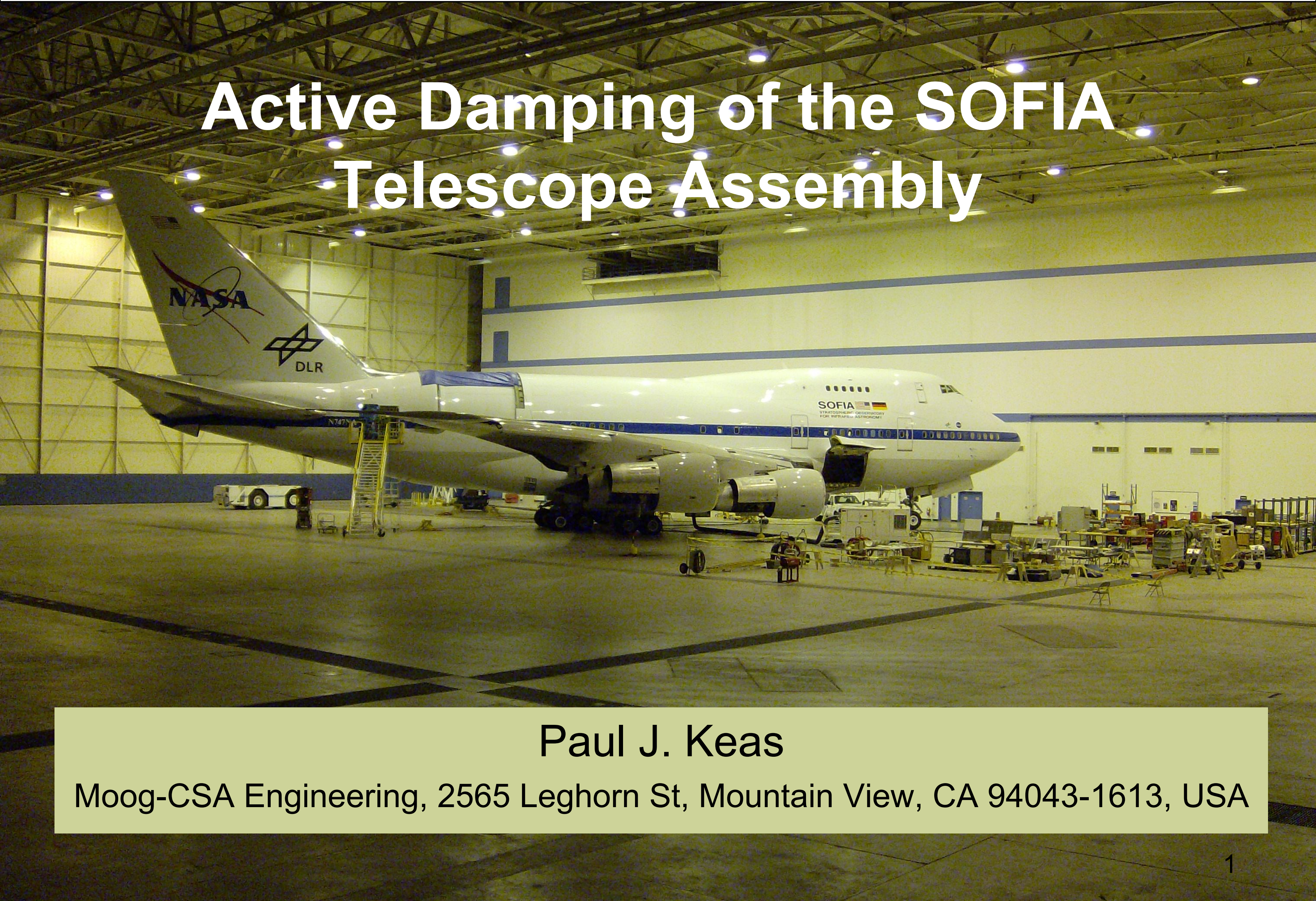
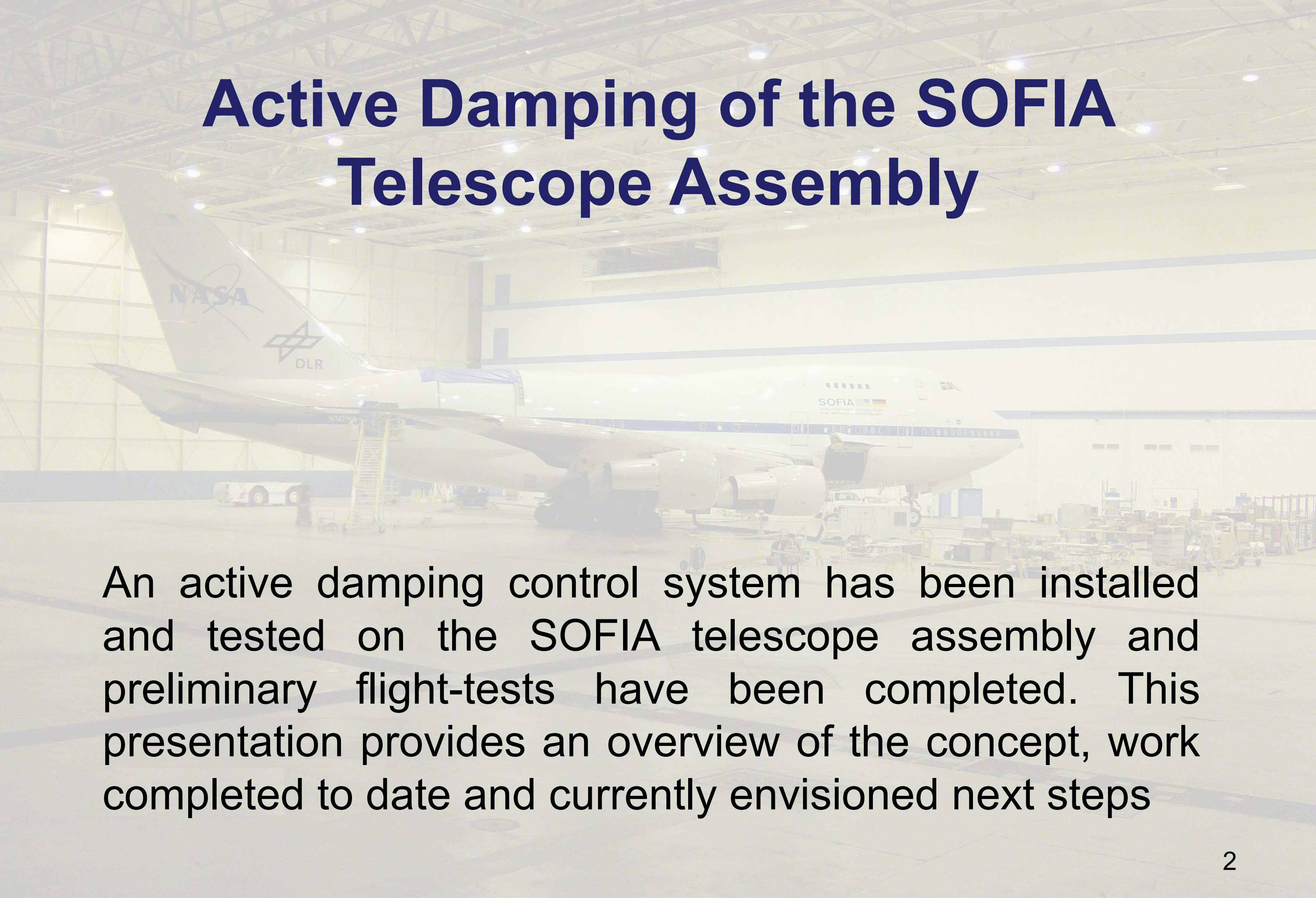


Active Damping of the SOFIA Telescope Assembly

Paul J. Keas

Moog-CSA Engineering, 2565 Leghorn St, Mountain View, CA 94043-1613, USA

Active Damping of the SOFIA Telescope Assembly



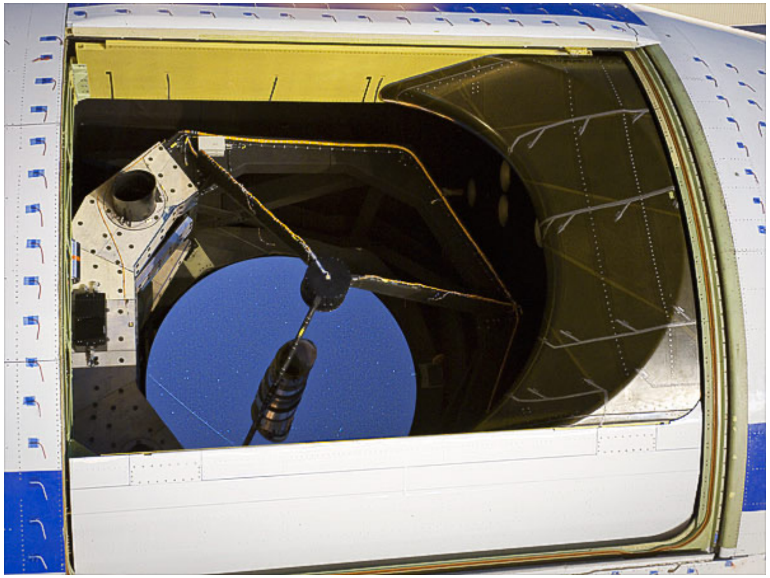
An active damping control system has been installed and tested on the SOFIA telescope assembly and preliminary flight-tests have been completed. This presentation provides an overview of the concept, work completed to date and currently envisioned next steps

