



Technological Development and Needs at ESO

Roberto Tamai
ESO

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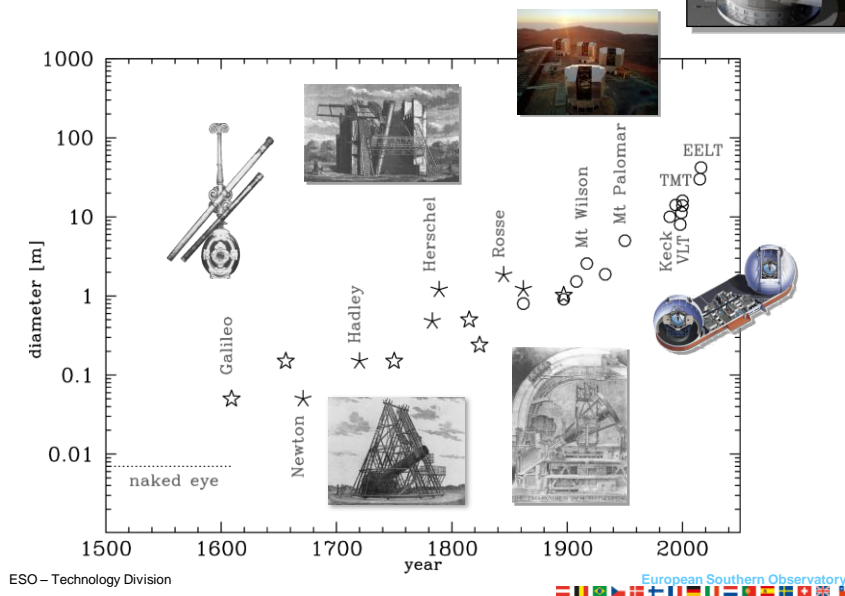
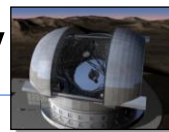
Technology in Astronomy

- From a small, manually pointed device for visual observations (around 400 years ago) to a large, sophisticated, computer-controlled instrument with full digital output.
- Two properties have been particularly important:
 - the light-collecting power, or diameter of the telescope's mirror (allowing for the detection of fainter and more distant objects), and
 - the image sharpness, or angular resolution (allowing smaller and fainter objects to be seen).
- The European Southern Observatory (ESO), as a worldwide leader in astronomy, has developed, together with industry, several advanced technologies that have enabled the construction of ever bigger telescopes, while maintaining optical accuracy.

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Technology in Astronomy



Technology in Astronomy

ESO has contributed to the progress of several technologies applied to the modern astronomy to improve the image sharpness, among these:

- **ACTIVE OPTICS**, now in use in most modern medium and large telescopes. It preserves optimal image quality by pairing a “flexible” mirror with actuators that actively adjust the mirror's shape during observations.
- **ADAPTIVE OPTICS**, the bigger a mirror, the greater its theoretical resolution, but even at the best sites for astronomy, large, ground-based telescopes observing at visible wavelengths cannot achieve an image sharpness better than telescopes with a 20- to 40-cm diameter, due to distortions introduced by atmospheric turbulence. One of the principal reasons for launching the Hubble Space Telescope was to avoid this image smearing.
- **INTERFEROMETRY**, the combination of the light collected by two or more telescopes can boost the resolution beyond what a single telescope can accomplish. ESO has been a pioneer in this field with the Very Large Telescope Interferometer (VLTI) at Paranal.



Active Optics

Optical telescopes collect light from the cosmos using a primary mirror. Bigger primary mirrors allow astronomers to capture more light, and so the evolution of the telescope has often followed a "bigger is better" mantra.

In the past, mirrors over several metres in diameter had to be made extremely thick to prevent them from losing their shape as the telescope panned across the sky. Eventually such mirrors became prohibitively heavy and so a new way had to be found to ensure optical accuracy.

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Active Optics

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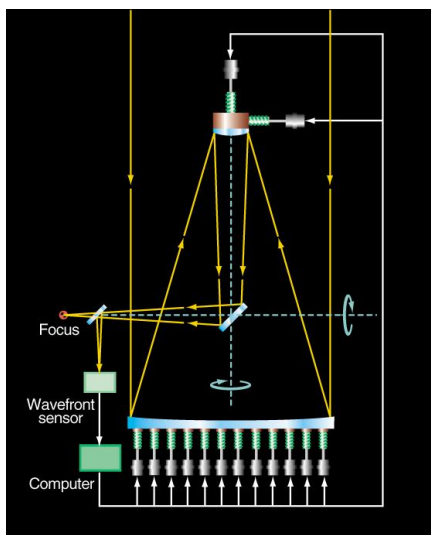
Telescope	Diameter (m)	Thkn (cm)	Dia/thkn	Year
ESO 3.6	3.6	60	6	1960s
ESO NTT	3.6	24	15	1970s
ESO VLT	8m class	17	47	1990s
ESO E-ELT	40m class	5	800	2010s

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Principle of Active Optics

Closed control loop with:

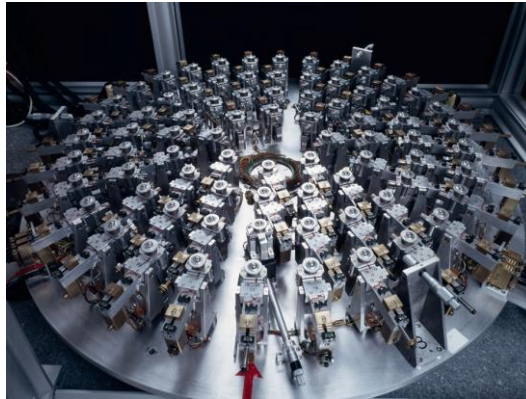
- 1.Measurement of wavefront error generated by the telescope itself
 - Integration times of 30 sec to partially average out errors introduced by the atmosphere
 - Modal analysis using optical aberrations and elastic modes of the flexible meniscus mirrors
- 2.Correction of the errors by the optical elements of the telescope
 - Rigid-body movements of the mirrors
 - Deformation of the mirrors by adjusting the support forces





Active Optics=>The NTT

A computer-controlled **active** optics system was first developed at ESO in the 1980s.



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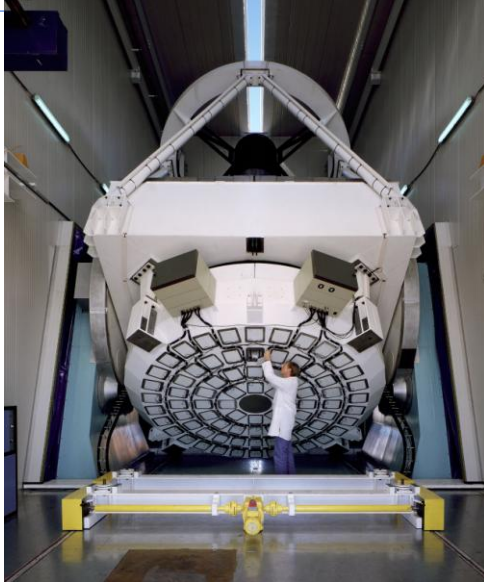
The first major telescope to benefit from this revolution in telescopic techniques was ESO's New Technology Telescope (NTT) at the La Silla Observatory.

