Precision Engineering and Control

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ESO

Thin mirror telescopes

- The ESO NTT
  - 3.58m
  - aO invented by Ray Wilson – Allowed a thin mirror design (15:1)
  - Careful dome thermal and airflow management
  - Commissioned in 1989 and had 0.33 arcsec images

- Paved the way for 8m telescopes such as the ESO VLT, Gemini & Subaru
  - Two other technologies were being pioneered at the same time, segmented mirrors (Keck) and massively light-weighted borosilicate thick mirrors (Magellan)

Thin mirror telescopes

- ESO VLT
  - 4 x 8.2M telescopes
  - 50:1 aspect ratio meniscus mirrors (23 tonnes)
  - Full aO
- “Aerospace technology”

VLT – Main axes drive system

VLT is well known for its excellent tracking performance. The four main contributors to this success are:

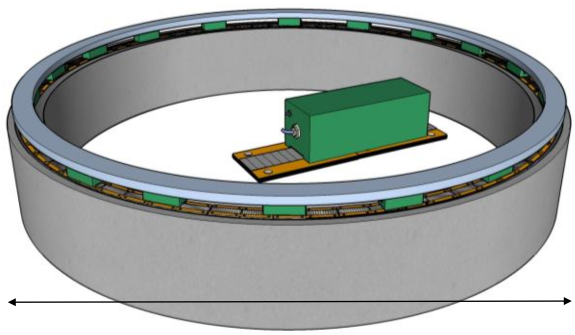
1. Direct drive motors
2. Collocated encoders
3. Hydrostatic bearing system
4. Innovative control algorithms

VLT – Direct drive motors

VLT was the first telescope to use large diameter direct drive motors; Altitude 2m and Azimuth 10m.

When designed in the beginning of the 1990s, this was a relatively new technology.

Such large motors have to be assembled by segments



VLT – Direct drive motors

- In comparison, they out-perform traditional gear or friction coupled drives due to their high stiffness and lack of backlash.
- Additional advantages are no maintenance, alignment or wear.

VLT altitude motor

VLT - encoders

- Direct drive motors offers the possibility to use collocated encoders. This is optimal from a controls point of view and superior to gear-coupled drive systems.
- The VLT encoders are high quality tape encoders with the same diameter as the motors. The are mounted together on the same structure and have an accuracy of 0.1 arcsecond.

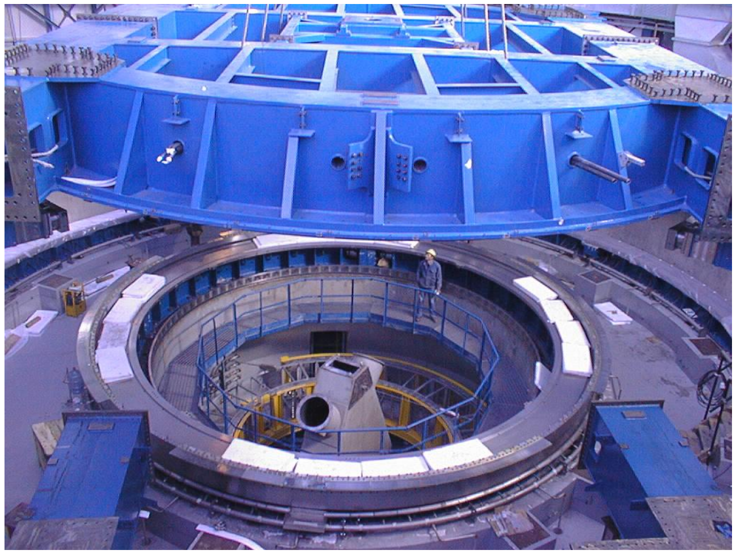
VLT - Hydrostatic bearing system

The VLT main axis use hydrostatic bearing systems.

This allows the entire telescope structure to float on an oil film of thickness 50 µm.

The result is not only very low friction (one person can move it) but also the fact that the absence of stick-slip friction make the system practically linear. Again a huge advantage for the control.

