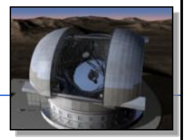
Technological Development and Needs at ESO

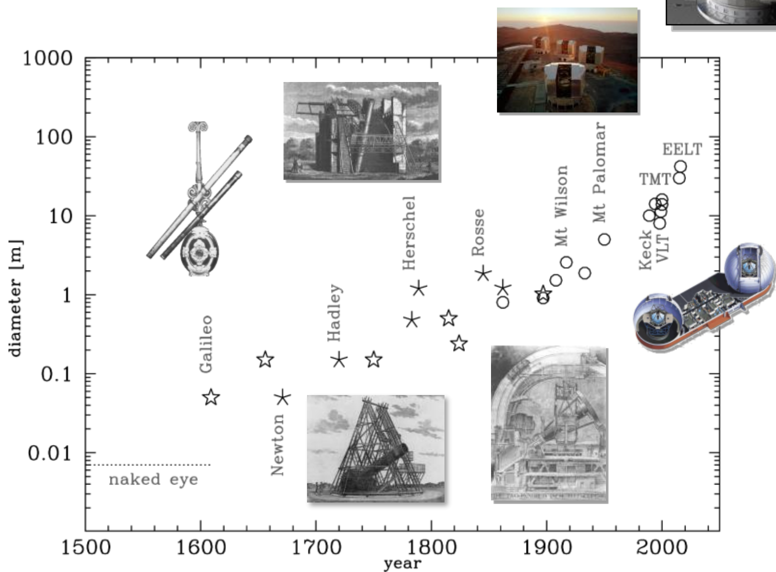
Roberto Tamai
ESO

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.

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.

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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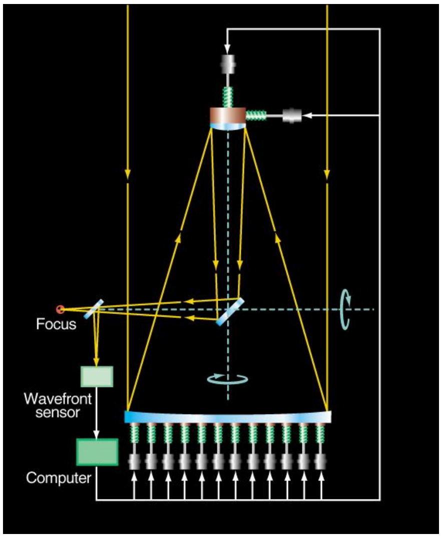
Principle of Active Optics

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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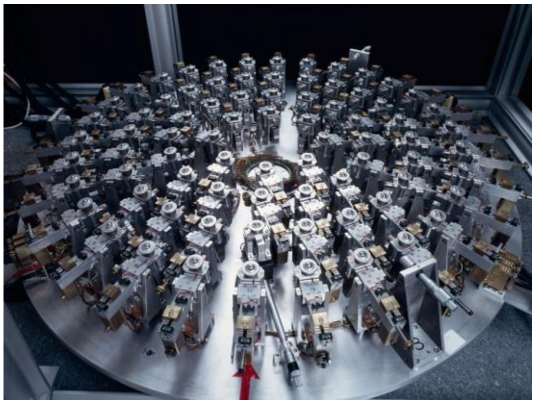

Active Optics=>The NTT

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

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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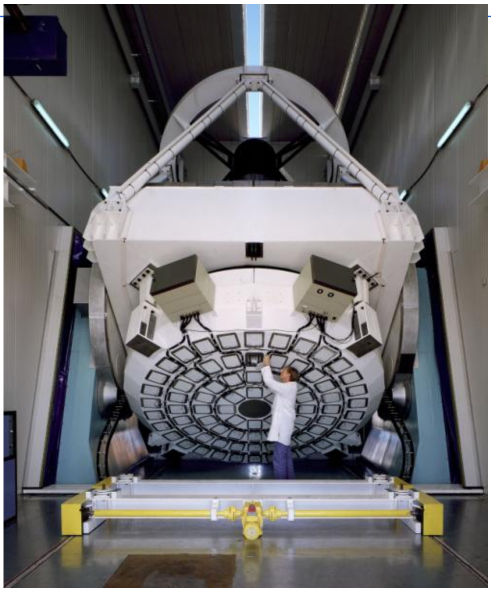
Active Optics=>The NTT



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VLT M1 Mirror

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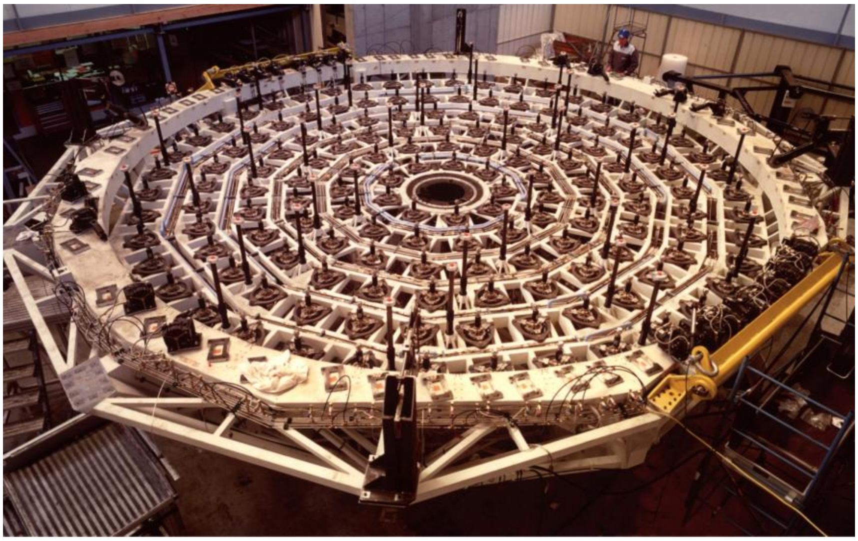
VLT M1 cell