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Active Optics=>The NTT

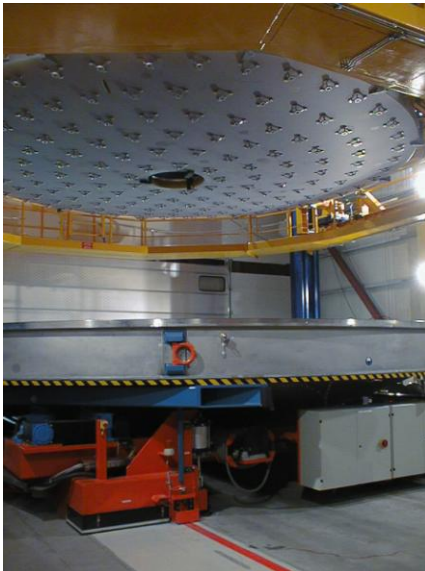


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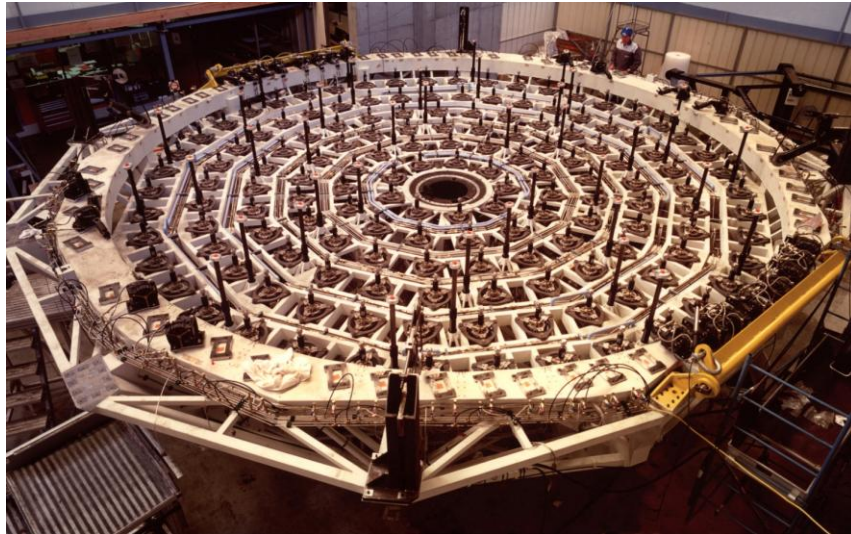
VLT M1 Mirror



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VLT M1 cell



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Adaptive Optics

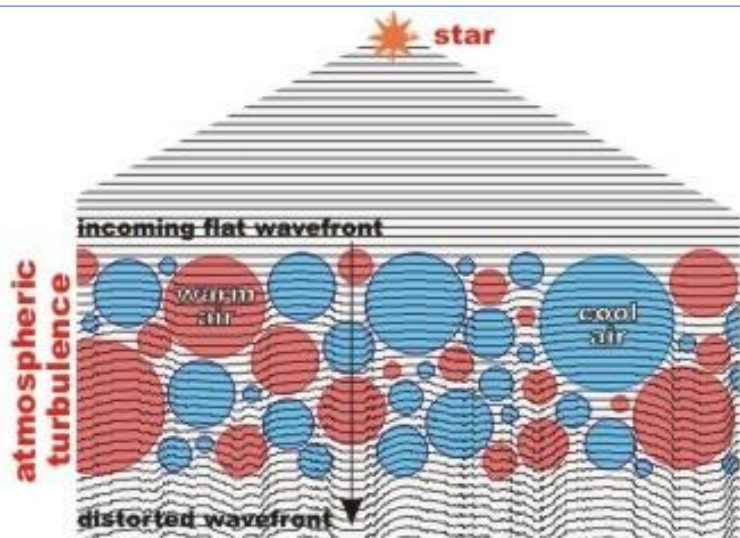
However, Active Optics does not correct for the turbulence in the atmosphere, which is done by a separate and much faster adaptive optics system.

A distinction is made between active optics, in which optical components are modified or adjusted by external control to compensate slowly changing disturbances, and adaptive optics, which applies to closed-loop feedback systems employing sensors and data processors, operating at much higher frequencies.

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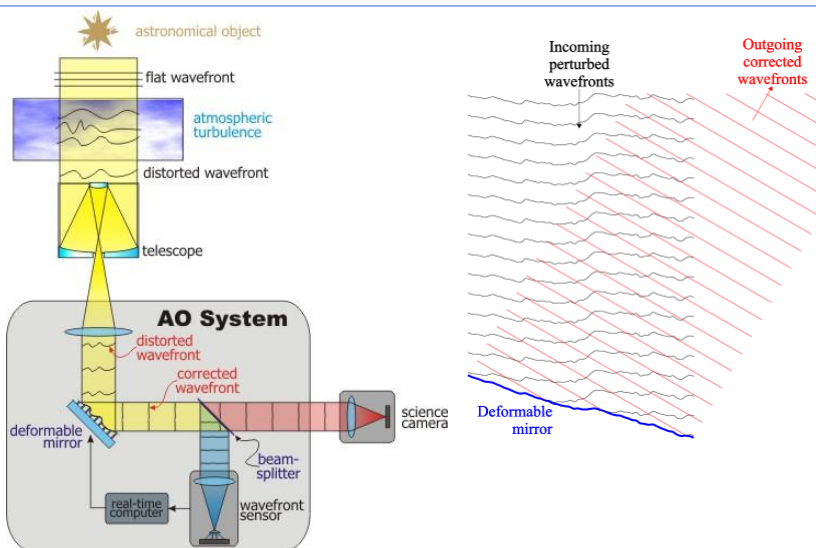
Adaptive Optics



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Adaptive Optics principle



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MAD on Nasmyth A UT3 (Melipal)

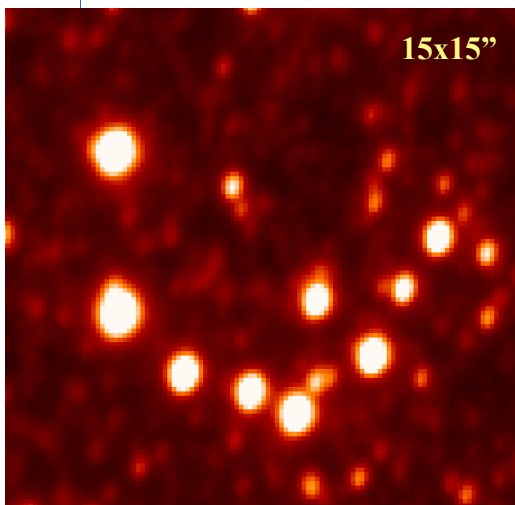


MAD: 2 arcmin FoV, at $2.2\mu\text{m}$ (K band), using two DMs, a SH WFS (for the Star oriented MCAO reconstruction), and a Multi-Pyramid WFS (for the layer oriented MCAO reconstruction)

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An AO milestone: MAD



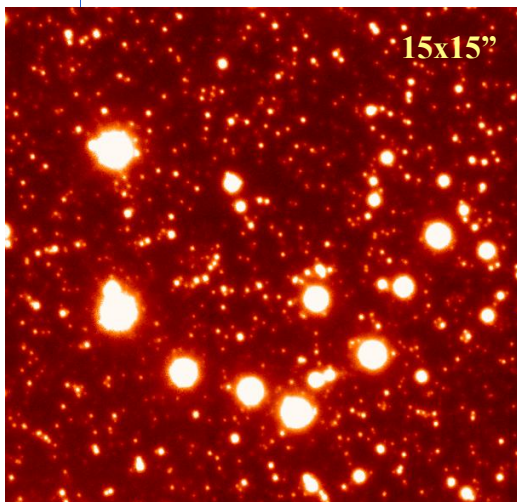
MCAO: 2 Guide “stars” (satellites Europa and Io)
 $2.14\mu\text{m} + 2.16\mu\text{m}$ filters
 90 mas resolution (300 km at Jupiter)