VLT - Hydrostatic bearing system



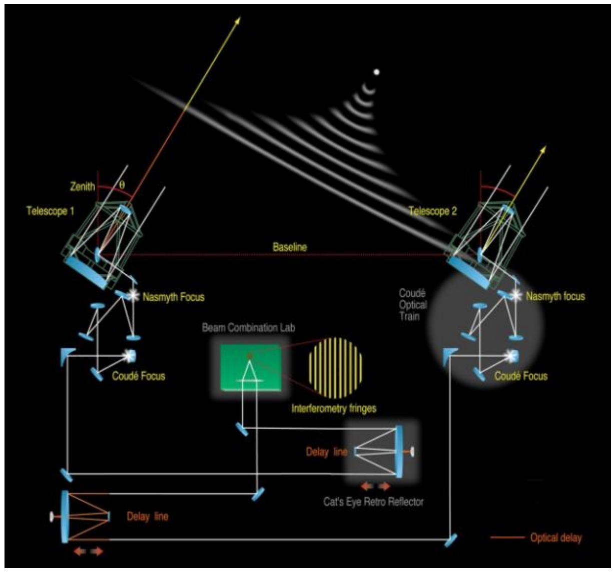
VLT - Control

First telescope with entire control system implemented in software

Real-time computer platform

High tech drive technology

VLTI Scheme - Subsystems



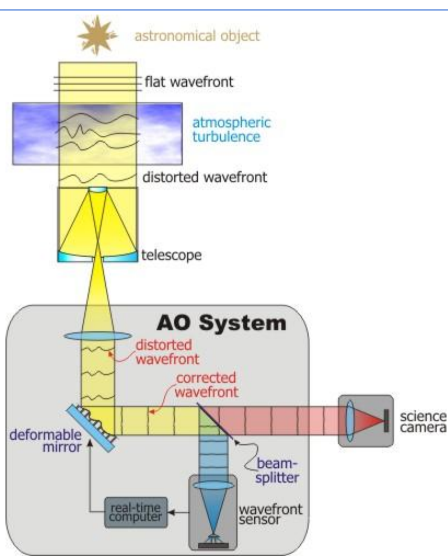
VLTI main Delay Lines (DL)

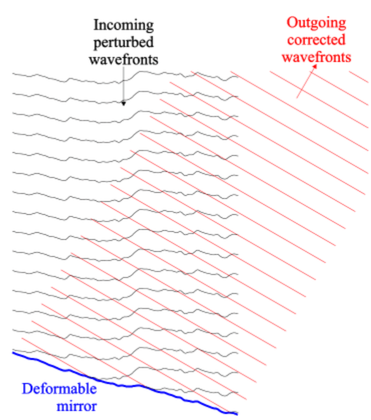
- Compensate for
  - Earth rotation => slow (5mm/s), large amplitude (length=60m)
  - atmospheric turbulence => fast (corrections at > 100Hz) and small (20µm) but with high accuracy (15nm) => needs a laser metrology
- Cat's eye => beams are stable in tip-tilt but not in lateral position =>
  - Rails have to be maintained straight and flat with an accuracy of < 7 µm despite seasonal variations => daily maintenance (measurement of the flatness & correction of supports)
  - Wheels and bearings have to be round and centered => regular maintenance.

The challenge of VLTI control

- Many large stroke, slow control loops:
  - telescope axes, focus / active optics,
  - lateral & longitudinal pupil alignment, delay line position …
- A very large number of real time fast control loops with sub-micron accuracy:
  - tip-tilt control at the telescope focus / adaptive optics
  - vibration control
  - fringe tracking on star light
  - tip-tilt control in the laboratory
  - fast pupil control in the laboratory
  - end-to-end metrology
  - chopping, scanning …
- These control loops are embedded and interlaced with each other, with complex interactions: feed-back + feed-forward, notch filters, offloading…
- Sensors / actuators are dispersed all over the system
- Needs a perfect synchronisation and a reliable, robust tuning

Adaptive Optics principle





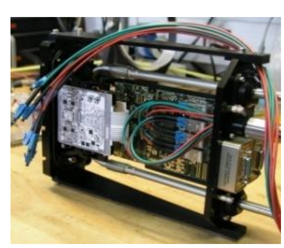
Road Map of WFS Detectors

MAD-WFS CCD	NAOS-WFS CCD	Future-WFS CCD-220
80x80 pixels	128x128 pixels	240x240 pixels
4outputs	2x8 outputs	8 L3 outputs
500Hz frame rate	25-600 Hz frame rate	0.25-1.2 kHz frame rate
RON: 8-6 e/pixel	RON: 2.5-6.5 e/pixel	RON: < 1(0.1)e/pixel
QE: 70-80%	QE: 80%	QE: 90%

