LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note	**LIGO-T1100595-v4-**	2014/03/26

ETM/ITM Quad Suspension Control Ranges

J. S. Kissel and N. A. Roberston

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW17-161
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

1 Introduction

This document defines the maximum range of the actuators on an Advanced LIGO (aLIGO) Quadruple (QUAD) suspension, used for input and end test masses (ITM and ETMs, respectively), given the final design of their respective signal 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 as a function of frequency in section 4. The mechanical response to force longitudinal, pitch, and yaw 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 $[V_p]$.

For the top three stages (TOP, UIM, and PUM), the force is calculated by multiplying the linear signal 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.

The test mass stage's, non-linear ESD's force is calculated as

$$F \;=\; \alpha \, (V_{bias} - V_{control})^2 \tag{2}$$

where α is the non-linear force coefficient of the ESD pattern (in $[N/V^2]$), $V_{bias} = G_{ED} V_{DAC}$ (the product of the ESD driver voltage gain, G_{ED} and the applied DAC voltage) is the voltage on the bias pattern, and $V_{control} = G_{ED} V_{DAC}$ is the voltage on the control pattern. The ESD driver, as currently designed, has a single, non-switchable pole at 2 $[kHz]$. As higher bias voltage means a smaller degree of non-linearity, the bias voltage is always operated at the maximum possible voltage for a given ESD driver. If the control voltage were equal, but opposite in sign, we could achieve a maximum force of

$$|F^{(ESD)}_{max}| \;=\; 4\alpha (G_{ED} V_{max})^2. \tag{3}$$

However, the ESD is inherently attractive and we wish to have both attractive and repulsive forces. We have therefore assumed that the control voltage is operated with a force offset of half the maximum possible, leaving the operational maximum force to be

$$|F^{(ESD)}_{op.\ max}| \quad = \quad 2\alpha(G_{ED}V_{max})^2. \tag{4}$$

For all 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 QUAD matlab model transfer functions between each stage's degree of freedom excitation and test mass displacement in the same degree of freedom.

Table 1: Frequency response for each state of the three upper-stage QUAD actuator driver types. Maximum range states are marked with †, low-noise states are marked with ♢.

Driver	**Drawing #**	**State Name**	**(zeros):(poles) [Hz]**
TOP	D0902747-v4	acq †	(31):(0.9)
		lp ♢	(10, 31):(0.9, 1)
UIM	D070481-v4	acq †	(50):(300)
		lp1	(10.5, 50):(1, 300)
		lp2	(10.5, 10.5, 50):(1, 1, 300)
		lp3 ♢	(10.5, 10.5, 10.5, 50):(1, 1, 1, 300)
MODUIM	T1400223-v1	acq †	(85):(300)
		lp1	(10.5, 85):(1, 300)
		lp2	(10.5, 10.5, 85):(1, 1, 300)
		lp3 ♢	(10.5, 10.5, 10.5, 85):(1, 1, 1, 300)
PUM	D070483-v5	acqOff lpOff	(12):(110)
		acqOn lpOff †	(1.35):(80.5)
		acqOff lpOn ♢	(6, 12, 20):(0.5, 110, 250)
		acqOn lpOn	(1.35, 6, 20):(0.5, 80.5, 250)

Table 2: Configurations of the test-mass stage electro-static drive.

Driver	**Driver Drawing #**	**State Name**	**Driver Gain** [V/V]	**Gap Size** [mm]	**Pattern Type**
ESD	T1000220-v1	acq5mm †	40	5.0	ETM (D0900949-v2)
		ln5mm ♢	1.1	5.0	ETM (D0900949-v2)
		acq20mm †	40	20.0	ITM (D080177-v4)
		ln20mm ♢	1.1	20.0	ITM (D080177-v4)

3 Maximum Displacement at DC

ETM/ITM Quad Suspension
Details of OSEMS, Magnets, ESDs and DC control ranges at each stage
T1100595-v4
Norna A Robertson and Jeff Kissel
26th May 2014

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]
Main and Reaction Chain Top (TOP)	BOSEM	NdFeB	10 x 10	1.694	0.001694
Upper-Intermediate Mass (UIM)	BOSEM	SmCo	10 x 10	1.694	0.001694
PenUltimate Mass (PUM)	AOSEM	SmCo	2 x 6	0.0309	0.0000309

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_pp) or (mA_rms)]	[Hz]
TOP (D0902747-v4)	9.943	99.43	198.86	200 (pp)	continuous
UIM (D070481-v4)	0.1535	1.535	3.07	2 (rms)	< 1
MODUIM (T1400223-v1)	0.6154	6.154	12.308	2 (rms)	< 1
PUM (D070483-v5)	0.2685	2.685	5.37	16 (rms)	200 - 5000

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)]	[(um_pp) or (urad_pp)]
Longitudinal	TOP	0.000348	1	2	1.179E-06	1.172E-04	117.23	2.345E-04	234.461
Pitch	TOP	0.033500	0.078	1	4.426E-06	4.401E-04	440.12	8.802E-04	880.238
Yaw	TOP	0.015100	0.12	2	6.139E-06	6.104E-04	610.41	1.221E-03	1220.813
Longitudinal	UIM	0.000630	1	4	4.269E-06	6.553E-06	6.55	1.311E-05	13.105
Pitch	UIM	0.047200	0.065	4	2.079E-05	3.191E-05	31.91	6.382E-05	63.822
Yaw	UIM	0.036500	0.065	4	1.608E-05	2.468E-05	24.68	4.935E-05	49.354
Longitudinal	MODUIM	0.000630	1	4	4.269E-06	2.627E-05	26.27	5.254E-05	52.541
Pitch	MODUIM	0.047200	0.065	4	2.079E-05	1.279E-04	127.93	2.559E-04	255.868
Yaw	MODUIM	0.036500	0.065	4	1.608E-05	9.893E-05	98.93	1.979E-04	197.864
Longitudinal	PUM	0.001060	1	4	1.310E-07	3.518E-07	0.35	7.036E-07	0.704
Pitch	PUM	0.078600	0.0707	4	6.868E-07	1.844E-06	1.84	3.688E-06	3.688
Yaw	PUM	0.053500	0.0707	4	4.675E-07	1.255E-06	1.26	2.511E-06	2.511

ESD Driver	DC Gain (Differential In to Single-ended Out)	DC Max Voltage Output	DC Voltage Range	DC Voltage Range Requirement	Frequency Range
Units	[V/V]	[V_p]	[V_pp]	[V_pp]	[Hz]
Acquisition Driver (T1000220-v1)	40	400	800	800	< 2000
Low Noise Driver (T0900567, see above)	1.1	11	22	30	< 2000

