Telescope Wavefront Errors

Henri Bonnet

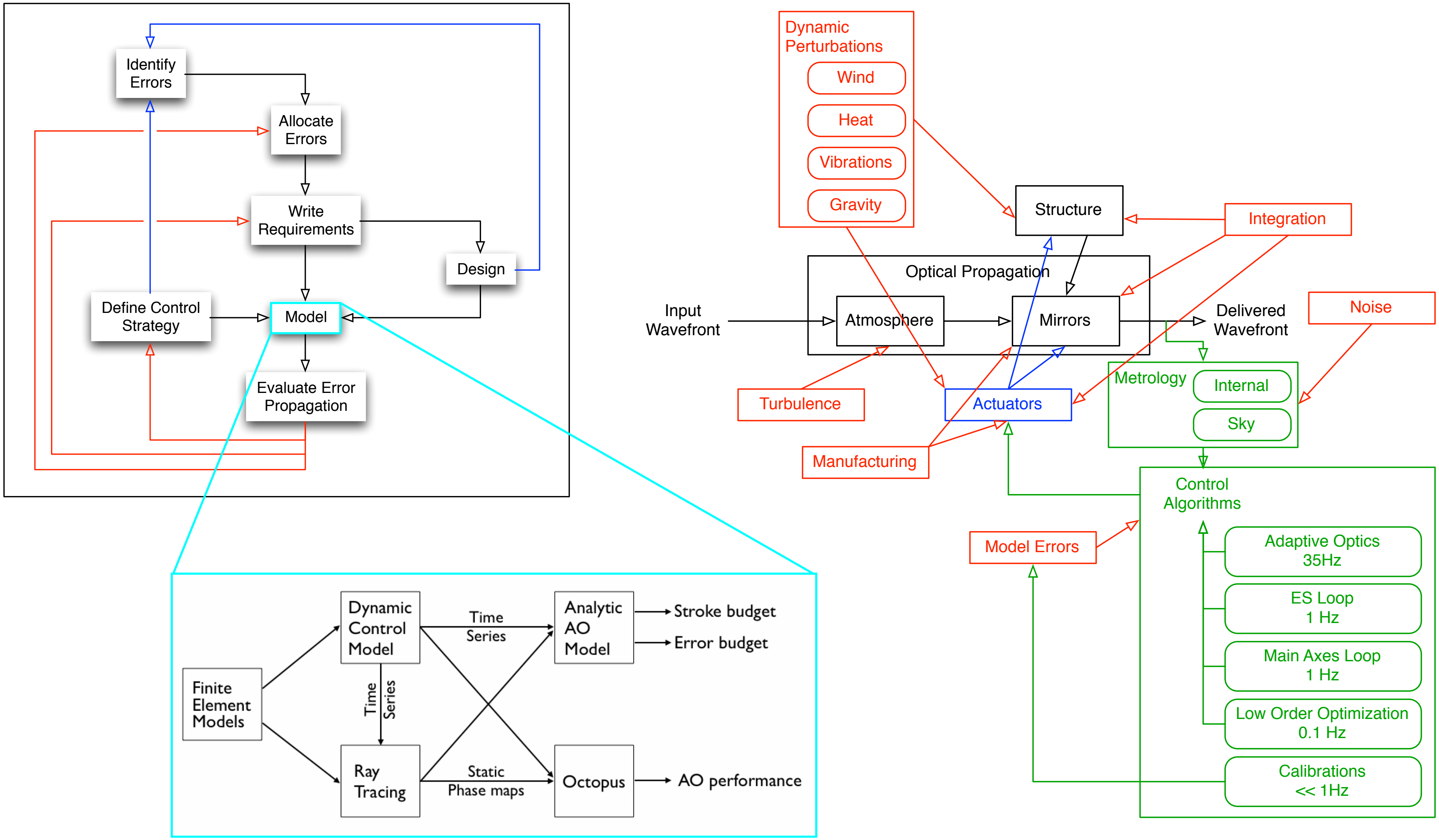
Tasks of WFC at E-ELT

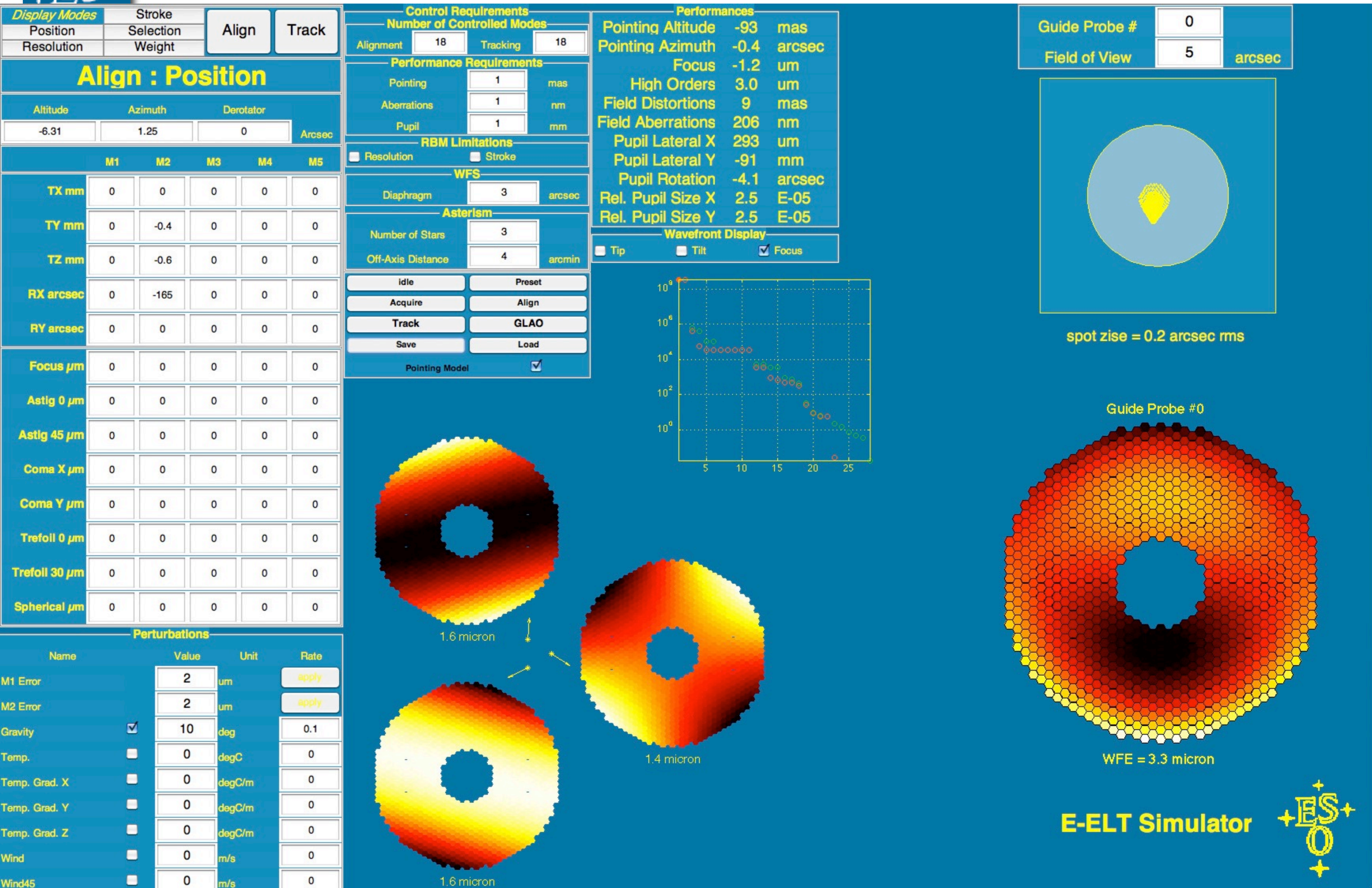
- Help System Engineering develop and maintain the technical budgets
- Develop Control Strategy
- Define WFC I/F to instruments.

