TMT
Thirty Meter Telescope

TMT Vibration Budget Update

AO4ELT5

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30th June 2017

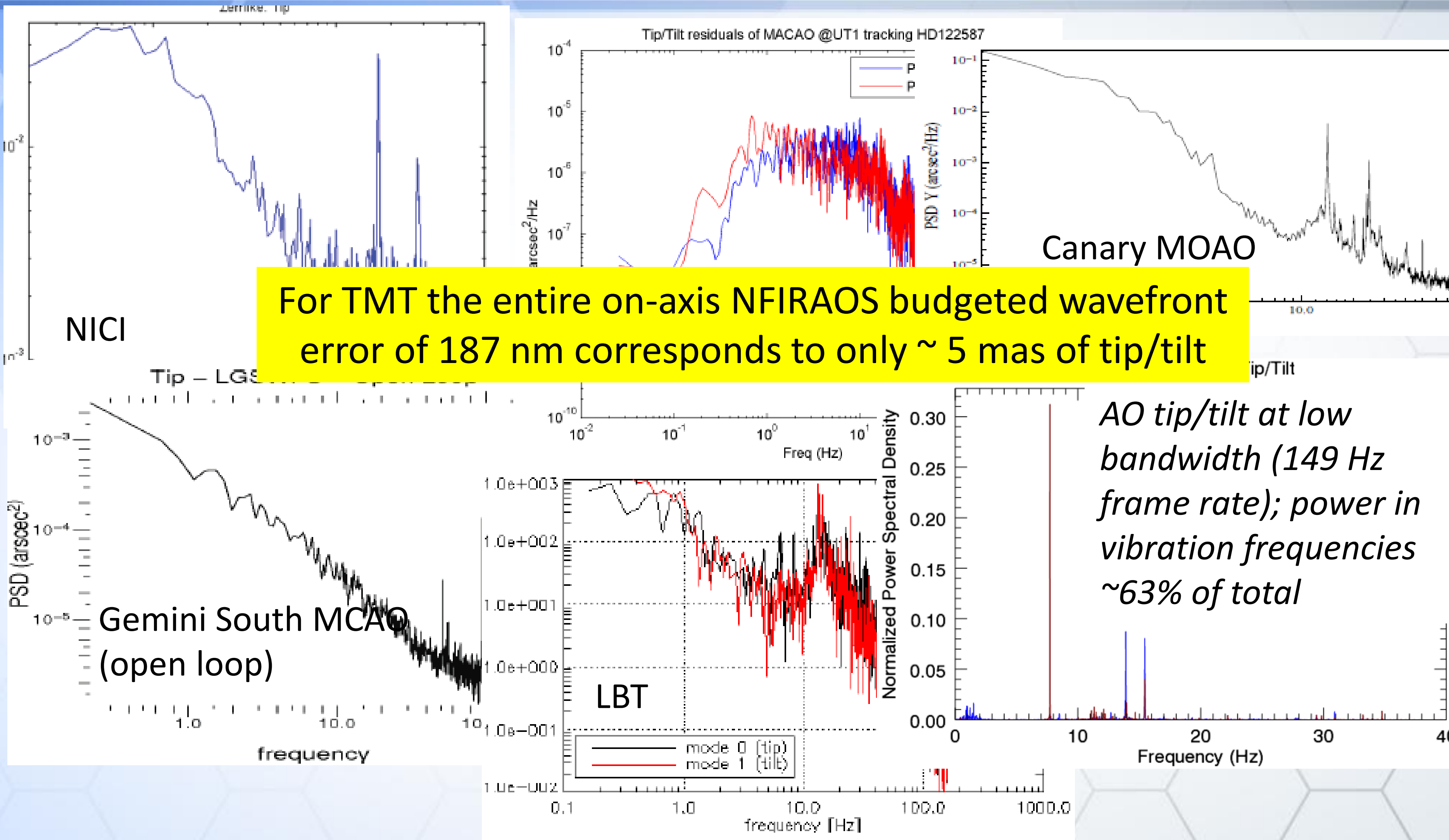
Outline

- Brief reprise about the TMT vibration budget
- Where our budget is today
- Highlight a few interesting measurements
- Deriving a vibration environment for instruments
- Where we still need to go (to your telescope!)

Some background

- Or, why is that mechanical engineer talking at AO4ELT again?
  - Many talks this week have been about addressing vibration, low wind or other physical disturbances using better reconstructors, better sampling or faster systems
  - LQG and other techniques using some of the AO rejection capability to address narrowband vibration tones will impact atmospheric rejection (Bode's "waterbed" theorem)
  - This talk is about doing everything we can to fix these problems before we reach the tip/tilt stage and DM's (reserve the AO system for atmospheric correction)

AO tip/tilt power spectra (Mostly from Kulcsár et al, 2012)

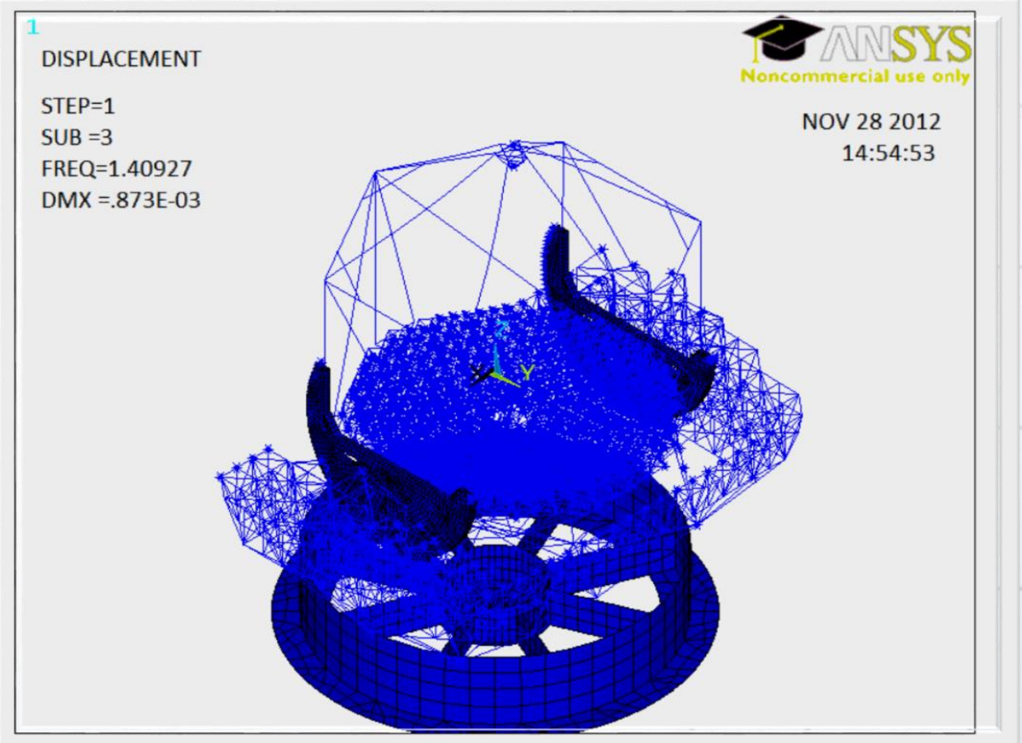


For TMT the entire on-axis NFIRAOS budgeted wavefront error of 187 nm corresponds to only ~ 5 mas of tip/tilt

AO tip/tilt at low bandwidth (149 Hz frame rate); power in vibration frequencies ~63% of total

Approach

- Use finite element model to establish sensitivity to forces at different telescope locations as a function of frequency (**nm WFE per Newton of Force**)
  - Measure vibration transmission through soil/foundation/pier
- Allocate forces between subsystems
  - Need data on representative forces to guide sensible allocation