MCAO: 3 Guide stars at $2''$
 K-band, FWHM: 100-120mas, Sr: >20%
 $0.7''$ seeing, Exposure 360 s





An AO milestone: MAD

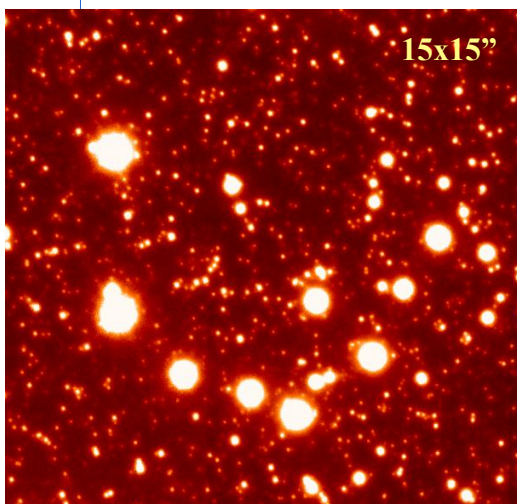


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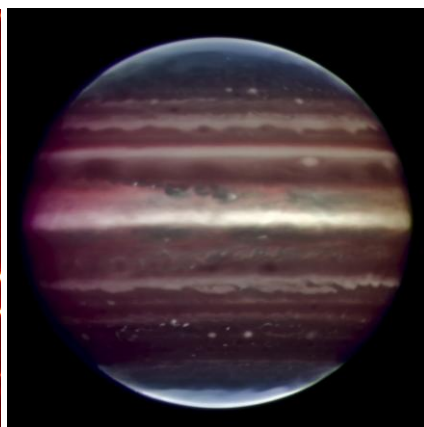
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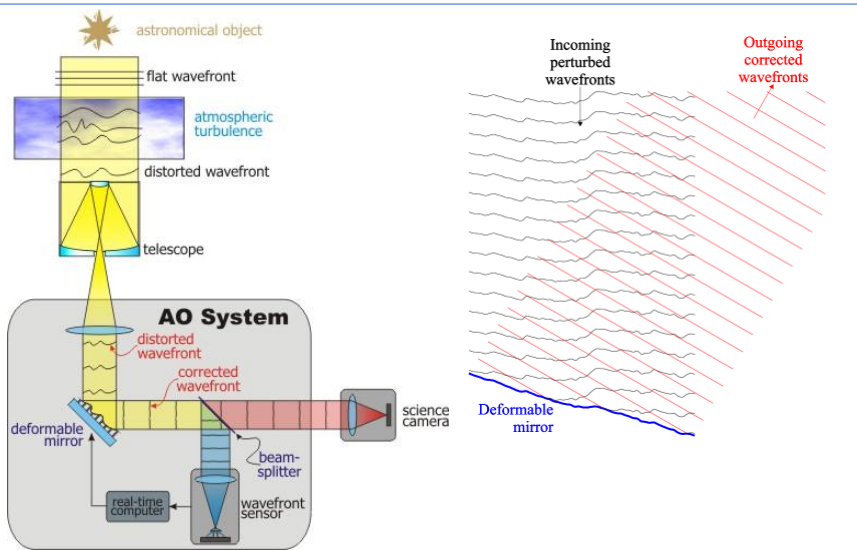
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Adaptive Optics principle

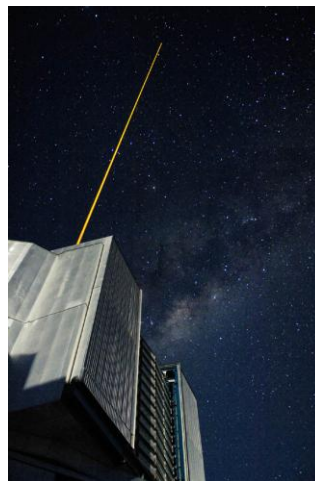
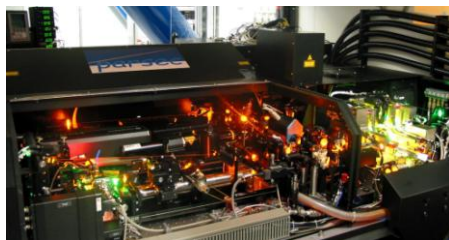


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Laser for Adaptive Optics

- Laser guide stars are artificial stars generated by exciting atomic sodium in the mesosphere at a height of 90km
- This requires a powerful laser beam launched from the telescope
- The yellow wavelength (589nm) is the colour of a sodium street lamp



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The VLT LGSF at UT4

One LGS-AO system is operational at VLT now



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VLT Laser Clean Room

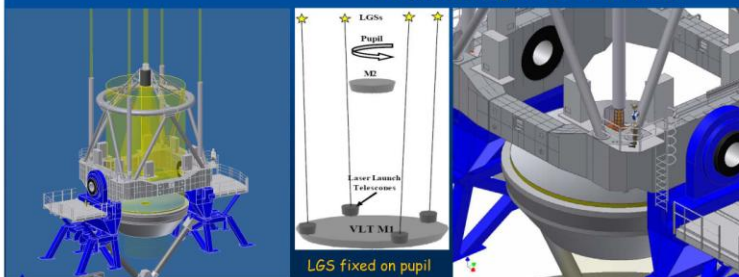


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4 Laser Guide Stars Facility

- 4 LGS, off axis up to 330"
- 2.5–5 Mphot/sec/m²
- LGS FWHM <1.2" on WFS
- Central LGS also operational
- 4LT mounted on UT4 Centerpiece
- Will Serve 2nd Gen AO systems on UT4
- Galacsi-MUSE and GRAAL-Hawki
- PDR in Jan 2008
- Commissioning in 2011–2012 (TBC)



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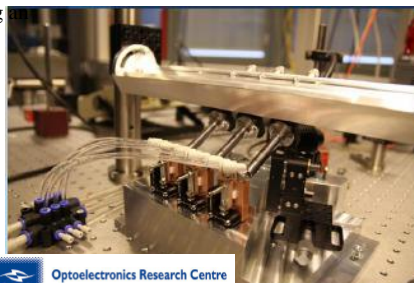
Laser Risk Reduction

- 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 infra-red oscillator demonstrator.

- Study Sodium Return (simulations)