Presentation Outline

- Introduction to SOFIA and the Image Stability Challenge
- Introduction to Structural Damping Techniques
- Reaction Mass Actuators
- The SOFIA RMA System
- SOFIA Flight Test Results
- Next Steps for SOFIA…

Introduction to SOFIA and the Image Stability Challenge

- SOFIA employs a 2.5-meter reflector telescope in a Boeing 747SP



- The telescope is housed in an open cavity and is subjected to aeroacoustic and inertial disturbances
- The image stability goal for SOFIA is 0.2 arc-seconds (RMS)

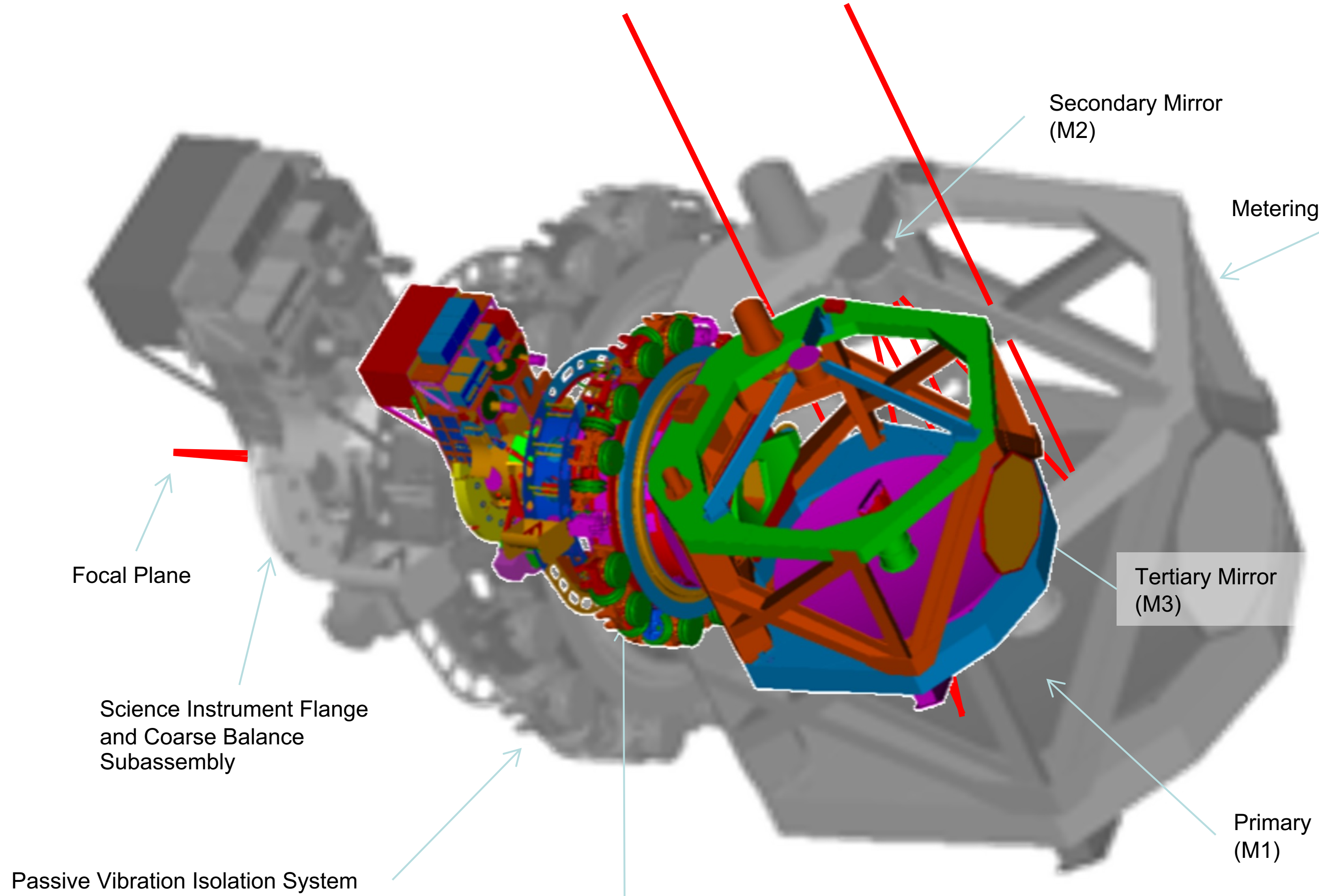
Introduction to SOFIA and the Image Stability Challenge

The NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)

Introduction to SOFIA and the Image Stability Challenge

The NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)

Introduction to SOFIA and the Image Stability Challenge



Secondary Mirror
(M2)

Metering Structure

Focal Plane

Tertiary Mirror
(M3)

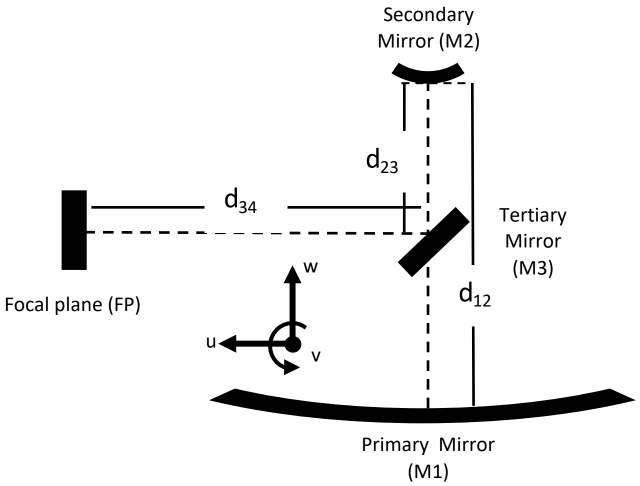
Science Instrument Flange
and Coarse Balance
Subassembly

Primary Mirror
(M1)

Passive Vibration Isolation System

Hydrostatic bearing (Rotation Isolation)
And fine-drive torque motors

Introduction to SOFIA and the Image Stability Challenge



Ray Trace Variables:

f = system focal length
f_1 = M1 focal length
f_2 = M2 focal length

d_{12} = w distance between M1 and M2
d_{23} = w distance between M2 and M3
d_{34} = u distance between M3 and FP

$$\begin{bmatrix} T_V \\ T_W \end{bmatrix} = \left[\underbrace{\begin{matrix} 0 & \frac{f}{f_1} & 0 & \boxed{-2f} & 0 & 0 \\ -\frac{f}{f_1} & 0 & 0 & 0 & \boxed{-2f} & 0 \end{matrix}}_{\text{M1}} \; \underbrace{\begin{matrix} 0 & 1-\frac{f}{f_1} & 0 & \boxed{2\left(d_{23}+d_{34}\right)} & 0 & 0 \\ \frac{f}{f_1}-1 & 0 & 0 & 0 & \boxed{2\left(d_{23}+d_{34}\right)} & 0 \end{matrix}}_{\text{M2}} \; \underbrace{\begin{matrix} 0 & 0 & 0 & \boxed{-d_{34}} & 0 & \boxed{d_{34}} \\ 1 & 0 & 1 & 0 & \boxed{-2d_{34}} & 0 \end{matrix}}_{\text{M3}} \; \underbrace{\begin{matrix} 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \end{matrix}}_{\text{FP}} \right] \begin{bmatrix} \left.\begin{matrix} U_{M1} \\ V_{M1} \\ W_{M1} \\ \alpha_{M1} \\ \beta_{M1} \\ \gamma_{M1} \end{matrix}\right\} \text{M1} \\ \left.\begin{matrix} U_{M2} \\ V_{M2} \\ W_{M2} \\ \alpha_{M2} \\ \beta_{M2} \\ \gamma_{M2} \end{matrix}\right\} \text{M2} \\ \left.\begin{matrix} U_{M3} \\ V_{M3} \\ W_{M3} \\ \alpha_{M3} \\ \beta_{M3} \\ \gamma_{M3} \end{matrix}\right\} \text{M3} \\ \left.\begin{matrix} U_{FP} \\ V_{FP} \\ W_{FP} \\ \alpha_{FP} \\ \beta_{FP} \\ \gamma_{FP} \end{matrix}\right\} \text{FP} \end{bmatrix}$$