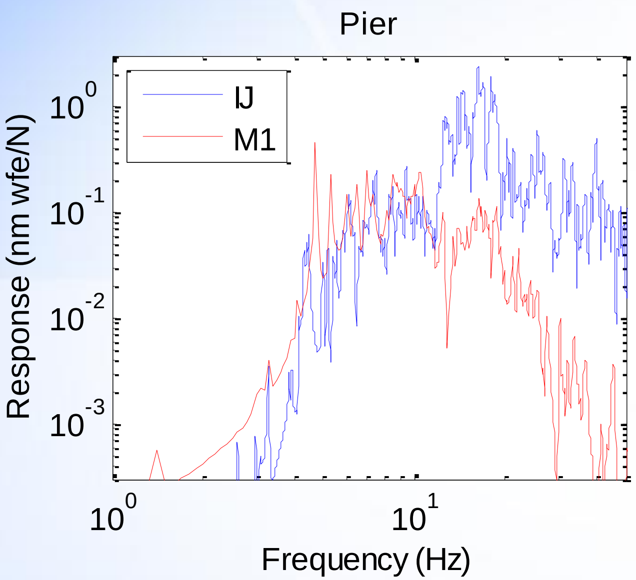


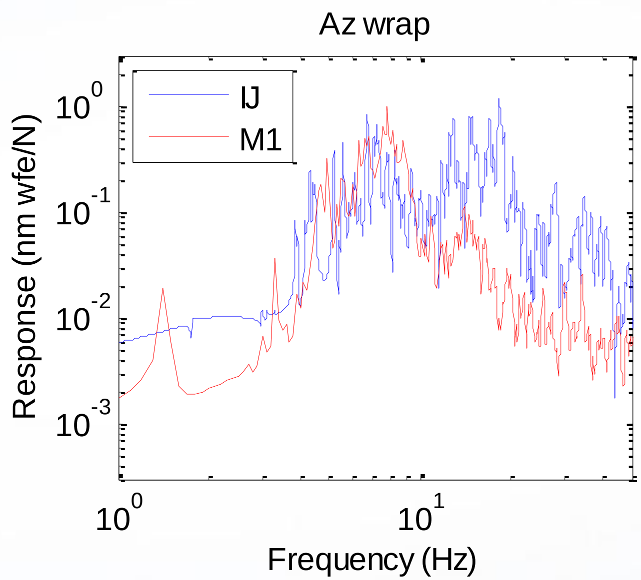
Modelling the Sensitivity

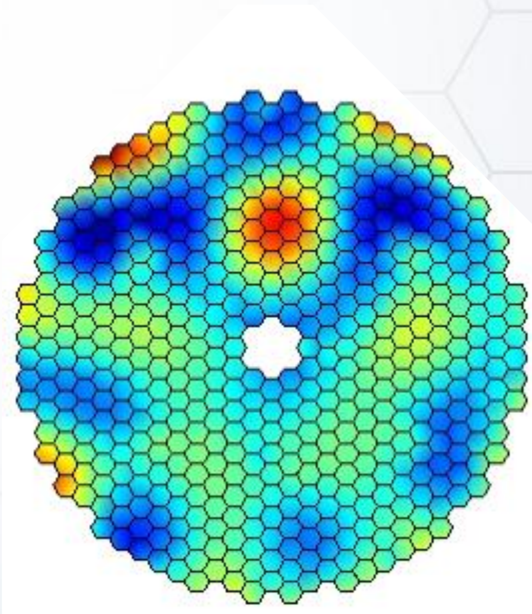
- Vibration forces result in
  - Image jitter
  - M1 segment dynamic motion
- Image jitter: FEM coupled to linear optical model
  - Internal resonances within instruments NOT included
- Include segment dynamics, actuator servo dynamics for M1 (requires 23,000 states)
- AO temporal rejection
  - Roughly 60 Hz for DM (high order)
  - 15 Hz Type II control for tip/tilt

Segment effects vs Image Jitter

- TMT has soft actuators (voice-coil) for M1CS
  - Mirror is isolated from mirror cell motion above ~8Hz bandwidth



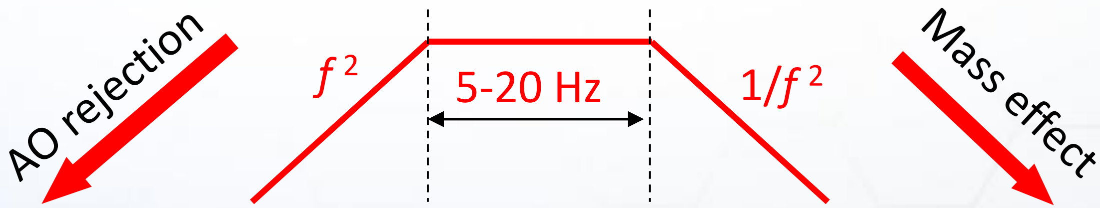




  - M1 surface motion is relatively "smooth" even at 30 Hz
    - AO rejection limited mostly by temporal bandwidth

Vibration Budget

- AO error budget allocation of 30nm to vibration
  - **Less than 1 mas tip/tilt**
- Place requirements on sources of vibration to meet overall budget
  - Specify requirements on RMS force levels in Newtons
  - After passing through shaping filter
    - Allowing more force at high & low frequencies



Example budget allocation: cryocooling is allowed 1 N on telescope

TMT.SEN.TEC.14.009.REL02

Requirement Number	Item name	Subcomponent name	Sensitivity Value (nm/N)	Reduction Factor	Aggregate Allowable Force (N rms)	Subcomponent Allowable Force (N rms)	Aggregate estimated AO WFE impact (nm)	Subcomponent estimated AO WFE impact (nm)	Notes
	Total						28.4		
	On Telescope				3.9		24.7		
[REQ-1-OAD-XXXX]	Telescope structure (STR)				2.6		9.2		
		Azimuth drives	0.7	1.0		1.0		0.7	
		Elevation drives	1.7	1.0		1.0		1.7	
		Azimuth cable wrap	0.5	1.0		1.0		0.5	
		Elevation cable wrap	1.3	1.0		1.0		1.3	
		HSB oil distribution	0.7	1.0		1.0		0.7	
		Chilled water distribution	7.6	1.0		1.0		7.6	
		Other	4.6	1.0		1.0		4.6	
[REQ-1-OAD-XXXX]	M2 System (M2)				0.5		5.1		
		M2 cell	25.0	1.0		0.2		5.0	
		M2 electronics	2.3	1.0		0.5		1.2	
[REQ-1-OAD-XXXX]	M3 System (M3)		4.3	1.0	0.5		2.2		
[REQ-1-OAD-XXXX]	Alignment and Phasing System (APS)		7.6	1.0	0.0		0.0		
[REQ-1-OAD-XXXX]	Engineering Sensors (ESEN)		25.0	1.0	0.0		0.0		
[REQ-1-OAD-XXXX]	Telescope Utility Services (TUS)		7.6	1.0	0.5		3.8		
[REQ-1-OAD-XXXX]	Narrow Field Near Infrared On-Axis AO System (NFIRAOS)		7.6	1.0	1.0		7.6		
[REQ-1-OAD-XXXX]	NFIRAOS Science Calibration Unit (NSCU)		7.6	1.0	0.0		0.0		
[REQ-1-OAD-XXXX]	Laser Guide Star Facility (LGSF)				0.7		9.5		
		Top-end	25.0	1.0		0.1		2.5	
		BTO	7.6	1.0		0.5		3.8	
		Lasers	16.0	1.0		0.5		8.0	
		Laser electronics	2.3	1.0		1.0		2.3	
[REQ-1-OAD-XXXX]	Communications and Information Systems (CIS)		7.6	1.0	1.0		7.6		
[REQ-1-OAD-XXXX]	Instrumentation Cooling (COOL)				1.4		10.7		
		Cryocooling	7.6	1.0		1.0		7.6	This may have contributions in locations other than the Nasmyth platforms.
		Refrigerant cooling	7.6	1.0		1.0		7.6	This may have contributions in locations other than the Nasmyth platforms.
[REQ-1-OAD-XXXX]	Adaptive Optics Executive Software (AOESW)								
[REQ-1-OAD-XXXX]	Instrumentation Cooling (COOL)								
[REQ-1-OAD-XXXX]	Infrared Imaging Spectrometer (IRIS)								
[REQ-1-OAD-XXXX]	Wide Field Optical Spectrometer (WFOS)								
[REQ-1-OAD-XXXX]	IRMS/MOSFIRE (IRMS)								
[REQ-1-OAD-XXXX]	High Resolution Optical Spectrometer (HROS)								
[REQ-1-OAD-XXXX]	Near-Infrared Multi-Object Sectrometer (IRMOS)								
[REQ-1-OAD-XXXX]	Planet Formation Instrument (PFI)								
[REQ-1-OAD-XXXX]	Mid-Infrared AO System (MIRAO)								
[REQ-1-OAD-XXXX]	Mid-Infrared Echelle Spectrometer (MIRES)								
[REQ-1-OAD-XXXX]	Near Infrared Echelle Spectrometer (NIRES-B)								
[REQ-1-OAD-XXXX]	Near Infrared Echelle Spectrometer (NIRES-R)								
[REQ-1-OAD-XXXX]	Wide-field Infrared Camera (WIRC)		0.7	10.0	5.0		0.4		
[REQ-1-OAD-XXXX]	Communications and Information Systems (CIS)		0.7	10.0	5.0		0.4		
[REQ-1-OAD-XXXX]	Common Software (CSW)		0.7	10.0	5.0		0.4		
[REQ-1-OAD-XXXX]	Data Management System (DMS)		0.7	10.0	5.0		0.4		
[REQ-1-OAD-XXXX]	Executive Software (ESW)		0.7	10.0	5.0		0.4		
[REQ-1-OAD-XXXX]	Science Operations Support Systems (SOSS)		0.7	10.0	5.0		0.4		
[REQ-1-OAD-XXXX]	Data Processing System (DPS)		0.7	10.0	5.0		0.4		
[REQ-1-OAD-XXXX]	Site Conditions Monitoring System (SCMS)		0.7	10.0	5.0		0.4		

Requirement Number	Subsystem	Subcomponent	Estimated sensitivity value (nm/N)	Estimated allowable force (N rms)	Estimated subcomponent contribution to AO WFE (nm)	Subsystem aggregate allowable AO WFE impact (nm)
	Observatory Total					**30.0**
	Contingency					**6.7**
	On Telescope					**23.9**
[REQ-1-OAD-1137]	Instrumentation Cooling (COOL)					9.9
		Cryocooling	7.0	1.0	7.0	
		Refrigerant cooling	7.0	1.0	7.0	
[REQ-1-OAD-1138]	Infrared Imaging Spectrometer (IRIS)		7.0	0.5	3.5	3.5
[REQ-1-OAD-1139]	Wide Field Optical Spectrometer (WFOS)		7.0	0.8	5.6	5.6
[REQ-1-OAD-1140]	IRMS/MOSFIRE (IRMS)		7.0	0.5	3.5	3.5

