Thesis Title: Adaptive Modal Damping of Advanced LIGO Suspensions

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Thesis Defense – Mechanical Engineering
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Abstract

Motivation: Observe gravitational waves from astrophysical sources (supernovae, pulsars, black hole mergers, etc) using the LIGO observatories.

Problem: Active control to suppresses time varying ground disturbances. This control introduces additional noise. Optimal control requires tuning the trade-off as the disturbances evolve.

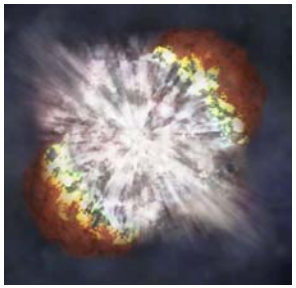
1. Many of the LIGO control loops contain non-negligible sensing noise
2. Seismic disturbances evolves in time
3. LIGO optical cavities have a small finite linear operating range

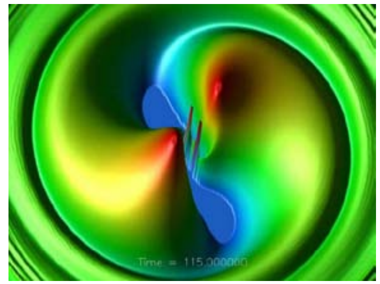
Solution: An adaptive algorithm to constantly monitor and tune the performance of this control. Applied to the method of modal damping. Adaptation optimized for astrophysical sources.

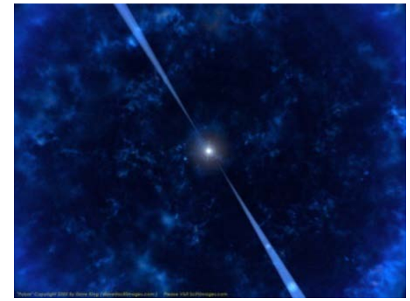
Outline

1. LIGO and gravitational waves
2. Seismic (vibration) isolation
3. Problems and challenges
4. Method of adaptive modal damping
5. Experimental results
6. Simulated results

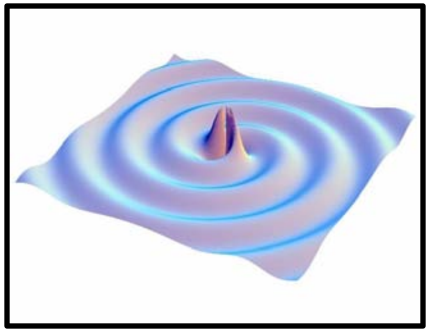
Gravitational Waves

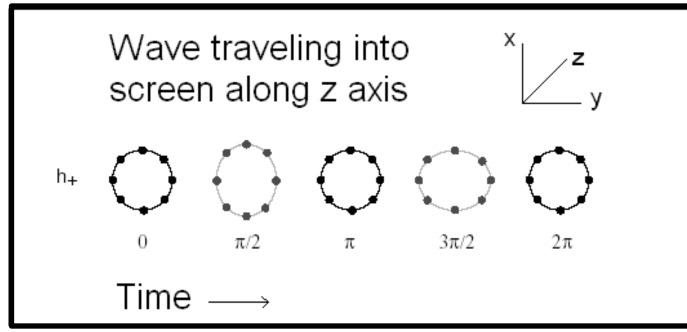

Supernova


Merging Black Holes


Pulsar

Wave of strain amplitude h

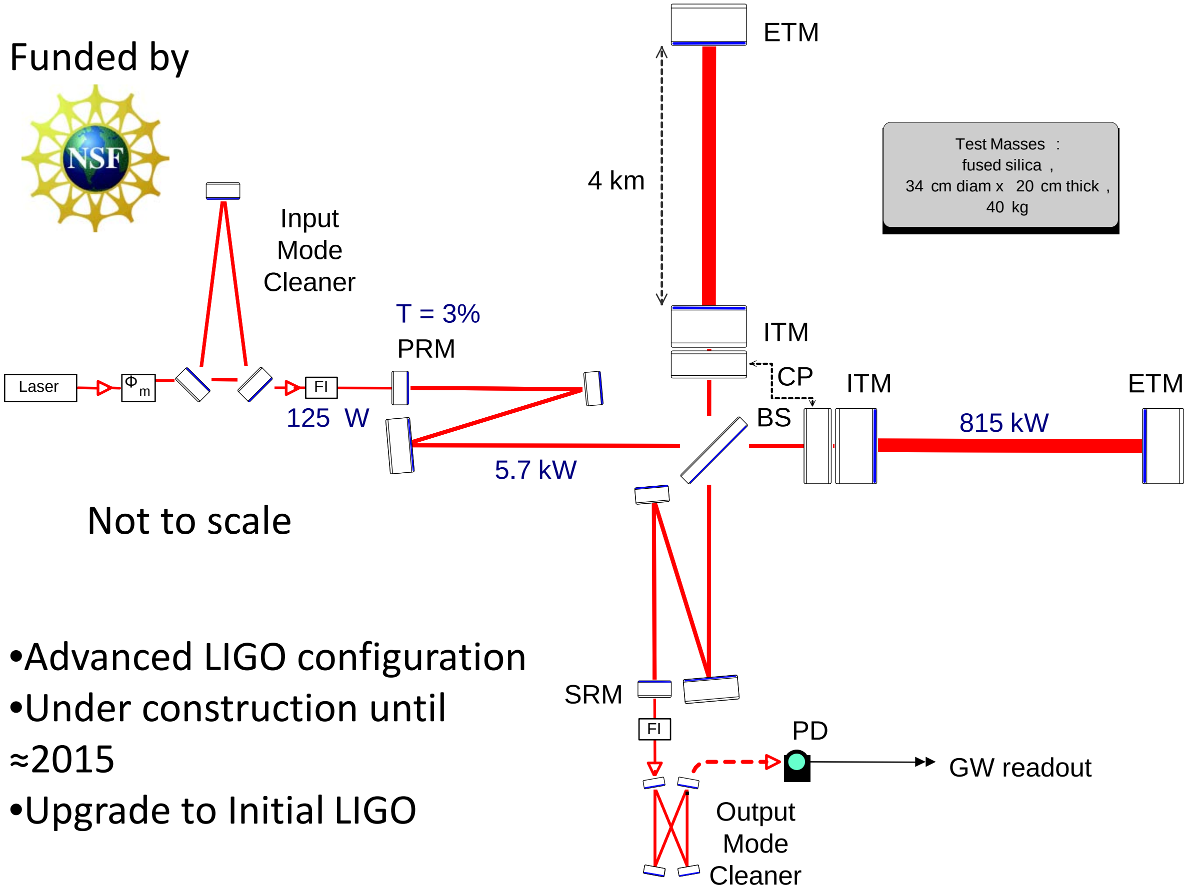




- Supernovae
  - ➢ Asymmetry required
- Coalescing Binaries
  - ➢ Black Holes or Neutron Stars Mergers
- Pulsars
  - ➢ Asymmetry required
- Stochastic Background (Big bang, etc.)

The Laser Interferometer Gravitational-wave Observatory (LIGO)

Funded by



Not to scale

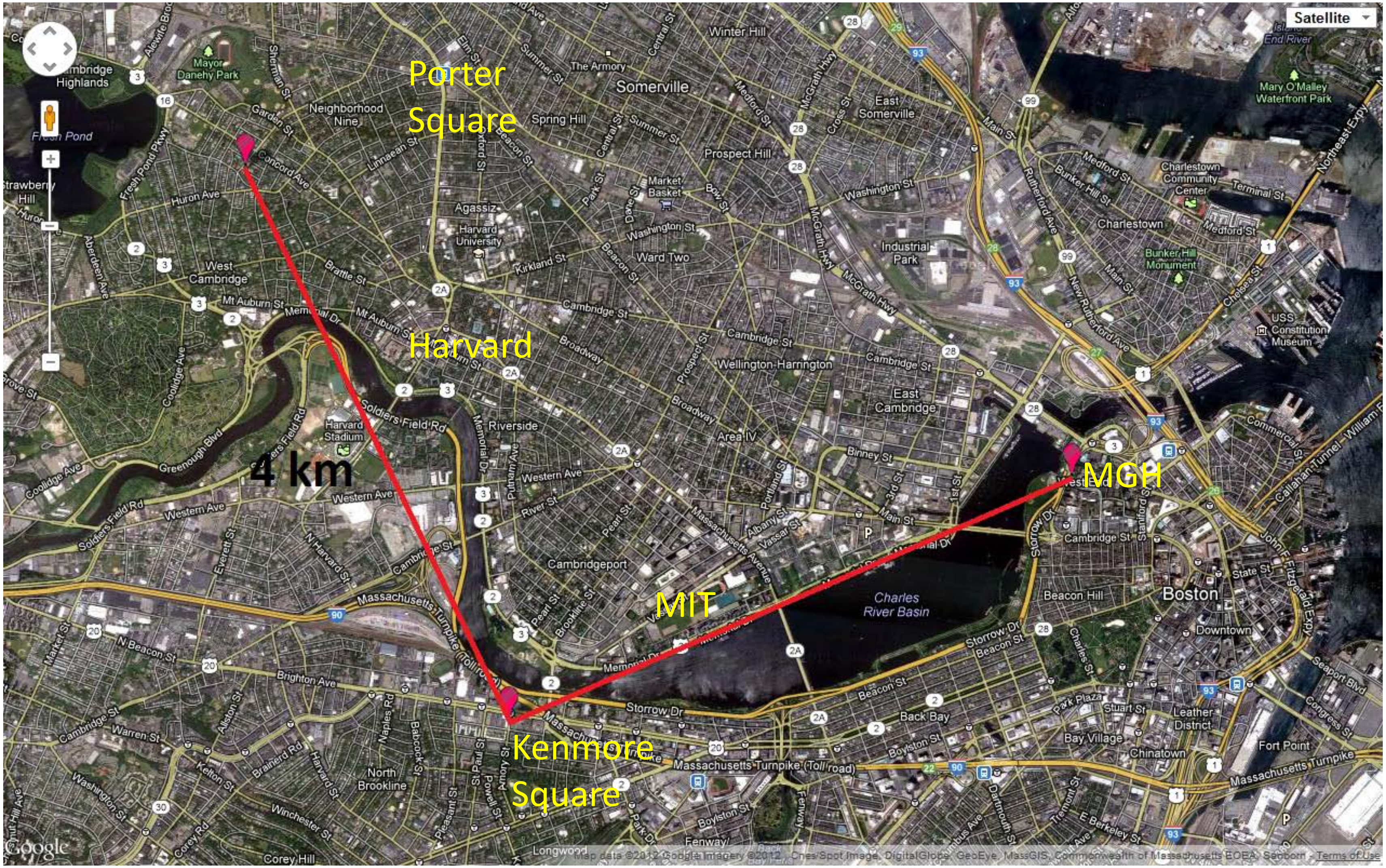
- Advanced LIGO configuration
- Under construction until ≈2015
- Upgrade to Initial LIGO

Hanford, WA

Livingston, LA

- ***3, 4 km interferometers at 2 sites in the US***
- ***Michelson interferometers with Fabry-Pérot arms***
- ***Optical path enclosed in vacuum***
- ***Sensitive to strains around 10^{-22} -> $10^{-19} m_{rms}$***
- ***LIGO Budget ≈ $60 Million per year from NSF.***
- ***Operated by MIT and Caltech.***

If we put LIGO in Cambridge, MA

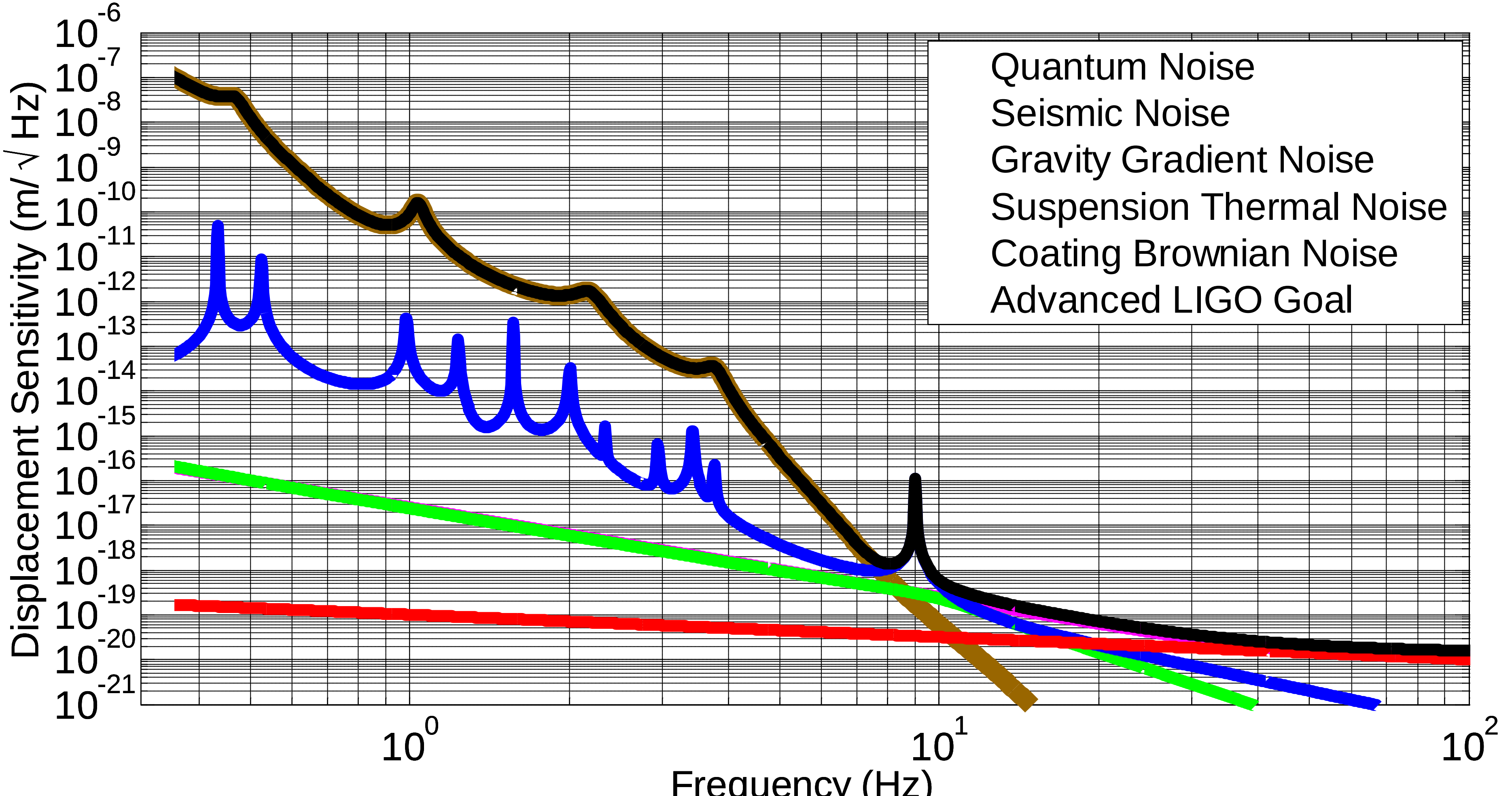


LIGO spans 16 km^2. Cambridge, MA covers 16.65 km^2 (wikipedia http://en.wikipedia.org/wiki/Cambridge,_Massachusetts).

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- CSU Fullerton
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Tsinghua University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

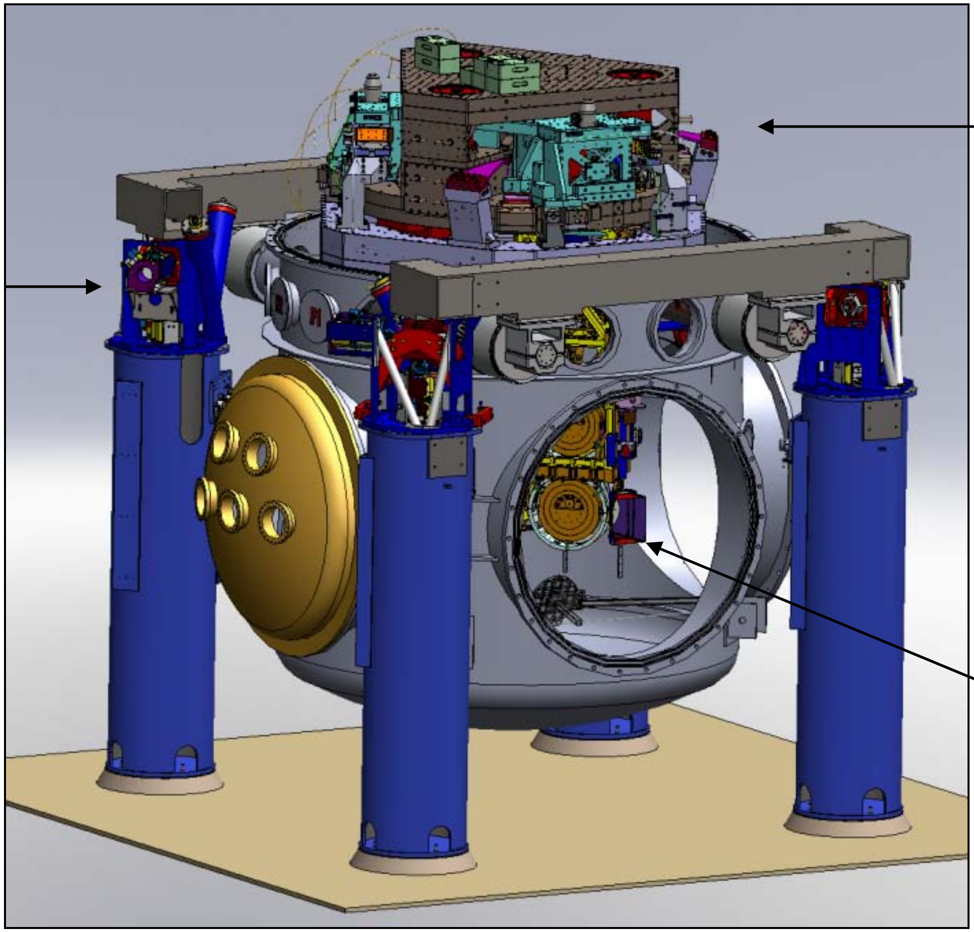
Projected Sensitivity for Advanced LIGO



Suspensions and Seismic Isolation

Advanced LIGO test mass isolation

hydraulic external pre-isolator (HEPI) (one stage of isolation)



active isolation platform (2 stages of isolation)

quadruple pendulum (four stages of isolation) with monolithic silica final stage

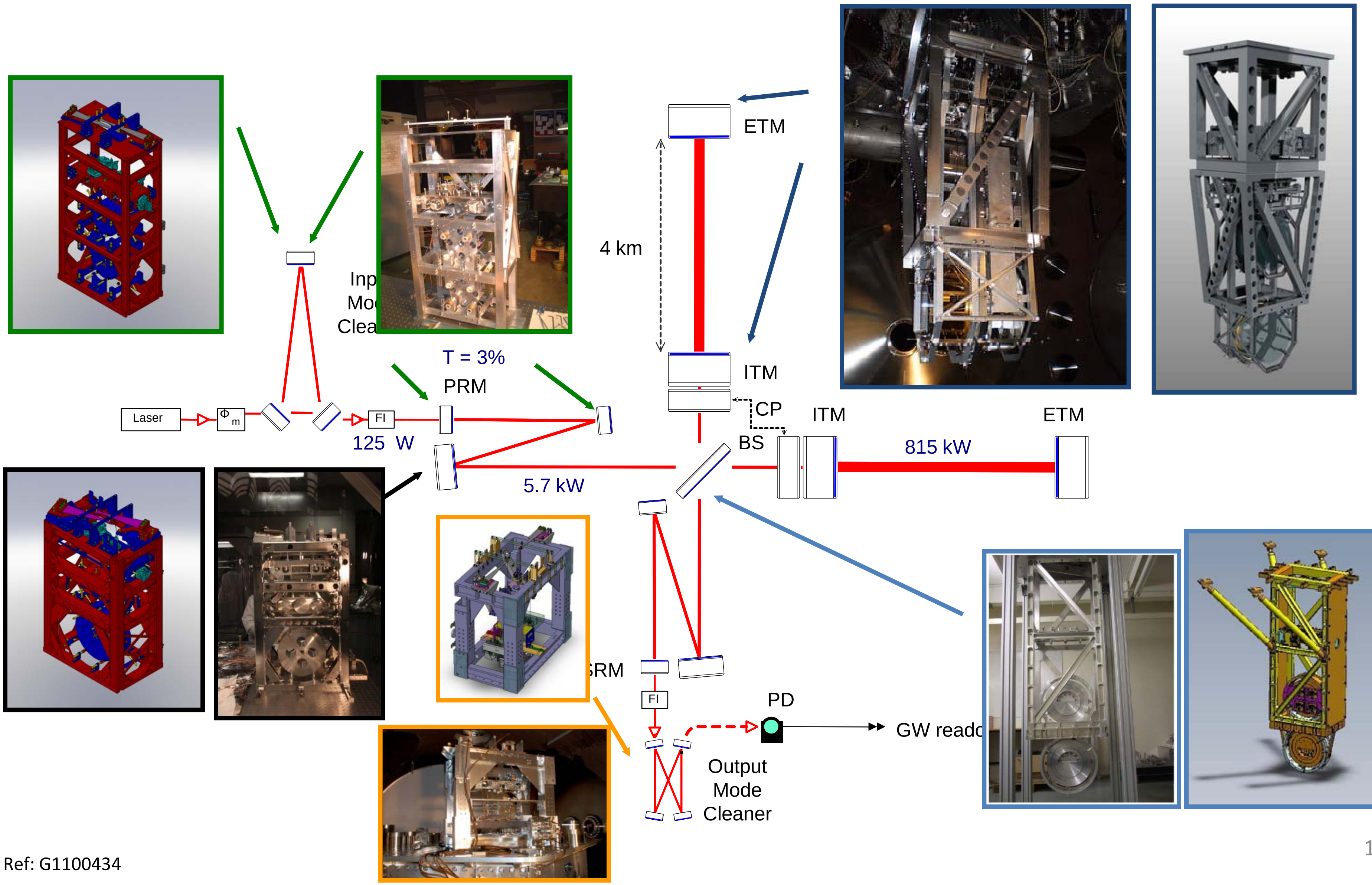
Ref: LIGO-G1000469-v1; Kissel PhD thesis

active isolation platform (2 stages of isolation)

quadruple pendulum (four stages of isolation)

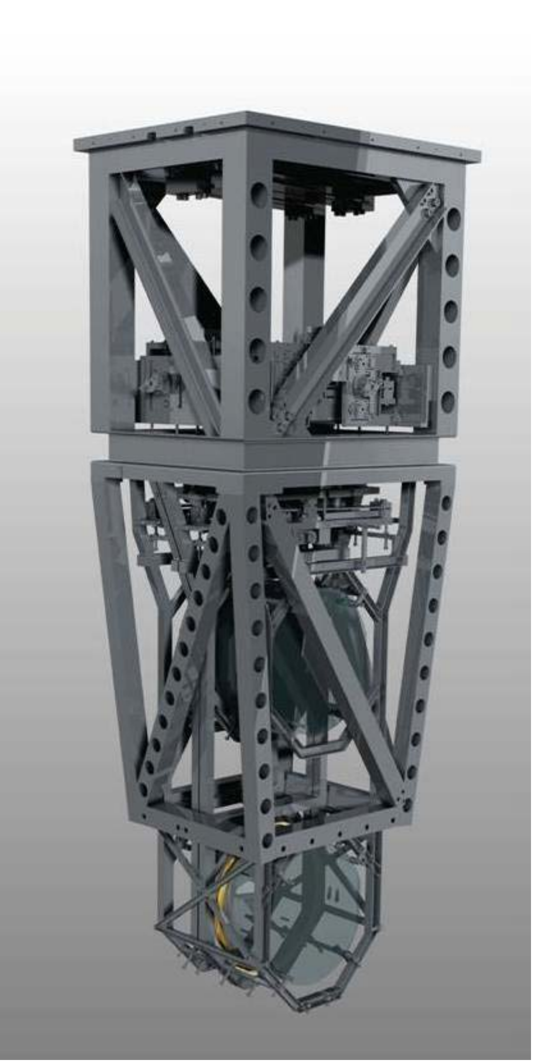
Installing prototype quad pendulum with glass optic on metal wires, Jan 2009 at MIT.

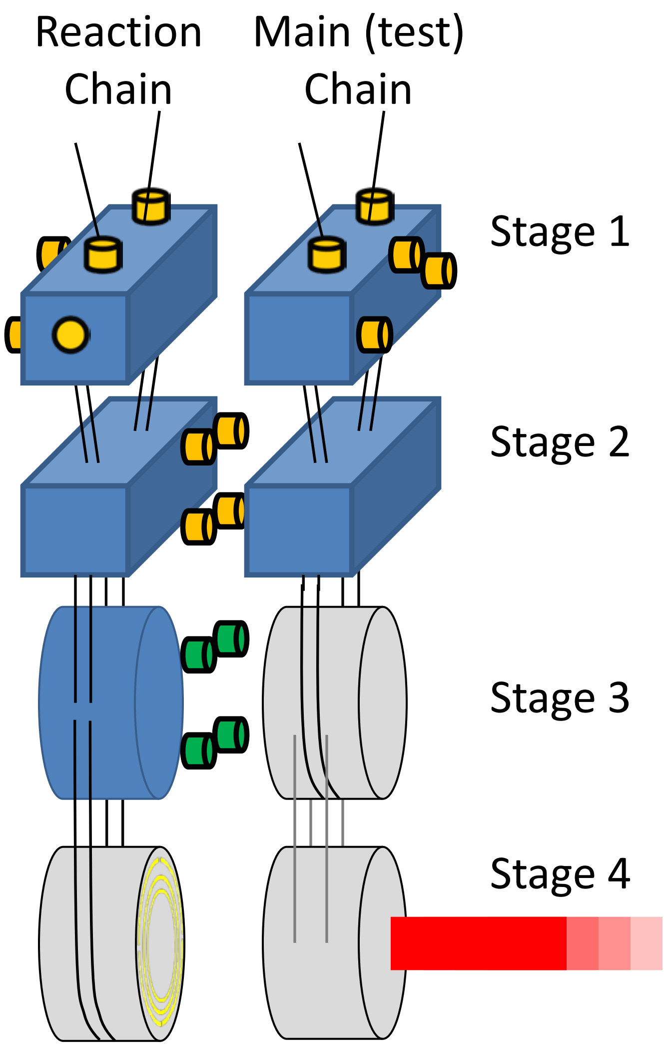
Five Pendulum Designs



Ref: G1100434

Quadruple Pendulum





Purpose

- Test mass (stage 4) isolation.
  the test mass consists of a 40 kg high reflective mirror

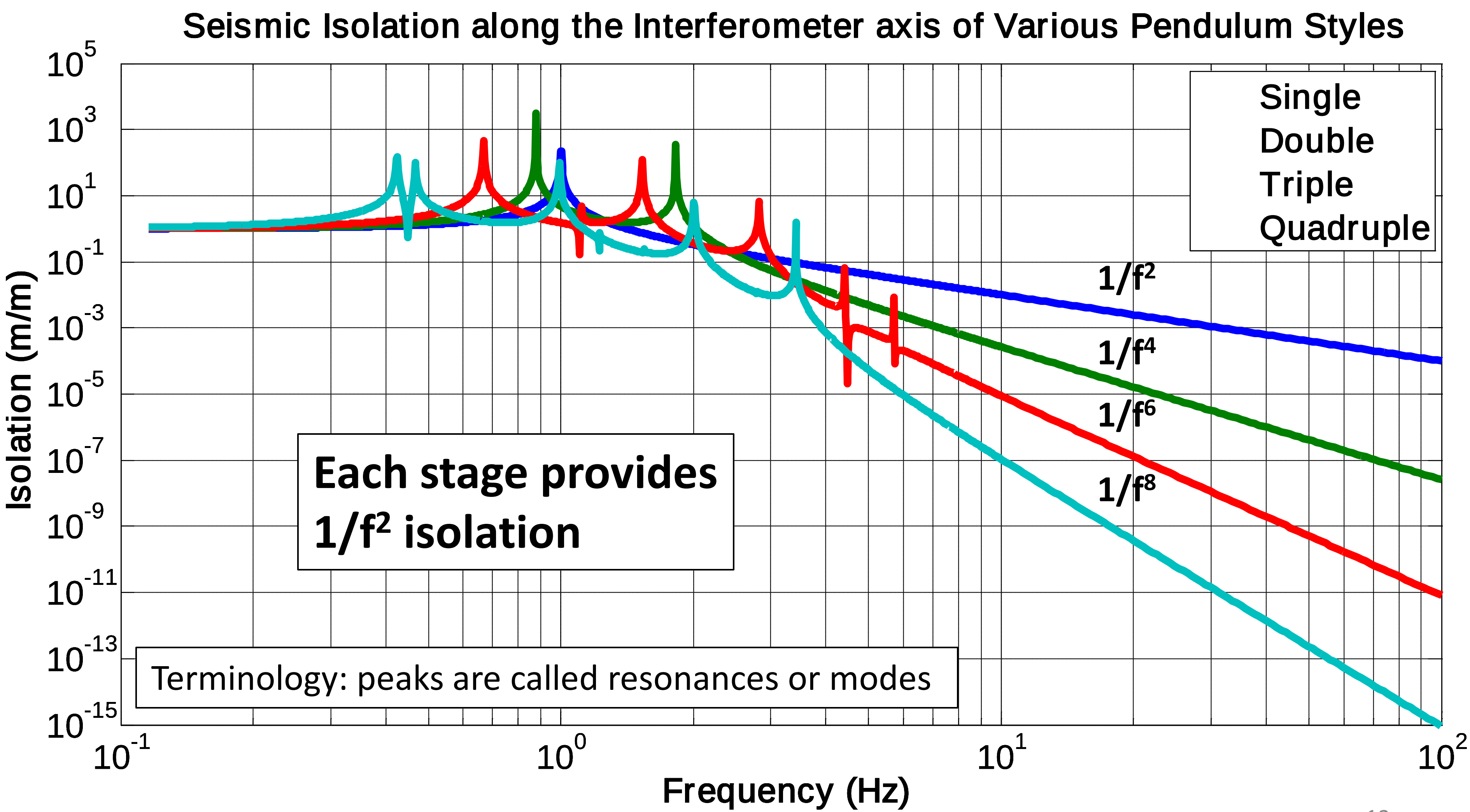
Control

- Damping –stage 1
- Cavity length - all stages

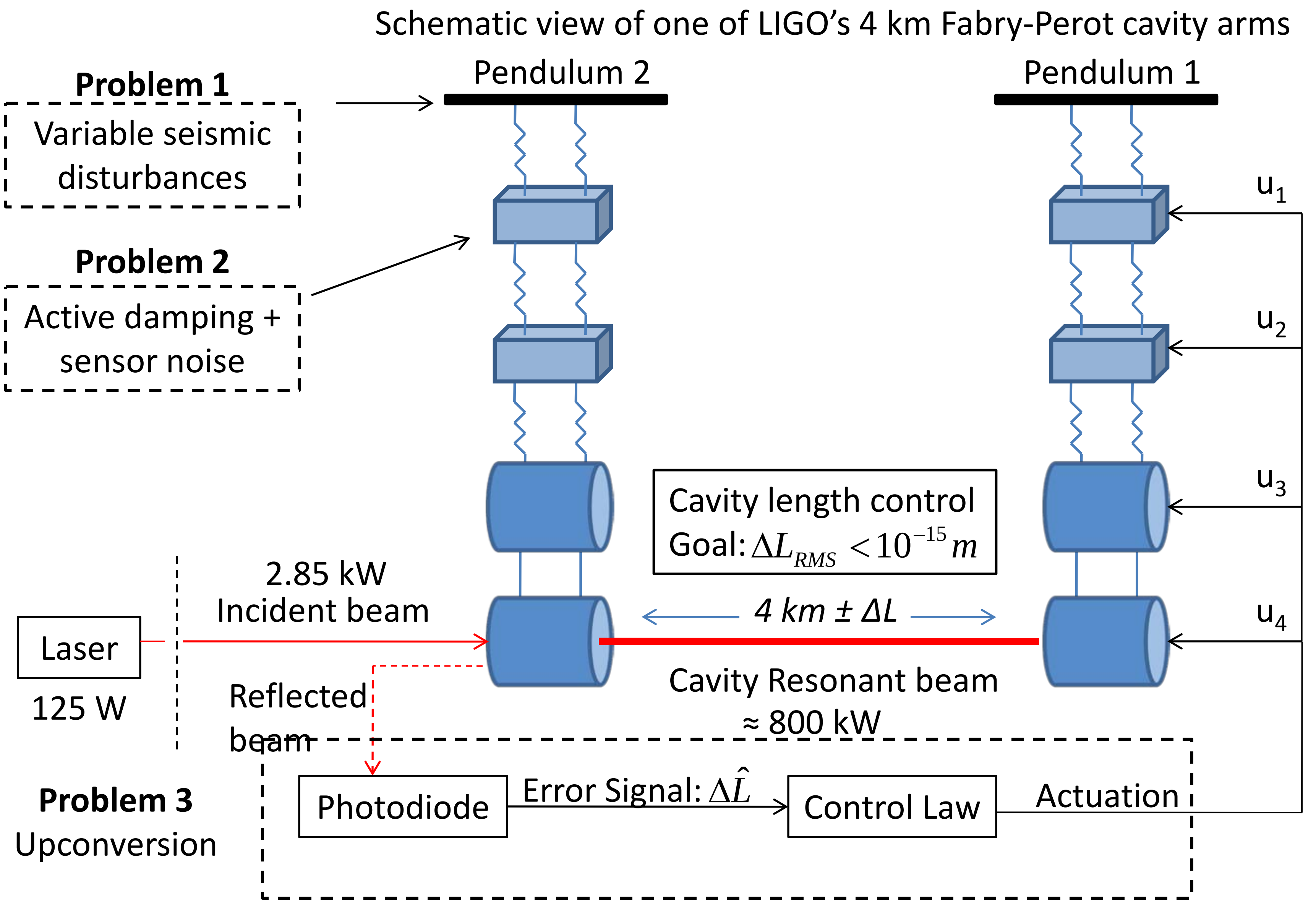
Sensors/Actuators

- (yellow circle) BOSEMs at stage 1 & 2
- (green circle) AOSEMs at stage 3
- Opt. levs. and interf. sigs. at stage 2
- Electrostatic drive (ESD) at stage 4