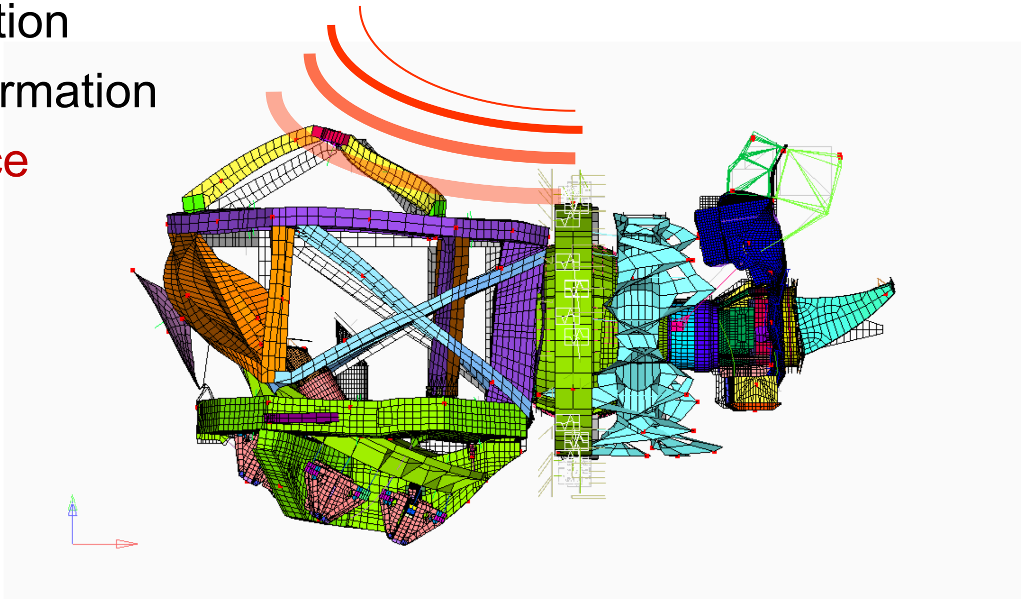
Image Translation

Optical DOF Sensitivity (Ray Trace Equation) Coefficients

Optical DOF

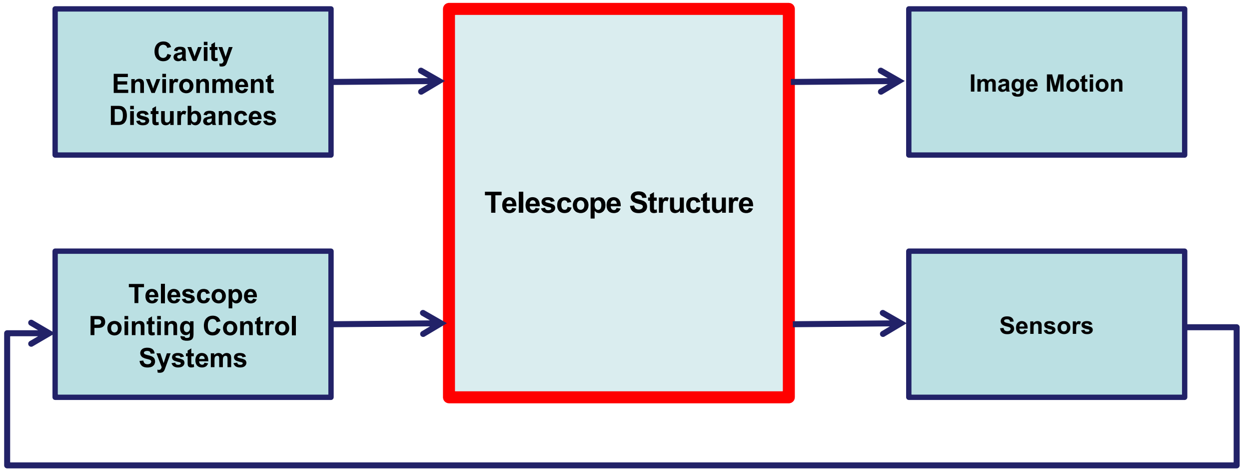
Introduction to SOFIA and the Image Stability Challenge

- Key aspects which determine pointing performance are:
  - Disturbance environment and relevant load-paths
  - Telescope modal behavior
- Image Motion and Image Quality can be adversely affected by:
  - Atmospheric effects
  - Rigid-body pointing error
  - Deformation of telescope assembly (optical DOFs in particular)
    - Quasi-static deformation
    - Forced dynamic deformation
    - Vibration at resonance



Integrated Pointing Model

- An Integrated pointing control model has been maintained/updated since 1995, and used to design control systems, predict image stability and evaluate structural modifications.
- The initial configuration of the PMA active damping system was based on analysis via the integrated model



Cavity Environment Disturbances

Telescope Pointing Control Systems

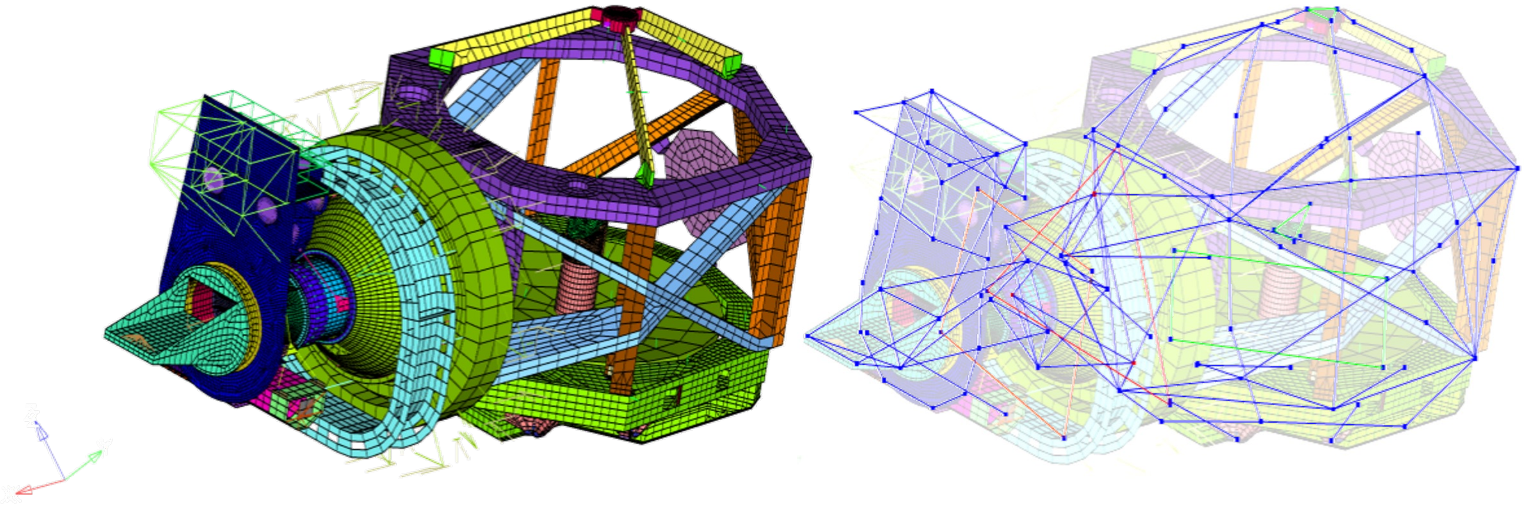
Telescope Structure

Image Motion

Sensors

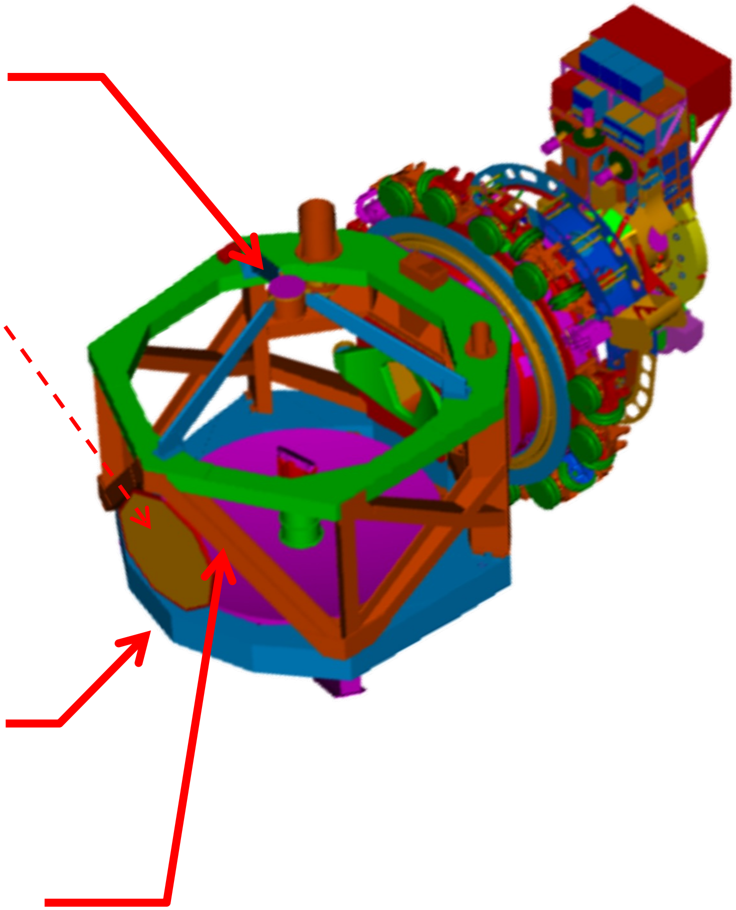
Ground and Flight Testing

- A 300 channel modal survey was conducted by Moog-CSA in 2008 to identify key modes of interest WRT image jitter, and quantify modal damping



- Open door flight tests subsequently quantified image jitter associated with resonance of known modes
- image jitter PSDs measured during flight testd were very close to those expected based on the integrated model, but with some unexpected contributors…

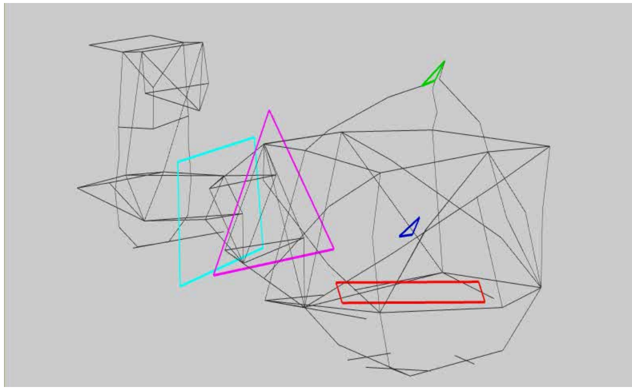
Introduction to SOFIA and the Image Stability Challenge