Estimated contribution to 30nm error budget

Sensitivity (nm/N) from modeling

Identify locations & sources for each subsystem

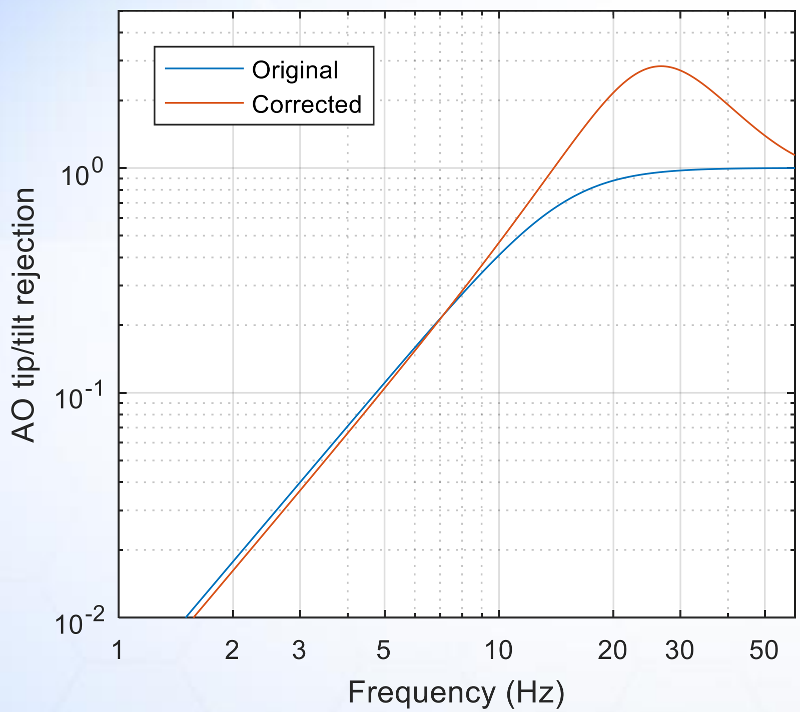
Allowable force level (in Newtons)

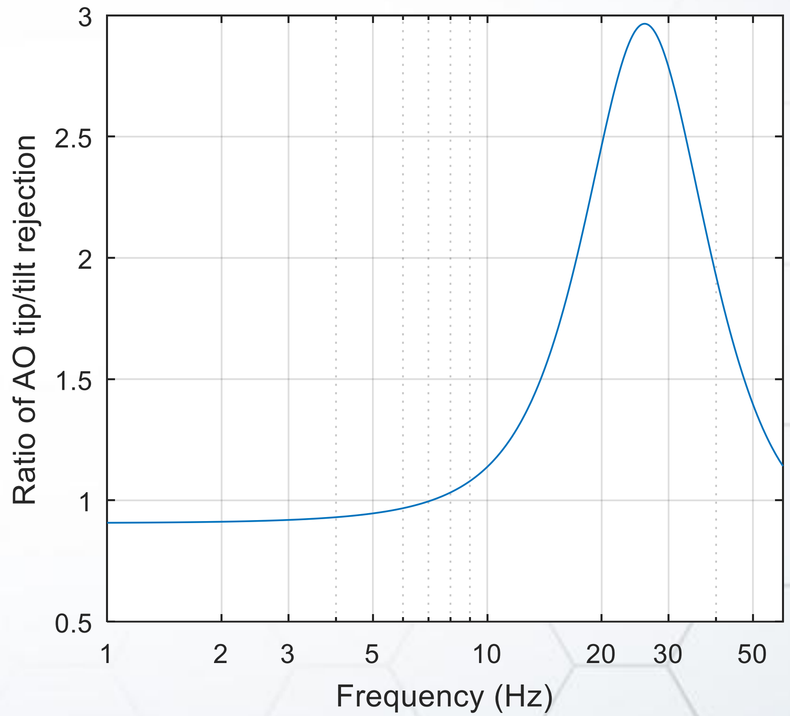
Where are we today?

- We have an error we completely forgot about (but Jean-Pierre Veran did not)
- We know more about a good fraction of our sources through a slow but steady measurement campaign
- We have a new source of problems we didn't adequately consider before (direct drive cogging)
- We have derived a usable vibration environment for instrument teams

What we forgot:
AO tip/tilt rejection in reality

- Previous vibration calculations used critically-damped second-order filter for AO rejection