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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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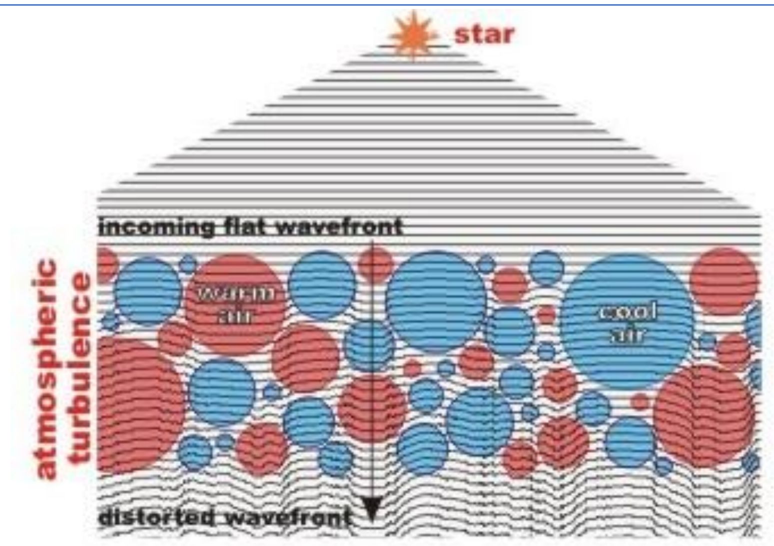
Adaptive Optics



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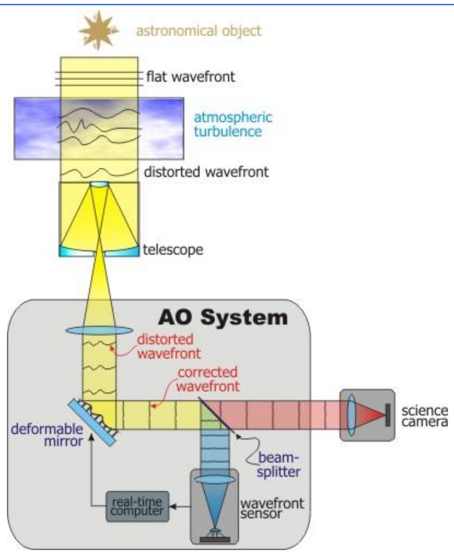
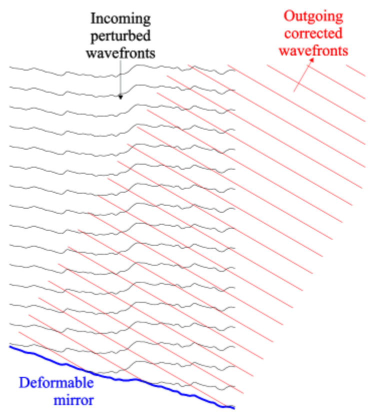
Adaptive Optics principle





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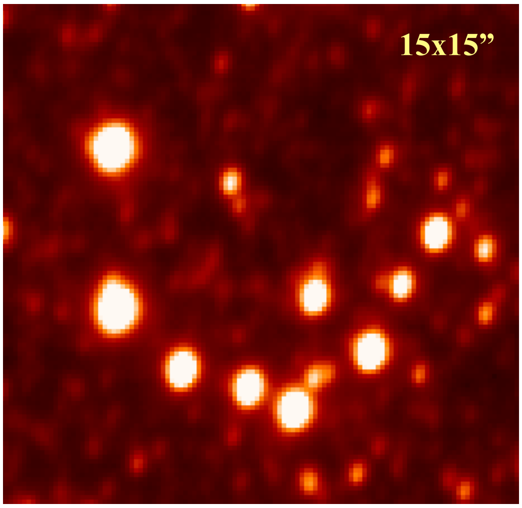
An AO milestone: MAD



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

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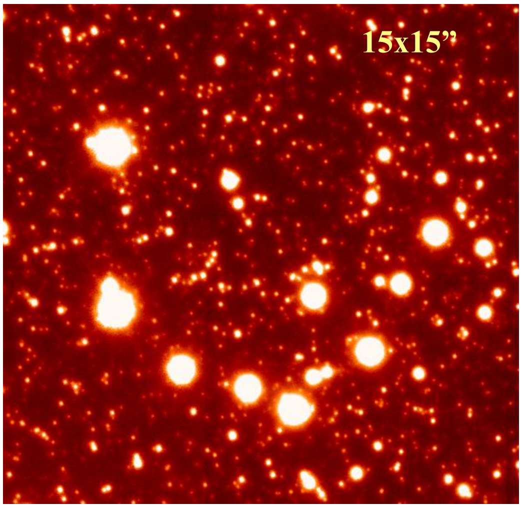

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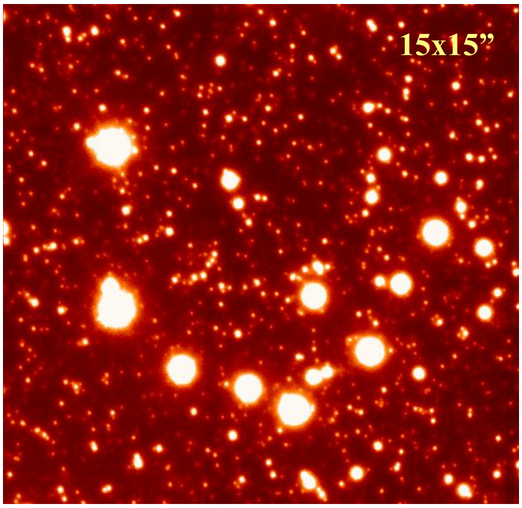

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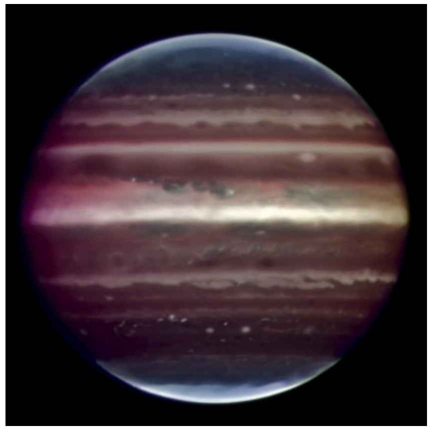
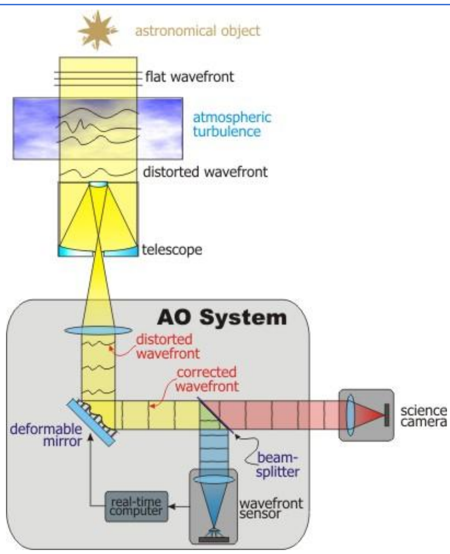
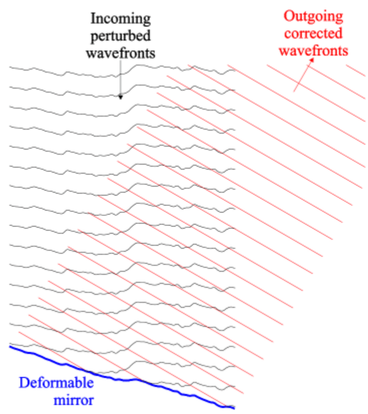