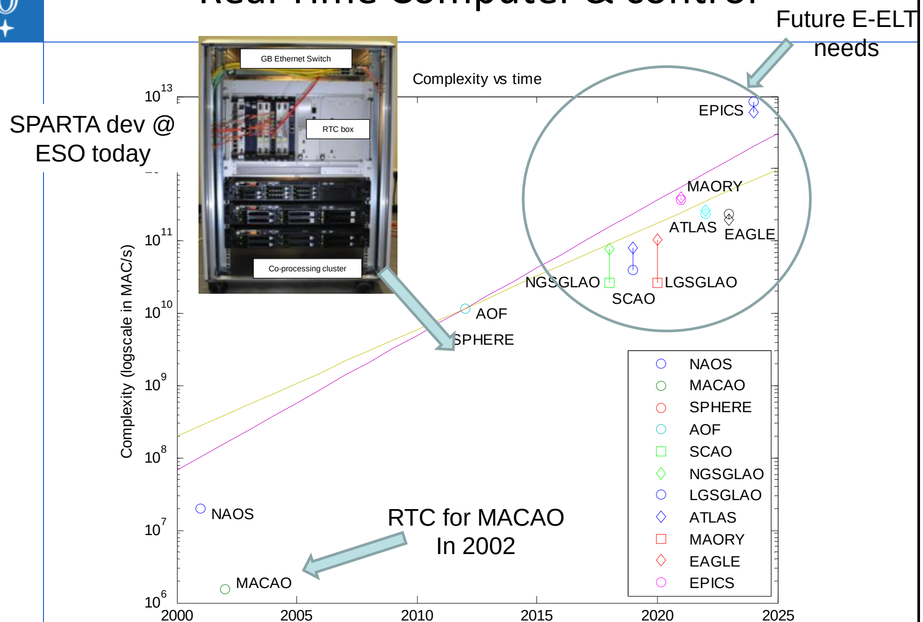
AO detector controllers

FIERA controller with 16 outputs
600Hz; 128x128 pixels

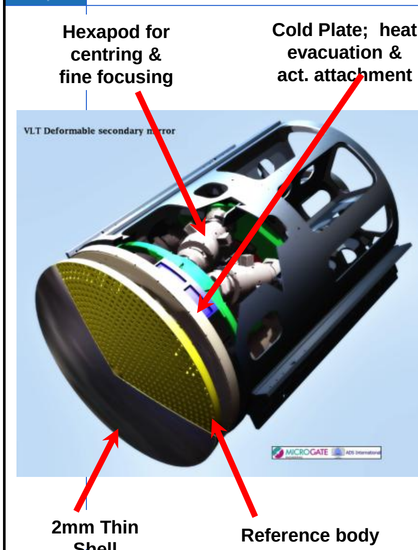
OCAM prototype and ESO NGC controller; 1.2-1.5kHz with
8 outputs; 600Hz; 128x128 pixels



Real Time Computer & control



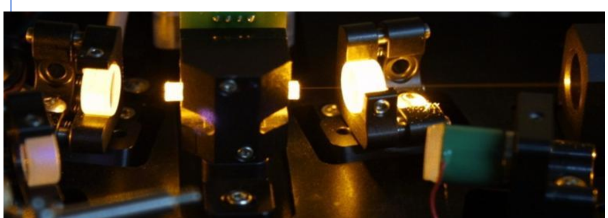
VLT Deformable Secondary Mirror



- 1170 actuators, 29 mm actuator pitch, 1ms response, stroke 50 / 1,5µm
- Shell diameter: 1.12m
- Shell thickness: 1.95mm
- 75 16ch DSP control boards, 3 double-crates
- 150 floating point DSPs, 150 GMACs/s FP
- ✓ EL+Mech components manufacturing completed
- Optical components manufacturing ongoing:
  SESO → reference body
  SAGEM → thin shell
- Mechanical components manufacturing ongoing:
  - ADS and MICROGATE for the hexapod, actuators, electronics and software
- Next steps:
  - Integration: 2011
  - Electromechanical acceptance: Q1 2012
  - Optical acceptance: Q3 2012
  - Commissioning Paranal: Q4 2013

Laser Developments

- Demonstration of >50W continuous output power at 589nm in a narrow spectral line by ESO researchers in 2009
- An optical fibre Raman amplifier technology for amplification of narrow-line laser light was developed at ESO and has been licensed to industry
- Milestone industrial demonstrator of 20W class laser using technology developed by ESO



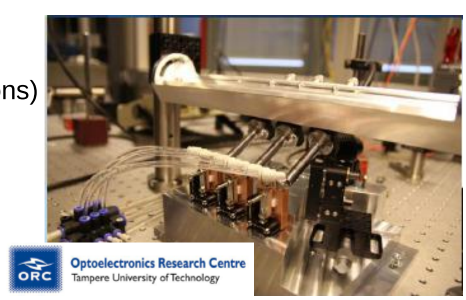
Laser Risk Reduction

- Mitigating risks for E-ELT Laser Supply
- Risks: technical risks, very few suppliers, cost increase, better understanding of mesospheric sodium results in slightly changed requirements
- Monitor new laser technologies, evaluate different suppliers:

One research-stage technology that has been identified is the optically pumped semiconductor. ORC Tampere are preparing an infra-red oscillator demonstrator.

- Study Sodium Return (simul.ions)

For the cases of 4LGSF and E-ELT lasers, the D2b re-pumping would increase the return flux by a factor ~2.5 on average, across the sky. => Laser power savings.



ALMA Environmental Conditions

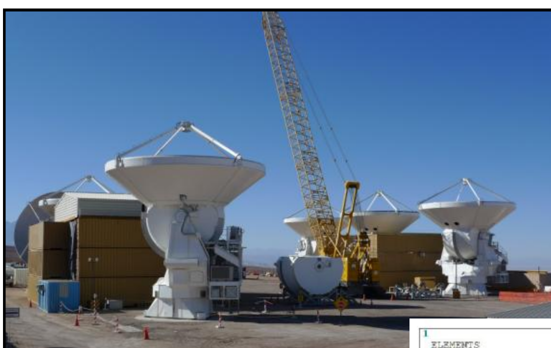
- Continuous day and night operation at the Array Operations Site (AOS) 5000m in the Atacama desert
- Under strong wind conditions of 6 m/s in the day and 9 m/s at night
- Temperature extremes of -20C to +20C
- Temperature gradients of $\Delta T \leq 0.6C$ in 10 minutes; $\Delta T \leq 1.8C$ in 30 minutes, and
- In a seismically active region