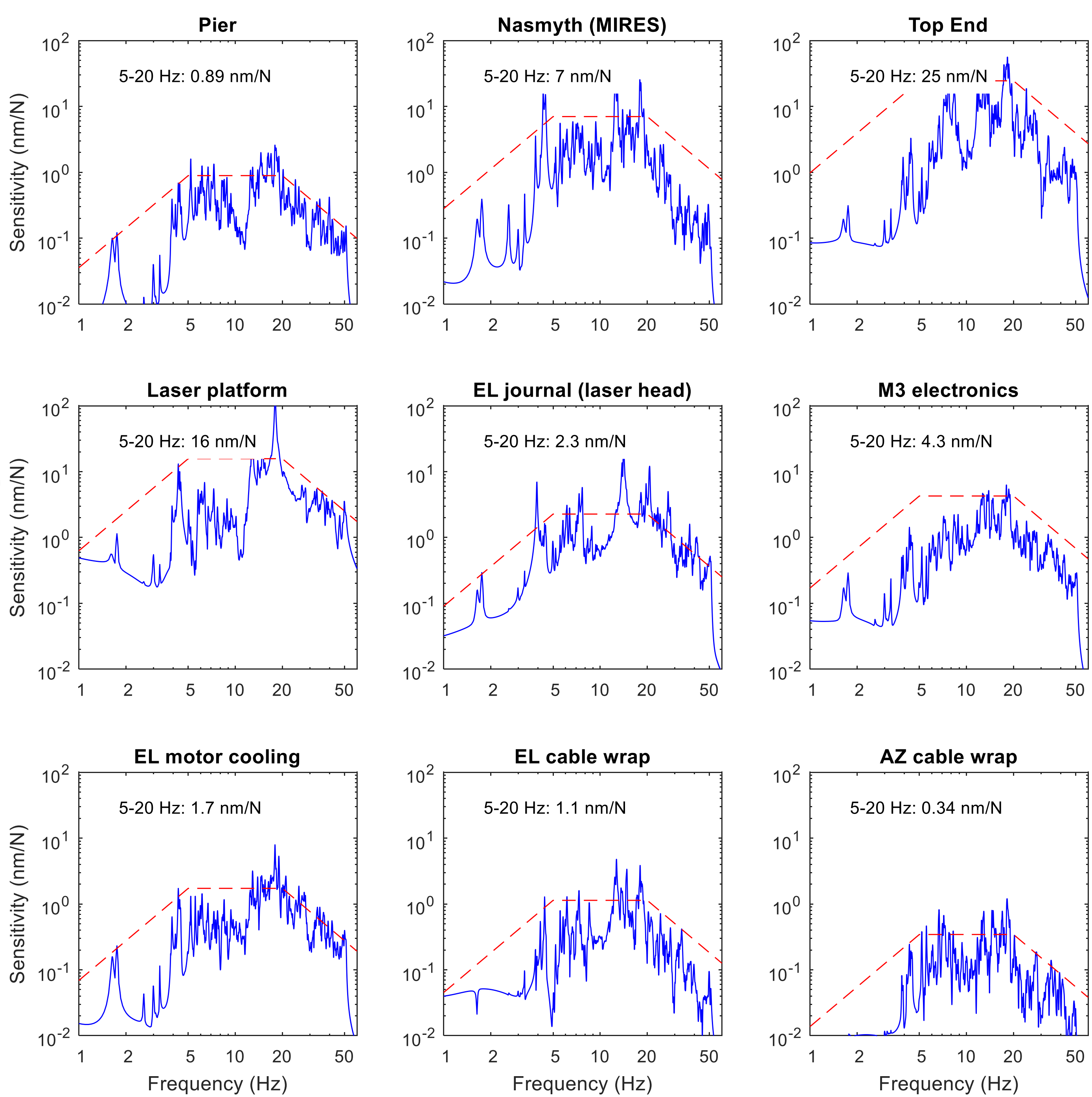




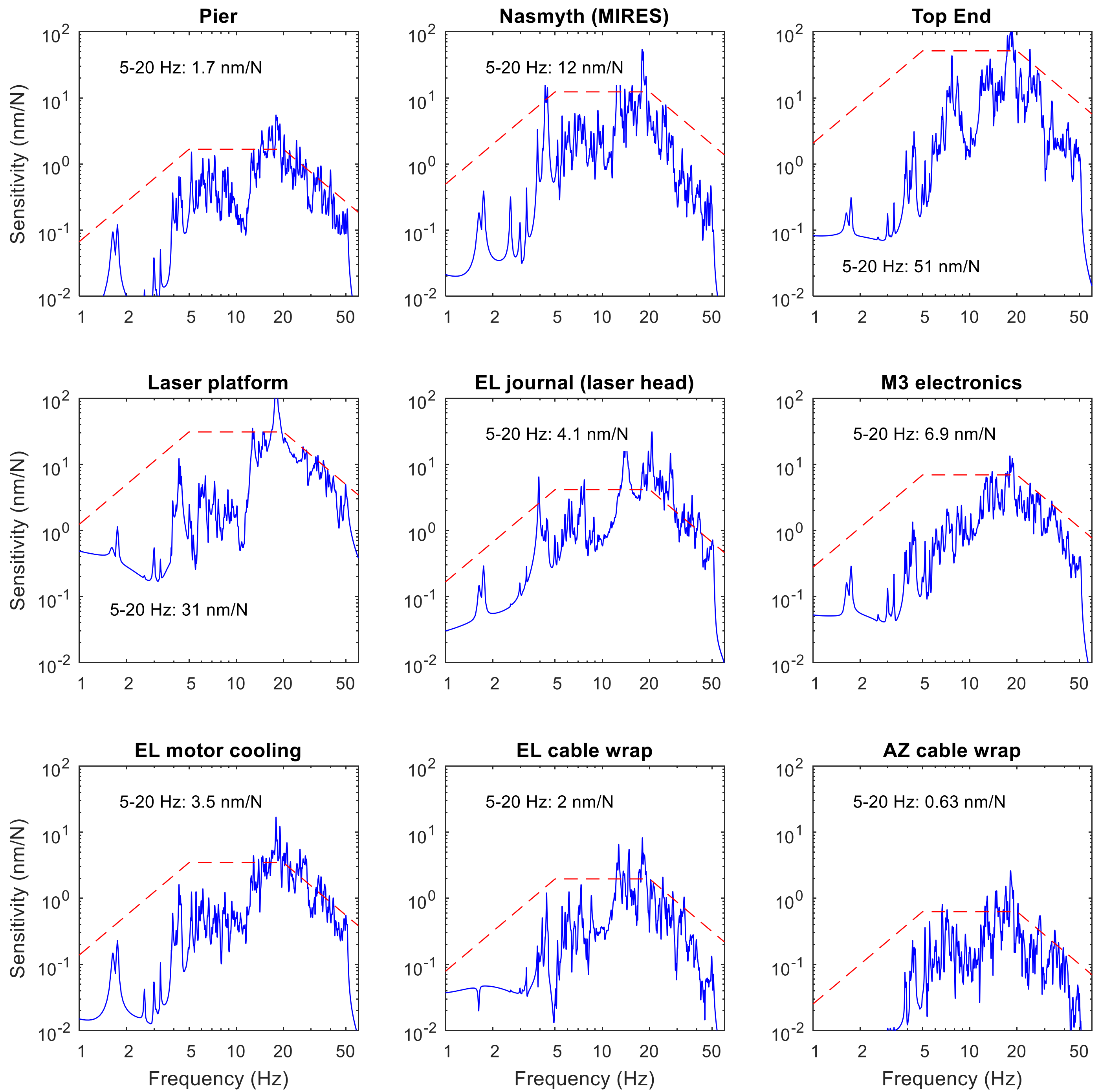
Vibration Sensitivities

- For each force input location, computed the AO-corrected image motion, vs frequency
- Typically most sensitive in 5-20 Hz range, less sensitive above and below that, so…
- We created force specifications allowing more force at higher and lower frequencies but otherwise only constraining the rms
  - With the rms calculated over 5-20 Hz band only.

Old Vibration Sensitivity Calculations

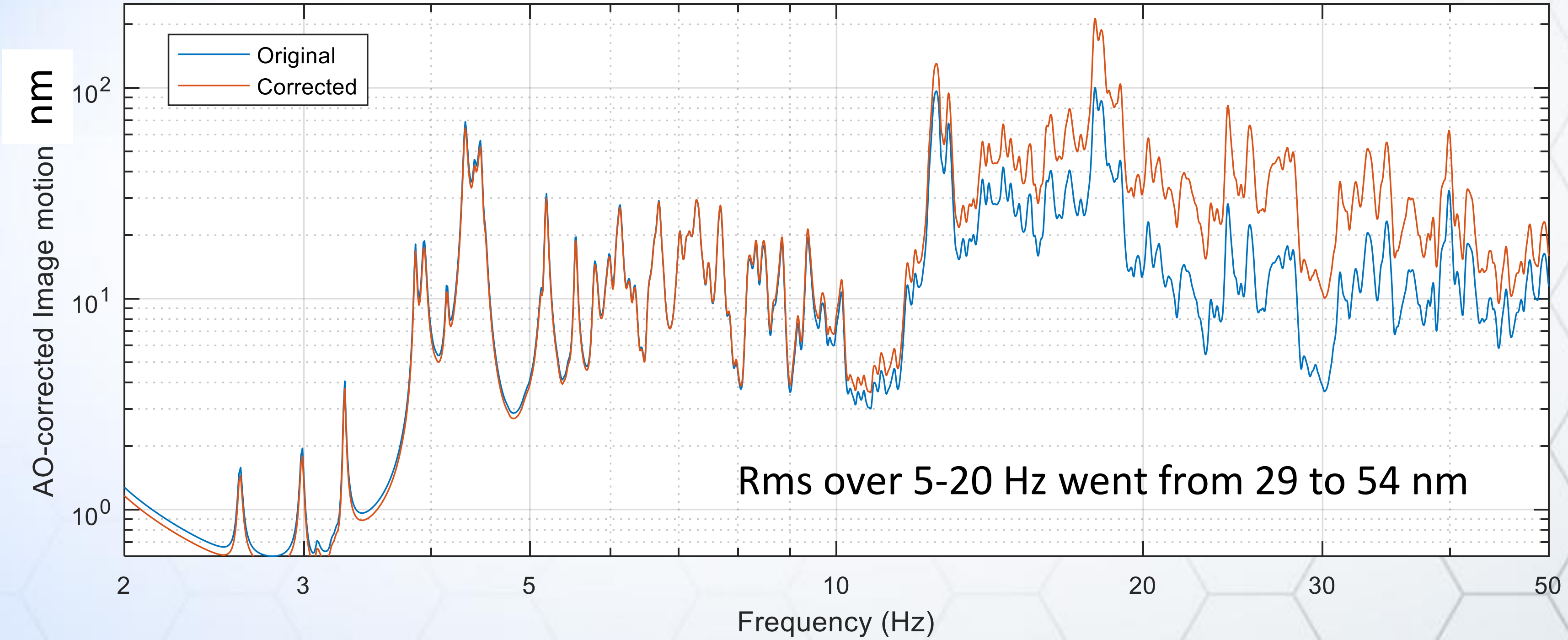


Revised Vibration Sensitivity Calculations



Effect of AO rejection curve

- Typically about 75-85% higher in 5-20 Hz band
- If every subsystem met the vibration force requirements exactly, and all at the same frequency:



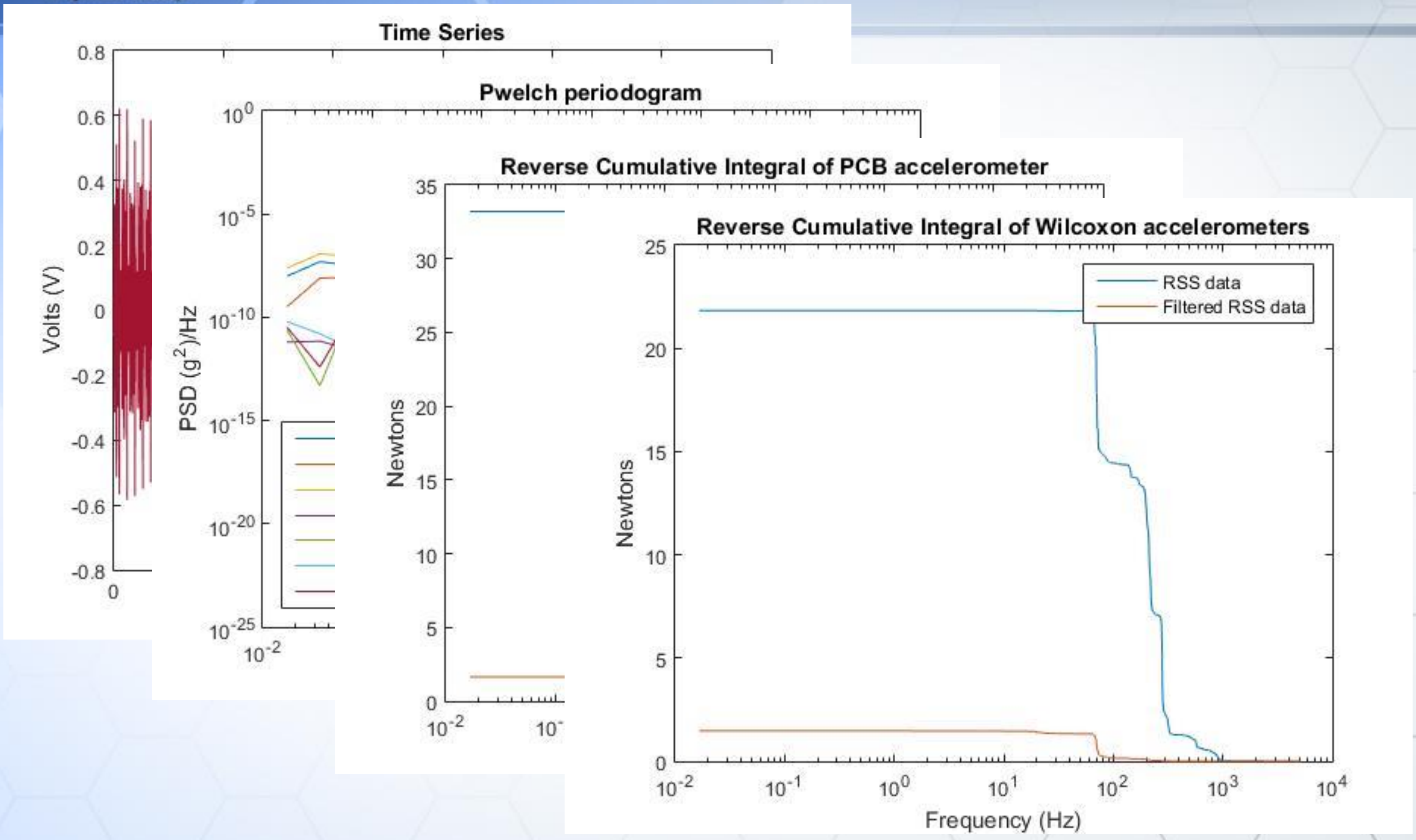
"Standard" cryocooler problem needs to be addressed

