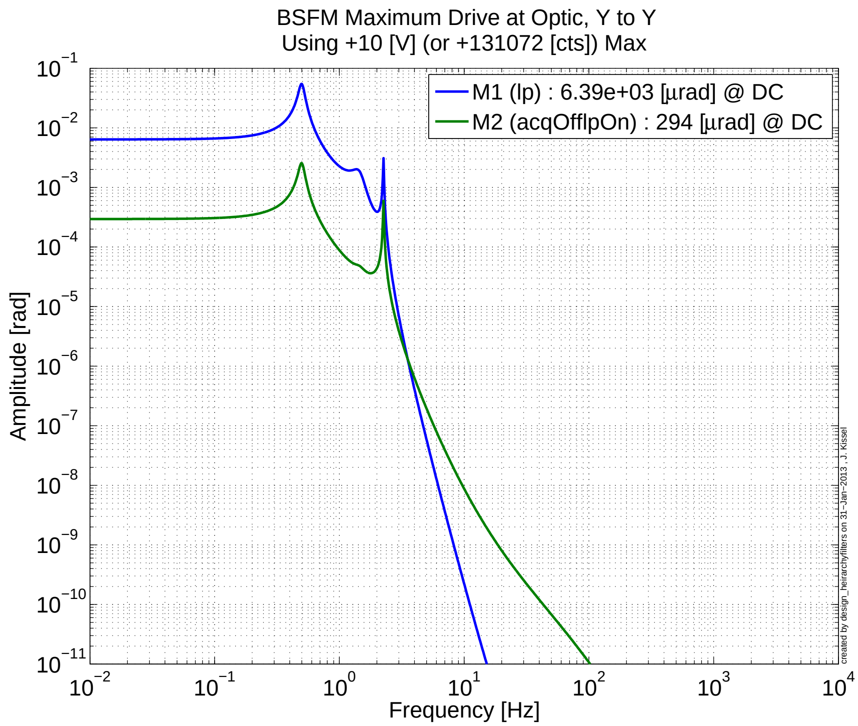

BSFM Maximum Drive at Optic, P to P
Using +10 [V] (or +131072 [cts]) Max
M1 (acq) : 1.53e+03 [µrad] @ DC
M2 (acqOnlpOff) : 272 [µrad] @ DC
Amplitude [rad]
Frequency [Hz]
created by design_heirarchyfilters on 31−Jan−2013 , J. Kissel


BSFM Maximum Drive at Optic, Y to Y
Using +10 [V] (or +131072 [cts]) Max
M1 (acq) : 6.39e+03 [µrad] @ DC
M2 (acqOnlpOff) : 294 [µrad] @ DC
Amplitude [rad]
Frequency [Hz]
created by design_heirarchyfilters on 31−Jan−2013 , J. Kissel

6.2 Low-Noise Configuration




BSFM Maximum Drive at Optic, P to P
Using +10 [V] (or +131072 [cts]) Max
M1 (lp) : 1.53e+03 [μrad] @ DC
M2 (acqOfflpOn) : 272 [μrad] @ DC
Amplitude [rad]
Frequency [Hz]
created by design_heirarchyfilters on 31−Jan−2013 , J. Kissel


BSFM Maximum Drive at Optic, Y to Y
Using +10 [V] (or +131072 [cts]) Max
M1 (lp) : 6.39e+03 [μrad] @ DC
M2 (acqOfflpOn) : 294 [μrad] @ DC
Amplitude [rad]
Frequency [Hz]
created by design_heirarchyfilters on 31−Jan−2013 , J. Kissel

References

[1] J. Kissel. DC Calibration Measurement of aLIGO 18bit DAC Channel. LIGO-T1200311-v1 (2012)

[2] General Standards PMC66-18AO8 Data Sheet. <http://www.generalstandards.com/download.php?catid=spec&file=66_18ao8_spec.pdf>

[3] J. O'Dell. BS/FM Final Design Document. LIGO-T080218-v2 (2009)

[4] J. Kissel. aLIGO BSFM Controls Design Description. LIGO-T1100479-v6 (2012)

[5] N. Roberston. Use of SmCo and NdFeB Magnets in Advanced LIGO Suspensions. LIGO-M0900034-v4 (2009)

[6] M. Barton. Calculation and Measurement of the OSEM Actuator Sweet Spot Position. LIGO-T1000164-v3 (2010)

[7] Advanced LIGO Production Triple Model. <https://redoubt.ligo-wa.caltech.edu/svn/sus/trunk/Common/MatlabTools/TripleModel_Production/t> (2012)

[8] J. Heenfer. AdL Beam Splitter, Input Mode Cleaner, Large Recycling and Small Recycling Triple Suspension Electronics Requirements. LIGO-T080065-v1 (2008)

[9] J. O'Dell, B. Moore, C. Torrie, K. Buckland. aLIGO BS/FM Main Assembly (SolidWorks Model). LIGO-D1000392-v8 (2010)

[10] Matlab 2011a. "std." Mathworks, Inc 1984-2011 <http://www.mathworks.com/help/techdoc/ref/std.html>