Multi-stage Isolation Performance

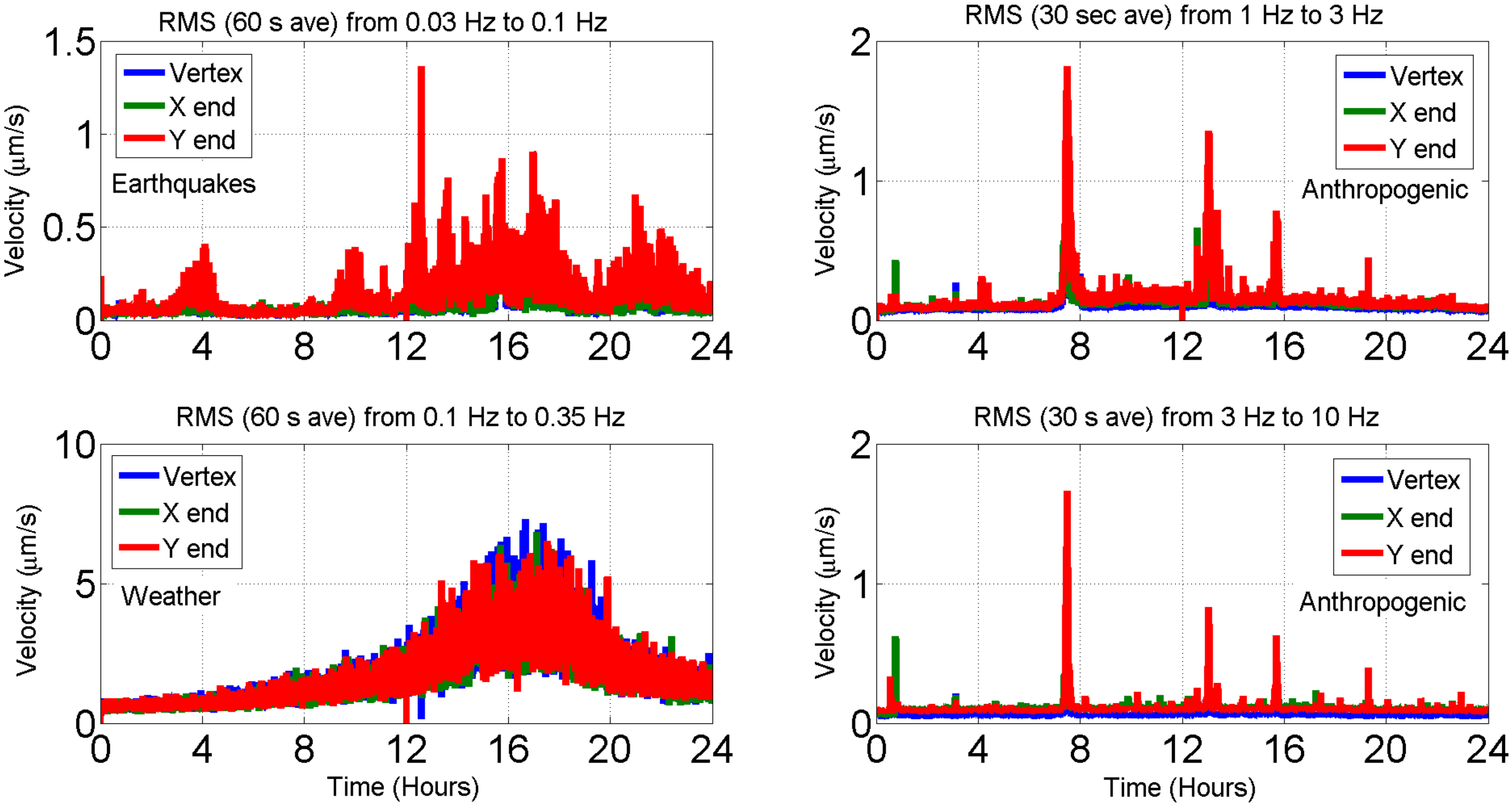


Control: Problems and Challenges

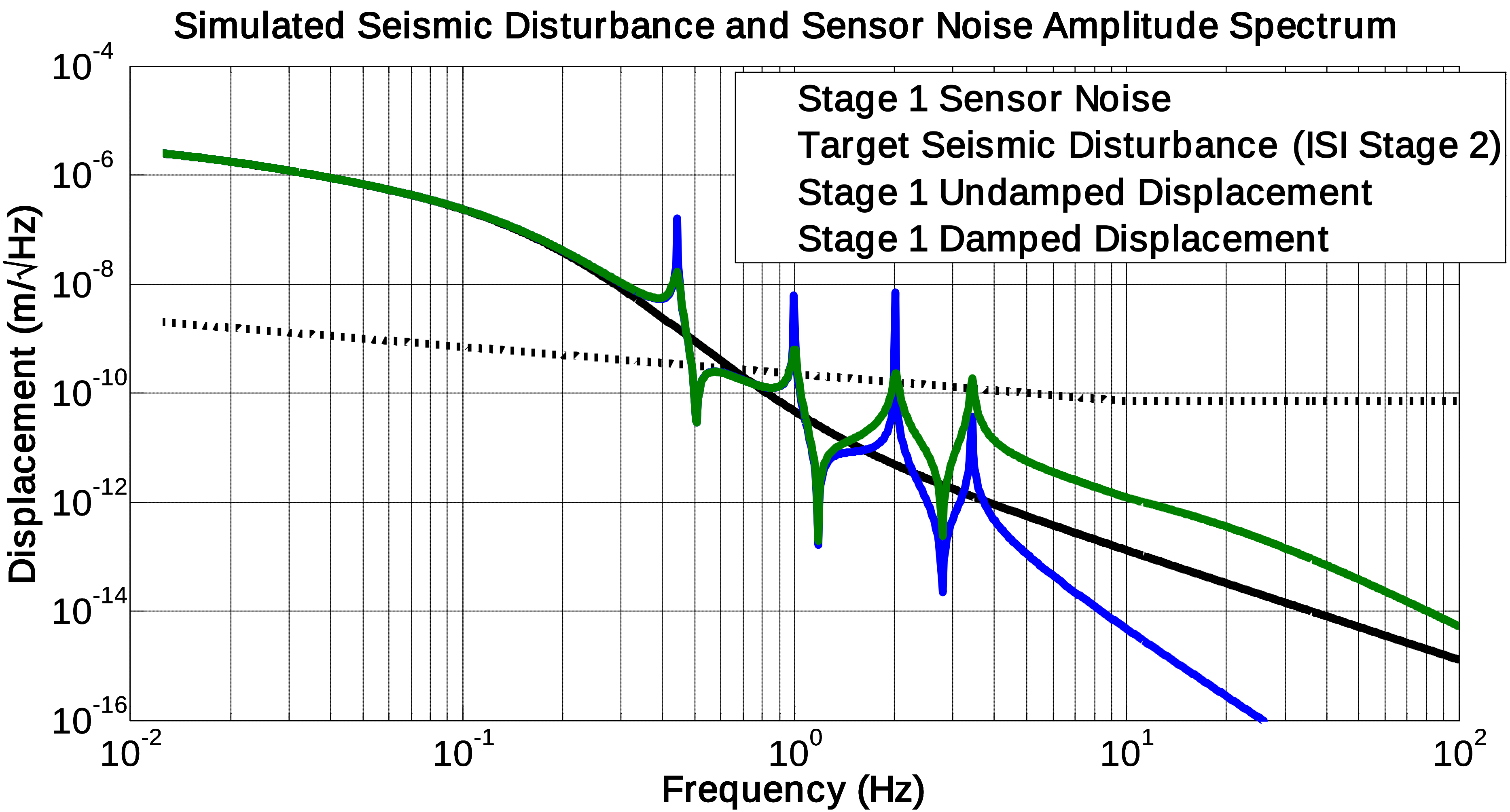


Problem 1: Nonstationary Disturbance

Seismic disturbance at Livingston Observatory on November 21, 2009

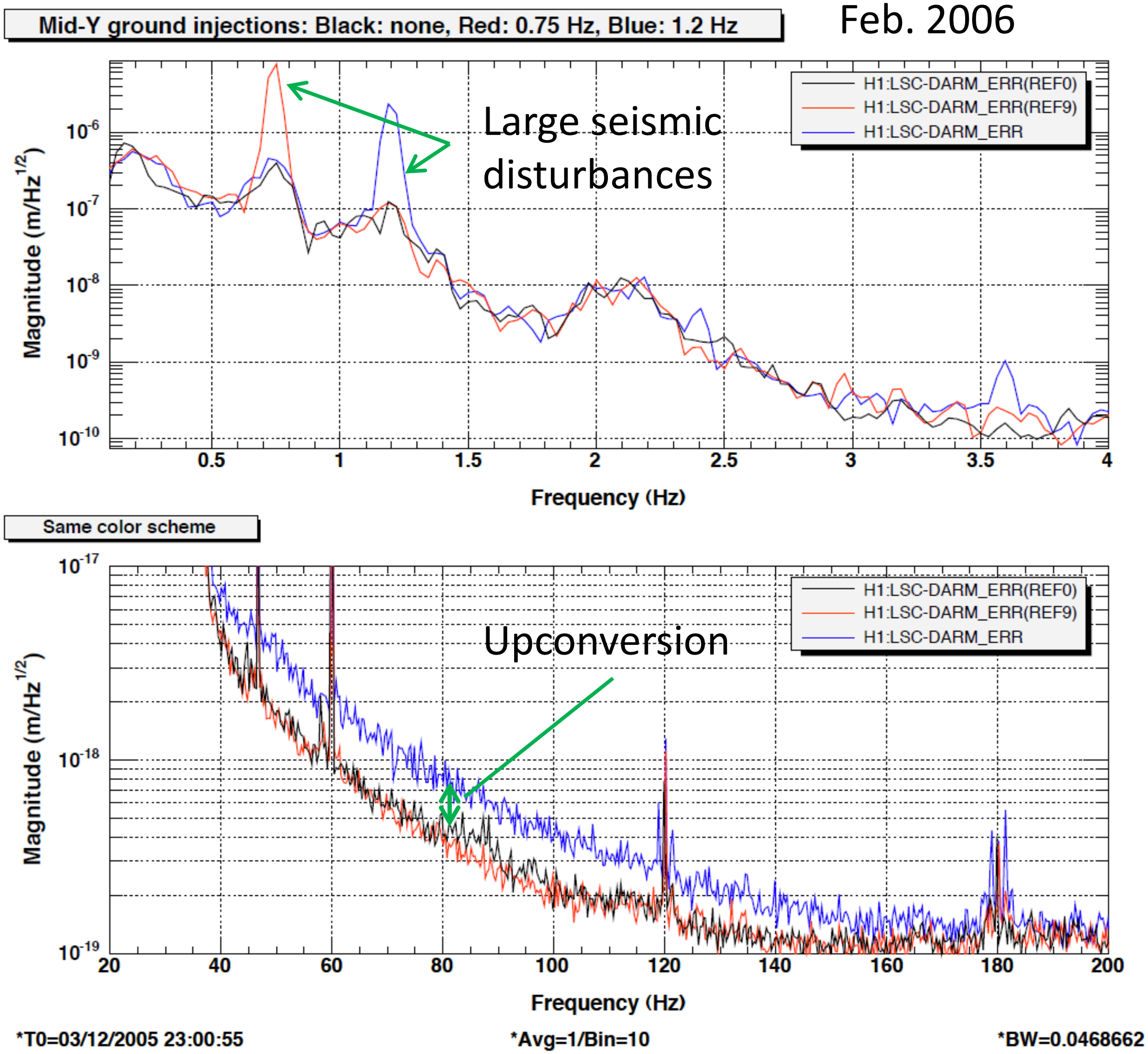


Problem 2: Damping Sensor Noise



Problem 3: Seismic Upconversion

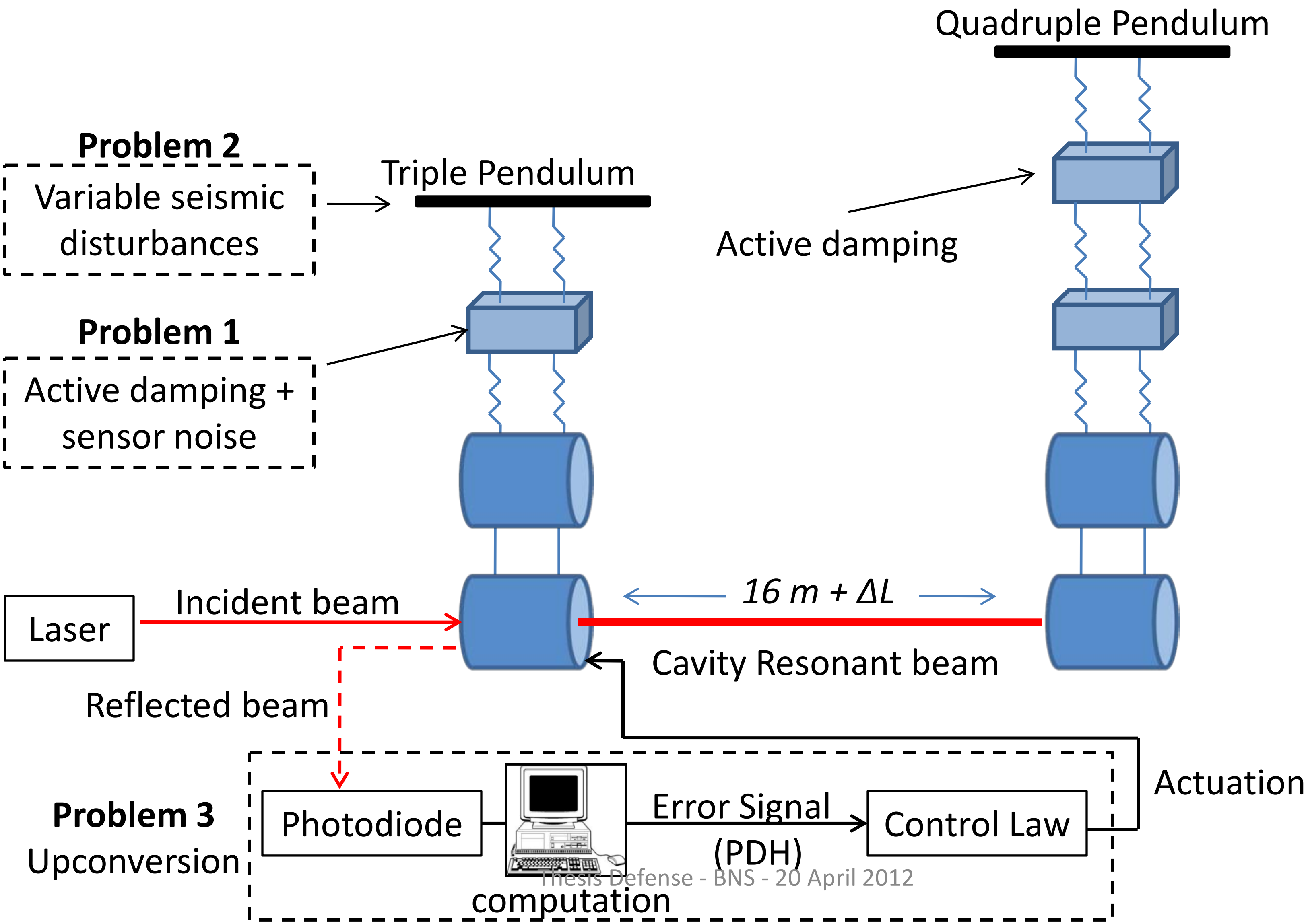
Feb. 2006



Mechanisms for upconversion:

1. Laser beams falling off mirrors
2. Laser scattering off vacuum walls and other objects
3. Interferometer readout method
4. Creak in pendulum springs
5. Actuator nonlinearities
6. ?
7. etc

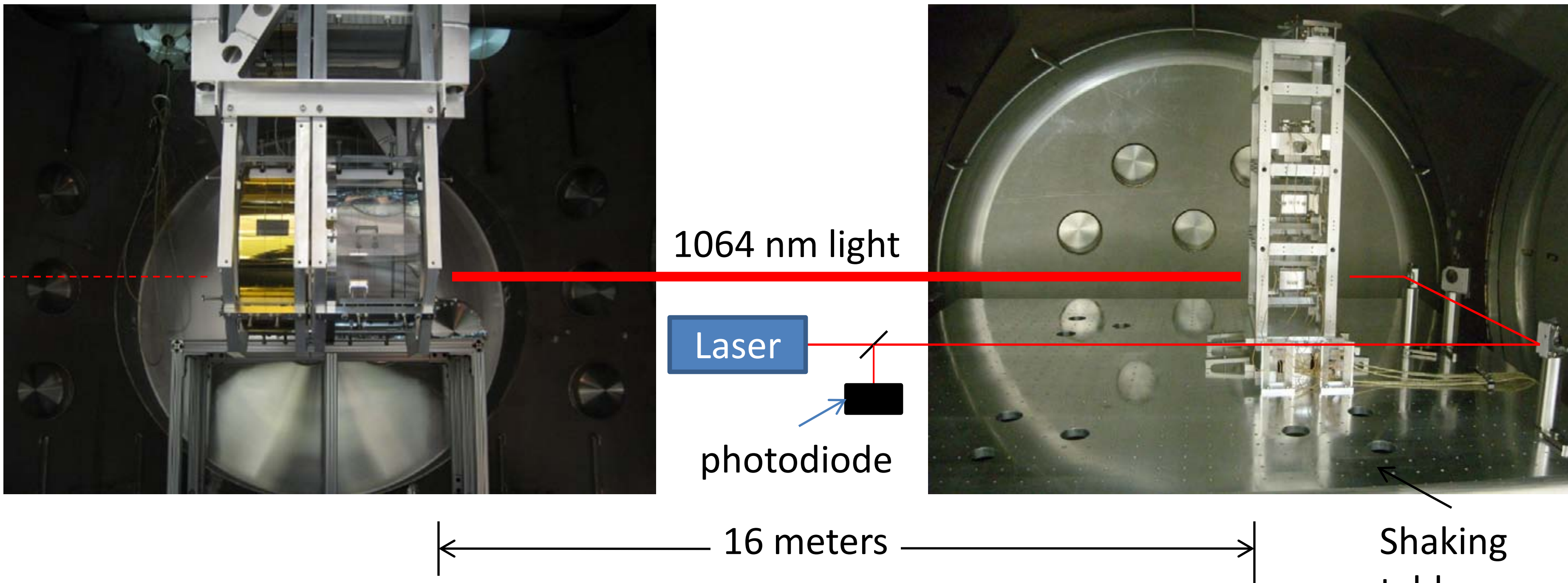
Experimental Setup at MIT



Experimental Setup at MIT

Quadruple Pendulum Mirror

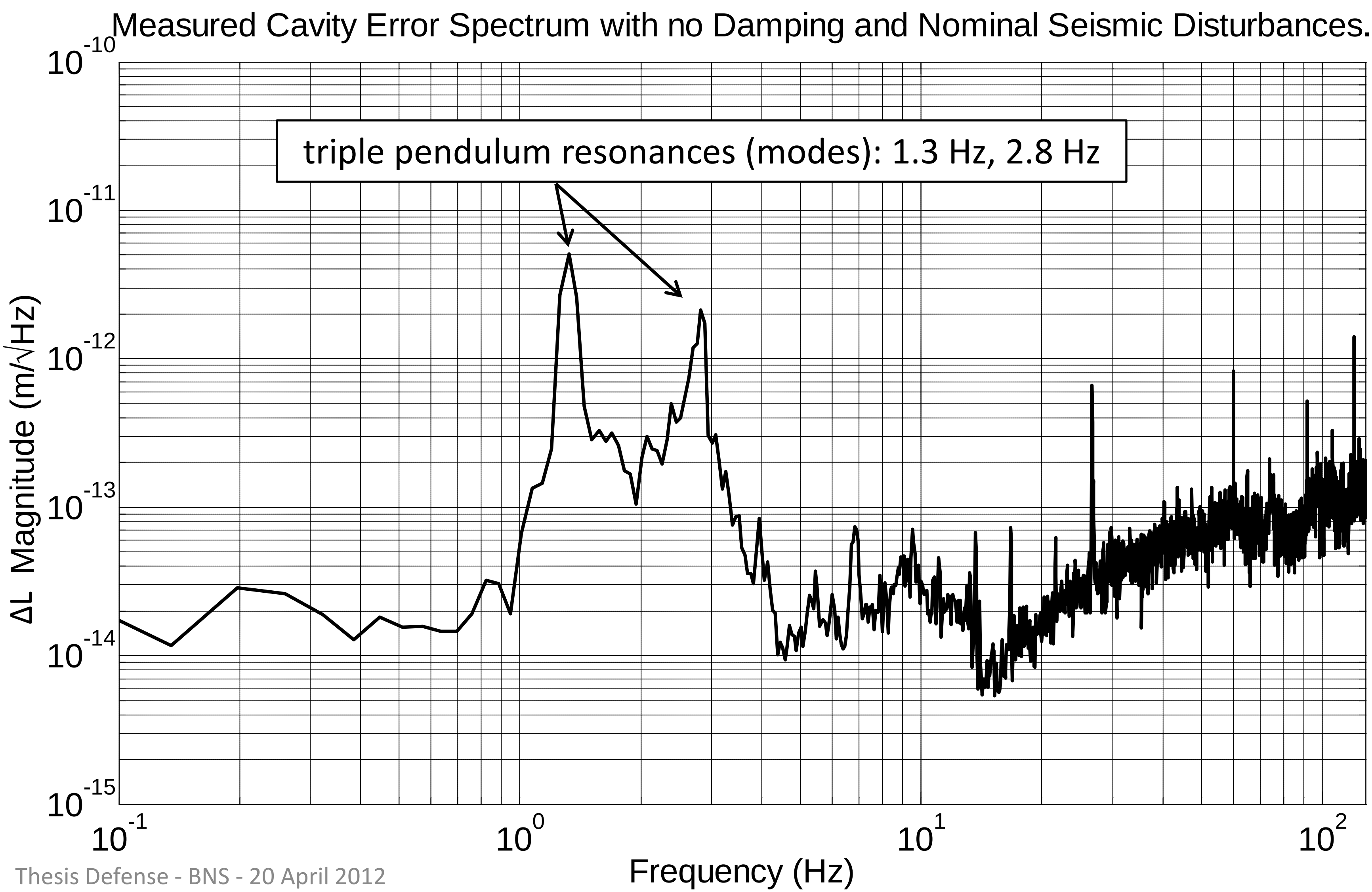
Triple Pendulum



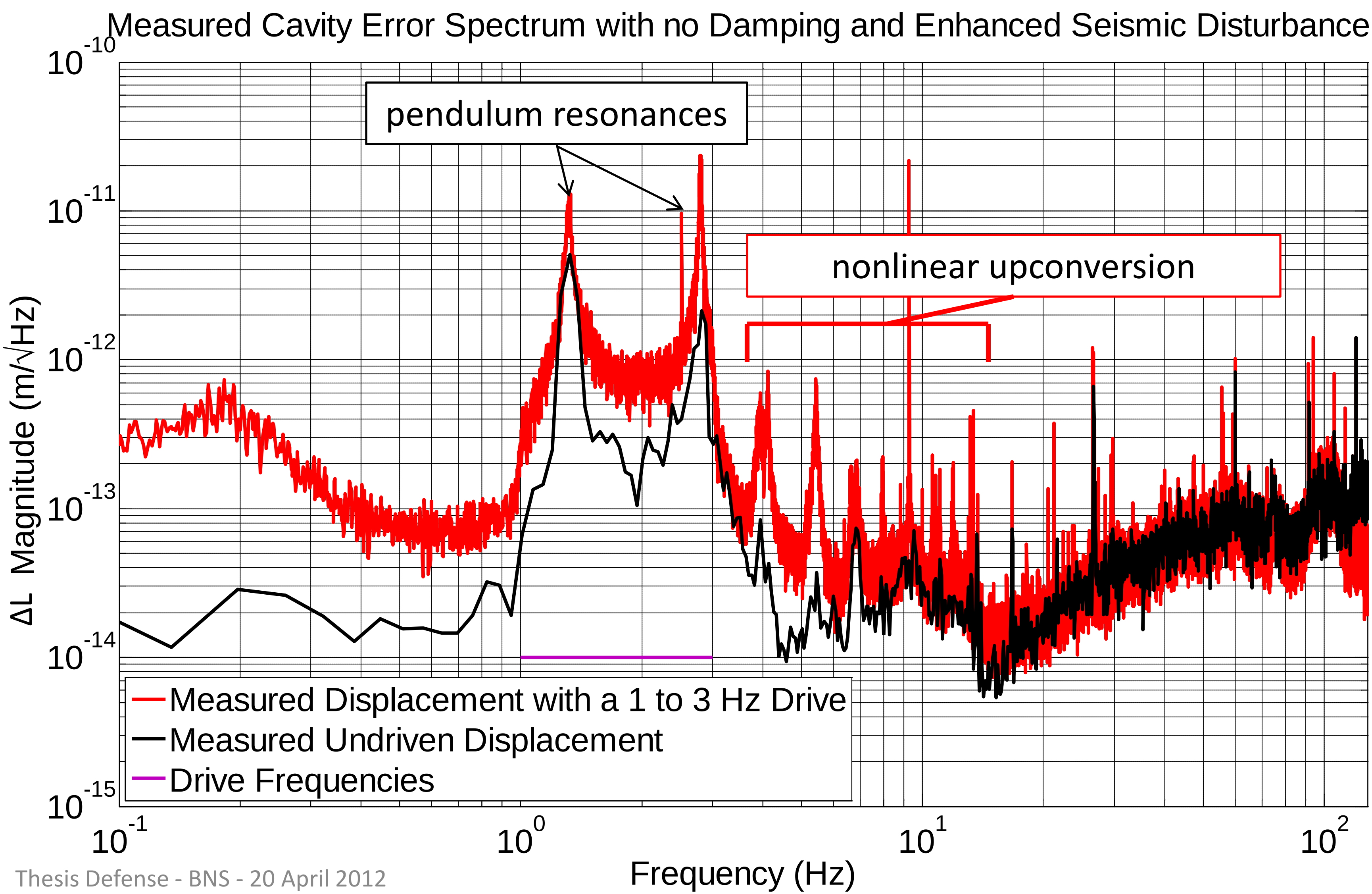
50 ppm light transmission through quad mirror

1% light transmission through triple mirror

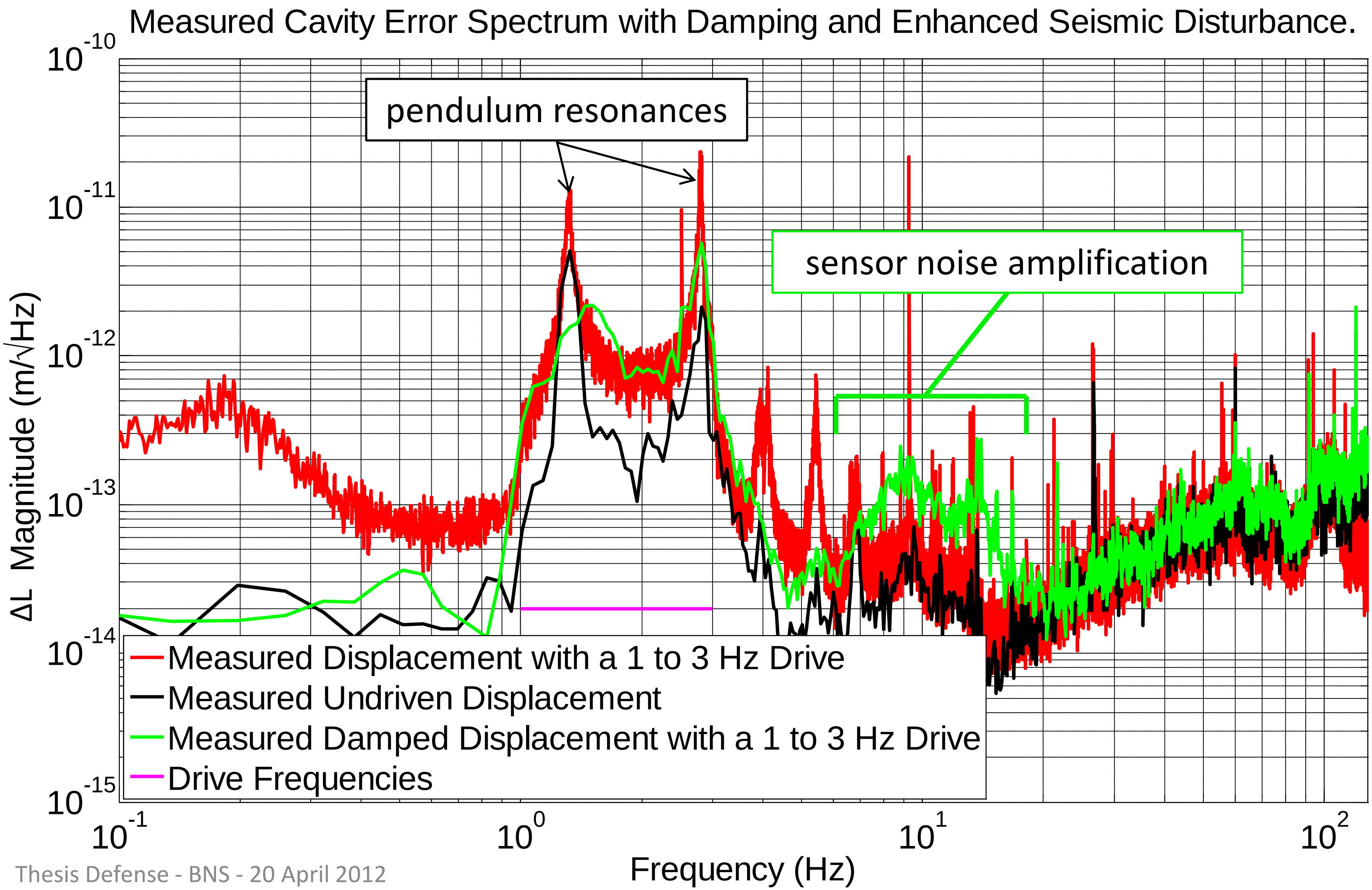
Measured Displacement Spectrum



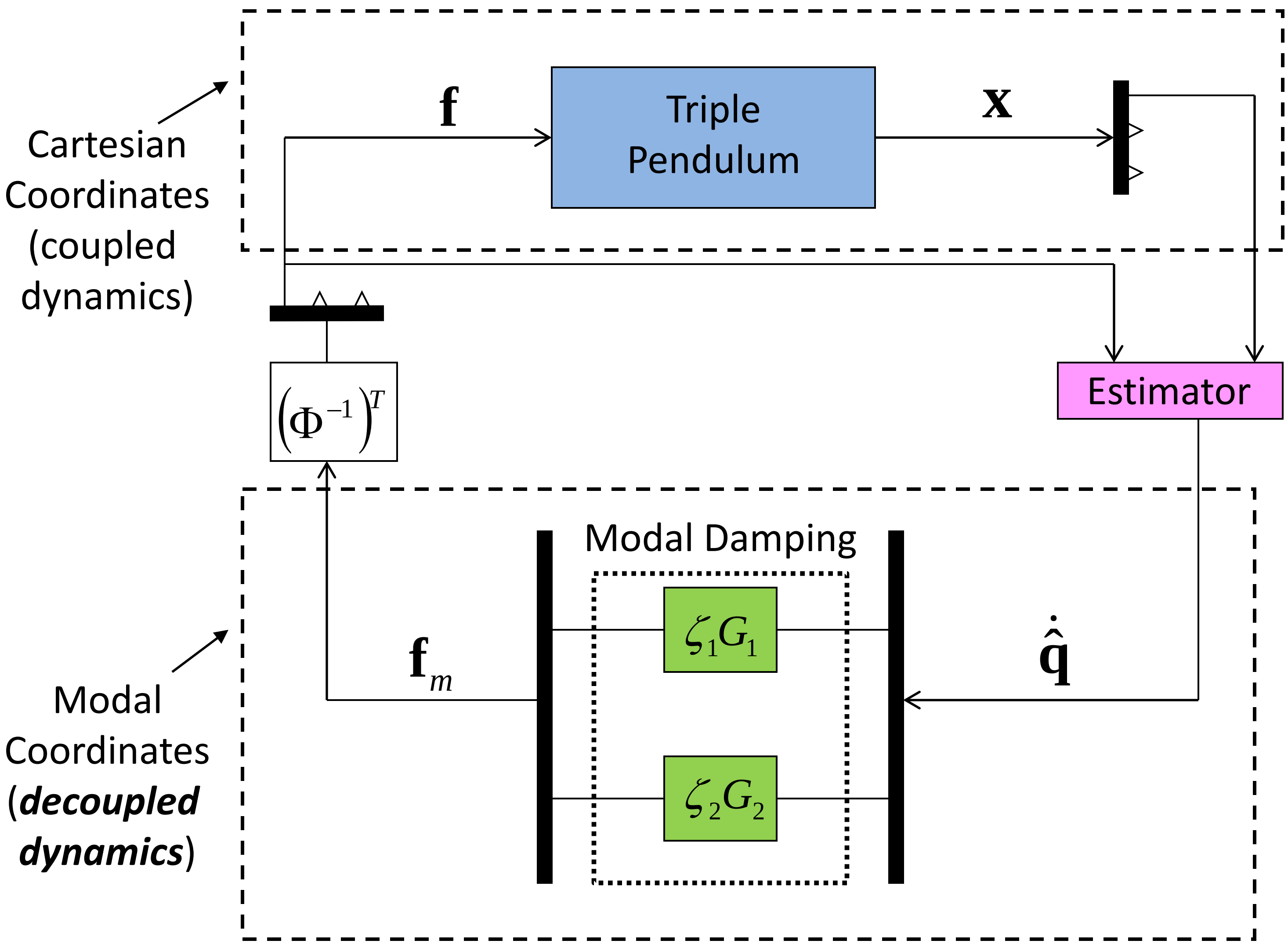
Measured Displacement Spectrum



Measured Displacement Spectrum

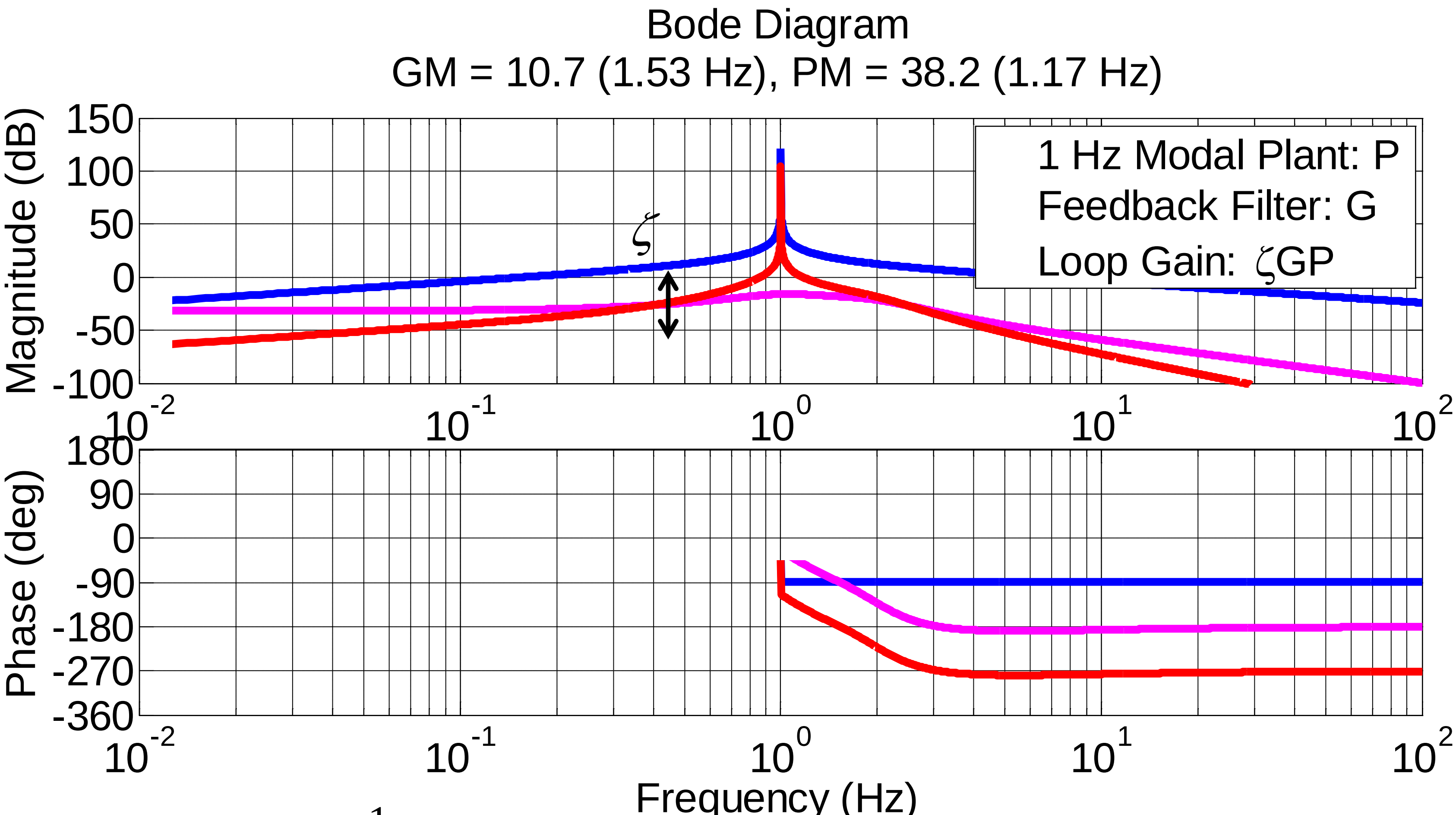


Modal Damping with State Estimation



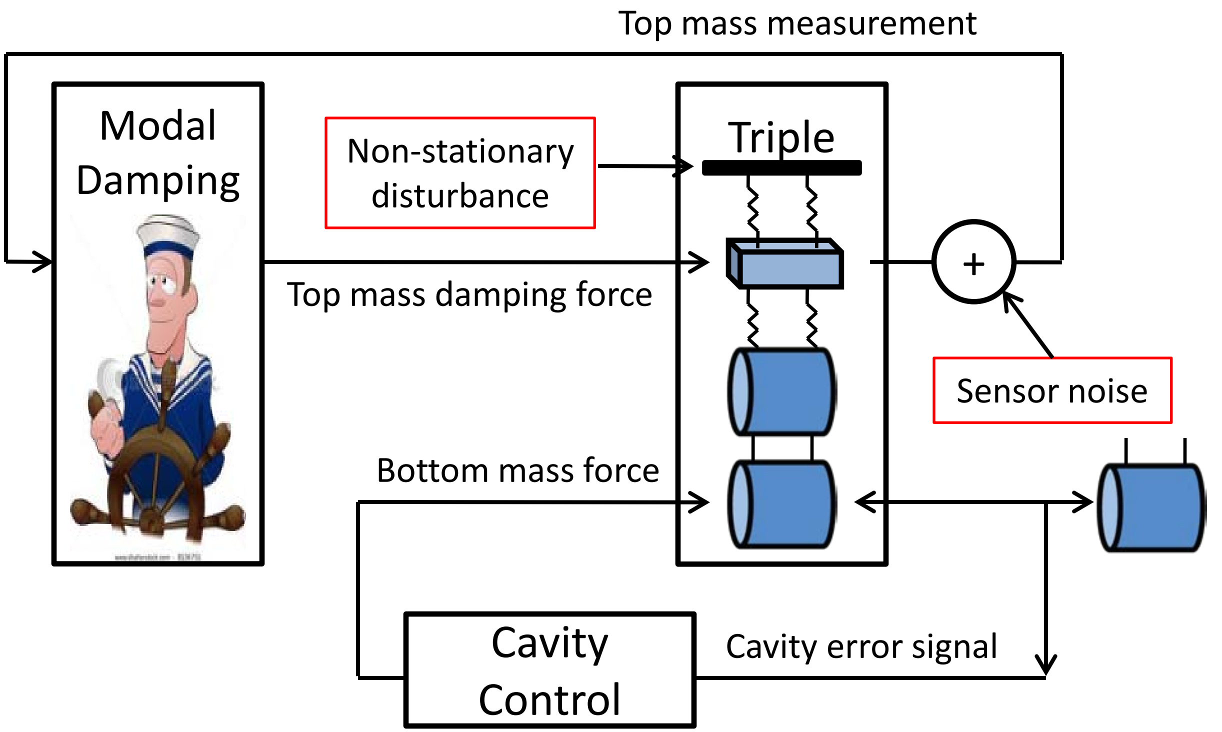
- $\mathbf{x} = \Phi \mathbf{q}$
- Φ = pendulum eigenvector matrix
- $\mathbf{x}$ = Cartesian coordinates
- $\hat{\mathbf{q}}$ = estimated modal coord.
- $\mathbf{f}$ = Cartesian damping forces
- $\mathbf{f}_m$ = modal damping forces
- $G_i = i_{\text{th}}$ mode damping filter
- $\zeta_i = i_{\text{th}}$ mode damping gain