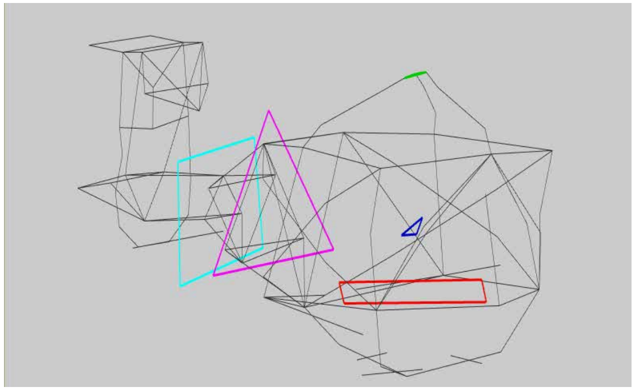
- Secondary Mirror Rocking Modes
  - More secondary mirror tip-tilt jitter than expected
  - Baffle plate structure apparently a major disturbance load path
- Primary Mirror Rocking Modes
  - This was anticipated based on prior analysis
  - Hard-points for RMA mounting exist on underside of whiffletree
- Metering Structure Pumping Modes
  - Relatively small contribution to image motion compared to primary mirror rocking, but still significant

Dominate Modes seen in Flight Test Image Jitter Data

89 Hz SMA Rocking Mode

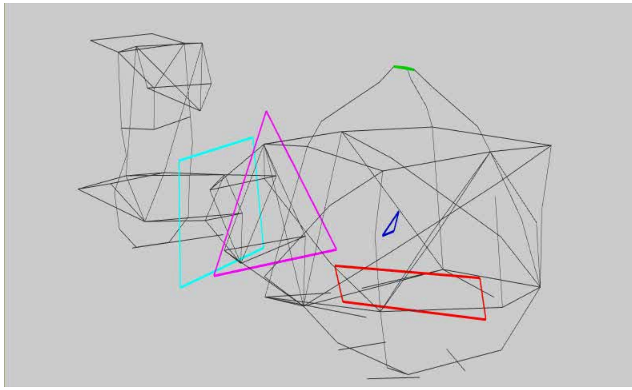


95 Hz SMA Rocking Mode

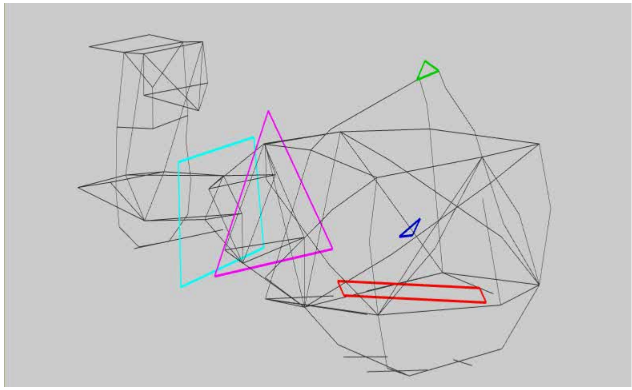


Dominate Modes seen in Flight Test Image Jitter Data

70 Hz Primary Mirror Rocking Mode

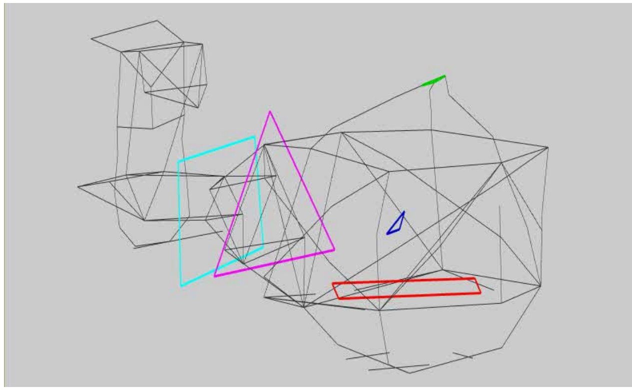


73 Hz Primary Mirror Rocking Mode

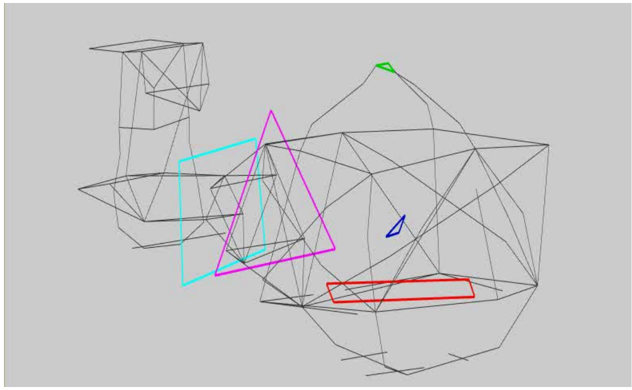


Dominate Modes seen in Flight Test Image Jitter Data

53 Hz Metering Structure Pumping mode



44 Hz Metering Structure Pumping mode

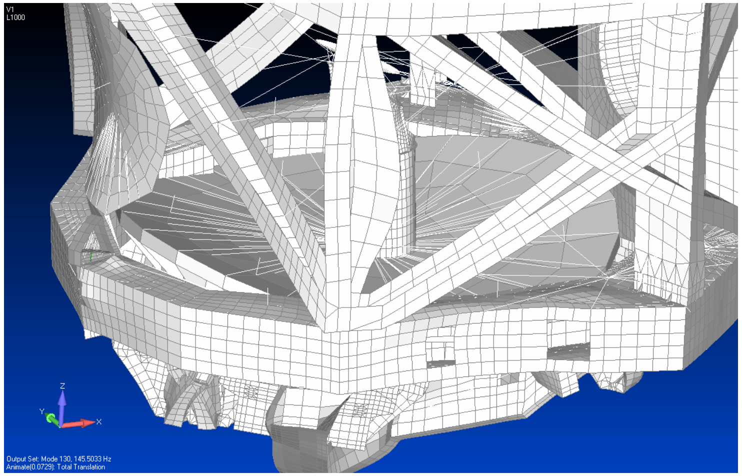


Introduction to SOFIA and the Image Stability Challenge

Flexible body modes of the primary mirror itself do not produce image centroid displacement, but they do show up in the *image size* spectra (FWHM)

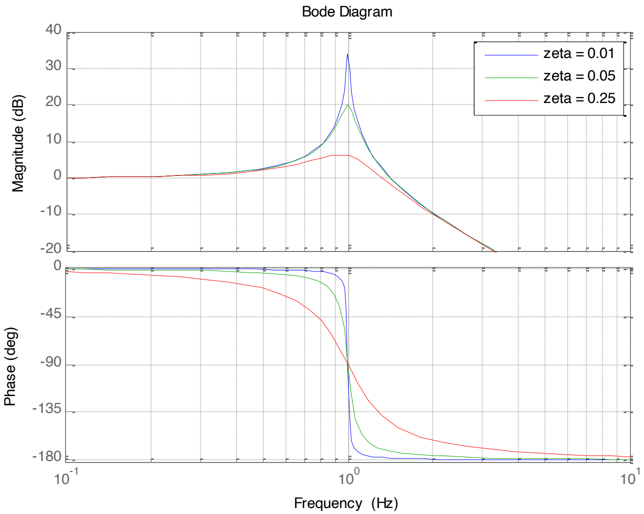
(first 2 bending modes occur at ~175 Hz)

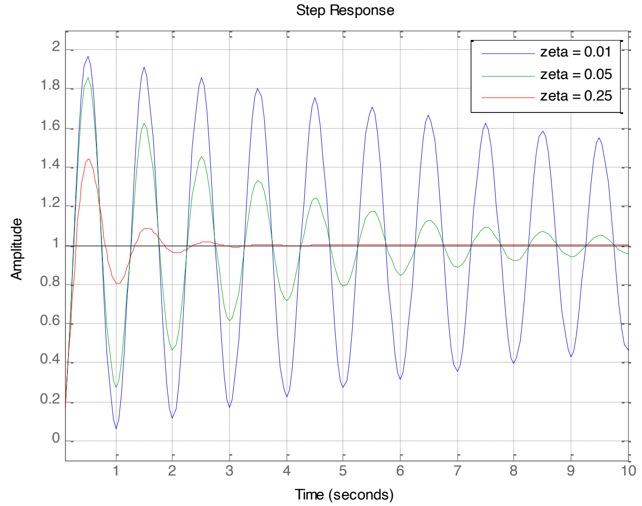
175 Hz Primary Mirror Flexible mode



Introduction to Structural Damping Techniques

- Lightly damped resonance in structures can be problematic
  - Lightly damped response to operating loads can cause excessive loads or fatigue
  - Interaction with motion control systems
  - Amplification of disturbance transmission WRT performance metrics
- Damping can be increased in a variety of ways
  - Constrained layer damping
  - Particle dampers
  - Tuned mass dampers (TMDs)
  - Reaction mass actuators (RMAs)