- Cryocoolers need to be closely coupled to detectors (an element in the image jitter chain)
  - Isolation is difficult to achieve
  - Mechanical forces to reciprocate pistons and pulse gas flow result in significant impulse forces that excite many system resonances
  - Non-impulse forces are often in detrimental frequency band
- **TMT needs to do better than previous telescopes in resolving cryocooler vibration issues**

GM coldhead measurements

- 250 kg suspended mass
- Isolation frequency around 2 Hz

GM coldhead measurements



GM coldhead measurements

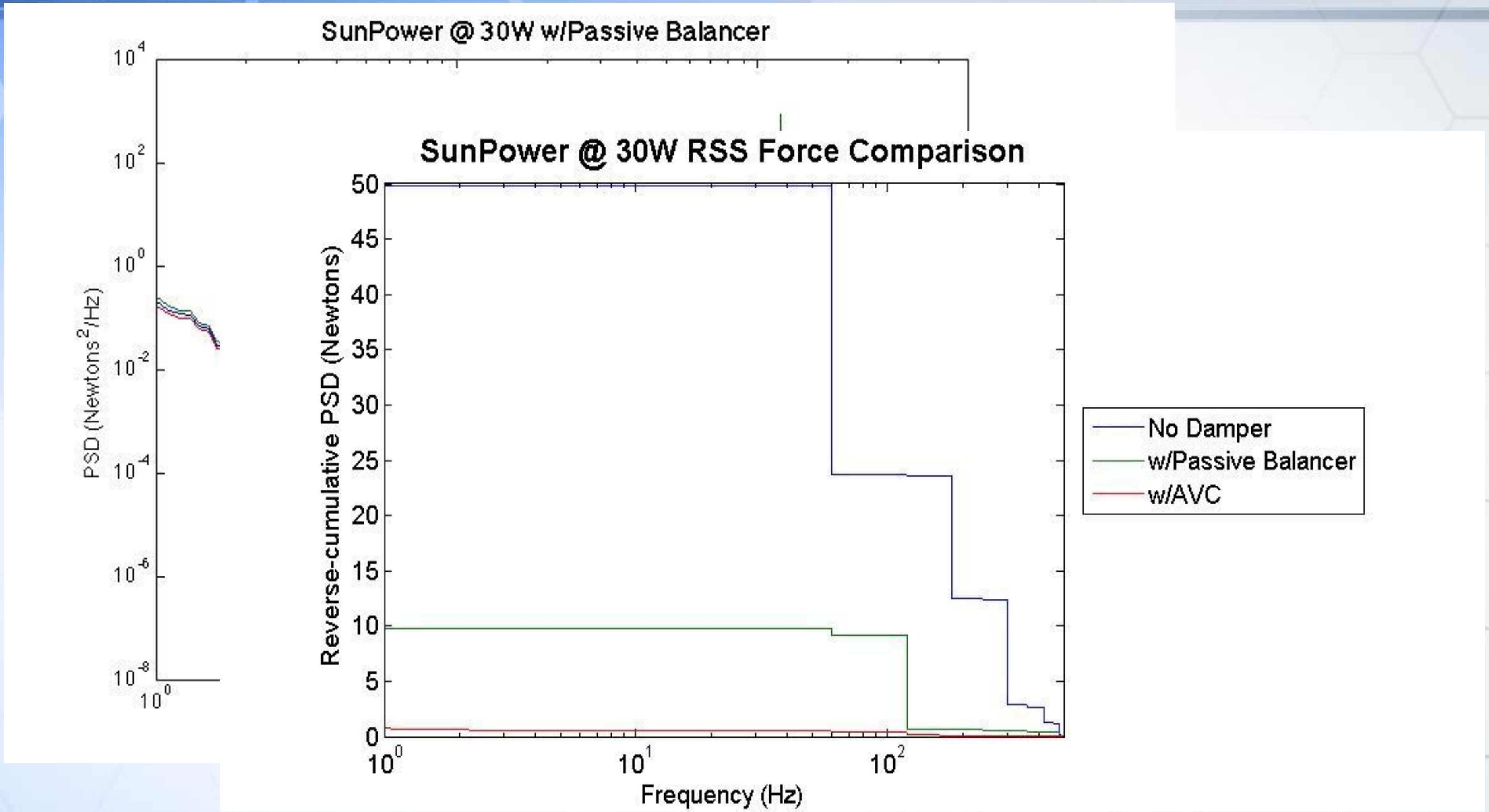
- PCB accelerometer results
  - Unfiltered Newtons in band = 33.2
  - TMT filtered Newtons in band = 1.6
- Wilcoxon accelerometer results
  - Unfiltered Newtons in band = 21.8
  - TMT filtered Newtons in band = 1.5

- CTI-1050 produces roughly 80W heat lift @77K
- 25 of these coolers implies 7 – 8 N

SunPower CryoTel (MT) Measurements

Many thanks to Tim Hardy at NRC Herzberg

SunPower CryoTel (MT) Measurements



SunPower CryoTel (MT) Measurements

	No damper	Passive Balancer	AVC	Ambient
RSS Newtons integrated from 10 Hz - 500 Hz	49.769	9.834	0.540	0.062
RSS Newtons integrated from 58 Hz - 62 Hz	43.778	3.560	0.216	0.006
RSS Newtons integrated from 118 Hz - 122 Hz	1.415	9.143	0.466	0.003

- Passive balancer helps
- AVC helps a lot more
- At 90W input power (5W heat lift at 77K) with AVC after TMT filter RSS force ~ 0.11 N
- Implies 400 of these for TMT would be ~ 2 N

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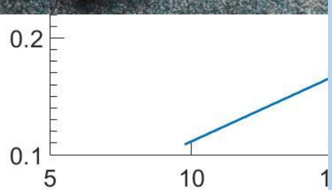
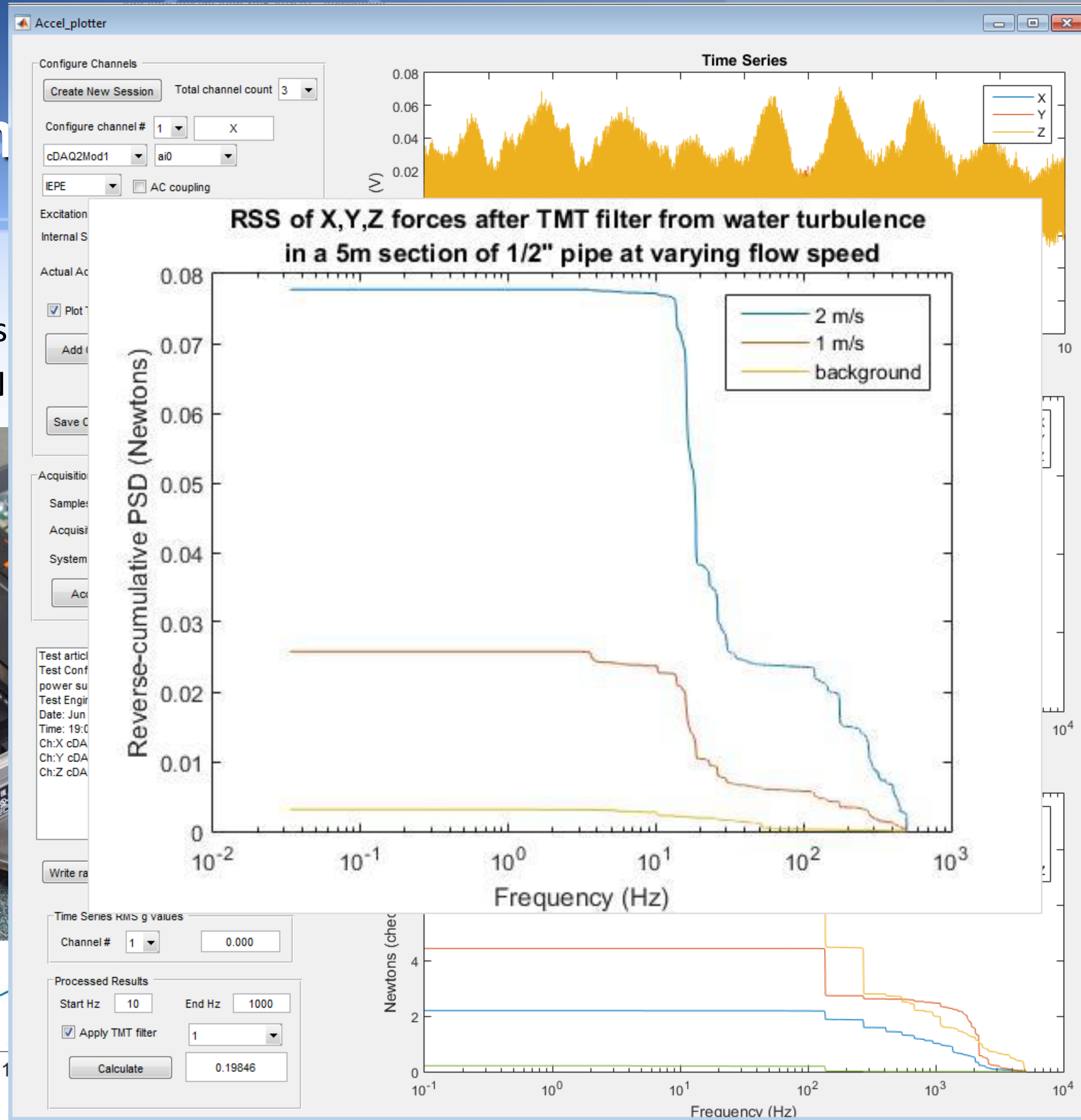
- Laser vibration
  - Fixture had s
  - Rms of 0.3 N



