SDL

Control of the UltraLITE Precision Deployable Test Article Using Adaptive Spatio-Temporal Filtering Based Control

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Overview

- UltraLITE Deployable Optical Telescope program
- DOT test beds
  - Mirror Mass Simulator
  - PDOS
  - DOT BGD
- Active structural control issues
- Spatio-Temporal Filtering (STF)
- STF based structural control
- PDOS test experience

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Acknowledgements

- Phase II SBIR award from Ballistic Missile Defense Organization (BMDO)
- Contract managed by and technical collaboration with Air Force Research Lab - Kirtland AFB

Air Force Research Laboratory Deployable Space Telescope Concept

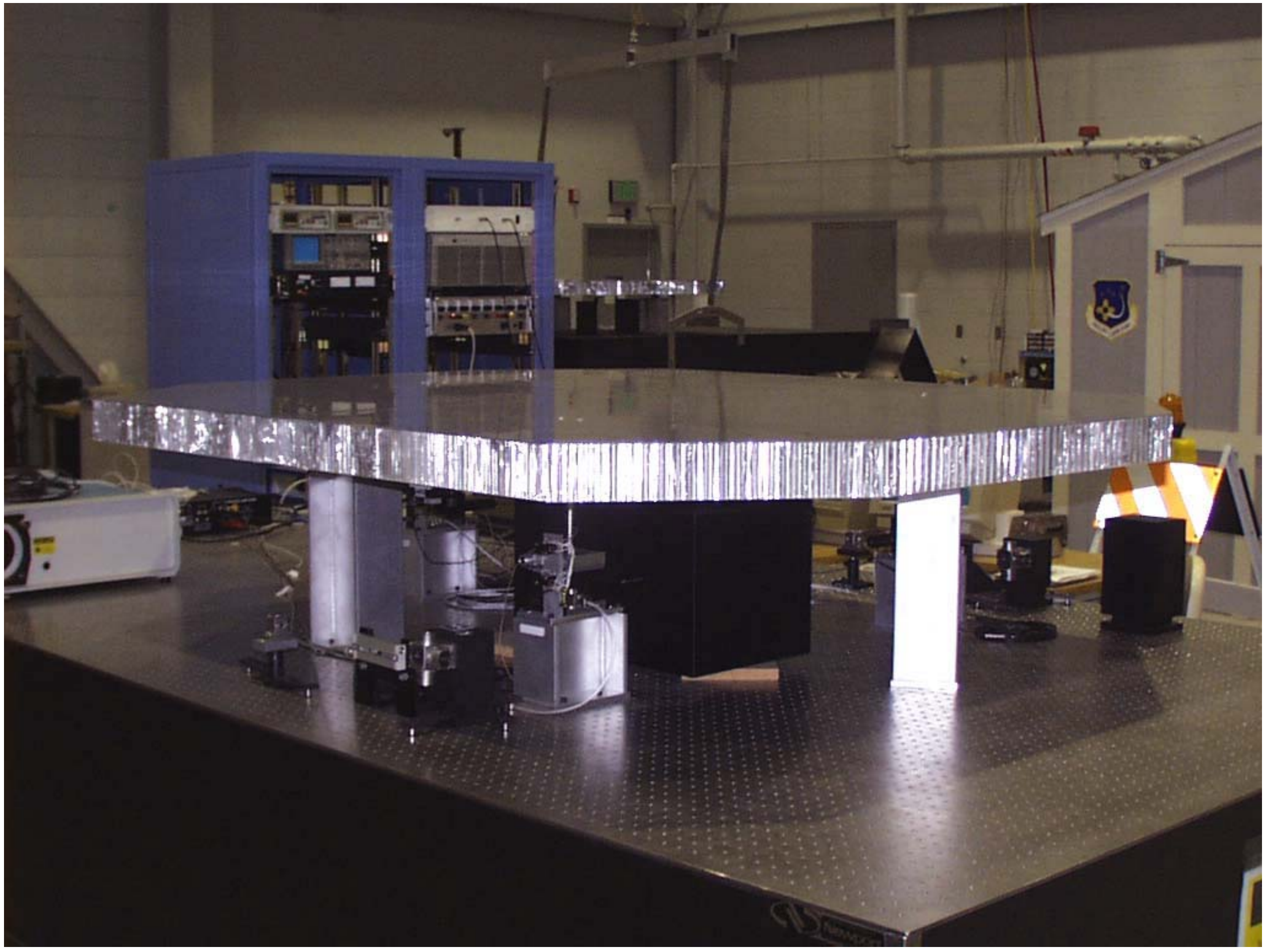
- Large aperature/resolution through deployable, sparse, optical array
- Deployable primary mirrors
- Golay 6 configuration
- Telescoping seconday tower

Deployable Optics Concepts Evaluation Experimental Test Beds

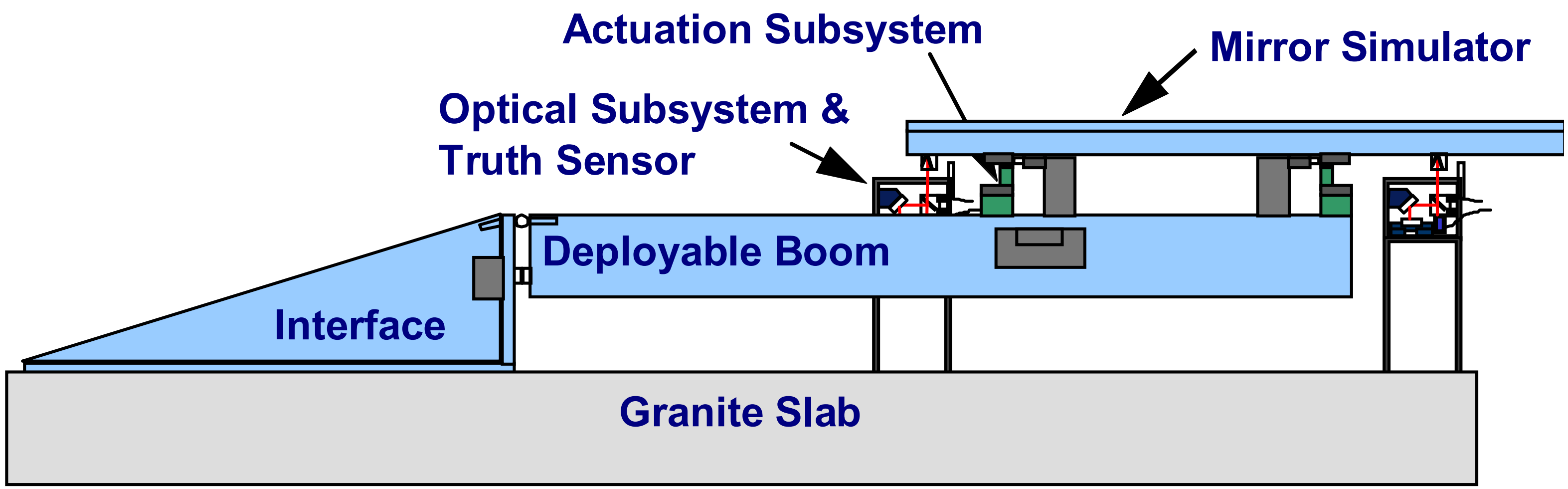
- Mirror Mass Simulator (MMS)
- Precision Deployable Optics Structure (PDOS)
- Deployable Optical Telescope Brassboard Ground Demonstration (BGD)

Preliminary DOT Evaluation - Mirror Mass Simulator

- Mirror Mass Simulator mounted to optics bench
- 3 interferometer displacement sensors
- 3 piezo stack actuators
- Electromagnetic disturbance shaker