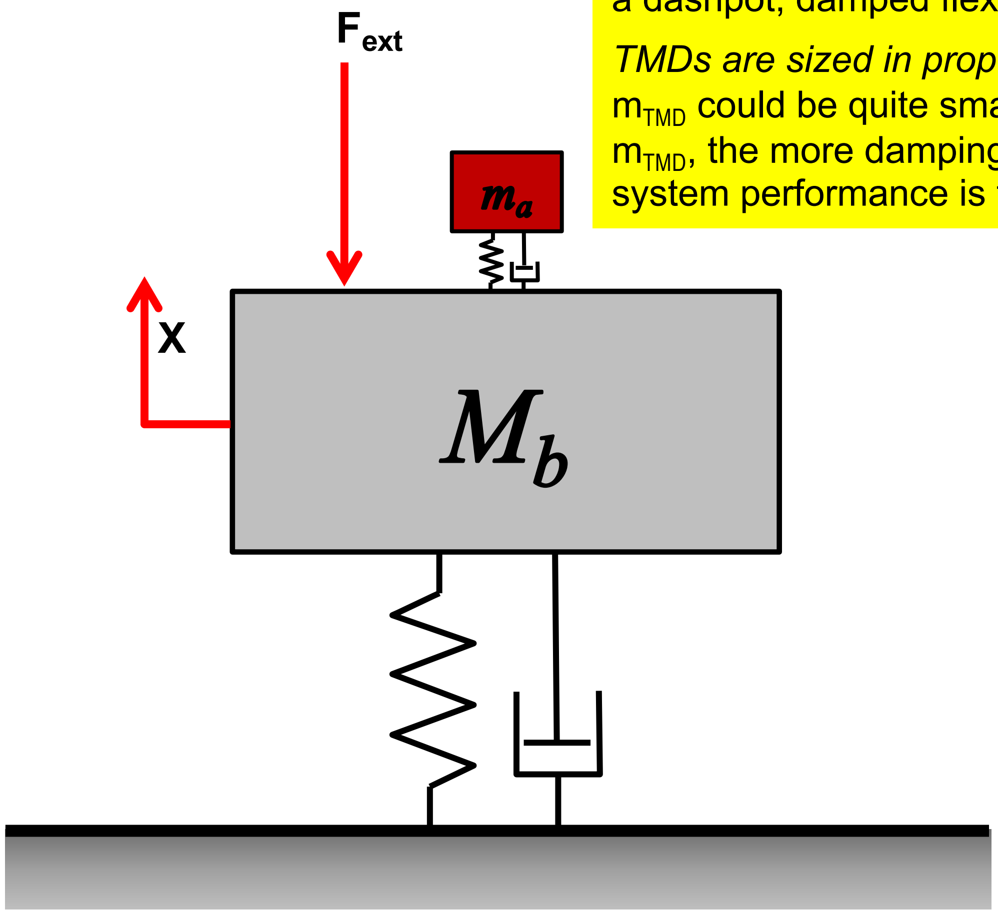


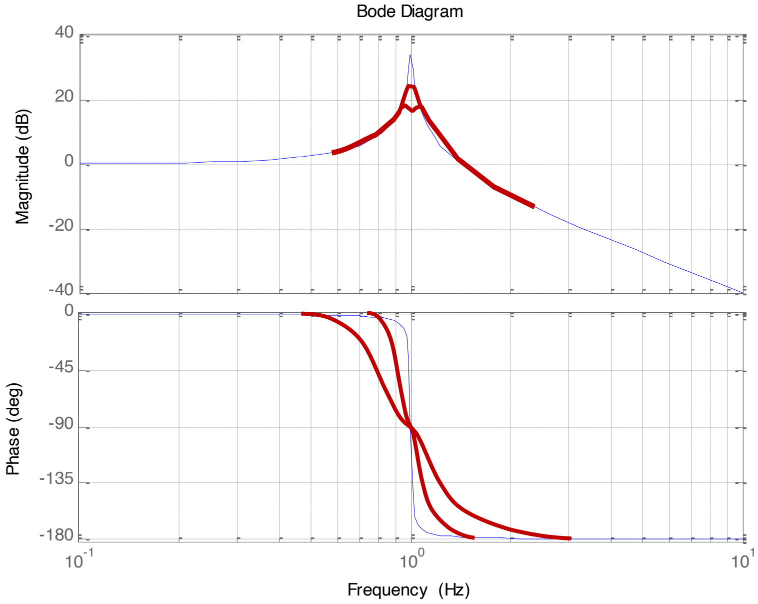
This presentation will focus on RMAs, which have been employed for SOFIA

Introduction to Structural Damping Techniques

Tuned mass dampers (TMDs) are tuned to couple strongly with the target mode and dissipate energy via a damping element (commonly a dashpot, damped flexure or, eddy-current damping element)

TMDs are sized in proportion to the modal mass of the target mode. m_{TMD} could be quite small (1% of M, for example), however the larger m_{TMD}, the more damping can be achieved, and the less sensitive system performance is to tuning error





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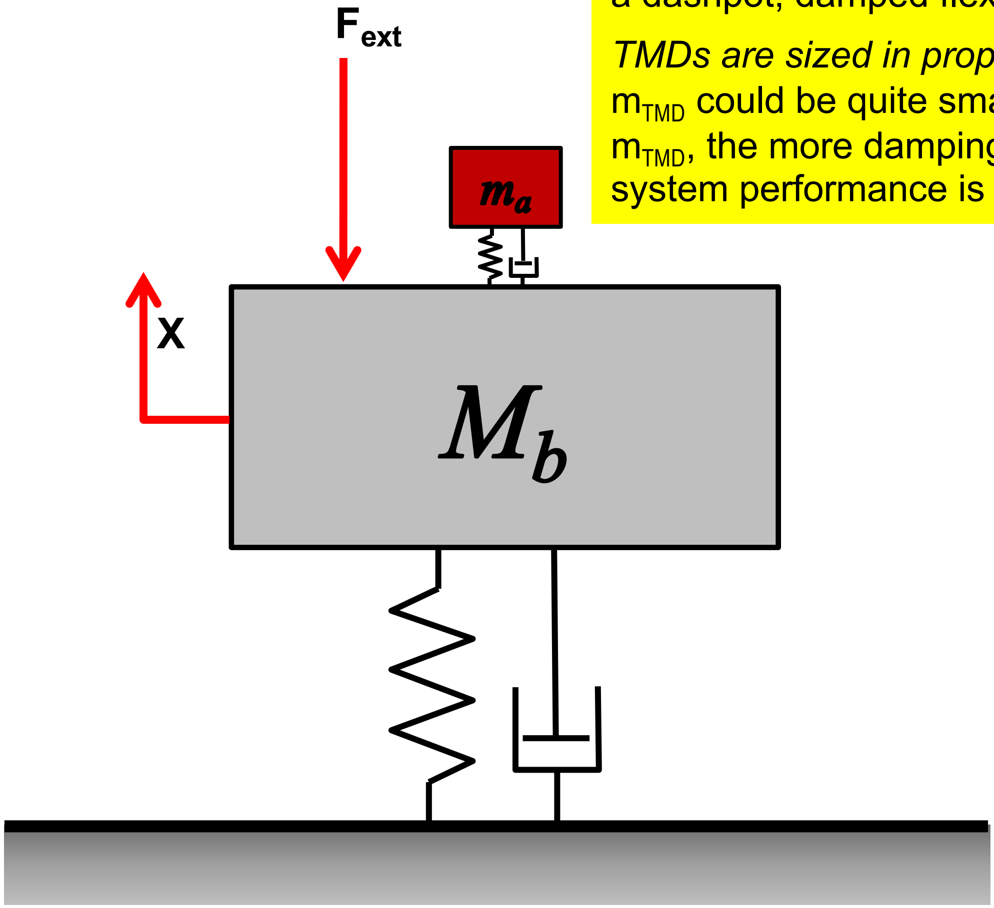
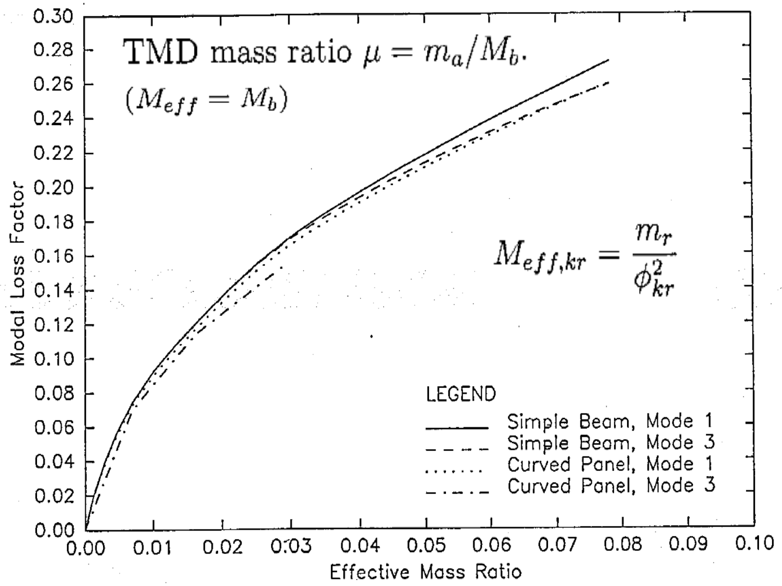
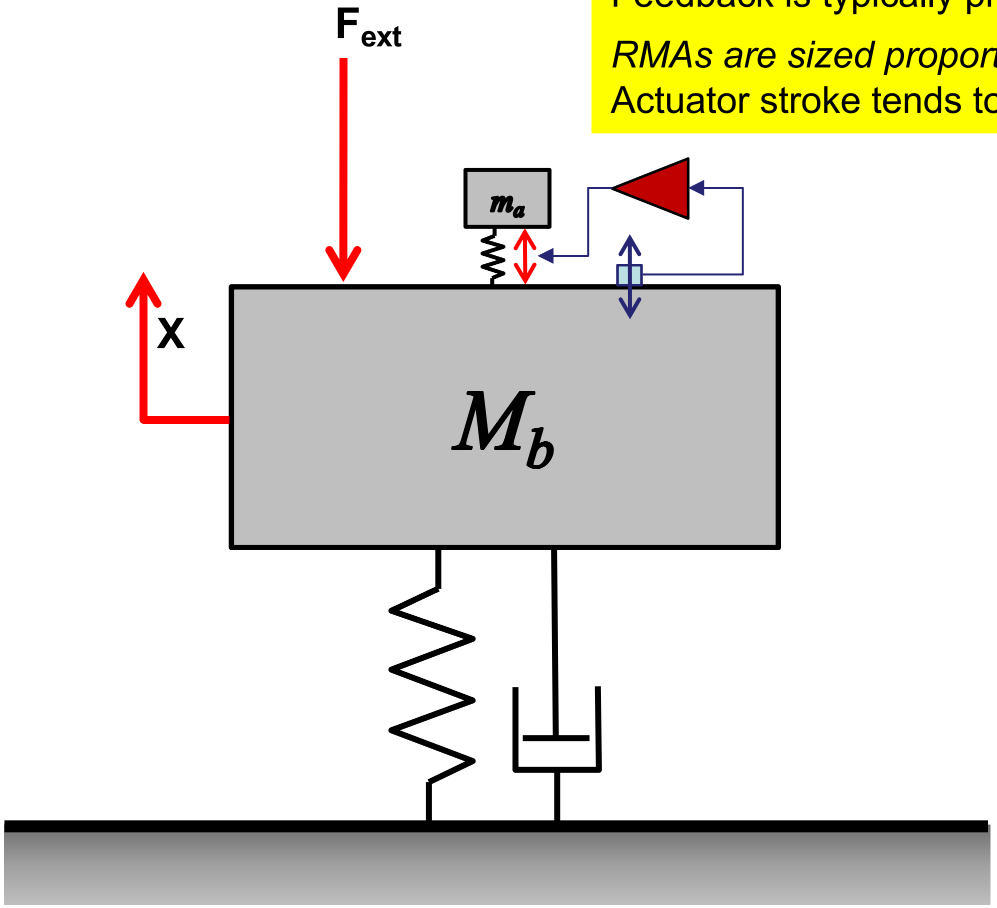