MCAO: 2 Guide “stars” (satellites Europa and Io)
2.14μm + 2.16μm filters
90 mas resolution (300 km at Jupiter)

Adaptive Optics principle





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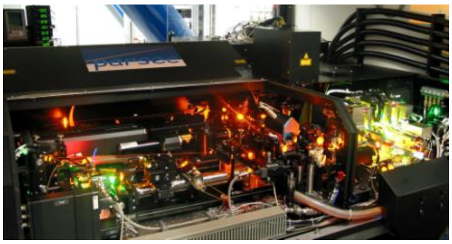
Laser for Adaptive Optics

• 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



The VLT LGSF at UT4

VLT Laser Clean Room

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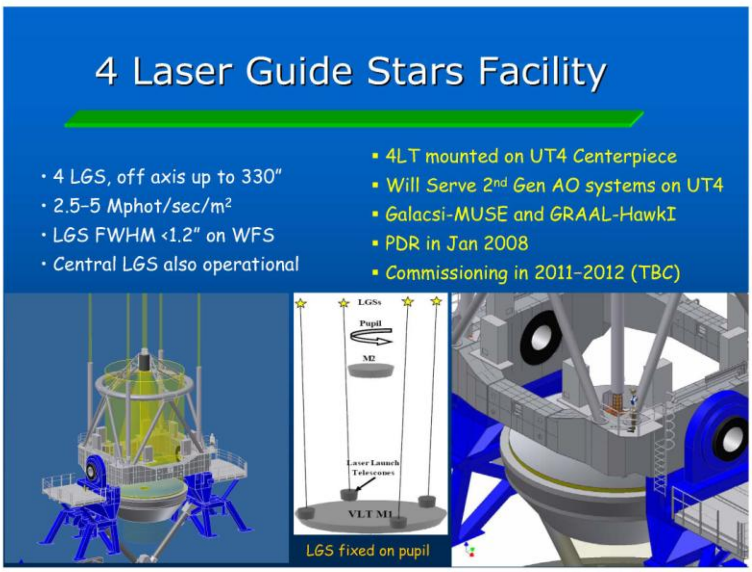

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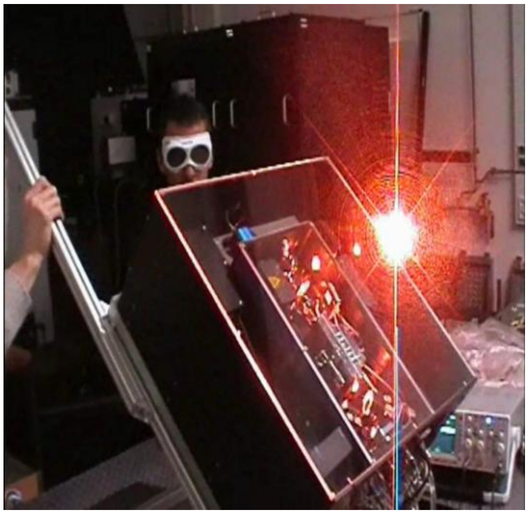
Fiber Laser demo



Road Map of WFS Detectors

MAD-WFS CCD
80x80 pixels
4outputs
500Hz frame rate
RON: 8-6 e/pixel
QE: 70-80%

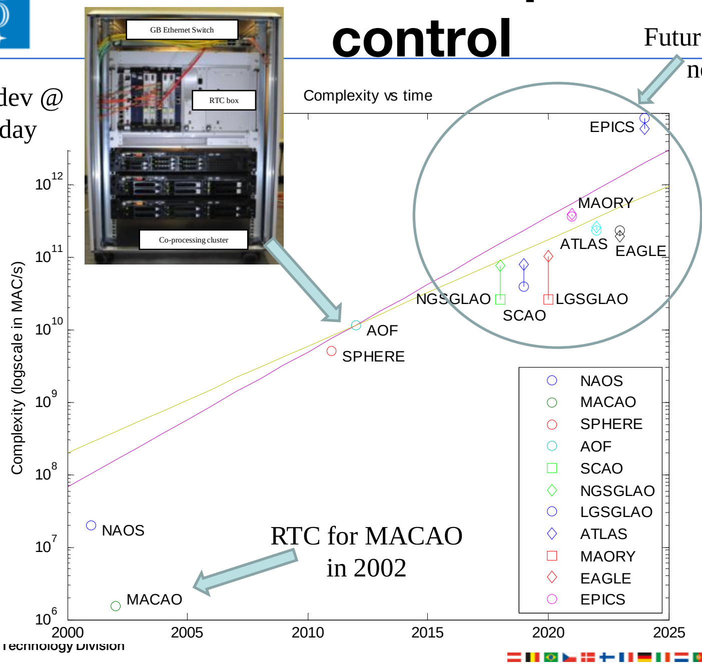
NAOS-WFS CCD
128x128 pixels
2x8 outputs
25-600 Hz frame rate
RON: 2.5-6.5 e/pixel
QE: 80%

Future-WFS CCD-220
240x240 pixels
8 L3 outputs
0.25-1.2 kHz frame rate
RON: < 1(0.1)e/pixel
QE: 90%

Real Time Computer & control

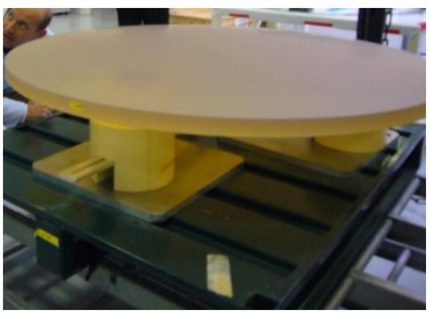
SPARTA dev @ ESO today

Future E-ELT needs



RTC for MACAO in 2002

Thin shells



1.1m Zerodur shell manufactured at SAGEM

2.6m glass shell, 2 mm thick at SAGEM

VLT – Main axes drive system

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

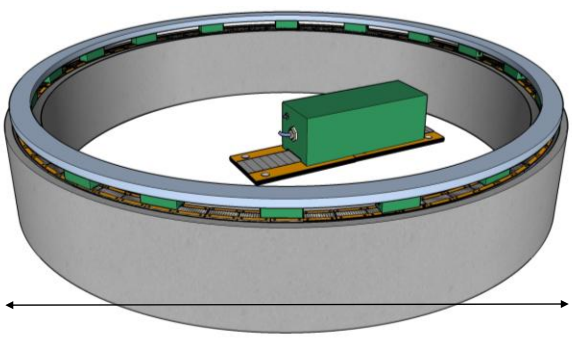
1. Direct drive motors
2. Collocated encoders
3. Hydrostatic bearing system
4. Innovative control algorithms

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.