Precision Deployable Optical Structure



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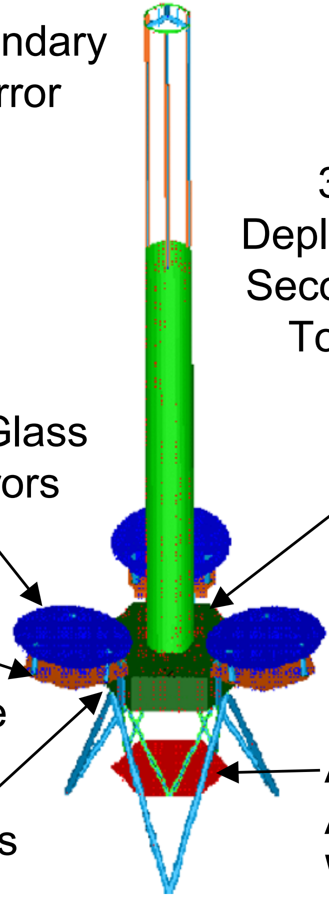
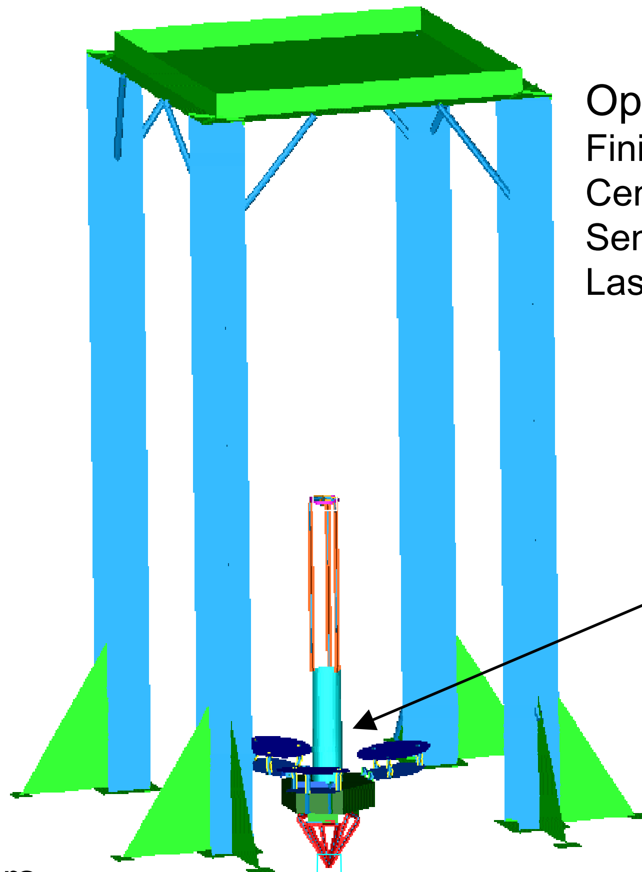
Deployable Optical Telescope

Brassboard Ground Demonstration





Integrated Technology in Simulated Space/Ops Environment

Supporting SBL, Global Virtual Presence, and Tactical Imaging Missions

Requirements

SDL's primary mission is to provide a Vibration Control System that will assist the Optical Control System in meeting the DOT mirror positioning requirements

- **Precision Deployable Optical Structure (PDOS):**

  Achieve 30 nanometers or less RMS value for relative displacement between the granite slab and the mirror mass simulator

- **Deployable Optical Telescope (DOT)**

  (1) Maintain the position of the primary mirror segments within:

Piston:	± 14 nanometers error per segment
Tilt:	± 95 nanoradians error per segment

  (2) Maintain the position of the secondary mirror within:

Decenter	±50 microns
Piston:	± 4 microns
Tilt:	± 20 microradians

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Deployable Optics - Jitter Requirements

- Disturbances
  - torque wheel actuators
  - slewing
  - space based laser
- Vibration Control
  - isolation
  - passive vibration control
  - high bandwidth position control
  - active vibration control

Active Structural Vibration Control Issues

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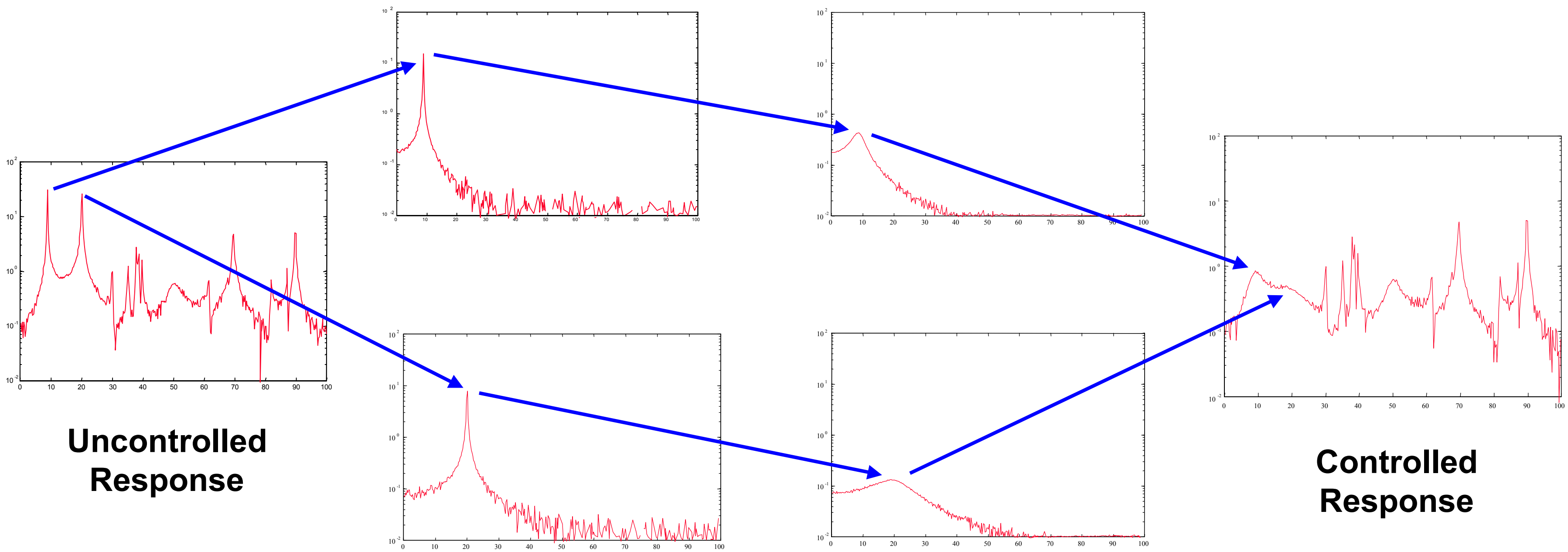
- Modeling - accurate and complete dynamic models of complex “real-world” systems are difficult to obtain.
- Time Variance - Often, by the time you’ve got the model the system has changed - It’s a moving target.
  - System dynamics - temperature, load, wear, damage
  - Discrete failures - sensors, actuators, signal conditioning
- Computational burden