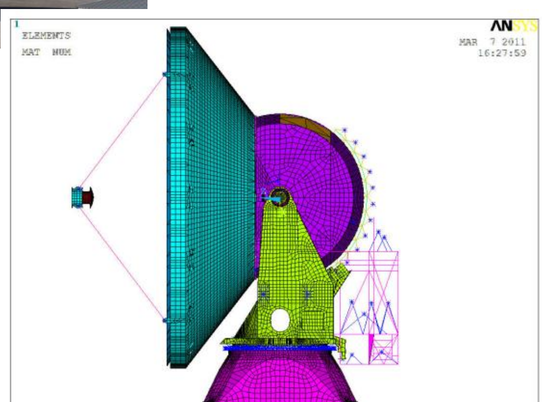
Antenna top level requirements

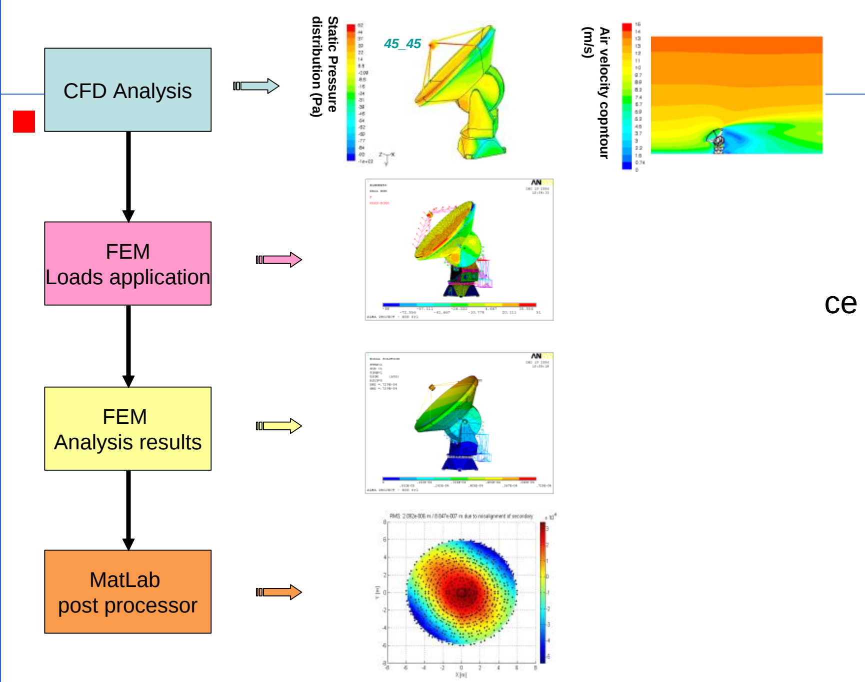
- 25 μm rms surface accuracy under all the environmental conditions
- Blind all sky pointing of 2 arcsec rms
- Offset pointing accuracy of 0.6 arcsec over a two degree field
- Tracking of 0.6 arcsec rms
- Pathlength variations less than 20 μm
- Fast position switching 1.5° in 1.5 sec, and
- Able to directly point at the sun

Technical Solution

- Extensive use of CFRP
- Monocoque design of the antenna backup structure with a CFRP skin and an aluminium honeycomb core
- Real time metrology to control pointing
- AEM
  - CRFP Receiver Cabin
  - Direct drive technology
  - Metrology using new Microgate high speed tiltmeter
    - Wind buffeting as well as static deflection
  - Thermal metrology using distributed temperature sensors in the mount





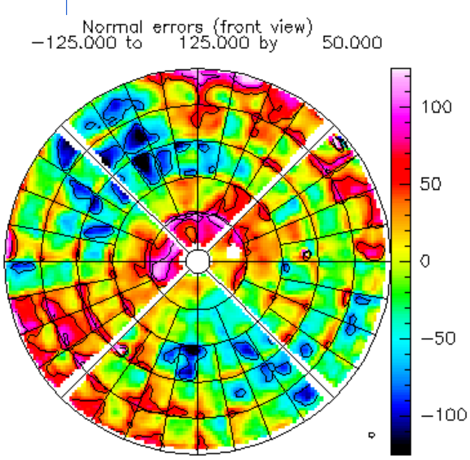


Antenna assembly and test

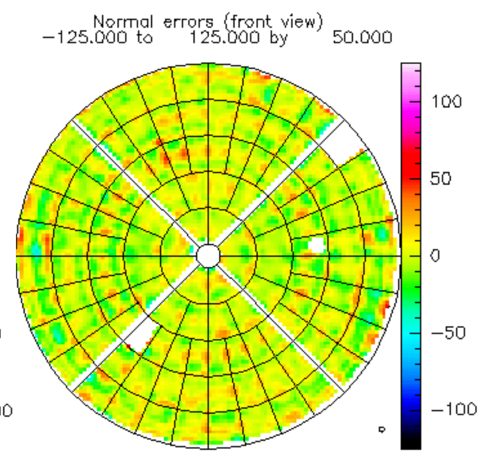
- Antennas assembled and tested at the OSF in Chile (9000 feet)
  - Environmental conditions here are not as extreme so test measurements have to be extrapolated to the high site conditions and verified later
- For all three Antenna Vendors
  - Pointing and Fast switching meet the specifications
  - Surface accuracy meets the requirements