ESD Pattern / Driver	RM to TST Gap Size	Actuation Strength (all four quadrants)	Max BIAS Voltage	Max QUAD Voltage	Max Force	Max Force w/ Bias Offset ***
Units	[mm]	[N/V^2]	[V_p]	[V_p]	[N_p]	[N_p]
ETM / Acquire	5	4.20E-10	400	400	2.69E-04	1.34E-04
ITM / Acquire	20	7.50E-12	400	400	4.80E-06	2.40E-06
ETM / Low Noise	5	4.20E-10	11	11	2.03E-07	1.02E-07
ITM / Low Noise	20	7.50E-12	11	11	3.63E-09	1.82E-09

*** In order to get both attractive and repulsive forces, we'll operate with a force offset of -1/2 Fmax, see reference P1000032 below

Degree of Freedom (DOF)	Stage / Driver	DC Compliance at Mass	Lever Arm	DC Max Disp. from ESD w/ Force Offset	DC Max Disp. from ESD w/ Force Offset	DC Disp Range from ESD w/ Force Offset	DC Disp. Range from ESD w/ Force Offset
Units	[ ]	[(m/N) or (rad/N.m)]	[m]	[(m_p) or (rad_p)]	[(nm_p) or (nrad_p)]	[(m_pp) or (rad_pp)]	[(nm_pp) or (nrad_pp)]
Longitudinal	ETM / Acq.	0.0026	1	3.494E-07	349.440	6.989E-07	698.880
Pitch	ETM / Acq.	0.116	0.14	2.183E-06	2182.656	4.365E-06	4365.312
Yaw	ETM / Acq.	0.105	0.14	1.976E-06	1975.680	3.951E-06	3951.360
Longitudinal	ITM / Acq.	0.0026	1	6.240E-09	6.240	1.248E-08	12.480
Pitch	ITM / Acq.	0.116	0.15	4.176E-08	41.760	8.352E-08	83.520
Yaw	ITM / Acq.	0.105	0.15	3.780E-08	37.800	7.560E-08	75.600
Longitudinal	ETM / Low Noise	0.0026	1	2.643E-10	0.264	5.285E-10	0.529
Pitch	ETM / Low Noise	0.116	0.14	1.651E-09	1.651	3.301E-09	3.301
Yaw	ETM / Low Noise	0.105	0.14	1.494E-09	1.494	2.988E-09	2.988
Longitudinal	ITM / Low Noise	0.0026	1	4.719E-12	0.005	9.438E-12	0.009
Pitch	ITM / Low Noise	0.116	0.15	3.158E-11	0.032	6.316E-11	0.063
Yaw	ITM / Low Noise	0.105	0.15	2.859E-11	0.029	5.717E-11	0.057

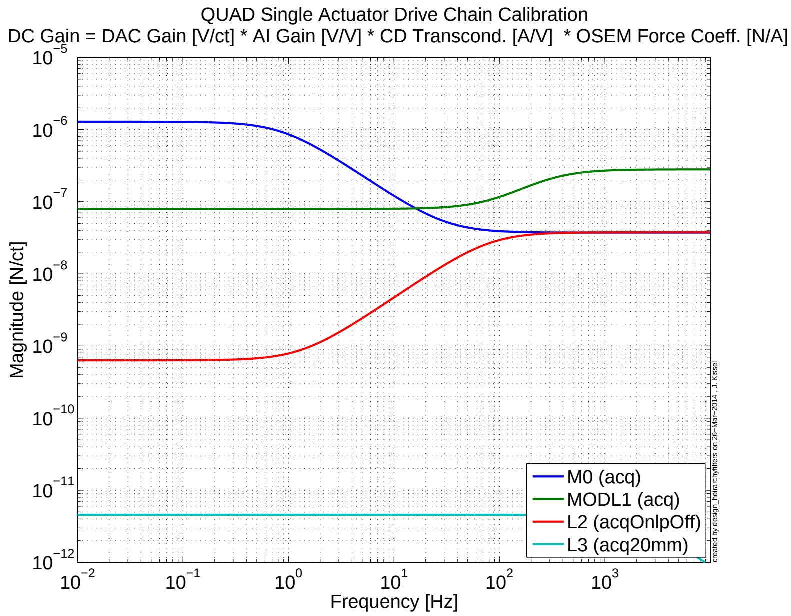
References

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/SusModelTags/Matlab/quadmodelproduction_rev3311_fiber_2012-09-06.mat
	Model: ssmake4pv2eMB5f_rev1797
	Parameters: quadopt_fiber.m rev2731
	DC compliance == Transfer function from given stage drive to test mass; L to L,P to P, and Y to Y
Coil driver requirements	T060067-v1
	Informed by http://www.its.caltech.edu/~rana/aLIGO/suselecreq.html
Coil Driver DC Transconductance	https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=4495 and T1400223
Lever Arms	D0901346 for TOP, UIM, and PUM drives; D0900949 / D080177 for ETM / ITM ESD Patterns (assumes that that effective lever arm for ESD is in the middle [radially] of the pattern)
Actuation strength for ESD drive	T1000119-v1, Figure 4, 20[mm] gap, Nominal Pattern data point for ITM, G0900956-v1, pg 7 for ETM
Peak Voltage for High Voltage ESD Driver	T1000222
Peak Voltage for Low Noise ESD Driver	T1200479, Section 5
Maximum Force Used (with - 1/2 Fmax offset)	P1000032-v3, Section 5.3.1.3, pg 251 (or 291 of the .pdf)

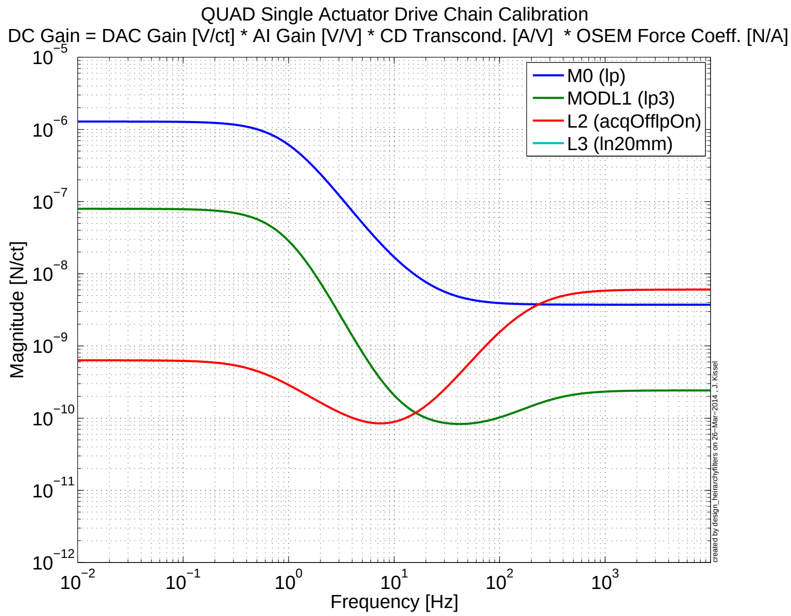
Figure 1: Explicit actuation range calculation at DC for aLIGO QUAD Suspension. As this calculation is prone to erroneous factors of two everywhere (differential vs. single ended, peak vs. peak-to-peak, etc.), the calculation is shown explicitly from both the maximum displacement (peak) and displacement 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 -v1 of this document should be compared against the peak-to-peak range.