Modal Feedback

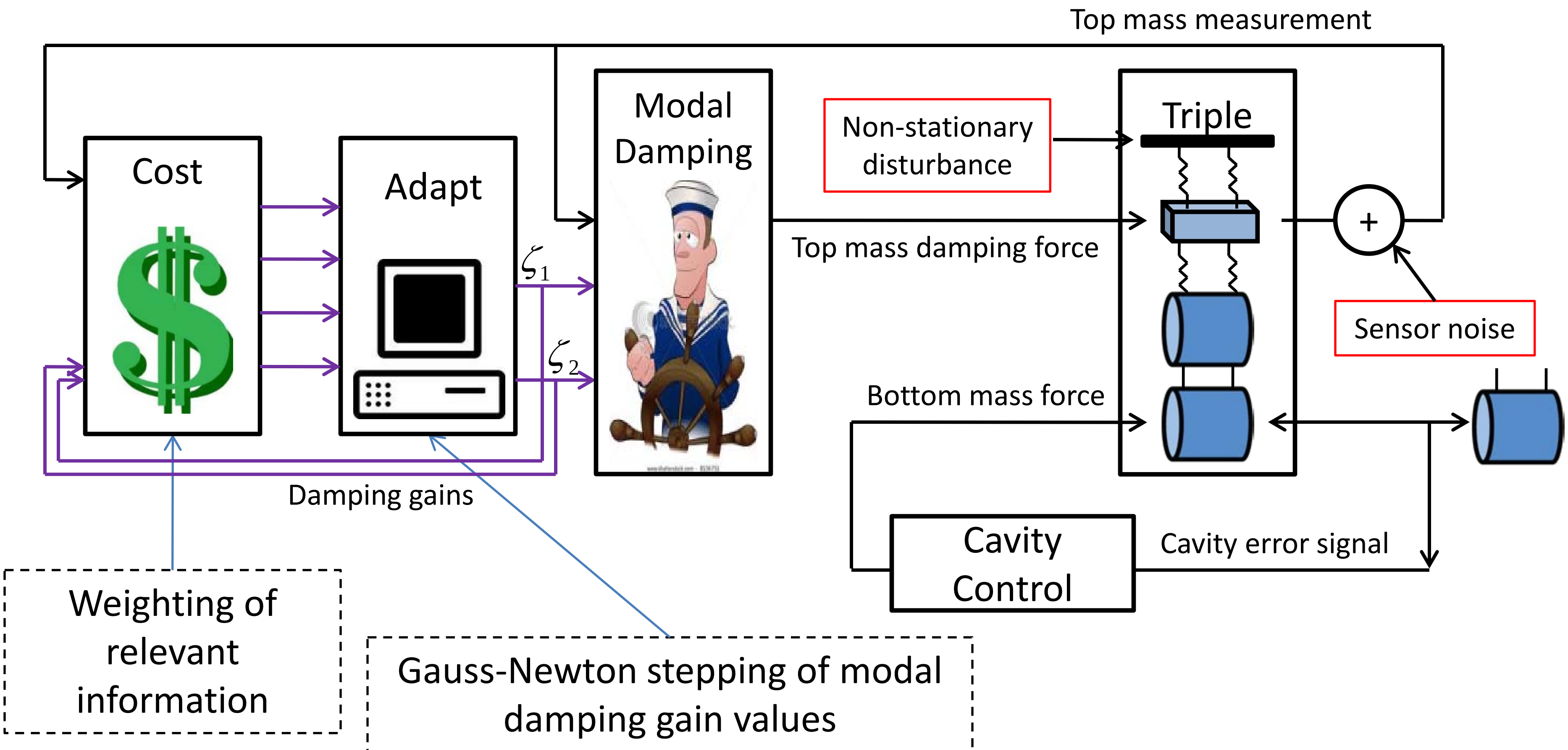


$$G = \frac{(s+\frac{1}{3}\omega_n)(s+3\omega_n)}{(s^2+\frac{2}{3}\omega_n s+\omega_n^2)(s^2+4\sin(20°)\omega_n s+4\omega_n^2)}, \quad 0 \le \zeta < 1, \quad P = \frac{s}{s^2+\omega_n^2}, \quad \omega_n = 2\pi$$

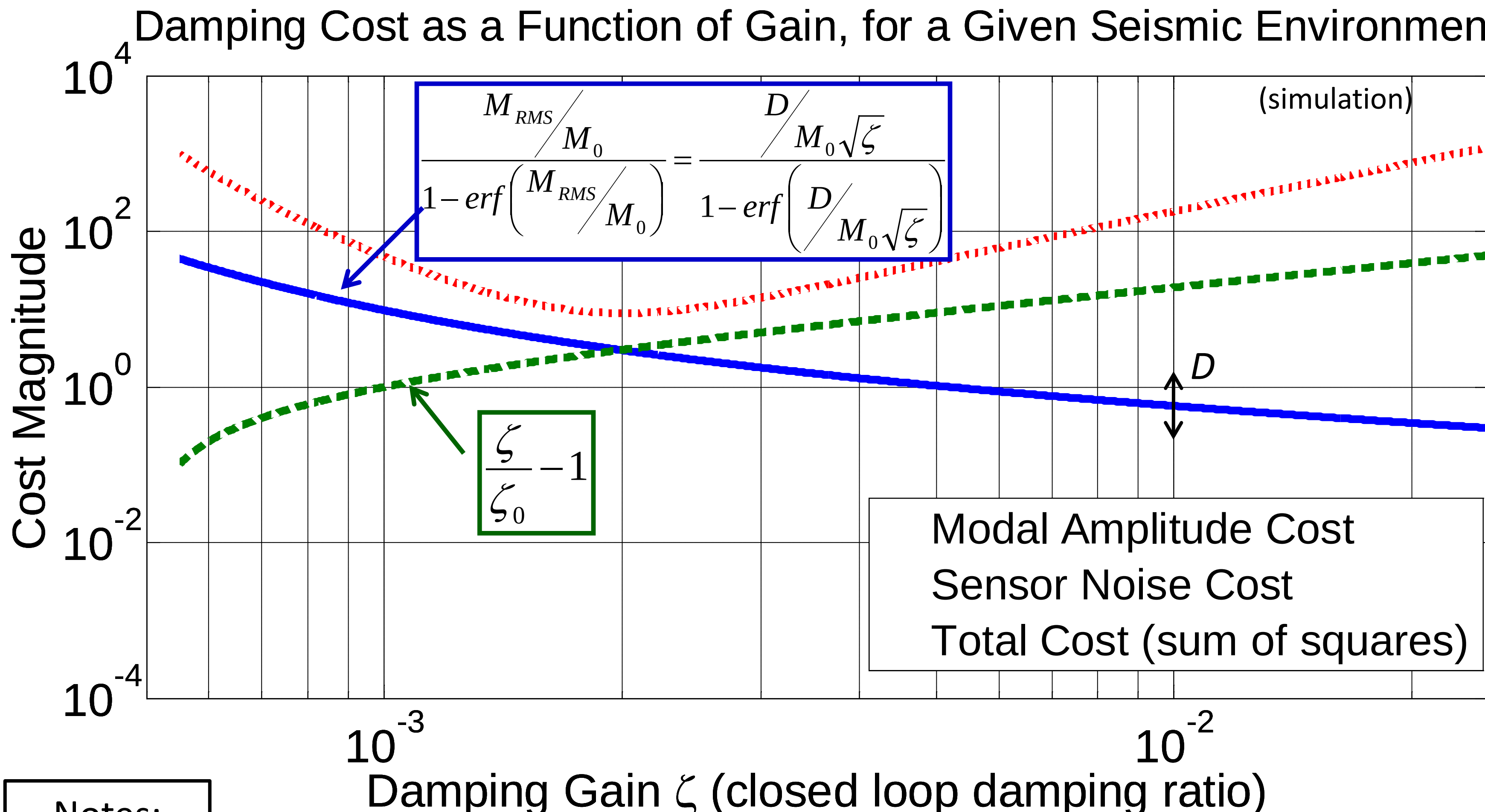
Cavity Control with Modal Damping



Cavity Control with Adaptive M.D.



Ex. Cost Gain Scaling Used in Exper.



Notes:

$$M_{RMS} = D/\sqrt{\zeta}$$

D = seismic amplitude at the modal frequency.

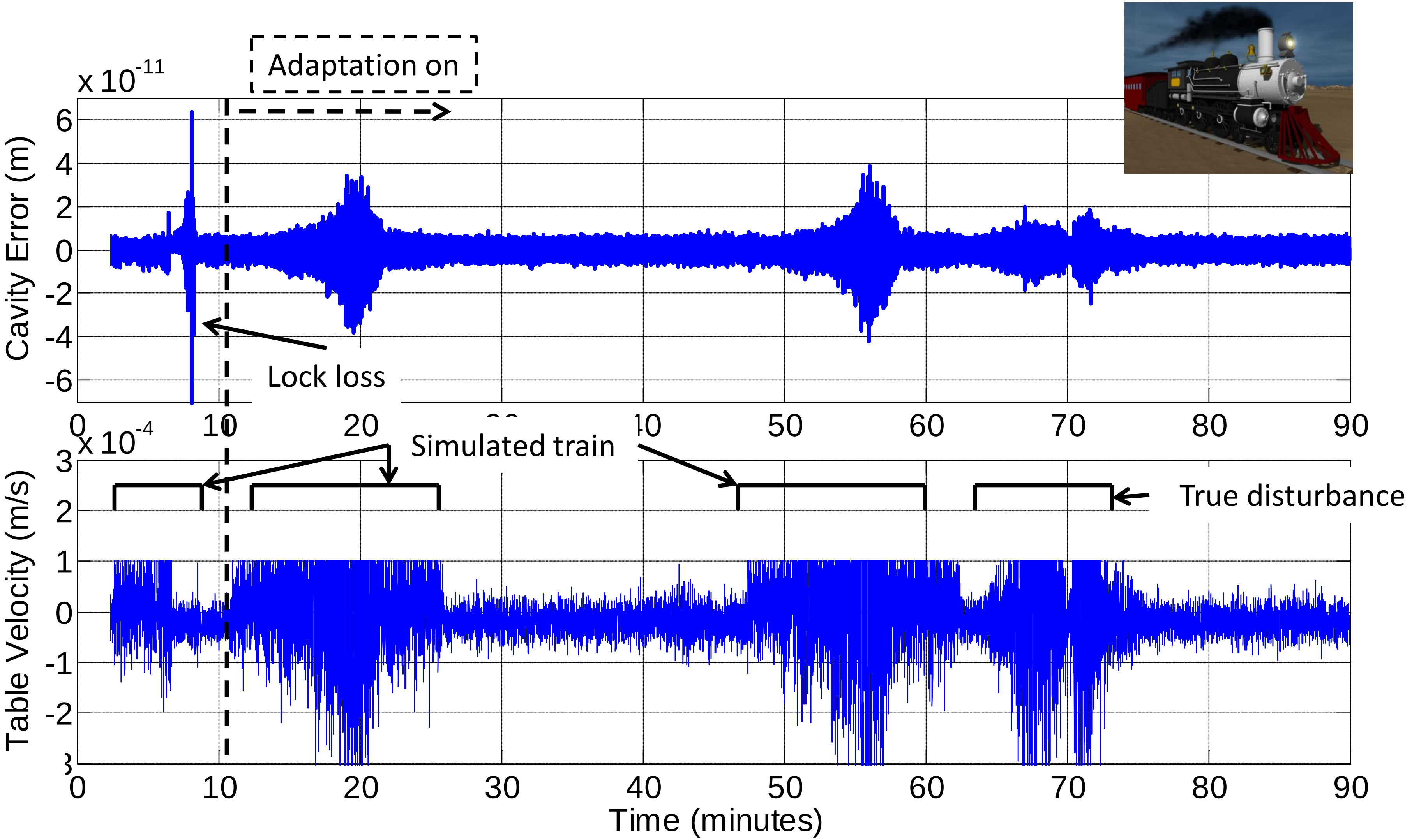
M_{RMS} = measured modal amplitude

M_0 = constant scaling term

ζ_0 = highest value where sensor noise is negligible.

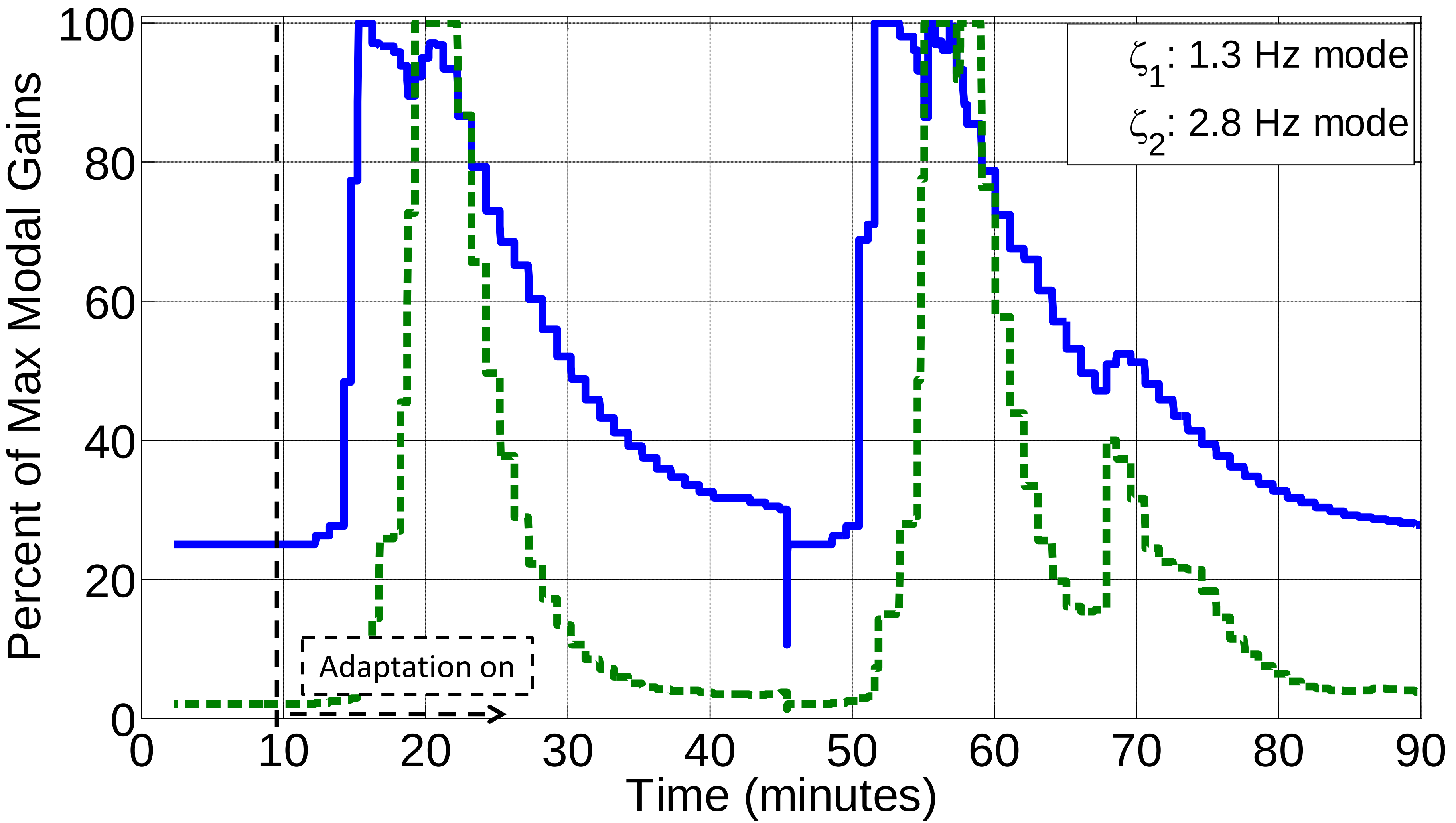
In this case, *D* = 0.53, $M_0 = 15$, and ζ_{ideal} = 5e-4.

Measured Response to a ‘Test’ Train



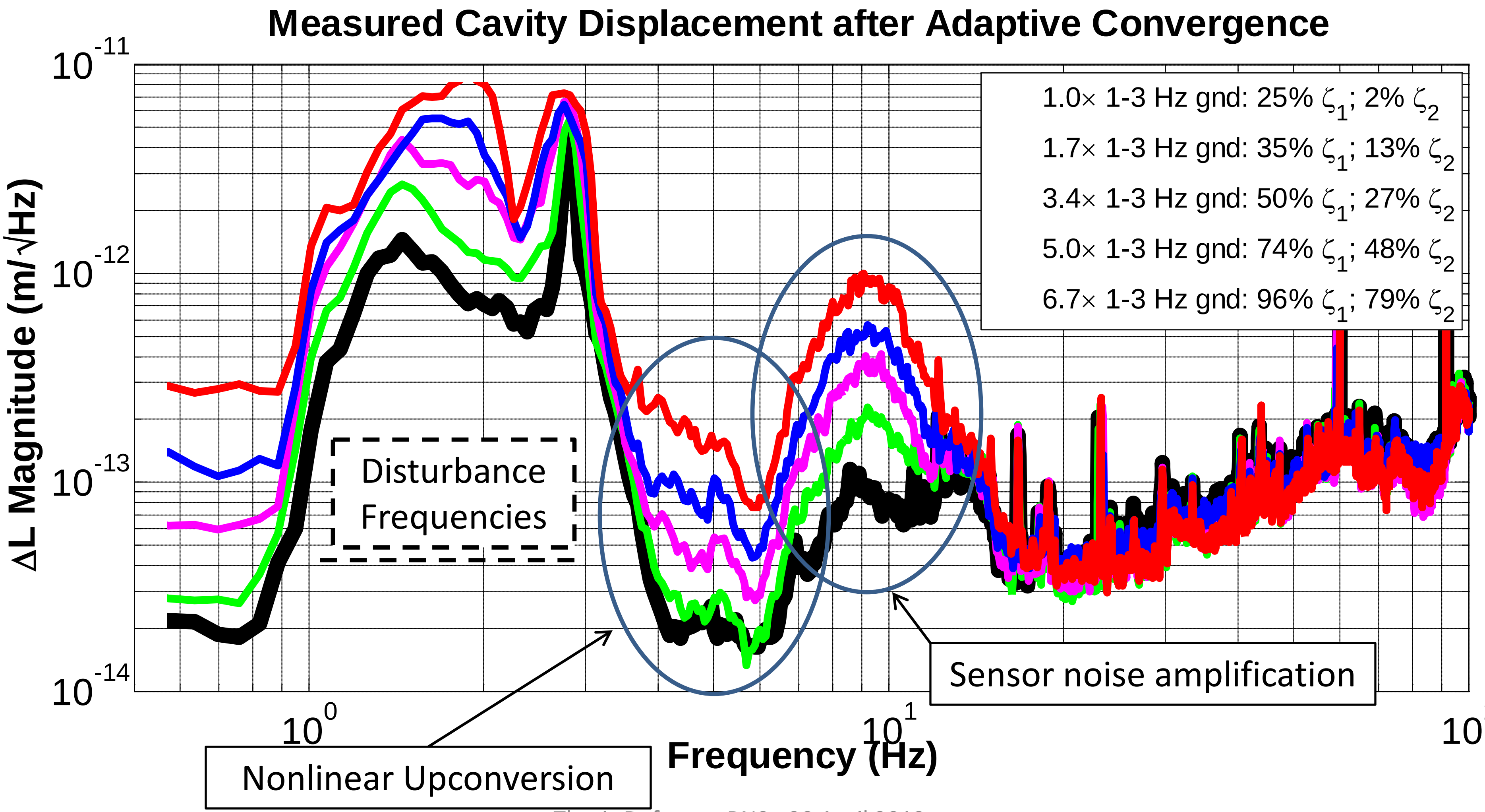
Notes: 1st , no adapt and lock loss; 2nd, 30 sec quicksteps; 3rd, 15 sec quicksteps.

Measured Response to a 'Test' Train

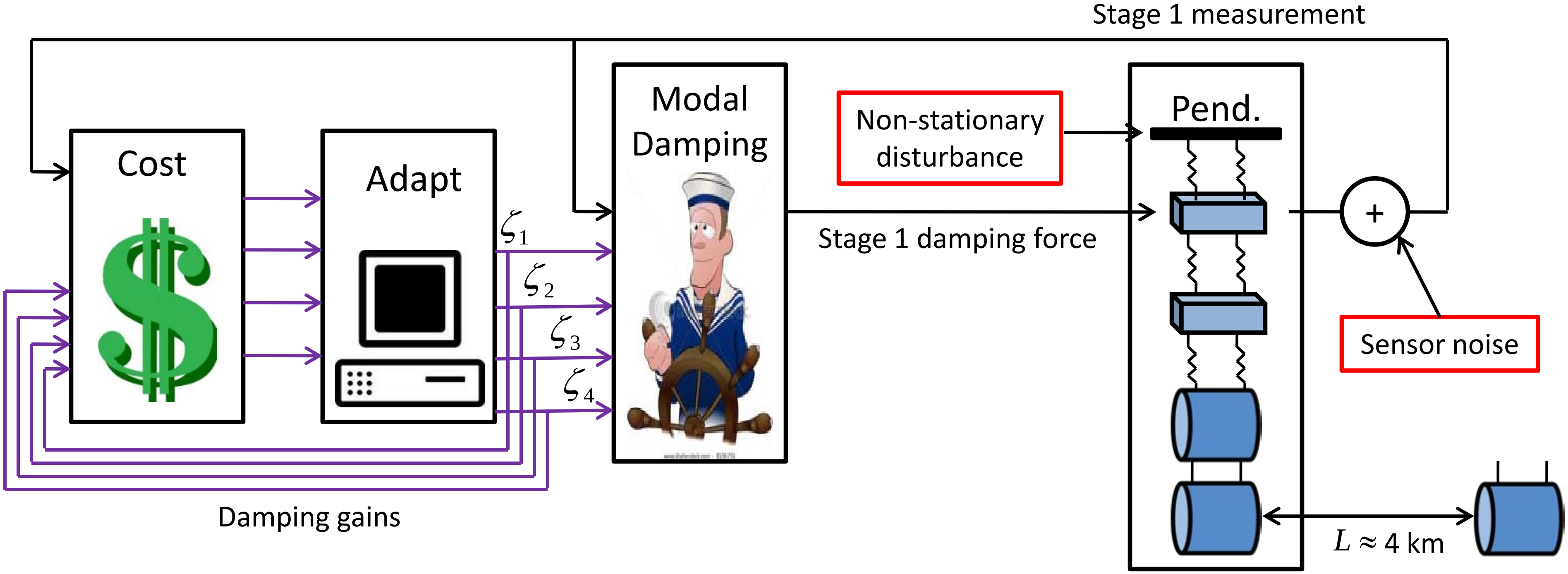


Notes: 1st , no adapt and lock loss; 2nd, 30 sec quicksteps; 3rd, 15 sec quicksteps.

Cavity Displacement Spectrum



Simulation of LIGO cavity with AMD



$$\Delta\hat{L} = \Delta L - \frac{\Delta L^2}{8\times 10^{-13}\ \text{meters}}$$

Interferometer signal w/ nonlinear model

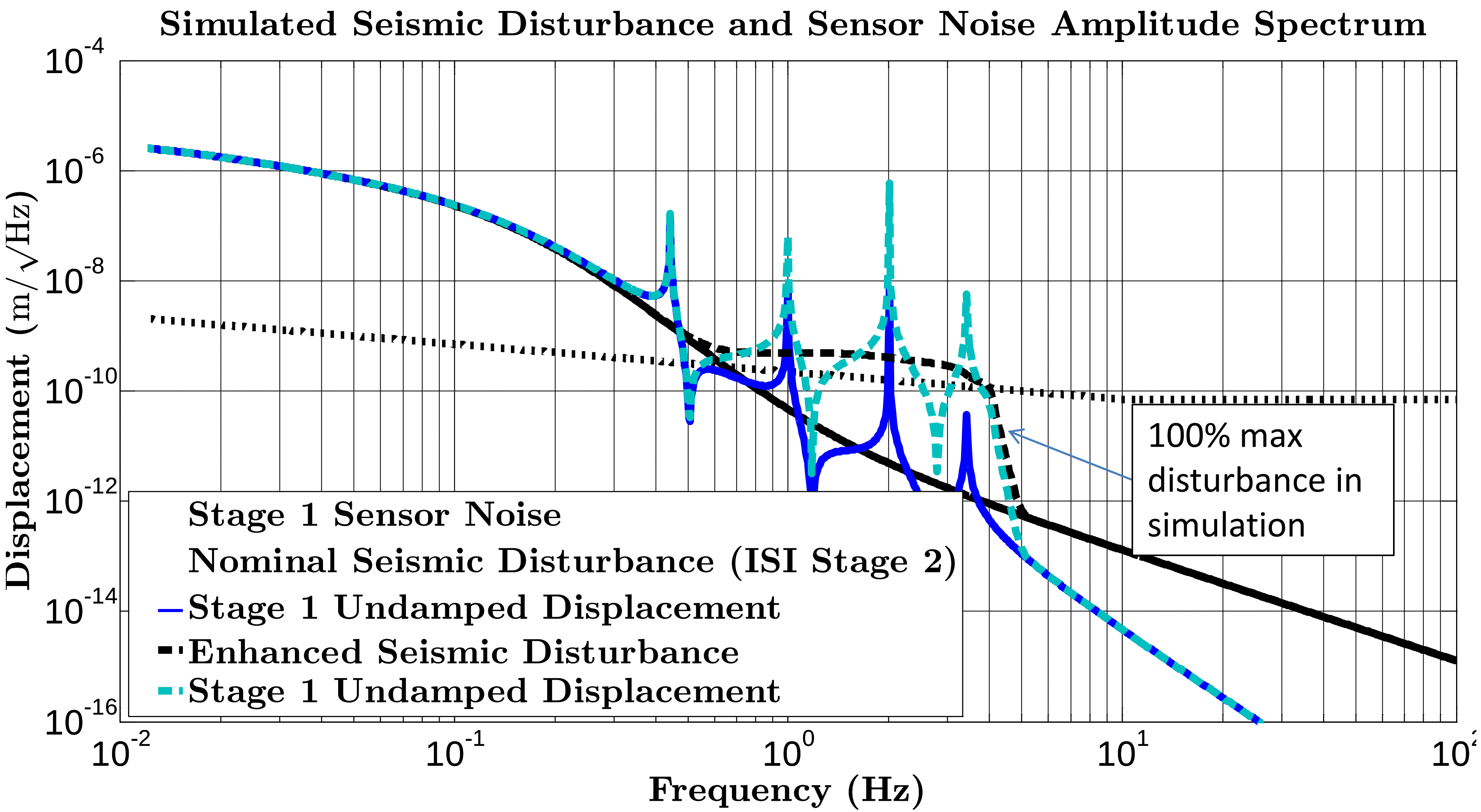
- To model the impact of AMD on LIGO's sensitivity to gravitational wave sources.

