Dynamic Performance of TMT
(Wind & Vibration)

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Outline

- Strategy and overview
- Modeling of wind loads
- Modeling and response of image jitter and low-order aberrations
  - Including forces on enclosure
- Modeling and response of M1 segment dynamic response
- Vibration (less mature)
Design strategy for wind:

- Enclosure designed to shield telescope top end (M2 & LLT)
  - On average, 15% of external wind (with vents closed), based on CFD
  - At Gemini, can exceed 60% of external (without windscreen)
  - Additional venting required for thermal management

- Minimize upper-end wind cross-section
  - TMT cross-section smaller than Keck or Gemini

- Stiff structure: mount control bandwidth comparable to Keck
  - Depends on structural dynamics, damping
  - Performance scales with $1/(Jfc^{2.2})$

- We should expect image jitter due to wind significantly lower than existing 8-10m telescopes
  - 17 mas rms image jitter

- M1 segment response will be higher than Keck (compliance x2, target wind speed x2)
Wind Response Summary

- Response includes ~1-D image motion due to torque
  - Response is mostly due to finite elevation-axis mount control bandwidth
  - High wind response mostly due to loads on top end and support structure

- High spatial frequency M1 segment response is relevant for both AO and seeing-limited

- Correlated with mirror/dome seeing through wind speed
  - Optimum combined performance for ~1m/s target M1 wind speed

Seeing-limited performance:
- Image jitter: Mean PSSn ~ 0.9983
- Optics misalignment: PSSn ~ 1
- M1 segment: PSSn ~ 0.9942
  - At 1 Hz M1CS bandwidth
  - Combined wind: 0.9925

AO performance:
- M1 segment: ~7 nm uncorrectable wavefront error at 1 Hz bandwidth

Budgets

\[ \begin{align*}
\text{Seeing-limited performance:} & \\
\text{Image jitter: Mean PSSn} & \approx 0.9983 \\
\text{Optics misalignment: PSSn} & \approx 1 \\
\text{M1 segment: PSSn} & \approx 0.9942 \\
\text{At 1 Hz M1CS bandwidth} & \approx 0.993 \\
\text{Combined wind:} & \approx 0.9925 \\
\text{AO performance:} & \\
\text{M1 segment:} & \approx 7 \text{ nm uncorrectable wavefront error at 1 Hz bandwidth} \\
\end{align*} \]
Modeling Overview

- CFD
- Soil/pier FEA
- Wind loads
- Vibrations
- Telescope FEA
- M1 CSI Model
- M1 segment Model
- Integrated Model
- Image jitter, low-order blur
- PSS Estimator
- PSS
- AO Simulation
- Residual WFE
- M1CS bandwidth
- M1 segment displacement
- static
dynamic
Wind tunnel test validate

Computation (CFD)

Design

Look-up table for integrated modeling simulations

Retain big picture, not details

Gemini data
Wind Probability Distributions

- Vent opening chosen to give a 1m/s target mean wind speed on M1
- Probability over orientation and external wind speed

\[ p_{\text{rms}} = \left( \frac{1}{2} \rho u^2_{\text{eff}} \right) \]

\[ F_{\text{rms}} = A \cdot C_D \left( \frac{1}{2} \rho u^2_{\text{eff}} \right) \]
- Spatially averaged pressure spectrum, compared with a von Karman fit
- Corner frequency set by local velocity and aperture or vent height

**Diagram Description:**

- **External wind variation (?)**
- **Corner frequency:** $u_{local}/D$
- **0/30 az/za**
- **11m/s external Vents o/h**
- **Some data sets have some extra high freq. turbulence**

**Axes:**
- **Frequency, normalized by $u_{external}/D$**
- **PSD amplitude**
Wind Modeling Spectrum

- We want the force spectrum, not the pressure spectrum
  - Need to account for frequency-dependent spatial decorrelation

- Spatial correlation assumes frozen turbulence
  - Introduces additional roll-off (aka “Aerodynamic attenuation”) with corner frequency dependent on spatial scale; $f_s = U/(2L)$
  - Number of independent turbulent structures along length $L$ is $n = 2Lf/U$
    - Correlation length is $\pm 1/4$ wavelength

$$\Phi_F(f) \propto \Phi_p(f) \frac{1}{(1+(f/f_s)^2)^{1/2}}$$
## Telescope Contributions

Contribution to image motion from structural members includes effects of decorrelation.