4 Single-Actuator Actuation Strength

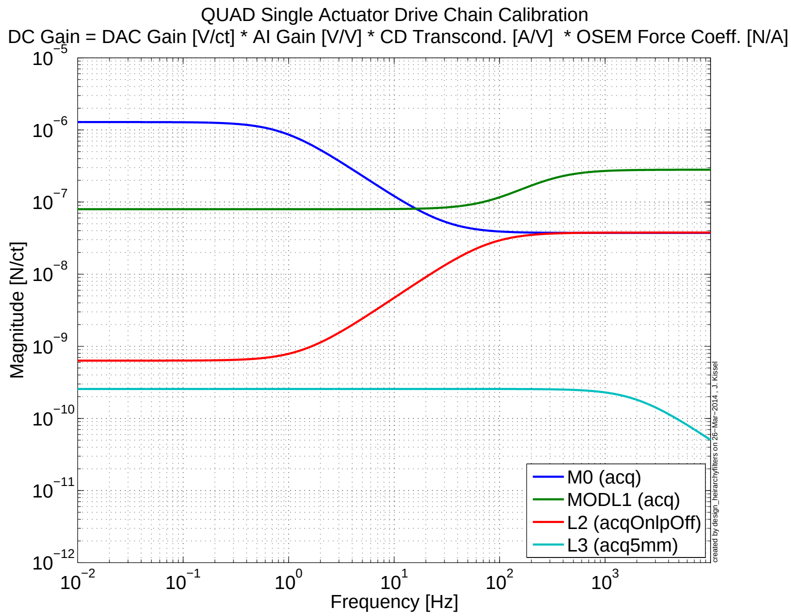
4.1 ITM, High-Range Configuration



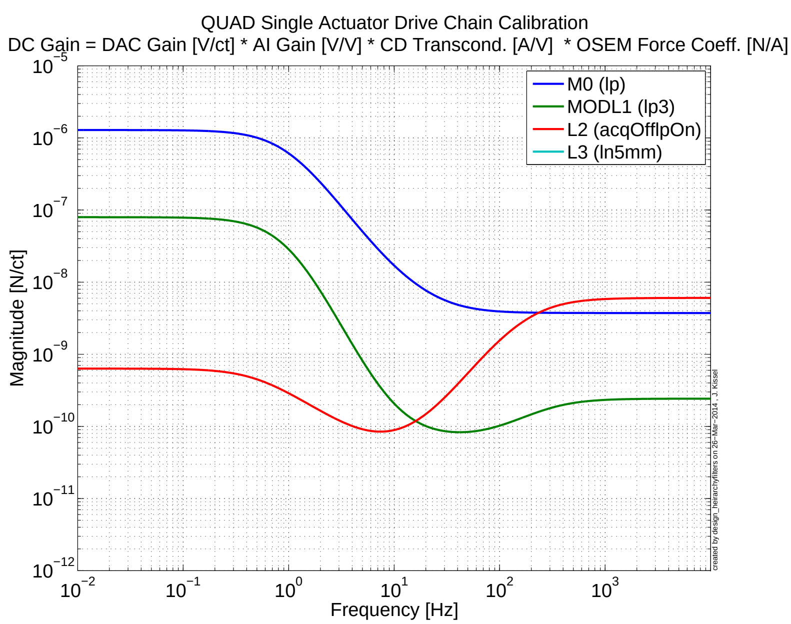
4.2 ITM, Low-Noise Configuration



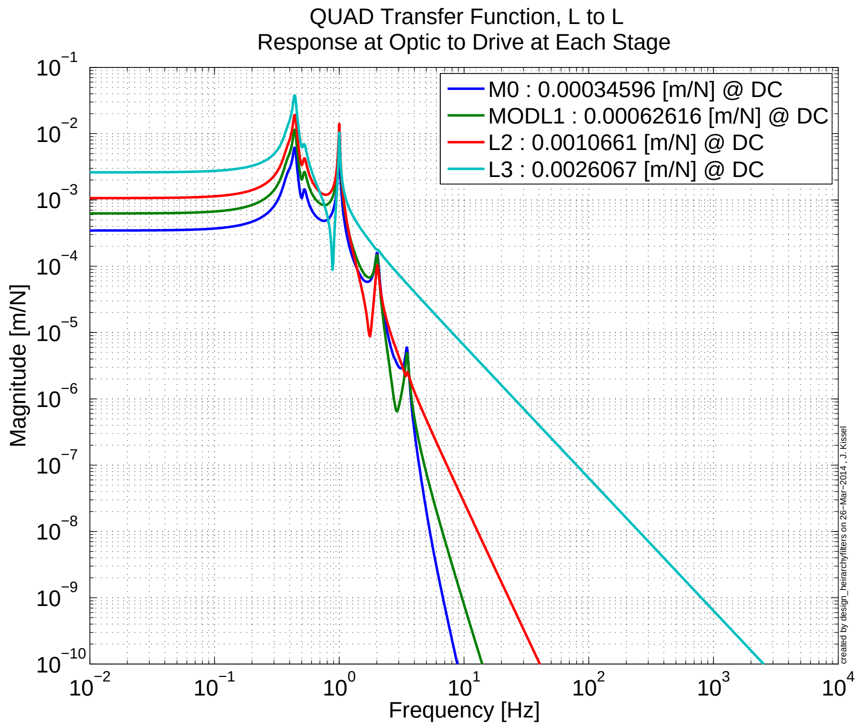
4.3 ETM, High-Range Configuration