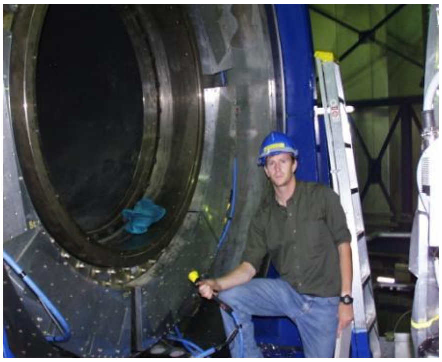
Such large motors have to be assembled by segments



10 m

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

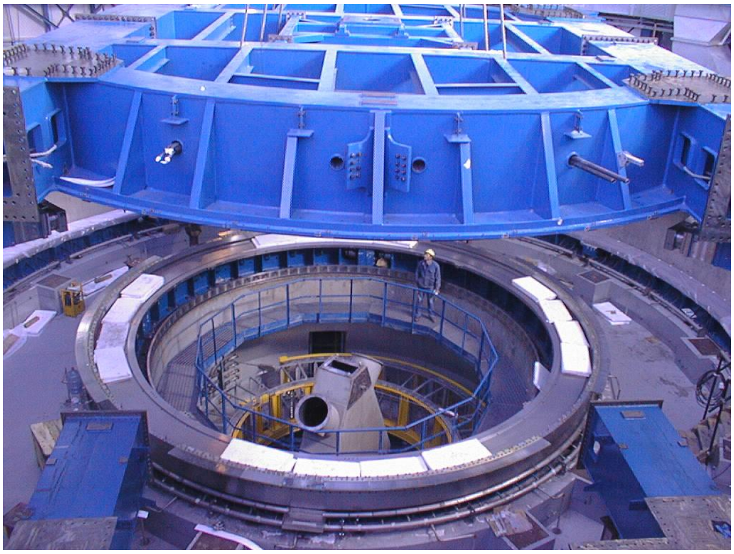
VLT – Hydrostatic bearing system

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 – Innovative Control Algorithms

First telescope with entire control system implemented in software

Real-time computer platform

High tech drive technology

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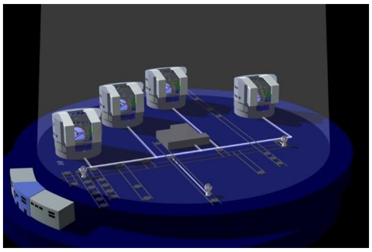
What is the VLTI

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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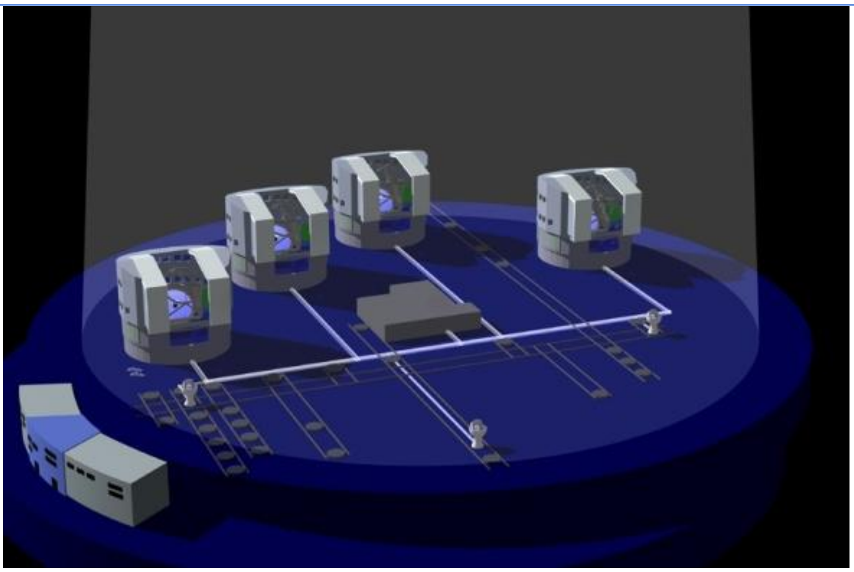
What is the VLTI



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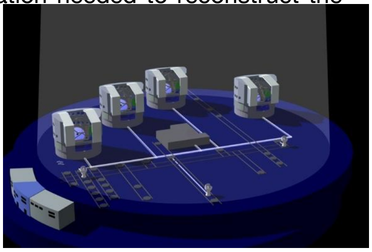
The delay lines help to synchronize the beams, before redirecting them to a central laboratory. The interference fringes produced when the beams are finally recombined provide the information needed to reconstruct the original image in unprecedented detail, giving a picture as sharp as if it had come 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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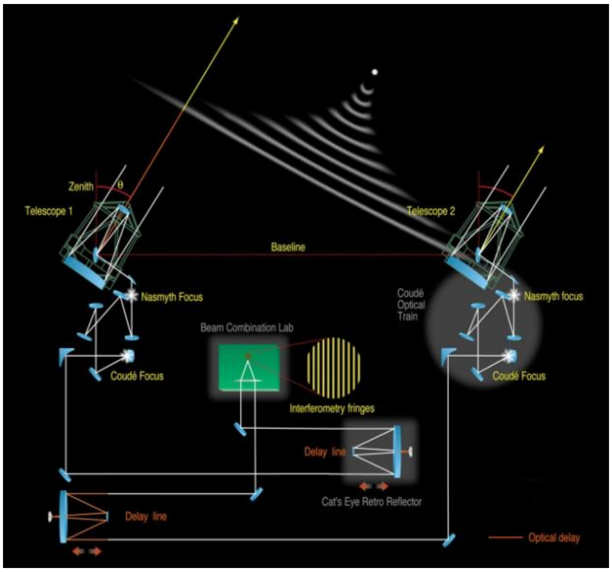
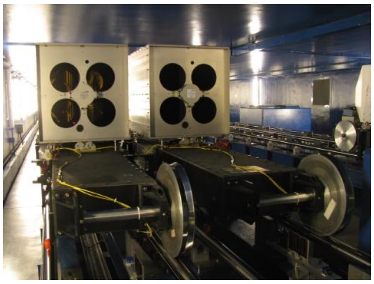
VLTI Scheme - Subsystems



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.