Assumption that

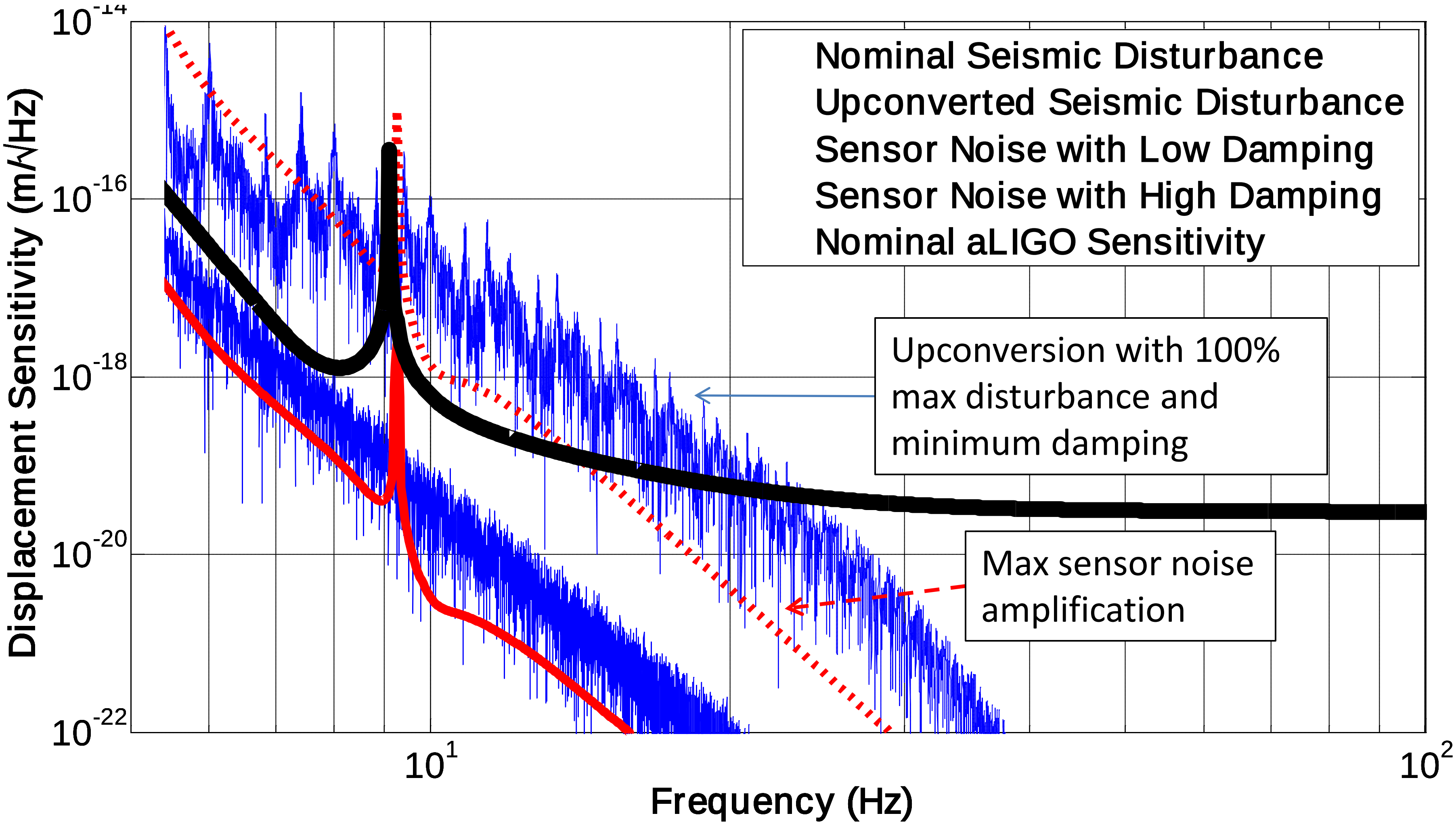
$$\Delta L_{RMS} < 10^{-15}\ \text{meters}$$

Removes nonlinearity

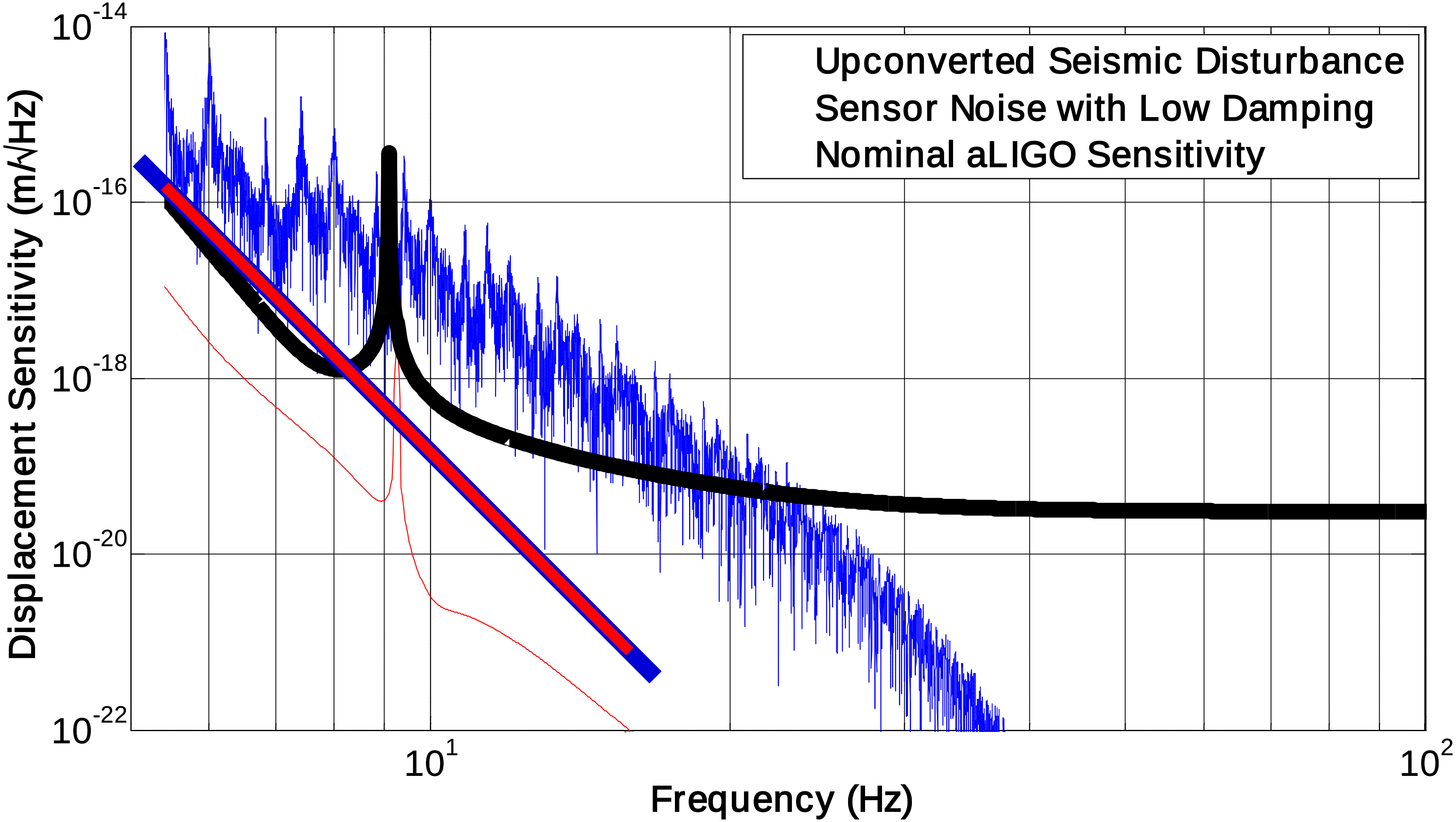
Simulated Disturbance and Noise



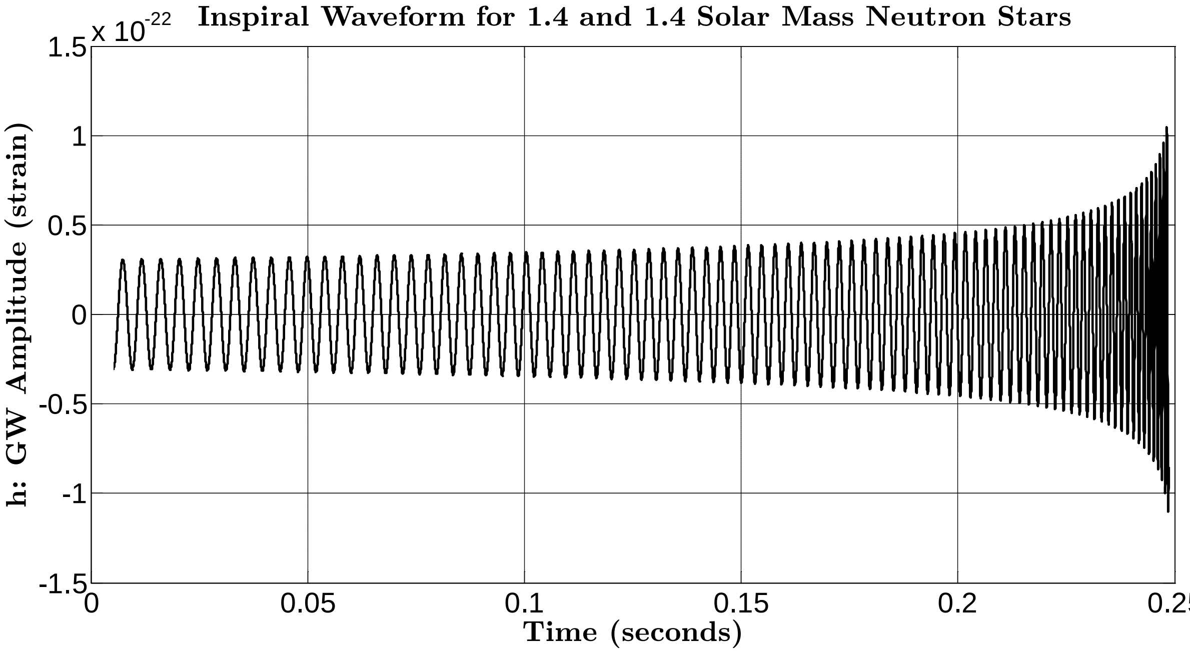
Relative Noise Scaling



Optimization Goal



GW Source: Binary Inspiral



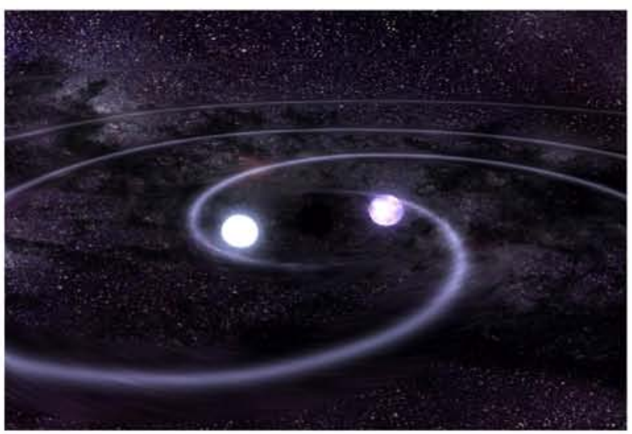
Detectable inspiral range r [1, 2]

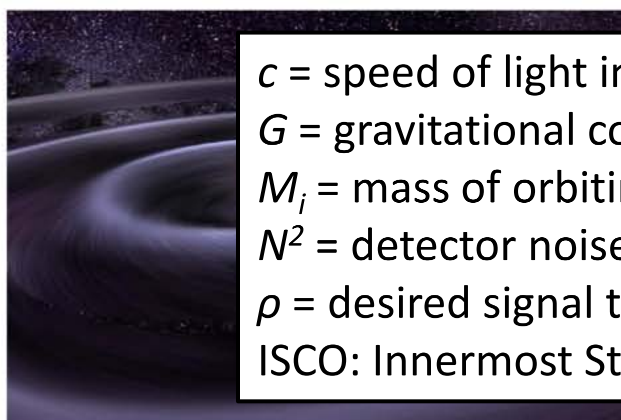
$$r^2 = 1.77^2 \frac{5c^{1/3}\mathrm{M}^{5/3}}{96\pi^{4/3}\rho^2}\int_0^{f_{ISCO}} \frac{df}{f^{7/3}N^2}$$

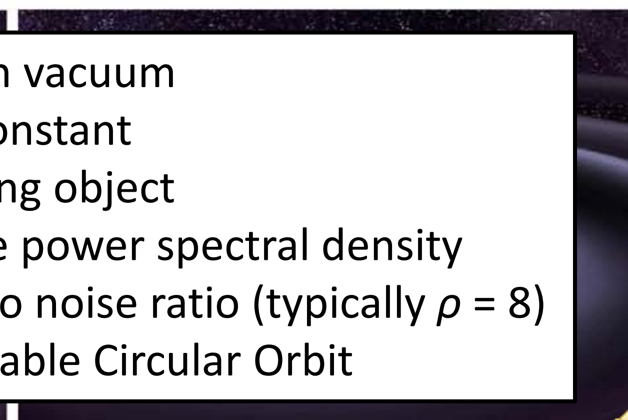
$$\mathrm{M} = \frac{G}{c^2}\frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}$$

$$f_{ISCO} = \frac{c^3}{6^{1.5}\pi G(M_1+M_2)}$$

1 Patrick Sutton - T030276
2 Duncan Brown PhD thesis

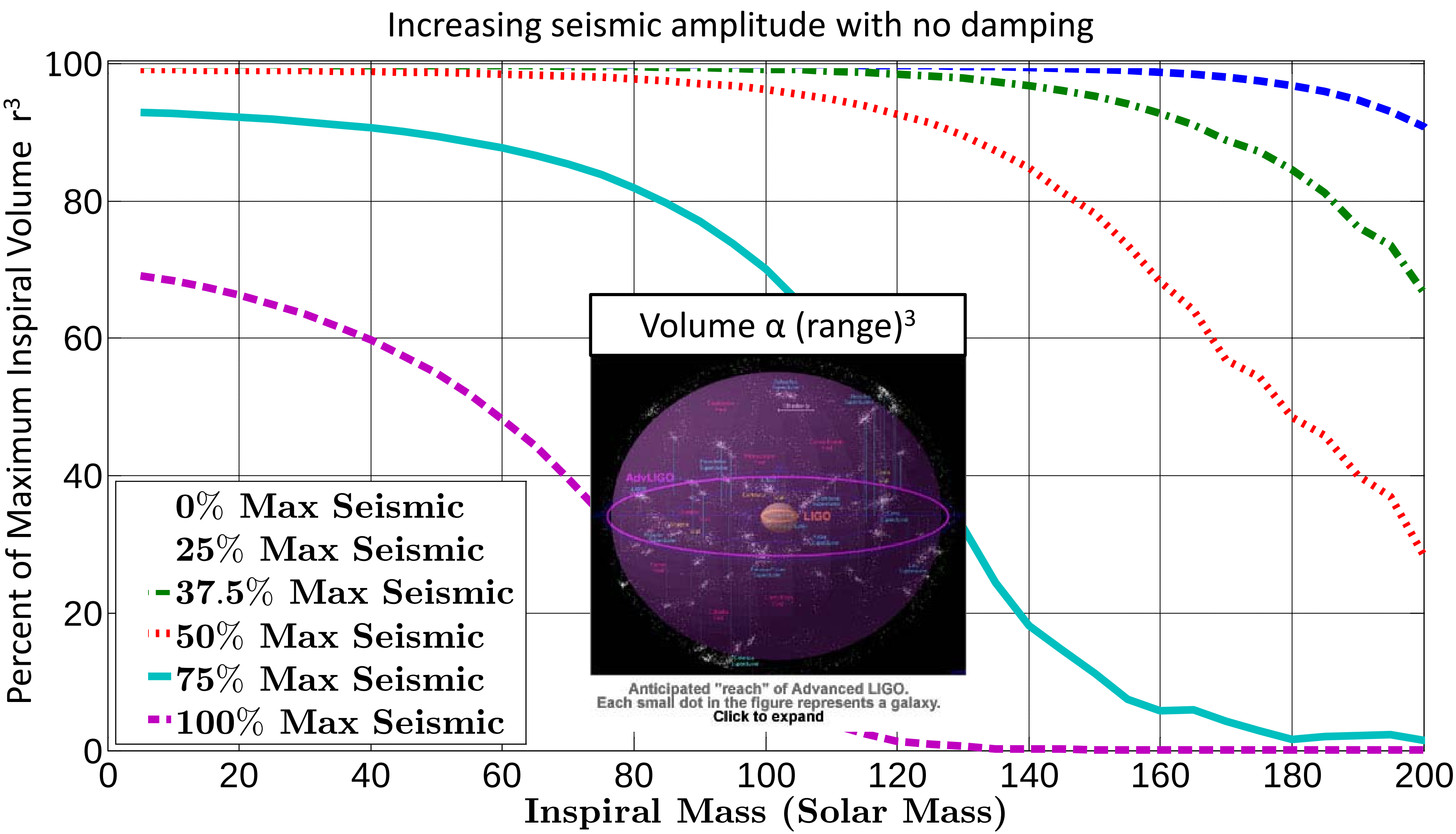






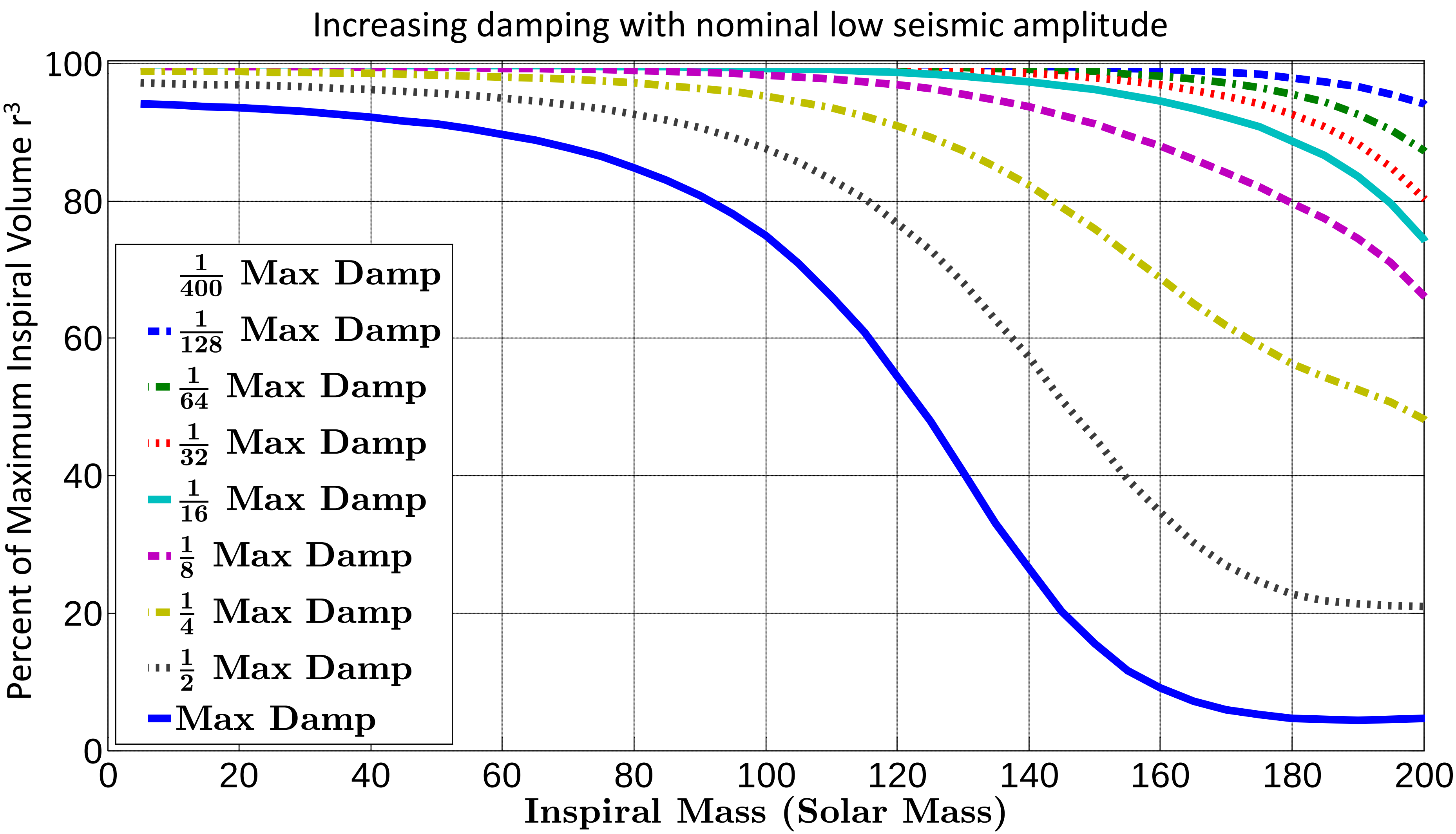
c = speed of light in vacuum
G = gravitational constant
M_i = mass of orbiting object
N^2 = detector noise power spectral density
ρ = desired signal to noise ratio (typically ρ = 8)
ISCO: Innermost Stable Circular Orbit

Visible Universe vs Binary Mass

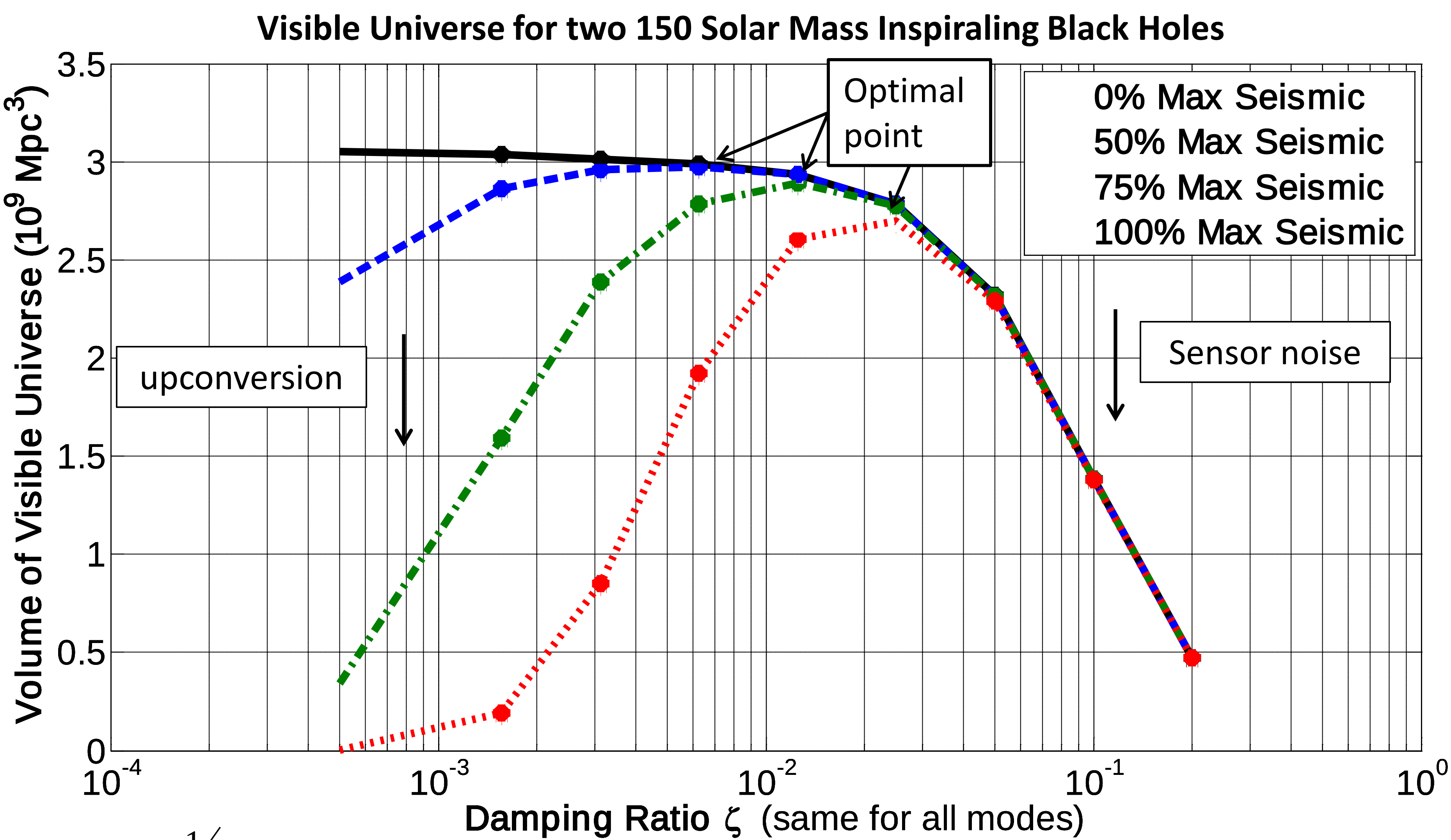


Click for more info

Visible Universe vs Binary Mass

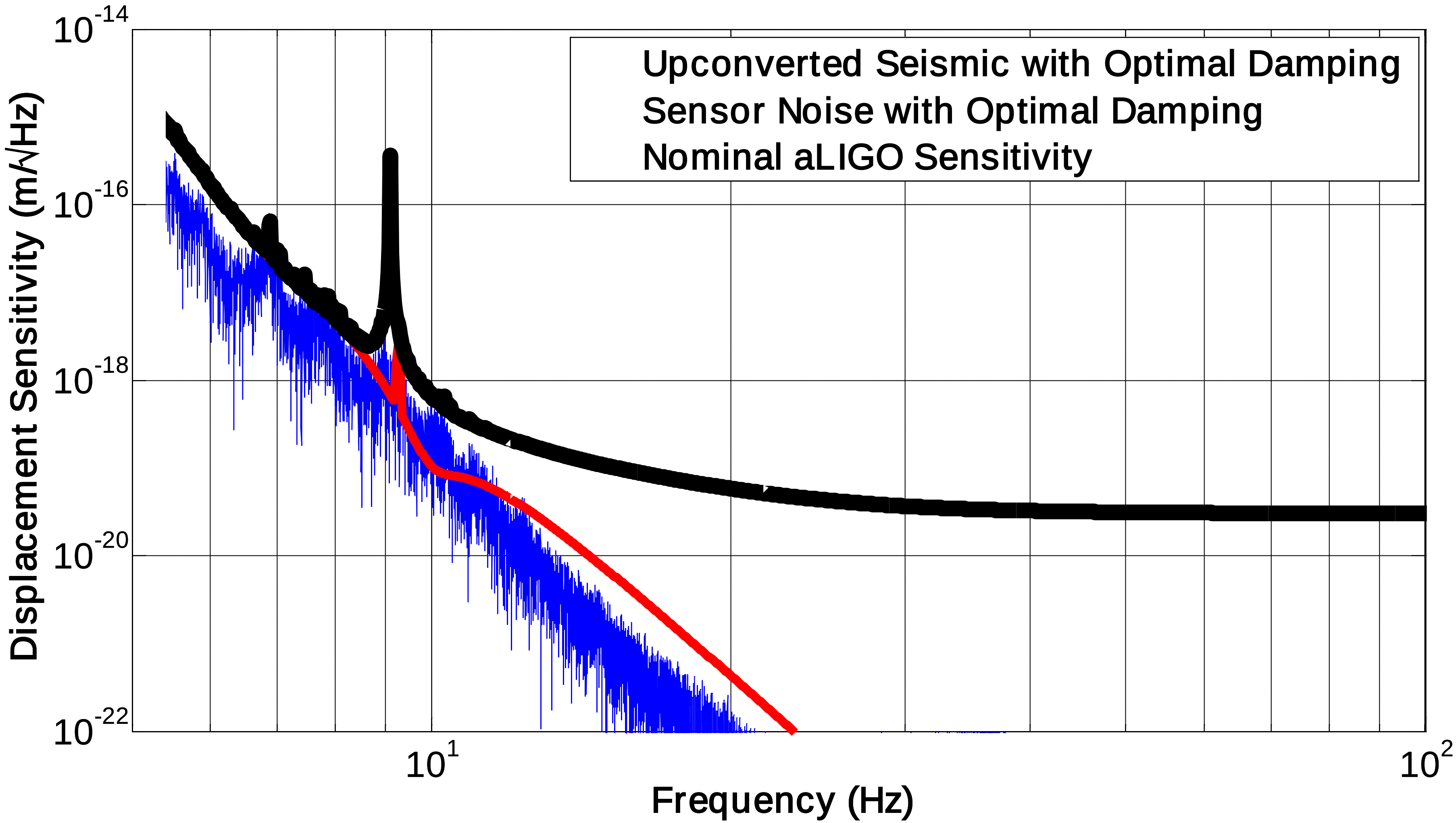


Combining Seismic and Sensor Noise

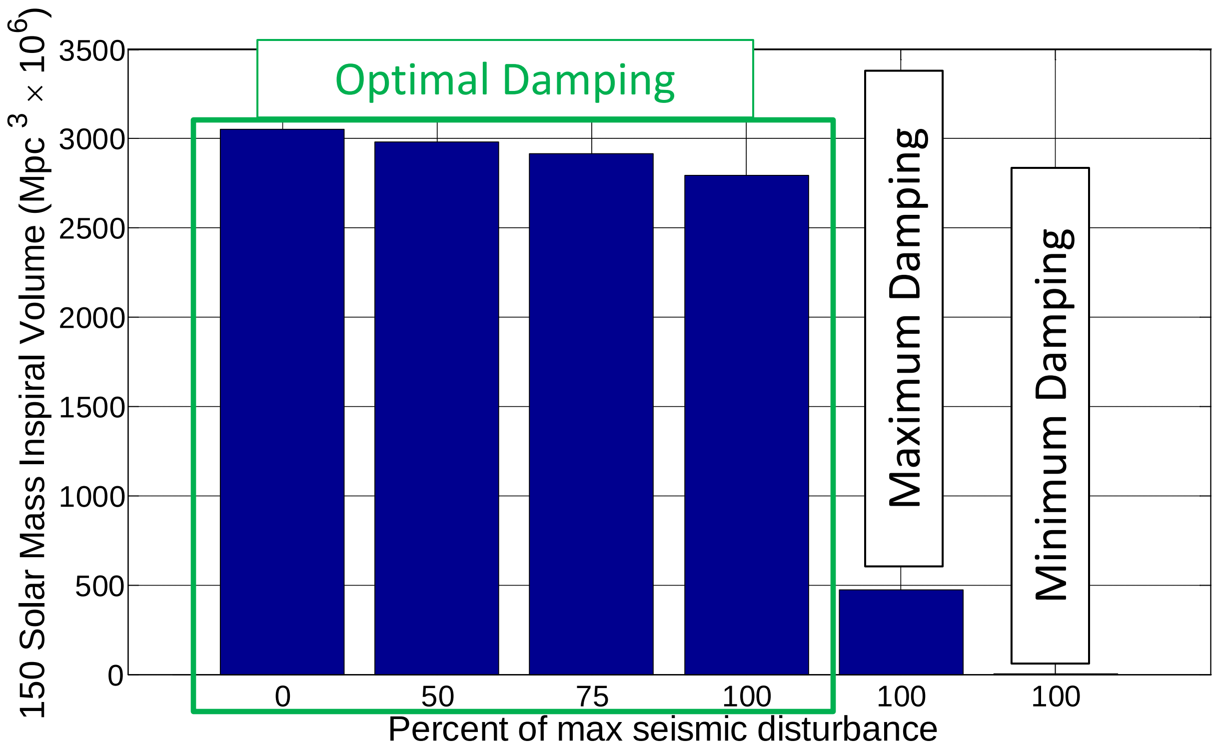


Note: $\varsigma = \frac{1}{2Q}$, Q = quality factor

Optimal Damping for Max Seismic with Adaptation



AMD Inspiral Simulation Results



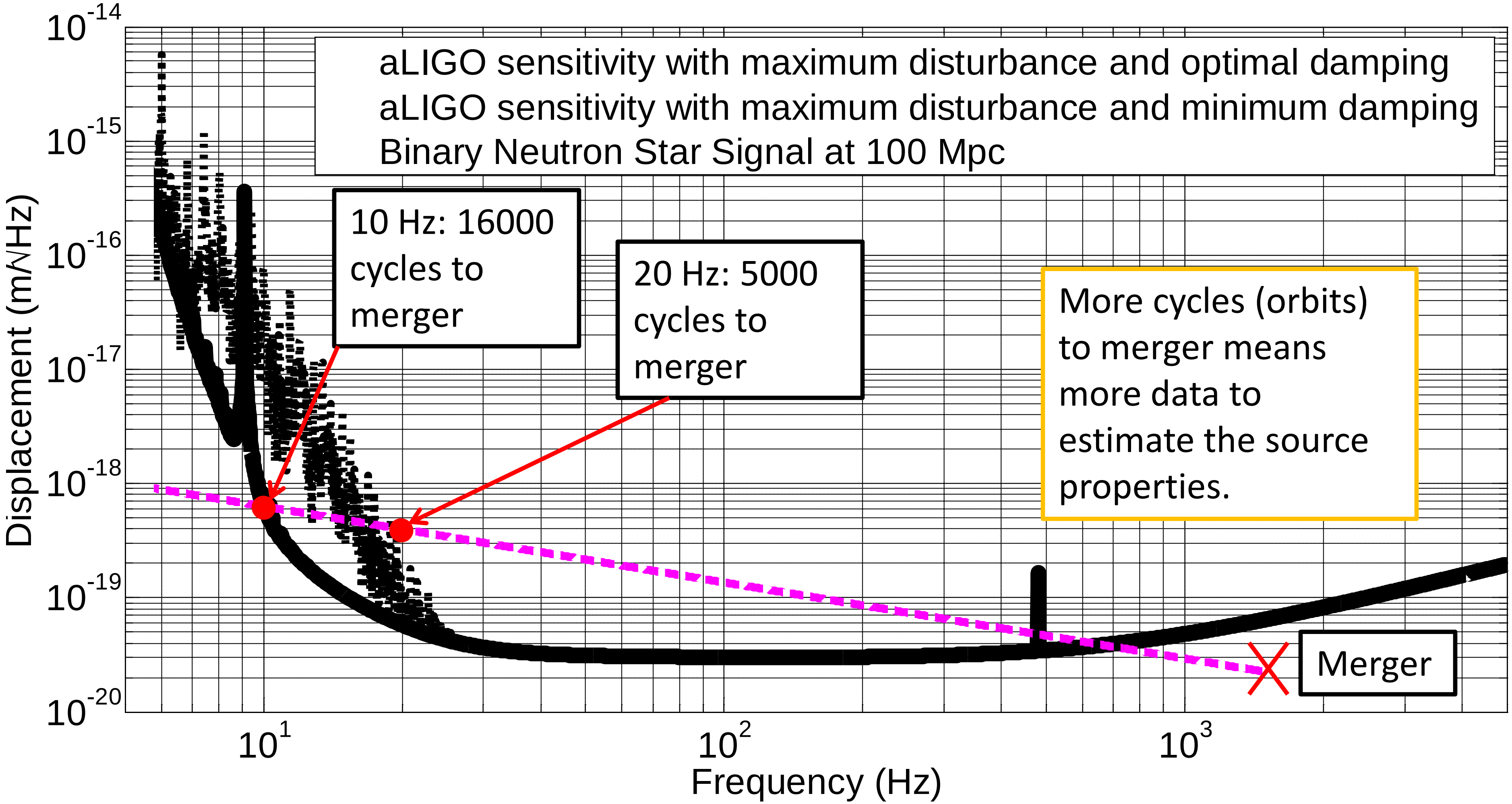
Seismic % of max	ς_1	ς_2	ς_3	ς_4	150 SM volume $Mpc^3 \times 10^6$	
0	0.00054	0.00055	0.00051	0.00050	3051	(100%)
50	0.00059	0.0051	0.016	0.0042	2982	(97.7%)
75	0.00073	0.0089	0.029	0.0090	2915	(95.5%)
100	0.00091	0.014	0.046	0.016	2796	(91.6%)
100	0.20	0.20	0.20	0.20	473	(15.6%)
100	0.00050	0.00050	0.00050	0.00050	3.05	(0.1%)

Optimal Damping

Maximum Damping

Minimum Damping

Binary Neutron Star Inspiral Sensitivity



AMD Conclusions

- AMD has the power to select modal damping gains that are optimal to the detection of high mass black hole inspirals (> 75 SM) for a range of disturbances.
- Lower mass inspirals benefit by extending observation time.
- The same gains are also optimal for the stochastic background, pulsars, and supernovae. However, these sources are insensitive to the lowest frequencies, so constant maximum damping is likely to be more reliable.
- This work explored adaptive damping for the quad pendulum, but similar adaption could be useful in other LIGO control loops.
- Practical application of this work depends on the behavior of the true Advanced LIGO interferometers still under construction.

Thesis Contributions, 1-2

- Adaptive algorithm for modal damping (AMD)
  - Adaptation optimizes the response in real-time to changing environmental conditions.
  - Switching of step rates, estimation time scales, and step sizes based on the measured proximity of these statistics to the optimal solution.
  - Easily adapted to other aspects of interferometer control.