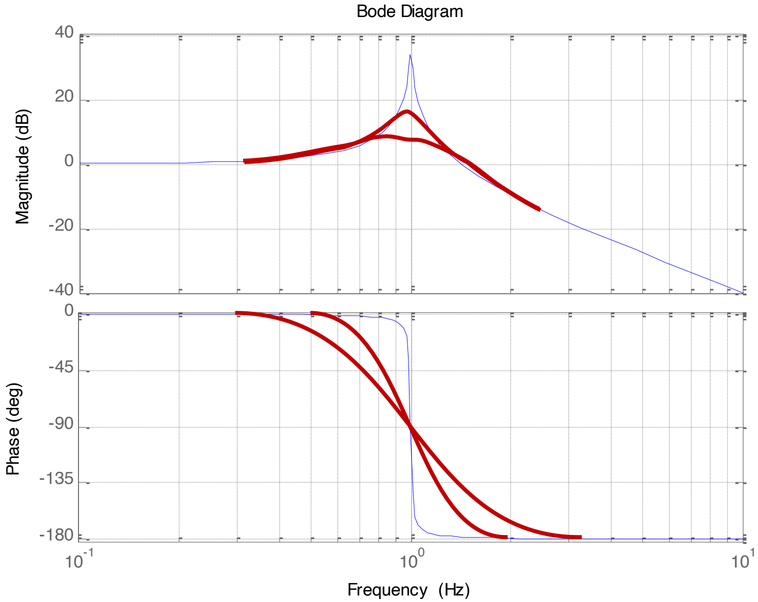
Introduction to Structural Damping Techniques

Reaction Mass Actuators (RMAs) are employed as part of an active feedback control system to add damping to a target mode. Feedback is typically provided by a collocated accelerometer.

RMAs are sized proportionally to the disturbance environment. Actuator stroke tends to be the limiting factor



For a given force requirement, RMA stroke will scale linearly with $1/m_a$



Introduction to Structural Damping Techniques

RMAs Vs TMDs:

RMAs have the following advantages:

1. RMAs can be much smaller than TMDs when high damping ratios are required for large structures where very small motions are of concern. This is because they are sized according to the *disturbance environment and required stroke* for a given moving mass sizing.
2. RMAs can be tuned via software (algorithms/filters) to fine-tune for subtle changes in structural dynamics
3. RMAs can be used to attack multiple modes (provided that mounting locations yield observability/controllability of more than one target mode)
4. RMAs can also be used for active cancellation (for example, if harmonic disturbances are an issue, and an appropriate reference signal is available)

Introduction to Structural Damping Techniques

RMAs Vs TMDs:

TMDs have the following advantages:

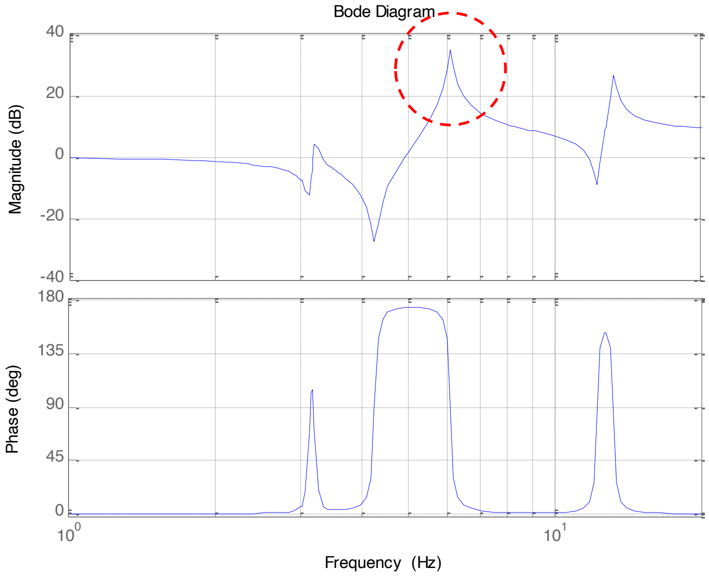
1. TMDs are simple and have few failure modes (can operate maintenance-free for many years)
2. TMDs require no software, electronics, power, cabling, etc

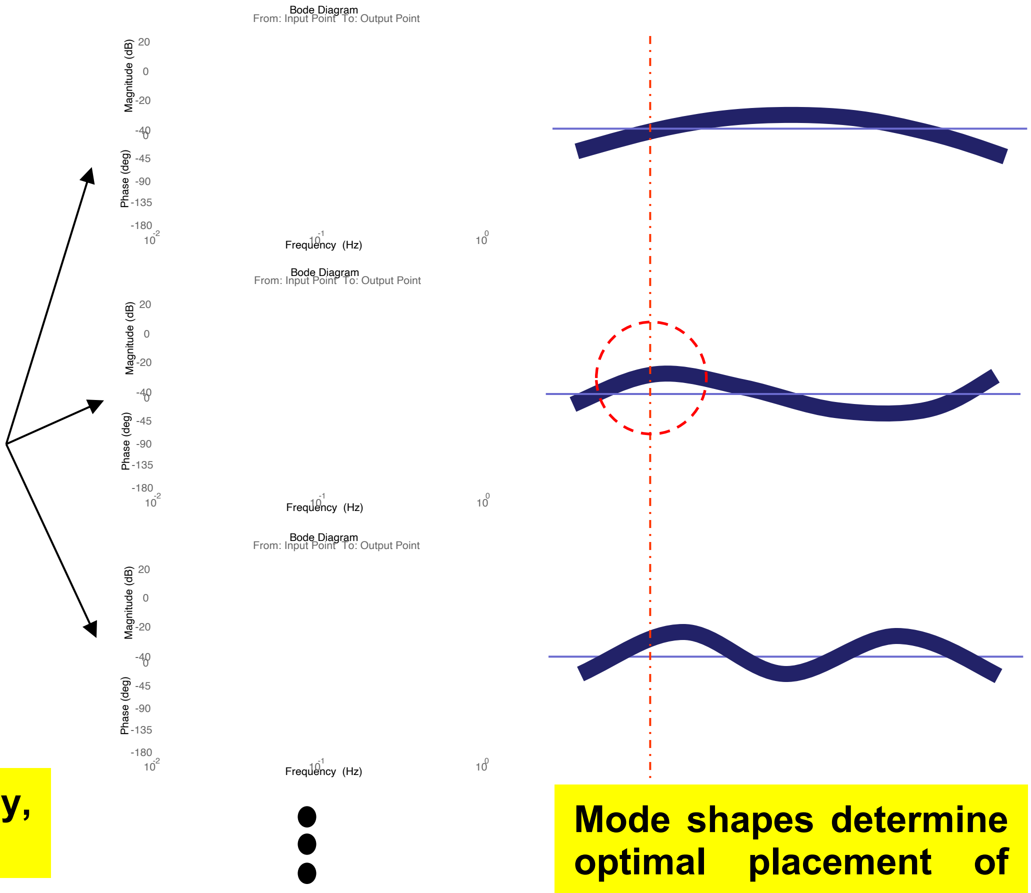
If performance requirements can be met by TMDs (and their mass/form-factor can be accommodated), then TMDs are almost always the preferred solution