ESO's Precision Engineering Requirements

- The next generation of big projects are €1B class projects
- ESO's approach to these projects embodies three major principles
  - Industrial Procurement
  - Exploit and push the current state of the art
    - In terms of industrial capability and design/analysis tools
  - Risk Management

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

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 x12-m and 12 x 7-m from Japan: MELCO, part of the Mitsubishi Electric Corporation

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 (survival 65m/s)
- 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

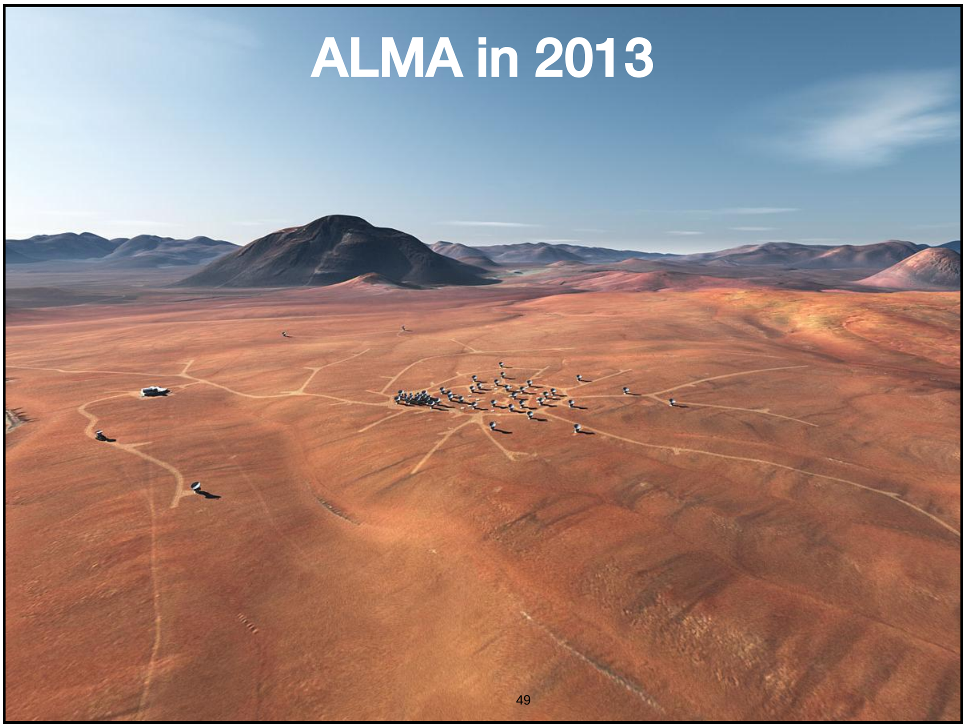
- 25 µm rms surface accuracy under all the environmental conditions
- Blind all sky pointing of 2 arcsec rms
- Offset pointing accuracy of 0.6 arcsec over a two degree field
- Tracking of 0.6 arcsec rms
- Pathlength variations less than 20 µm
- Fast position switching 1.5° in 1.5 sec, and
- Able to directly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