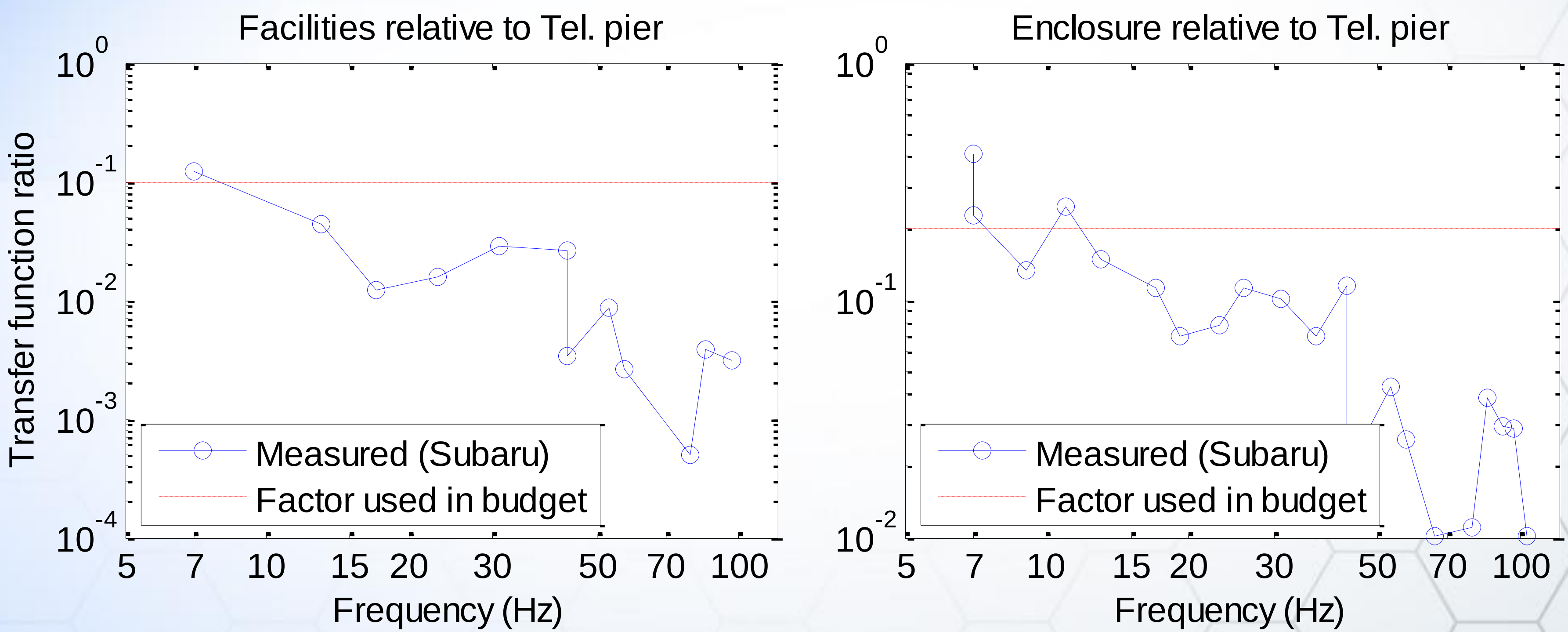


Things to keep in mind

- Isolate cryocoolers from your detector
- Isolate everything else and make sure your isolation actually works
  - 2.5 cm of gravity sag is a 3 Hz isolator
  - Damped isolators have worse roll-off with frequency than just springs

Things to keep in mind

- Moving vibration to your facility building only helps by a factor of 10 (at low frequency, more at higher frequency)



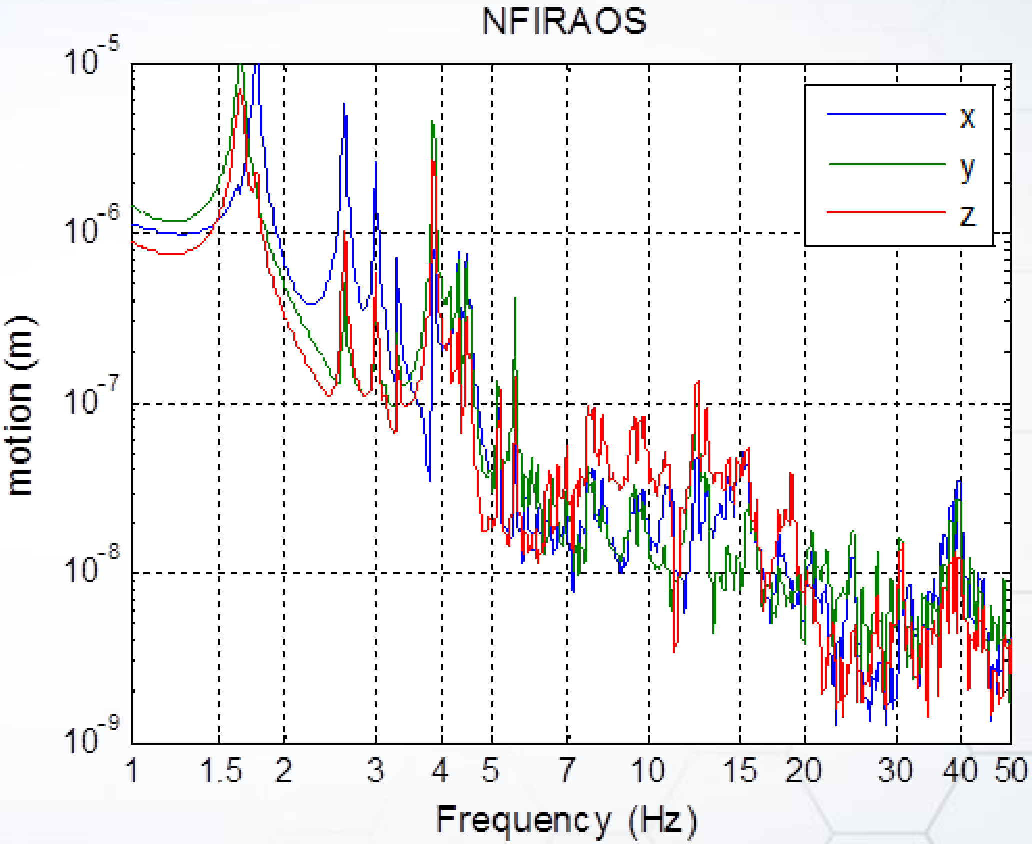
Vibration Environment for Subsystems

- To evaluate the vibration environment experienced by different subsystems (e.g. LGSF pointing),
  - Assume every vibration source exactly meets its requirement and all at the same frequency

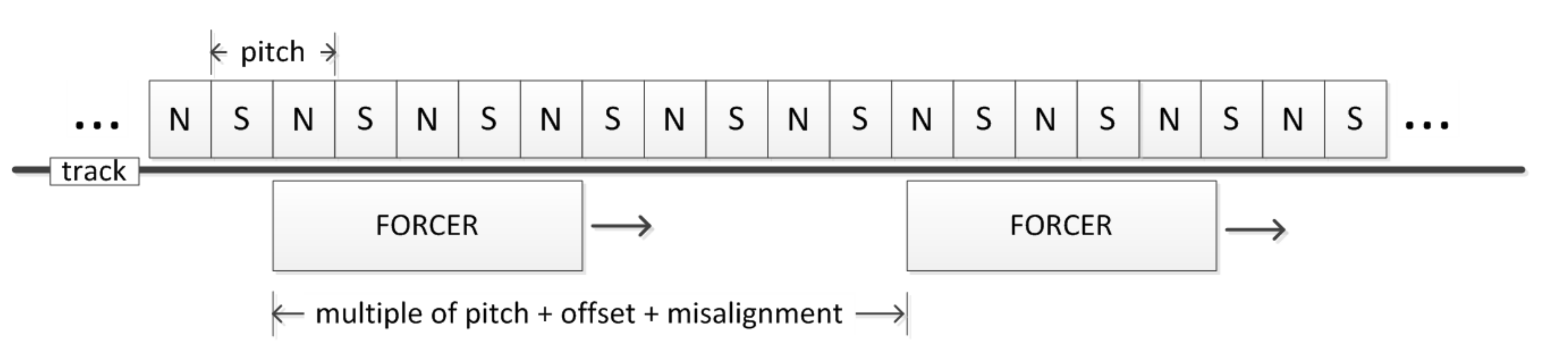
- Response envelope can be interpreted either as
  - The worst case possible at any frequency, one at a time, or
  - The power spectrum (appropriately scaled) if all forces are uniformly distributed across some range of frequencies

NFIRAOS vibration environment

- If our vibration budget was completely filled at each frequency this is the motion that would be seen at NFIRAOS

