Technological Development and Needs at ESO

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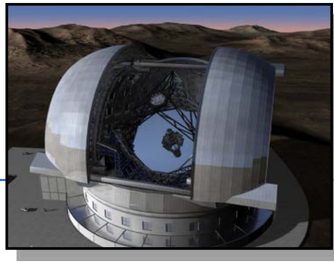
ESO

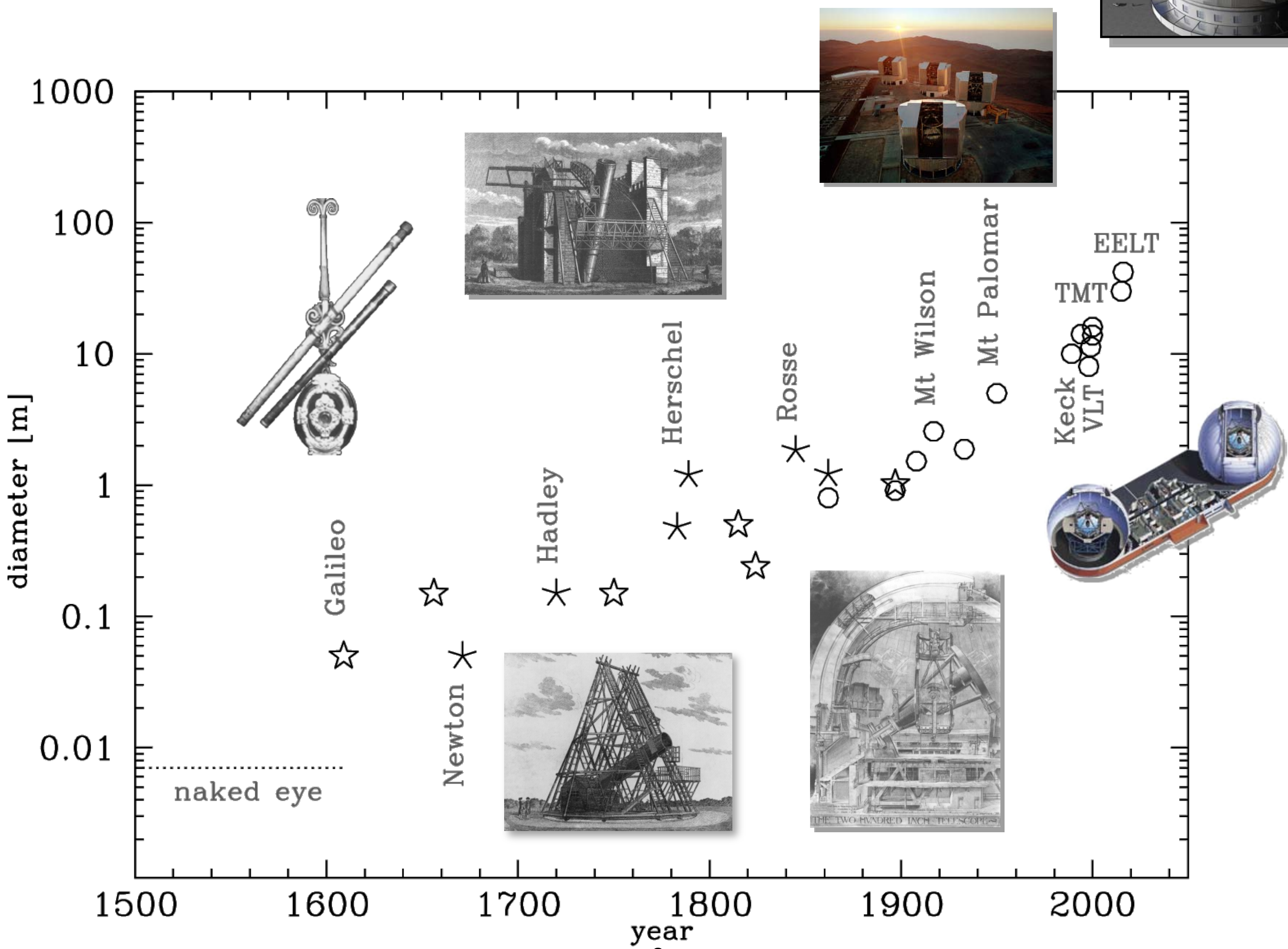
Deputy Director of Engineering

Technology in Astronomy

- From a small, manually pointed device for visual observations (around 400 years ago) ⇨ 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
  - Preserves optimal image quality by adjusting a “flexible” mirror’s shape with actuators during observations
  - In use in most modern medium and large telescopes
- ADAPTIVE OPTICS
  - Technology to reduce 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

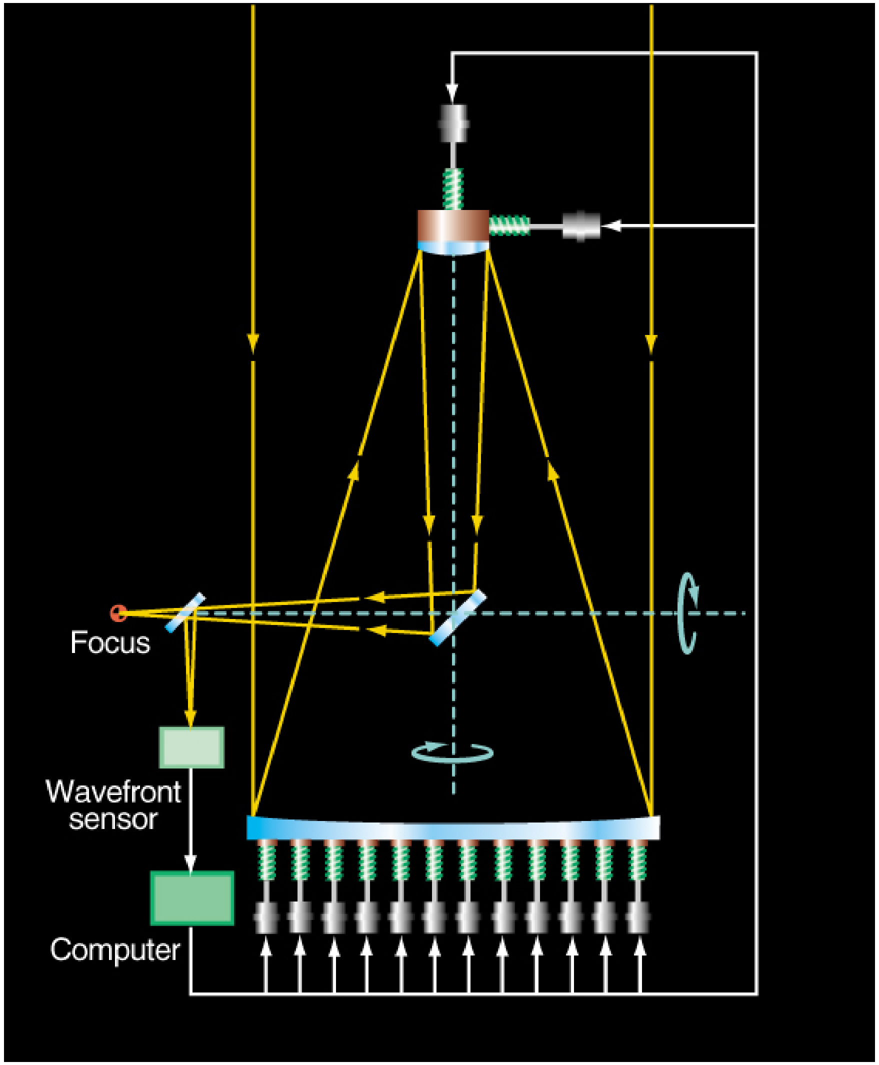
Optical telescopes collect light from the cosmos using a primary mirror.

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

Eventually such mirrors became prohibitively heavy: a new way had to be found to ensure optical accuracy.

Principle of Active Optics

1. During observation telescope and mirrors deform (gravity, thermal)
2. Reference star is monitored
3. Computer image analyzer detects deviations from optimal shape (modal analysis using optical aberrations and elastic modes of meniscus mirror)
4. Based on these signals the shape of M1 and relative positions of mirrors are automatically adjusted at regular intervals (30 – 60 sec)
5. Stellar image remains as round and sharp as possible