Spatio-Temporal Filter Based Control



Uncontrolled Response

Uncontrolled Modal Responses Extracted with STF

Controlled Modal Responses

Controlled Response

SDL Modal Coordinate Transformation Uncouples System into SDOF Modes

$$M\ddot{x} + C\dot{x} + Kx = f$$

↓ **Modal Coordinate Transformation**

$$\begin{bmatrix} \ddots & & \\ & m & \\ & & \ddots \end{bmatrix}\ddot{\eta} + \begin{bmatrix} \ddots & & \\ & c & \\ & & \ddots \end{bmatrix}\dot{\eta} + \begin{bmatrix} \ddots & & \\ & k & \\ & & \ddots \end{bmatrix}\eta = \Phi^T f$$

$$x(t) = \sum_{r=1}^{N} \phi_r \eta_r(t) = \Phi\eta(t)$$

STF Origin - Modal or Spatial Filtering

Spatial filter vector ψ

$$\psi_i^T \phi_r = 0 \quad i \neq r$$
$$= 1 \quad i = r$$

Extract single mode response from measured response

$$\psi_i^T x(t) = \psi_i^T \sum_{r=1}^{N} \left[\phi_r \eta_r(t) \right]$$
$$= \psi_i^T \phi_i \eta_i(t)$$
$$= \eta_i(t)$$

Spatio-Temporal Filtering

Spatial filter estimate of η at time *k*

$$\hat{\eta}_k = \psi^T x_k$$

Spatio-Temporal filter estimate of η at time *k*

$$\hat{\eta}_k = \psi^T \begin{Bmatrix} x_k \\ x_{k-1} \\ \vdots \\ x_{k-Nt} \end{Bmatrix}$$

SDL Spatio-Temporal vs. Modal Filtering

- FIR or “all-zero” filter on each channel
- Pole-zero cancellation & preferential pass filter
  - fewer sensors required
- Inherent estimation of modal velocity
- Compensation for filter delays, sensor & signal conditioning dynamics
- Non-homogeneous sensor suites - piezo patches, accelerometers, etc.

SDL Adaptive Calculation of STF Coefficients using Reference Model Approach

- Know only poles of controlled modes
- Don't know
  - mode shapes
  - modal scaling factors (modal mass)
  - modal participation vectors
  - anything about uncontrolled modes (not even poles)

Adaptive Calculation of STF Coefficients using Reference Model Approach

SDOF (Single Mode) Reference Model

$$\eta_{k+1}^{(r)} = z_\lambda \eta_k^{(r)} + l^T f_k$$

$$\eta_{k+1}^{(r1)} = z_\lambda \eta_k^{(r1)} + f_k^{(1)}$$

$$\vdots$$

$$\eta_{k+1}^{(rN_i)} = z_\lambda \eta_k^{(rN_i)} + f_k^{(N_i)}$$

+

$$\eta_k^{(r)} = l^T \begin{Bmatrix} \eta_k^{(r1)} \\ \vdots \\ \eta_k^{(rN_i)} \end{Bmatrix}$$

$$= l^T \eta_k^r$$

Adaptive Calculation of STF Coefficients using Reference Model Approach

$$e_k = \eta_k^{(r)} - \hat{\eta}_k$$

$$= l^T \eta_k^r - \psi^T \begin{Bmatrix} x_k \\ x_{k-1} \\ \vdots \\ x_{k-Nto} \end{Bmatrix} = \begin{Bmatrix} \psi \\ l \end{Bmatrix}^T \begin{Bmatrix} -x_k \\ \vdots \\ -x_{k-Nto} \\ \eta_k^r \end{Bmatrix}$$

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STF Based Modal Velocity Feedback Control

Control Command Vector for i'th mode

Modal Coordinate Velocity Estimate

$$f_c^{(i)} = \hat{\dot{\eta}}^{(i)} \alpha^{(i)} v^{(i)}$$

Force Vector

Scalar Feedback Gain

$$f_c^{(i)} = \hat{\dot{\eta}}^{(i)} \alpha^{(i)} l^{(i)}$$

Estimated Modal Participation Vector is Ideal Force Vector

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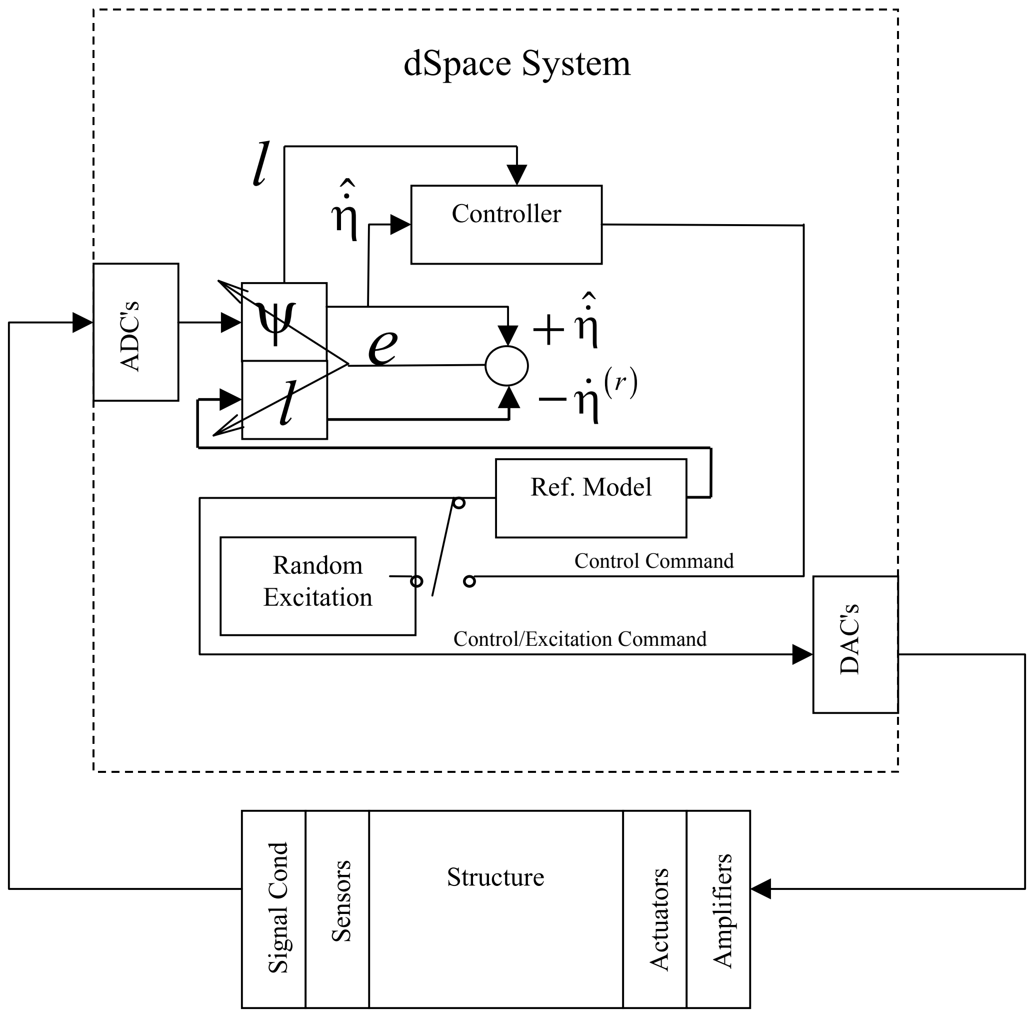
Initial Mirror Mass Simulator Control Experiments

- STF based velocity feedback
- 3 inputs, 3 outputs, 5 controlled modes
- Random disturbance excitation
- 1 1/2 days to implement
  - familiarization with test bed
  - all system ID
  - control implementation and testing