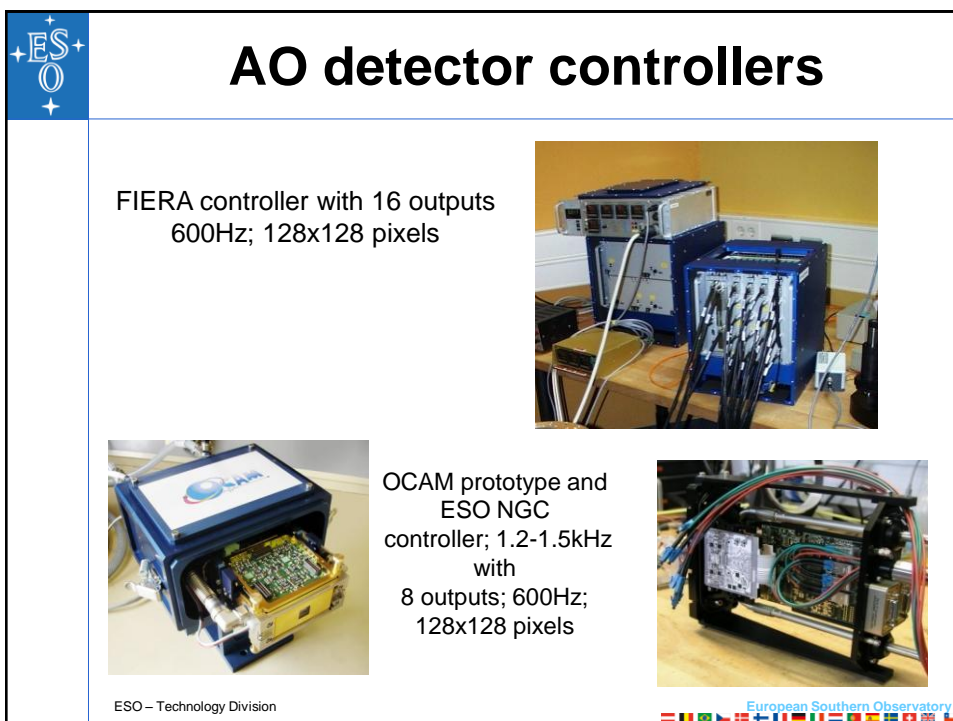
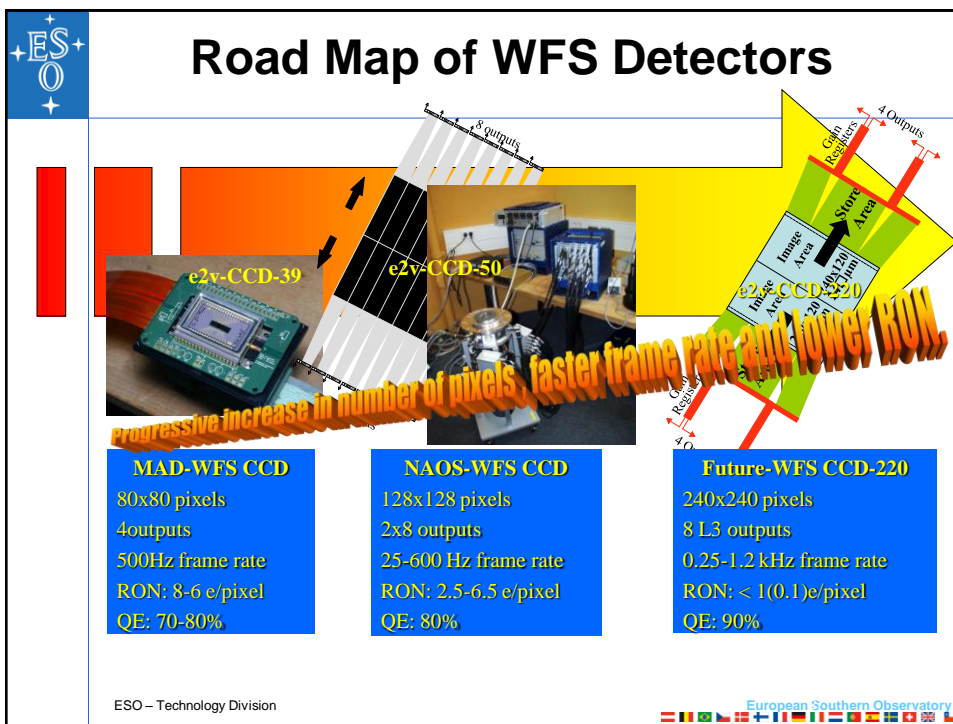
For the cases of 4LGSF and E-ELT lasers, the D2b re-pumping would increase the return flux by a factor ~2.0 on average, across the sky. => Laser power savings.

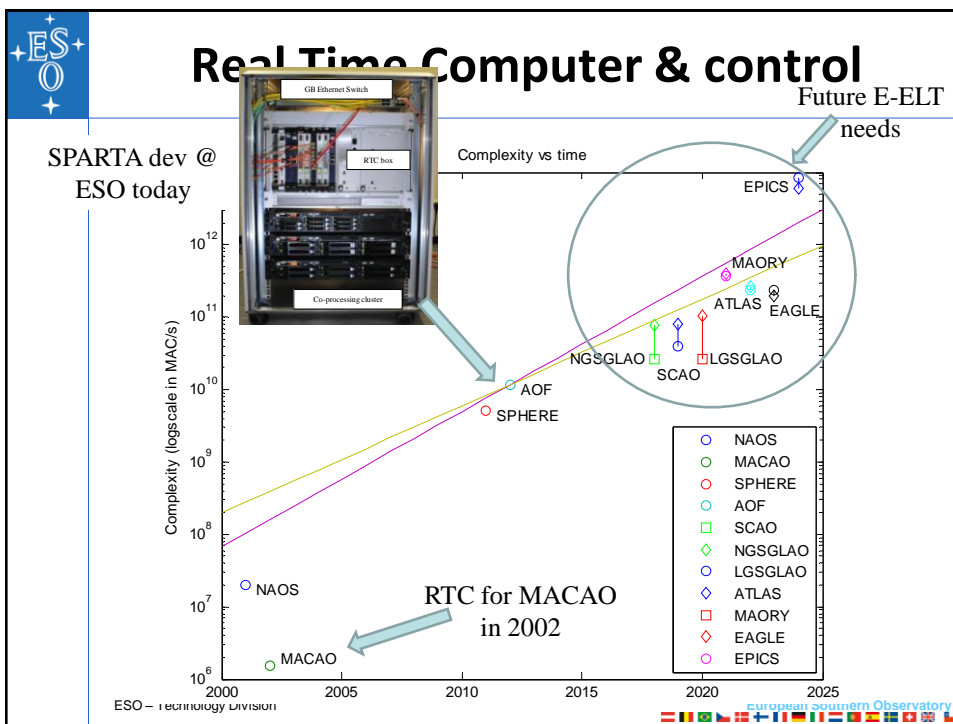


Optoelectronics Research Centre
Tampere University of Technology

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VLT – Key technologies

VLT is well known for its excellent tracking performance. Four technologies that contributed to this success are:

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

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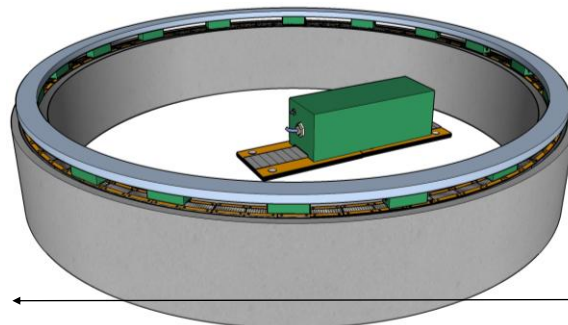
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VLT – Direct drive motors

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



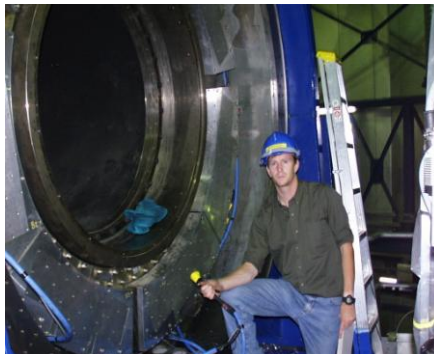
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10 m

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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

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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. These are mounted together on the same structure and have an accuracy of 0.1 arcsecond.



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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 .

