Telescope Wavefront Errors

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Tasks of WFC at E-ELT

- Help System Engineering develop and maintain the technical budgets
- Develop Control Strategy
- Define WFC I/F to instruments.
How we do it

• Define a WFC plan, describing:
  – how we phase M1
  – how we maintain the telescope collimation
  – how we reject the dynamic perturbations

• Evaluate error propagations -> Simulate
  – FEM
  – Dynamic simulations
  – Ray tracing of segmented model
  – AO simulations

• Wide range of spatial and temporal time scales
  – No end to end simulations
  – Simulation tools are customized and interfaced to one another for each question addressed by the team.
Performance Analysis Purpose & Process

1. Identify Errors
2. Allocate Errors
3. Write Requirements
4. Design
5. Define Control Strategy
6. Model
7. Evaluate Error Propagation
8. Optimal Propagation
9. Atmospheric Propagation
10. Mirrors
11. Structure
12. Actuators
13. Turbulence
14. Internal Sky
15. Manufacturing
16. Integration
17. Noise
18. Model Errors
19. Control Algorithms
20. Adaptive Optics
21. ES Loop 35Hz
22. Main Axes Loop 1 Hz
23. Low Order Optimization 0.1 Hz
24. Calibrations << 1Hz
WFC Products

• Sensitivity analyses
  – Provides the connection between sub-systems requirements and error budget.

• Calibration and wavefront control baseline

• WF interfaces

• Requirements to control equipments
  – Wavefront Sensors
  – Metrologies (e.g. Edge Sensors)
  – Actuators (stroke, resolution, ...)

E-ELT Data Simulation Workshop, 2016-04-15
Differences VLT vs. E-ELT

• The wavefront delivered by the VLT is seeing limited:
  – Wavefront errors created by the telescope are continuous and slow
  – Always a minor distortion to the power spectrum of the free atmosphere.
  – Outstanding exception = vibrations
    • 10 to 15 mas rms of tip-tilt at a few harmonic frequencies.

• VLT has few sensors and actuators
  – Failure of an equipment = down time

• E-ELT is not like this.
Wind shake: Altitude Structure

- From VLT to E-ELT:
  - Larger structure
    - Lower eigen frequencies
    - Higher sensitivity to dynamic perturbations
  - K band diffraction limit from 56 to 12 mas.
- Large effort invested during all design phases
  - Driver to Main Structure requirements
  - 2 stage control strategy (M4 + M5) with enhanced rejection at low frequency
- Resulted in satisfactory performance
  - 1.6 mas rms in standard conditions
- E-ELT is VLT-like in this respect.
Wind Shake: M1

$\text{t} = 5.208\text{sec, M1: 375}$

$\text{t} = 5.208\text{sec, Residual: 4}$
Telescope collimation

- **M2**
  - High optical sensitivity
  - Large inertia
- **Resolution of positioning system incompatible with AO performance**
- **Phase B design conducted under constrained that M2 would not be repositioned during observation (1 hour).**
- **Studies concluded that this was not doable**
- **L1 requirement relaxed to 1 repositioning every 5 minutes.**
  - Performance and stroke budgets now ok
  - 20 mas (post AO) transient at low order optimization.
Plate Scale / field rotation

• The goal is that CCS holds the plate scale for 1 hour.

• Field rotation may not be predictable at the diffraction limit.

=> Instruments may need to incorporate secondary guiding for plate scale / field rotation.
M1

Error Budget, Level 1: M1
WFE = 78nm

- Segment Misfigure: 60nm
- Segment In Plane Displacement: 9nm
- Wind: 5nm
- Mirror Seeing: 15nm
- Edge Sensors: 30nm
- Segment Exchange: 35nm
Segment Misfigure Polishing

Polishing Requirements (E-SPE-ESO-300-0150.2)

Warping Harness Model and Fitting Error

First polished prototype at SAGEM

Higher orders: 1/f² PSD

Prototype measurement

Simulated samples
Phasing

• Phasing procedure demonstrated at GTC.

• Baseline:
  – update of phasing solution every 2 weeks.
  – Local metrologies (Edge Sensors) maintain the phasing between calibrations
Offline Machine

Ray Tracing Model → Template

Online processing

Data → Fringes

Post-Processing

Sensitivity Matrices → Alignment Reference

Modus Operandi

FTP

Telescope

FTP

Sequence

Guiding (manual)

GTC Data

Measured OPD (nm)

Error Budget, Level 2: Prefocal Station - Phasing Probe

WFE = 36nm
Scalloping

• Scalloping is the result of a large focus error in M1 compensated elsewhere (e.g. with M2).

• Consequence: mismatch between radii of curvature of
  – Segments
  – Segments assembly

• High order wavefront error with first order discontinuities.

• Scalloping budget ~35nm but this is considered a technical risk.

• Risk mitigation:
  – Make Edge Sensors sensitive to M1 focus mode (PSG sensors).
  – Guide Probe WFS capable of observing scalloping at preset.
Segment in plane displacements

**Piston – Shear – Gap Edge Sensors**
- Optical calibration (Phasing) every 2 weeks
- PSG features
  - Full observability of mirror state
  - Performance against gravity and thermal perturbations limited by mounting errors.
- Installation Accuracy
  - Rotation Error = 1 mrad
    - To be measured with an accuracy of 0.1 mrad
  - Translation Error = 100 µm
    - Driven by capture range budget

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<th>amplitude</th>
<th>Corrections</th>
<th>SCAO</th>
<th>Error</th>
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<tr>
<td>Integration</td>
<td>1mm / 1mrad</td>
<td>✗</td>
<td>×</td>
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<td></td>
<td>6K</td>
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<tr>
<td>Temperature gradient</td>
<td>1K/42m/axis</td>
<td>✗</td>
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<td>3 nm</td>
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<td><strong>Total 11 nm</strong></td>
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Impact of differential gravity load from zenith to 45 deg

Impact of 20K ambient temperature change

1 mrad clocking error on segment #429
Phasing

• Difficulties:
  – Large number of DOF
  – In plane motions (PSG sensors)
  – Coupling between in-plane motion and ES signals.
  – New segments every day (re-coating)
  – Shape of segments behind the spider poorly observable
  – Local vibrations

=> Locally large discontinuities in the wavefront.
   ⇒ Diffraction effects in WFS?
• Shape of segments hidden by spider are poorly observable
  – Surface discontinuities at the edges of these segments
  – Propagation of phasing error

• Spider width = 530mm > r_0
  – Fragmentation of AO pupil
Operational incidents

• ES / PACT failures
• Missing segments