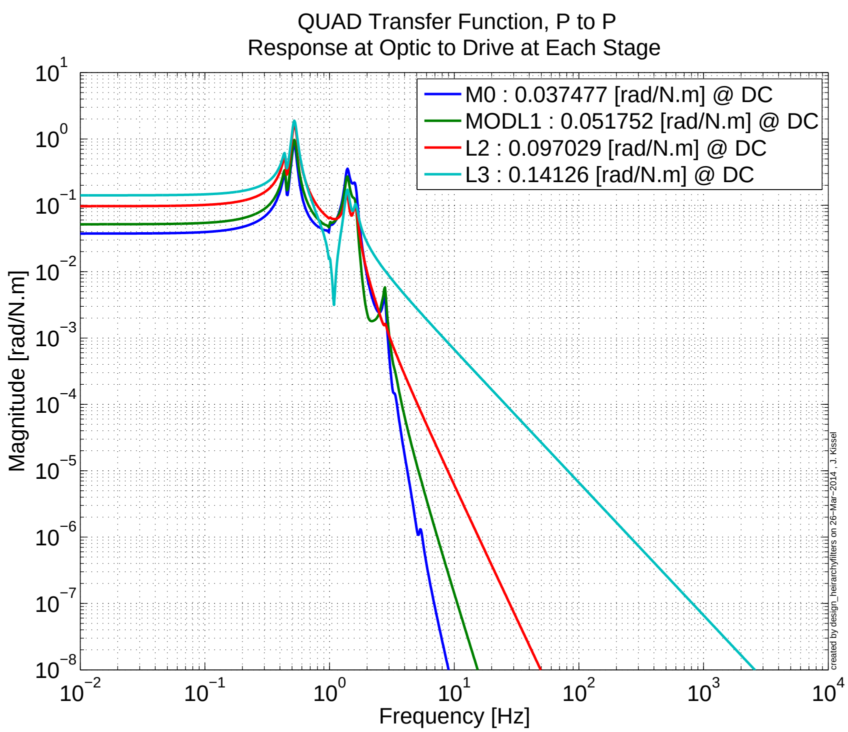


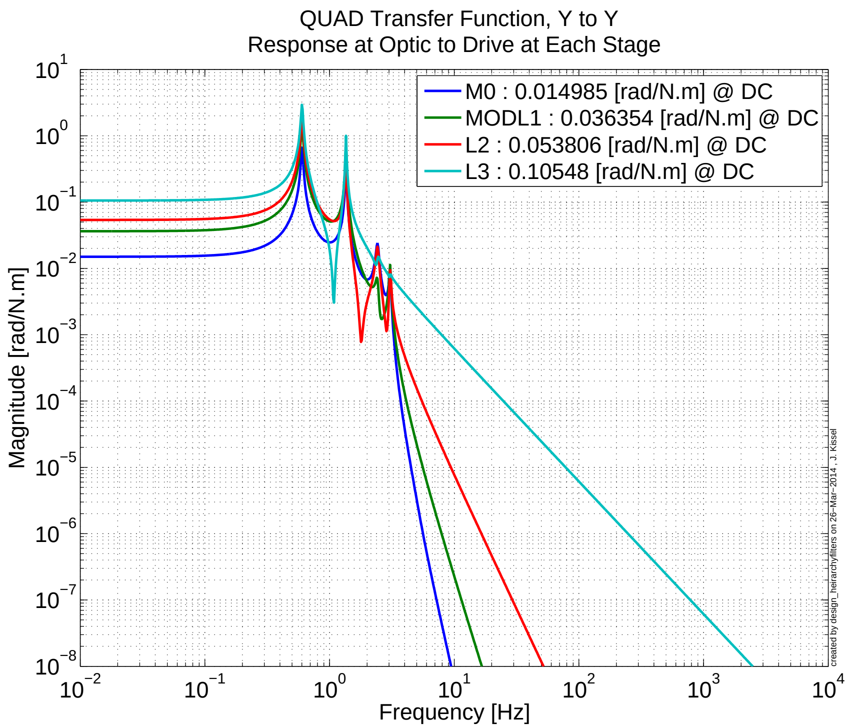
4.4 ETM, Low-Noise Configuration



5 Mechanical Transfer Functions

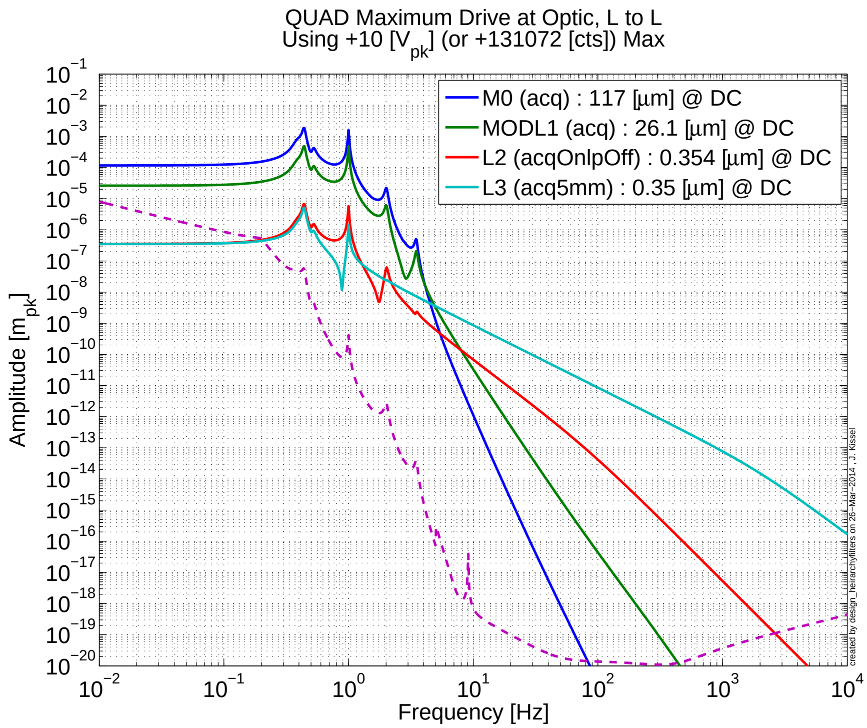


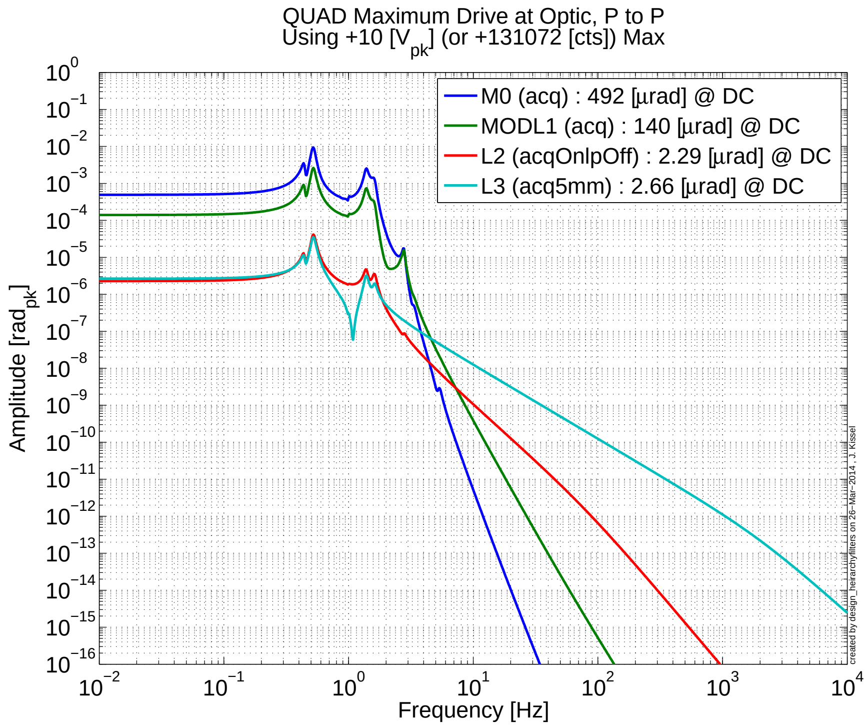


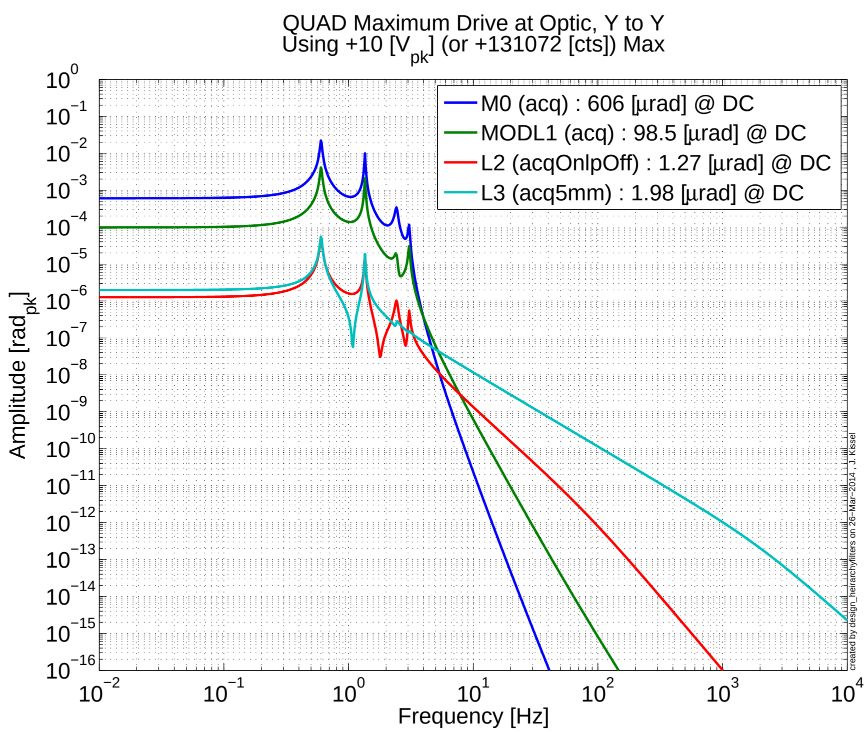

QUAD Transfer Function, Y to Y
Response at Optic to Drive at Each Stage
M0 : 0.014985 [rad/N.m] @ DC
MODL1 : 0.036354 [rad/N.m] @ DC
L2 : 0.053806 [rad/N.m] @ DC
L3 : 0.10548 [rad/N.m] @ DC
Magnitude [rad/N.m]
Frequency [Hz]
created by design_hierarchyfilters on 26-Mar-2014 , J. Kissel