Active Optics=>The NTT

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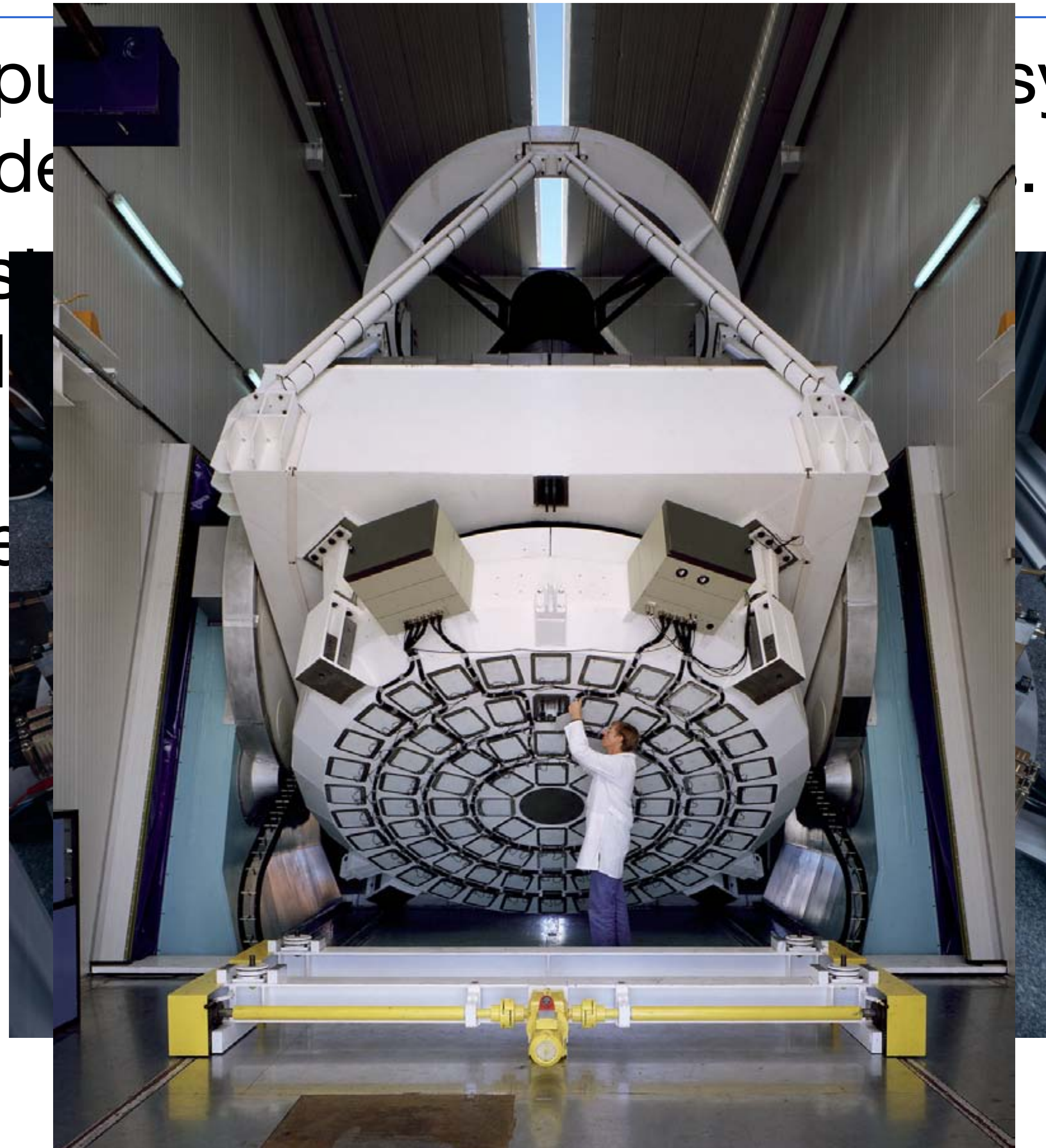
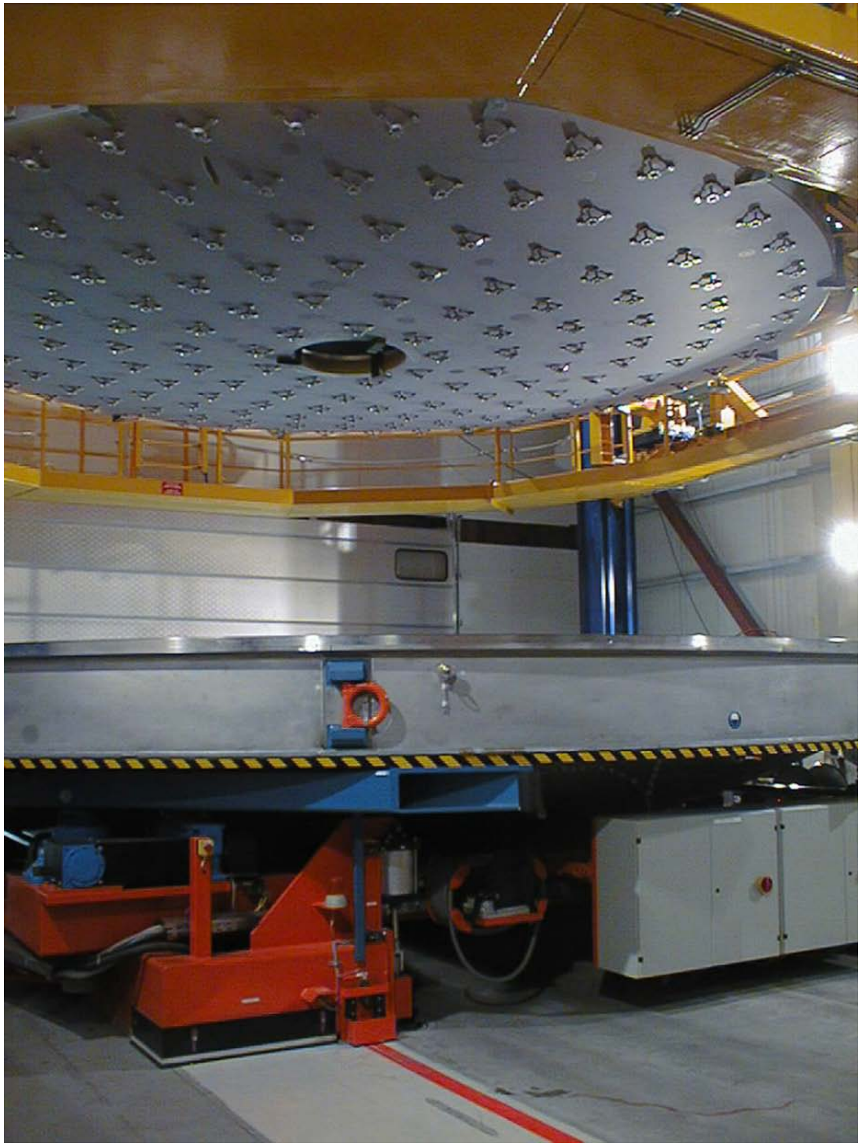
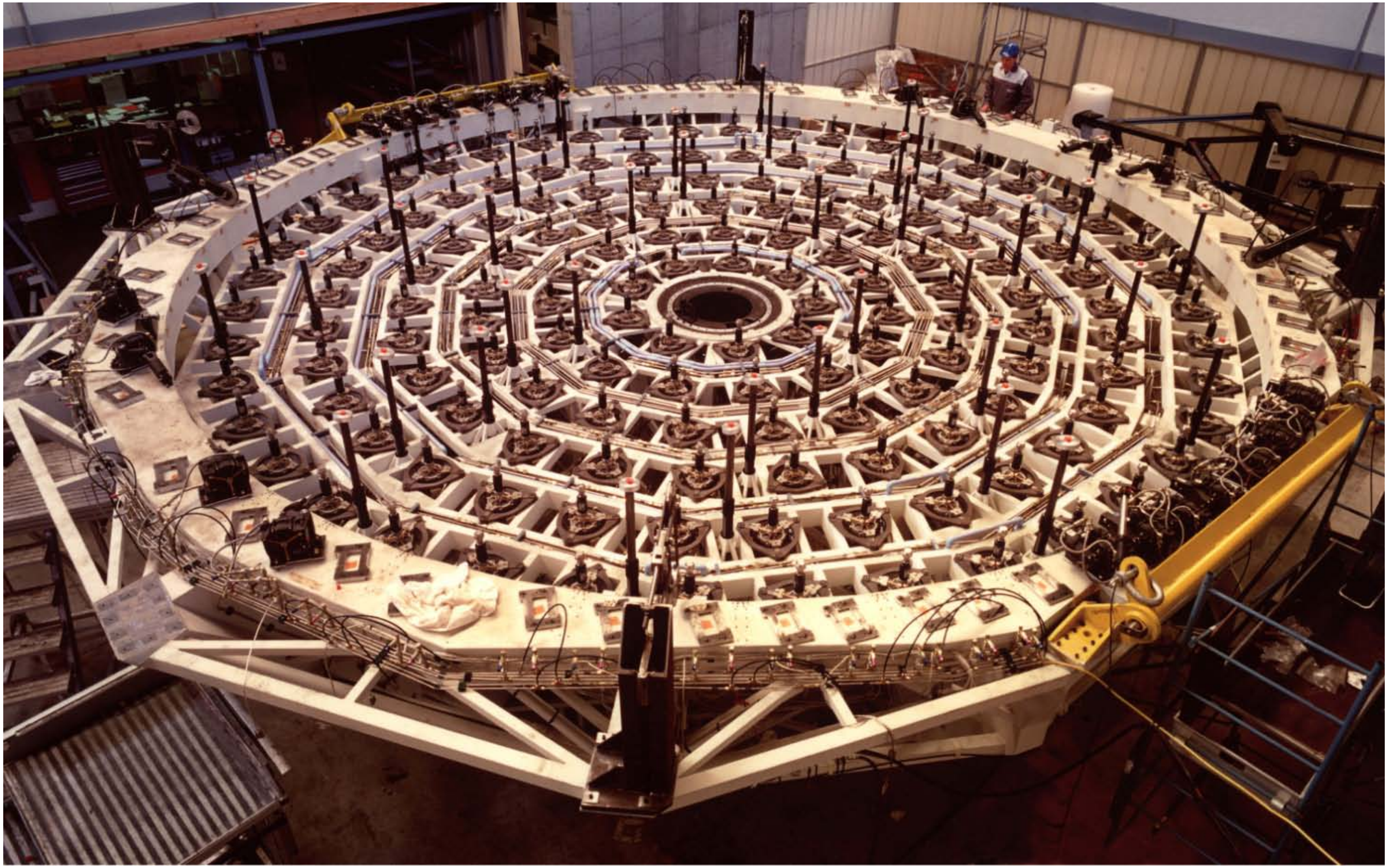


VLT M1 Mirror



VLT M1 cell



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 between

- **Active optics**:

  Optical components adjusted by external control to compensate slowly changing disturbances

- **Adaptive optics**:

  Applies to closed-loop feedback systems employing sensors and data processors, operating at much higher frequencies (kHz range). Very thin deformable mirrors (VLT DM 2 mm)

