E-ELT vibration modeling, simulation, and budgeting

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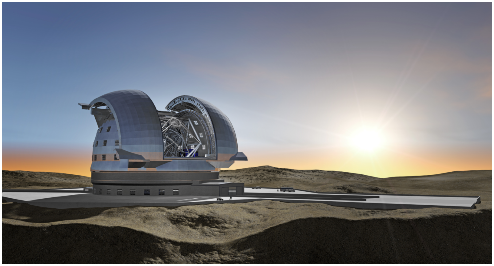
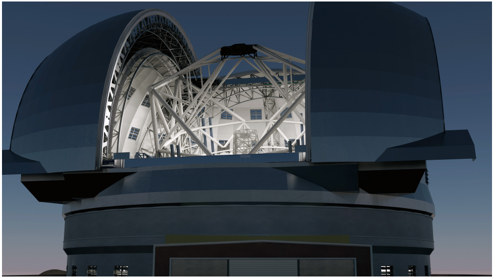
E-ELT





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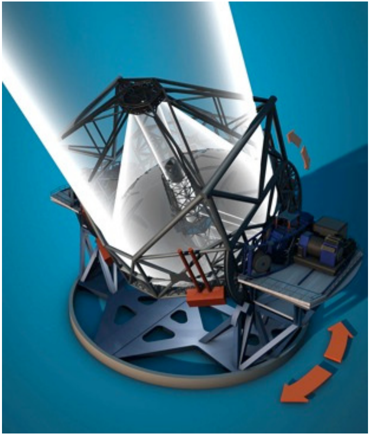
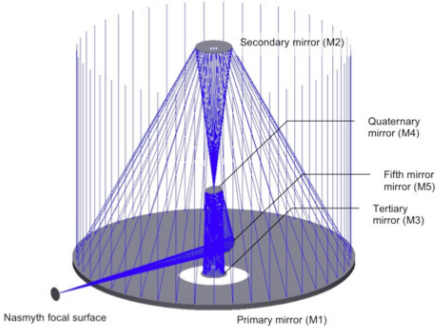


- Alt-Az structure each $\simeq$ 2000 T
- Altitude supported and driven on cradles
- Azimuth supported and driven on two rings

E-ELT



- 5 mirrors
- M1 (40-m class) aspherical segments (798 hexagons of 1.4-m)
- M2 and M3 convex and concave aspherical: active position and shape control
- M4: adaptive mirror
- M5: compensate image motion (field stabilization)
- Nasmyth platforms: instruments and on-sky metrology for wavefront control

Outline

- E-ELT modeling, analyses and simulation approach (3 main toolkits)
  - Active Optics and Phasing Toolkit (ray-tracing, see Henri)
  - Adaptive Optics Toolkit (Octopus, see Miska)
  - Telescope and Hosting units Dynamical and Control Toolkit

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  - Active Optics and Phasing Toolkit (ray-tracing, see Henri)
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  - Telescope and Hosting units Dynamical and Control Toolkit
- Vibration modeling, simulation and budgeting
  - Example: vibrations at Nasmyth platform

Modeling, Analyses and Simulation: Philosophy

Objective: Analyze impact of various error sources, e.g. gravity, temperature, wind, vibration, atmosphere

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Objective: not only to predict the performance of the telescope

- error budgeting
- derive requirements for subsystems
- understand the behavior of the sub-units in the telescope
- evaluate various control strategies

Modeling, Analyses and Simulation: Philosophy

- Differences in temporal and spatial frequencies of the perturbations
- Time scale differences in dynamics and control loops

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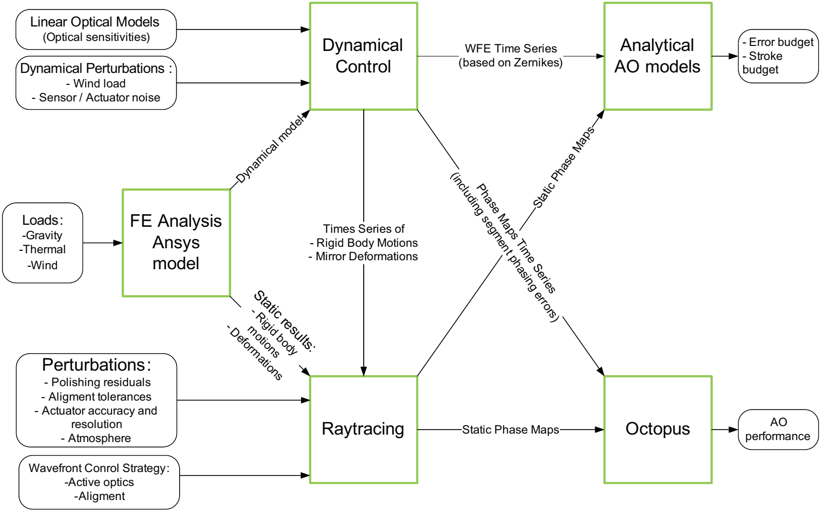
Splitting the analyses and simulation environments $\Rightarrow$