Implementation of STF Based Control



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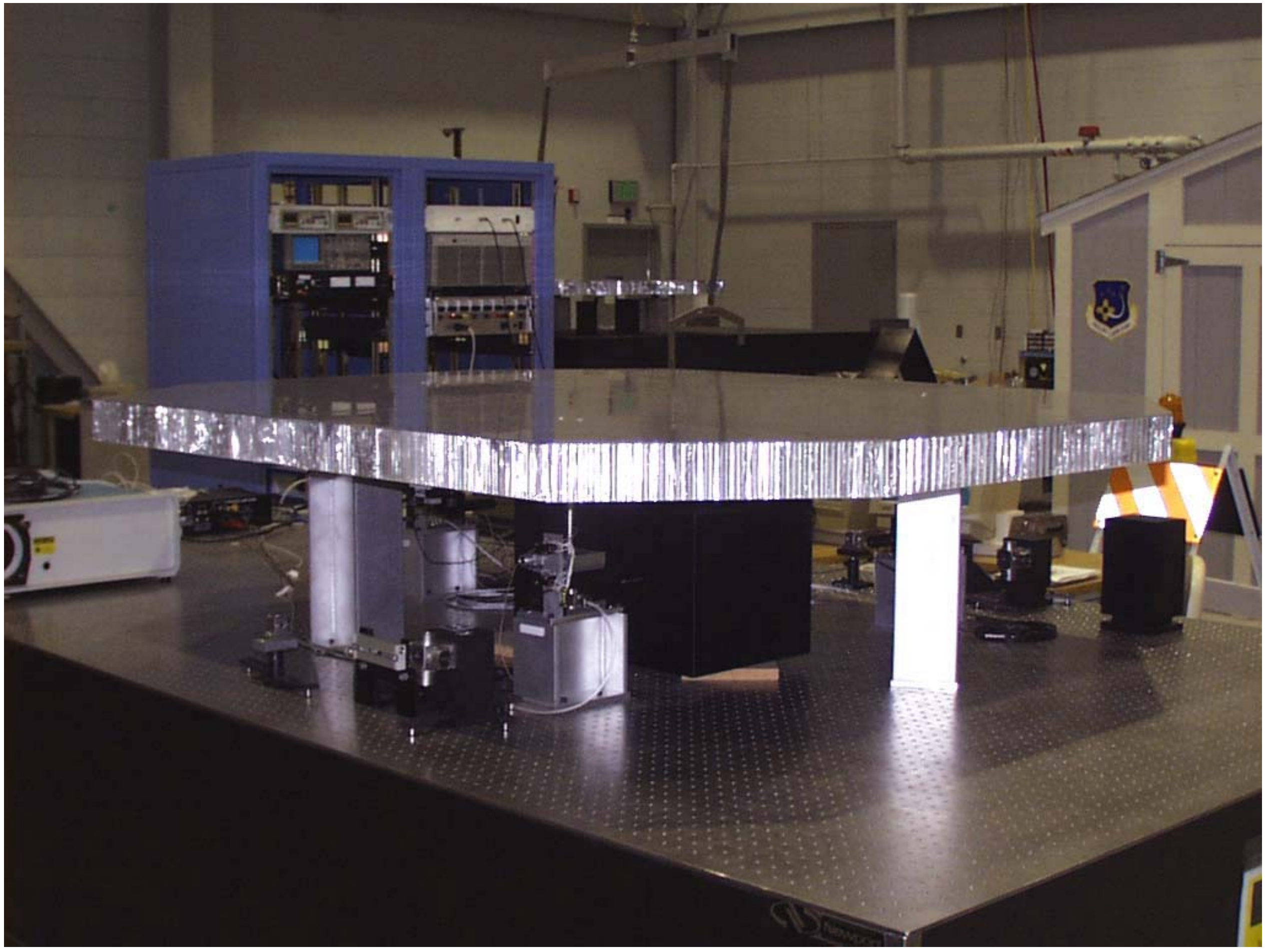
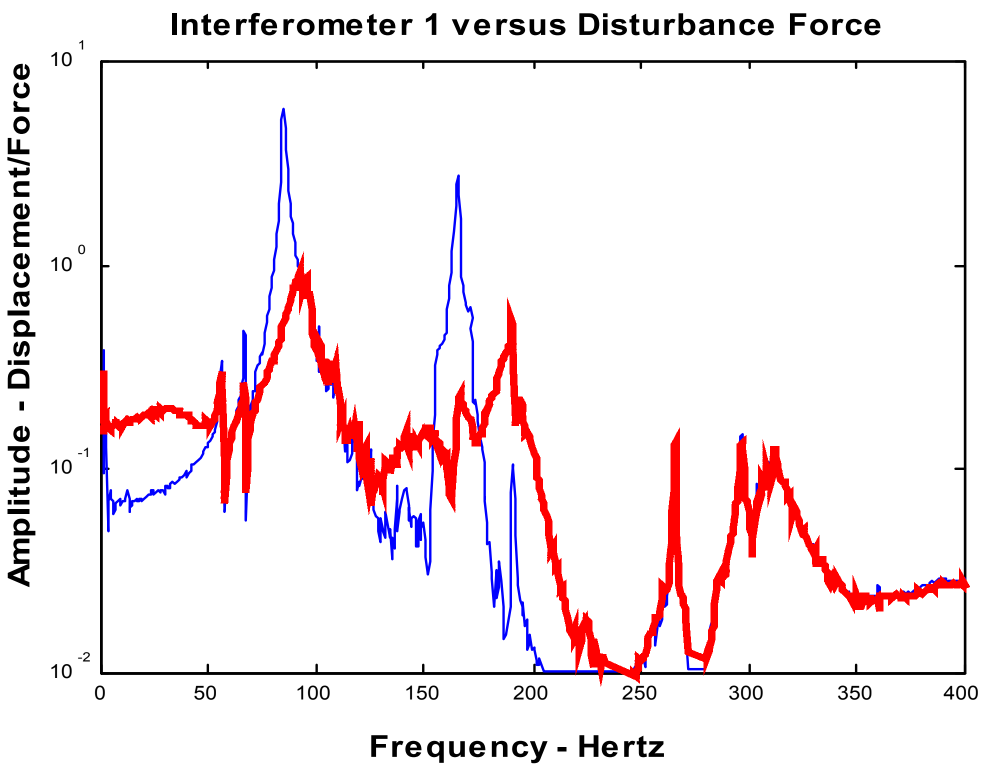