In the case of SOFIA, RMAs were preferred due to considerable weight/size advantage and requirement for very high damping (30% of critical or more) in the targeted modes. Variation in structural dynamics for different science-instrument installations was also of concern

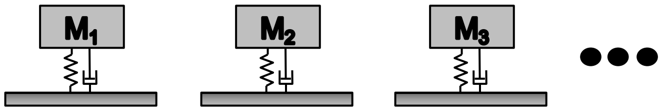
Introduction to Structural Damping Techniques

The concept of modal decomposition allows us to consider arbitrary deformations of a structure in terms of a superposition of modal basis functions





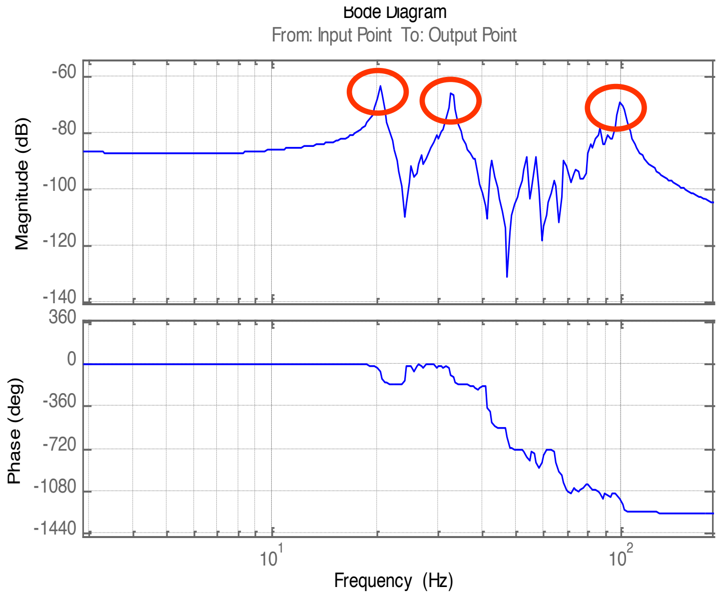
Each mode as an associated frequency, shape, mass and percentage damping

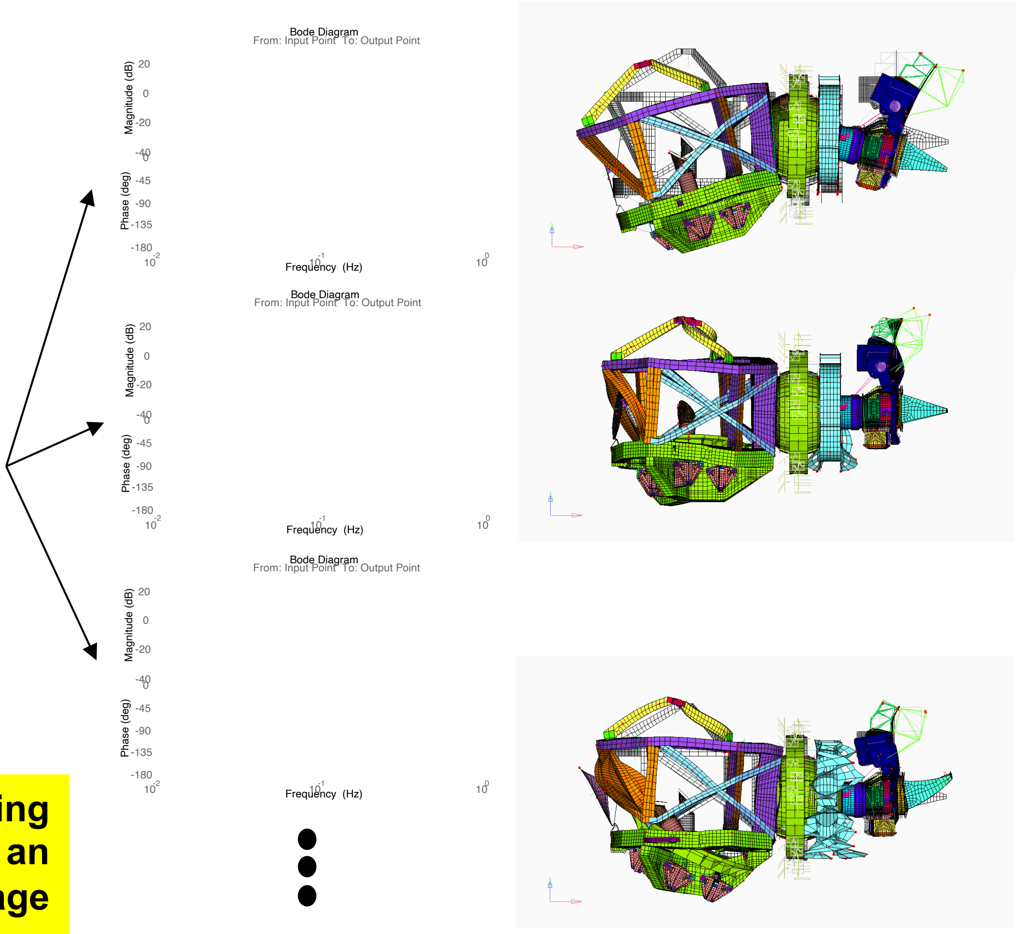


Mode shapes determine optimal placement of RMAs

Introduction to Structural Damping Techniques

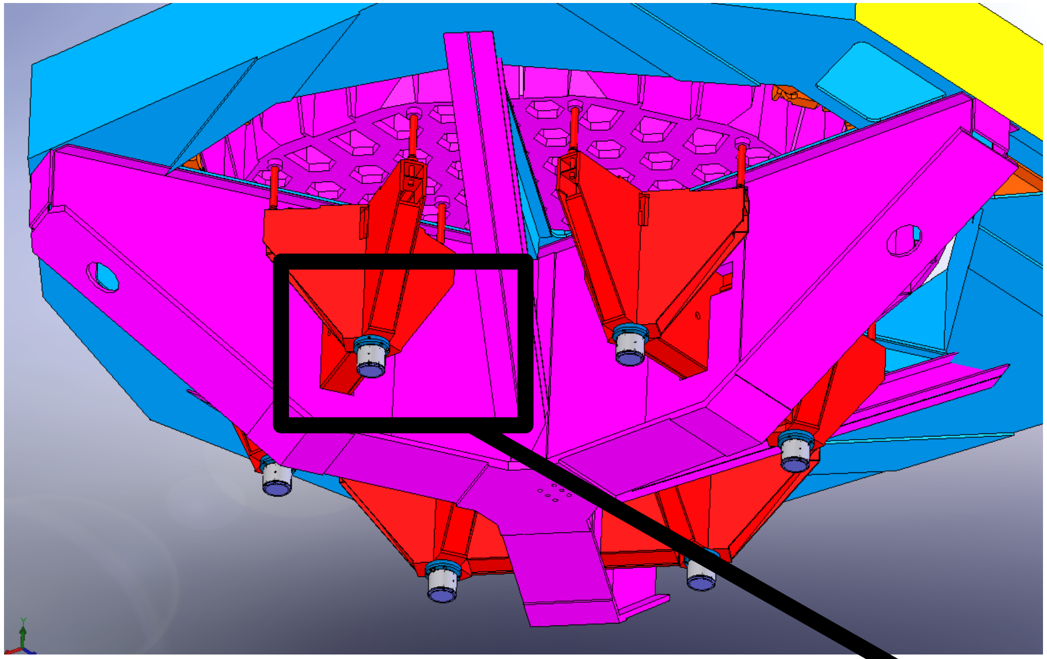
For lightly damped structures under operational loads, it is typical for a handful of these modes to dominate a particular measure of merit (image deflection or image quality, in context of an optical telescope such as SOFIA)

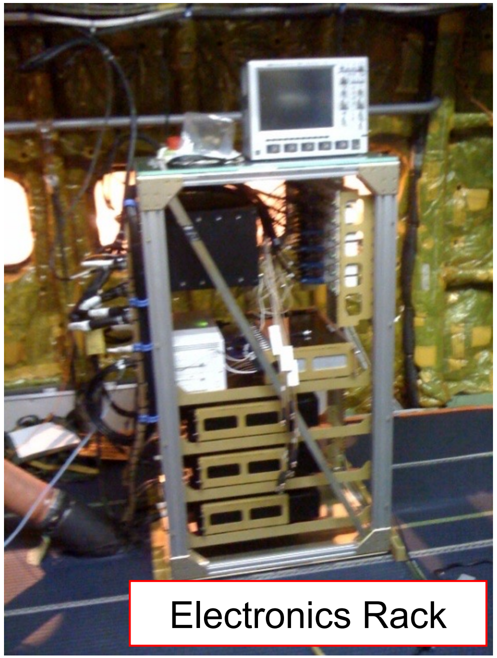




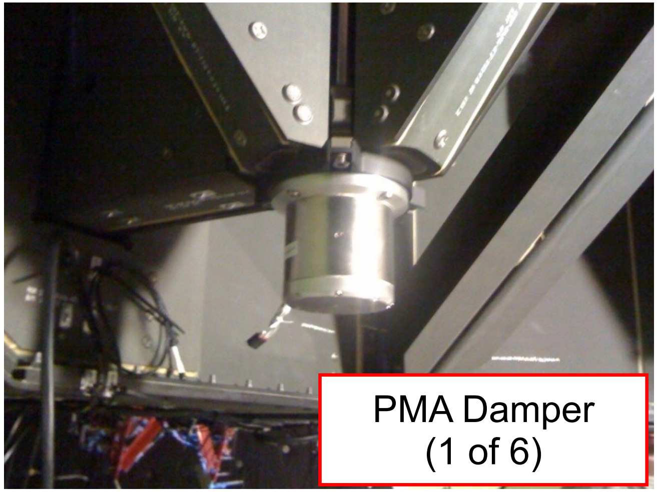
In a scenario such at this, adding damping (via passive or active means) can be an extremely effective way to improve image stability and/or image quality