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




Display Modes
Stroke
Position
Selection
Resolution
Weight
Align
Track
Align : Position
Altitude
Azimuth
Derotator
-6.31
1.25
0
Arcsec
M1 M2 M3 M4 M5
TX mm 0 0 0 0 0
TY mm 0 -0.4 0 0 0
TZ mm 0 -0.6 0 0 0
RX arcsec 0 -165 0 0 0
RY arcsec 0 0 0 0 0
Focus μm 0 0 0 0 0
Astig 0 μm 0 0 0 0 0
Astig 45 μm 0 0 0 0 0
Coma X μm 0 0 0 0 0
Coma Y μm 0 0 0 0 0
Trefoil 0 μm 0 0 0 0 0
Trefoil 30 μm 0 0 0 0 0
Spherical μm 0 0 0 0 0
Perturbations
Name Value Unit Rate
M1 Error 2 um apply
M2 Error 2 um apply
Gravity 10 deg 0.1
Temp. 0 degC 0
Temp. Grad. X 0 degC/m 0
Temp. Grad. Y 0 degC/m 0
Temp. Grad. Z 0 degC/m 0
Wind 0 m/s 0
Wind45 0 m/s 0
Control Requirements
Number of Controlled Modes
Alignment 18 Tracking 18
Performance Requirements
Pointing 1 mas
Aberrations 1 nm
Pupil 1 mm
RBM Limitations
Resolution
Stroke
WFS
Diaphragm 3 arcsec
Asterism
Number of Stars 3
Off-Axis Distance 4 arcmin
idle
Preset
Acquire
Align
Track
GLAO
Save
Load
Pointing Model
Performances
Pointing Altitude -93 mas
Pointing Azimuth -0.4 arcsec
Focus -1.2 um
High Orders 3.0 um
Field Distortions 9 mas
Field Aberrations 206 nm
Pupil Lateral X 293 um
Pupil Lateral Y -91 mm
Pupil Rotation -4.1 arcsec
Rel. Pupil Size X 2.5 E-05
Rel. Pupil Size Y 2.5 E-05
Wavefront Display
Tip
Tilt
Focus
1.6 micron
1.4 micron
1.6 micron
Guide Probe # 0
Field of View 5 arcsec
spot zise = 0.2 arcsec rms
Guide Probe #0
WFE = 3.3 micron
E-ELT Simulator

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, …)