Initial Mirror Mass Simulator Control Experiments



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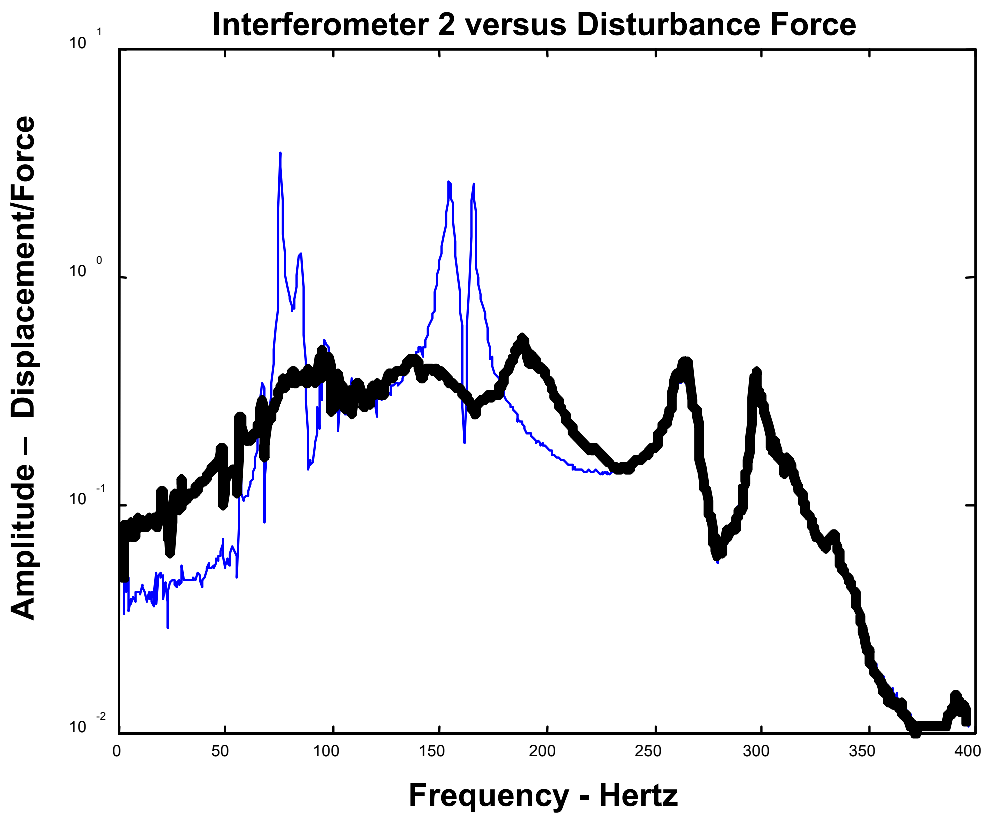
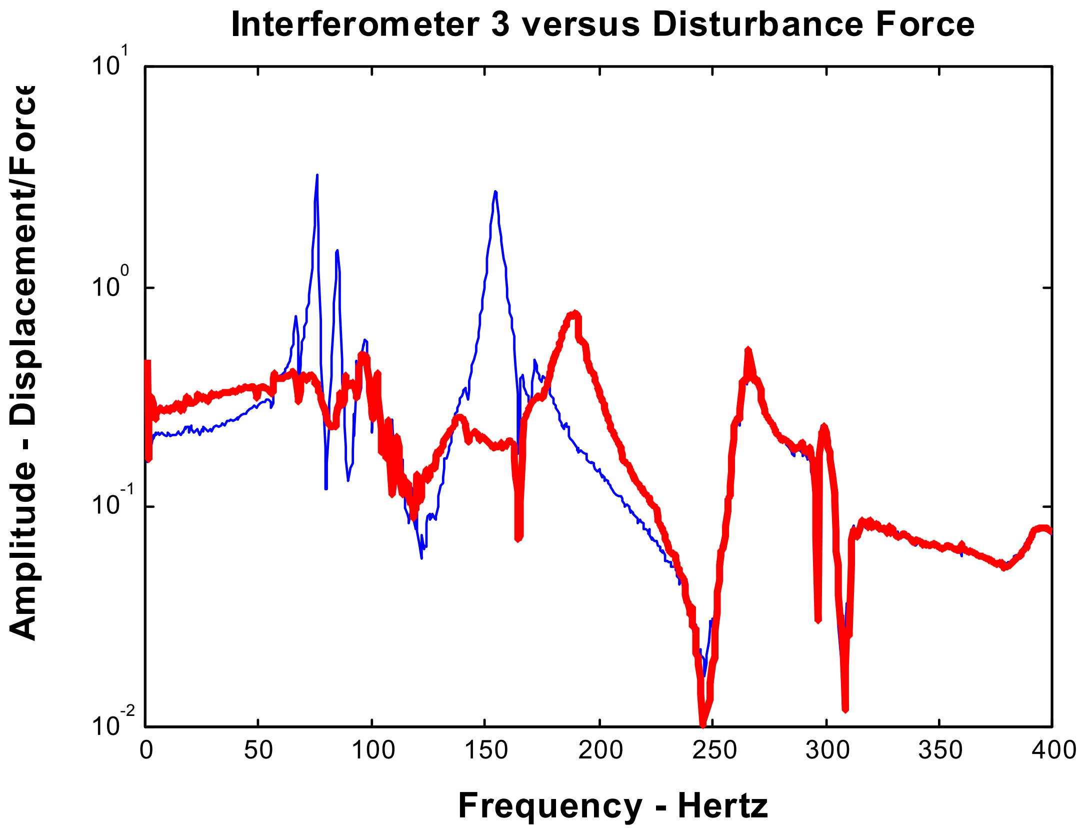


Initial Mirror Mass Simulator Control Experiments



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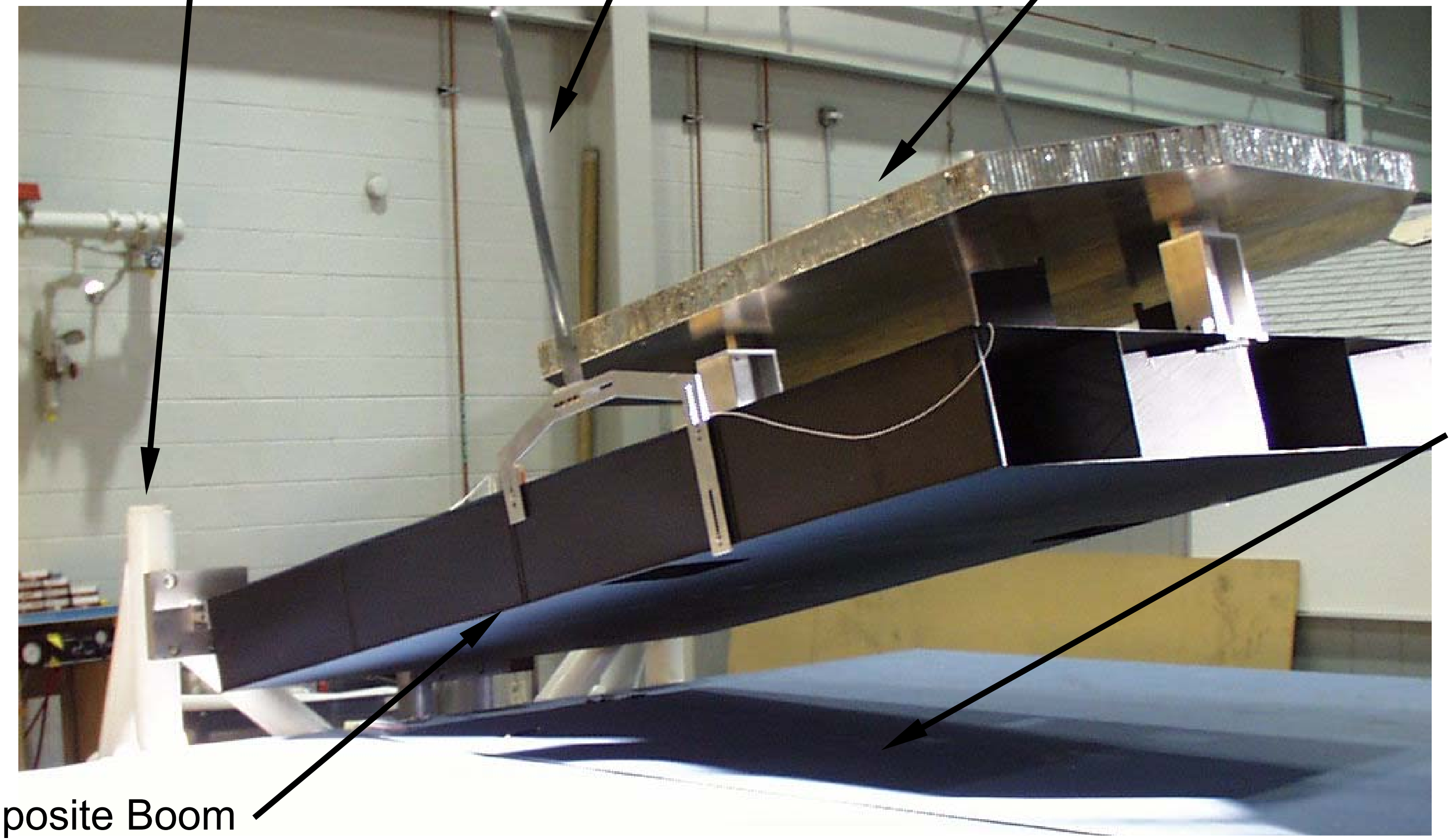
Precision Deployable Optical Structure