<table>
<thead>
<tr>
<th>Number</th>
<th>Projected Length L (m)</th>
<th>Diameter or width D (m)</th>
<th>Number n</th>
<th>$C_D$</th>
<th>Moment arm M (m)</th>
<th>Product $DLMC_D\sqrt{n}$ (Nm/Pa)</th>
<th>Relative Image Motion variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.5*</td>
<td>0.66**</td>
<td>3</td>
<td>2</td>
<td>19.9</td>
<td>614</td>
<td>26%</td>
</tr>
<tr>
<td>2</td>
<td>15.5*</td>
<td>1</td>
<td>4</td>
<td>1.2</td>
<td>14.4</td>
<td>536</td>
<td>10%</td>
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<tr>
<td>3</td>
<td>14.4</td>
<td>1</td>
<td>6</td>
<td>1.3***</td>
<td>7.2</td>
<td>322</td>
<td>1%</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>1</td>
<td>6</td>
<td>1.2</td>
<td>7.2</td>
<td>487</td>
<td>1%</td>
</tr>
<tr>
<td>Top end</td>
<td>$A = 10m^2$</td>
<td></td>
<td></td>
<td>1.5</td>
<td>25</td>
<td>375</td>
<td>63%</td>
</tr>
</tbody>
</table>

*includes projection wrt wind  **increased for LGSF ducting  ***increased due to ladders
Outline

- Modeling of wind loads
  - Orientation dependence, spectra, cross-sectional areas
- Modeling and response of image jitter and low-order aberrations
  - Parametric wind, telescope FEM, MCS, enclosure forces
- Modeling and response of M1 segment dynamic response

- Vibration
Integrated Performance Model

- Wind disturbance (Parameterized fit to CFD)
- Structure (finite element model of TMT structure)
- Optics (Linear optical model)
- Control: drives (encoder feedback), optical guiding (to mount), M1, M2
- Coded in Matlab using DOCS toolbox
Design by DSL (Vancouver, Canada)
- Some design iterations to maximize mount control bandwidth

Modes extracted from ANSYS and imported into Matlab
- 500 modes used for MCS design, low spatial-frequency response
- 2000 modes used for M1CS design, M1 segment (high spatial-frequency) response

0.5% structural damping assumed
- Only affects achievable control bandwidths (MCS, M1CS)
Mount Control

- Finite bandwidth of elevation mount drives performance
  - Image motion due to wind scales approximately with $1/(Jf_c^{2.2})$
  - Damping of 0.25% → bandwidth reduced by ~6% (15% higher image jitter)
  - Azimuth motion significantly smaller

- Straightforward SISO PID with structural filter
- Optical tip/tilt (guiding) via Az/El (~0.1 Hz bandwidth)

Elevation loop TF
-3 dB Bandwidth = 0.63 Hz

Torque response $G/(1+GK)$
Image Jitter
Wind Performance

- Image jitter probability distribution over orientation and wind speed:
  - Median: 5 mas,
  - Mean: 10 mas,
  - Rms: 17 mas
  - 85th%: 18 mas

- Contribution due to misalignment is negligible

- Contribution to PSS (point source sensitivity) is small
Wind Loads on Enclosure

- Image jitter due to wind loads on enclosure not included above

1. Estimate wind force on enclosure from CFD
2. Pier motion due to wind force is obtained from FEA of soil/pier
3. Telescope response due to pier motion is obtained from integrated model

Conclusion:
- For Armazones, not a significant contributor (~1 mas at 10m/s external)
- For Mauna Kea (softer soil), increases image jitter by ~10%
Outline

- Modeling of wind loads
  - Orientation dependence, spectra, cross-sectional areas
- Modeling and response of image jitter and low-order aberrations
  - Parametric wind, telescope FEM, MCS, enclosure forces
- **Modeling and response of M1 segment dynamic response**
  - Time-domain frozen turbulence, quasi-static telescope, M1CS

- Vibration (less mature)
M1 Segment Dynamics
Wind Modeling Approach

Goal:
- Seeing-limited: contribution to PSSn > 0.9993, \( \theta(80) < 20 \text{mas} \)
- With adaptive optics: uncorrectable residual wavefront less than 10nm rms (dominated by segment edge discontinuities)
- Need to accurately capture spatial correlation of wind
- Achievable M1CS bandwidth is separately estimated
  - Assume 1Hz, with 0.5 Hz on astigmatism and 0.1 Hz on M1 focus

Time domain analysis: propagate von Karman pressure screen
- Integrate force, moments on each segment
- Response includes mirror cell (quasi-static) and segment (dynamic if soft actuator used)
- Global piston/tip/tilt projected out of all responses
No M1CS global control
223 nm rms surface error

With control:
14 nm rms surface error

Estimate with AO:
7 nm rms WFE
Requirements:
- AO: 10nm uncorrectable wavefront error \( \rightarrow \) roughly 0.65 Hz bandwidth
- Seeing-limited: PSSn contribution exceeds requirement at 1 Hz bw, but acceptable (unacceptable at 0.5 Hz M1CS bandwidth)