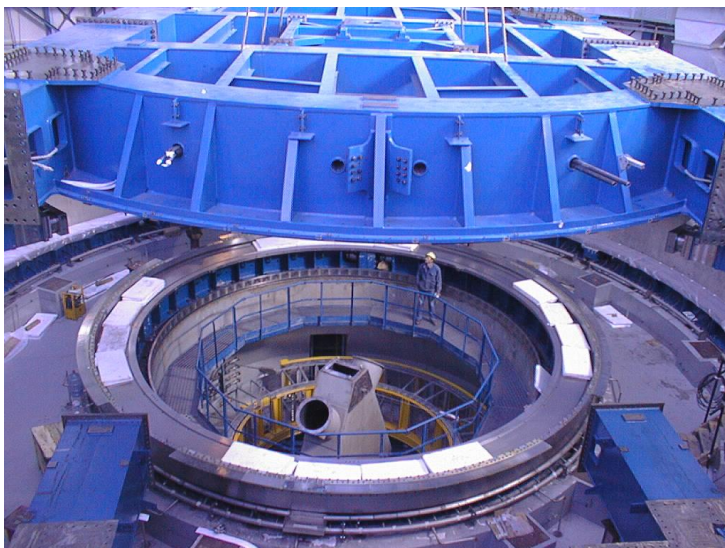
The result is not only very low friction (one person can move it) but also the fact that the absence of stick-slip friction make the system practically linear. Again a huge advantage for the control.

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VLT - Hydrostatic bearing system



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VLT – Innovative Control Algorithms

First telescope with entire control system implemented in software



Real-time computer platform



High tech drive technology

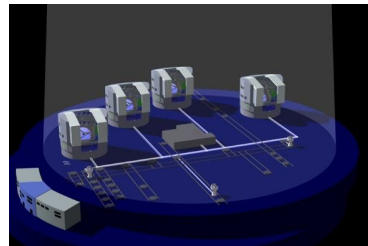
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What is the VLTi

The Very Large Telescope Interferometer (VLTi), equivalent to a single instrument with a mirror 16 m in diameter, combines the light from the four big Unit Telescopes and from several moveable 1.8-m Auxiliary Telescopes, spaced across baselines of up to 200 m, by way of the Interferometric Tunnel. Inside this 130-m-long underground cavern, the light beams gathered by the telescopes are passed through delay lines to compensate for the slightly different path-lengths they have taken in reaching the instruments.

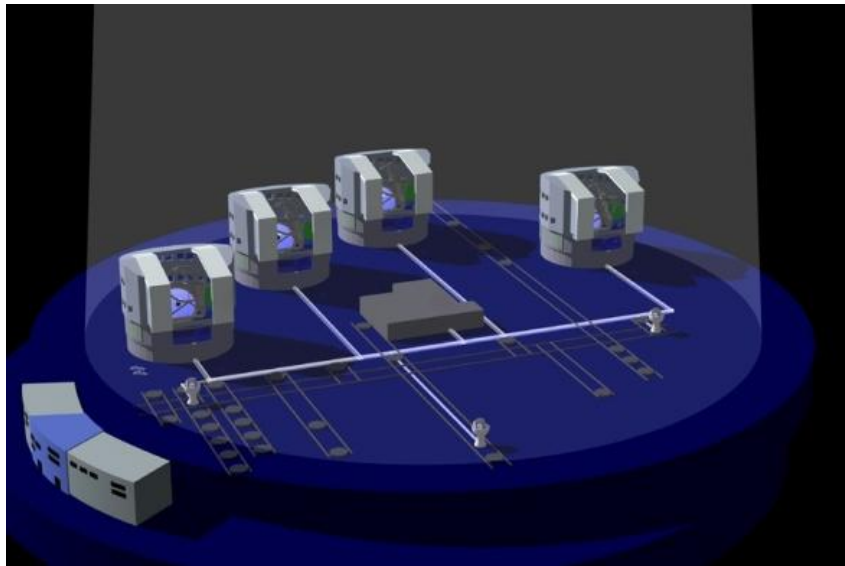


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What is the VLTi



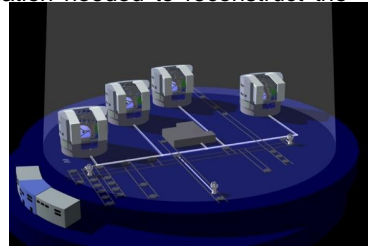
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What is the VLTI

The Very Large Telescope Interferometer (VLTI), equivalent to a single instrument with a mirror 16 m in diameter, combines the light from the four big Unit Telescopes and from several moveable 1.8-m Auxiliary Telescopes, spaced across baselines of up to 200 m, by way of the Interferometric Tunnel. Inside this 130-m-long underground cavern, the light beams gathered by the telescopes are passed through delay lines to compensate for the slightly different path-lengths they have taken in reaching the instruments.

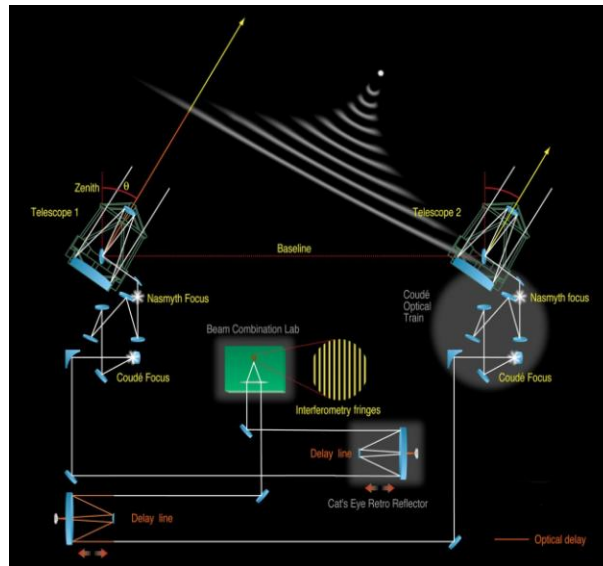
The delay lines help to synchronize the beams, before redirecting them to a central laboratory. The interference fringes produced when the beams are finally recombined provide the information needed to reconstruct the original image in unprecedented detail, giving a picture as sharp as if it had come from a single telescope 200 m across. This gives the VLT a maximum angular resolution of about 0.001 arc-second at 1 micron wavelength (in the near- infrared), which is equivalent to about 2 meters at the distance of Moon.



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VLTI Scheme - Subsystems

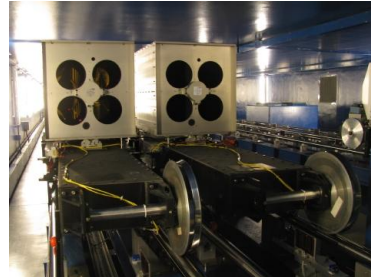


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VLTI main Delay Lines (DL)

- 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.