Proved Deployment, Acquisition, Maintenance and Control System for a 2m Optical Segment

Precision Deployable Optical Structure

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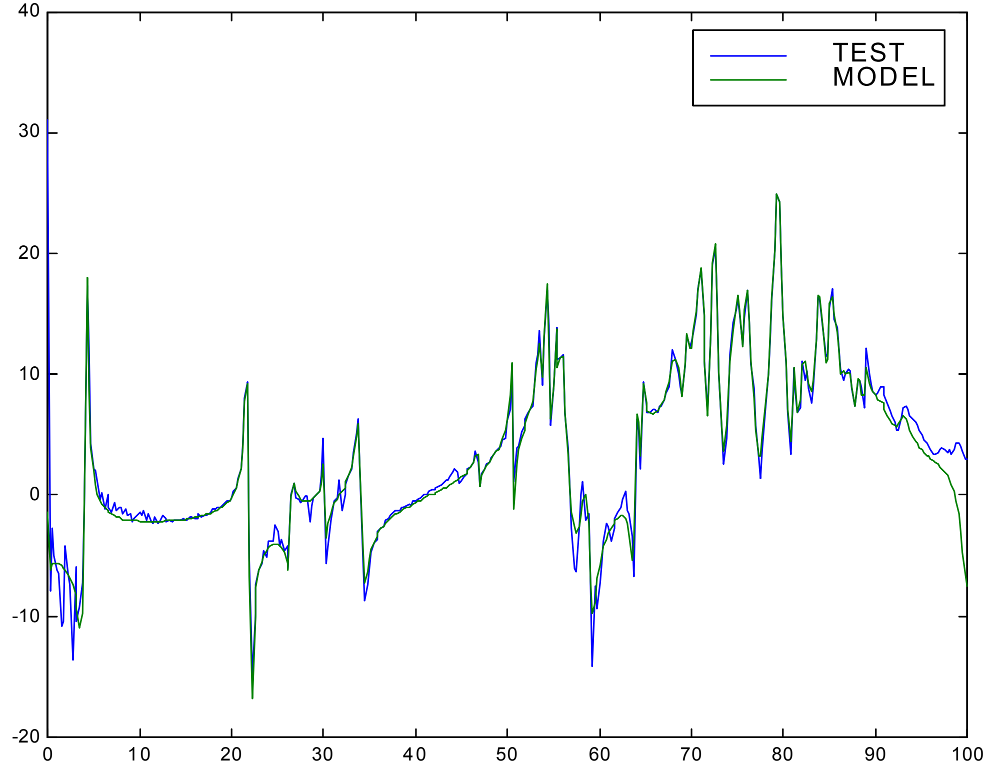
Precision Deployable Optical Structure

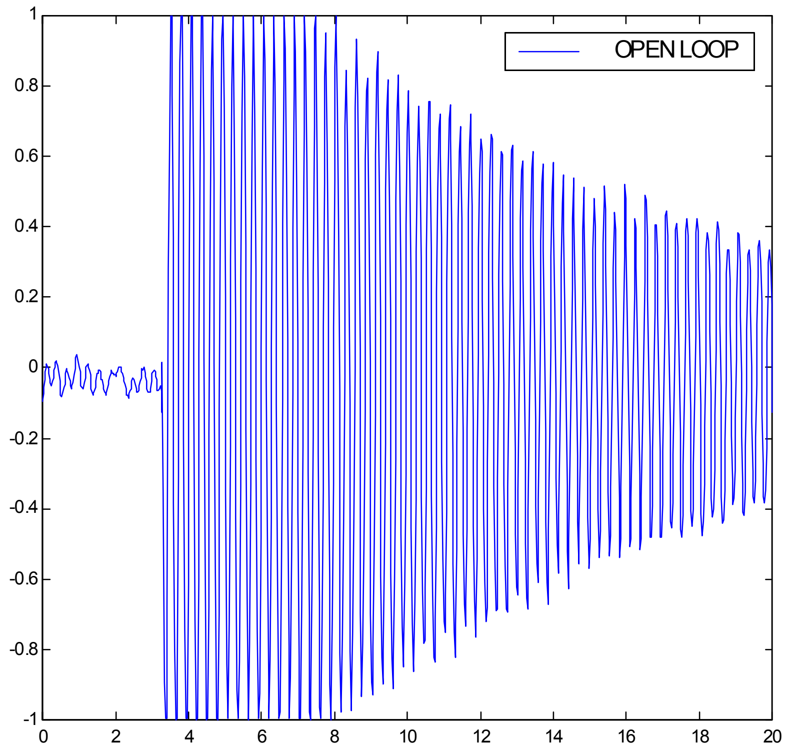
PDOS Frequency Response Function

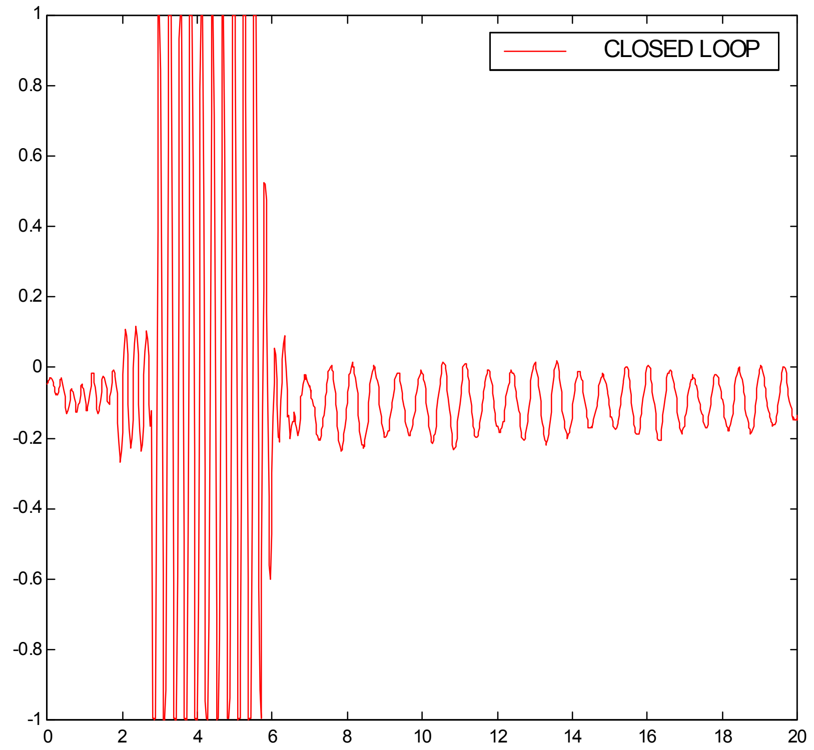
Interferometer 1 / PZT 2 FRF

- 5 Hertz boom mode only mode in low frequency range
- 1.6 Hertz slab mode not apparent - must treat as a disturbance