Adaptive Optics

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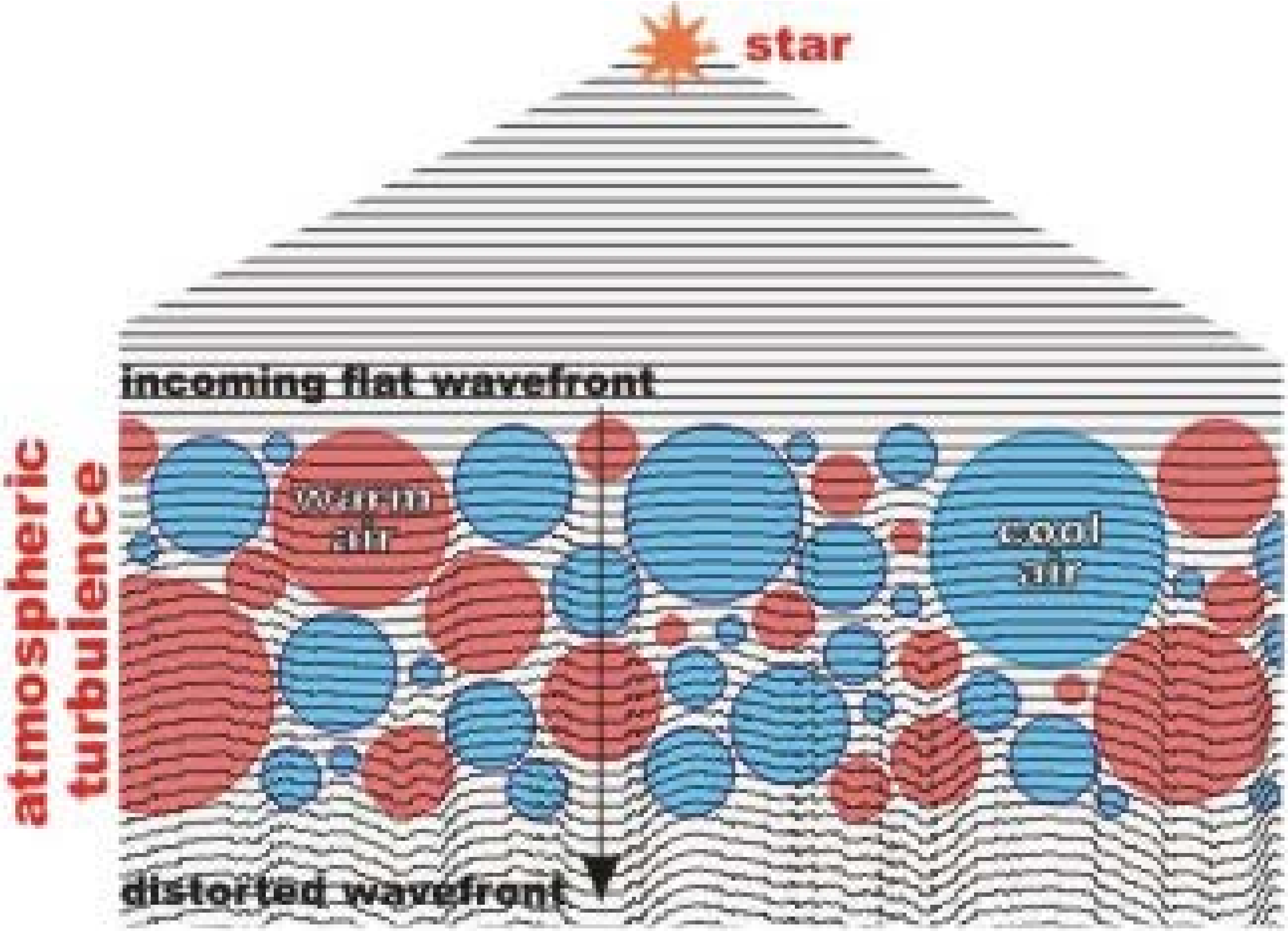
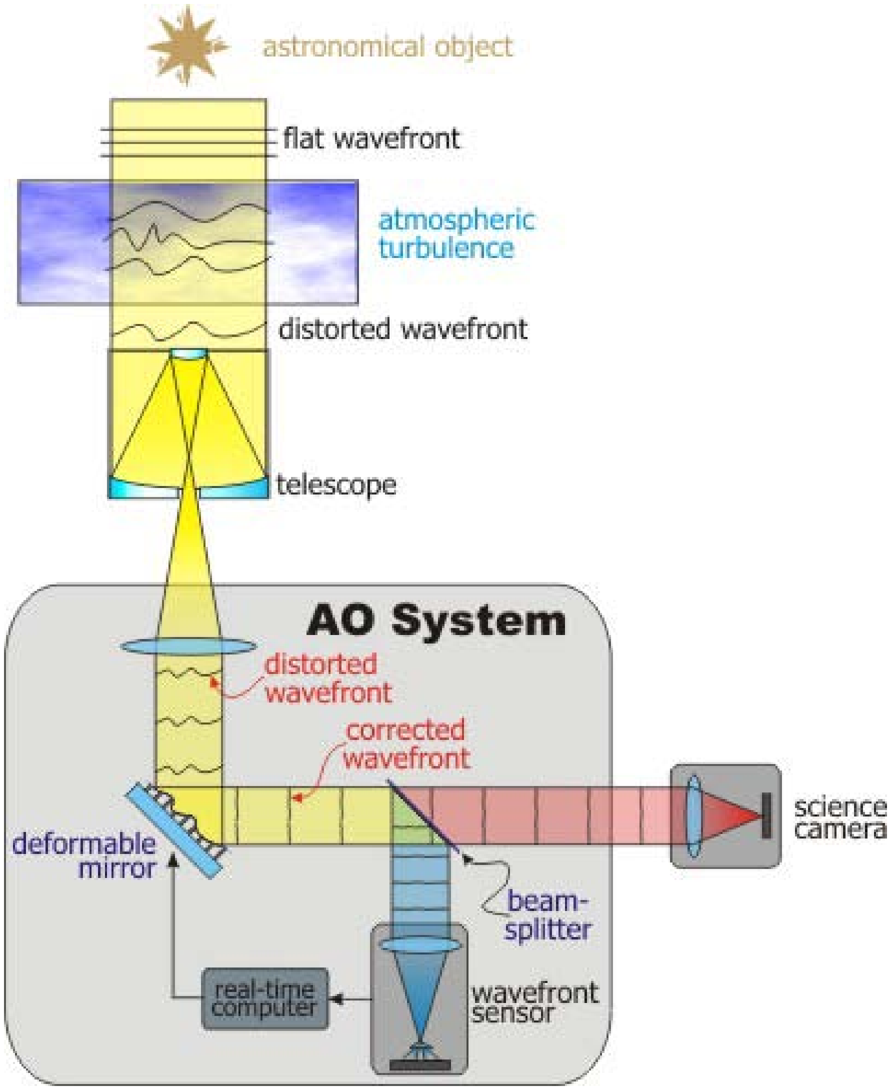
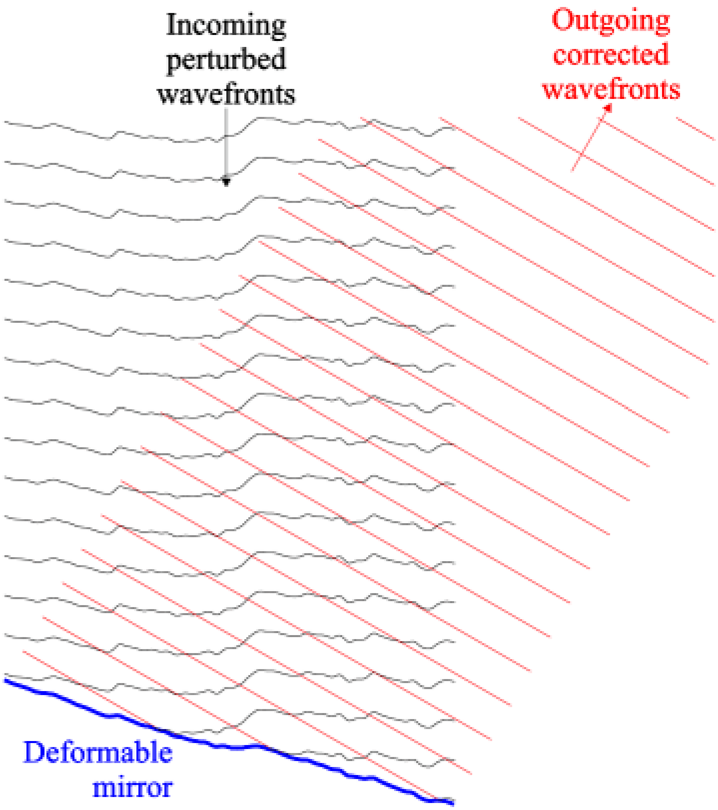


Adaptive Optics principle

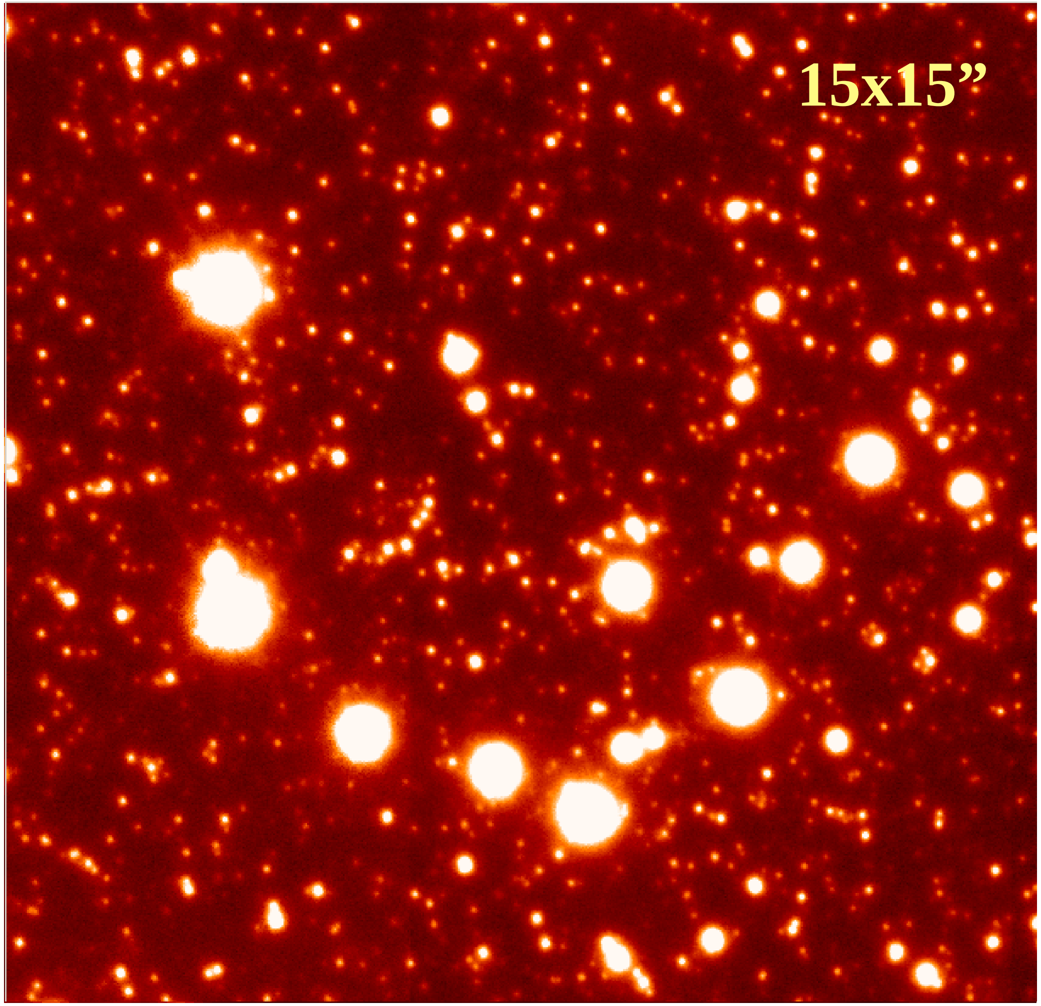




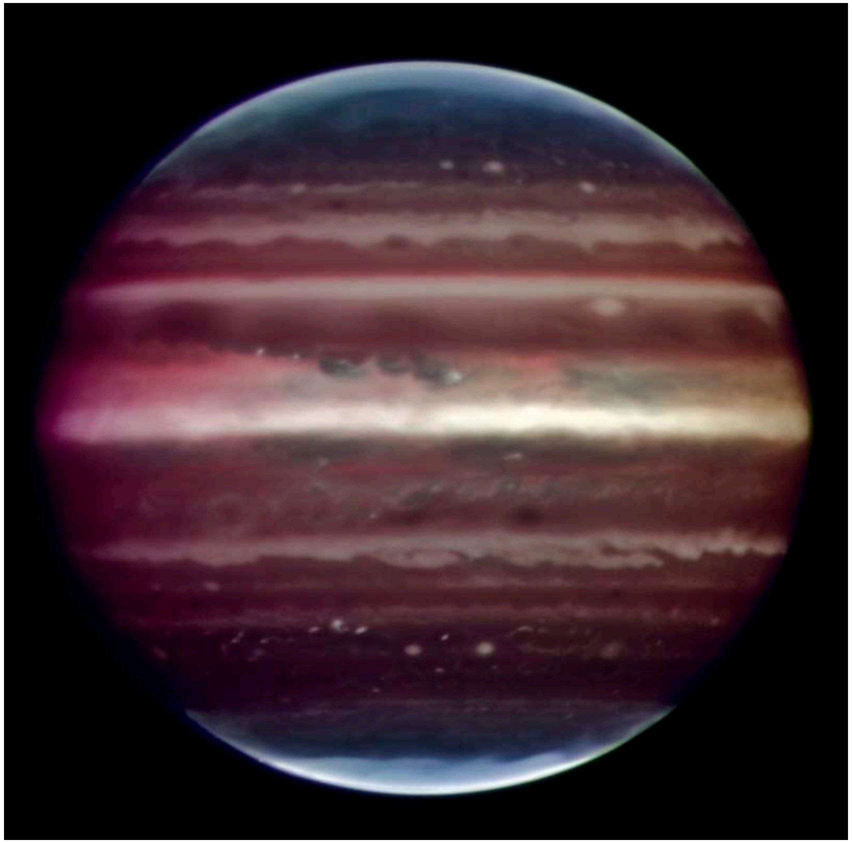
MAD on Nasmyth A UT3 (Melipal)

Multi-Conjugate Adaptive Optics Demonstrator (MAD):
2 arcmin FoV, at 2.2µm (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)