6 Frequency-dependent Maximum Displacement

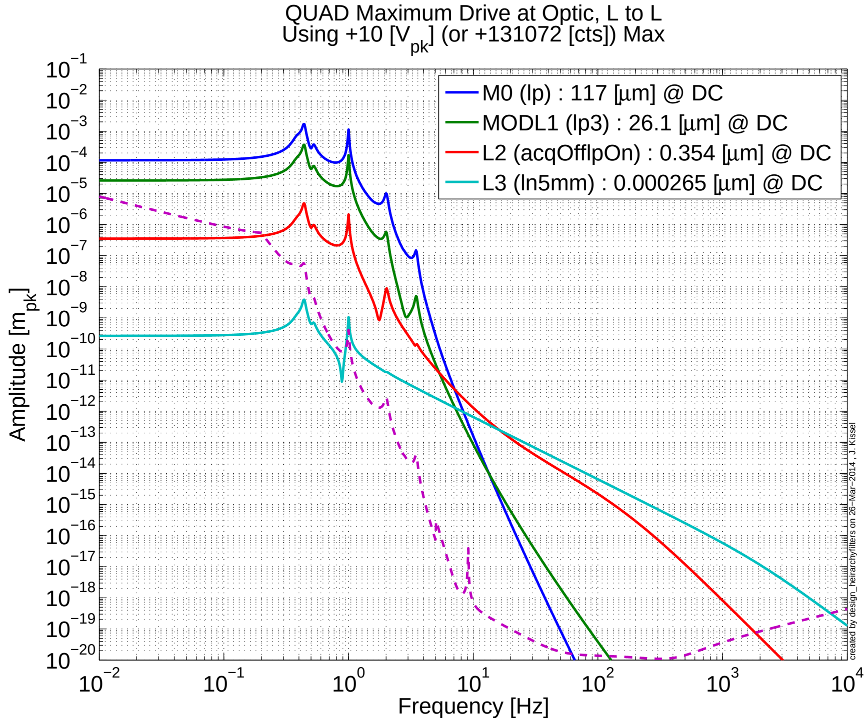
6.1 ETM, High-Range Configuration

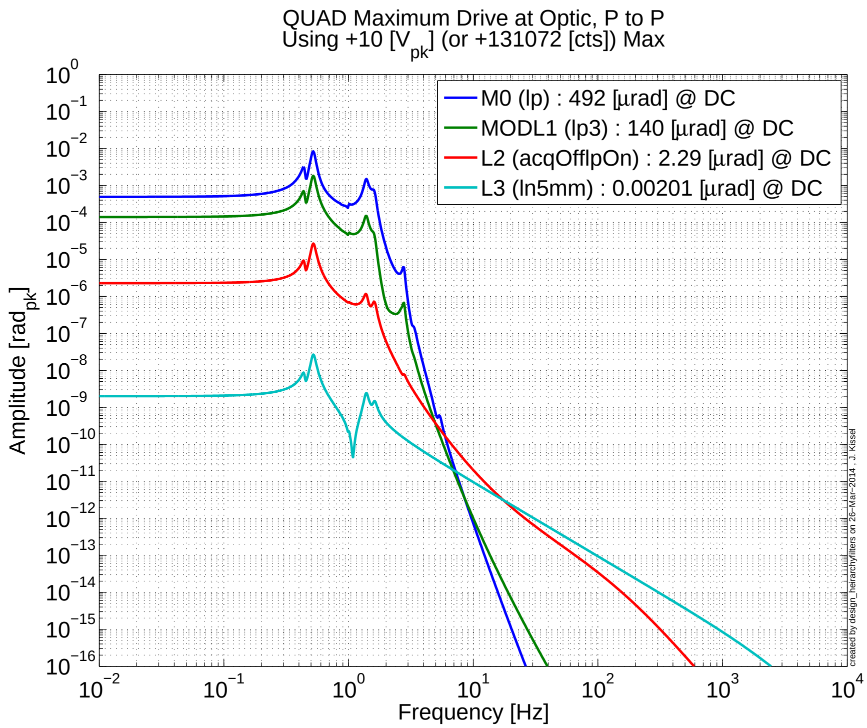


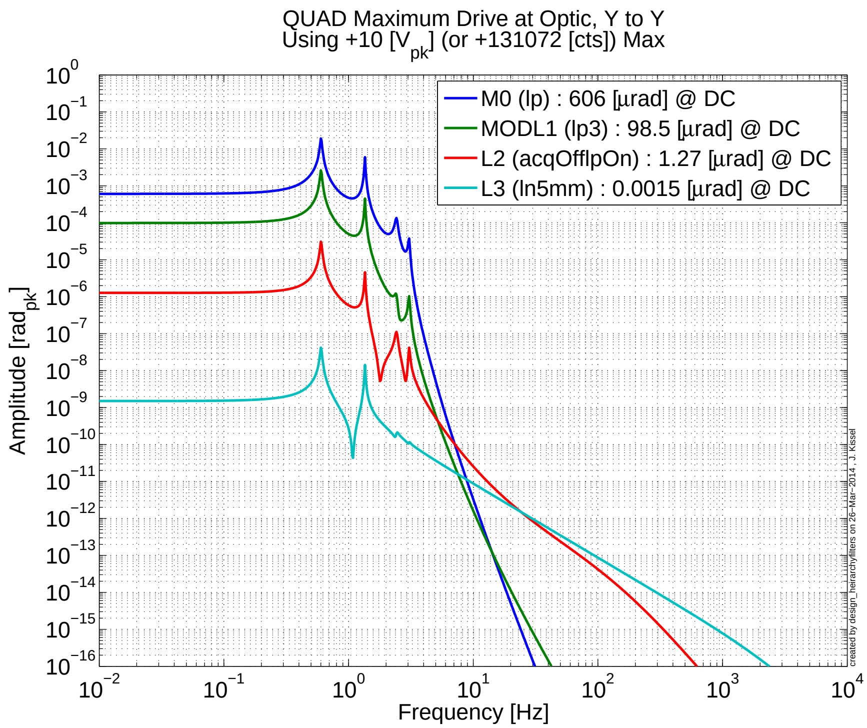

QUAD Maximum Drive at Optic, P to P
Using +10 [V_pk] (or +131072 [cts]) Max
M0 (acq) : 492 [μrad] @ DC
MODL1 (acq) : 140 [μrad] @ DC
L2 (acqOnlpOff) : 2.29 [μrad] @ DC
L3 (acq5mm) : 2.66 [μrad] @ DC
Amplitude [rad_pk]
Frequency [Hz]
created by design_heirarchyfilters on 26-Mar-2014 , J. Kissel


QUAD Maximum Drive at Optic, Y to Y
Using +10 [V_pk] (or +131072 [cts]) Max
M0 (acq) : 606 [μrad] @ DC
MODL1 (acq) : 98.5 [μrad] @ DC
L2 (acqOnlpOff) : 1.27 [μrad] @ DC
L3 (acq5mm) : 1.98 [μrad] @ DC
Amplitude [rad_pk]
Frequency [Hz]
created by design_heirarchyfilters on 26-Mar-2014 , J. Kissel