ALMA Cryogenic System High Altitude Qualification Tests

September 2011

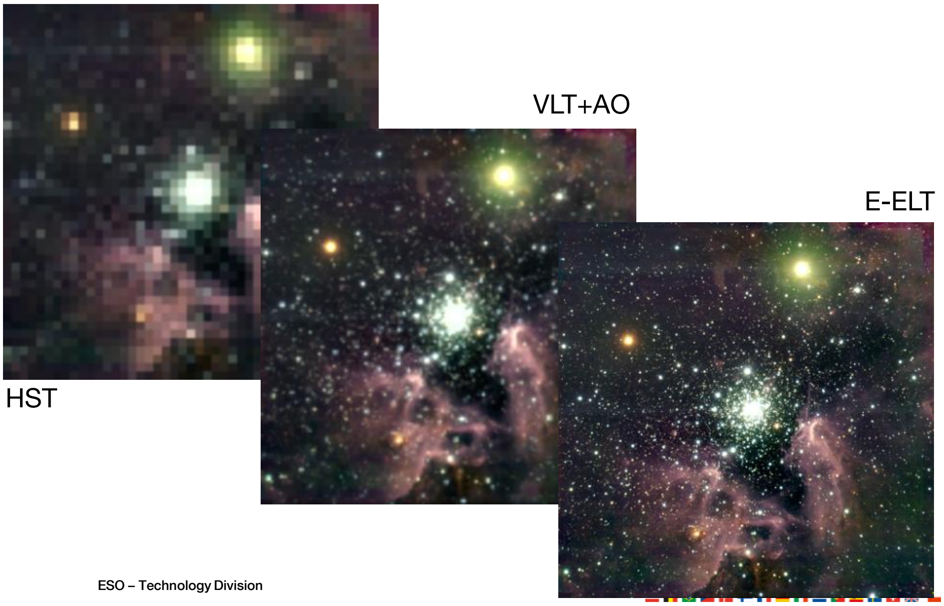
47

ALMA in 2011

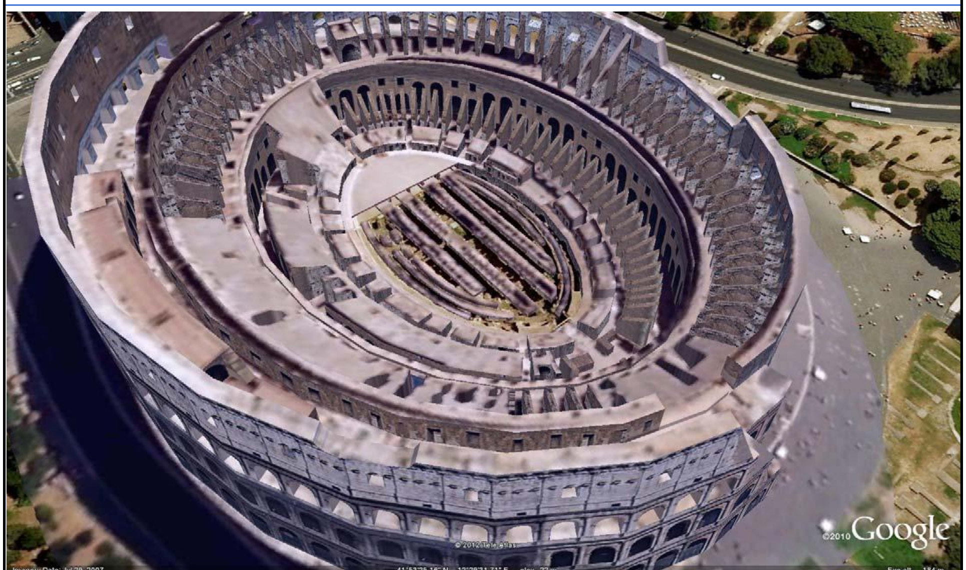

ALMA in 2013
49


The E-ELT
50

Spectacular Resolution



To put it in perspective…



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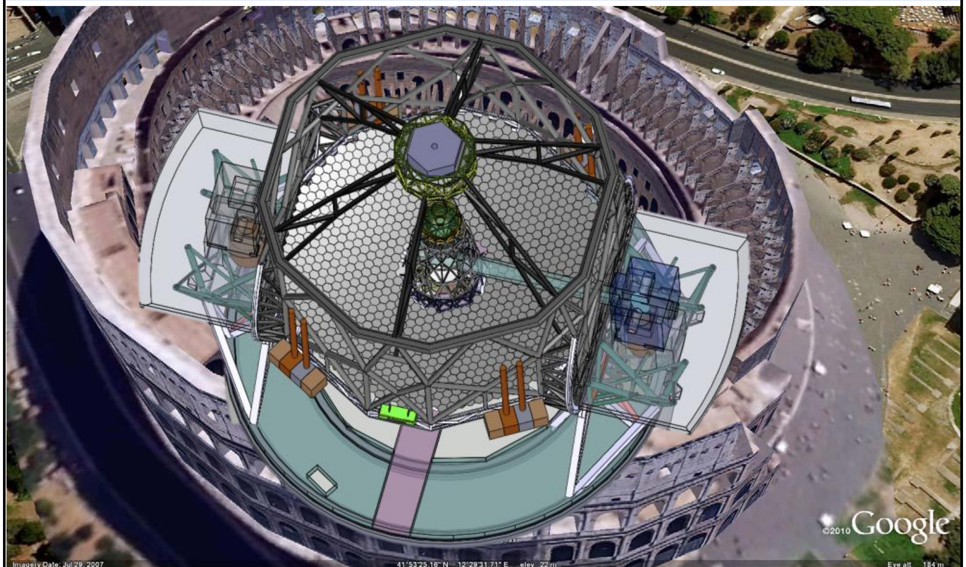
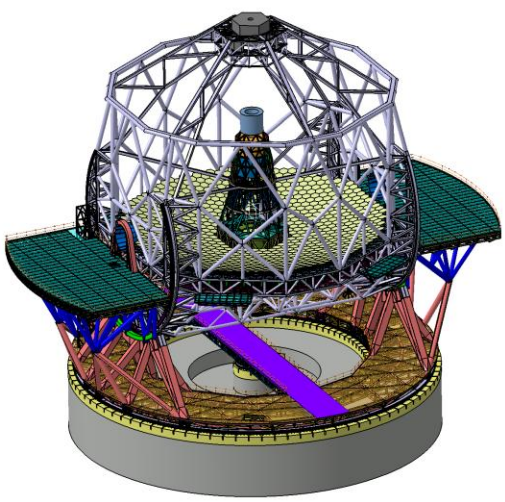
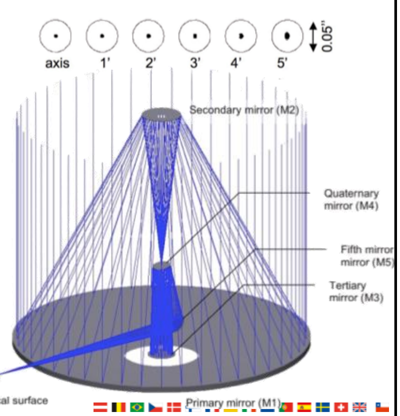


The E-ELT: overview

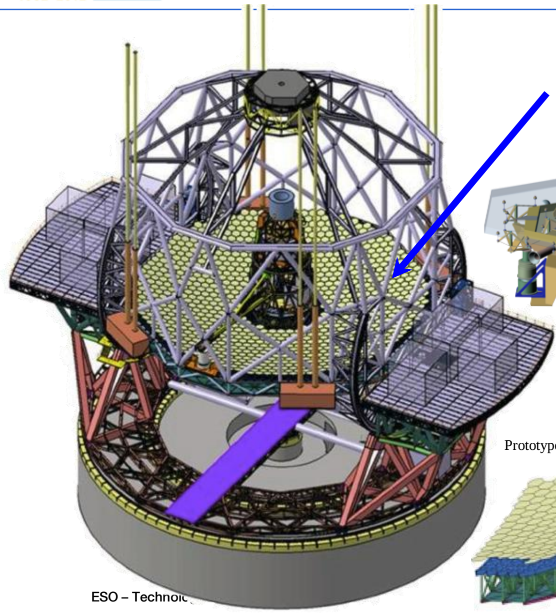


Optical design

• 3-mirror anastigmat on axis + 2 flats
• diffraction limited over full 10′ FoV Nasmyth, coudé foci
• very low LGS wavefront aberrations