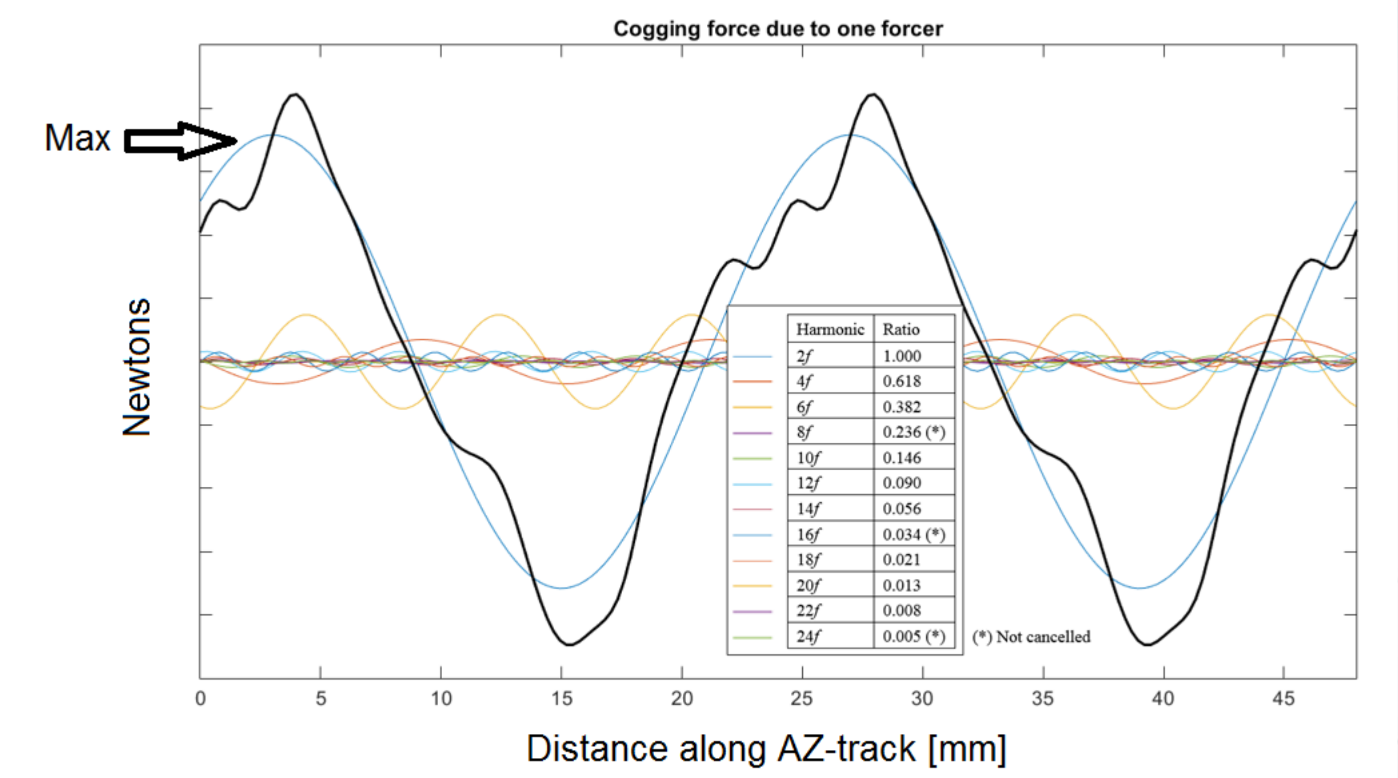


Source of Cogging



- Direct drive AZ-axis uses forcers and permanent magnets
- Cogging is generated due to non-uniform magnetic attraction
- Total force = constant + periodic cogging force
- Period over the magnet pitch, can be decomposed into harmonics
- This occurs both horizontally and vertically

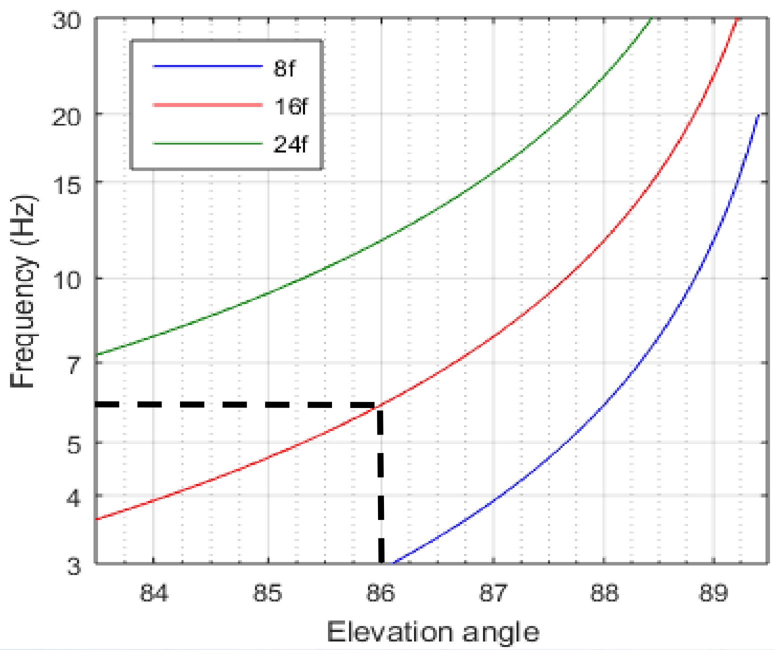
Example of Single Forcer Cogging

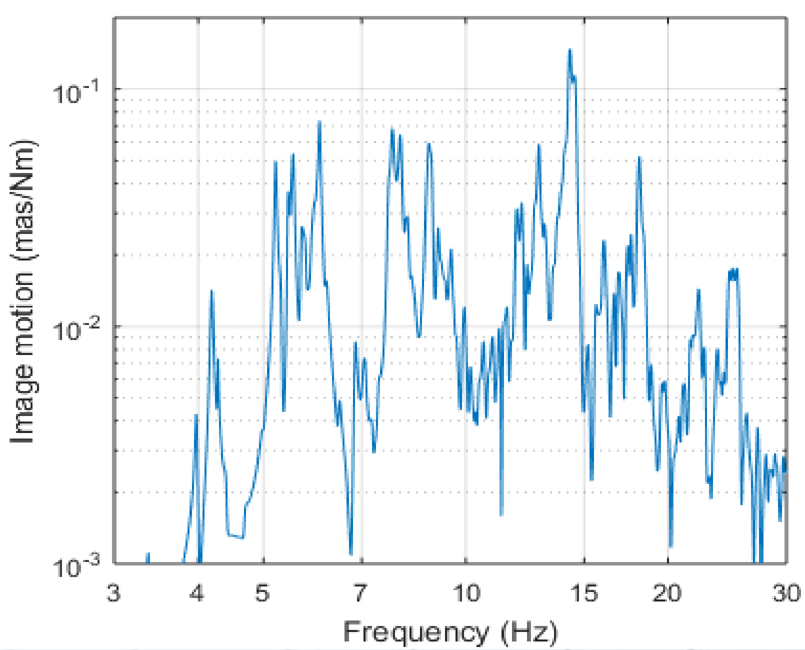


- Reference value: max force of the fundamental harmonic
- The reference value can be large, tens of Newtons for one forcer
- And hundreds of Newtons for multiple forcers with no reduction

Summary: Why is cogging a problem?

- The magnitudes are large, worst case hundreds of Newtons
  - TMT requirement for vibration due to AZ-drive is ~1 Newton
- Cogging frequencies are in the range of structural resonances
  - E.g., at EL=86°, 16f harmonic is ~6 Hz and excites structural resonance



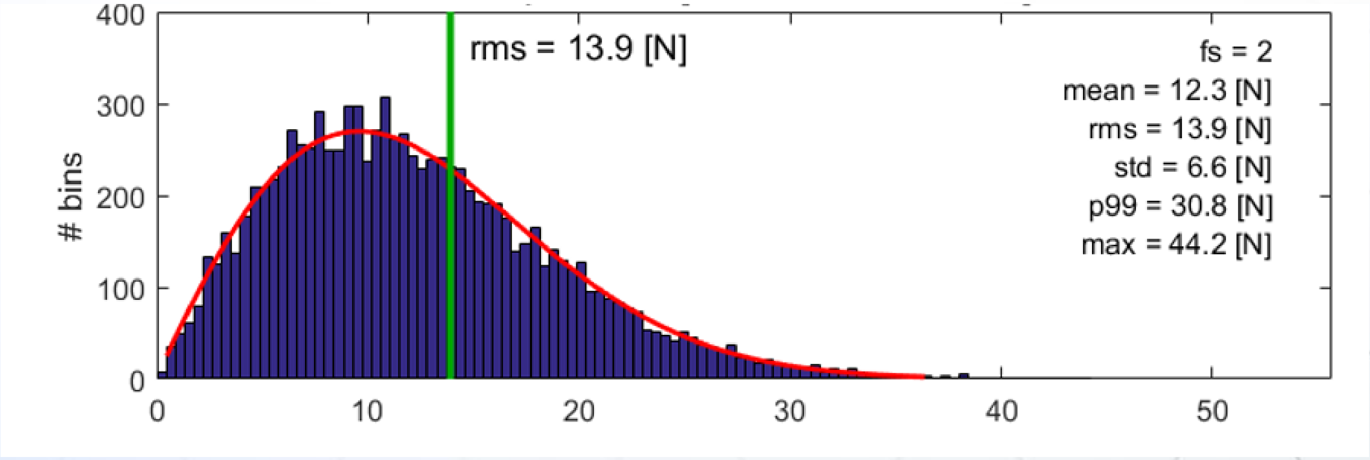


Methods for reducing cogging

- Methods for reducing cogging force:
  - Change the forcer design ($$$...)
  - Measure cogging forces and use open loop cancellation
  - Use spatial offset of forcers to cancel harmonics (so forces at different locations act out of phase)
    - Can't cancel all harmonics simultaneously
    - Can only cancel net torque, still have residual effect from non-collocated forces
    - Any misalignment limits effectiveness of strategy
  - Use adaptive optics for vibration reduction
    - Frequencies of harmonics are well known