Thesis Contributions, 2-2

- Optimization of AMD for astrophysical sources
- Optimization and limitations of modal damping
  - Optimal state estimation (ACC 2011)
  - Maximum achievable closed loop damping
- Modeling – procedure for identifying most important measurements and parameter uncertainties of quadruple pendulum.
- Actuator sizing – min. least squares actuation required when driving many DOFs (ACC2012)

Acknowledgements

Committee

Nergis Mavalvala
Richard Mittleman
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LIGO-MIT

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Matt Evans
Jeff Kissel
Myron MacInnis
David Shoemaker
Sam Waldman
Marie Woods

Family

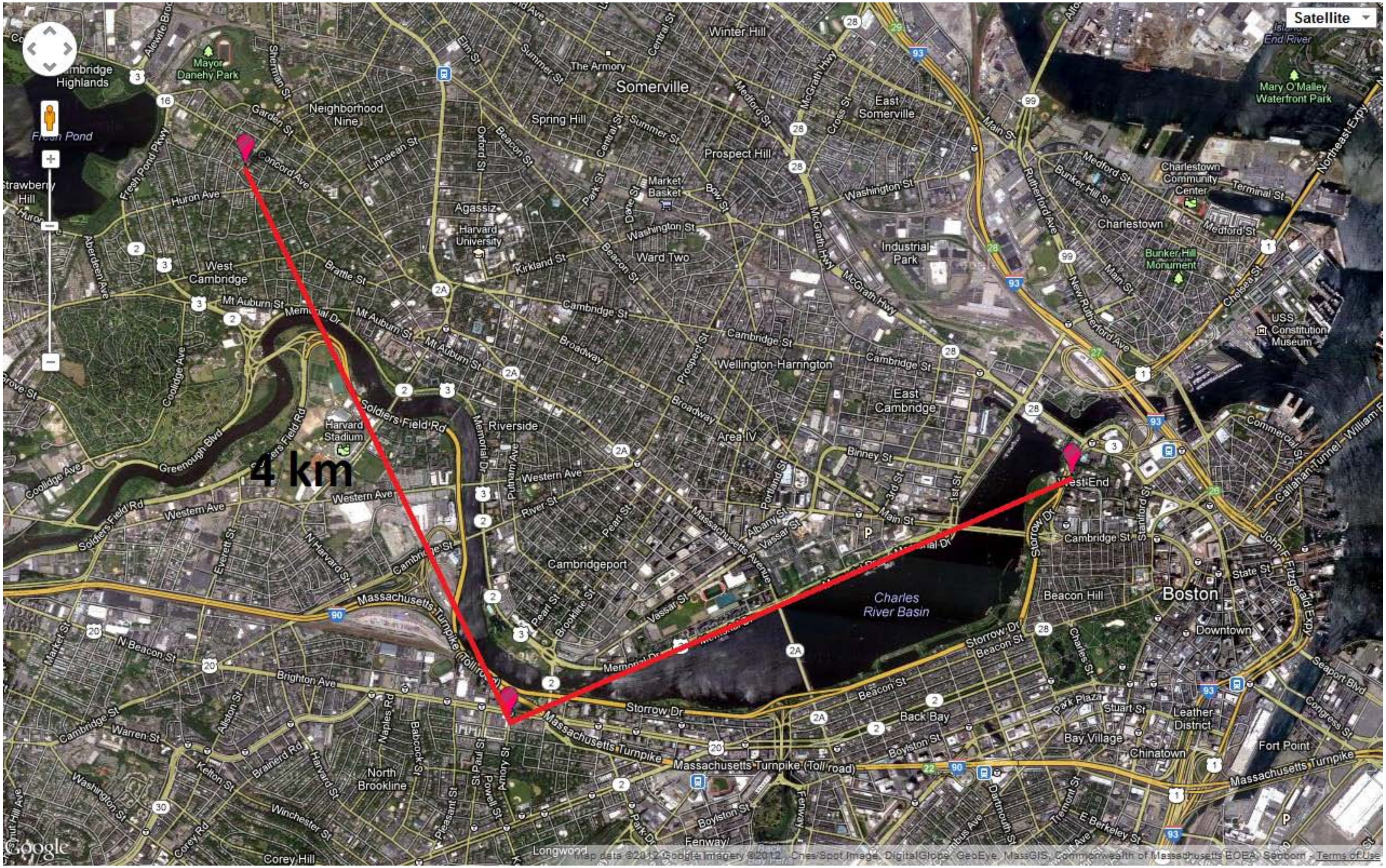
Mom
Dad
Nina
Darren
Jamie

LIGO-Suspensions Group

Mark Barton
Norna Robertson
Janeen Romie
Ken Strain

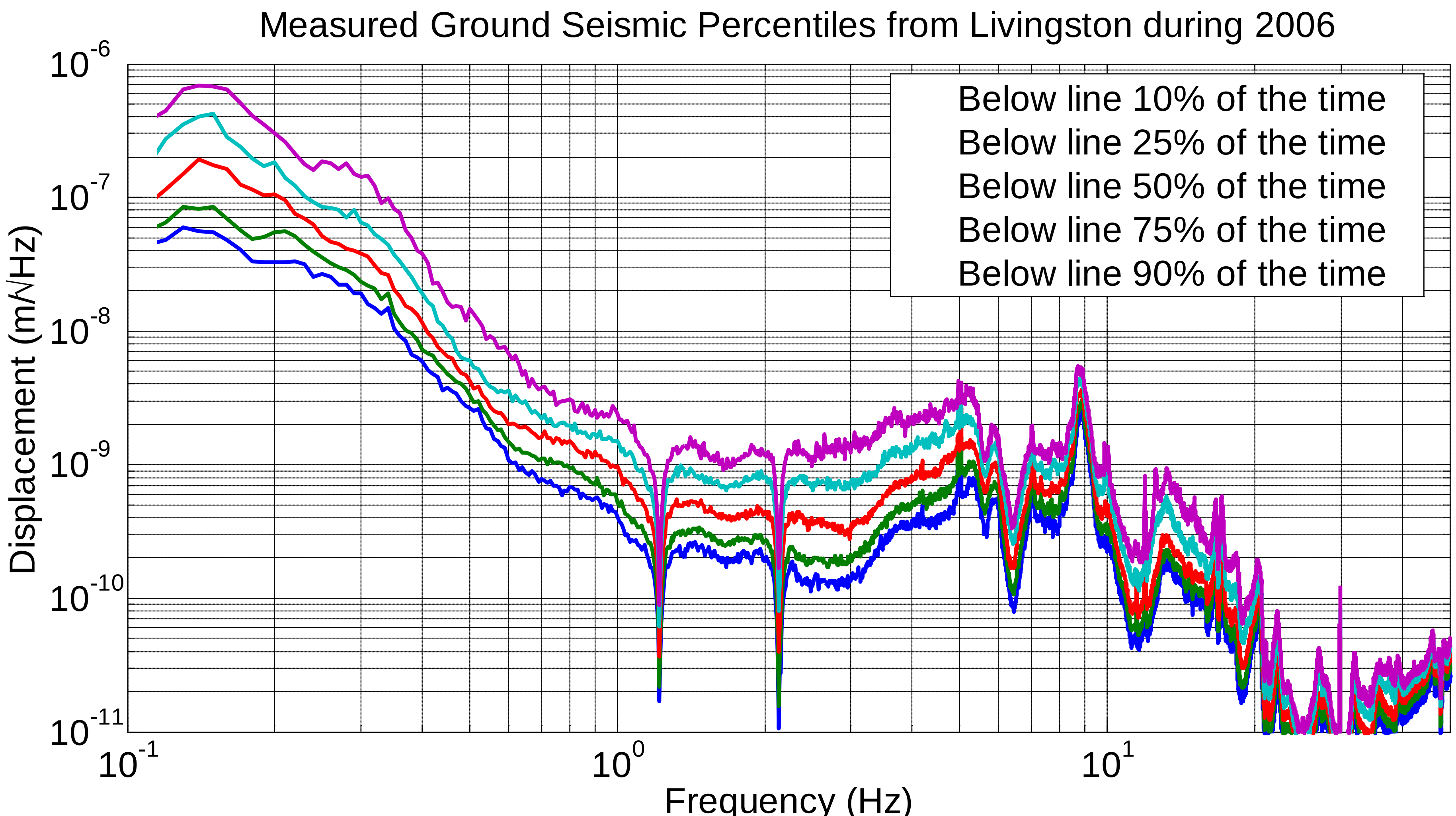
National Science Foundation

Backups



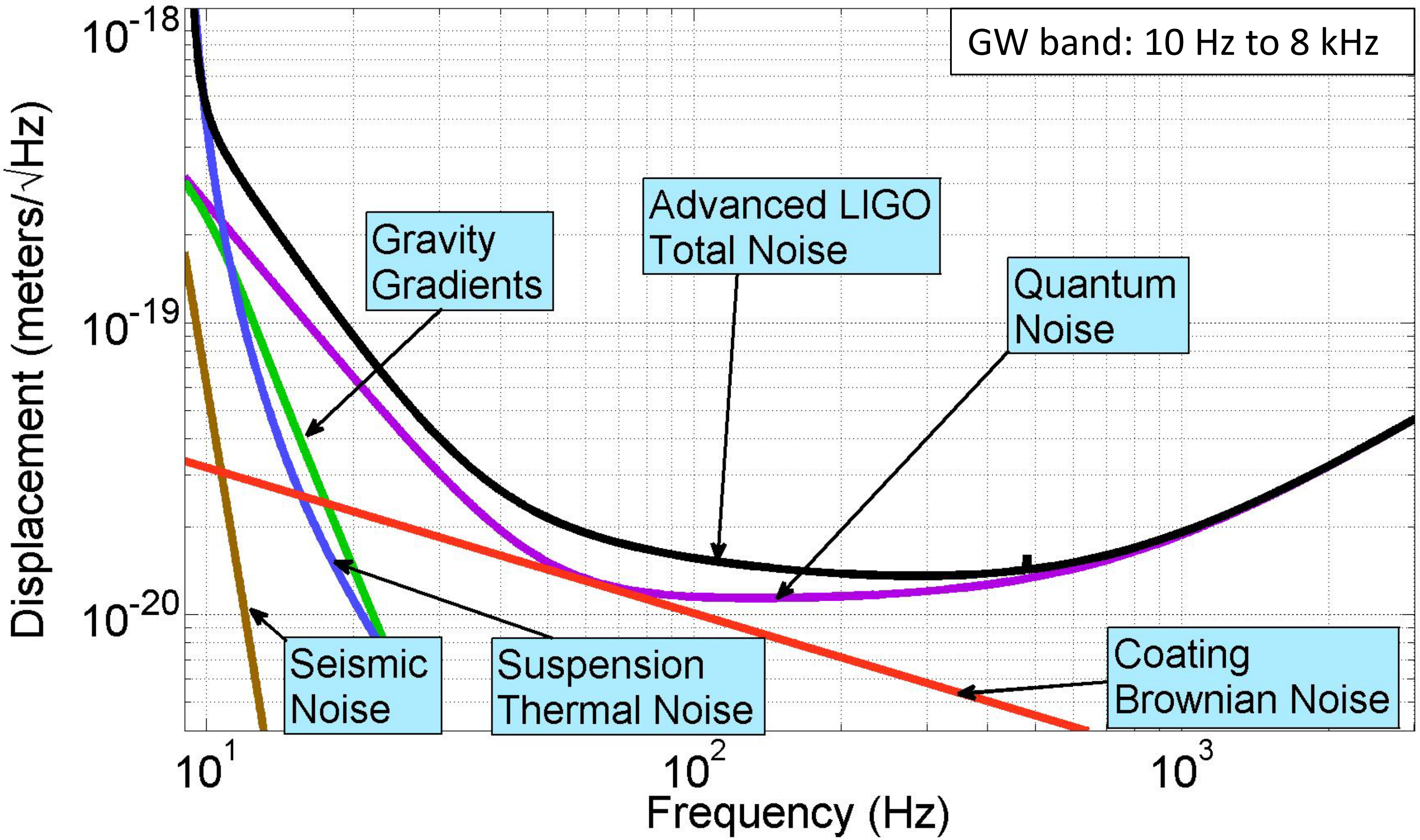
LIGO spans 16 km^2. Cambridge, MA covers 16.65 km^2 (wikipedia).

Problem 1: Nonstationary Disturbance



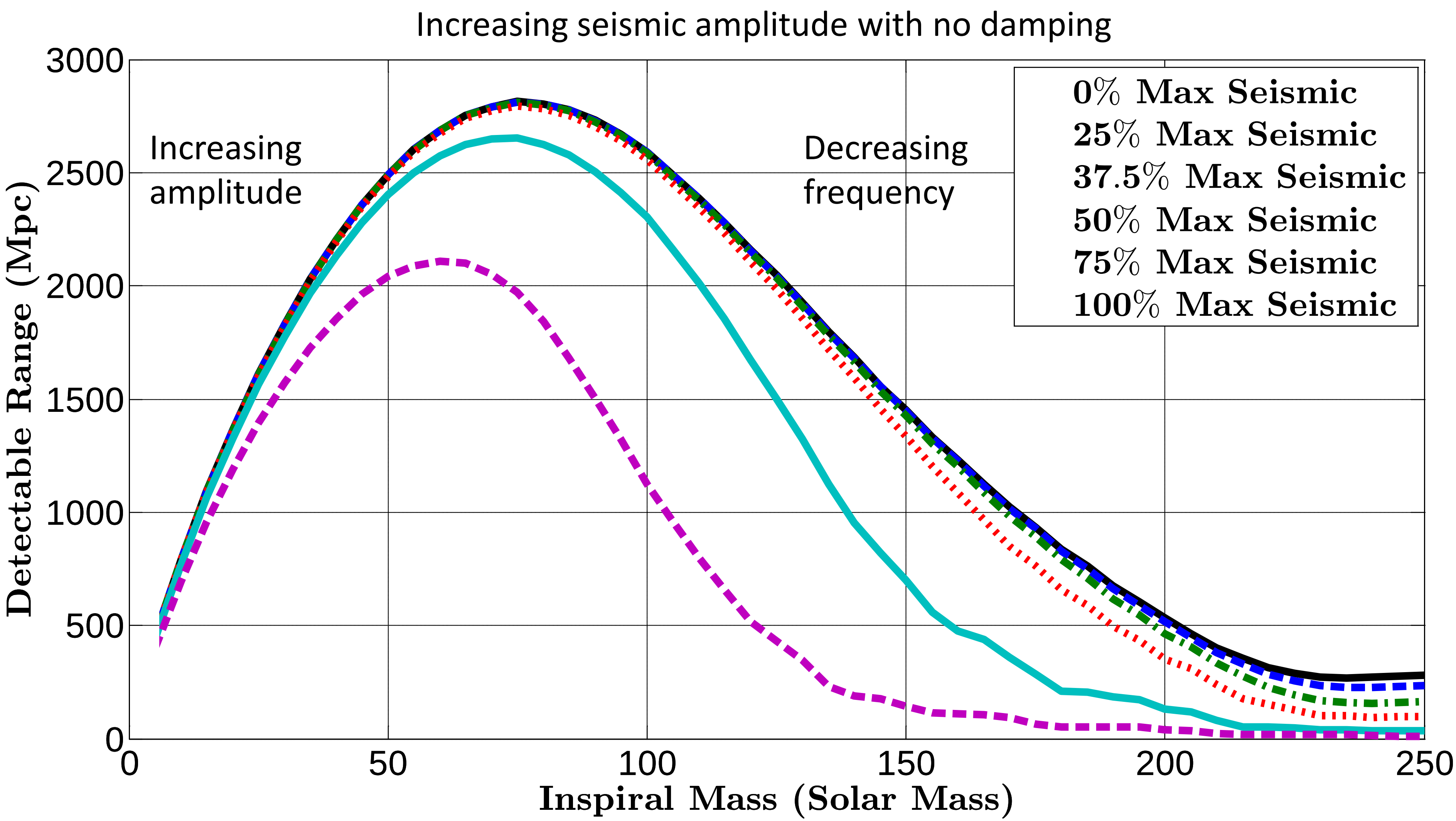
Ref: T0900312-v1, plot L1:SEI-ITMX_GEO_SEN_X

Projected Sensitivity for aLIGO



Adapted from Gregg Harry. "Advanced LIGO: the next generation of gravitational wave detectors" . Classical and Quantum Gravity, vol. 27, April 2010

Inspiral Range vs Binary Mass



1 pc = 3.26 ly

AMD Inspiral Simulation Cost Functions

Sensor noise cost = $\dfrac{\varsigma_i}{\varsigma_{0,i}} - 1$

Modal amplitude cost = $\dfrac{M_{RMS,i}/M_{0,i}}{1 - erf\left(M_{RMS,i}/M_{0,i}\right)}$

Total cost per mode $= \left[\dfrac{M_{RMS}/M_0}{1 - erf\left(M_{RMS}/M_0\right)}\right]^2 + \left[\dfrac{\varsigma}{\varsigma_0} - 1\right]^2$

M_{RMS} measured modal displacement amplitude. Model behavior -> $M_{RMS} = \dfrac{\text{open loop amplitude}}{\sqrt{\varsigma}}$

M_0 modal cost scale factor

ς modal closed loop damping ratio

ς_0 minimum closed loop damping ratio

i mode index

Table I: Adaptive modal damping cost function parameters.

Parameter	Mode 1	Mode 2	Mode 3	Mode 4
ς_0	0.0005	0.0005	0.0005	0.0005
M_{RMS} with ς_0 & max seis	$1.45*10^{-8}$	$6.54*10^{-9}$	$1.17*10^{-8}$	$2.00*10^{-9}$
M_0	$2*10^{-8}$	10^{-9}	$8*10^{-10}$	$5*10^{-10}$
M_{RMS}/M_0	0.725	6.54	14.625	4

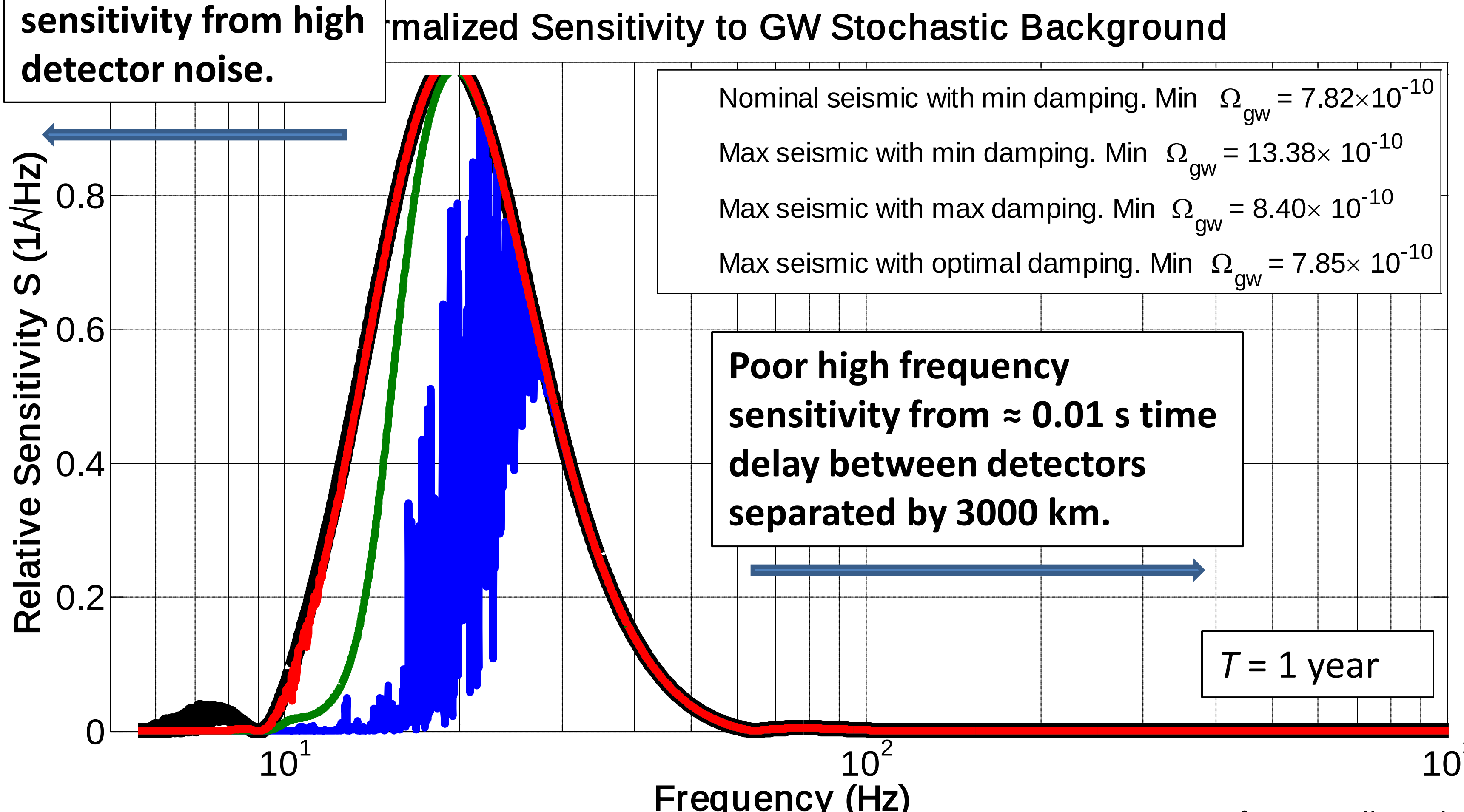
AMD Inspiral Simulation Results

Table II: Optimal damping values determined by the selected cost function parameters.

Seismic % of max	ς_1	ς_2	ς_3	ς_4	150 SM volume $\mathrm{Mpc}^3 \times 10^6$
0	0.00054	0.00055	0.00051	0.00050	3051 (100%)
50	0.00059	0.0051	0.016	0.0042	2982 (97.7%)
75	0.00073	0.0089	0.029	0.0090	2915 (95.5%)
100	0.00091	0.014	0.046	0.016	2796 (91.6%)
100	0.20	0.20	0.20	0.20	473 (15.6%)
100	0.00050	0.00050	0.00050	0.00050	3.05 (0.1%)

Stochastic Sensitivity

Poor low frequency sensitivity from high detector noise.



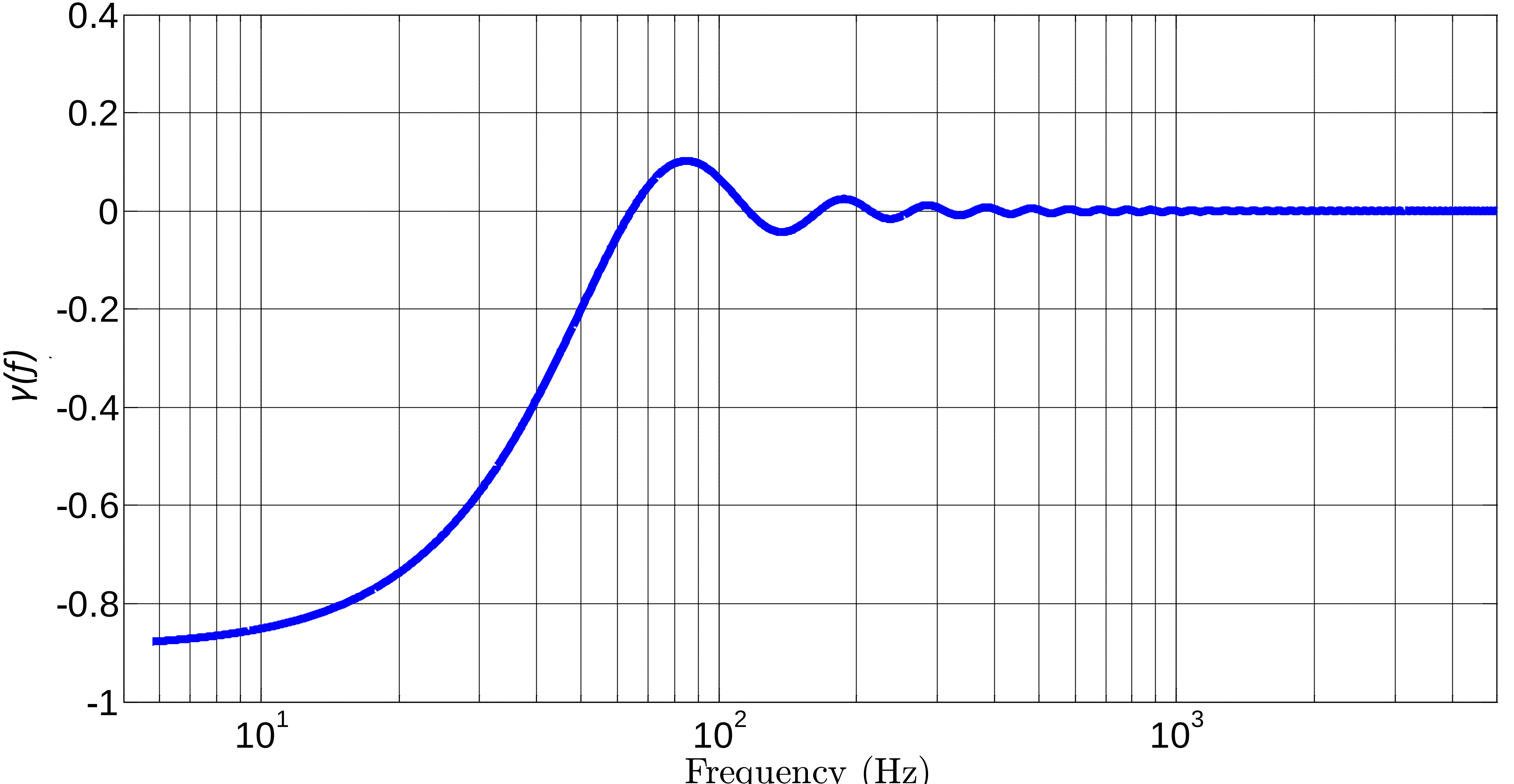
Poor high frequency sensitivity from ≈ 0.01 s time delay between detectors separated by 3000 km.

$$\Omega_{gw} = \frac{1.65}{\rho_{critical}}\left[\frac{32G^2}{25c^4\pi^2} T\int_0^\infty S^2(f)\,df\right]^{-0.5}$$

$$\rho_{critical} = \frac{3c^2H_0^2}{8\pi G} \qquad S(f) = \frac{\gamma(f)}{f^3 P(f)}$$

Ref: Bruce Allen. The Stochastic Gravity-wave Background: Sources and Detection. 1996.

Stochastic Overlap Reduction Function



Backups: Science from Observations

- Binary black holes
  - Probe nonlinear dynamics of spacetime curvature during merger phase.
  - GW scattering during inspiral phase.
  - Characterize number of neutron star and/or black hole binaries
  - Characterise ringdown phsase after merger
  - Test Hawking's law that the event horizon must increase in area
  - Naked singularity test

Backups: Science from Observations

- Stochastic background
  - Observe early universe from 10^{-22} sec after Big Bang. Currently, CMB observations only get us to about 100,000 years after big bang (≈35 orders of magnitude improvement).
  - Quantify background from incoherent sum of many weak/distant sources such as binaries, supernovae, etc.

Backups: Science from Observations

- Inspirals
  - Quantity in Milky Way
  - Neutron star structure
  - Neutron star ellipticity (how big are the mountains)
  - Neutron star quakes
  - Theory of maximum spin rate of X-ray binaries due to GW emmission
- Supernovae
  - Evolution of stellar collapse - no complete models exist.

Backups: GW Signal Calibration

Cavity Displacement (Eq. 1):

$$x = \frac{1}{1 + P1_{13}C}\left[GW + v_2 + P1_{11}d_1 + P1_{12}v_1 + P1_{13}d_2 + P2_{11}d_3 + P2_{12}v_3 + P2_{13}d_4\right] < 10^{-9}m$$

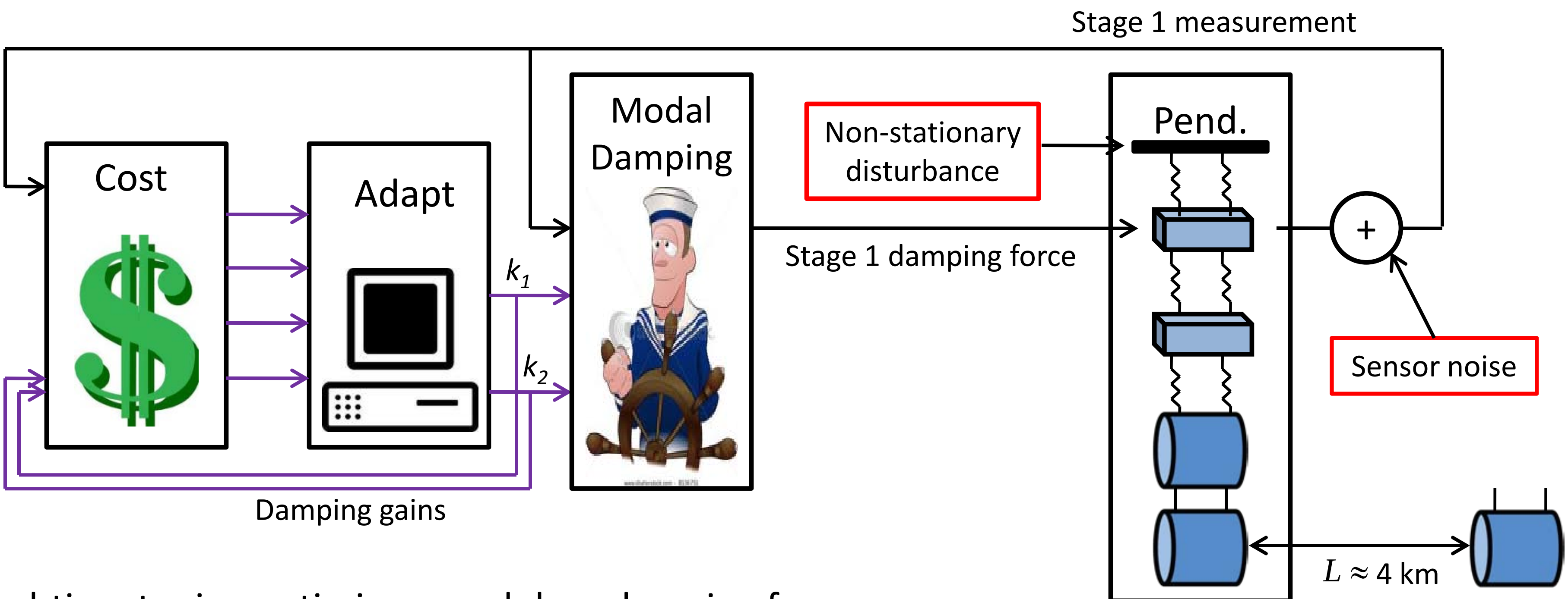
Solving for the GW (Eq. 2):

$$x(1 + P1_{13}C) = GW + v_2 + P1_{11}d_1 + P1_{12}v_1 + P1_{13}d_2 + P2_{11}d_3 + P2_{12}v_3 + P2_{13}d_4$$
$$\approx GW$$

Calibrated cavity signal (effectively open loop)

If *GW* is much greater than everything else on the right hand side of (2), then the calibrated signal is approximately *GW*.

Simulation of LIGO cavity with AMD



$$e = \Delta L - \frac{\Delta L^2}{8 \times 10^{-13}\ \text{meters}}$$

Interferometer signal w/ nonlinear model

Real-time tuning optimizes pendulum damping for:

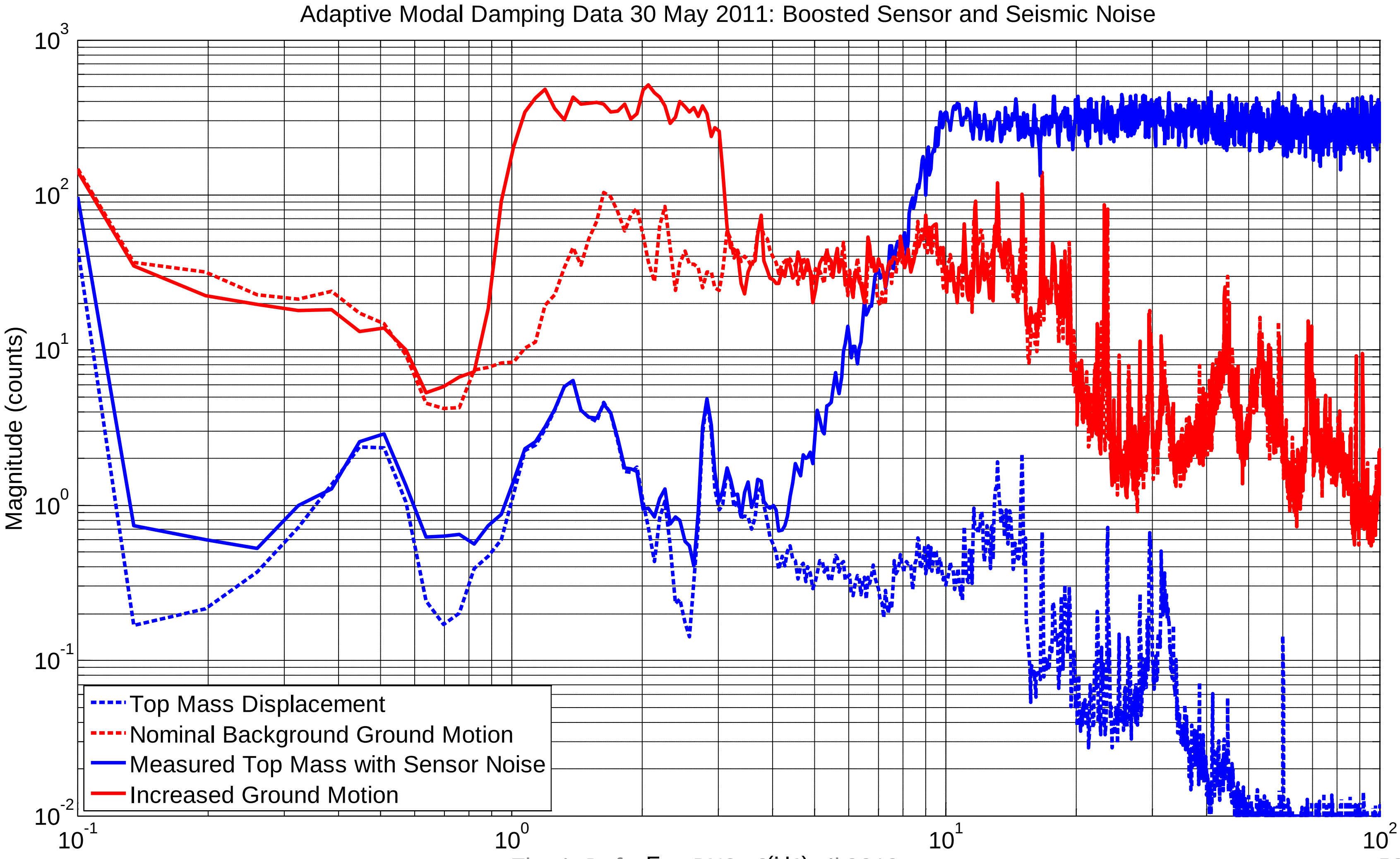
1. Nonstationary disturbance
2. Sensor noise
3. Nonlinear interferometer response
   - A. Laser beams falling off mirrors
   - B. Laser scattering off vacuum walls and other objects
   - C. Interferometer readout method
   - D. Creak in suspension springs
   - E. etc

Assumption that

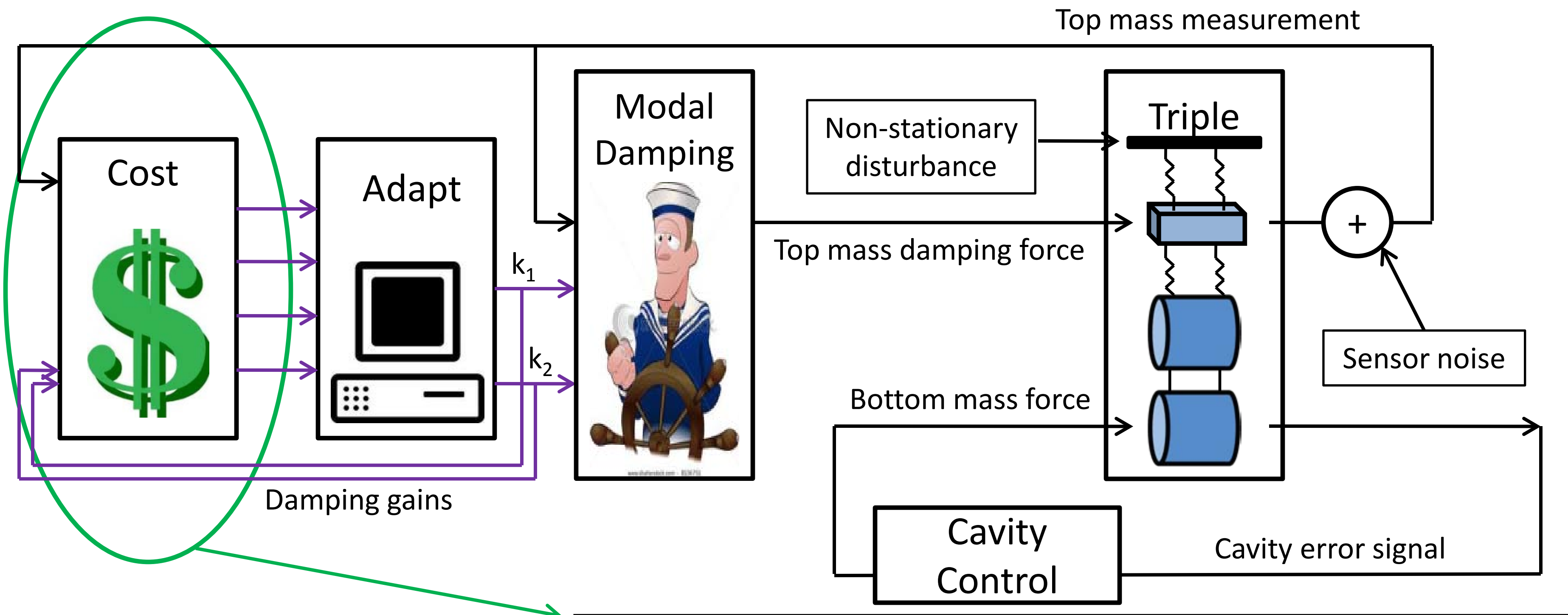
$$\Delta L_{RMS} < 10^{-15}\ \text{meters}$$

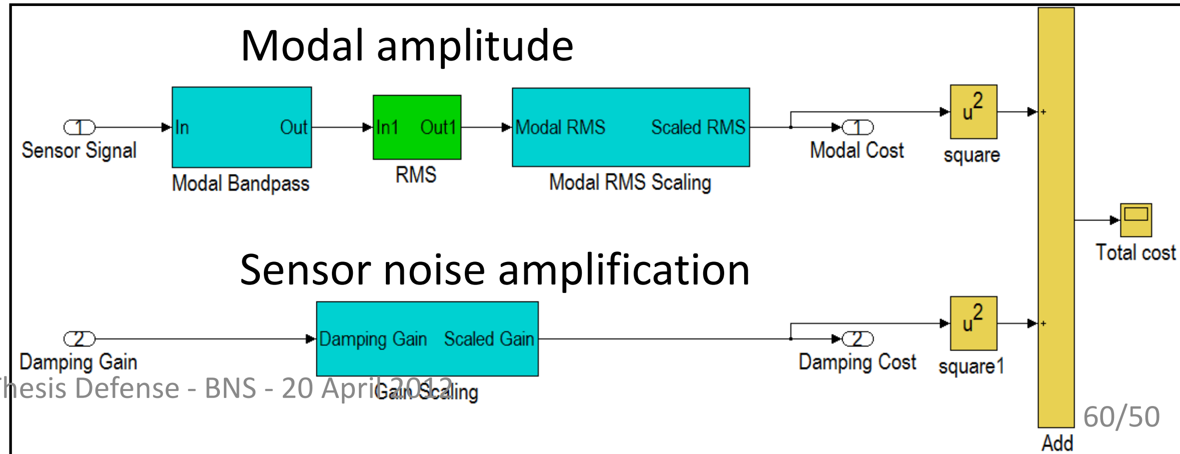
Removes nonlinearity

Backups: Boosted Experimental Noise



Cavity Control with Adaptive M.D.