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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

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The VLT Telescopes



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The ALMA Partnership

- ALMA is a global partnership in astronomy to deliver a truly transformational instrument
 - Europe (ESO)
 - North America (US, Canada, Taiwan)
 - East Asia (Japan, Taiwan)
- Located on the Chajnantor plain of the Chilean Andes at 5000-m (16500')
- ALMA will be operated as a single Observatory with scientific access via regional centers
- Total Global Budget ~\$1.3B

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ALMA Antennas

- 66 Antennas delivered by the ALMA partnership
- Three separate companies are constructing the ALMA antennas
 - 25 x 12-m from Europe: AEM – Thales-Alenia Space, European Industrial Engineering and MT Mechatronics
 - 25 x 12-m from North America: Vertex, a part of the General Dynamics Corporation
 - 4 x 12-m and 12 x 7-m from Japan: MELCO, part of the Mitsubishi Electric Corporation

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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 -30C to +40C
- 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

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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

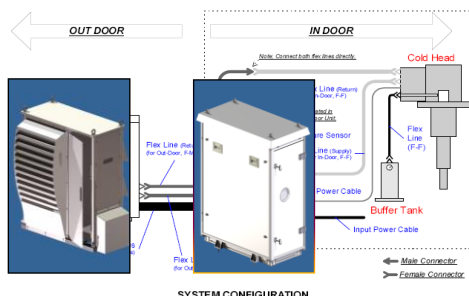
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ALMA Cryogenic System High Altitude Qualification Tests

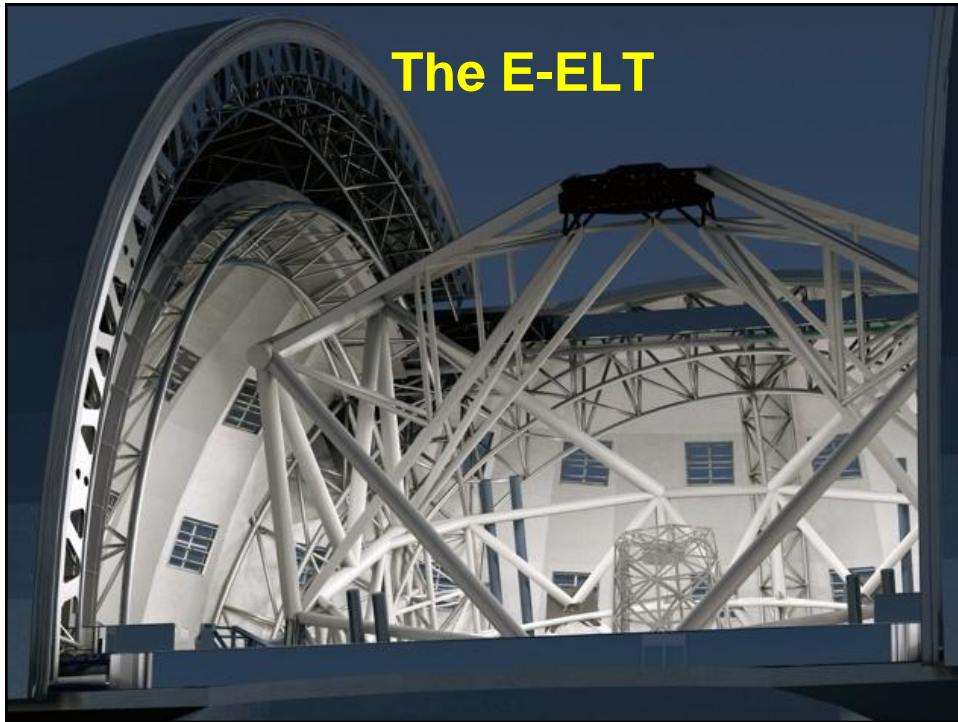
3-Stage Cold Head + He-pot on the 4K stage


- Test of **Air Cooled He-Compressors** (Indoor/Outdoor)
- Low noise receiver are cooled to less than 4K
- Temperature Stability shall be better than $\pm 5\text{mK}$
- Conditions influencing the system reliability
 - **Temperature** Range -30C to $+40\text{C}$
 - Strong **Wind** (operational limit 20m/s , survival 65m/s)
 - Ambient air pressure $\sim 550\text{mbar}$ (typical air density $\sim 0.7214 \text{ Kg/m}^3$)
 - **Rain, Snow and Icing**



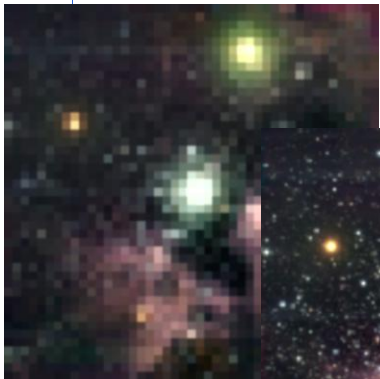
ALMA Cryogenic System High Altitude Qualification Tests









Spectacular Resolution



HST




VLT+AO



E-ELT

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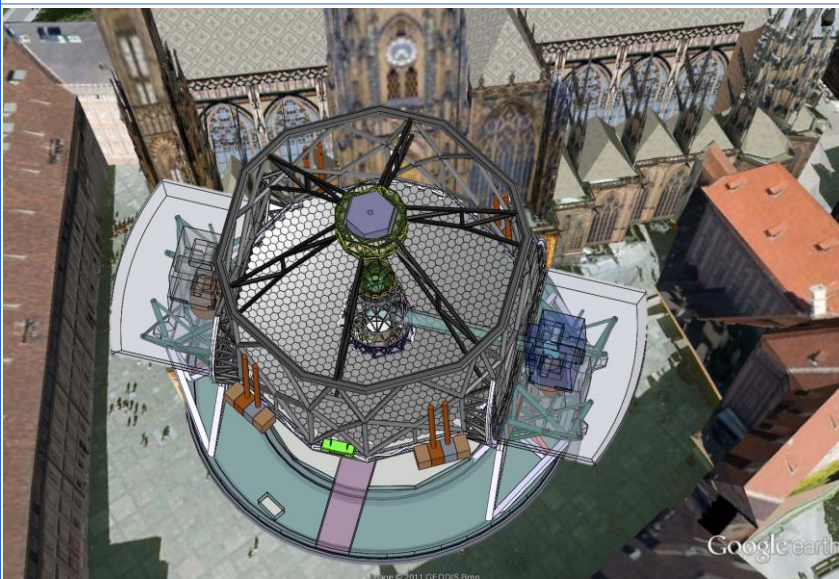
To put it in perspective...



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To put it in perspective...