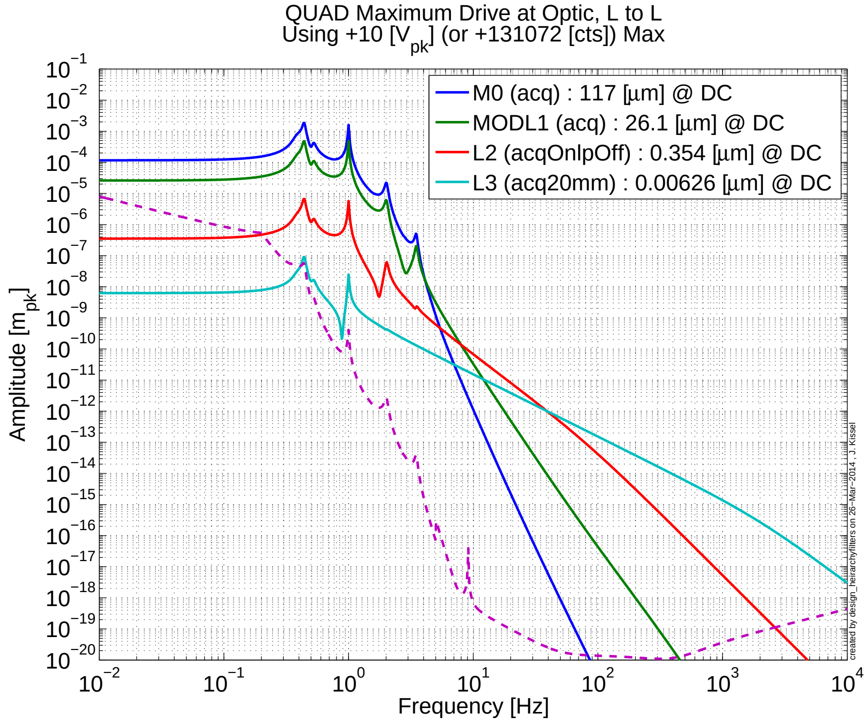
6.2 ETM, Low-Noise Configuration

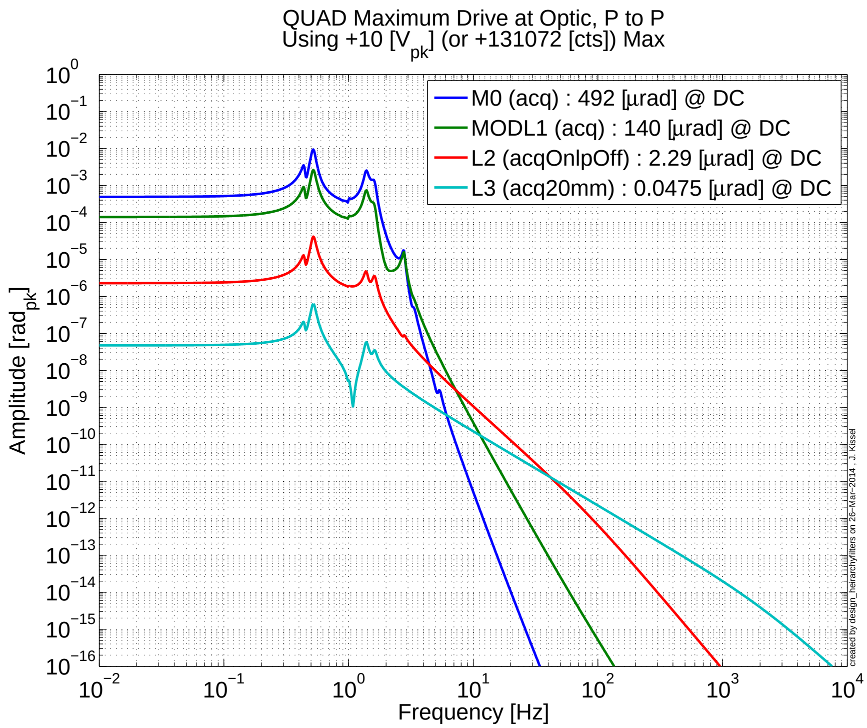


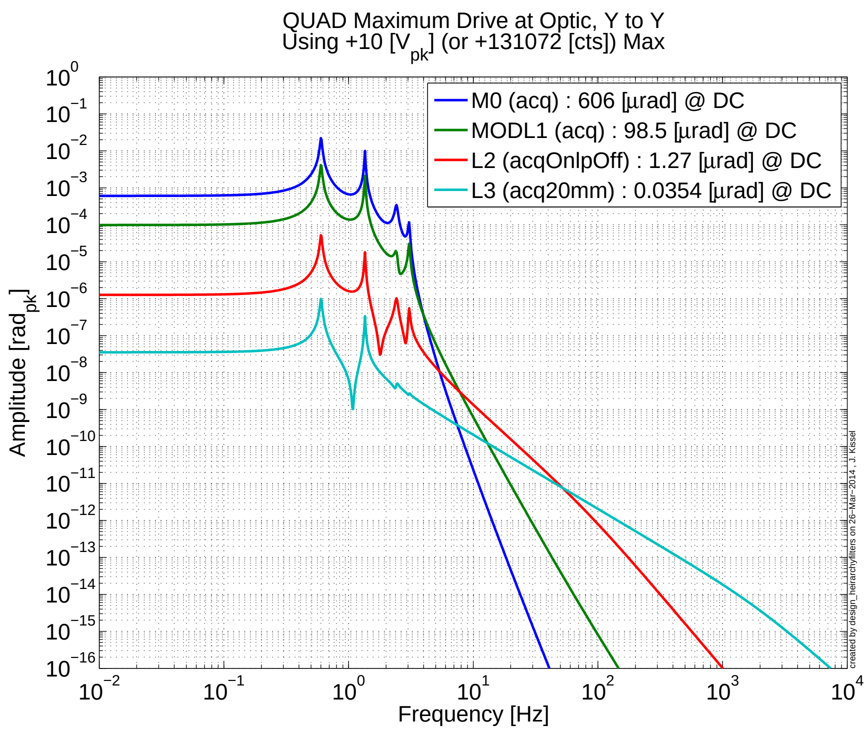



QUAD Maximum Drive at Optic, Y to Y
Using +10 [V_pk] (or +131072 [cts]) Max
M0 (lp) : 606 [µrad] @ DC
MODL1 (lp3) : 98.5 [µrad] @ DC
L2 (acqOfflpOn) : 1.27 [µrad] @ DC
L3 (ln5mm) : 0.0015 [µrad] @ DC
Amplitude [rad_pk]
Frequency [Hz]
created by design_hierarchyfilters on 26-Mar-2014 , J. Kissel