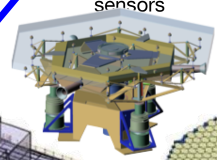


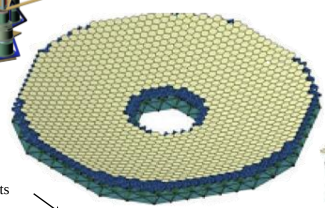
The E-ELT: overview



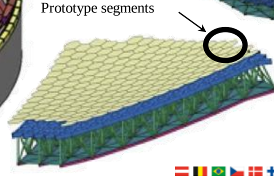
39m Primary Mirror

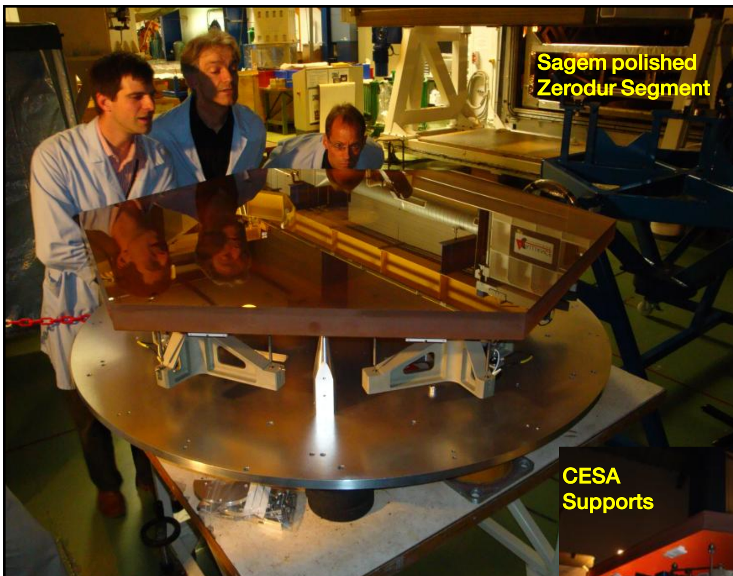
- 798 segments mirror (6 families of 133+1/family)
- 2 x 7 prototypes FEEDs
- prototype support, PACTs, edge sensors