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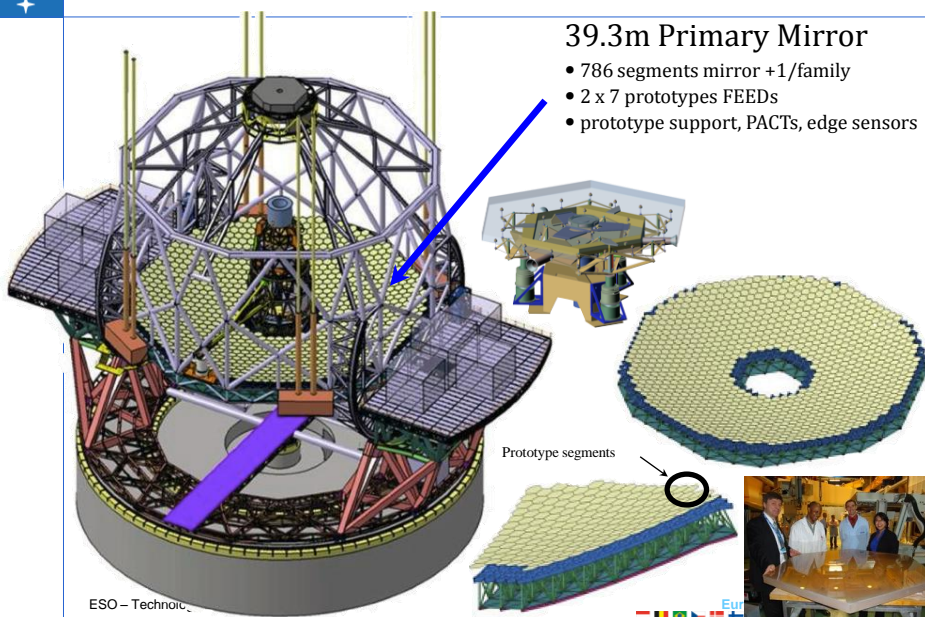
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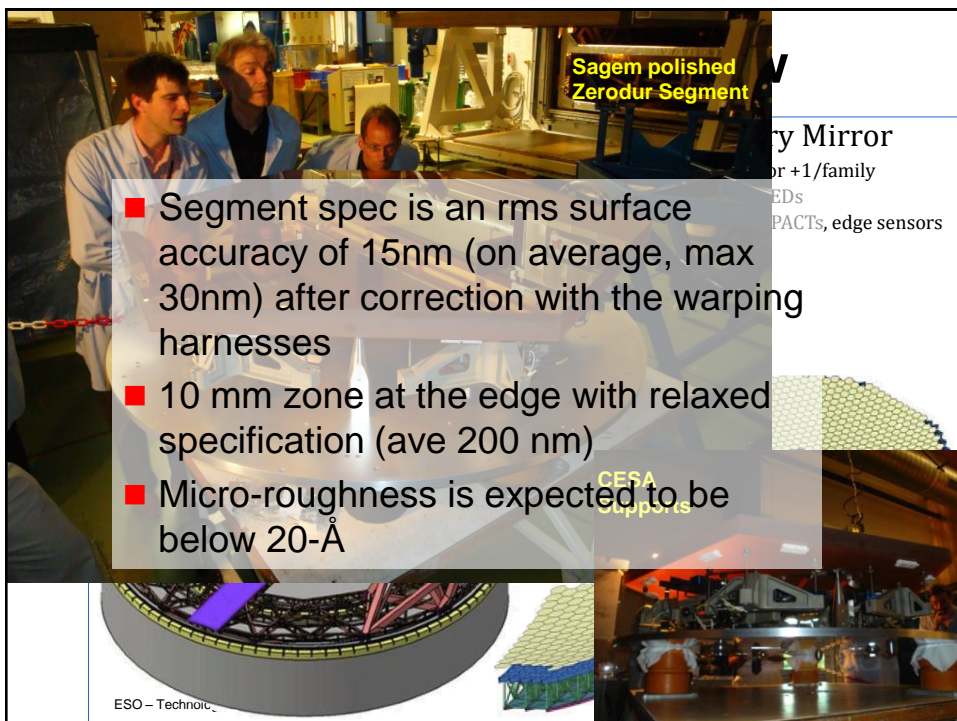
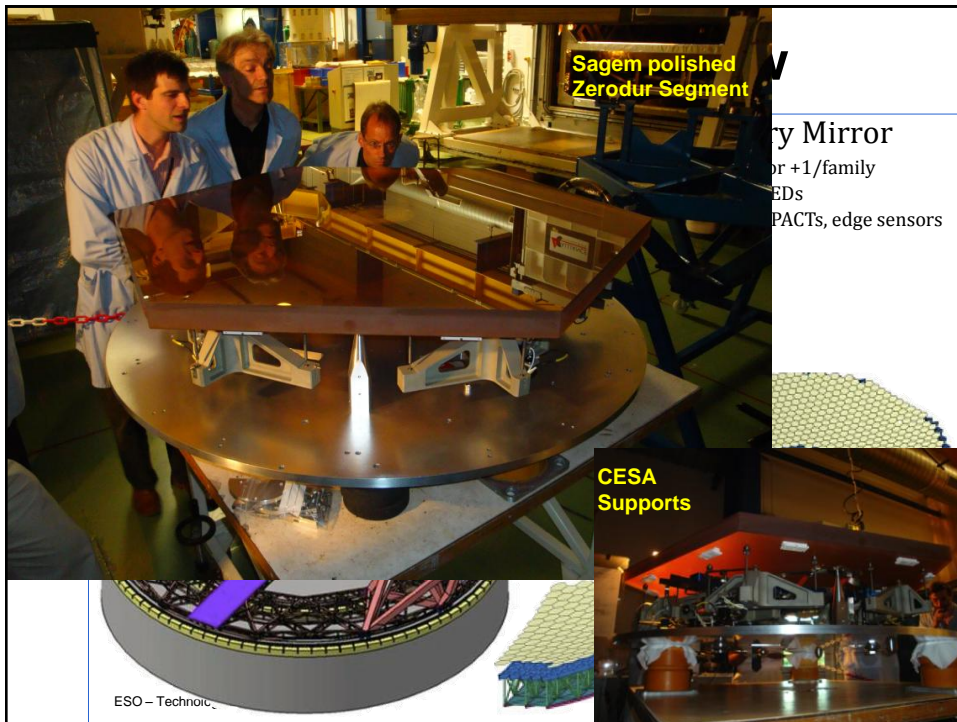
The process


- 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 $\lambda 2.2$ microns
 - Wavefront error less than 210-nm rms
 - 99% sky coverage

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The E-ELT: overview



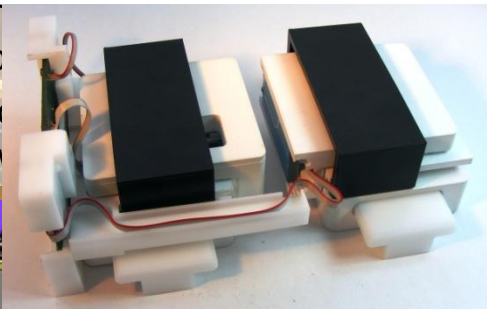


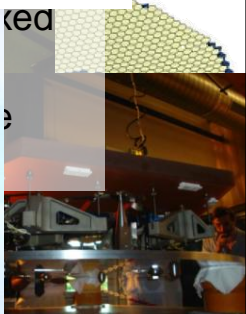


- Inductive edge sensors from micro-Epsilon
- Detect piston, gap and shear
- Requirements are to be able to measure piston with a resolution of 0.5-nm over a range of $\pm 200\text{-}\mu\text{m}$ with a repeatability of 1-nm

ror
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lge sensors

- 10 m spec
- Micro below






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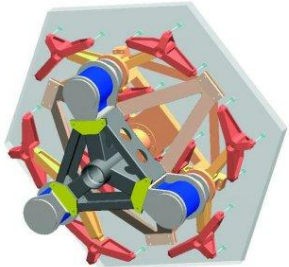
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E-ELT TCS (M1)


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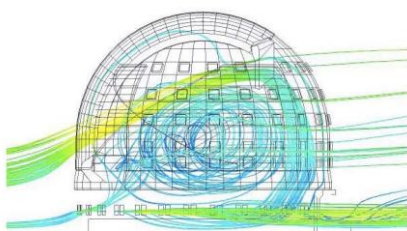
- The position of the ~800 mirrors must be coordinated to deliver a continuous surface with an error below 50nm across the M1 mirror (around 40 m diameter).
- 3000 actuators and 6000 sensors must work in a 1Khz closed loop to meet this requirement.
- Moreover 12000 actuators (12 motors per segment, the 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

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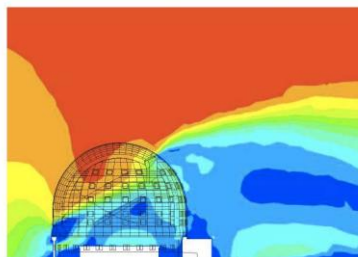
CFD Studies

- 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

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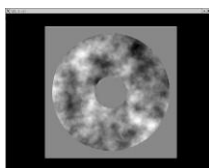
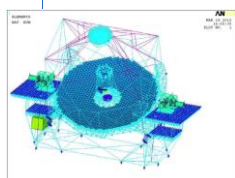


Velocity distribution in the E-ELT Dome at the symmetry plane.