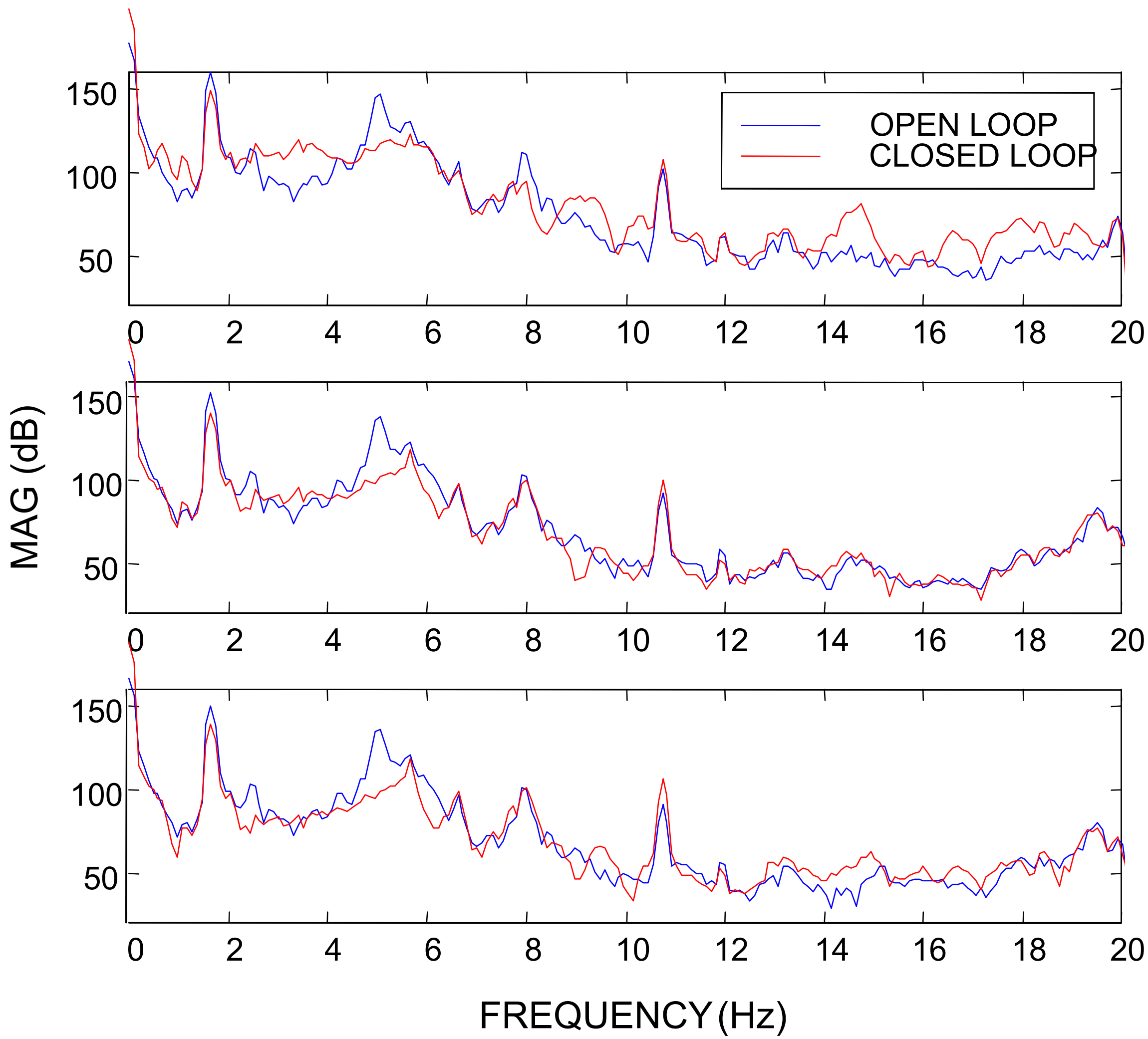


STF Control
PDOS 5 Hz Boom Mode



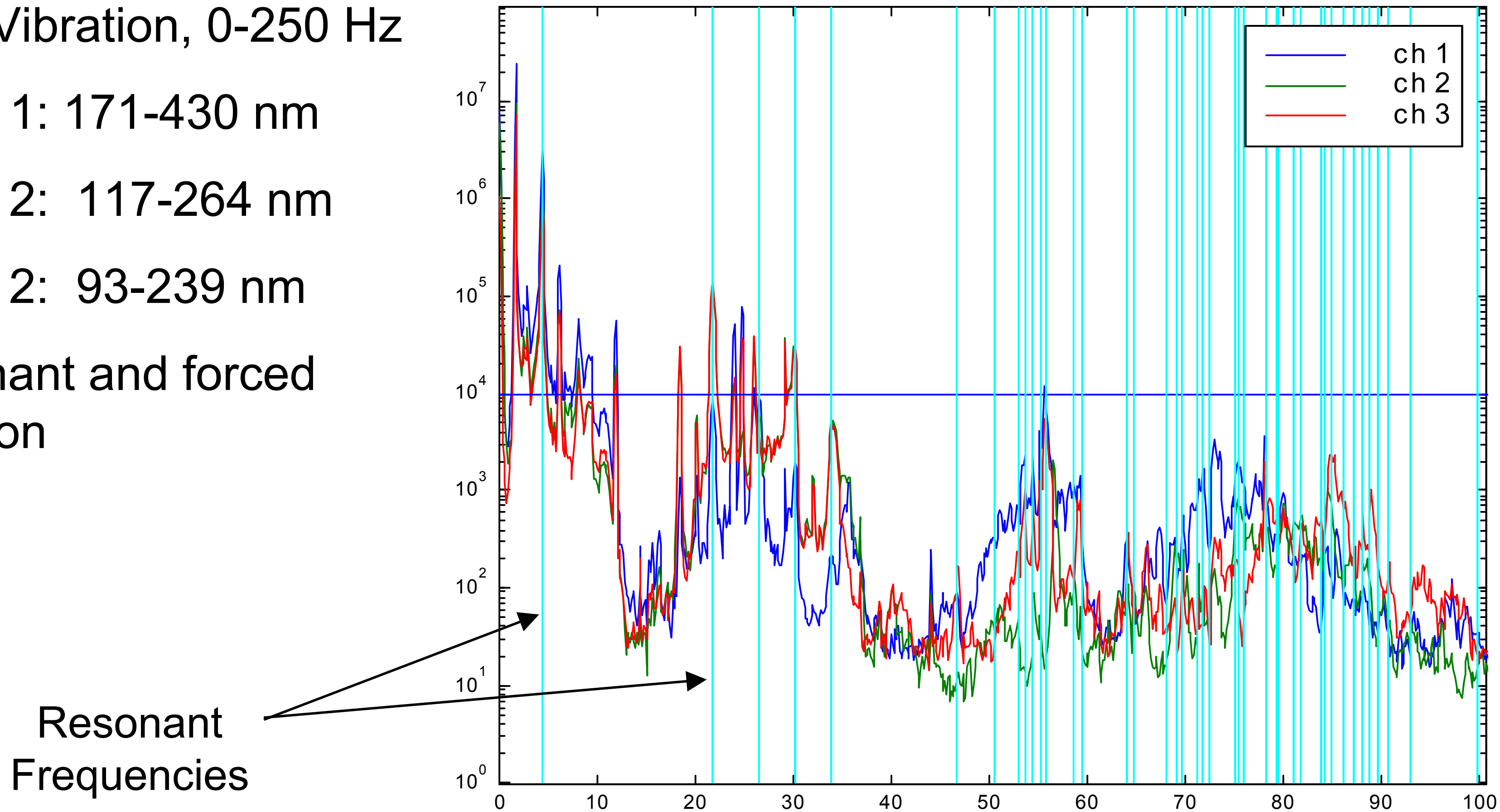


Open and Closed Loop Interferometer PSD's

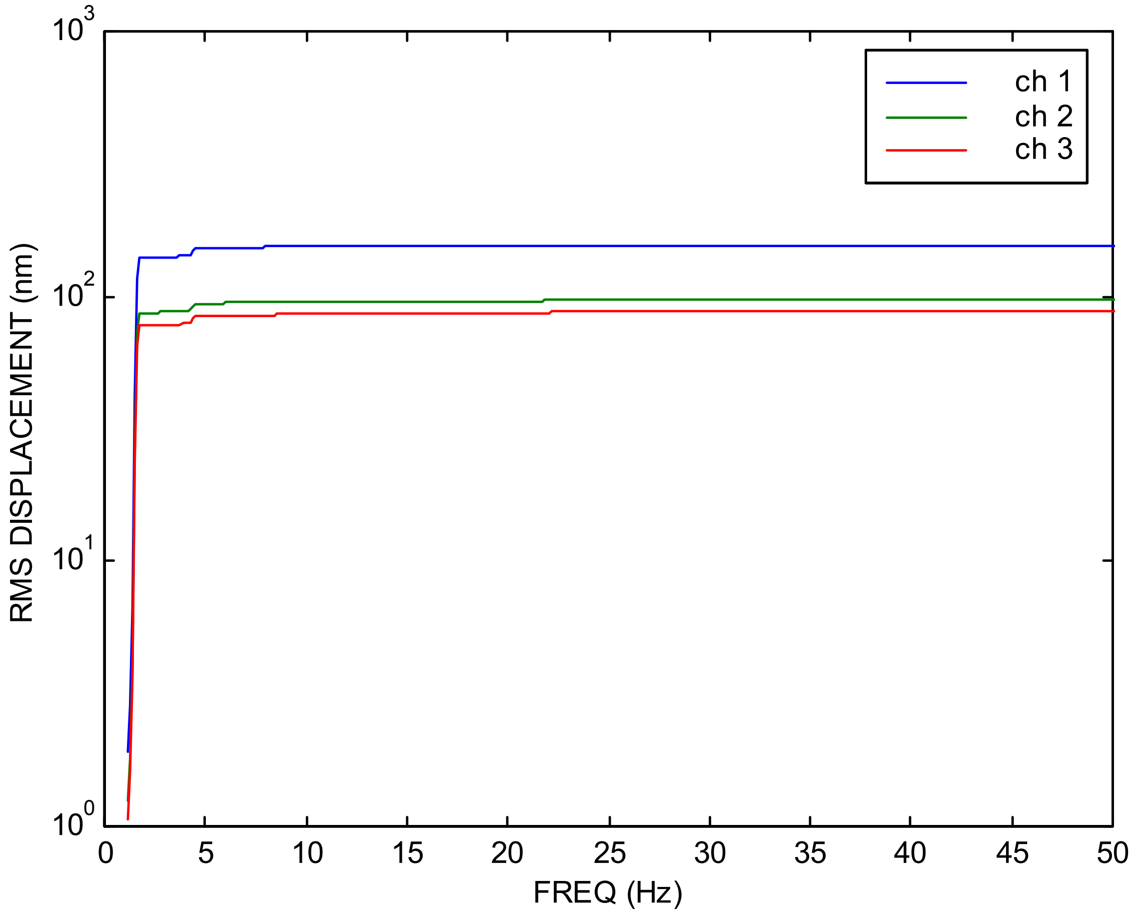


PDOS Ambient Vibration

- RMS Vibration, 0-250 Hz
  - Int 1: 171-430 nm
  - Int 2: 117-264 nm
  - Int 2: 93-239 nm
- Resonant and forced vibration

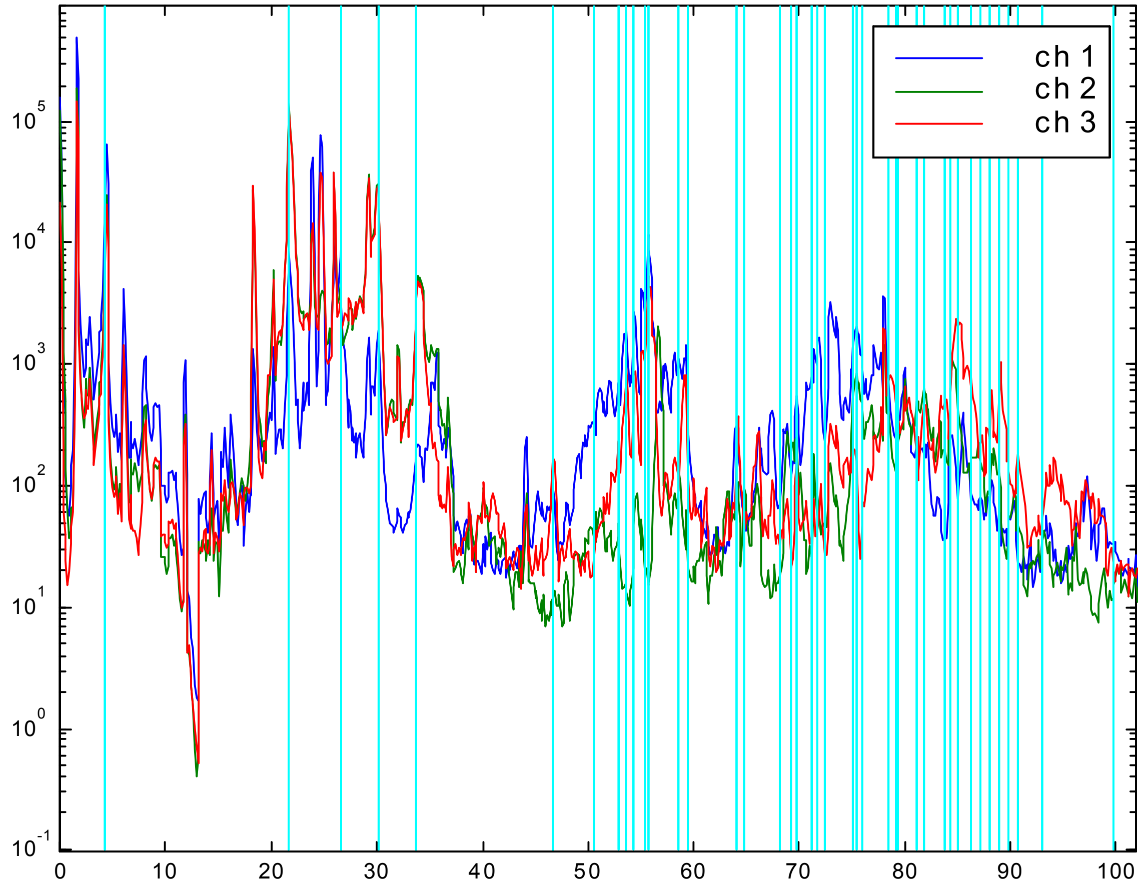


Interferometer RMS Value Versus Frequency Band



PDOS Low Frequency Control

- RMS Vibration, 0-250 Hz
- Assuming 50x reduction 0-13 Hz.
  - Int 1: 29.99 nm
  - Int 2: 28.51 nm
  - Int 3: 27.42 nm



- Note the control objective is 30 nm RMS vibration levels

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Conclusions

- Resonant control alone is not sufficient to meet PDOS/DOT optical jitter control requirements
- "High" bandwidth position control in conjunction with resonant mode control required
- STF based modal control is practical approach for resonant mode control;
  - Implement effective MIMO control on complex, "real-world" structures with little knowledge of dynamics
  - Adapts to sensor/actuator failure
  - Accommodates filter/signal conditioning dynamics
  - Easily updated to accommodate changing system dynamics (only update poles of controlled modes)