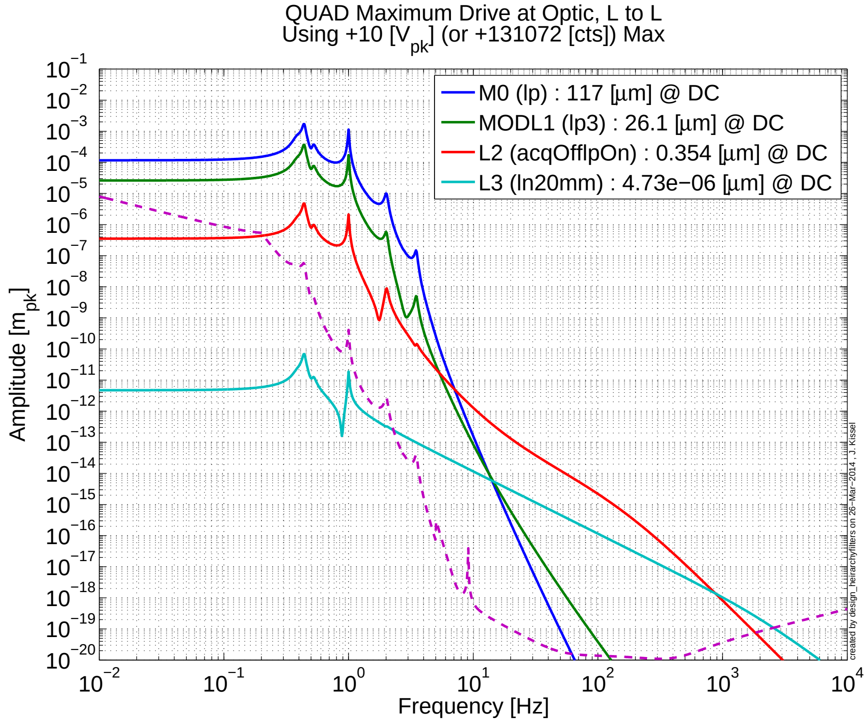
6.3 ITM, High-Range Configuration

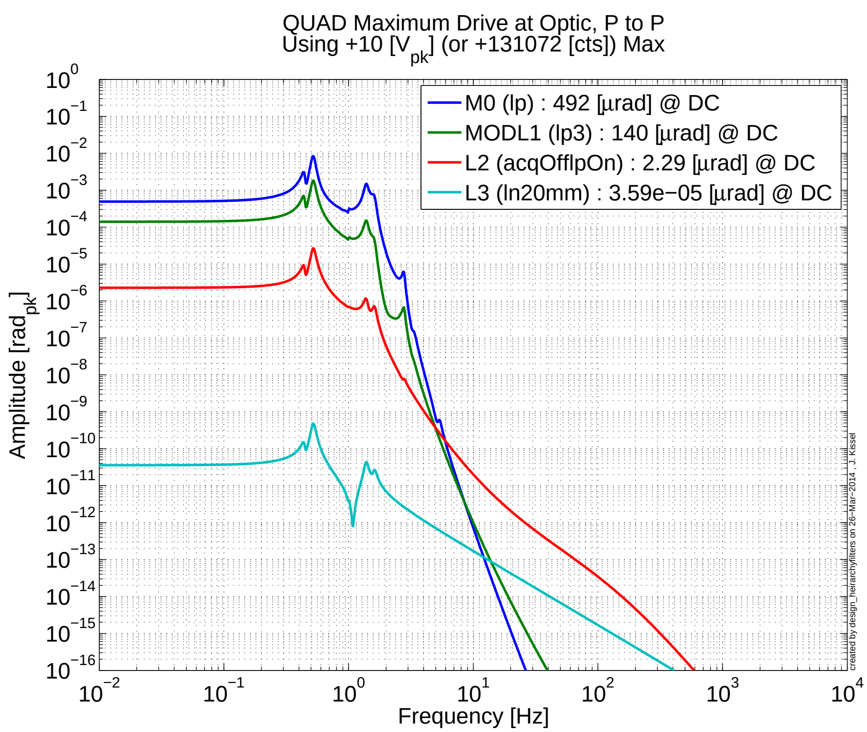


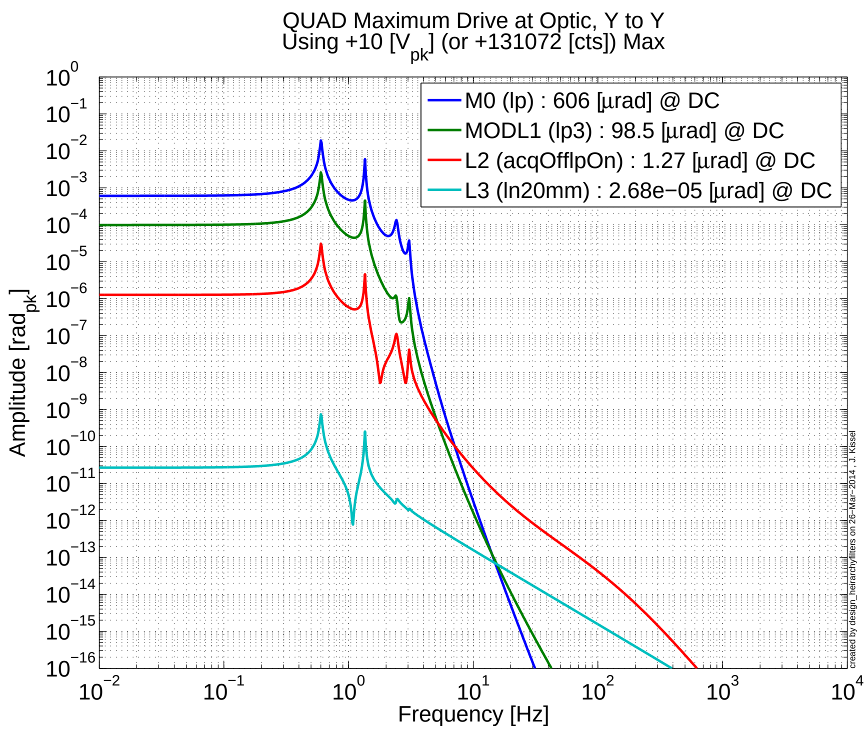



QUAD Maximum Drive at Optic, Y to Y
Using +10 [V$_{pk}$] (or +131072 [cts]) Max
M0 (acq) : 606 [µrad] @ DC
MODL1 (acq) : 98.5 [µrad] @ DC
L2 (acqOnlpOff) : 1.27 [µrad] @ DC
L3 (acq20mm) : 0.0354 [µrad] @ DC
Amplitude [rad$_{pk}$]
Frequency [Hz]
created by design_hierarchyfilters on 26-Mar-2014 , J. Kissel

6.4 ITM, Low-Noise Configuration






QUAD Maximum Drive at Optic, Y to Y
Using +10 [V_pk] (or +131072 [cts]) Max
Amplitude [rad_pk]
Frequency [Hz]
M0 (lp) : 606 [µrad] @ DC
MODL1 (lp3) : 98.5 [µrad] @ DC
L2 (acqOfflpOn) : 1.27 [µrad] @ DC
L3 (ln20mm) : 2.68e−05 [µrad] @ DC
created by design_heirarchyfilters on 26−Mar−2014 , 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. Kissel, J. Heefner. aLIGO QUAD Controls Design Description. LIGO-T1100378-v6 (2012)

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

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

[6] Advanced LIGO Production QUAD Model. <https://redoubt.ligo-wa.caltech.edu/svn/sus/trunk/Common/SusModelTags/Matlab/quadmodelproduction_rev3311_fiber_2012-09-06.mat> (2012)

[7] J. Heenfer. AdL Quad Suspension UK Coil Driver Design Requirements. LIGO-T060067-v1 (2006)

[8] R. Adhikari. LSC Motivated SUS Requirements. <http://www.its.caltech.edu/~rana/aLIGO/suselecreq.html> (2005)

[9] J. O'Dell, M. Hilliard. Advanced LIGO Quadruple Suspension (SolidWorks Model). LIGO-D0901346-v9 (2009)

[10] G. Billingsley, M. Phelps. End Reaction Mass ESD Coating Face Pattern. LIGO-D0900949-v2 (2009)

[11] G. Billingsley, K. Buckland, C. Torrie. Compensation Plate ESD Pattern. LIGO-D080177-v4 (2009)

[12] J. Miller, M. Evans. Summary of ESD Force Coefficient Simulations. LIGO-T1000119-v1 (2010)

[13] J. Miller, M. Evans. Proposed New ESD Patterns. LIGO-G0900956-v1 (2009)

[14] N. Lockerbie. Electrostatic Driver E3074User Manual (Short Version). LIGO-T1000222-v4. (2011)

[15] P. Fritschel. Electro-Static Driver Range and Noise. LIGO-T1200479-v2 (2012)

[16] J. Miller. On Non-Gaussian Beams and Optomechanical Parametric Instabilities in Interferometric Gravitational Wave Detectors. LIGO-P1000032 (2010)

[17] J. Kissel, LLO aLOG 4495. <https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=4495> (2012)

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