An AO milestone: MAD

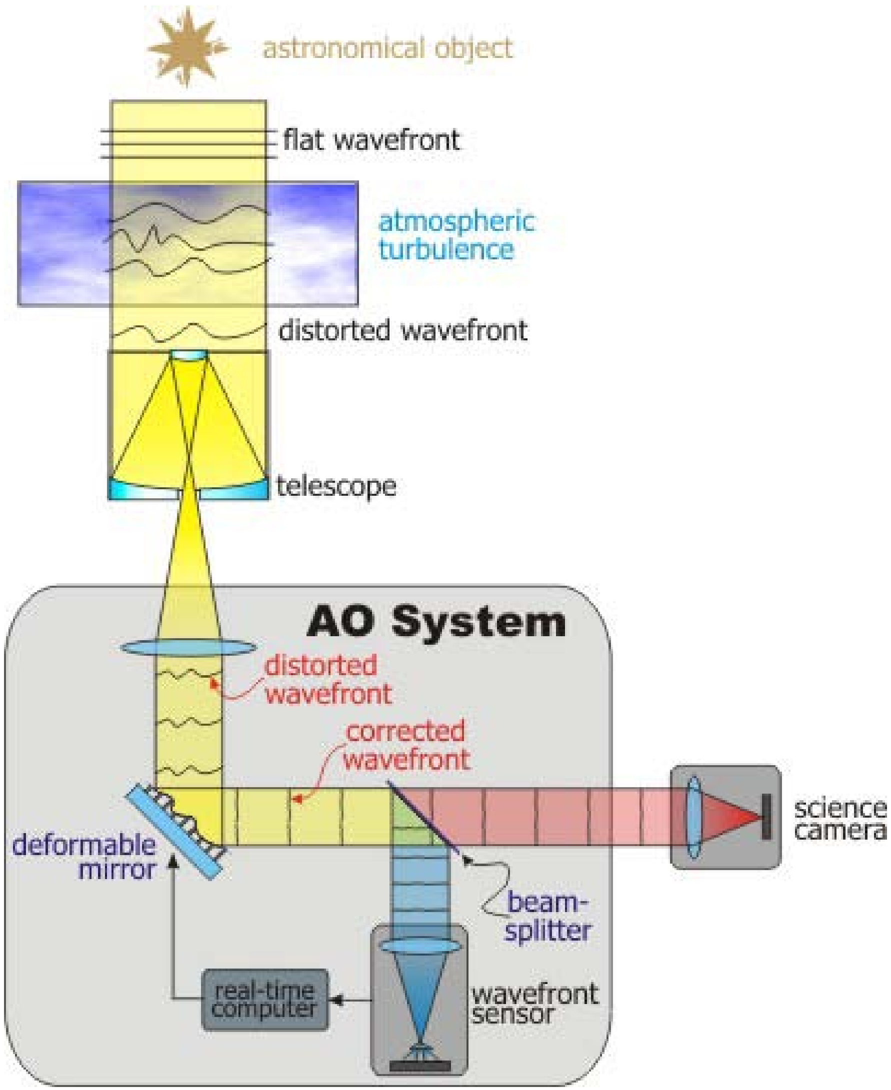


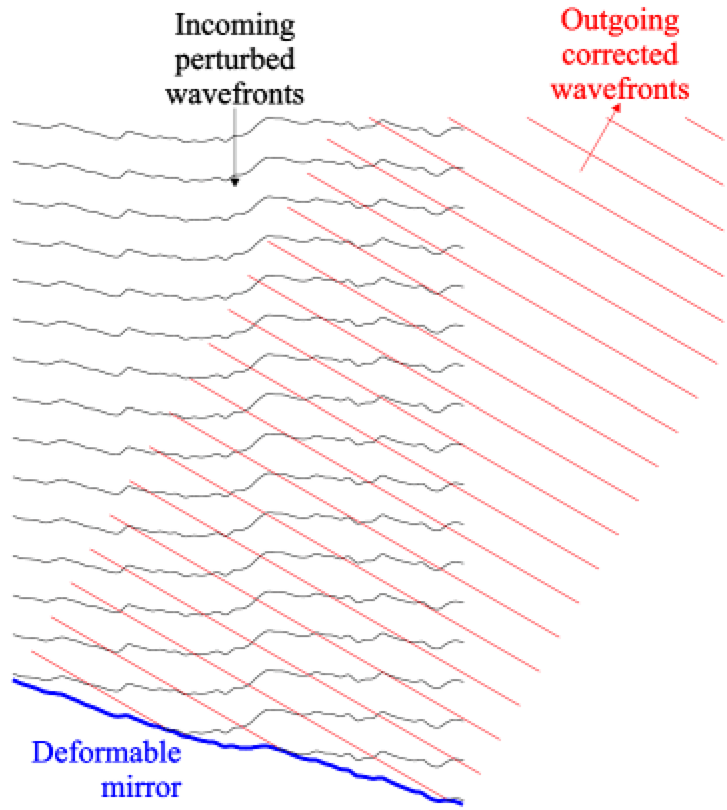
MCAO: 3 Guide stars at 2’
K-band, FWHM: 100-120mas, Sr: >20%
0.7” seeing, Exposure 360 s



Sharpest whole-planet picture ever taken from ground.
MCAO: 2 Guide “stars” (satellites Europa and Io)
2.14µm + 2.16µm filters
90 mas resolution (300 km at Jupiter)

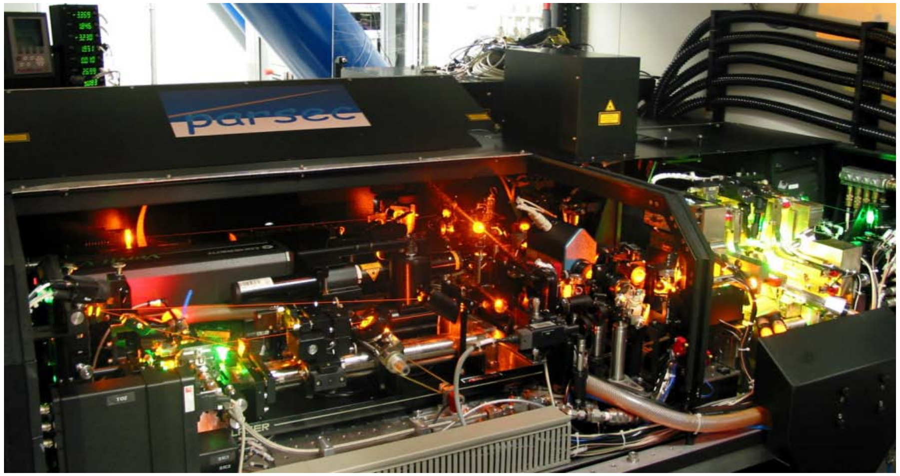
Adaptive Optics principle

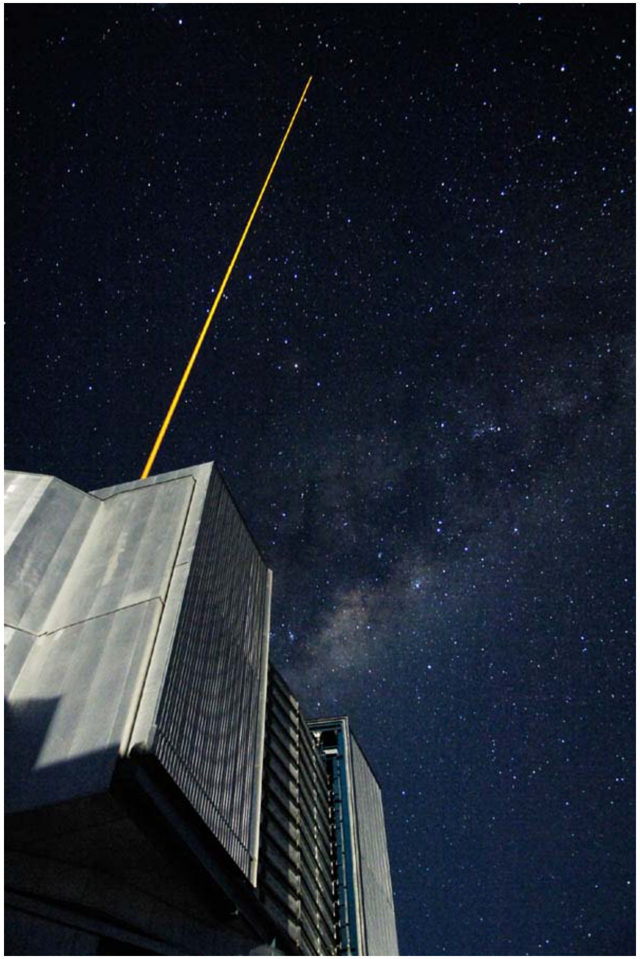




Laser for Adaptive Optics

- 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





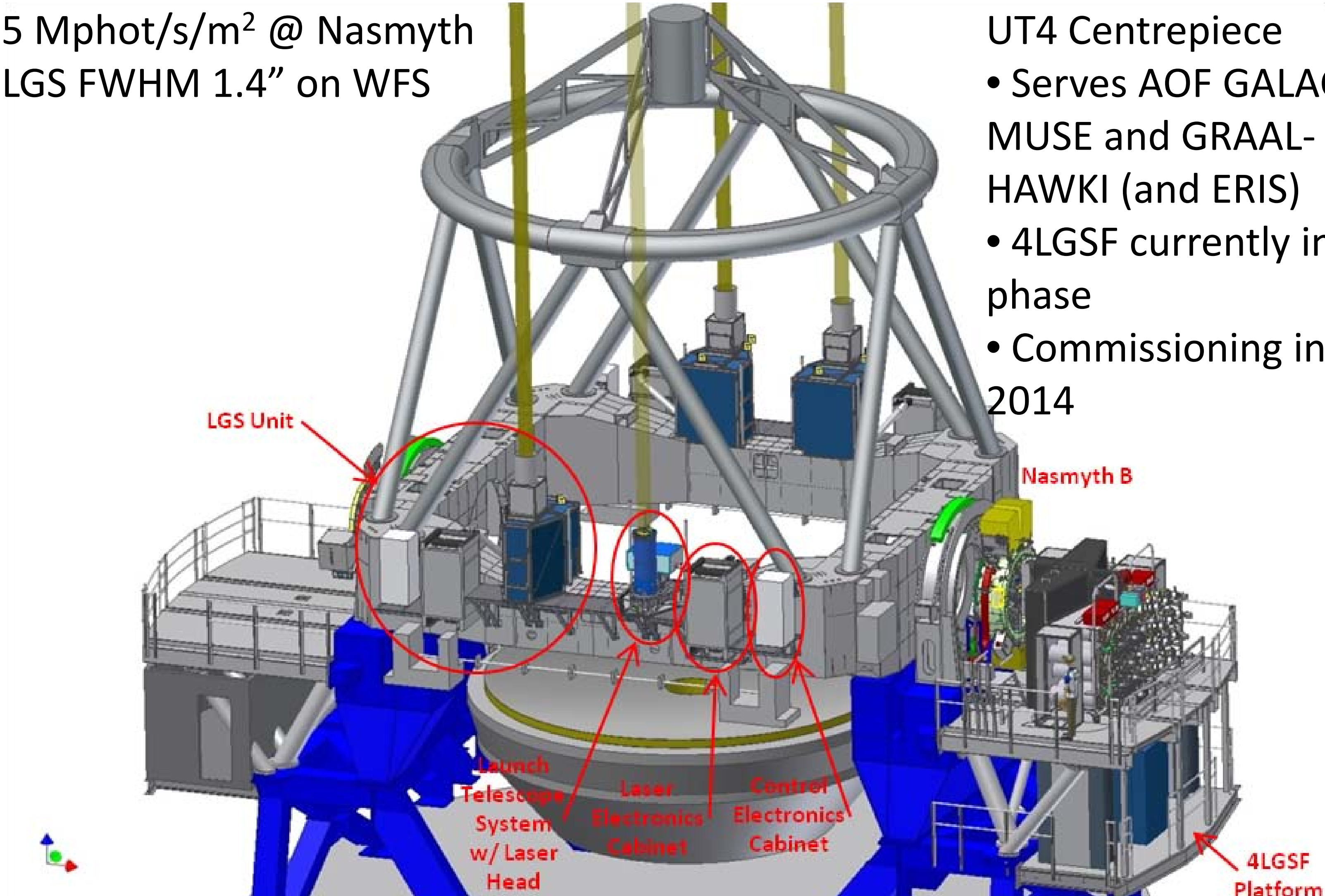
The VLT LGSF at UT4

VLT Laser Clean Room

Four Laser Guide Star Facility (4LGSF)