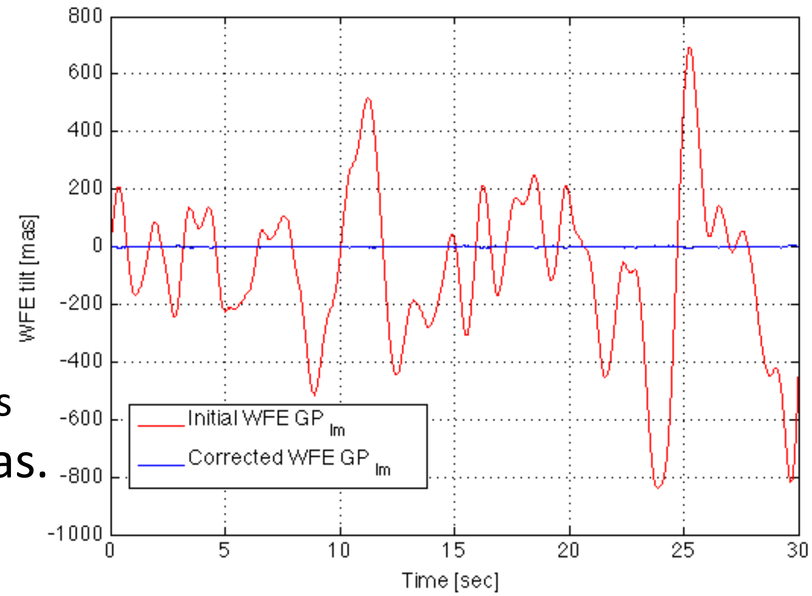
Differences VLT vs. E-ELT

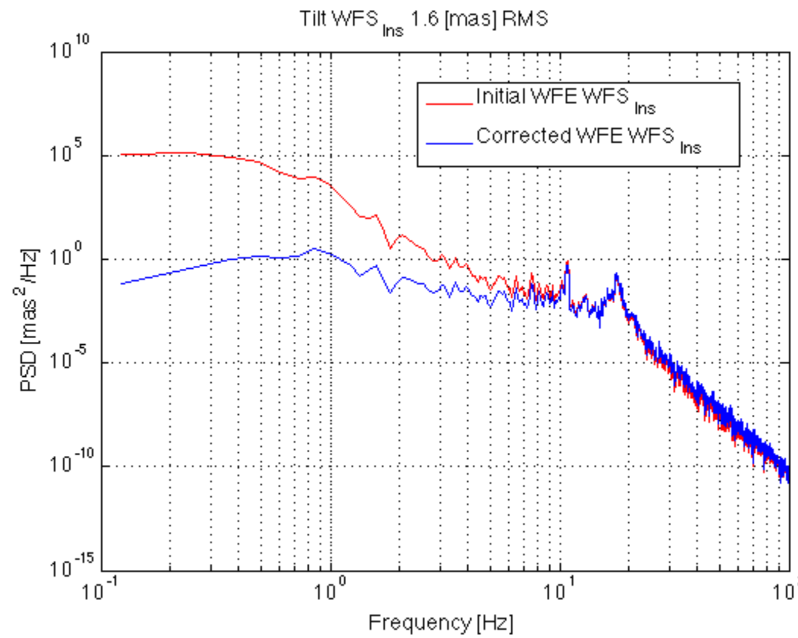
- The wavefront delivered by the VLT is seeing limited:
  - Wavefront errors created by the telescope are continuous and slow
  - Always a minor distortion to the power spectrum of the free atmosphere.
  - Outstanding exception = vibrations
    - 10 to 15 mas rms of tip-tilt at a few harmonic frequencies.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

- E-ELT is not like this.

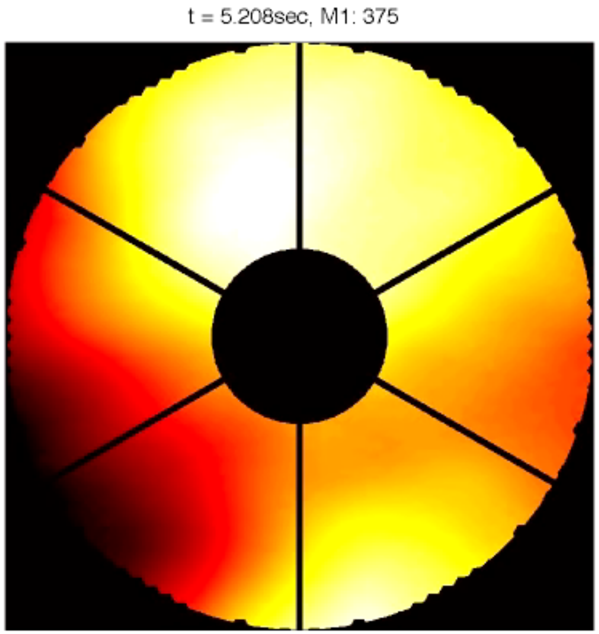
Wind shake: Altitude Structure

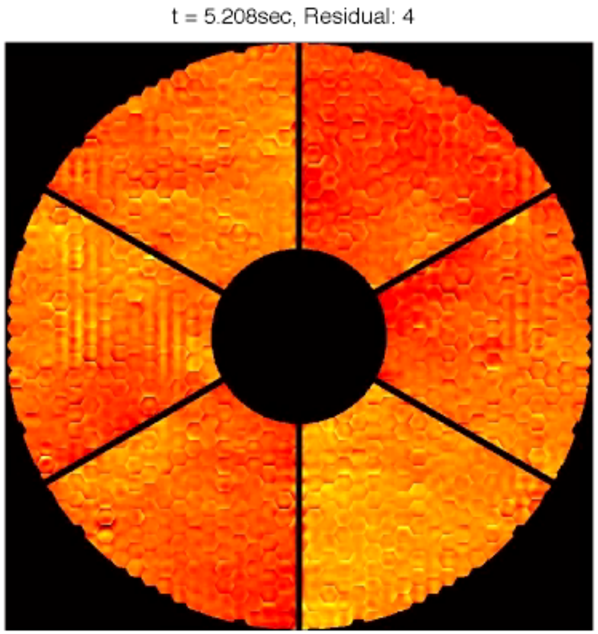
- From VLT to E-ELT:
  - Larger structure
    - Lower eigen frequencies
    - Higher sensitivity to dynamic perturbations
  - K band diffraction limit from 56 to 12 mas.
- Large effort invested during all design phases
  - Driver to Main Structure requirements
  - 2 stage control strategy (M4 + M5) with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





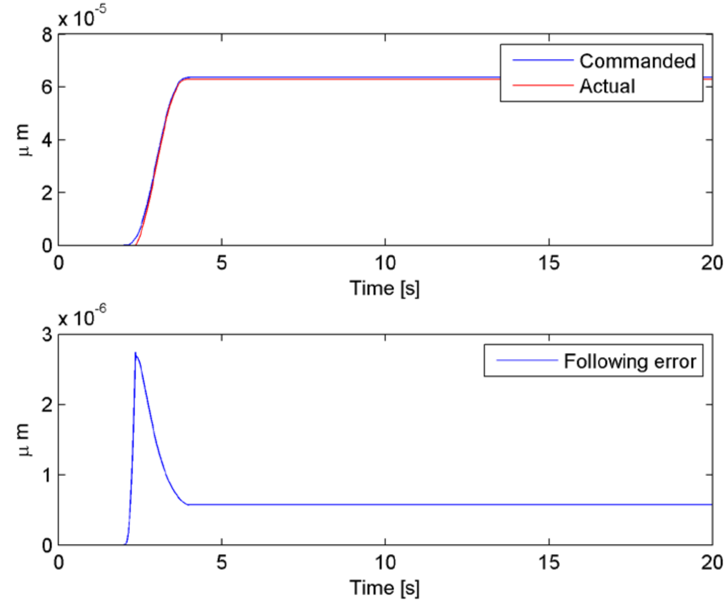
Wind Shake: M1





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.