Antenna assembly and test

Antenna assembly and test



44 microns rms

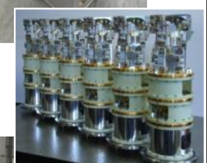


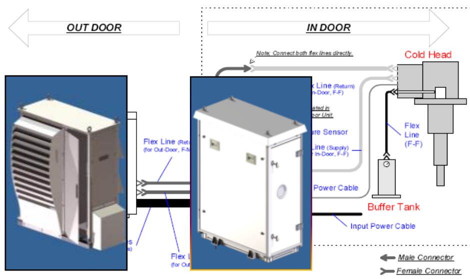
10.9 microns rms

ALMA Cryogenic System
High Altitude Qualification Tests

3-Stage Cold Head + He-pot on the 4K stage

- Test of Air Cooled He-Compressors (Indoor/Outdoor)
- Low noise receiver are cooled to less then 4K
- Temperature Stability shall be better than ± 5mK
- Conditions influencing the system reliability
  - Temperature Range -30C to +40C
  - Strong Wind (operational limit 20m/s, survival 65m/s)
  - Ambient air pressure ~550mbar (typical air density ~0.7214 Kg/m³)
  - Rain, Snow and Icing



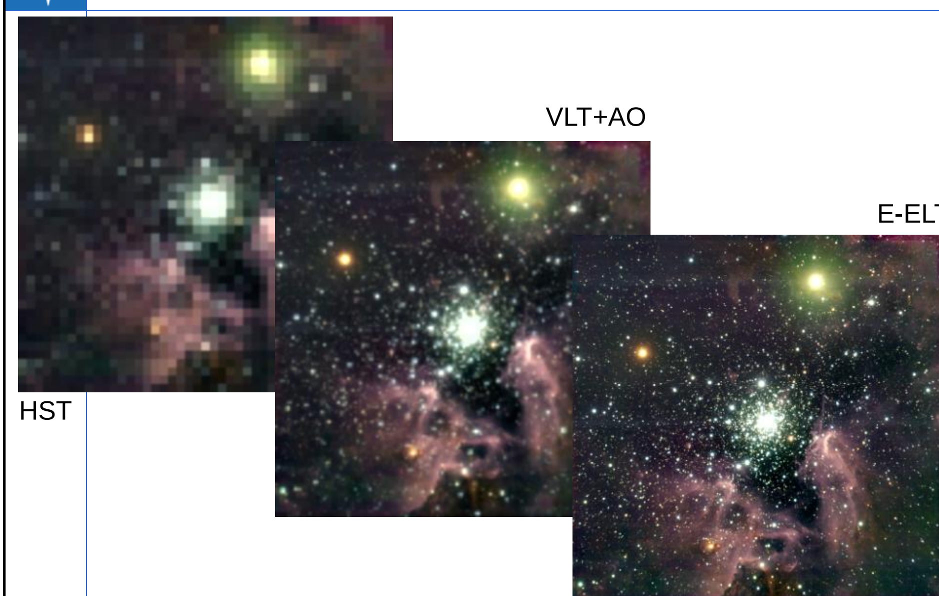


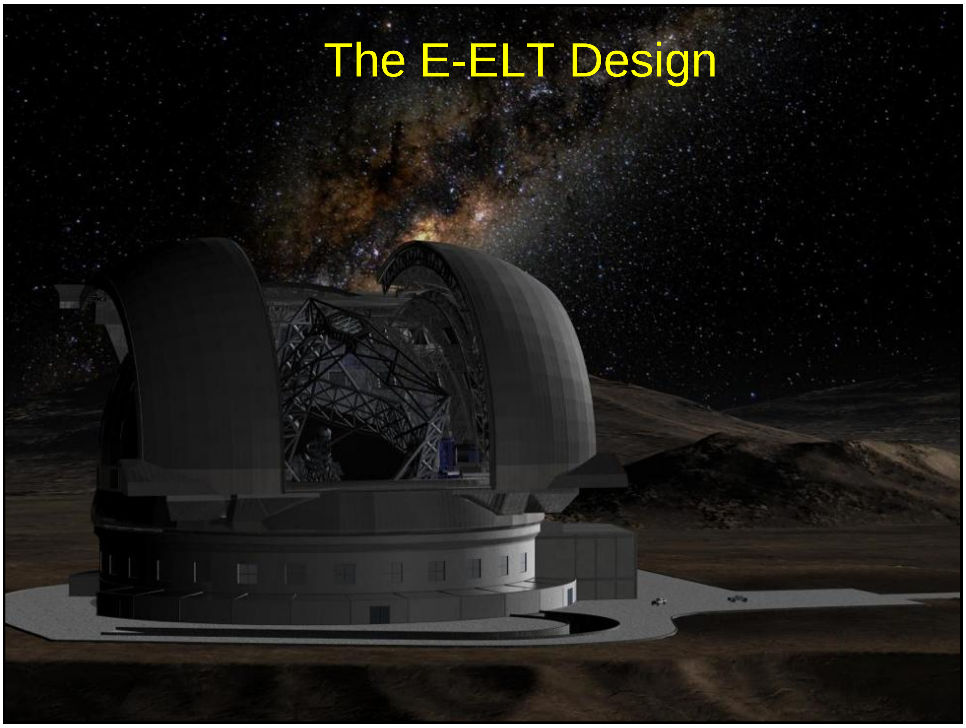
SYSTEM CONFIGURATION

ALMA Cryogenic System