- 4 sodium LGS, off-axis up to 6’
- 5 Mphot/s/m^2 @ Nasmyth
- LGS FWHM 1.4” on WFS

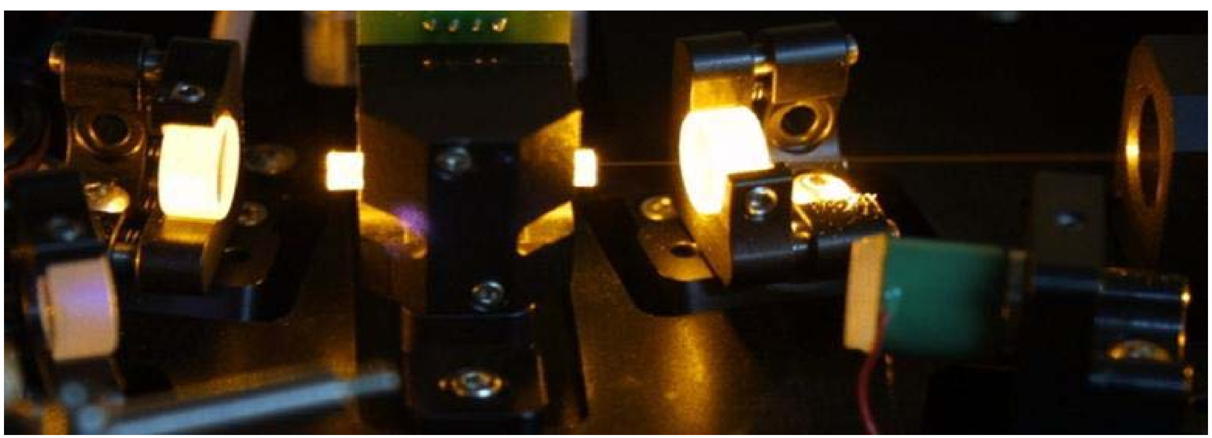
- 4 launch telescopes on UT4 Centrepiece
- Serves AOF GALACSI-MUSE and GRAAL-HAWKI (and ERIS)
- 4LGSF currently in AIT phase
- Commissioning in 2014



Fiber Laser demo

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



Road Map of WFS Detectors

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

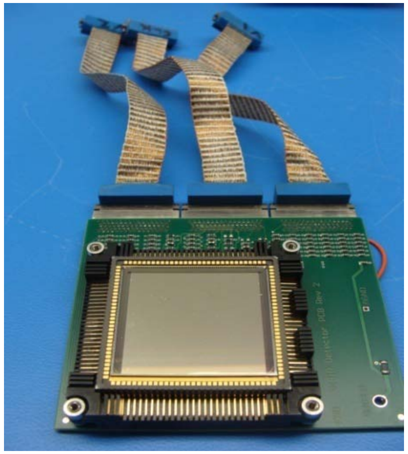
NAOS-WFS CCD
128x128 pixels
2x8 outputs
25-600 Hz frame rate
RON: 2.5-6.5 e/pixel
QE: 80%

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

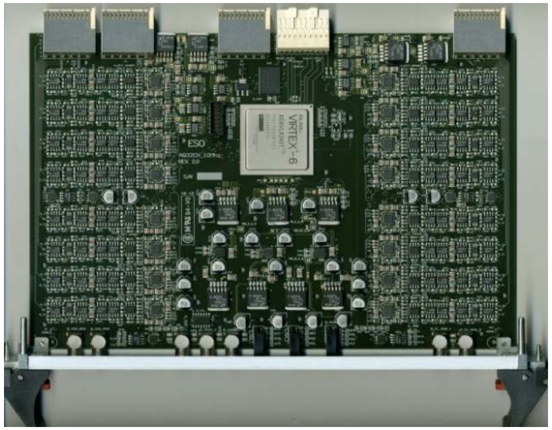
Development of mid-IR λ = 3-28 μm detector : AQUARIUS

ESO contract placed with detector manufacturer :-

- 1024x1024 pixels (30 μm square)
- Si:As, Impurity Band Conduction technology
- Hybridised construction, silicon MUX + indium bumps
- Developed for high background applications
- 64 outputs giving 150 Hz frame rate, 300 Mbytes/s (windowed rate is much faster)
- < 1 e/pixel/second dark current at 7K



AQUARIUS detector on PCB also shown are woven manganin ribbon cables



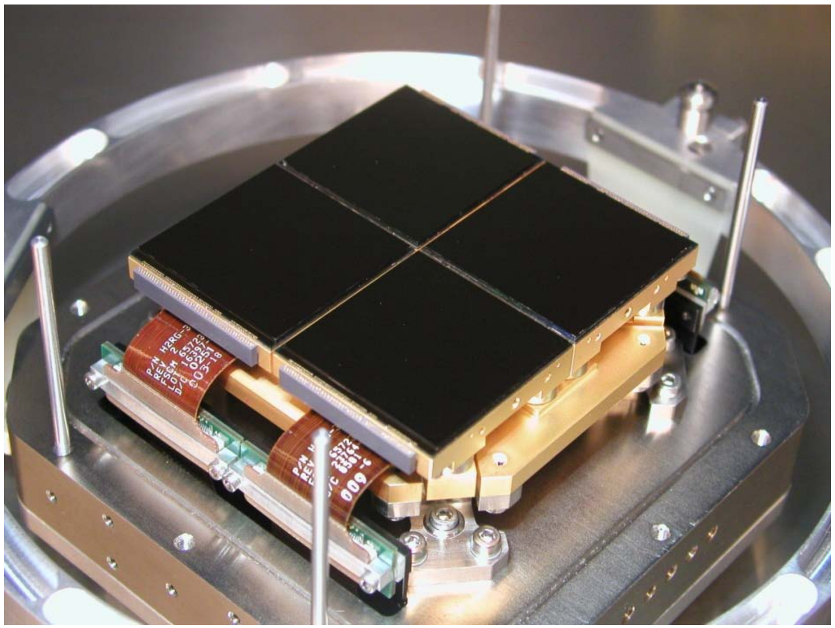
Detector system digitisation board, 32 channels, 16 bits, 10 MHz operation with 2.5 Gbaud fiber data link

Detector Control system development :-

- Uses mixture of commercial and bespoke in-house designed boards, commerical components include -
  - PCIe interface boards,
  - VHDL IP,
  - power supply units,
  - advanced cabling for cryogenic operation
- All PCB layout, manufacture and population done by industry

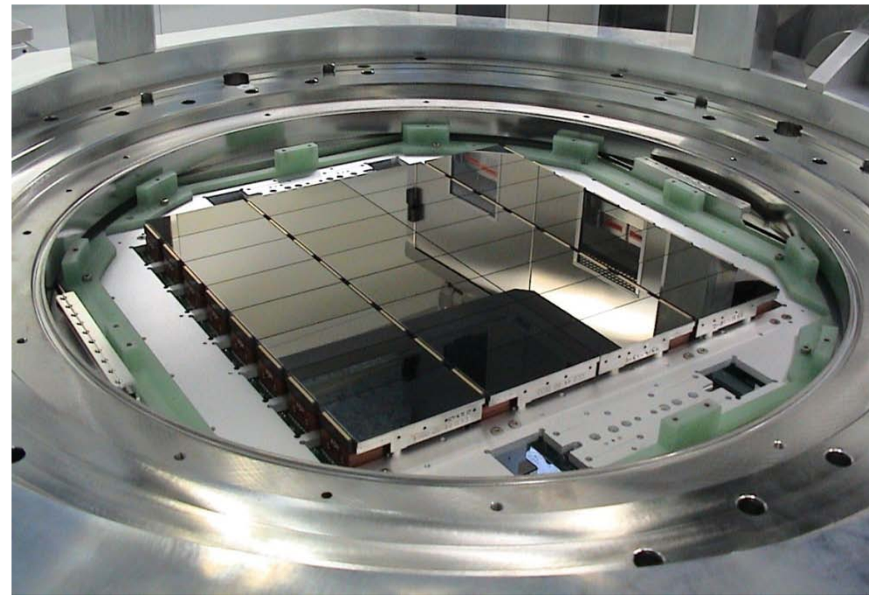
DETECTOR MOSAICS TO BUILD LARGE FOCAL PLANES

Near infrared



HAWKI near infrared mosaic
4 x 2Kx2K HgCdeTe Hawaii2RG arrays
Cutoff wavelength $\lambda_c = 2.5\ \mu m$
128 parallel video outputs
cryogenic preamplifiers