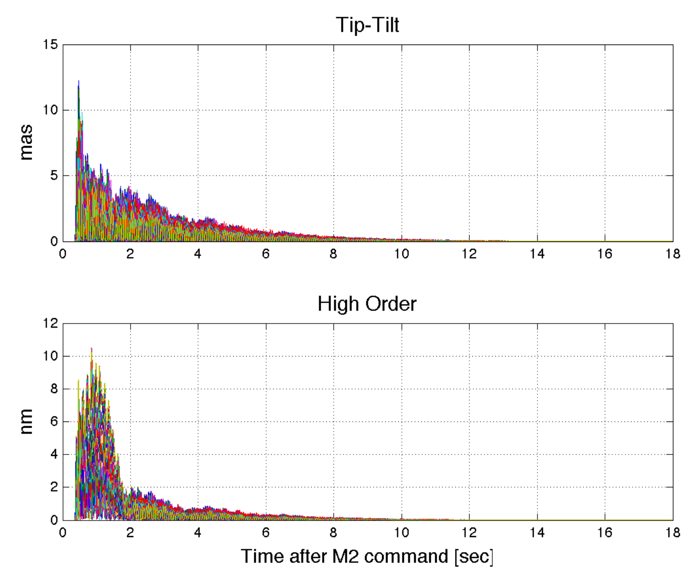
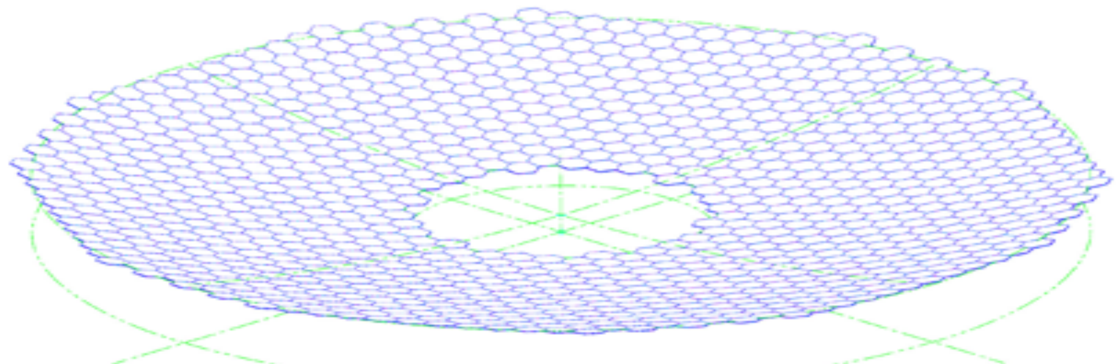


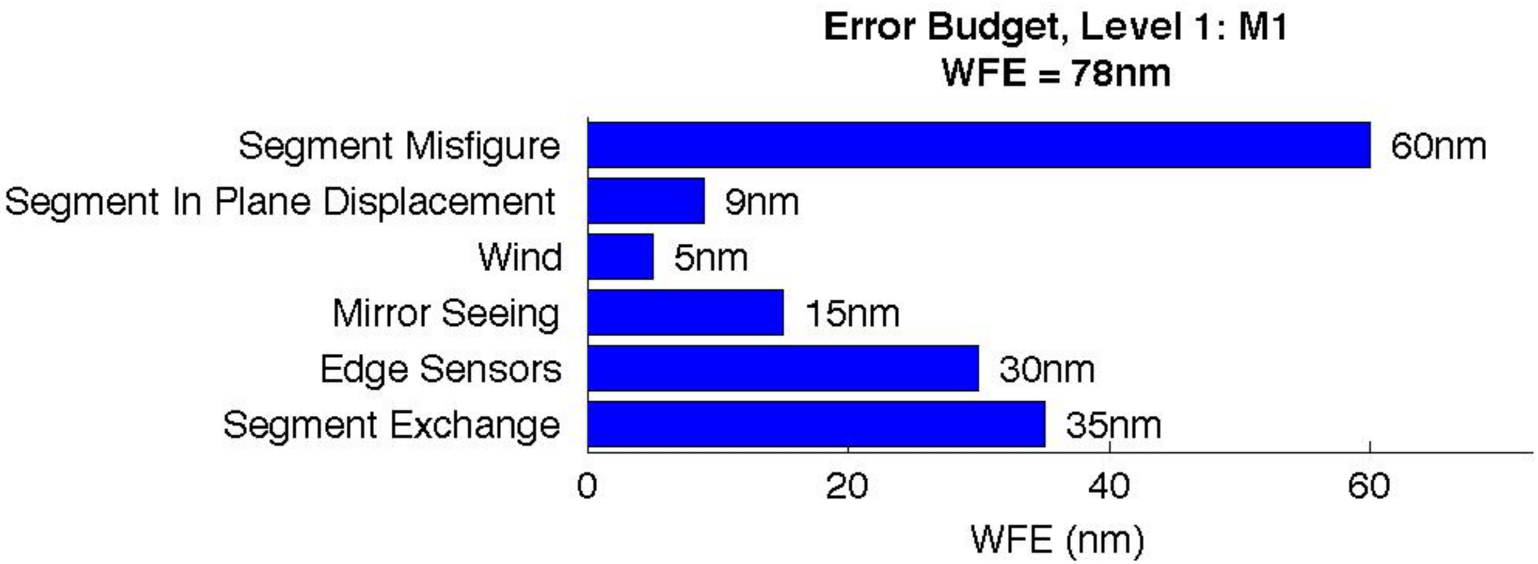
Plate Scale / field rotation

- The goal is that CCS holds the plate scale for 1 hour.
- Field rotation may not be predictable at the diffraction limit.

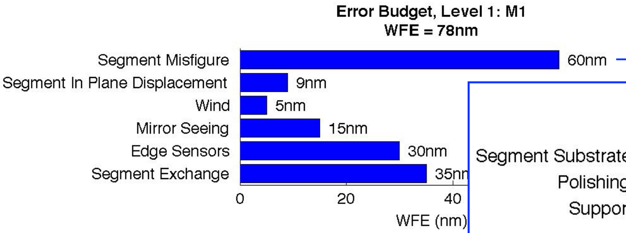
=> Instruments may need to incorporate secondary guiding for plate scale / field rotation.