- provides more flexibility to adjust models to dedicated purposes
- reduce the computational effort

Modeling, Analyses and Simulation: Toolkits



Dynamical Toolkit: Vibration

One of the main contributors to the wavefront error: 'Vibrations'

- Excitations resulting from different equipments on the observatory
- Forces $\Rightarrow$ exciting the mechanical resonant modes of the telescope structure and hosted units
- Transmitted through the mechanical structure $\Rightarrow$ WFE

Vibration error budget

- total: 50 [nm] rms for all vibration sources
- top down ad-hoc allocation
- dynamical model of telescope structure/hosted unit + optical model + control model

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$\Rightarrow$ Sensitivity Analysis

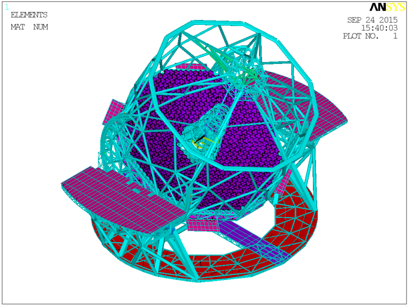
identify the most sensitive units (contributors), sources and respective frequency zones

Approach: Sensitivity analysis

1. deriving the frequency responses from the potential vibration sources at different locations in the telescope to the optical wavefront error
2. identification or estimation of potential vibration sources frequency and amplitudes

Sensitivity analysis: Modeling

Finite Element Model (FEM) of structure + hosted units



- Dome and Main Structure: mainly input from telescope pier
- Instruments: six instruments located at the Nasmyth platforms
- Prefocal stations (PFS): two input sources
- Laser Guide Stars (LGS): four laser units at the location of the launching telescopes
- M2 to M5 units: separate input source at the center of gravity of each unit
- M1 unit: More than hundred electronic concentrator cabinets uniformly distributed over the M1 cell structure

Sensitivity analysis: Modeling

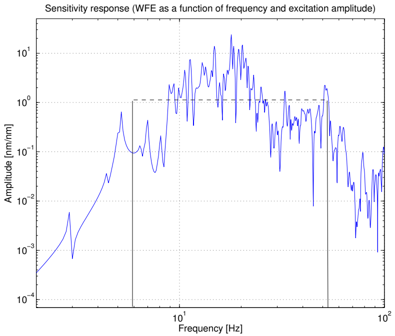
- FEM: telescope structure + detailed model of M2 and M3 units
- 7000 modes (14000 states)
- Inputs: three directional forces in [N]
  - six instruments at Nasmyth A and B platforms
  - four laser heads
  - mirror units M2 to M5
  - electronic cabinets distributed over M1 unit
  - at telescope pier: three directional motions instead of forces
- Outputs:
  - six rigid body motions of each mirror units
  - interface motions of telescope structure to the hosted units
- Optical model: sensitivity matrix
- Control model: rejection responses of main control loops, e.g. main axes servo, field stabilization, AO loops

Sensitivity analysis: Simulation

- Model order reduction for selected inputs-outputs: state-space models (400 states)
- both time simulation and frequency analysis $\Rightarrow$
  - level of motion/acceleration/velocity at different mirrors, interface points
  - wavefront error

Sensitivity analysis: example

transmission function from telescope pier motion to wavefront (tilt error)



- $< 5Hz$ less sensitive: global motion of the structure and the efficiency of the control loops
- $[5Hz \quad 50Hz]$ most sensitive: local modes + high optical sensitivity, e.g. M2 unit
- $> 50Hz$ less sensitive: overall inertia (structure and mechanical units) roll-off

Error budgeting

- Derive sensitivity responses for all mentioned sources
- Sensitivity is not uniform over all temporal frequency ranges $\Rightarrow$ requirement breakdown for different frequency

1. Allocate WFE to the main sources
2. Estimate the allowable force or produced motions at key interface points
3. Express them in verifiable engineering quantities: e.g Force/acceleration rms in different frequency intervals
4. Based on experience/measurement data and engineering judgment iterate and refine the initial allocations

Model uncertainty + Multiple inputs: what to do?

- exact frequency and shape of the mechanical modes in the model are not necessarily identical to those of the final design (model uncertainty)
- cumbersome and none trivial/realistic trying to guess and derive the requirements for each possible source and direction individually (multiple inputs)

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$\Rightarrow$ Introduce conservatism

But how?

Conservatism: How?

- $G(j\omega)$: mechanical frequency response + optical sensitivity
- $S(j\omega)$: wavefront control rejection frequency response
- $||WFE||_2$: wavefront error rms
- $||X||_2$: vibration (forces/motions) rms

Conservatism: How?