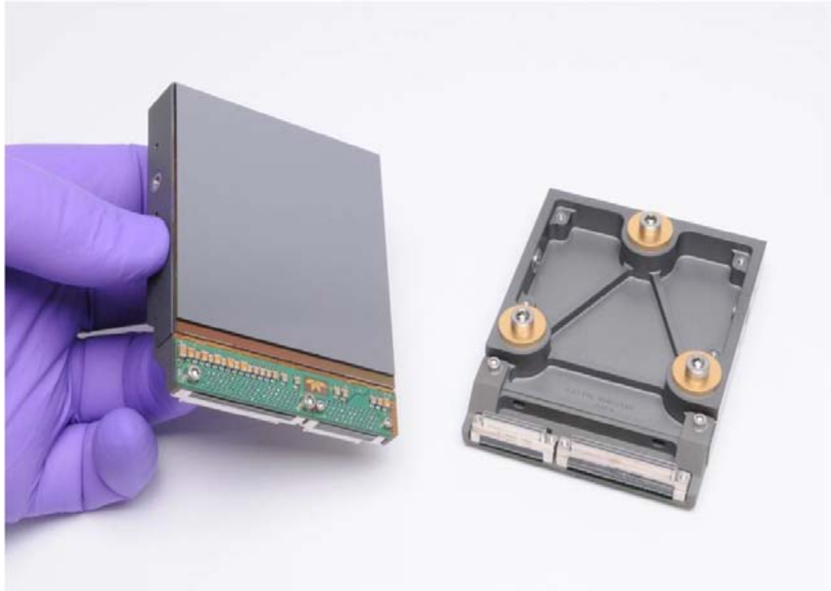
Optical



OmegaCAM CCD mosaic
268 M Pixel,
32 CCDs,
~ 24 x 24 cm^2 light sensitive area

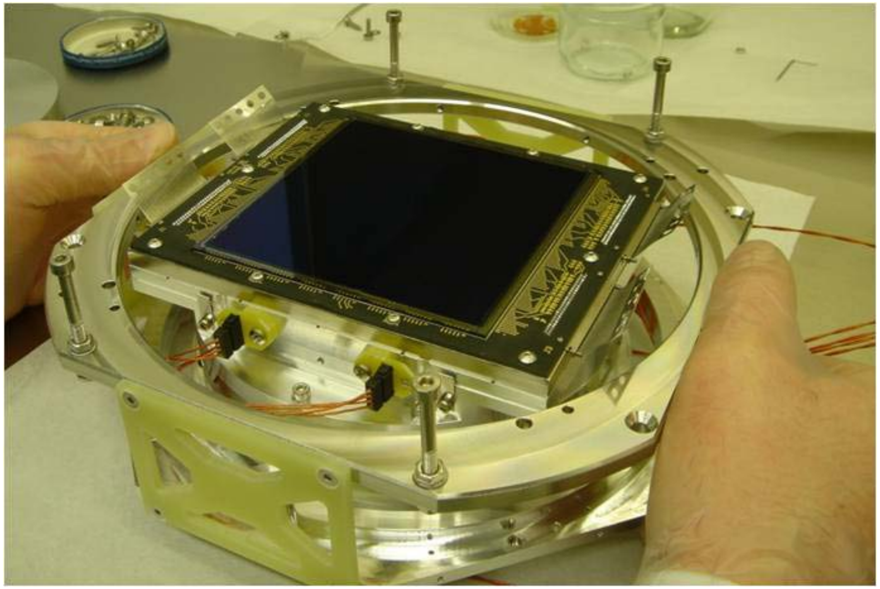
Large format detectors

Near infrared



Hawaii4RG -5
4Kx4K HgCdeTe array
Cutoff wavelengths λ_c = 1.7, 2.5 and 5 μm
64 parallel video outputs
SiC package
4 arrays needed for MOONS

Optical

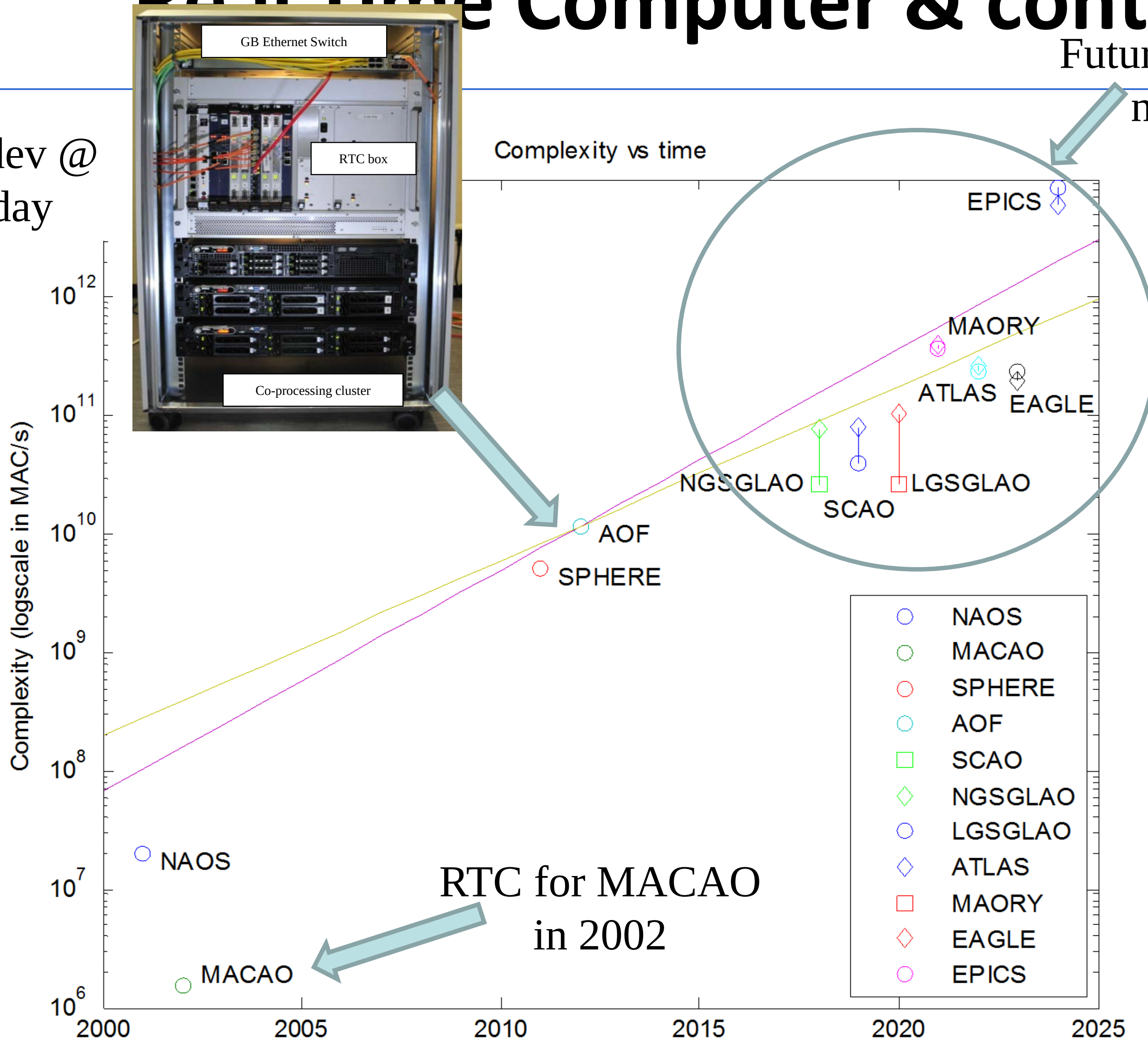


Semiconductor Technology Associates (STA)10Kx10K array
Pixel size 9 μm
e2v 9Kx9K for ESPRESSO