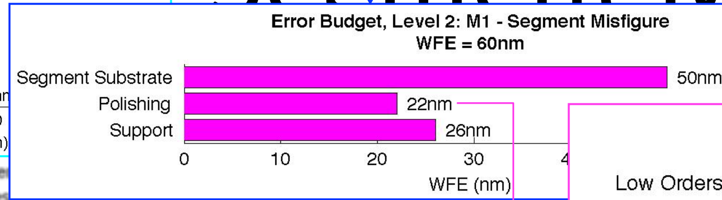
M1

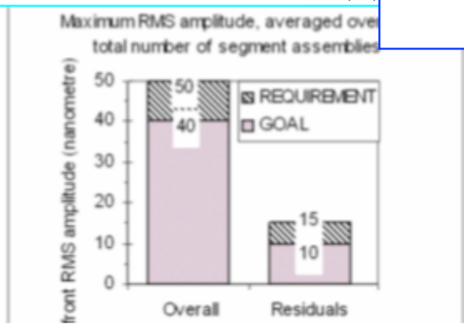



Error Budget, Level 1: M1
WFE = 78nm
Segment Misfigure
Segment In Plane Displacement
Wind
Mirror Seeing
Edge Sensors
Segment Exchange
60nm
9nm
5nm
15nm
30nm
35nm
0
20
40
60
WFE (nm)

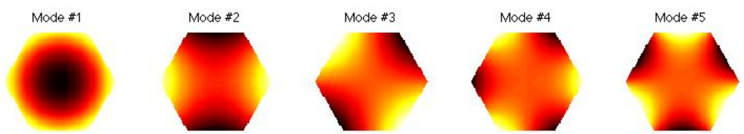
Segment Misfigure



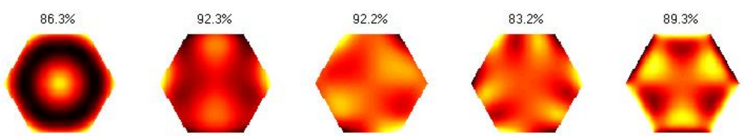




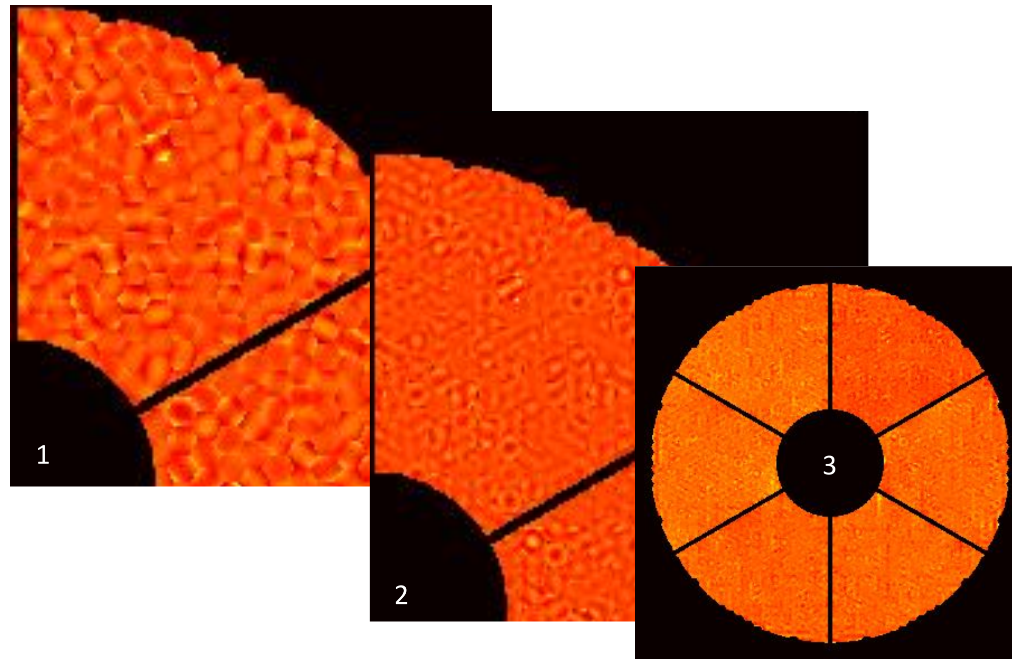
Polishing Requirements (E-SPE-ESO-300-0150.2)