RMA Control System for Primary Mirror Modes





Electronics Rack



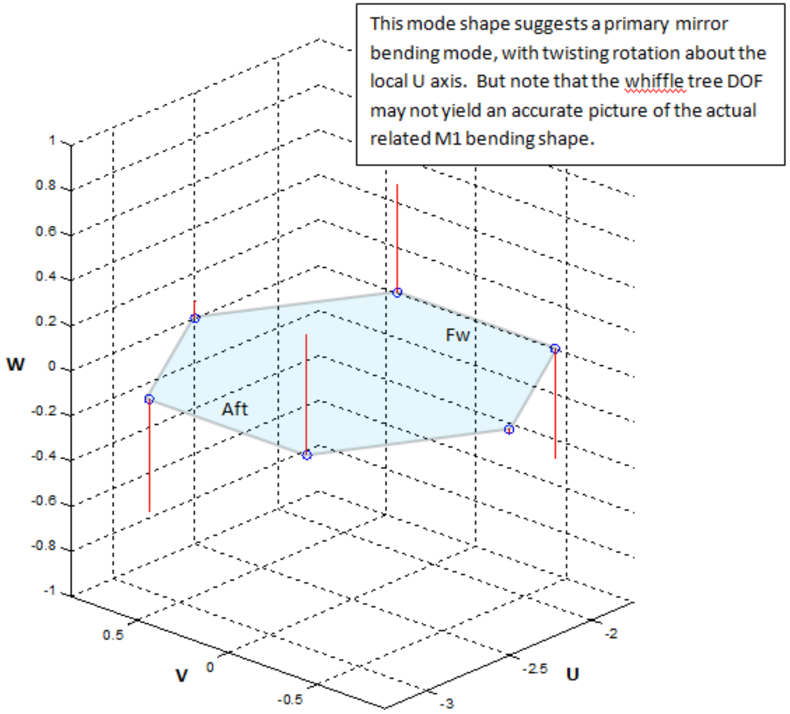
PMA Damper
(1 of 6)

Fortunately, primary mirror rocking on the whiffletree was anticipated as a major contributor to image motion when the telescope assembly was being designed 10 years ago…

Hard points for RMA mounting were provided at six points on the underside of the whiffletree.

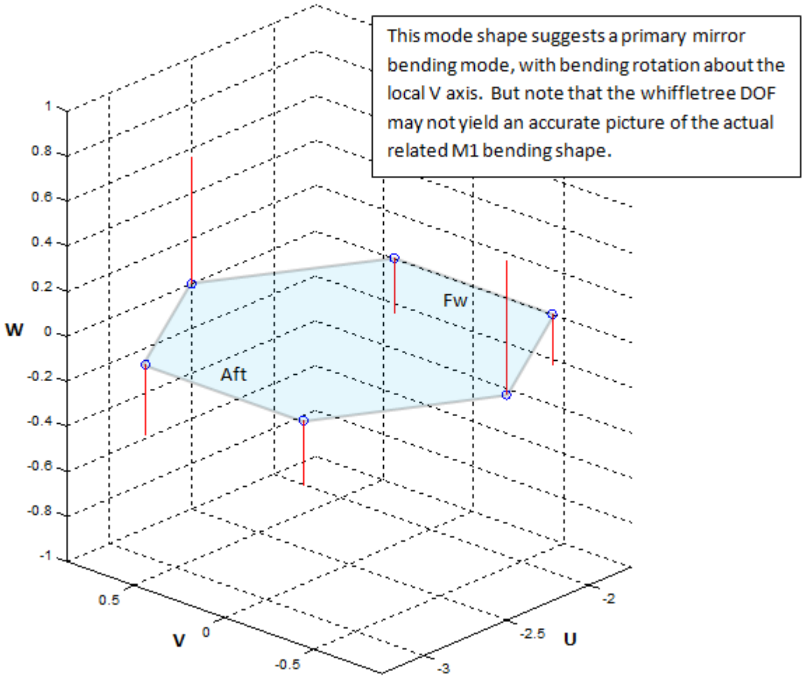
RMA Control System for Primary Mirror Modes

Modal Coordinates
(Flexible Body Modes of Primary Mirror)



This mode shape suggests a primary mirror bending mode, with twisting rotation about the local U axis. But note that the whiffle tree DOF may not yield an accurate picture of the actual related M1 bending shape.

Figure 5: 173.0625 Hz Mode Shape Whiffle Tree Deflection

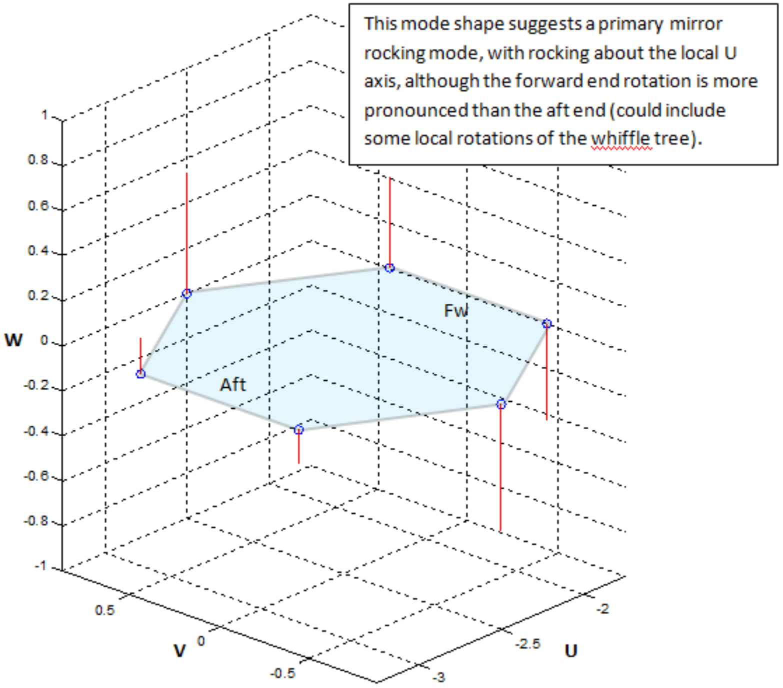


This mode shape suggests a primary mirror bending mode, with bending rotation about the local V axis. But note that the whiffletree DOF may not yield an accurate picture of the actual related M1 bending shape.

Figure 3: 174.75 Hz Mode Shape Whiffle Tree Deflection

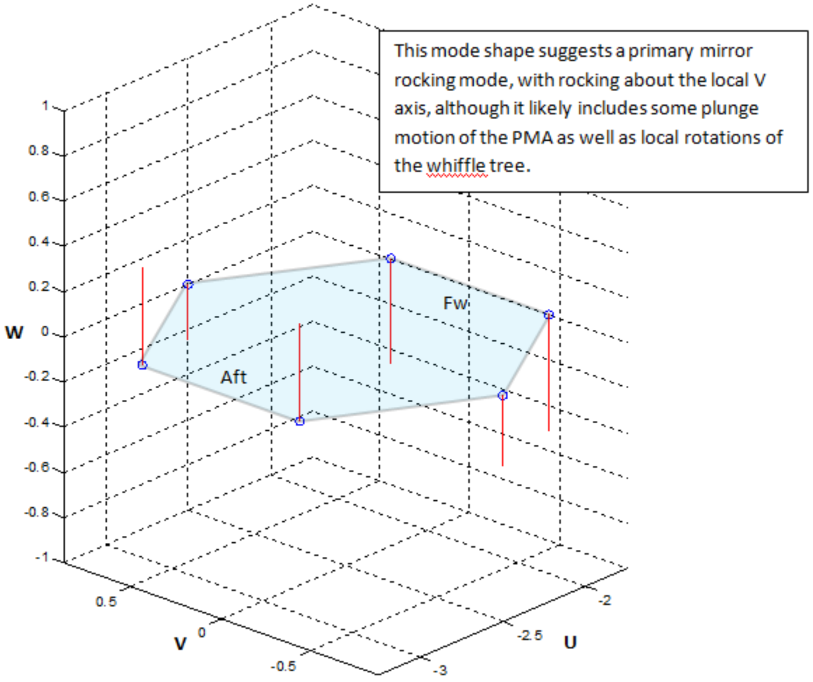
AMD System In Assembly and Test

Modal Coordinates
(Rocking Modes of Primary Mirror on Whiffletree)



This mode shape suggests a primary mirror rocking mode, with rocking about the local U axis, although the forward end rotation is more pronounced than the aft end (could include some local rotations of the whiffle tree).

Figure 7: 73.2500 Hz Mode Shape Whiffle Tree Deflection



This mode shape suggests a primary mirror rocking mode, with rocking about the local V axis, although it likely includes some plunge motion of the PMA as well as local rotations of the whiffle tree.

Figure 9: 69.1250 Hz Mode Shape Whiffle Tree Deflection

RMA Control System for Primary Mirror Modes

RMA Controller Architecture:
Control law is synthesized in modal coordinates