Real Time Computer & control

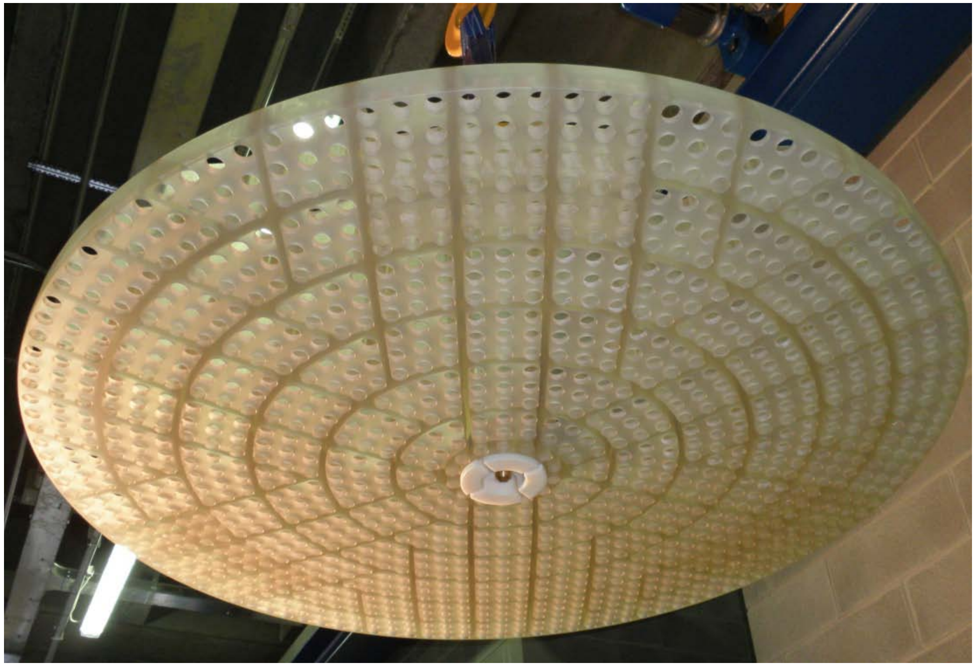
SPARTA dev @ ESO today

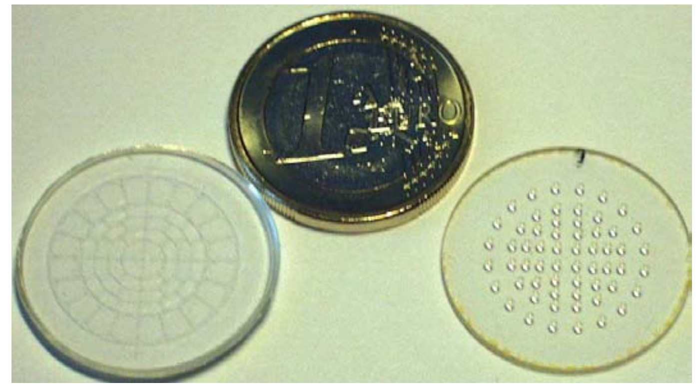
Future E-ELT needs



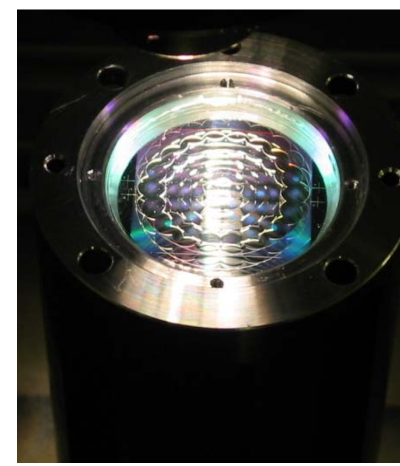
RTC for MACAO in 2002

Special optics for AO



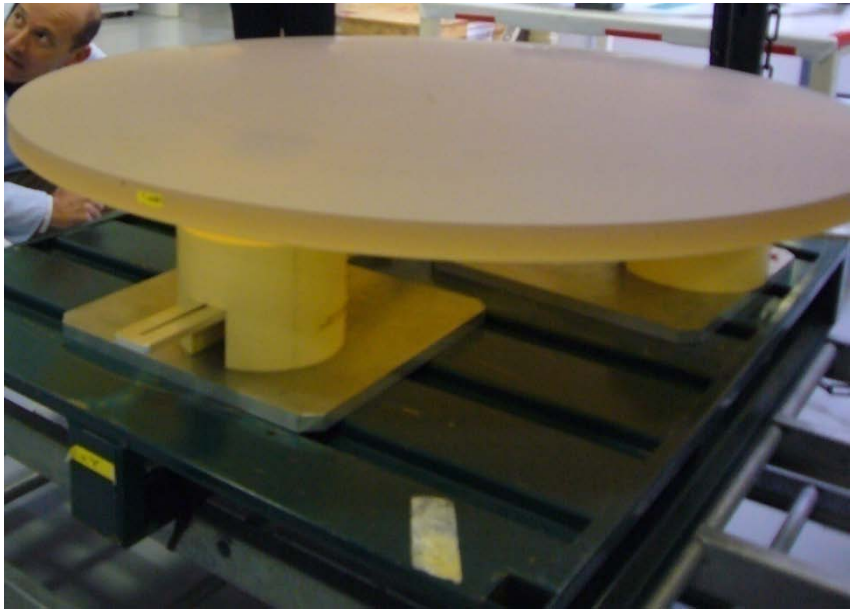


Custom lenslet arrays for MACAO



1.1 m light-weighted reference body
for the VLT Deformable secondary mirror

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

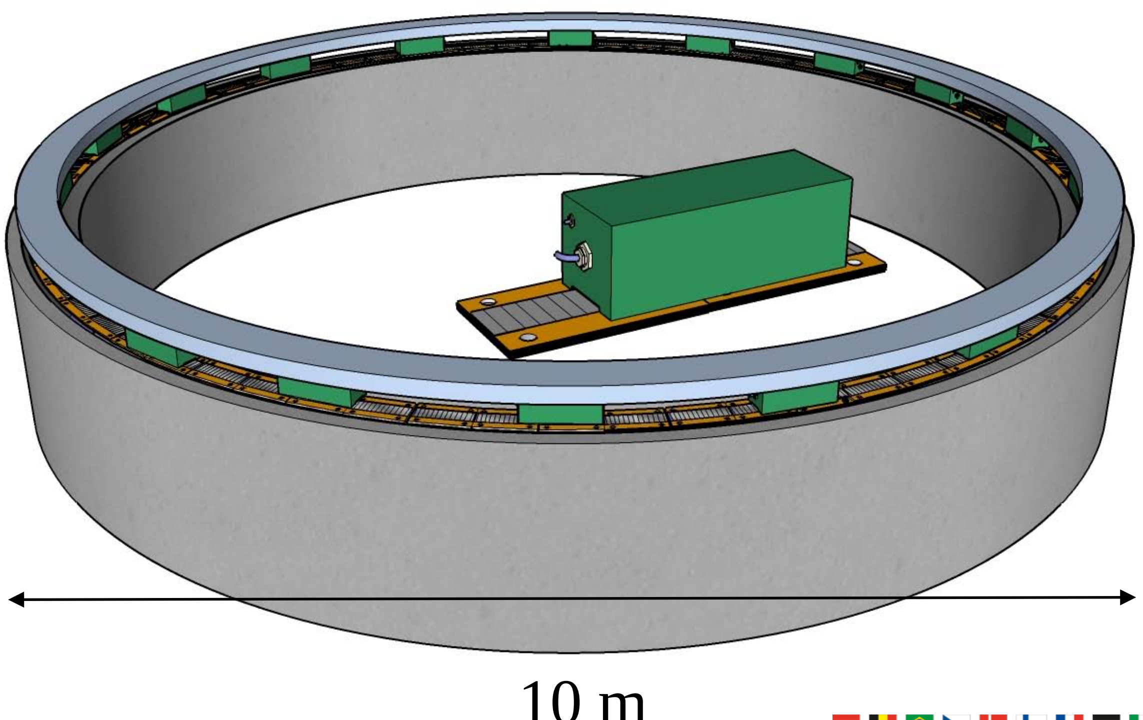
1. Direct drive motors
2. Collocated encoders
3. Hydrostatic bearing system
4. Innovative control algorithms