Warping Harness Model and Fitting Error

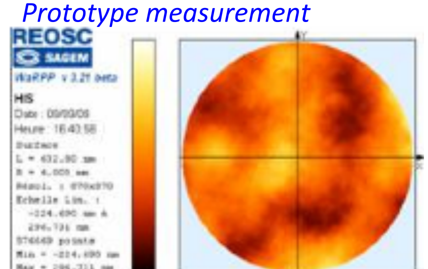


First polished prototype at SAGEM

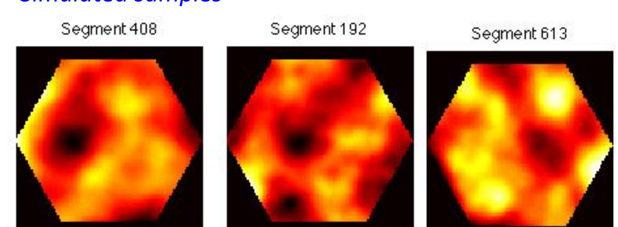


Higher orders: $1/f^2$ PSD

Prototype measurement

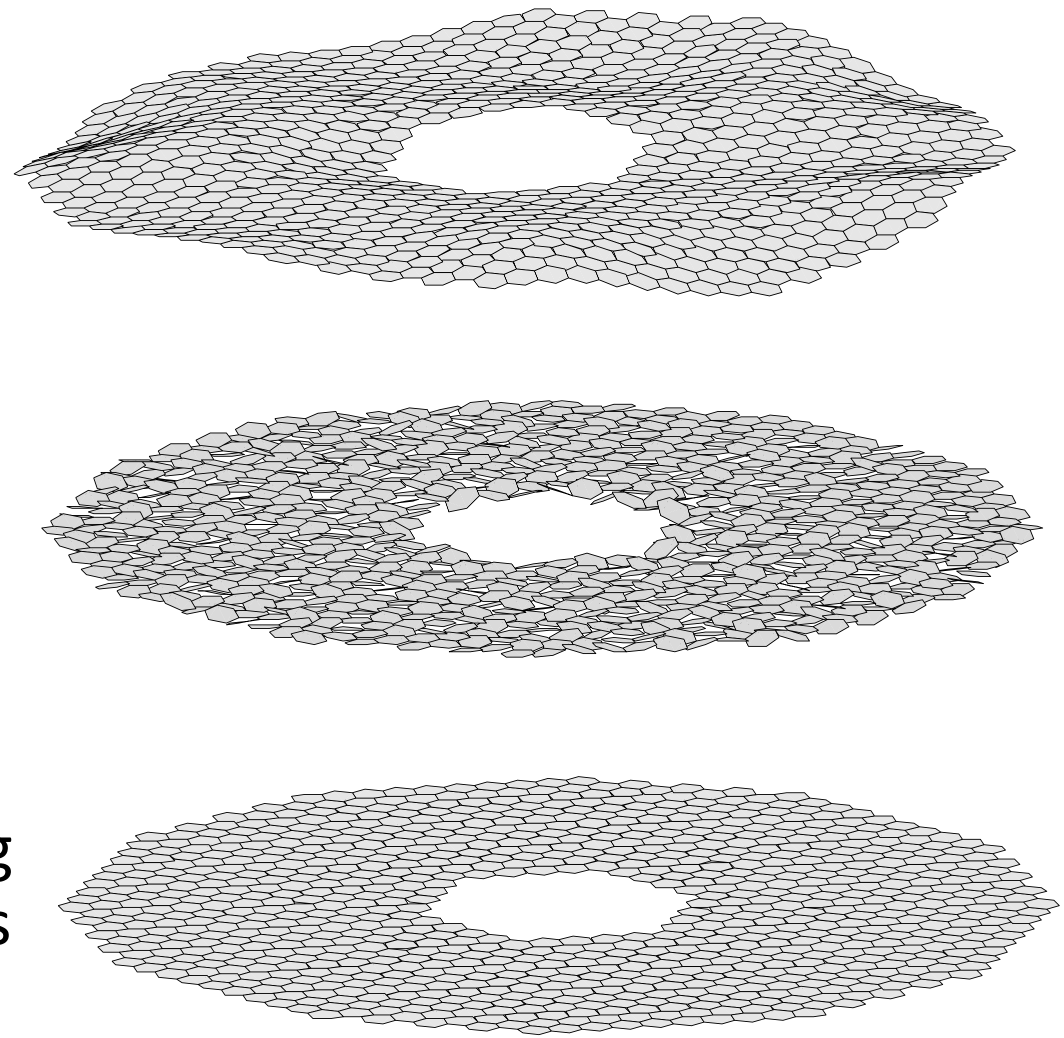


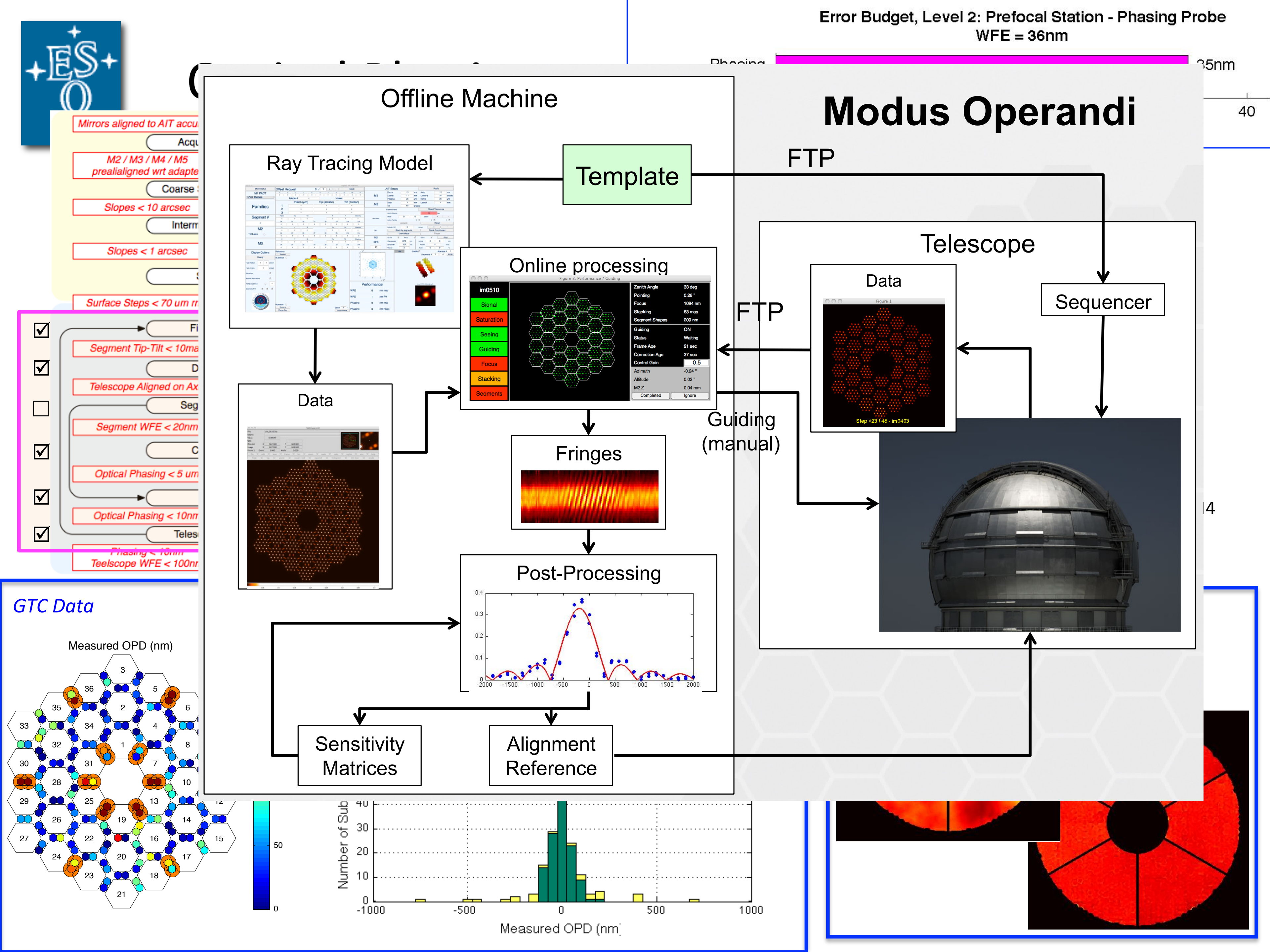
Simulated samples



Phasing

- Phasing procedure demonstrated at GTC.
- Baseline:
  - update of phasing solution every 2 weeks.
  - Local metrologies (Edge Sensors) maintain the phasing between calibrations