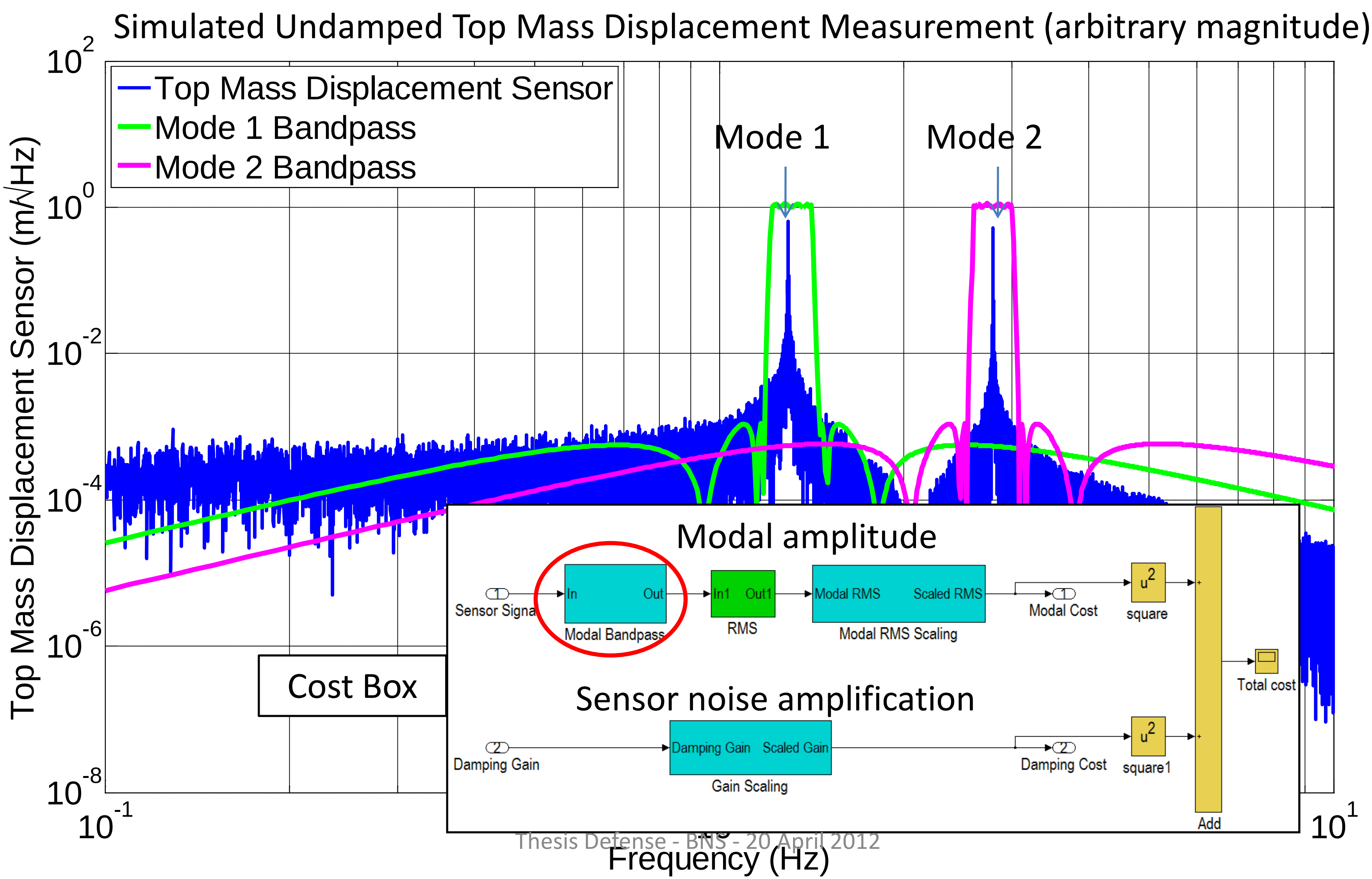




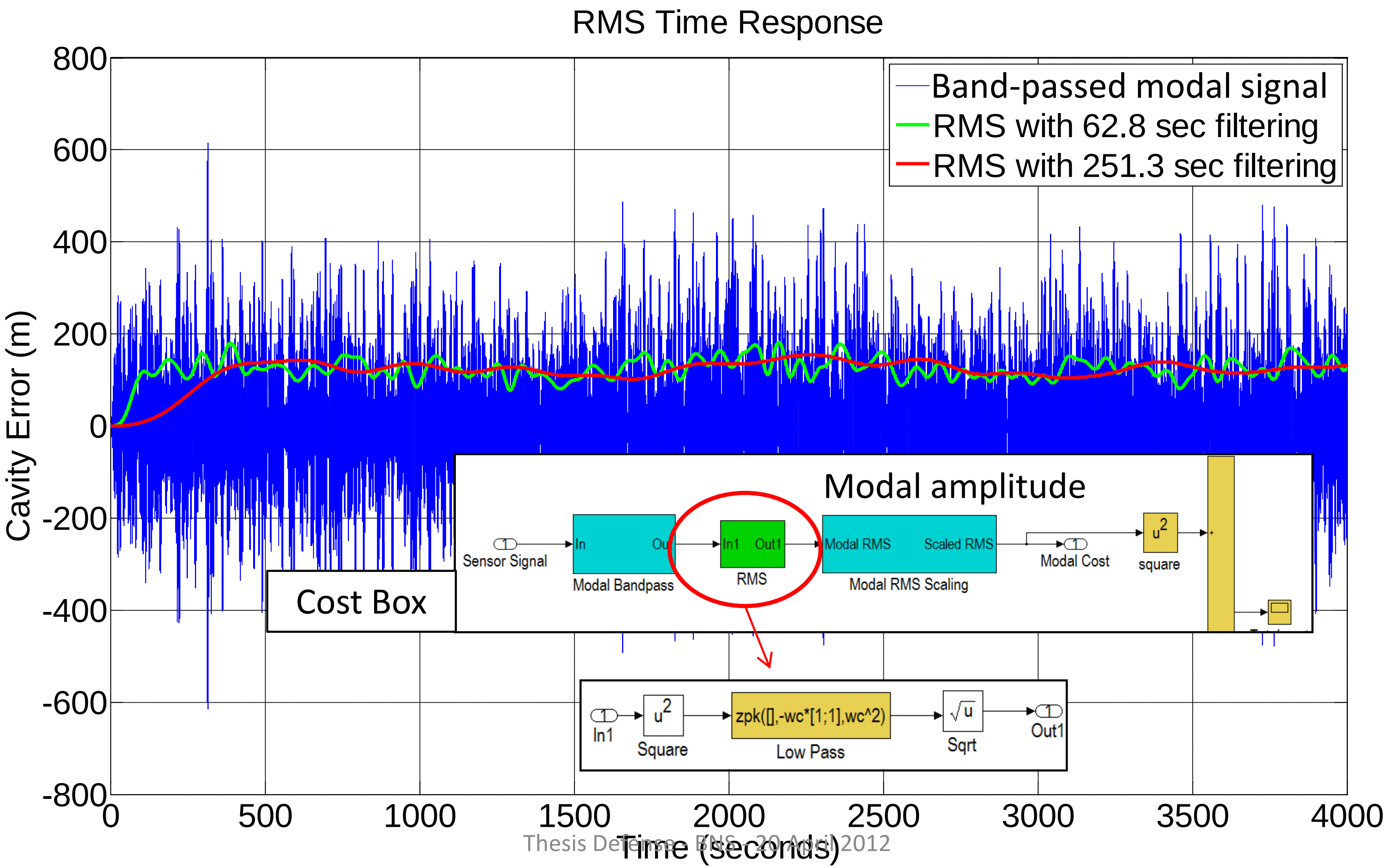
The cost box measures the performance values we care about and scales them to get the costs:

1. Modal Amplitudes
2. Noise Amplification
   - directly proportional to damping gain

Cost Input 1: Modal Amplitudes

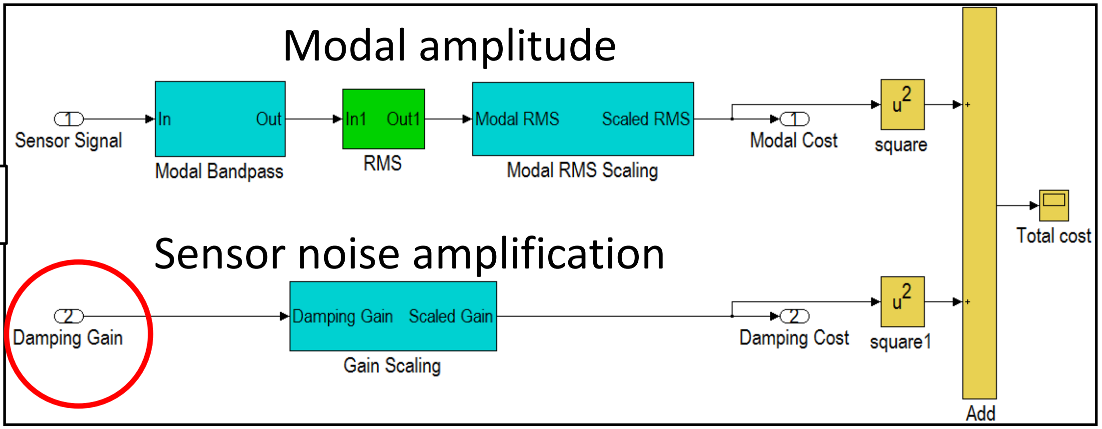


Modal Amplitude Variance Estimation



Cost Input 2: Noise Amplification

Cost Box



For frequencies ≥ 10 Hz :

$$P_1 = \frac{k_1 G_1}{1 + (Plant)_1 k_1 G_1} v \approx k_1 G_1 v \quad \Longrightarrow \quad P_i \propto k_i v$$

mode 1 damping force

stationary sensor noise

linear in k_i

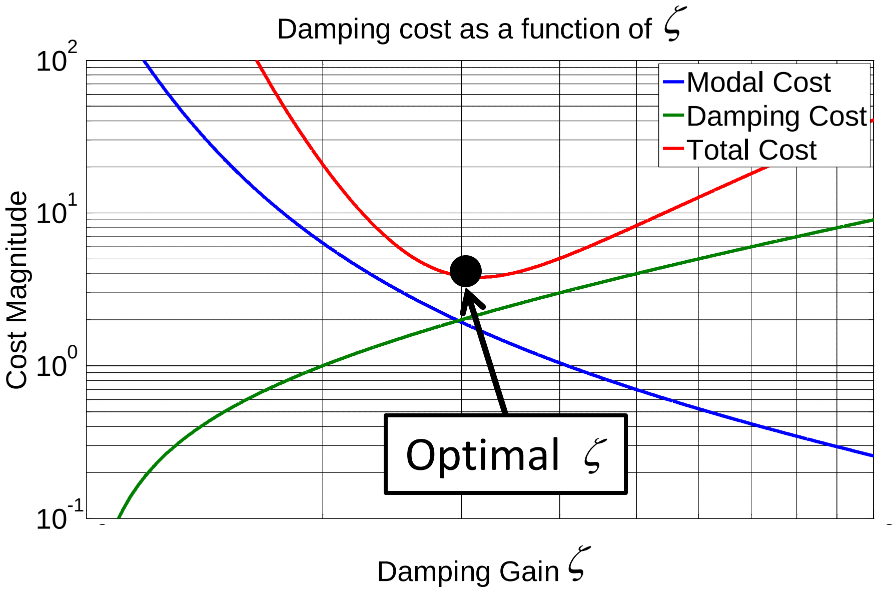
Since the sensor noise amplification for a given mode is directly proportional to its damping gain, the damping gain, rather than a measured noise term is used for this calculation. This is a quicker and more accurate estimate then measuring the noise directly like the modal amplitude.

Gauss-Newton Adaptation

Recursive damping gain equation

$$\zeta_{i,n+1} = \zeta_{i,n} - \alpha_{i,n} J^{+}_{i,n} \vec{c}_{i,n}$$

$^{+} =$ pseudoinverse



Notes

$k_{i,n}$ = i_{th} mode damping gain at time step *n.* Each time step is 30 to 60 sec.

$J^{+}_{i,n}$ = pseudoinverse of the i_{th} mode Jacobian descent matrix at time step *n* (model based).

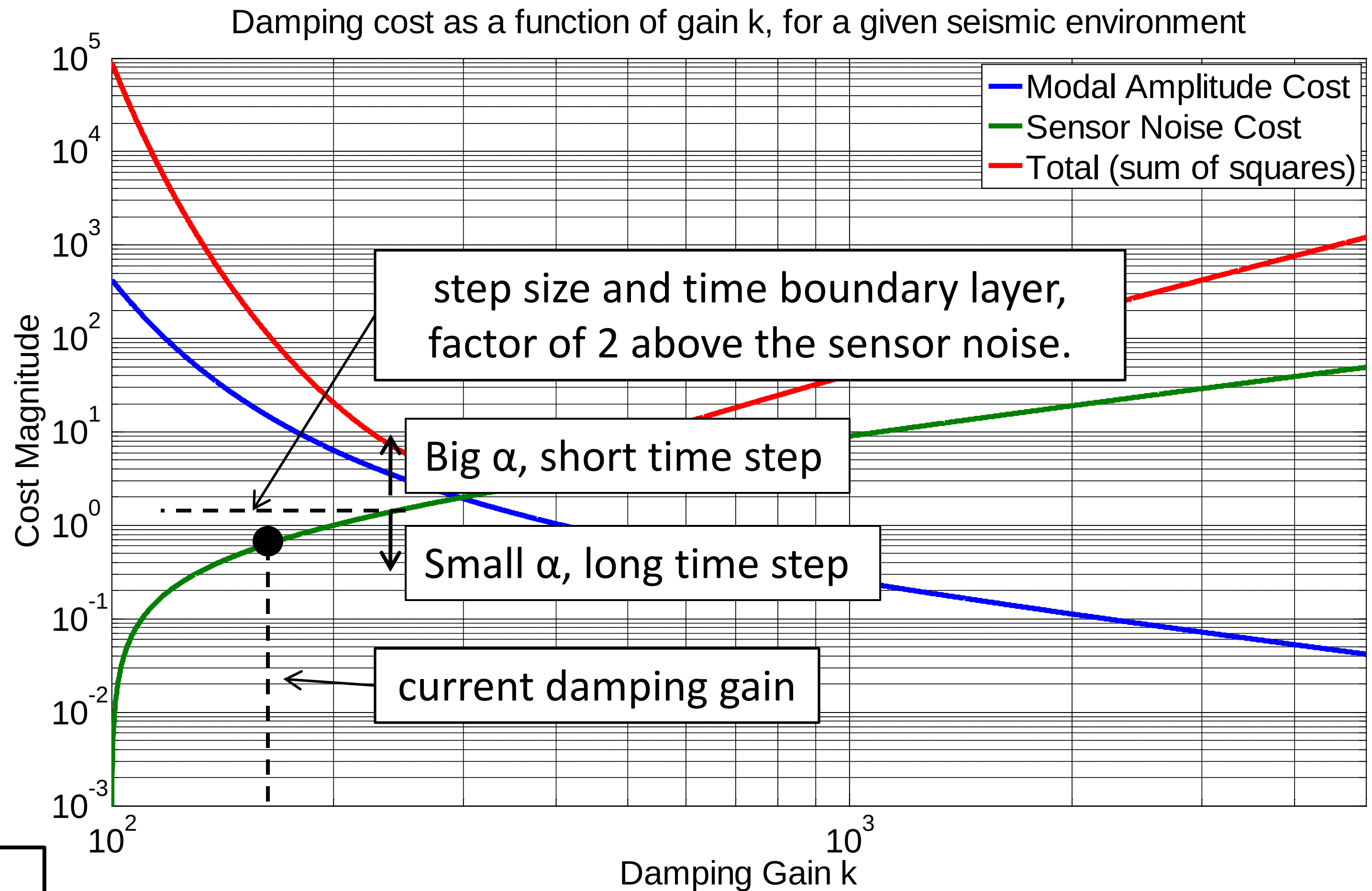
$$J_{i,n} = \begin{bmatrix} \text{(Modal amplitude gradient wrt } k_i\text{)} \\ \text{(modal noise amp. gradient wrt } k_i\text{)} \end{bmatrix}$$

$\vec{c}_{i,n}$ = cost vector of the i_{th} mode at time step *n.*

$$\vec{c}_{i,n} = \begin{bmatrix} \text{(scaled modal amplitude)} \\ \text{(scaled modal noise amplification)} \end{bmatrix}$$

$\alpha_{i,n}$ = step size of the i_{th} mode damping gain at time step *n.*

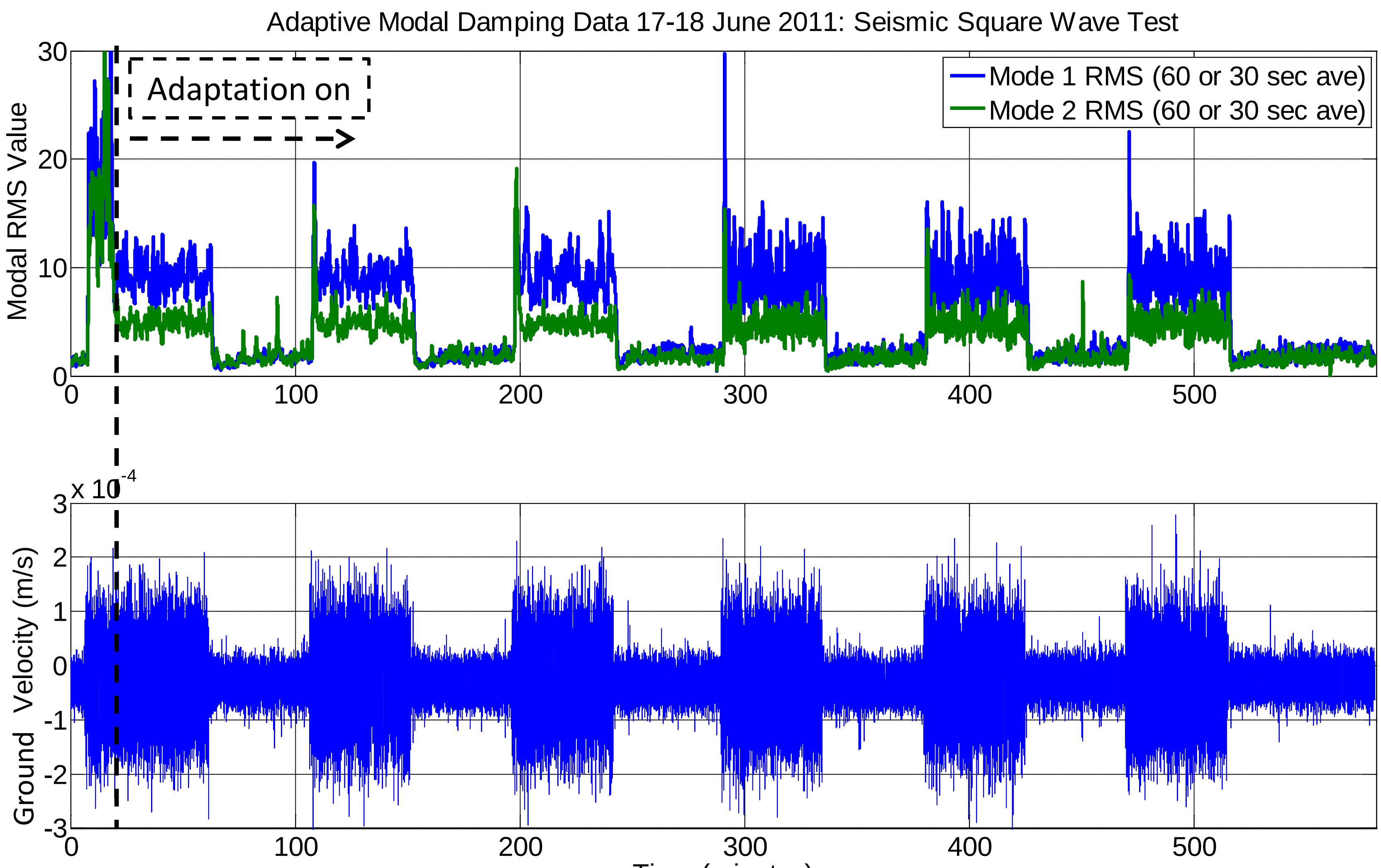
Adaptive Step Sizes and Step Rates



Notes:

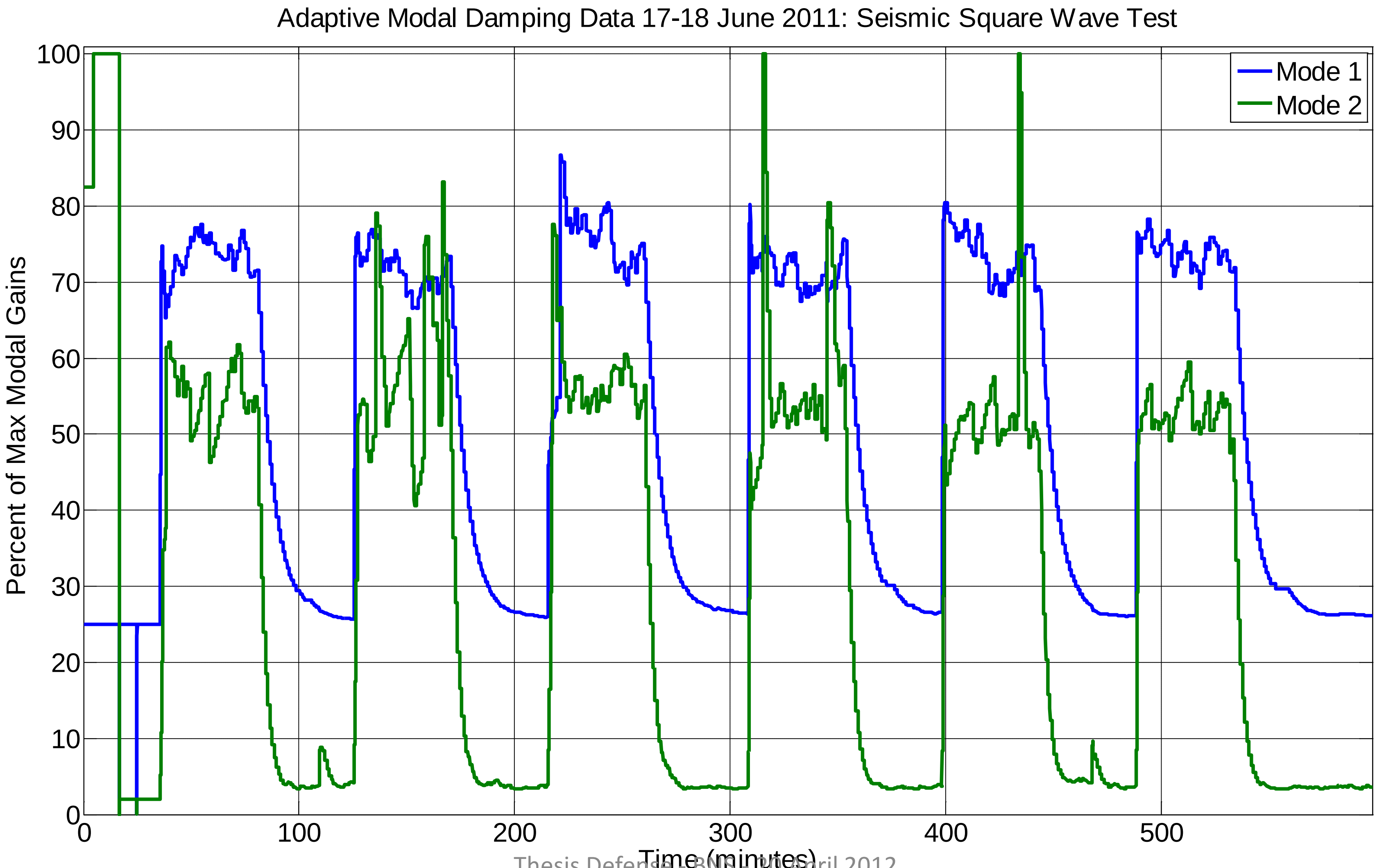
- If the measured modal amplitude is above the moving boundary layer, the adaptation takes large, quick steps with short RMS time constants to respond to sudden seismic events quickly.
- When the modal amplitude goes below the line, the adaptation takes small slow steps with long RMS time constants to converge accurately to the optimal damping solution.

Measured Response to a Seismic Square Wave: Modal RMS



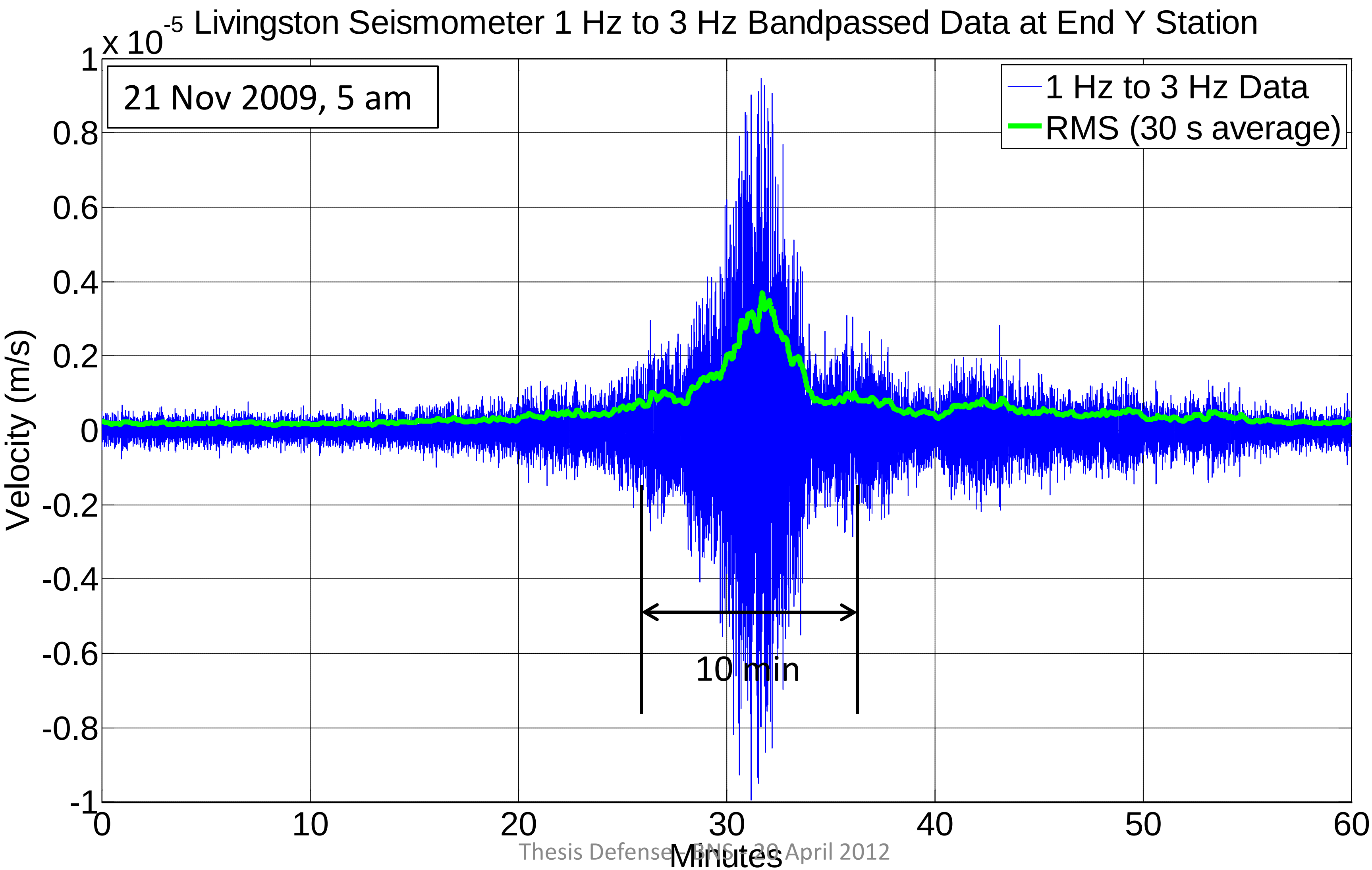
Notes: 3, 30 sec quicksteps steps; 3, 15 sec quicksteps steps; all 60 sec slow steps.

Measured Response to a Seismic Square Wave: Damping Gains

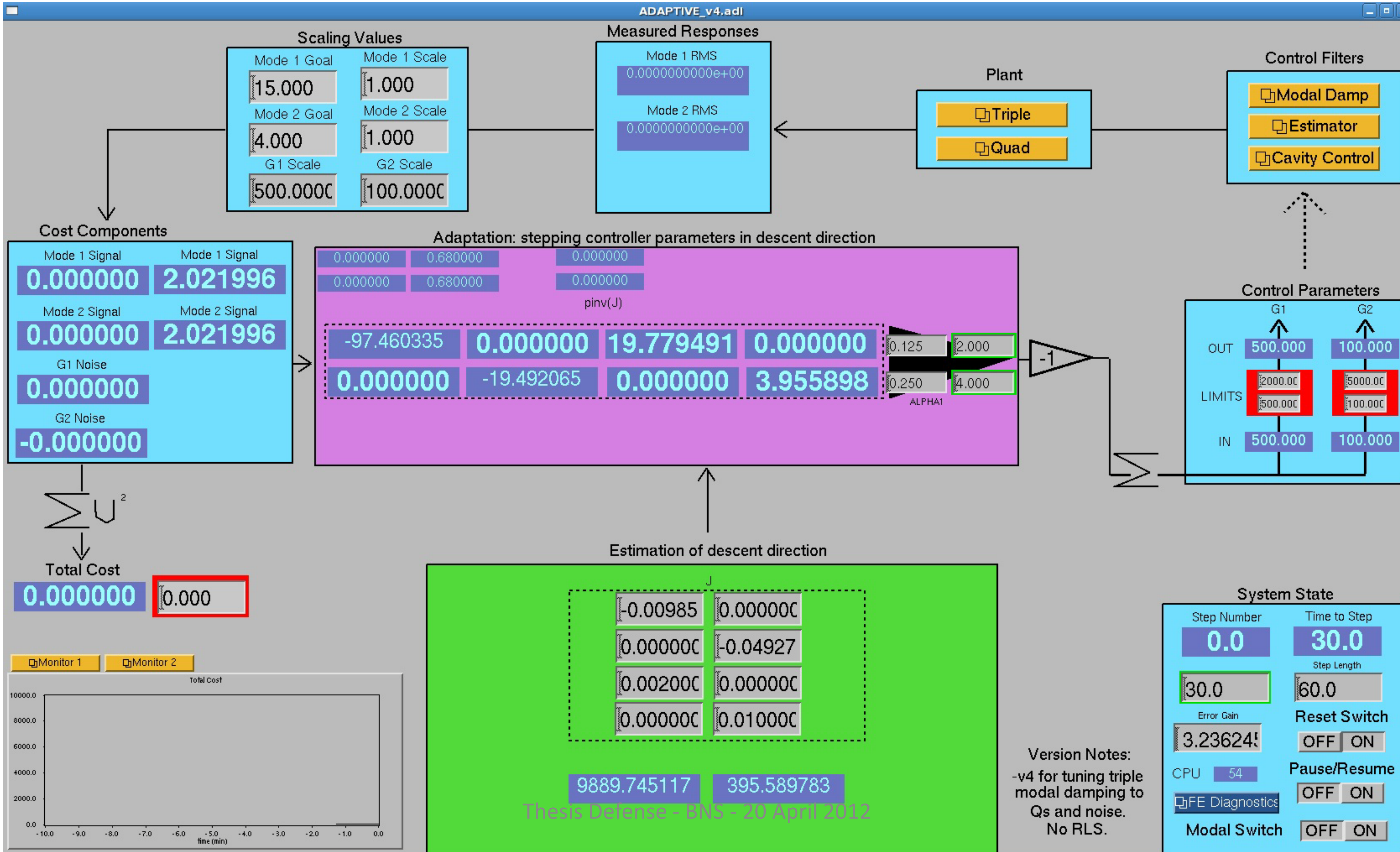


Notes: 3, 30 sec quicksteps steps; 3, 15 sec quicksteps steps; all 60 sec slow steps.