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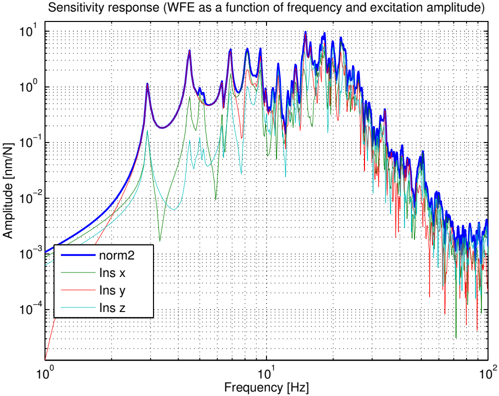
$$||WFE||_2 \leq ||G(j\omega)S(j\omega)||_\infty ||X||_2, \qquad \forall \omega \in [\omega_i, \omega_j]$$

Largest direction (maximum singular value) and largest amplitude for a given frequency interval

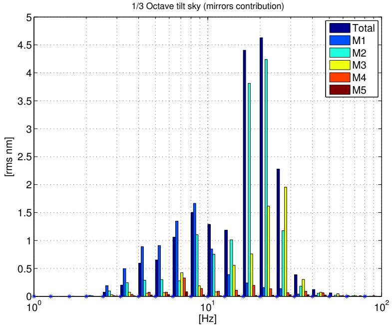
Example: Vibration sources at Nasmyth platform

- excitations at interface of the instruments to Nasmyth in three directions (x, y, z)
- input is defined as force in [N] for these three directions



Example: Sensitivity analysis

- Simulation (in time domain)
- Inputs: uncorrelated, limited bandwidth white noise
- Amplitude Spectral Density: 0.5 $N/\sqrt{Hz}$, [0-100] Hz (equivalent to a force of 5[N] rms)
- Frequency intervals: example 1/3-octave bands



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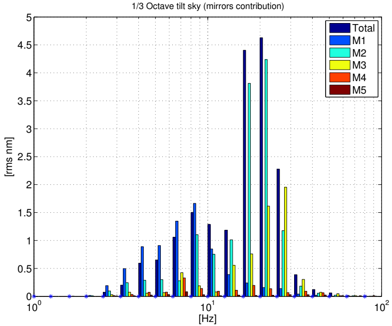
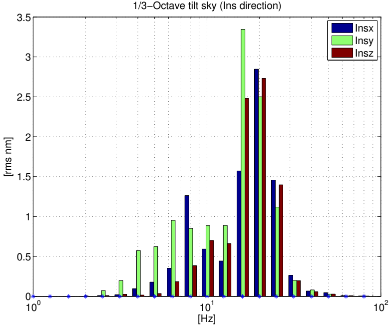
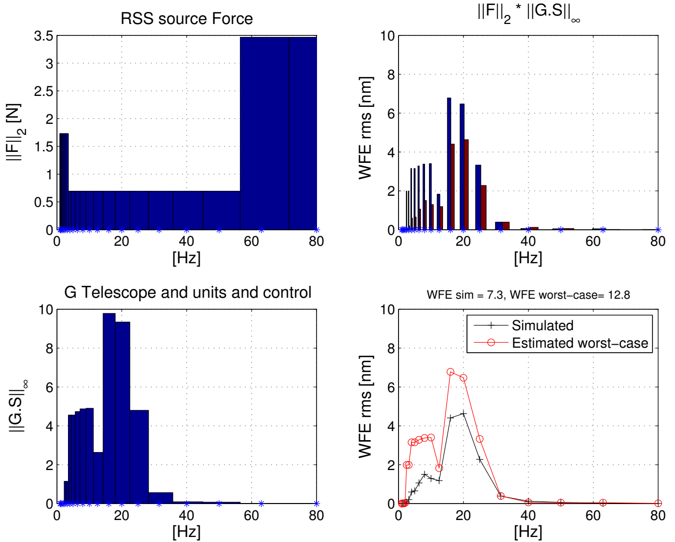




Specified requirements, budget verification



Conclusions

- A model-based vibration budgeting approach
- A sensitivity analysis at the heart of the budgeting effort
  $\Rightarrow$ Identify the most sensitive locations of vibration sources and frequency zones
- Requirements are expressed in terms of rms force/motion in different frequency intervals
- Reduce risk:
  $\Rightarrow$ Use largest possible amplification and direction in different frequency intervals

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  $\Rightarrow$ Identify the most sensitive locations of vibration sources and frequency zones
- Requirements are expressed in terms of rms force/motion in different frequency intervals
- Reduce risk:
  $\Rightarrow$ Use largest possible amplification and direction in different frequency intervals
- Further investigations, measurement campaigns, developing verification methods, better understanding of the complex mechanism of generation and transmission of vibrations