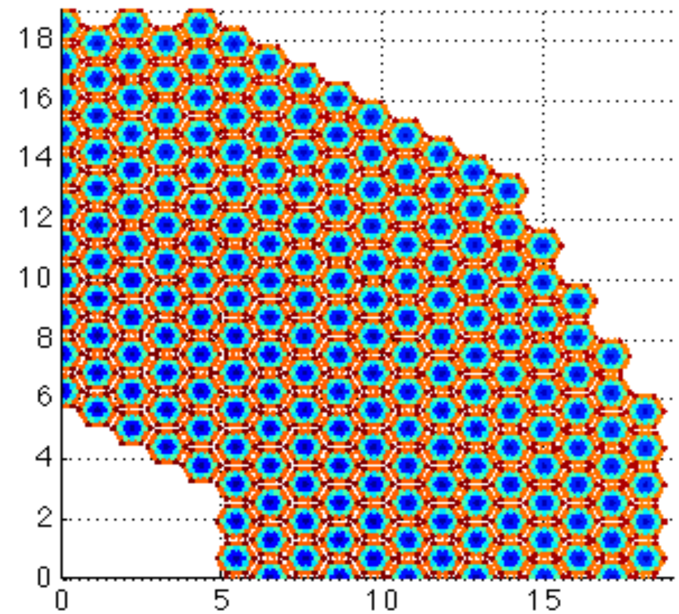


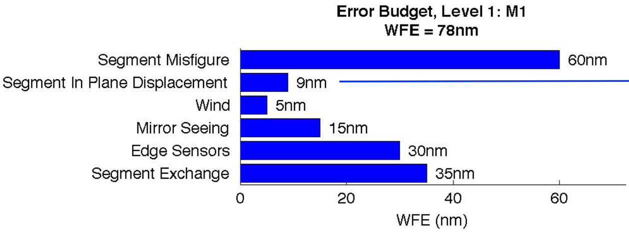


Error Budget, Level 2: Prefocal Station - Phasing Probe
WFE = 36nm
35nm
40
Modus Operandi
Offline Machine
Ray Tracing Model
Template
FTP
Telescope
Sequencer
Data
Online processing
FTP
Guiding (manual)
Fringes
Post-Processing
Sensitivity Matrices
Alignment Reference
Mirrors aligned to AIT accu
M2 / M3 / M4 / M5 prealialigned wrt adapte
Slopes < 10 arcsec
Slopes < 1 arcsec
Surface Steps < 70 um
Segment Tip-Tilt < 10ma
Telescope Aligned on Ax
Segment WFE < 20nm
Optical Phasing < 5 um
Optical Phasing < 10nm
Phasing < 10nm
Teelscope WFE < 100nm
GTC Data
Measured OPD (nm)
Number of Sub
Measured OPD (nm)

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.



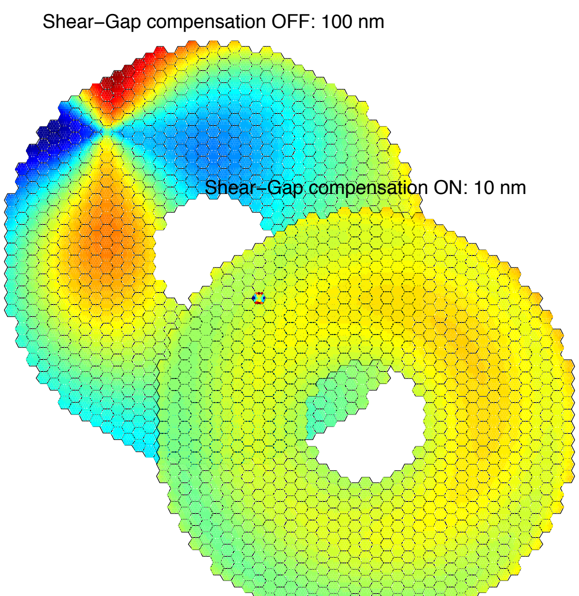


Segment in plane displacements

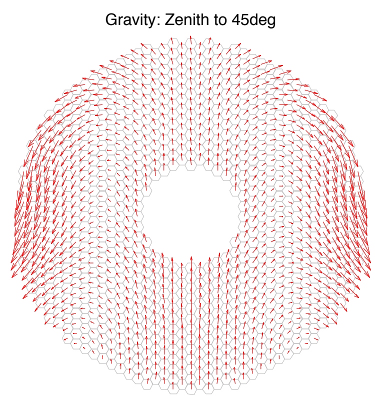
Piston – Shear – Gap Edge Sensors

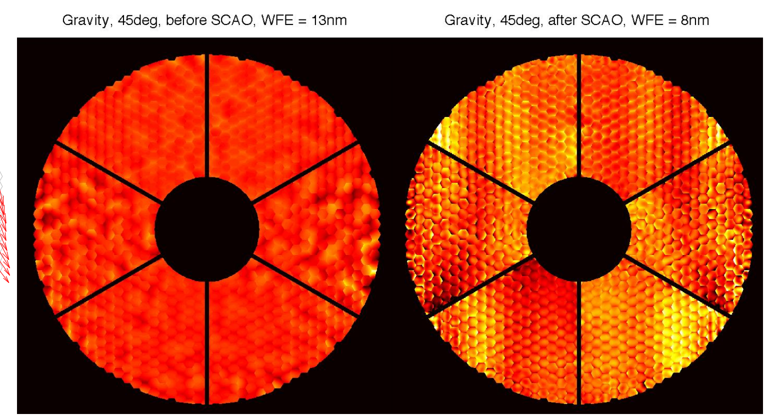
- Optical calibration (Phasing) every 2 weeks
- PSG features
  - Full observability of mirror state
  - Performance against gravity and thermal perturbations limited by mounting errors.
- Installation Accuracy
  - Rotation Error = 1 mrad
    To be measured with an accuracy of 0.1 mrad
  - Translation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

		amplitude	Corrections			Error
			Optical Phasing	Warping Harness	SCAO	
Integration		1mm / 1mrad	✗	✗	✗	4 nm
Gravity		from FEA			✗	8 nm
Ambient Temperature	seasonal	6K	✗	✗	✗	2 nm
	2 weeks	4K			✗	6 nm
Temperature gradient		1K/42m/axis			✗	3 nm
					Total	**11 nm**