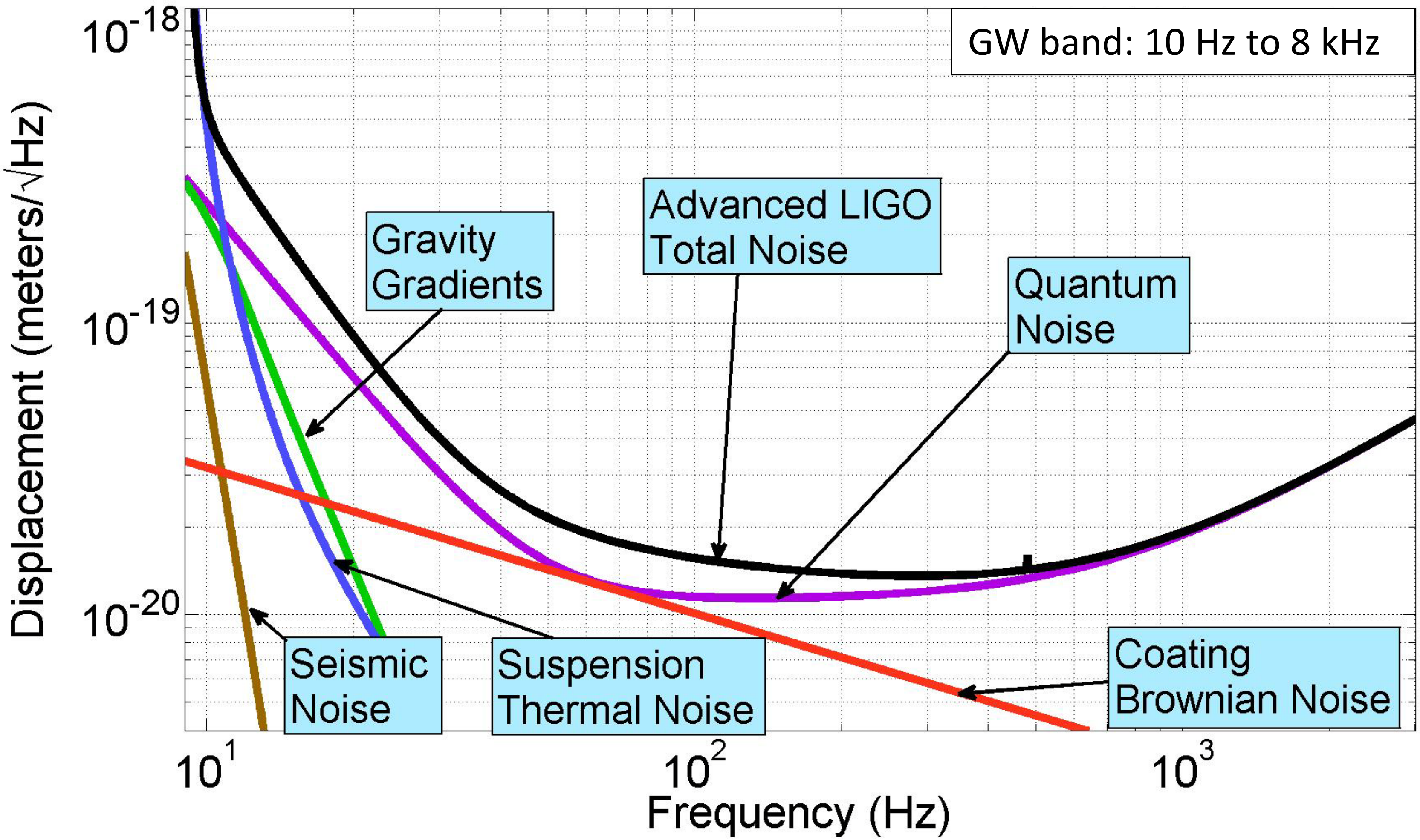
Ex. Train Passing Through Livingston



Backups: Adaptive Damping Interface Screen

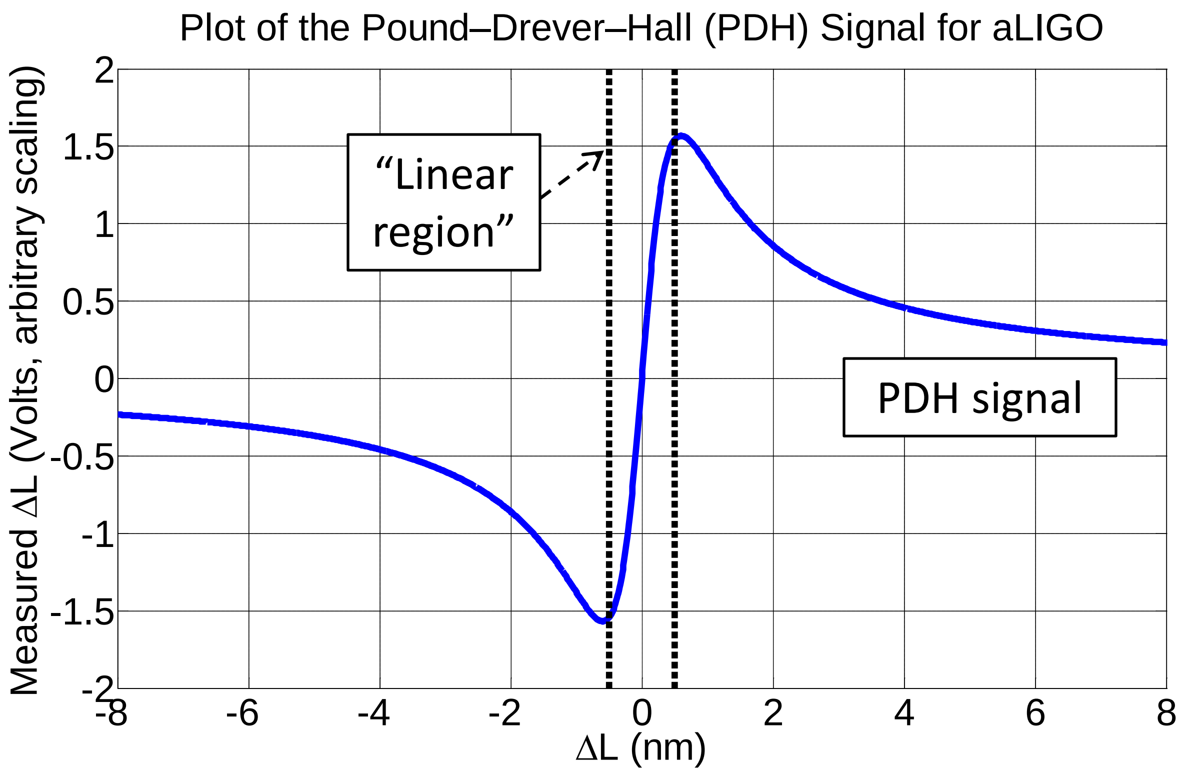


Projected Sensitivity for aLIGO



Adapted from Gregg Harry. "Advanced LIGO: the next generation of gravitational wave detectors" . Classical and Quantum Gravity, vol. 27, April 2010

Problem 3: Cavity Signal



The PDH signal for a 4 km aLIGO Fabry-Perot cavity with mirror power transmissions of 1.4% and 7.5 ppm. The cavity finesse is 445. The linear region between the dashed lines is 1 nm wide.

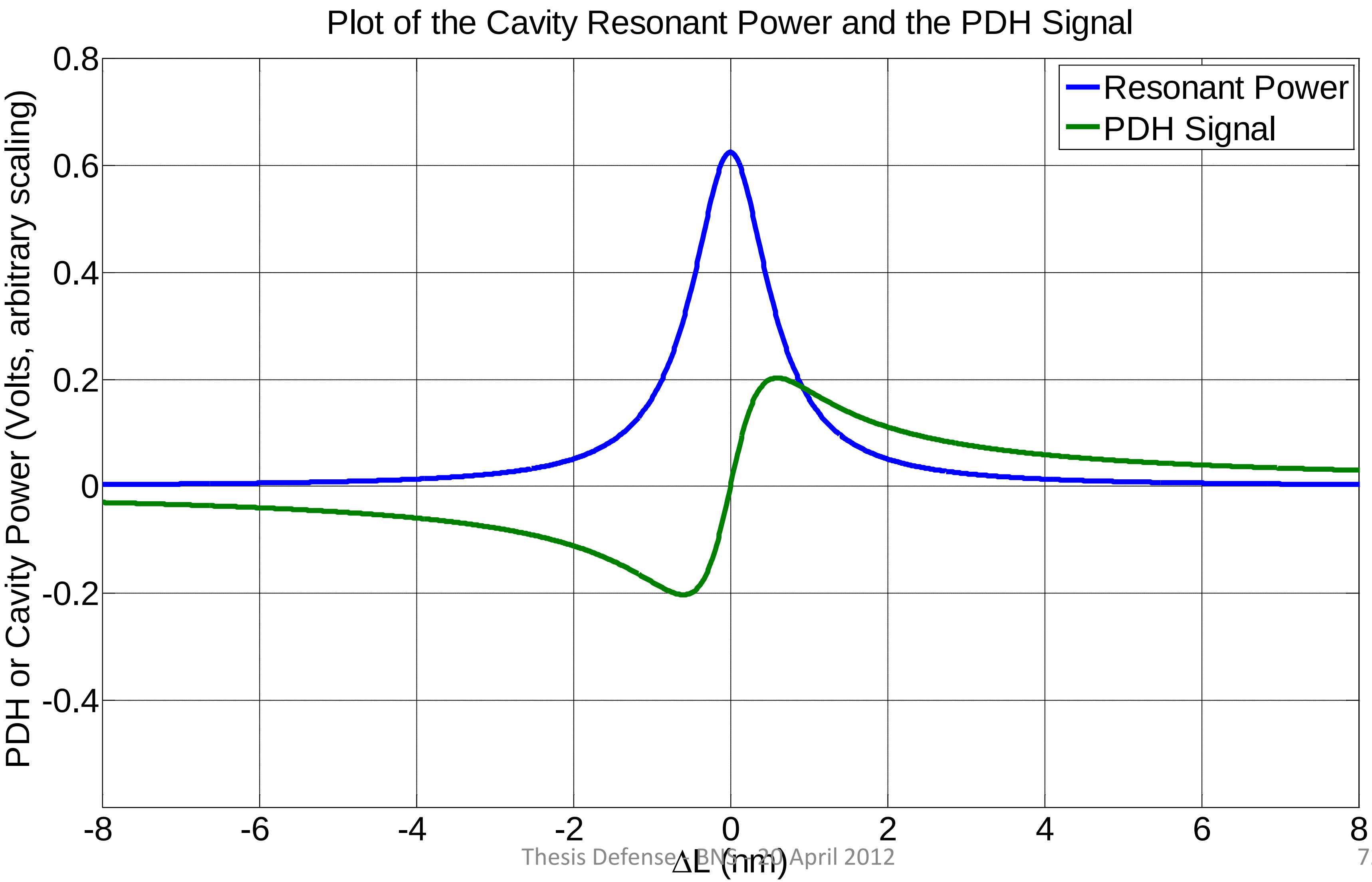
$$PDH = C \frac{\sin\left(4\pi \frac{\Delta L}{\lambda}\right)}{1+\left[\frac{2F}{\pi}\sin\left(2\pi\frac{\Delta L}{\lambda}\right)\right]^2}$$

F = cavity finesse = 445

λ = laser wavelength = 1064 nm

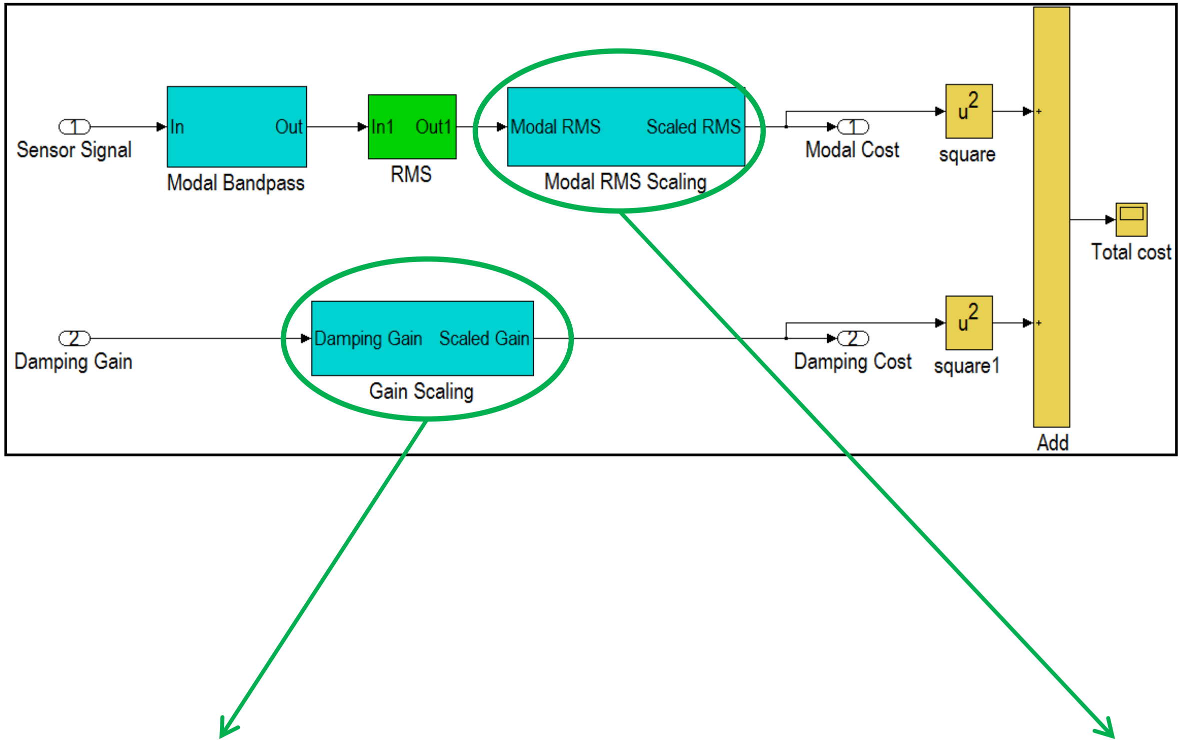
C = arbitrary electronic scaling

Backups: PDH and Resonant Cavity Power



Backups: Cost Scaling Details

Backups: Cost Scaling Details



$$\frac{G}{G_0}$$

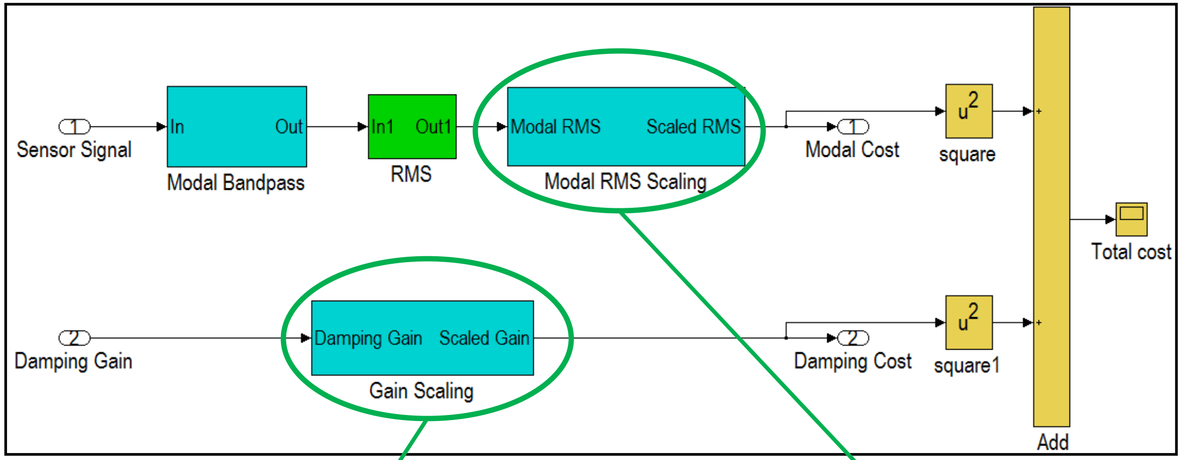
<- equal trade off ->

$$\frac{M_{RMS}}{M_0}$$

Damping Gain Scaling

Modal RMS Scaling

Backups: Cost Scaling Details



$$\frac{G}{G_0}$$

Damping Gain Scaling

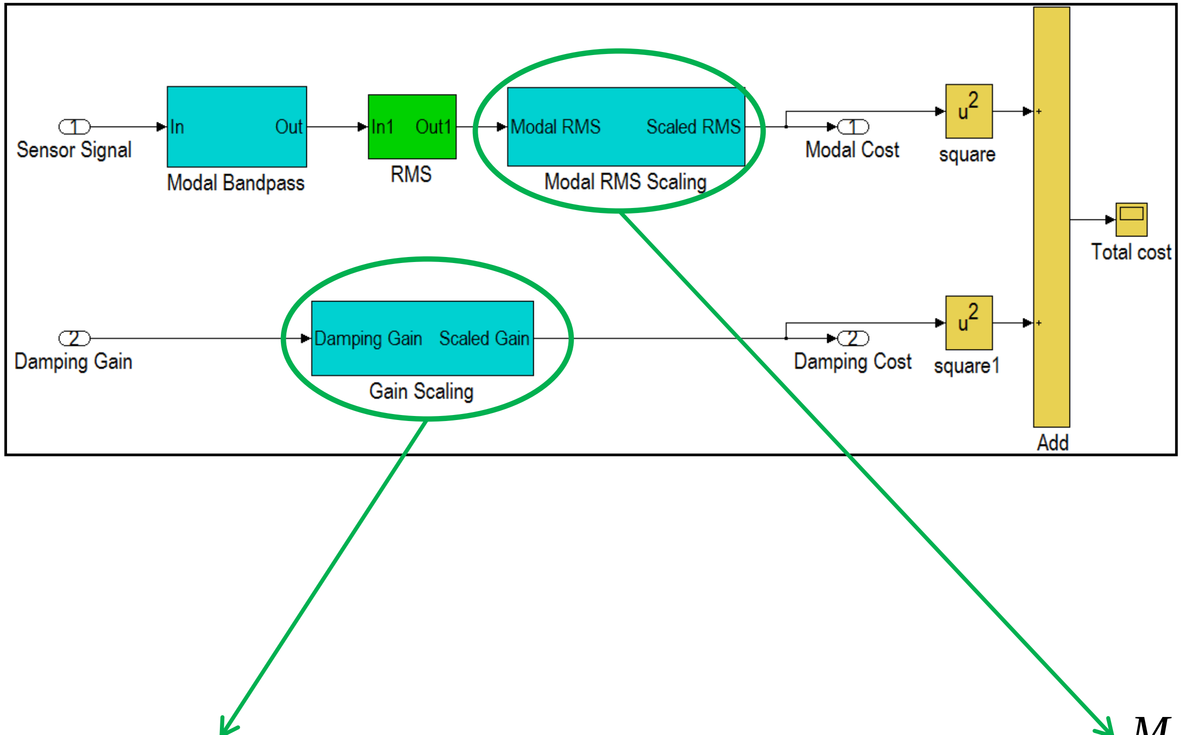
<- progressive trade off ->

$$\frac{M_{RMS}/M_0}{1 - M_{RMS}/M_0}$$

Modal RMS Scaling

- Progressive trade off anticipates cavity lock loss for large amplitude disturbances.

Backups: Cost Scaling Details



$$\frac{G}{G_0}$$

Damping Gain Scaling

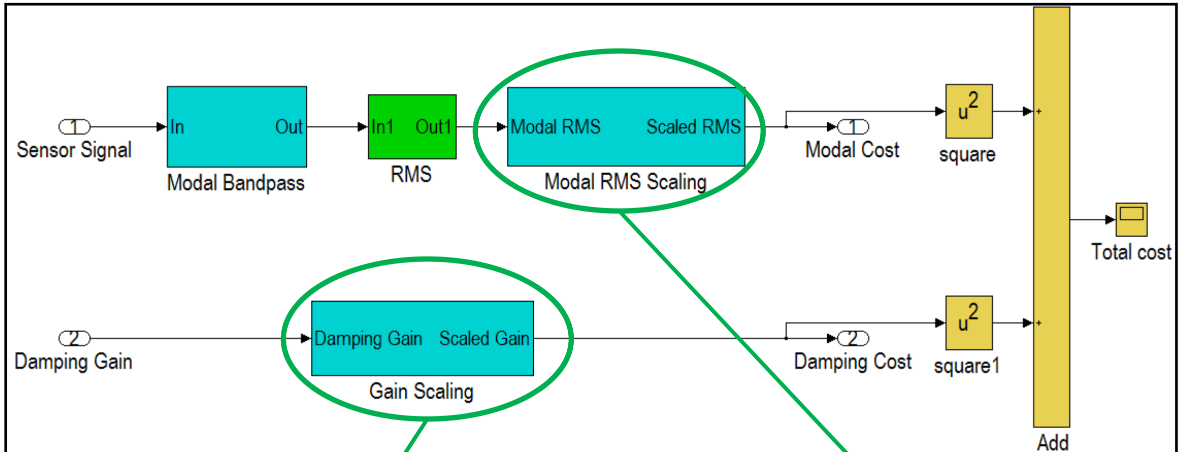
<- progressive trade off ->

$$\frac{M_{RMS}/M_0}{1-erf\left(M_{RMS}/M_0\right)}$$

Modal RMS Scaling

- Progressive trade off anticipates cavity lock loss for large amplitude disturbances.
- erf() removes the pole and reduces the aggressiveness.

Backups: Cost Scaling Details



$$\frac{G}{G_0} - 1$$

Damping Gain Scaling

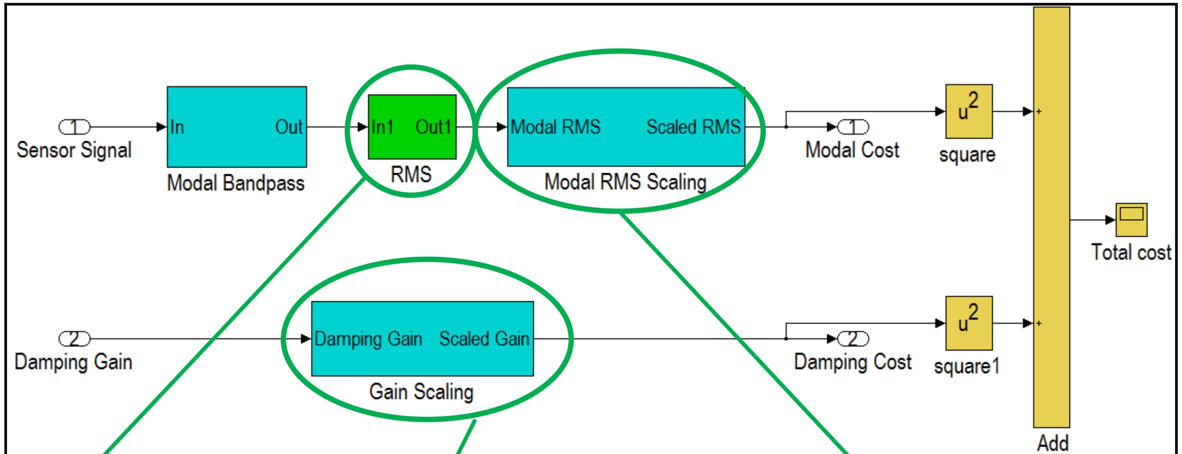
<- progressive trade off ->

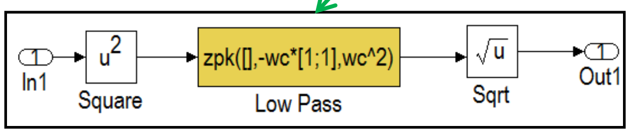
$$\frac{M_{RMS}/M_0}{1 - erf\left(M_{RMS}/M_0\right)}$$

Modal RMS Scaling

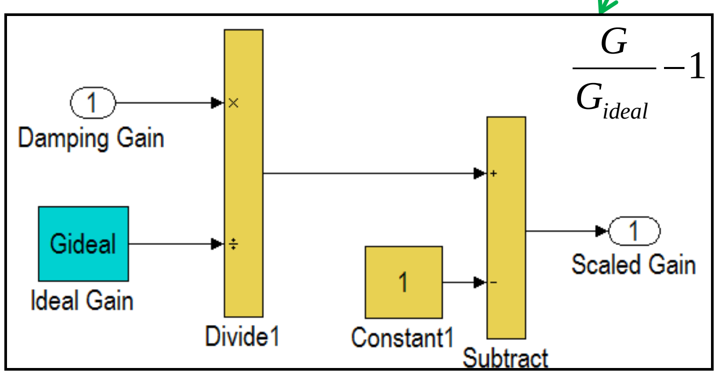
- Progressive trade off anticipates cavity lock loss for large amplitude disturbances.
- erf() removes the pole and reduces the aggressiveness.
- Subtracting 1 from the gain scaling simply provides a '0' cost target gain.

Backups: Cost Box Details





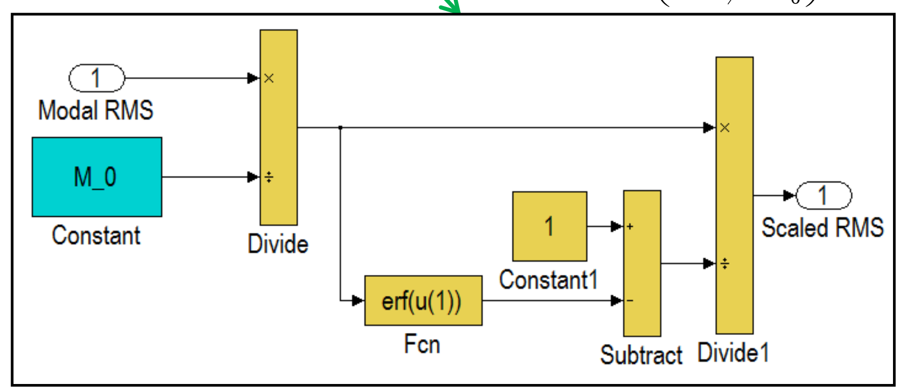
RMS Filter



$$\frac{G}{G_{ideal}} - 1$$

Damping Gain Scaling

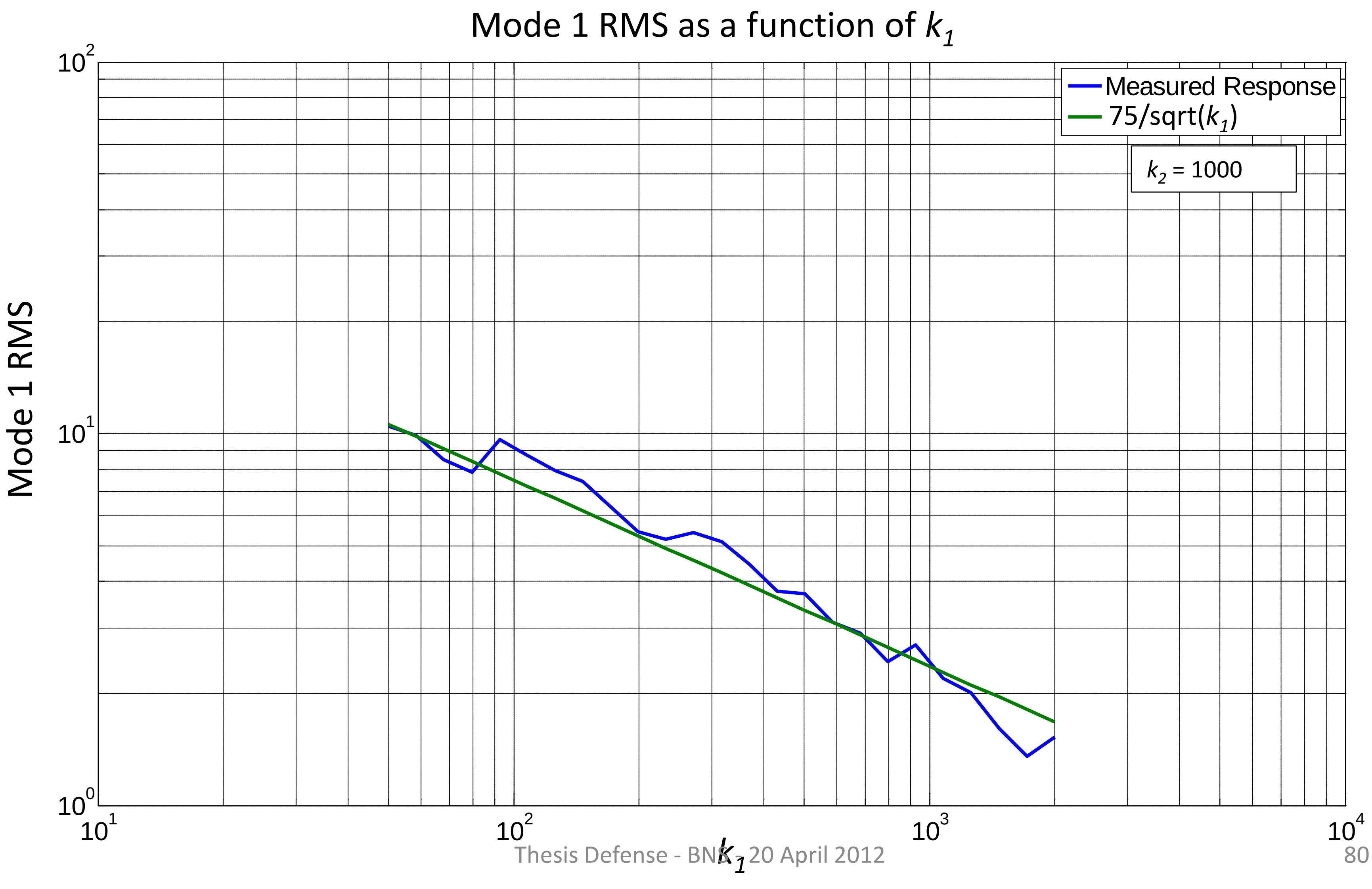
$$\frac{M_{RMS} / M_0}{1 - erf\left(M_{RMS} / M_0 \right)}$$



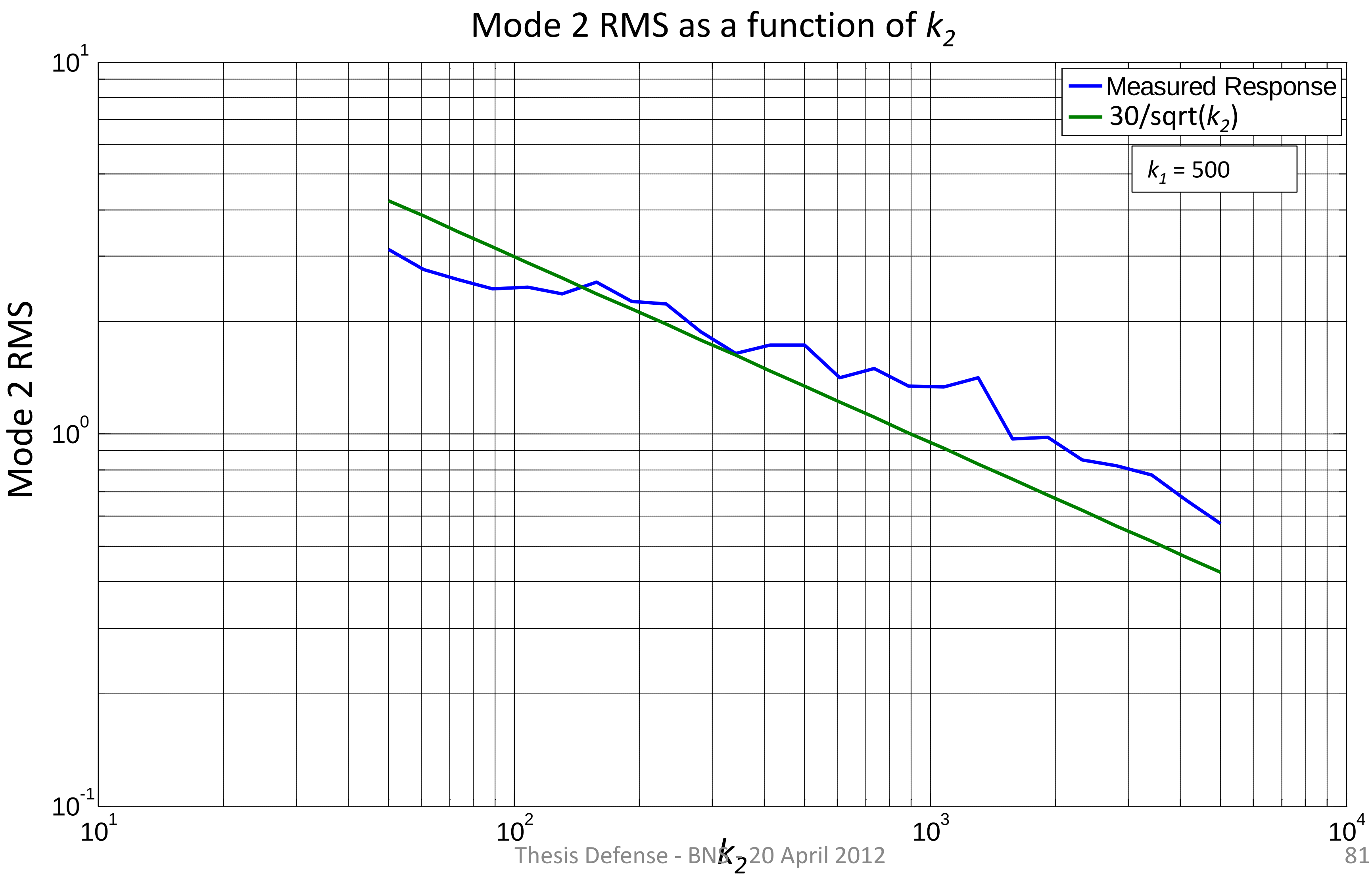
Modal RMS Scaling

Backups: Measurement of modal RMS dependence of damping gain (Jacobian Measurement)