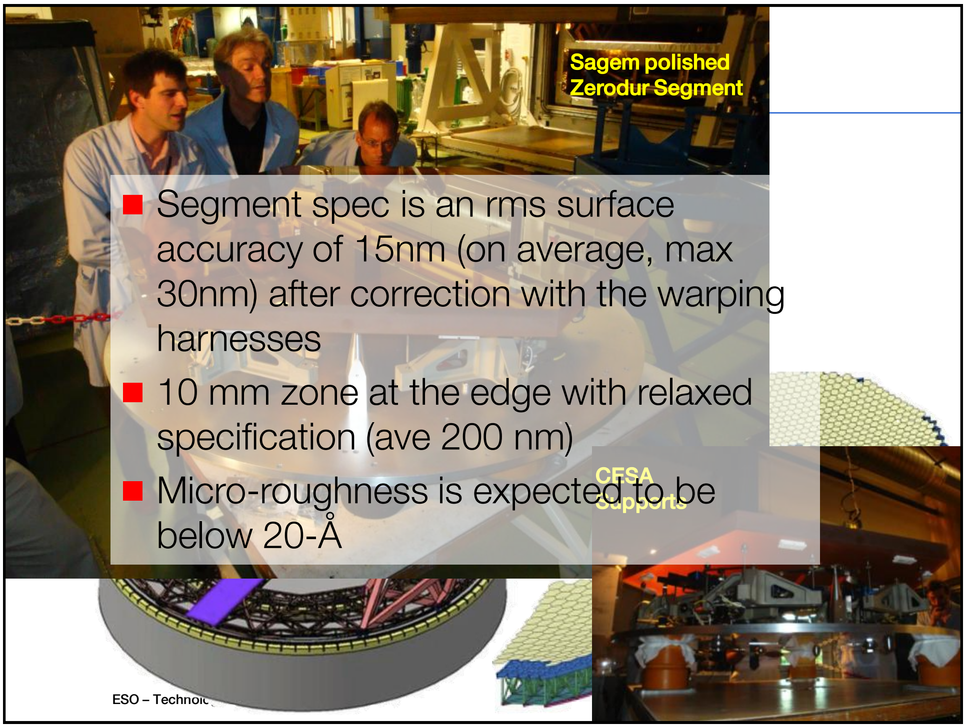


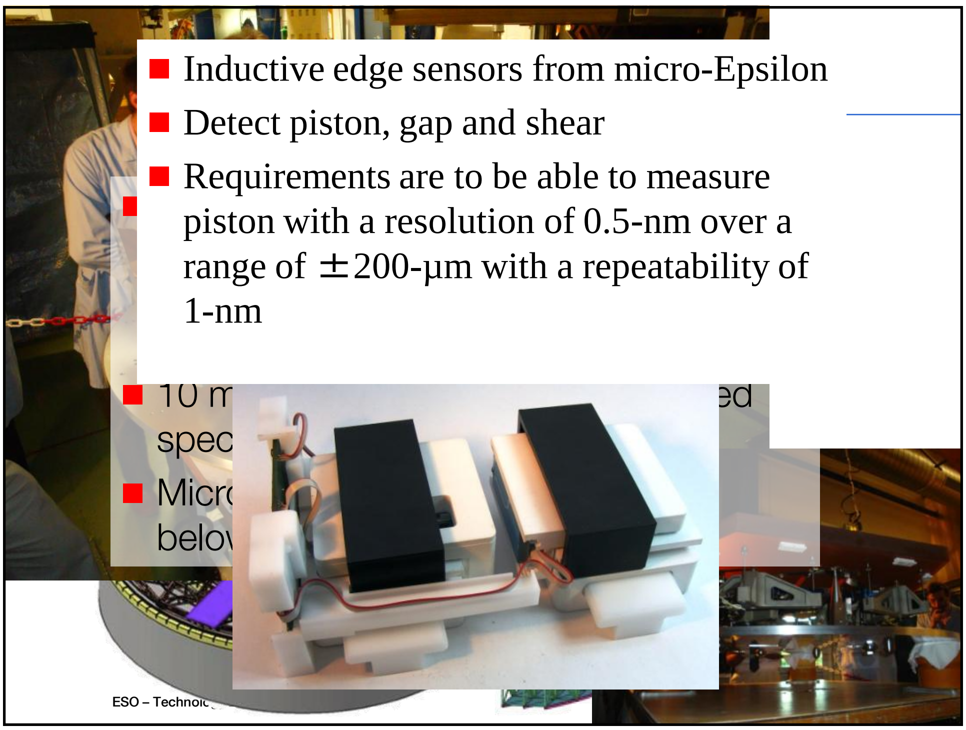


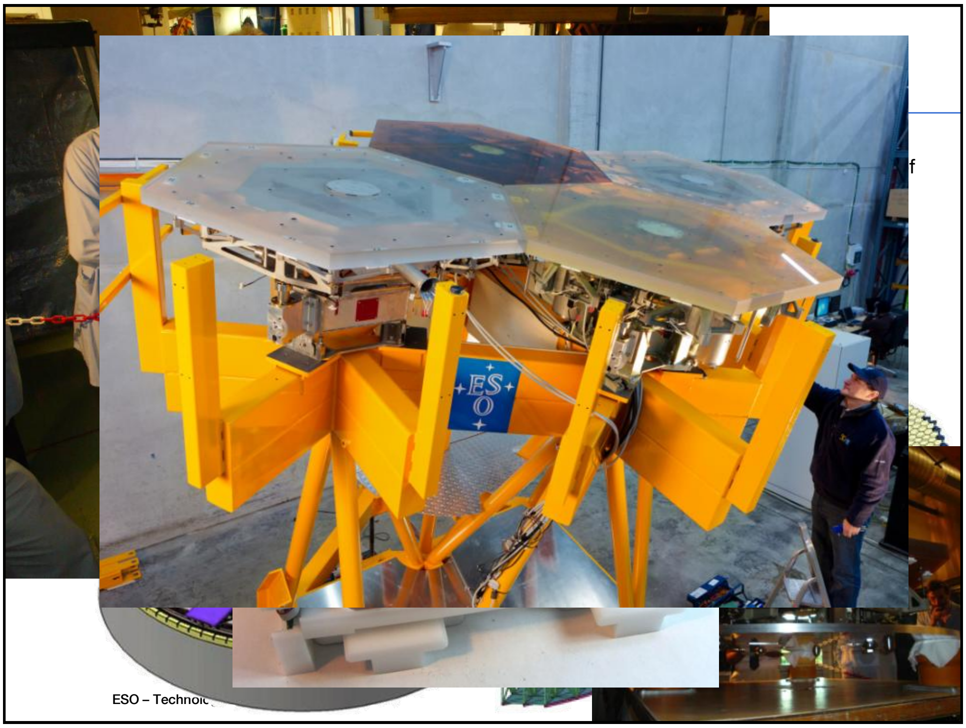
Prototype segments



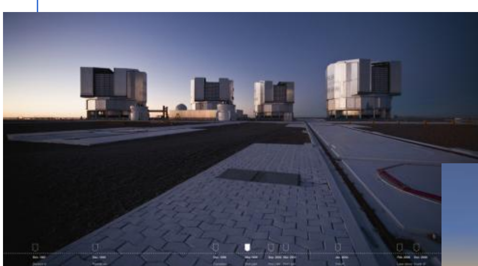



Sagem polished
Zerodur Segment
Segment spec is an rms surface accuracy of 15nm (on average, max 30nm) after correction with the warping harnesses
10 mm zone at the edge with relaxed specification (ave 200 nm)
Micro-roughness is expected to be below 20-Å
CESA
Supports
ESO – Technolo

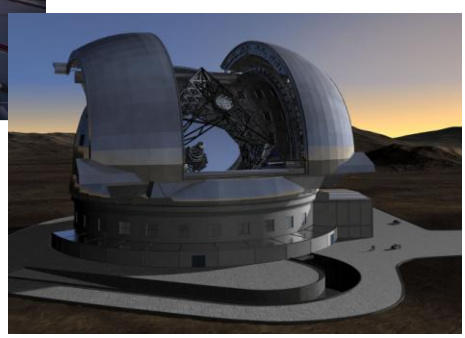

Inductive edge sensors from micro-Epsilon
Detect piston, gap and shear
Requirements are to be able to measure piston with a resolution of 0.5-nm over a range of ±200-μm with a repeatability of 1-nm
ESO – Technolo



VLT / E-ELT Observatory
Electrical grid connection



We need electricity...



Chilean grids

We need a grid connection as soon as possible.

ESO Paranal-Armazones connection

The existing Paranal power generating system

A power generating station is currently operating at Paranal, which is used to supply the power demand of the VLT Observatory.

This station is currently comprised of:

- one multi-fuel turbine-generator set (rated about 2.6 MW_e at the site);
- three diesel-generator sets (3x 856 kW_e).

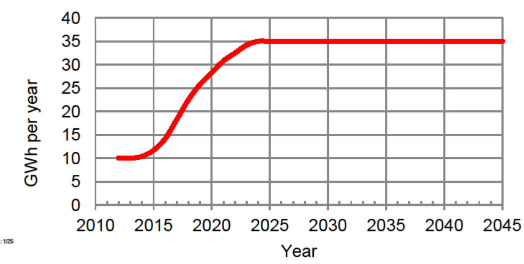
All generators are directly connected to the MV (10 kV) distribution network of Paranal.

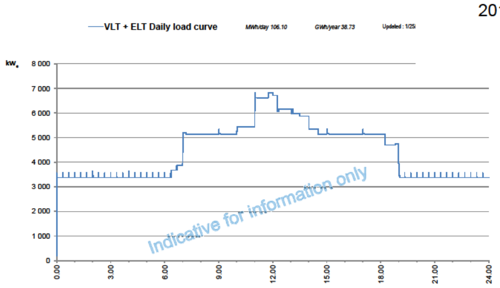
VLT & ELT Observatory Electric Energy Requirements

35 GWh/year

VLT: 10 GWh/year
ELT: 25 GWh/year

Forecast of total yearly energy consumption



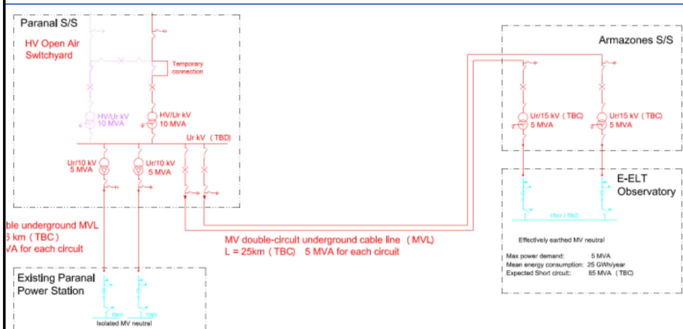


7 MW peak

VLT : < 2 MW already in operation

ELT: 1st transformer 2.0 MVA
2nd transformer 2.0 MVA
3rd transformer 1.6 MVA

Standby power for ELT in Armazones



The existing Paranal generation facility, upgraded if necessary, can be used as standby power generating system for both Paranal (VLT) and Armazones (E-ELT) after the connection of the Observatory to the grid. So the connection Paranal generation–HV Paranal S/S–Armazones has to be able to be used for this operation. Or, a dedicated UPS flywheels system at Armazones will provide back-up power to the E-ELT.

Technology needs in Astronomy

- Optics
- Detectors
- Mechanical structures
- Cooling and chiller system
- HVAC
- Cranes and handling equipments
- Mirror coating facilities
- Actuators
- Controllers
- SW
- Power grid connection and generation systems
- Power distribution
- Transportation of goods
- Waste and chemicals treatment
- (Pulsed) laser at specific frequency/wavelength
- Consultancy (RAMS, PA, QA)