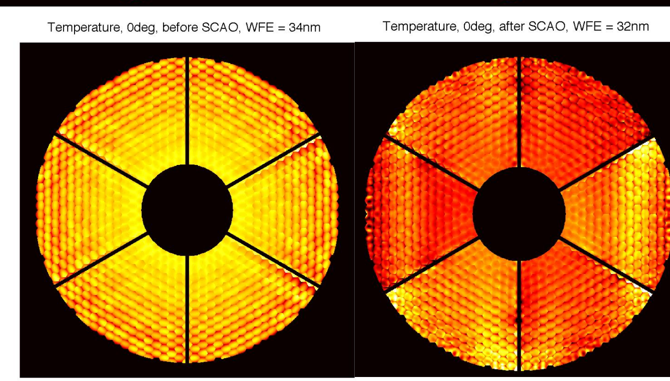


1 mrad clocking error on segment #429





Impact of differential gravity load from zenith to 45 deg



Impact of 20K ambient temperature change

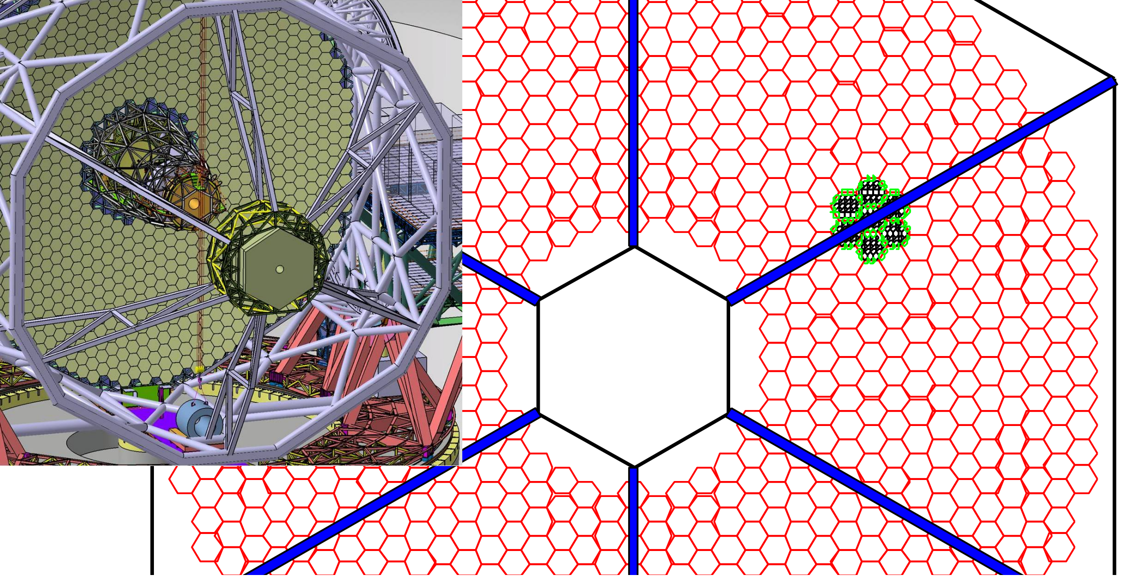
Phasing

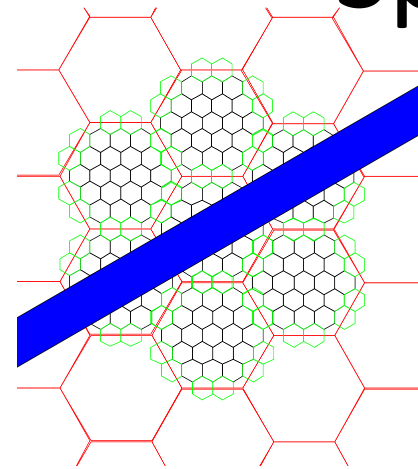
- Difficulties:
  - Large number of DOF
  - In plane motions (PSG sensors)
  - Coupling between in-plane motion and ES signals.
  - New segments every day (re-coating)
  - Shape of segments behind the spider poorly observable
  - Local vibrations

=> Locally large discontinuities in the wavefront.

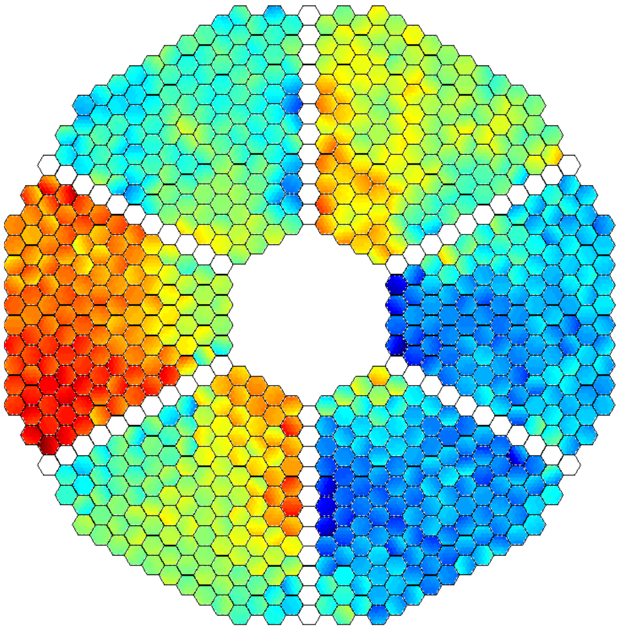
$\Rightarrow$ Diffraction effects in WFS?

Spider





- 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