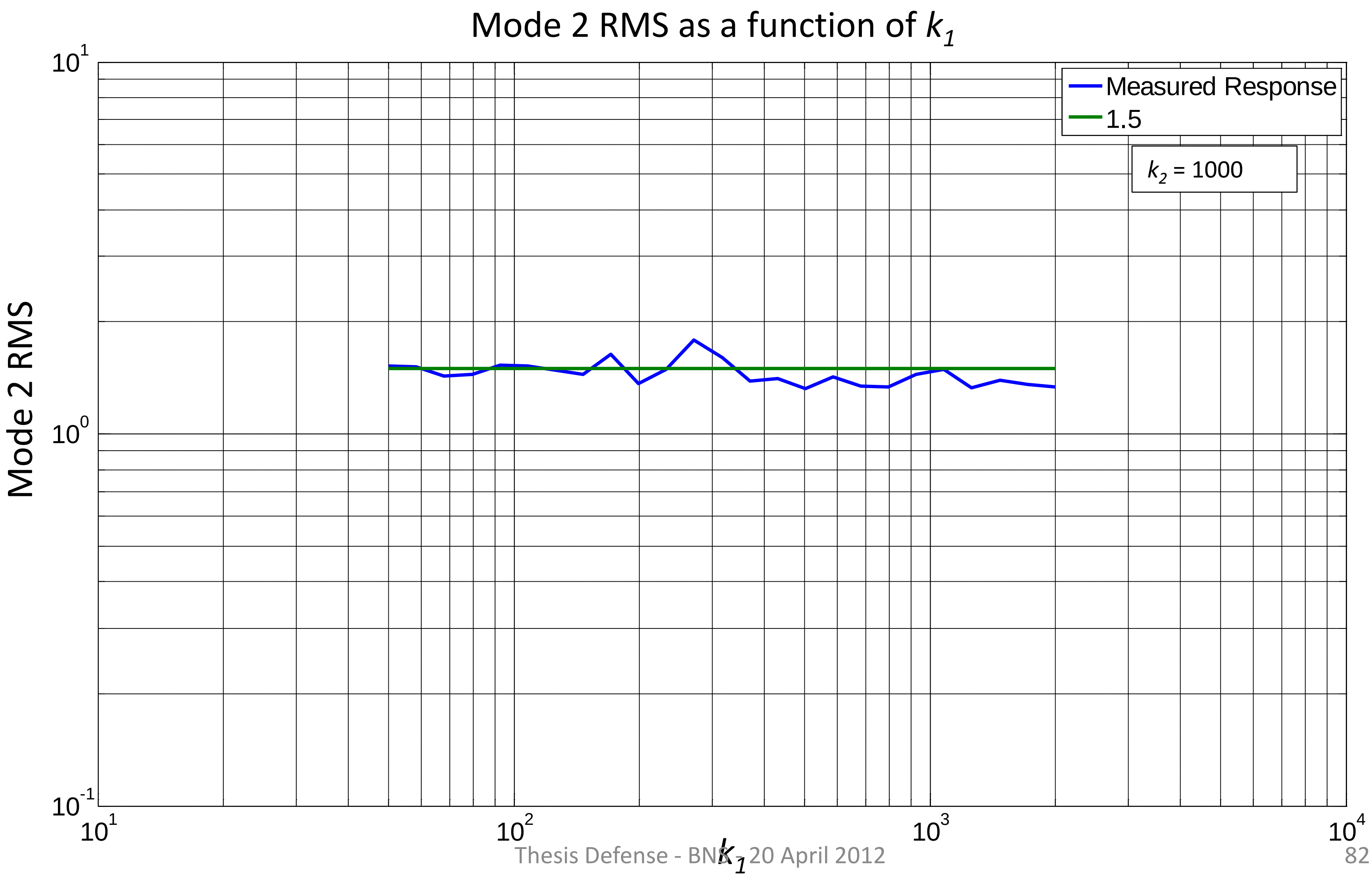
Backups: Jacobian Measurement



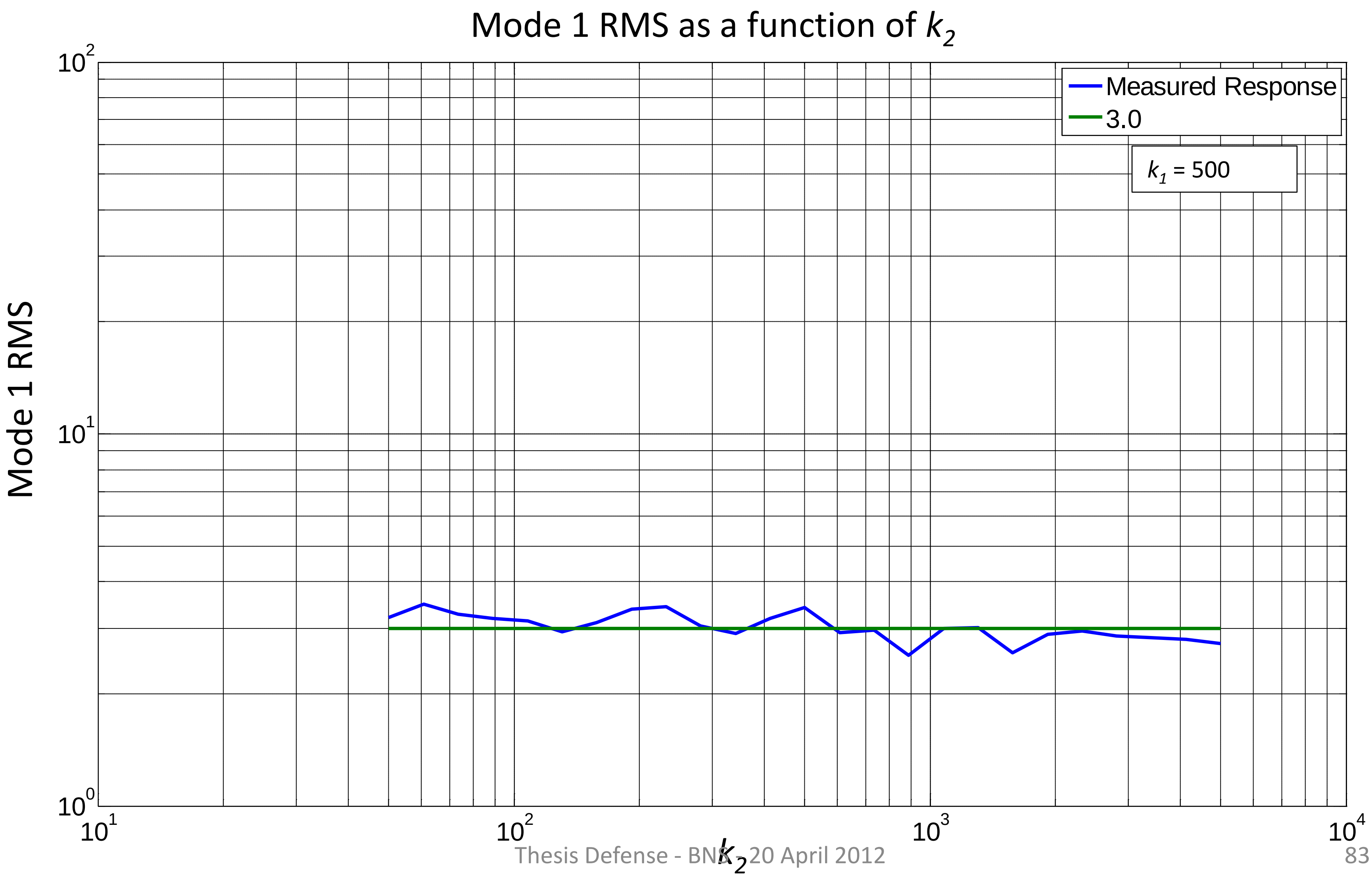
Backups: Jacobian Measurement



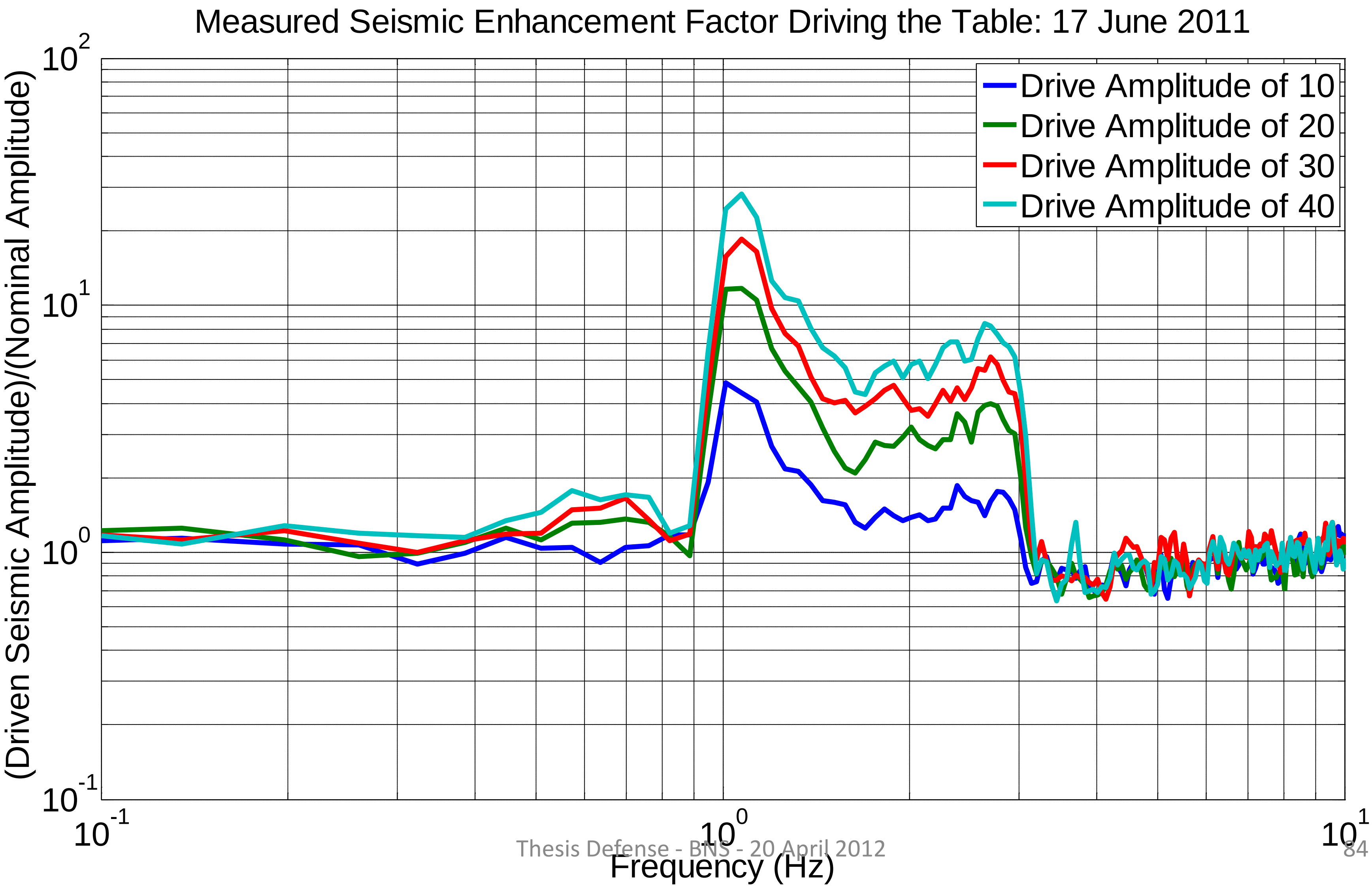
Backups: Jacobian Measurement



Backups: Jacobian Measurement

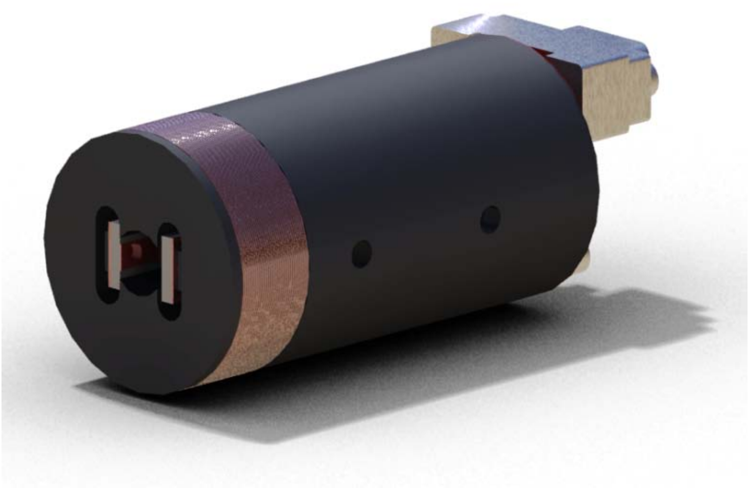


Backups: Driven Seismic Amplitudes

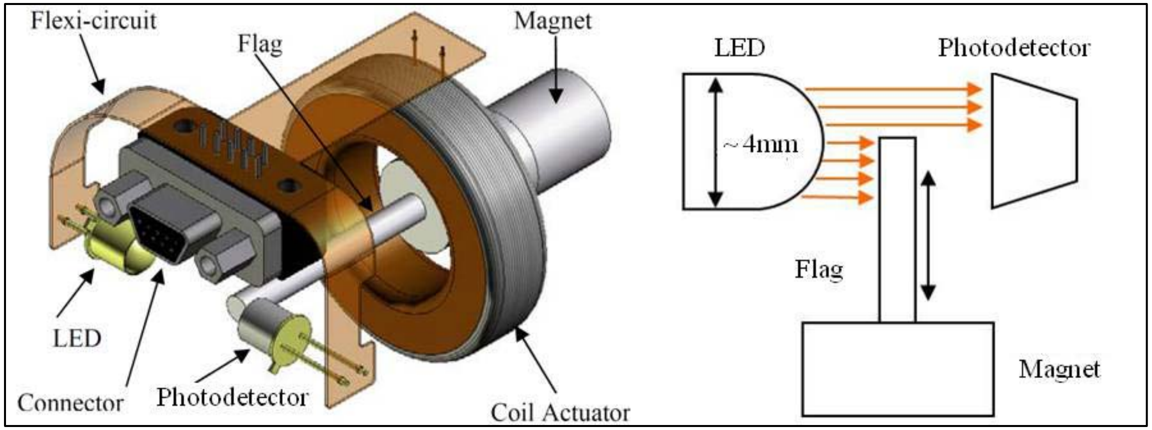


Backups: Optical Sensor ElectroMagnet (OSEM)

Birmingham OSEM (BOSEM)



Advanced LIGO OSEM (AOSEM)
- modified iLIGO OSEM

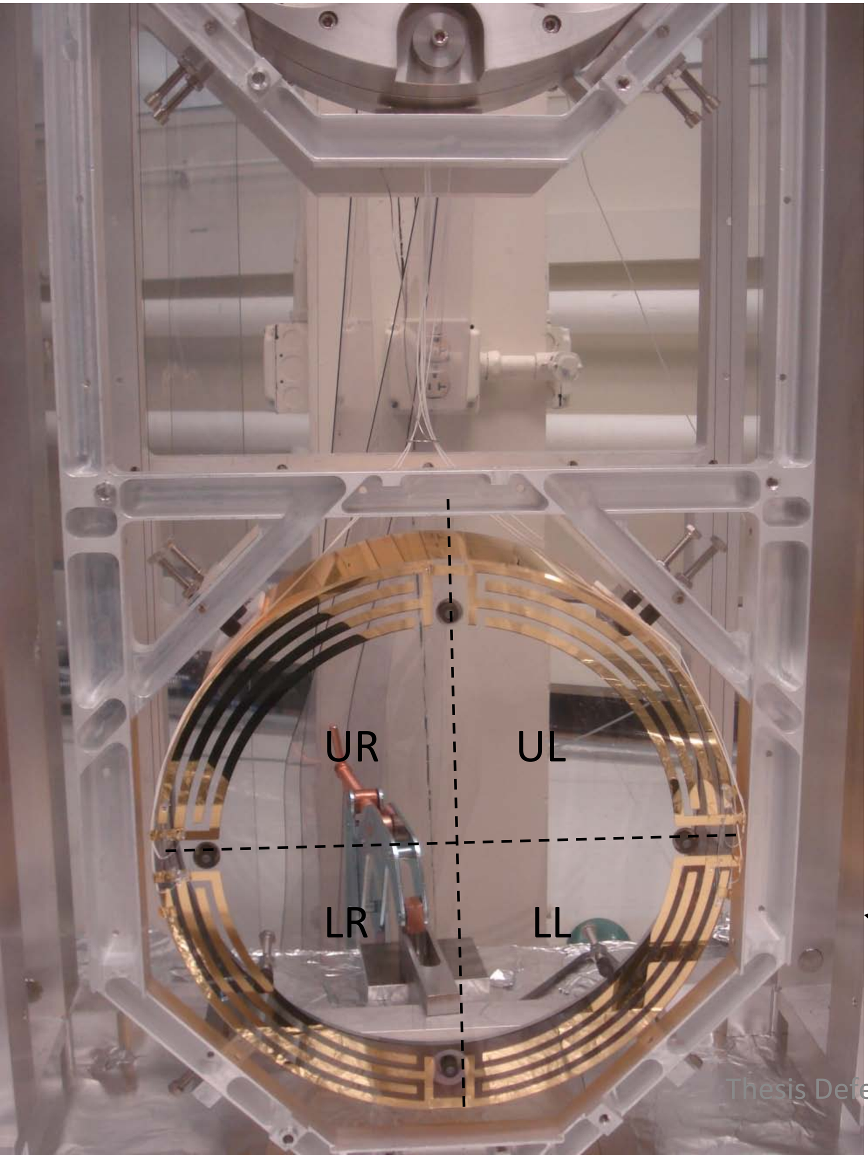


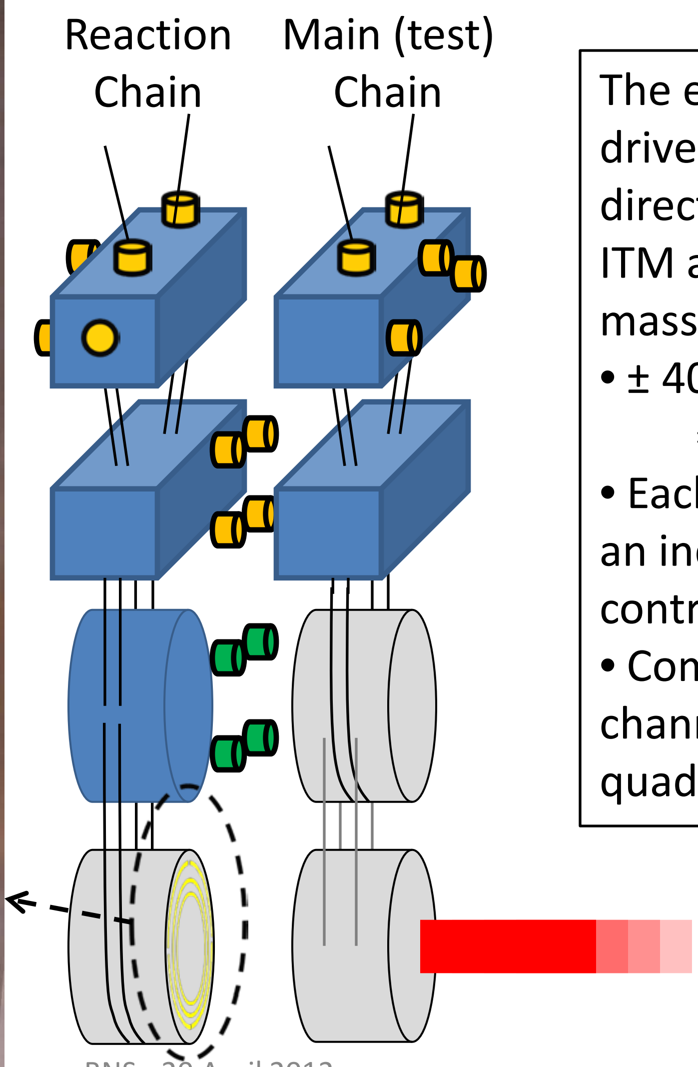
BOSEM Schematic

Magnet Types (M0900034)

- BOSEM – 10 X 10 mm, NdFeB , SmCo
  10 X 5 mm, NdFeB, SmCo
- AOSEM – 2 X 3 mm, SmCo
  2 X 6 mm, SmCo
  2 X 0.5 mm, SmCo

Backups: Quadruple Suspension ESD

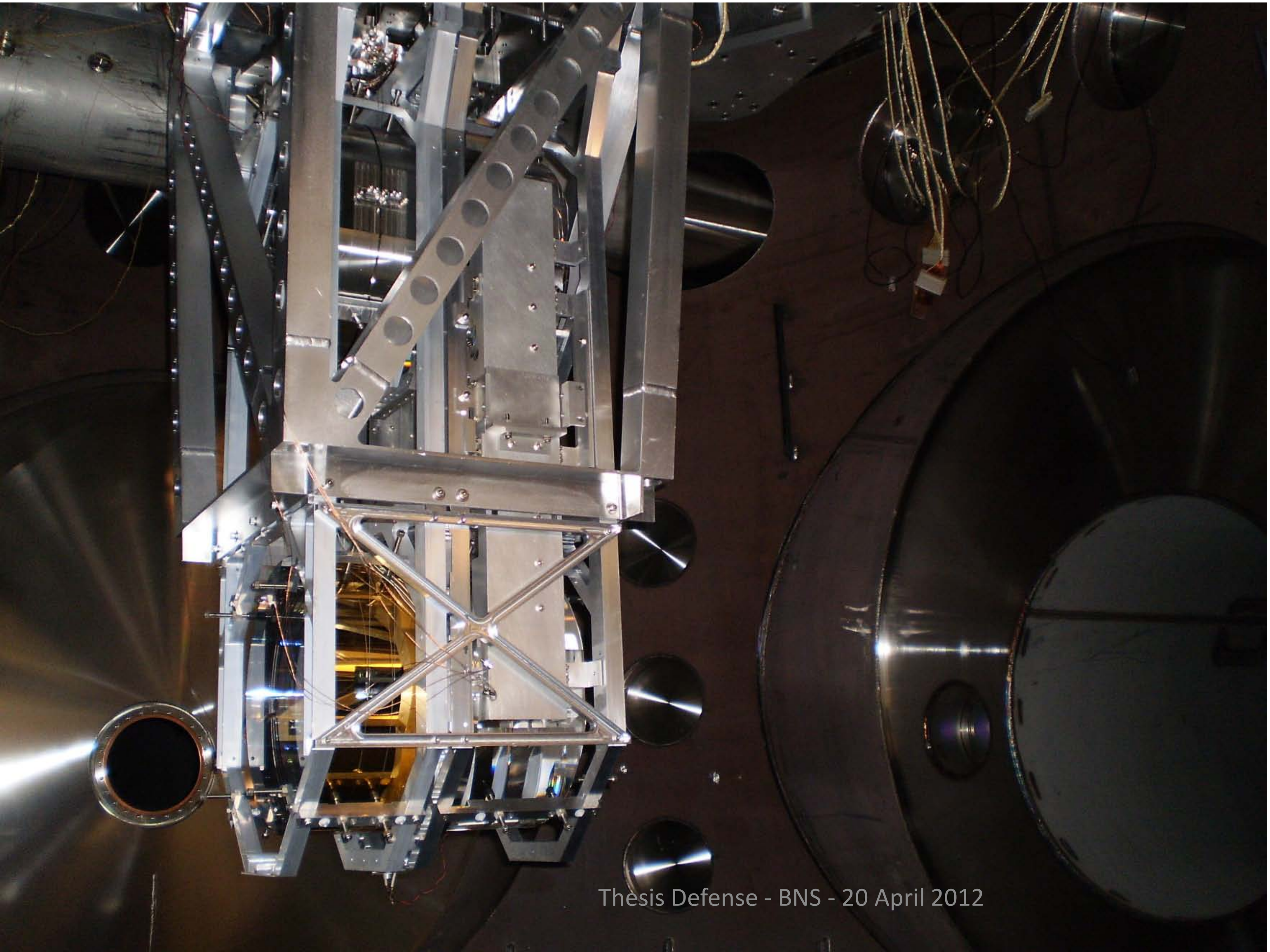




The electrostatic drive (ESD) acts directly on the test ITM and ETM test masses.

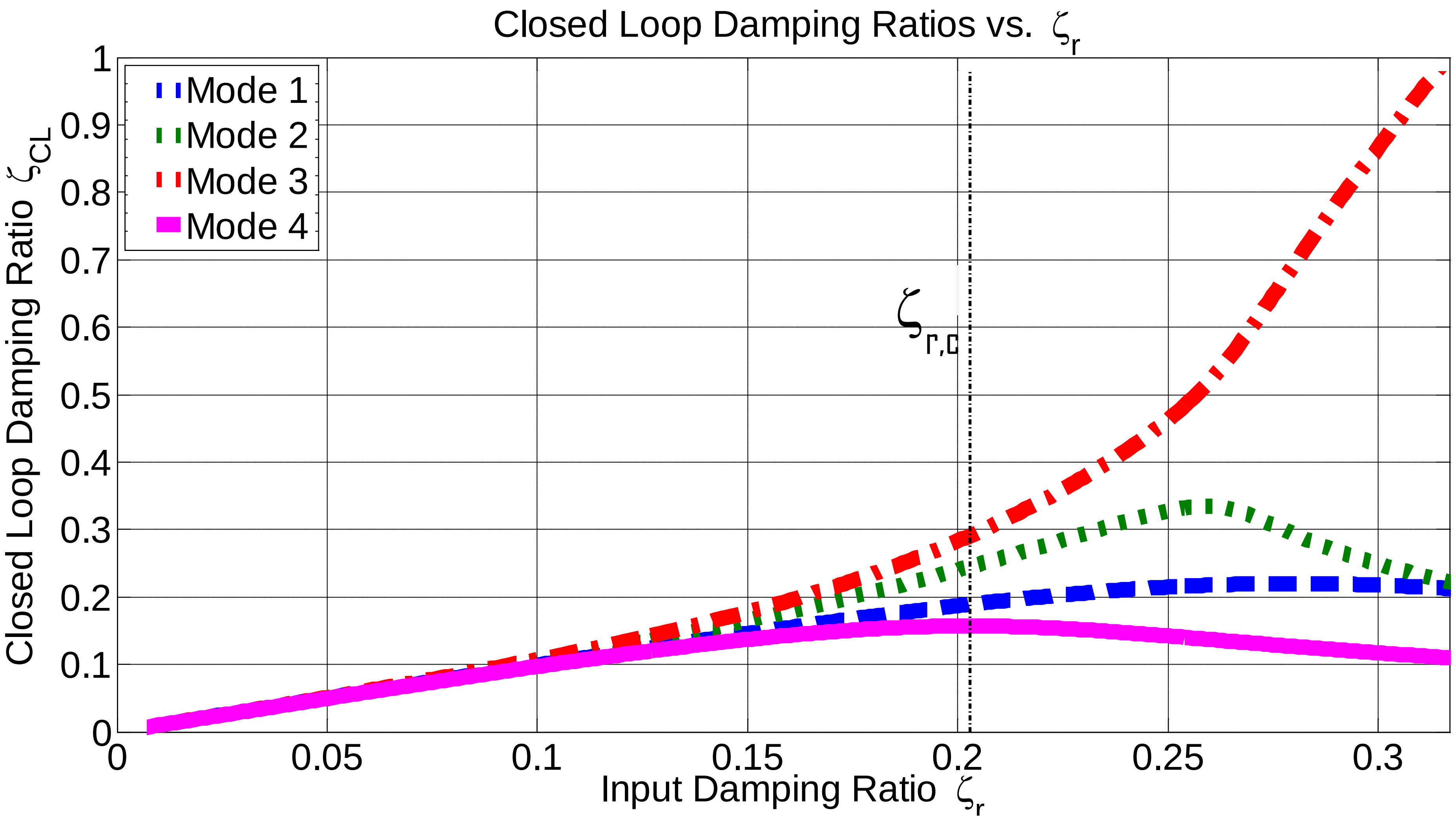
- ± 400 V (ΔV 800 V) ≈ 100 μN
- Each quadrant has an independent control channel
- Common bias channel over all quadrants

Backups: Quadruple Suspension



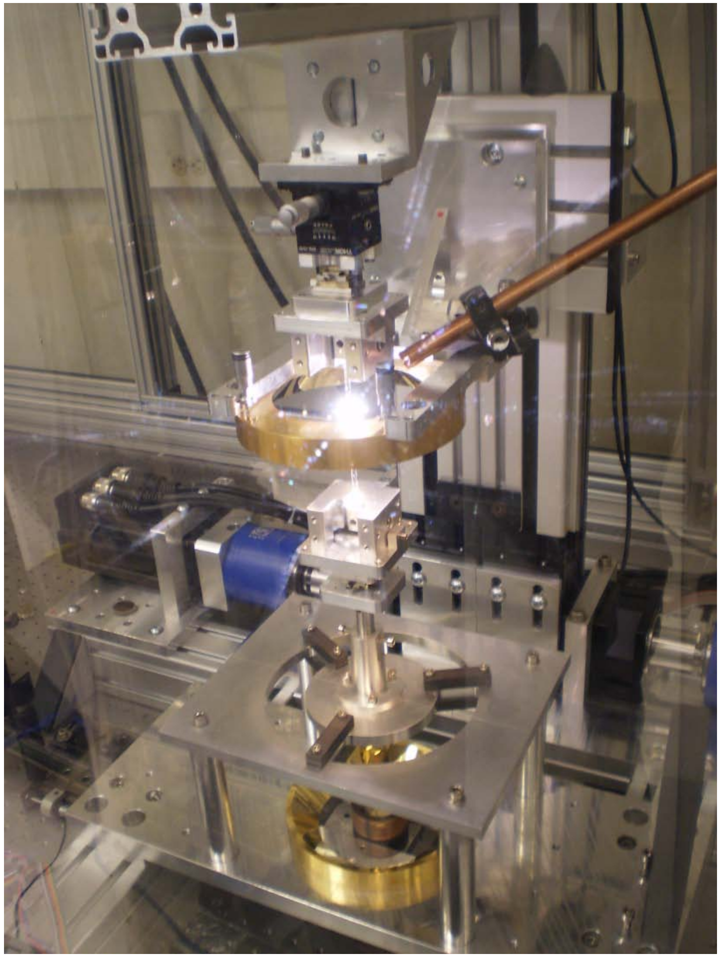
MIT monolithic quad in BSC

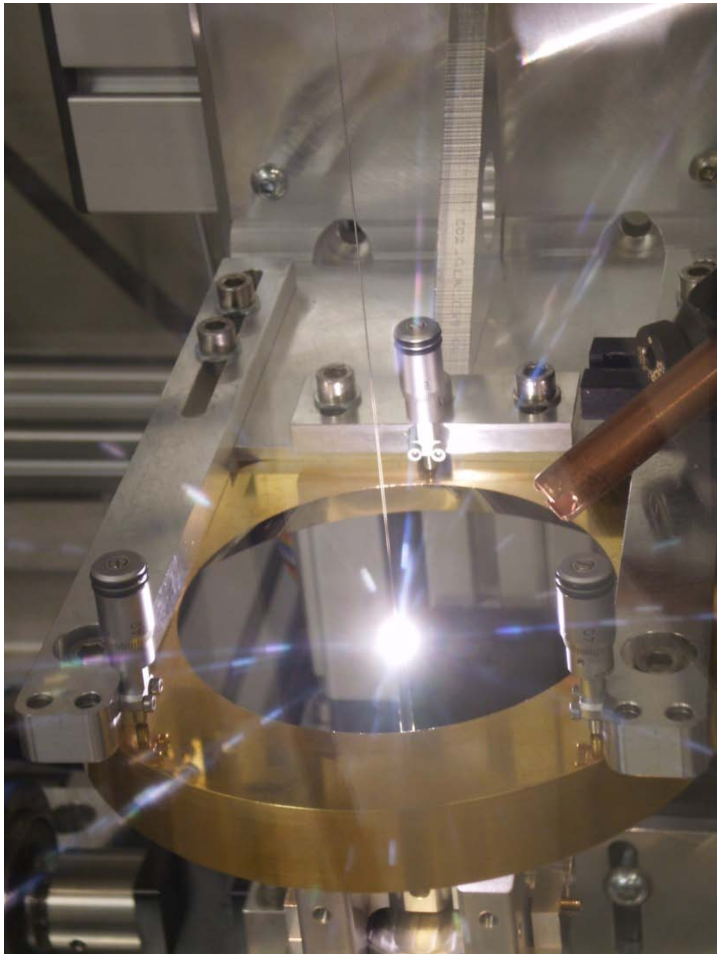
June 2010



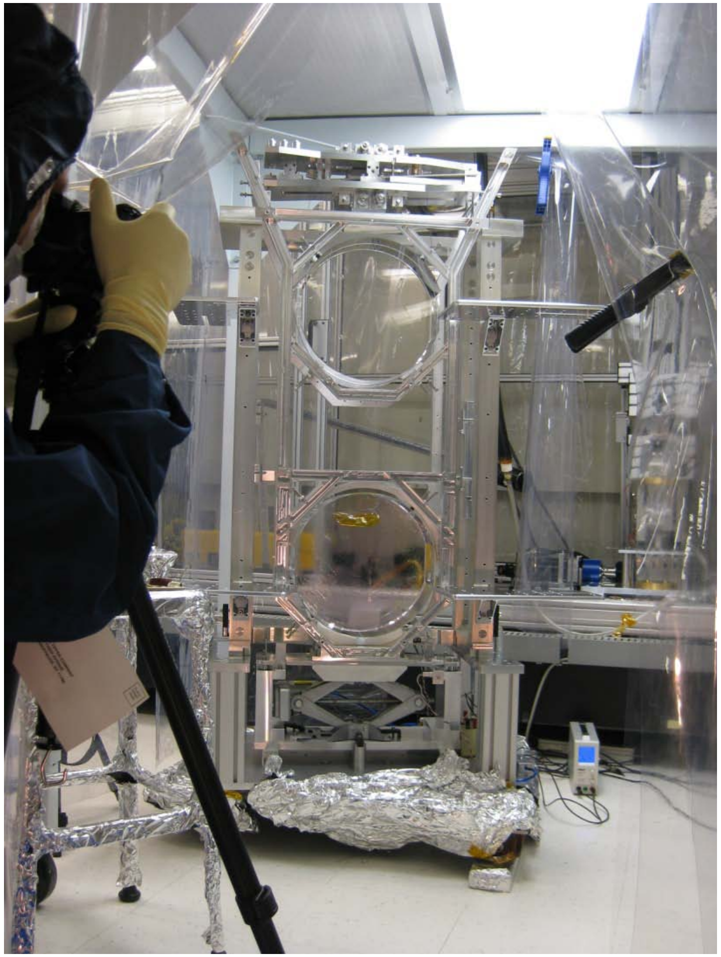
Closed Loop Damping Ratios vs. ζ_r
Closed Loop Damping Ratio ζ_{CL}
Input Damping Ratio ζ_r
Mode 1
Mode 2
Mode 3
Mode 4
$\zeta_{r,cr}$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.05
0.1
0.15
0.2
0.25
0.3

Pulling Fibers

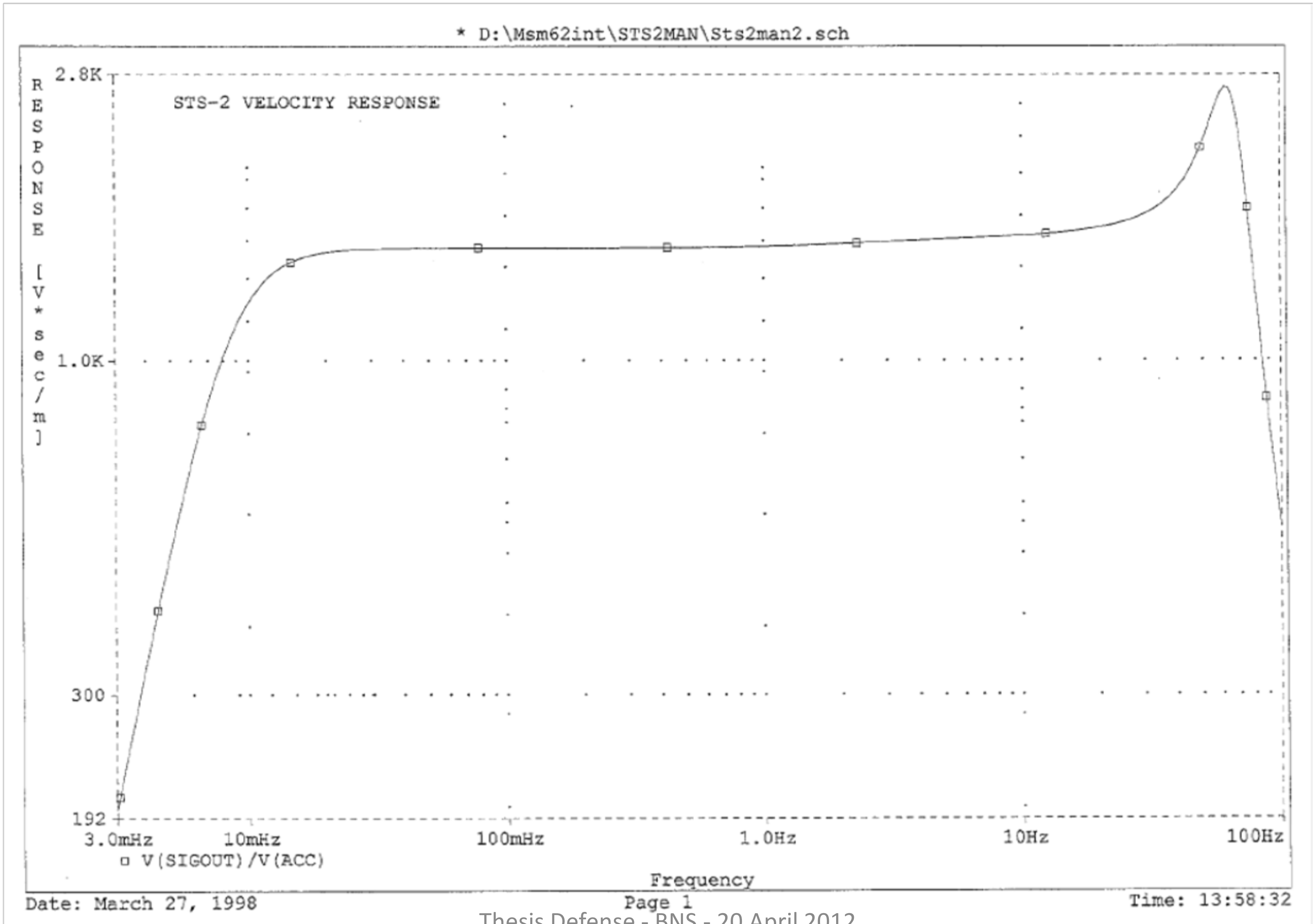




Quad Monolithic Stages



Streckeisen STS-2 Seismometer



Ref: http://www.passcal.nmt.edu/content/instrumentation/sensors/broadband-sensors/sts-2-bb-sensor

Scratch

LIGO GW sources with sound files
http://www.ligo.org/science//GW-Burst.php