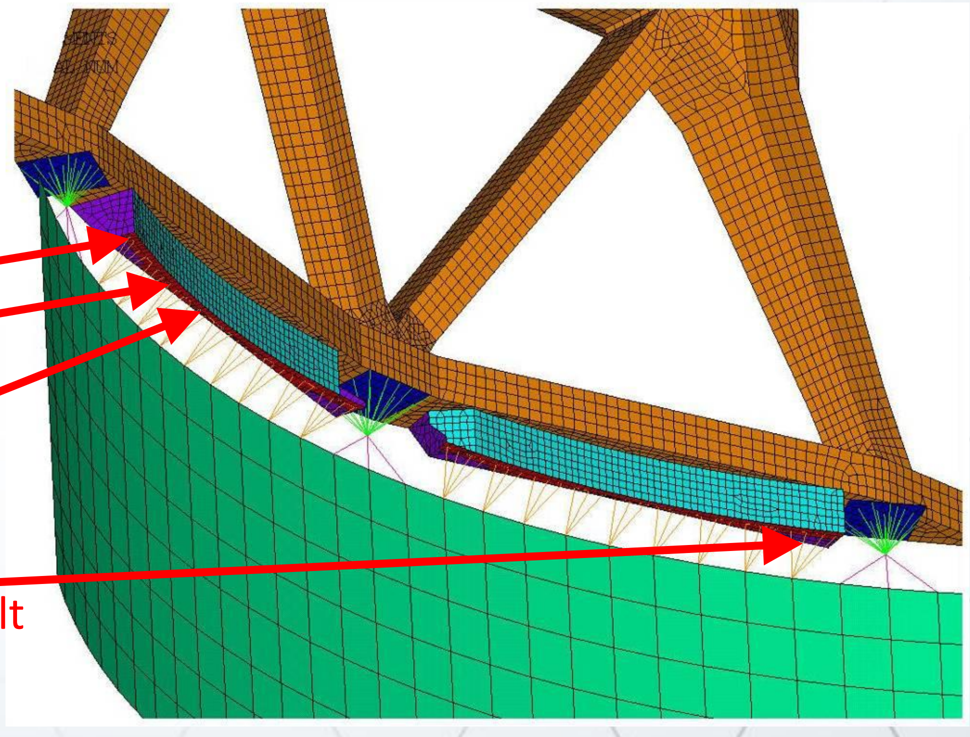
Cogging vibration due to misalignment (Monte Carlo)

- Forcer installation tolerance with precision alignment ±0.2 [mm]
- Small - less than 1% of pitch - but matters
- Distribution of residual cogging force for 2nd harmonic
  - Worst case (no offsets) is hundreds of Newtons
  - RMS value due to misalignment is 13.9 Newtons
  - Further reduced by AO bandpass



Non-collocation effect

- Strategy so far: adjust relative phase between forcers to (mostly) cancel net torque from all 56 forcers
- However, even with zero net torque, there is still a response because the forcers are not collocated

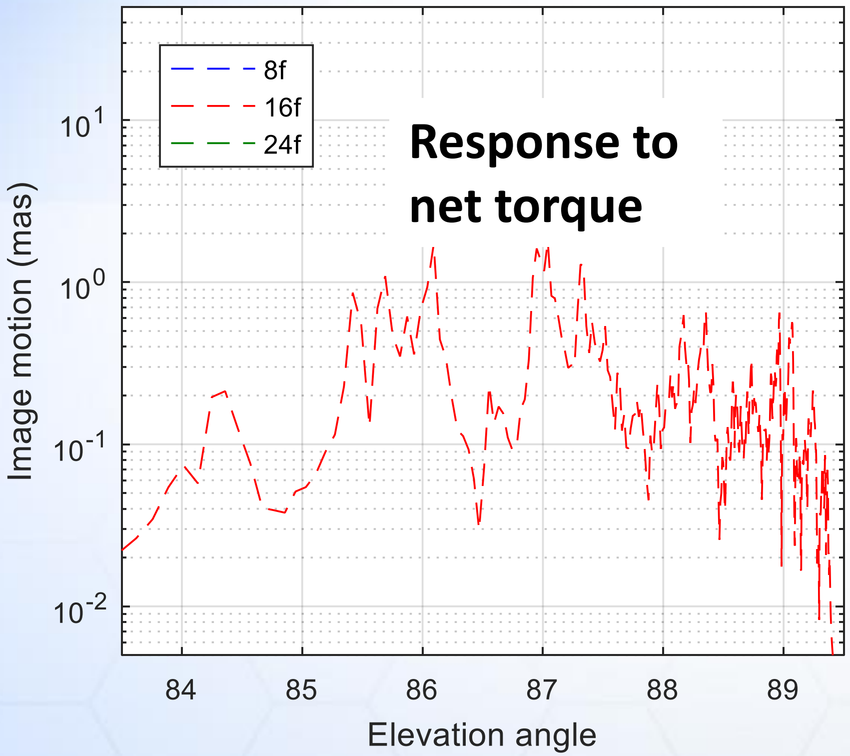


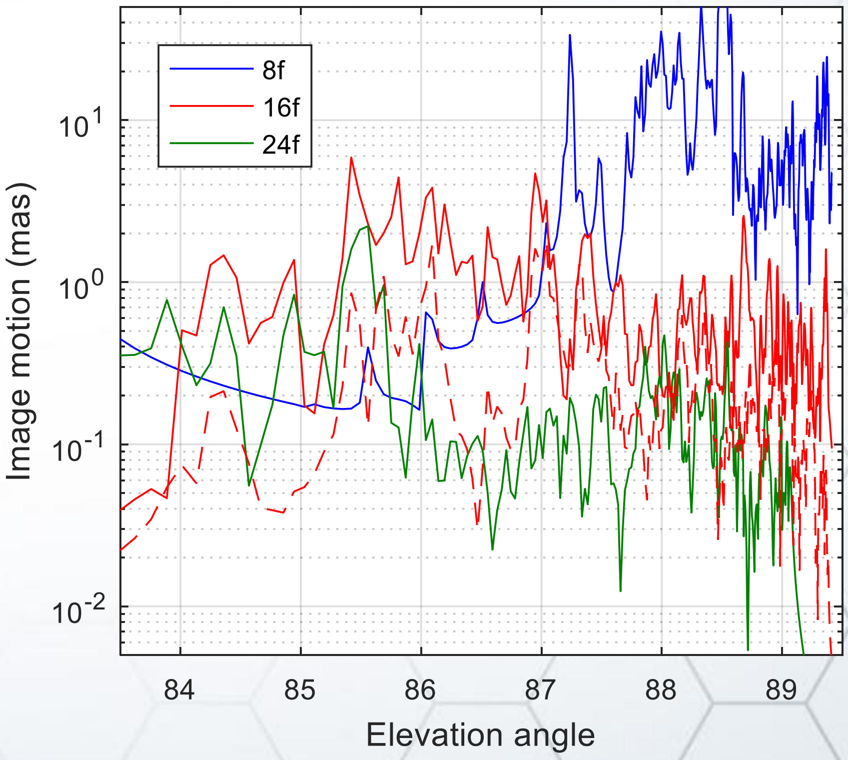
+1N here and -1N here result in small image motion

+1N here and -1N here may result in significant image motion

Non-collocated effect can be significant

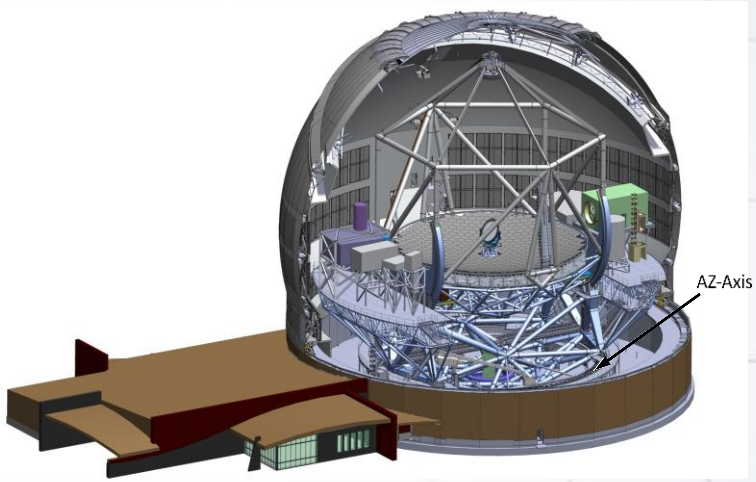
- Example assumes offsets with no misalignments
- Exactly cancels 8f and 24f harmonics, and most of 16f (left plot)
- 8f and 24f "pop back up" due to non-collocations (right plot)





Cogging Conclusions

- Cogging frequencies overlap structural resonances for extremely large telescopes, leading to significant vibration and increased wavefront error
- Spatial offsets between forcers can reduce, but
  - Misalignment limits effectiveness
  - Can cancel net torque, but still produces image motion due to non-collocation



- Possibly increase keyhole restriction
- May need multiple narrow-band notches in AO rejection
  - Frequencies are well-known

Conclusions

- The traditional route of “best engineering practices” first and mitigate vibration problems afterwards is not sufficient in the era of GSMT’s designed for AO
- AO rejection error means we likely need to increase our WFE allocation to vibration and/or tighten specifications on allowable forces
- Measurements to date suggest TMT vibration budget is possible but far from easy
- Would like to measure more equipment at observatories
- Ideally perform an end-to-end measurement at a telescope with a FEM
- We hope this will be a model for future observatory design!

Acknowledgments

The TMT Project gratefully acknowledges the support of the TMT
collaborating i … ia Institute of
Technology, the … al Astronomical
Observatory of … bservatories of
China and their … t of Science and
Technology of I … nd the National
Research Counc … d as well by the
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U.S. National Sc … tutes of Natural
Sciences of Japan, and the Department of Atomic Energy of India.