High Altitude Qualification Tests

The E-ELT

Spectacular Resolution





To put it in perspective…

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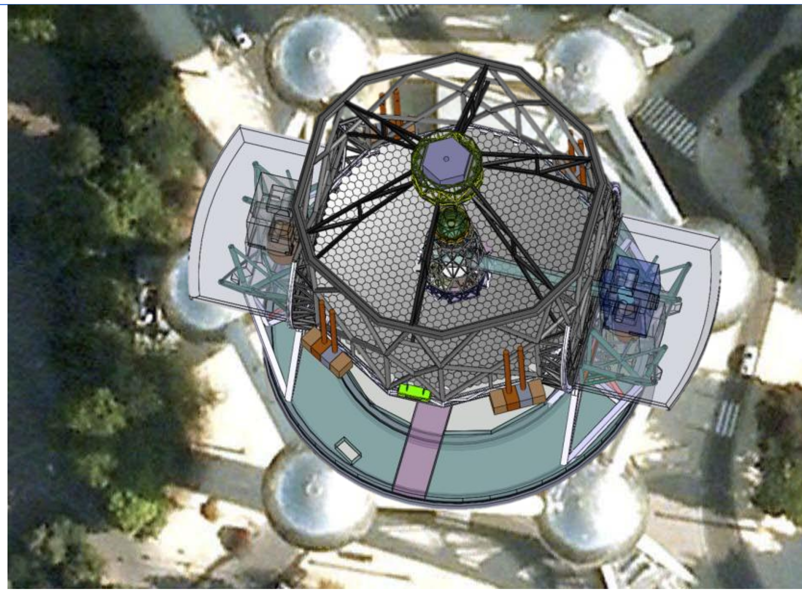


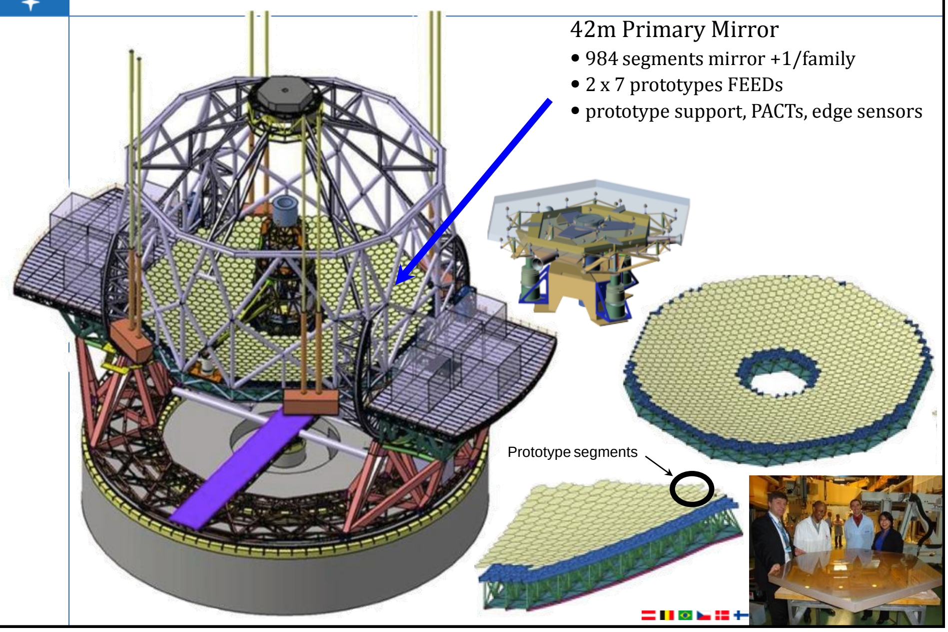
The process

- Top down science driven requirements capture
- Strong Systems Engineering
- “ESO specify, Industry solve and build” rather than “ESO solve and industry build”
- Multiple competitive industrial studies, designs and prototyping
  - FEED process
- Top Level Requirements
  - 40-m class
  - Strehl > 70% at λ2.2 microns
    - Wavefront error less than 210-nm rms
  - 99% sky coverage

The E-ELT: overview

42m Primary Mirror

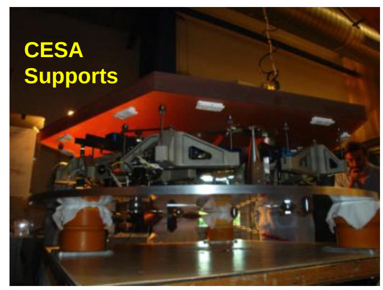
- 984 segments mirror +1/family
- 2 x 7 prototypes FEEDs
- prototype support, PACTs, edge sensors