Simulation parameters:
- Mean, rms wind = 1m/s
- OS = 30m, 5m, 1m
- Fraction of energy = 25, 50, 25% respectively
- Scales with \( u^3 \)
- Depends mainly on 5 & 1m turbulence
Wind Response Summary

- **Image jitter, rms 17mas → mean PSSn = 0.9983**
  - Mostly due to wind on top end
  - Mostly due to finite elevation axis bandwidth
  - Response due to enclosure wind is small (<1mas at 10m/s external)

- **M1 segment dynamic response, WFE = 7nm, PSSn = 0.9942**
  - At $u_{M1} = 1$m/s (proportional to $u_{M1}^3$)
  - At 1 Hz M1CS bandwidth

- Doesn’t meet error budget, but relatively small numbers
  - Image jitter will be significant some of the time
Outline

Wind

- Modeling of wind loads
  - Orientation dependence, spectra, cross-sectional areas
- Modeling and response of image jitter and low-order aberrations
  - Parametric wind, telescope FEM, MCS and aO loops
- Modeling and response of M1 segment dynamic response
  - Time-domain frozen turbulence, quasi-static telescope, M1CS

Vibration
Vibration

- Requirement: LOS < 1mas, WFE < 10nm (above 20 Hz)
- Includes equipment vibration and micro-seismic
- Narrowband vibration from equipment is clearly an issue at Keck
  - TMT AO needs vibration response significantly lower than Keck
- Difficult to predict vibration levels

- Approach:
  - Characterize vibration transmission through structure (see paper)
  - Use to set requirements on source amplitudes
  - Compare with measurements at existing observatories to assess whether requirements are realistic (SPIE 7017-xx has LIGO example)
  - Implement best practices on all sources to minimize vibration
    - Choose quiet equipment, locate away from telescope, and isolate
    - Avoid lightly-damped segment resonances in 25-30 Hz range
Keck Experience...

Equipment vibration sources:
- Hydraulic oil cooling pumps
- Keck exhaust fans (broad frequency)
- Office air conditioning system attached to concrete slab
- Instrumentation and electronics fans
- Fluctuations in Alt, Az drive hydraulic oil pressure from main and booster circulation pumps
- Air compressor and vacuum pumps
- Compressed air distribution system
- Glycol cooling systems for instruments, building and oil chillers
- Closed cycle refrigerator of NIRSPEC in Nasmyth platform
- Dome bogies and motors
- 60Hz power lines (seen at Keck with all equipment off and at Gemini)
- Water chillers
- Humidifiers

Recommended best practices:
- Vibrationally isolate the pier & observatory floor
- Construct a machine room that is a long way from the telescope, houses ALL machinery, and has a very heavy floor, isolated from ground
- Vibrationally isolate all machinery
- Smooth and damp all fluid (air, oil, coolant) lines
- Use only flexible pipes for fluids
- Use quiet low vibration high frequency machinery
- Maintain fluid lines, smoothing equipment regularly
- Make sure dome drive, brakes, motion is smooth
- Do not put any machinery on Nasmyth platforms
- Do not use a/c (office, clean rms) while observing
- Over-spec power cabling, cut power w. observing
- Vib. mitigation procedures, continuous monitoring
- Drive all machinery w/ programmable variable speed drives
- Design out mechanical resonances
- Vibrationally isolate all electronics racks
- Vibration review for all Eng. Change Requests
Keck M1 Vibration
(Dataset may not be representative)

- Rms over 6 accels on M1
- 29.6 Hz tone in particular has been problematic at Keck

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Position PSD (nm²/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1 Hz</td>
<td>81 nm</td>
</tr>
<tr>
<td>29.6 Hz</td>
<td>20.5 nm</td>
</tr>
<tr>
<td>32.9 Hz</td>
<td>10.3 nm</td>
</tr>
<tr>
<td>47.4 Hz</td>
<td>7.03 nm</td>
</tr>
</tbody>
</table>
Status & Future Work

- (Mean) Contribution to error budget due to wind is exceeded
  - PSSn of 0.9925 vs 0.9973
  - Mostly due to M1 segment dynamic response (at 1 Hz bandwidth)
  - AO performance acceptable at M1CS bandwidth of 0.7 Hz
- Vibration propagation quantified, but source amplitudes unknown

Future work:
- Wind-tunnel test planned to validate enclosure design
- Further measurements at Keck on wind to improve comparison
- Measure source and response vibrations at Keck, measure acoustic environment
- Refine M1 segment response analysis to incorporate CFD knowledge of spatial variability of mean and rms wind
Acknowledgments

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