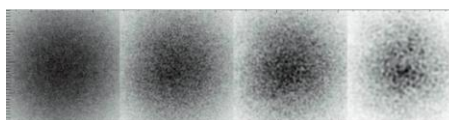
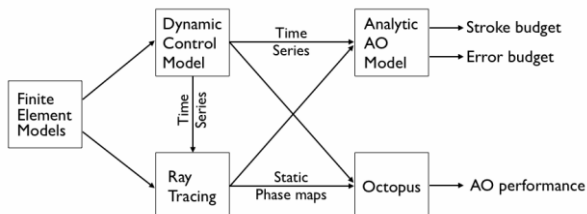
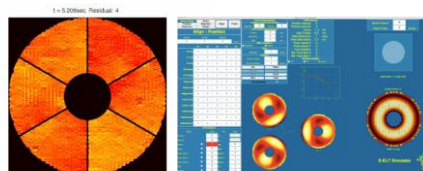


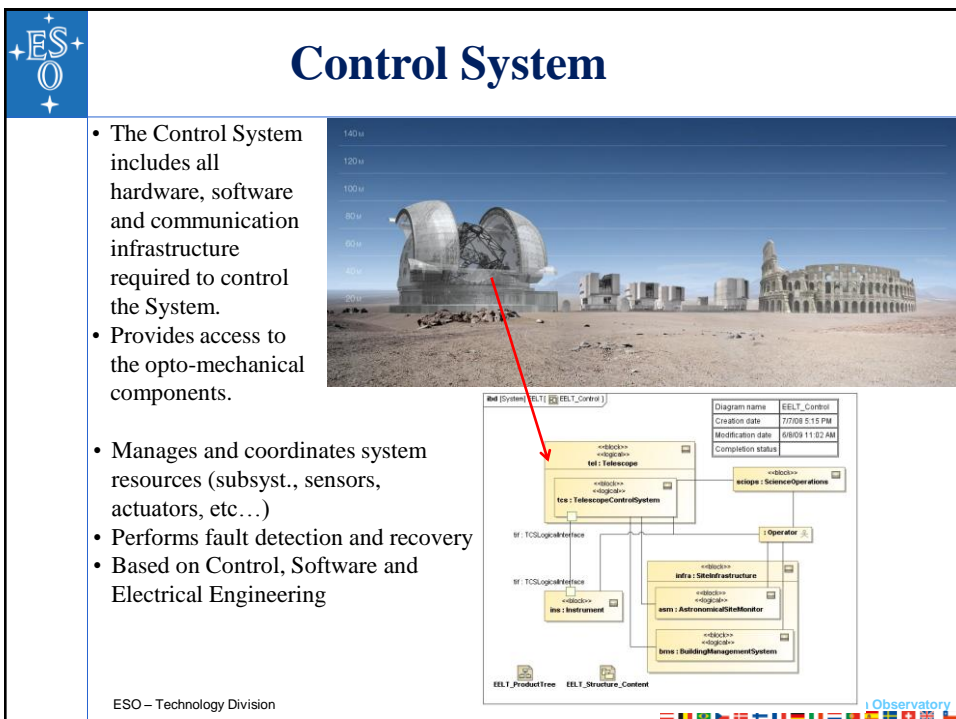
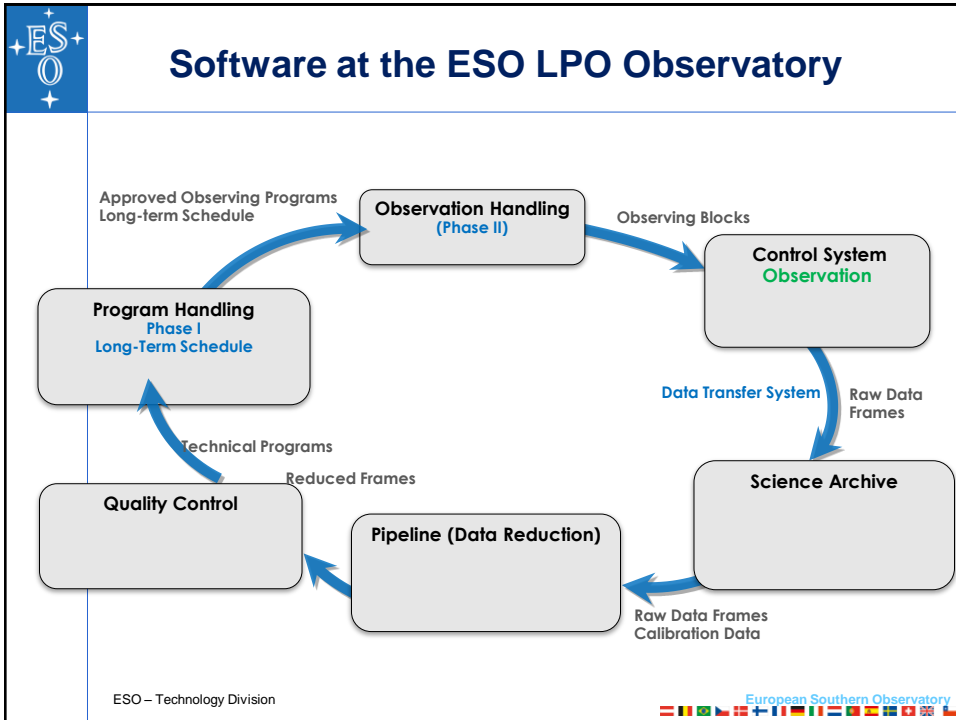
Analysis and simulation crucial

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.



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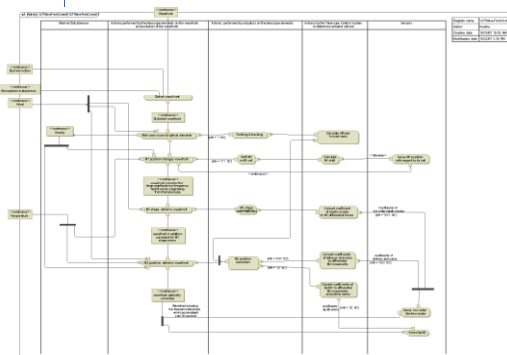




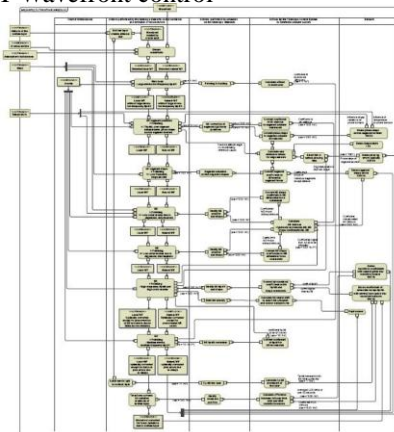


E-ELT Telescope Control System (cont)

VLT Wavefront control



E-ELT Wavefront control

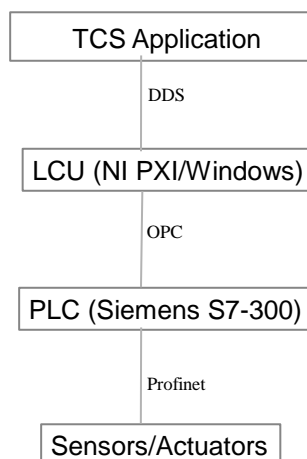


- 10000 tons of steel and glass
- 20000 actuators, 1000 mirrors
- 60000 I/O points, 700Gflops/s, 17Gbyte/s
- Many distributed control loops
- Use SysML to model the control system since 2008

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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)

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Thank you!