The E-ELT: overview

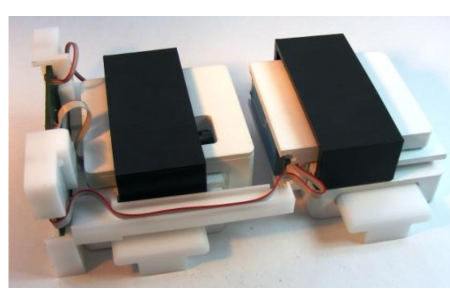
The E-ELT: overview

- Segment spec is an rms surface accuracy of 15nm (on average, max 30nm) after correction with the warping harnesses
- 10 mm zone at the edge with relaxed specification (ave 200 nm)
- Micro-roughness is expected to be below 20-Å



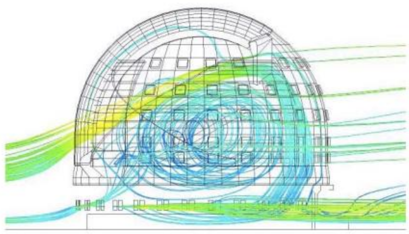
The E-ELT: overview

- Inductive edge sensors from micro-Epsilon
- Detect piston, gap and shear
- Requirements are to be able to measure piston with a resolution of 0.5-nm over a range of ±200-µm with a repeatability of 1-nm

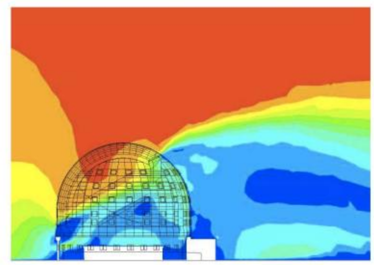


CFD Studies

- Computational Fluid Dynamics analyses of the E-ELT dome were performed to assess the wind flow conditions in view of telescope seeing. The analysis results caused the decision to implement louvers in the dome foundation design



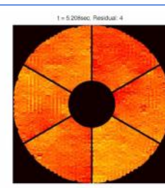
Streamlines distribution in the E-ELT Dome structure

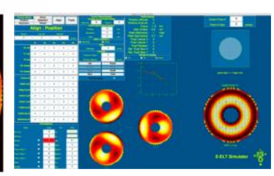


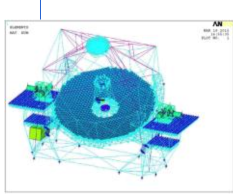
Velocity distribution in the E-ELT Dome at the symmetry plane.

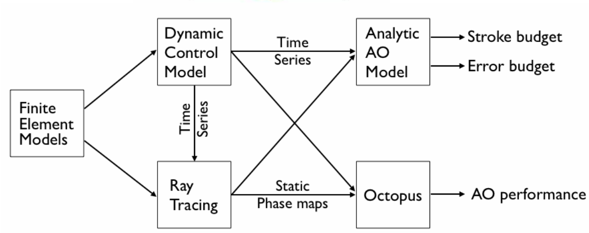
Analysis and simulation crucial

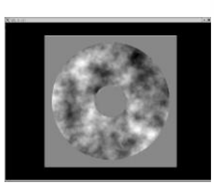
Optical performance analyses of the E-ELT were carried out to simulate the propagation of numerous error sources and the impact on System Engineering aspects. This is supported by instantiations of the telescope's ray tracing models with temporal and spatial resolutions adapted to the spectral properties of the errors.

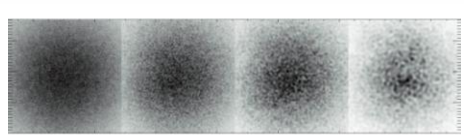




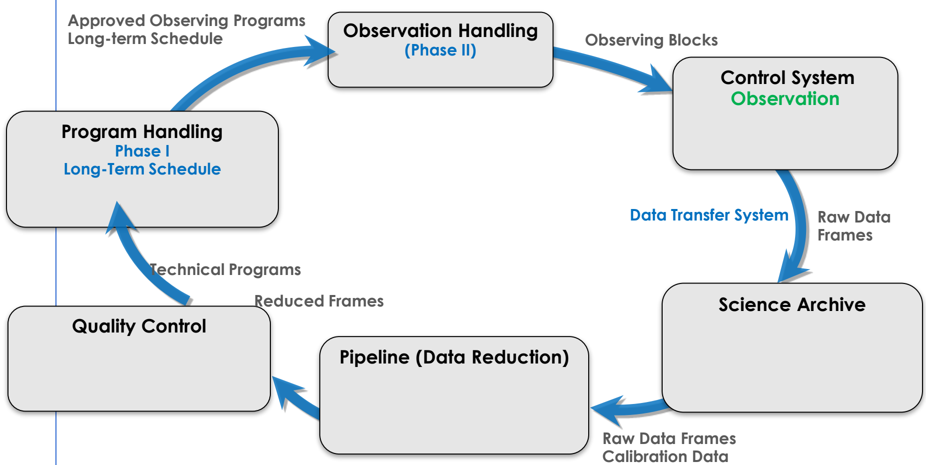






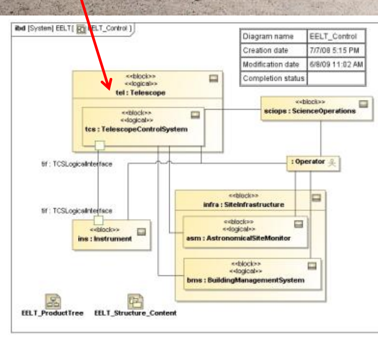


Software at the ESO LPO Observatory



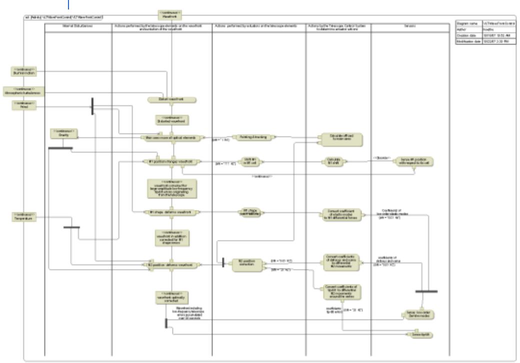
Control System

- The Control System includes all hardware, software and communication infrastructure required to control the System.
- Provides access to the opto-mechanical components.
- Manages and coordinates system resources (subsyst., sensors, actuators, etc…)
- Performs fault detection and recovery
- Based on Control Eng.ing, Software and Electrical Engineering

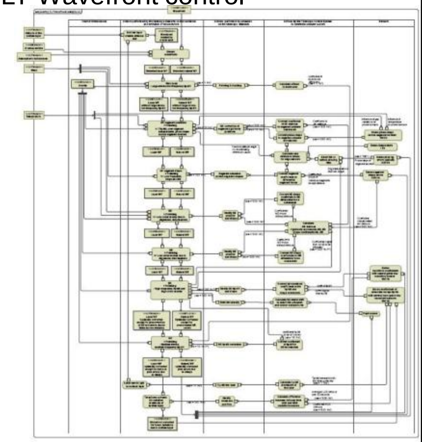


E-ELT Telescope Control System (cont)

VLT Wavefront control

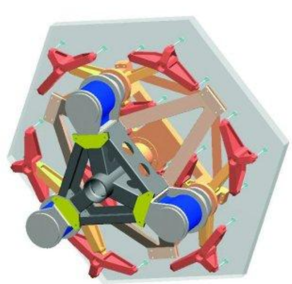


E-ELT Wavefront control



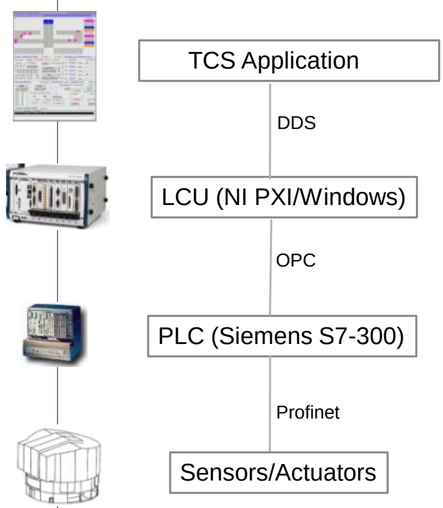
- 10000 tons of steel and glass
- 20000 actuators, 1000 mirrors
- 60000 I/O points, 700Gflops/s, 17Gbyte/s
- Many distributed control loops
- Use SysML to model the control system since 2008

E-ELT TCS (M1)



- The position of the 1000 mirrors must be coordinated to deliver a continuous surface with an error below 50nm across the M1 mirror (around 40 m diameter).
- 3000 actuators and 6000 sensors must work in a1Khz closed loop to meet this requirement.
- Moreover 12000 actuators (12 motors per segment, the warping harness) are responsible for deforming each individual segment in order to correct aberrations at a lower rate
- The control strategy must be flexible and adaptable to e.g. failure of sensors

E-ELT Control System Baseline Technologies



Integration & High-level applications

- Data oriented architecture (DDS)
- User Interface (LabVIEW)

Subsystem local control:

- PLCs
- OPC standard (open automation interface)
- Field buses (Profinet, Ethercat....)
- Safety functions

Multi-core for large MIMO control.

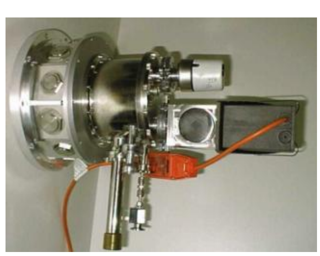
- LabVIEW graphical parallel computing

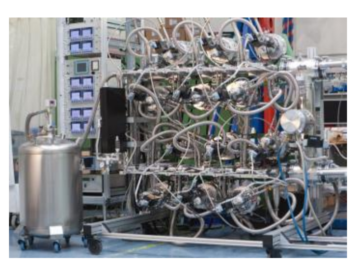
Dedicated time distribution system (µsec).

- Evaluation of IEEE1588-2008 standard protocol
- Sub-microsecond synchronization
- COTS network equipment (Cisco, NI-PXI, Ethernet)

Continuous Flow Cryostats

- Need for small, light and orientation in-sensitive system to cool CCD detector to 140 K
  - A compact (8 Kg) cryostat have been designed based on a continuous circulation of LN2
  - Actually 15 of these cryostats are in operation
  - One of the future instrument MUSE will be fitted with 24 of them






Thank you!