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

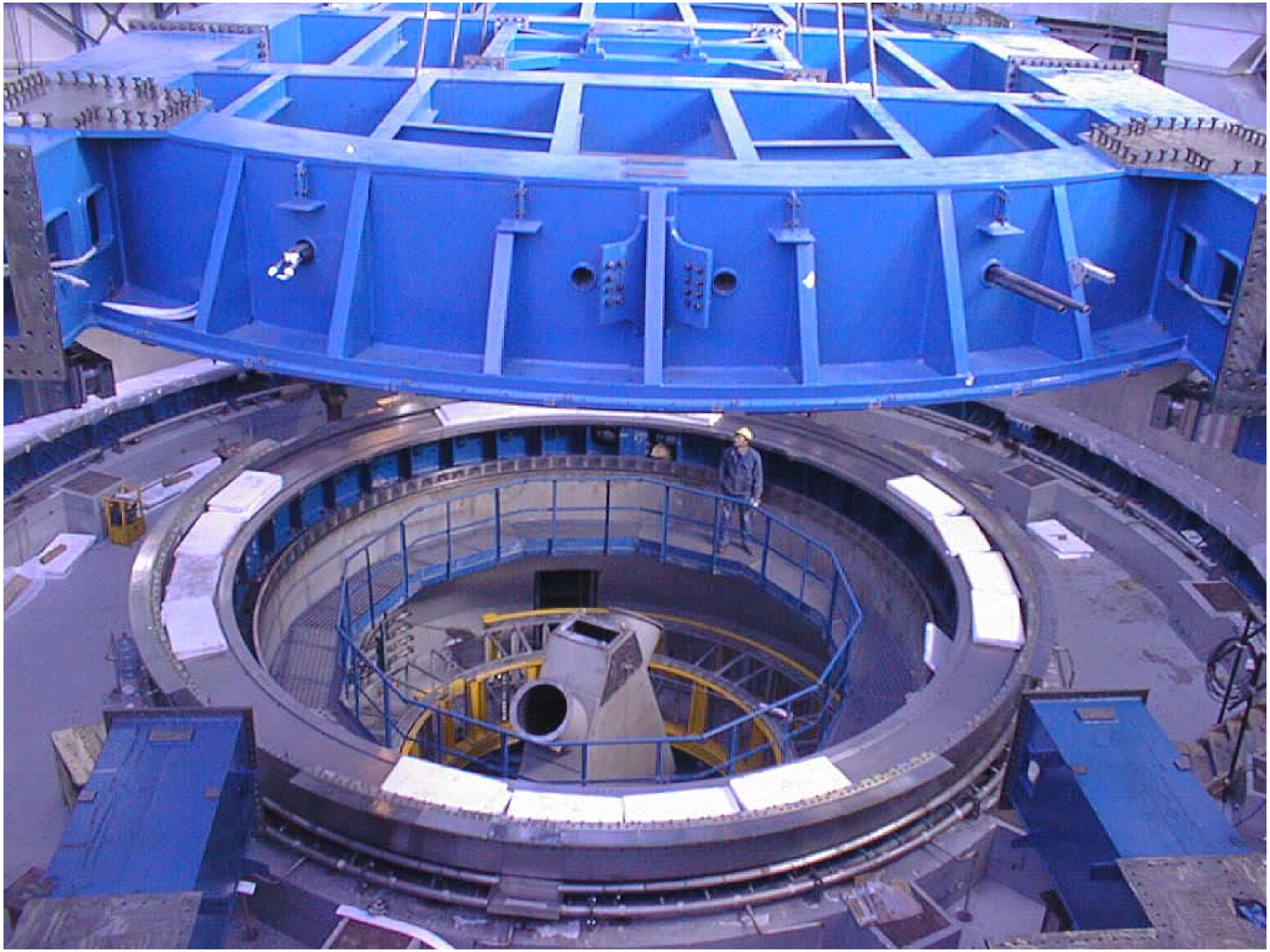
VLT – Hydrostatic bearing system

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



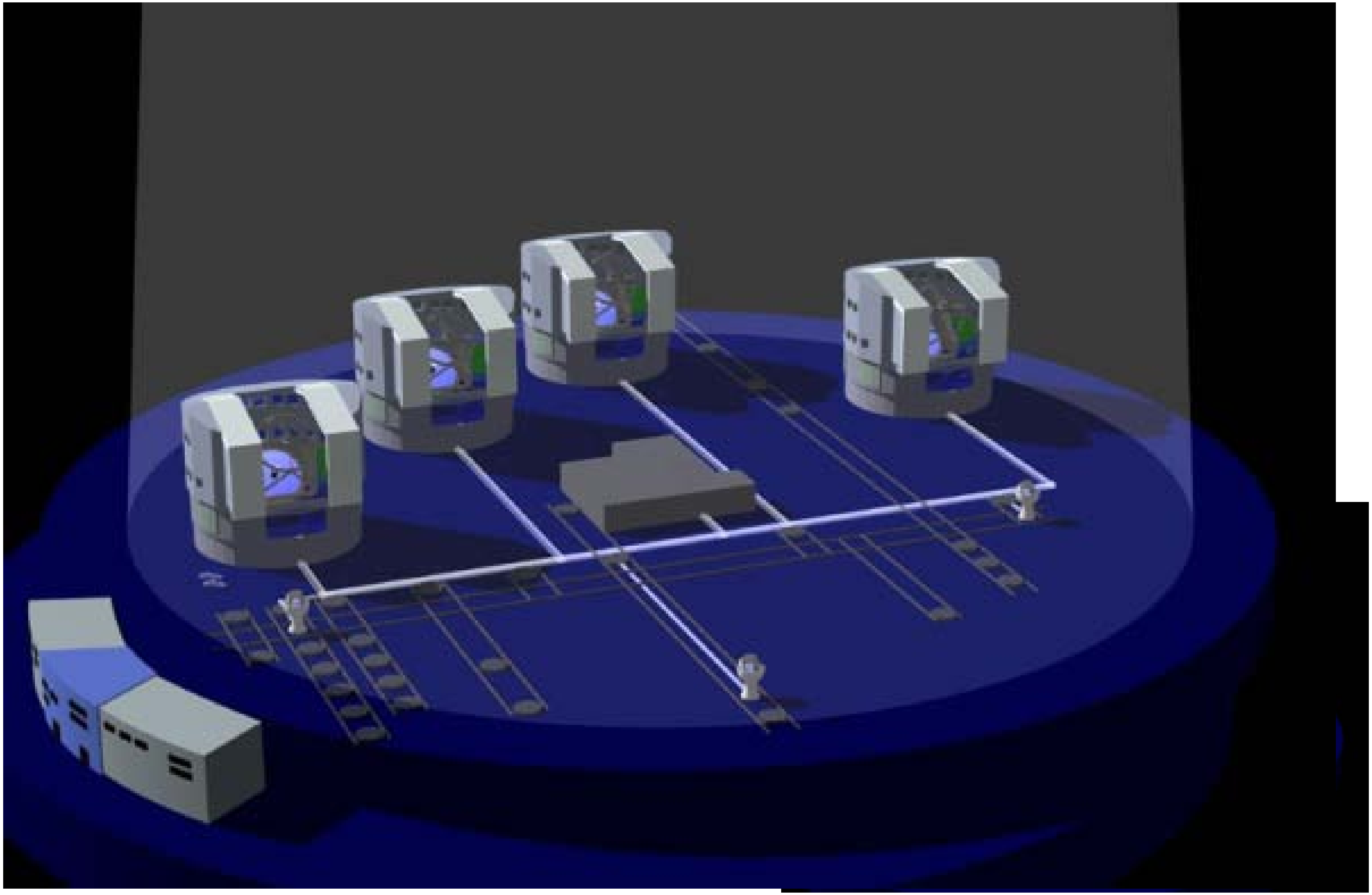
VLT – Innovative Control Algorithms

- First telescope with entire control system implemented in software

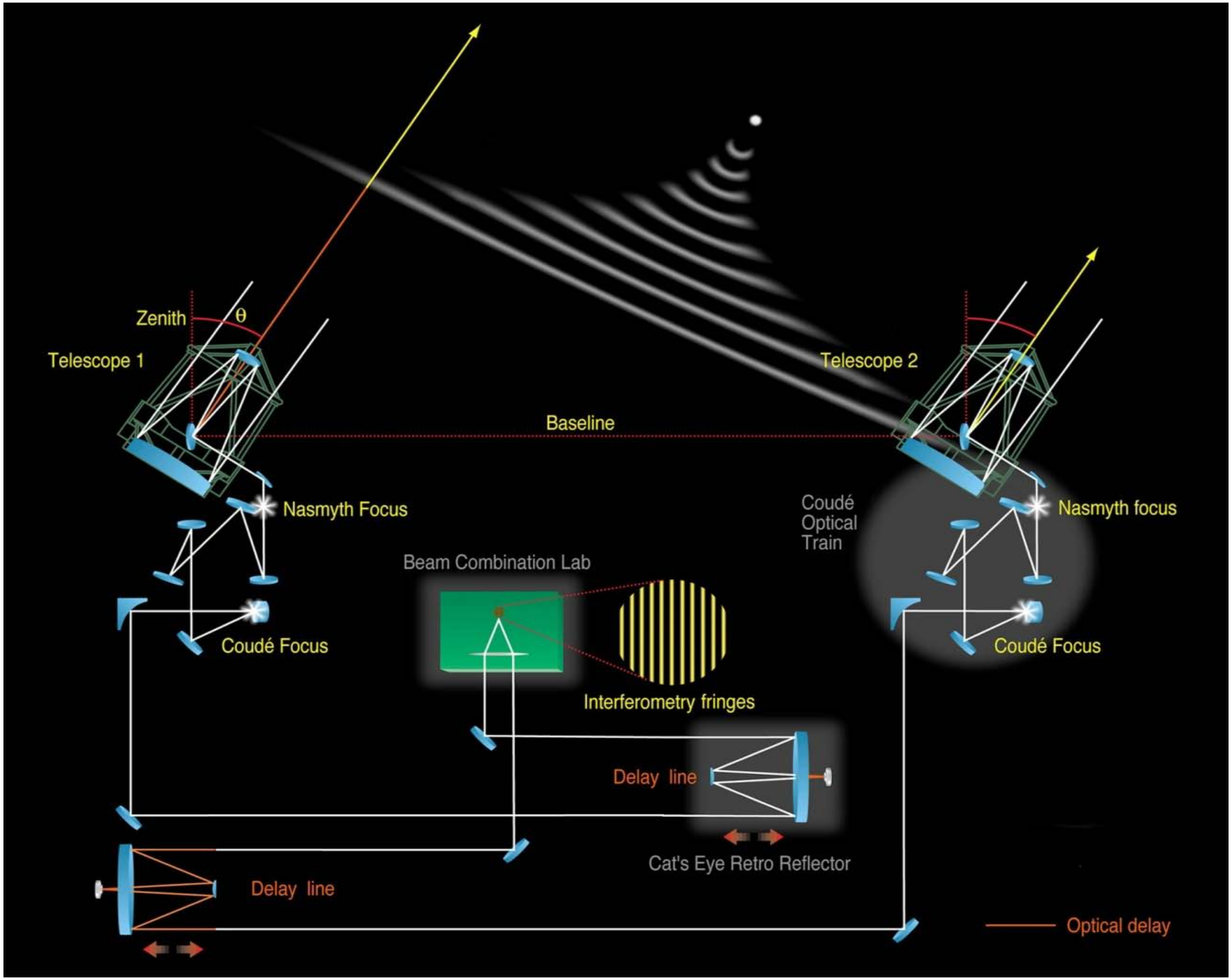
Real-time computer platform

High tech drive technology

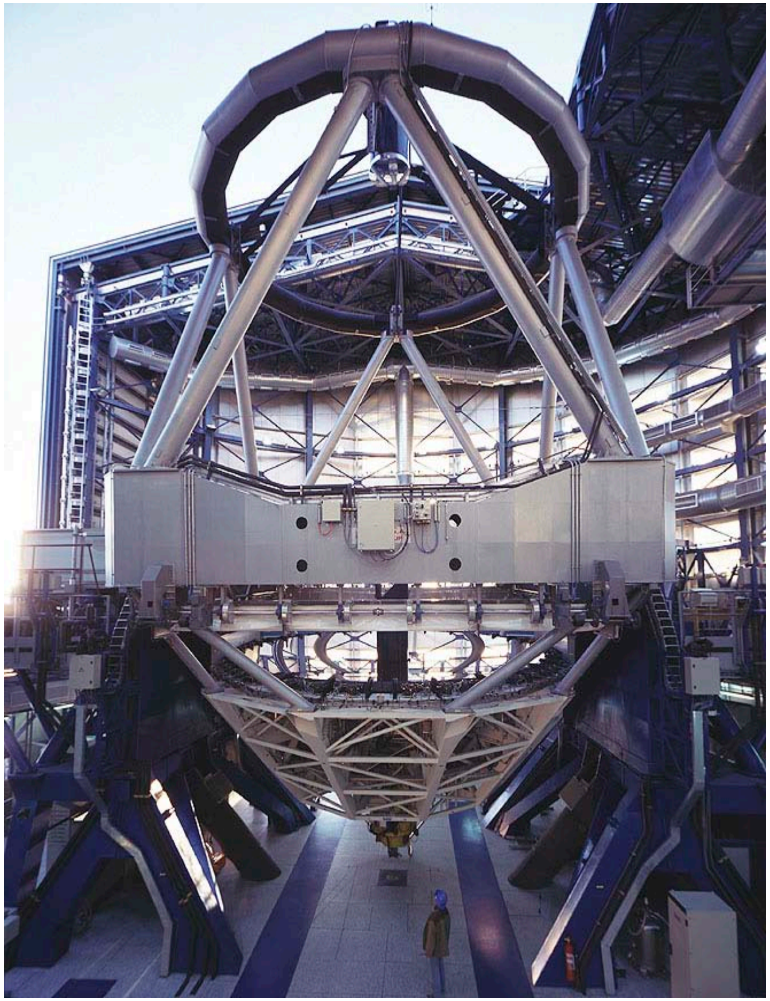
What is the VLTI



VLTI Scheme - Subsystems

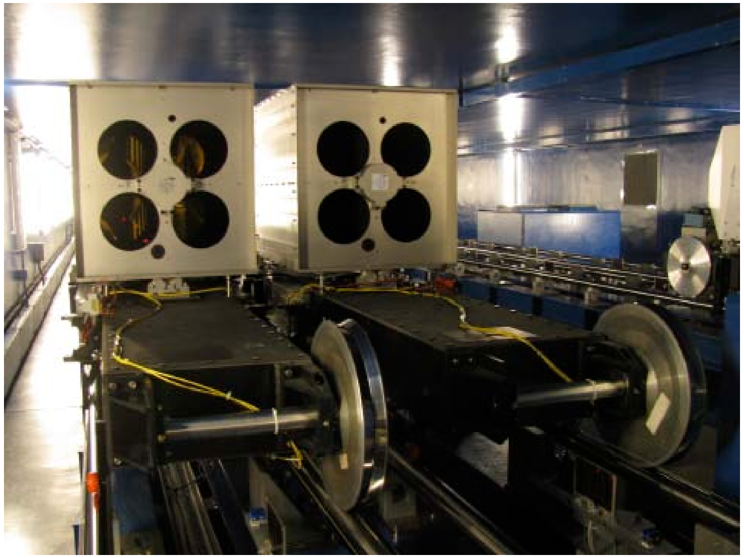


The VLTI Telescopes

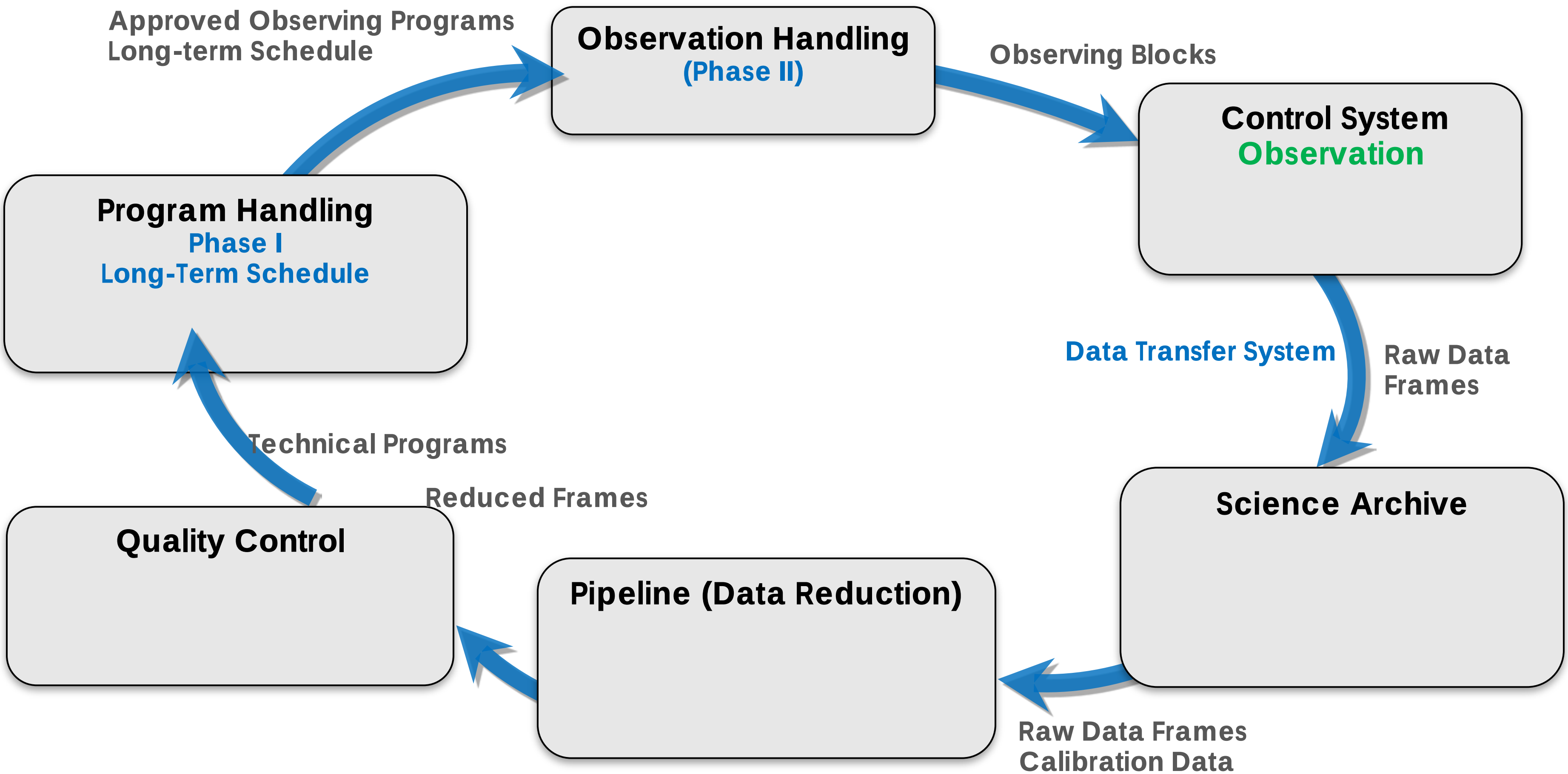


VLTI main Delay Lines (DL)

- 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.



Software at the ESO LPO Observatory



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

- 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

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 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

ALMA Cryogenic System
High Altitude Qualification Tests

ALMA latest news…

European
Southern
Observatory

ESO News
1 October 2013

1 October 2013 — ESO Organisation Release eso1342

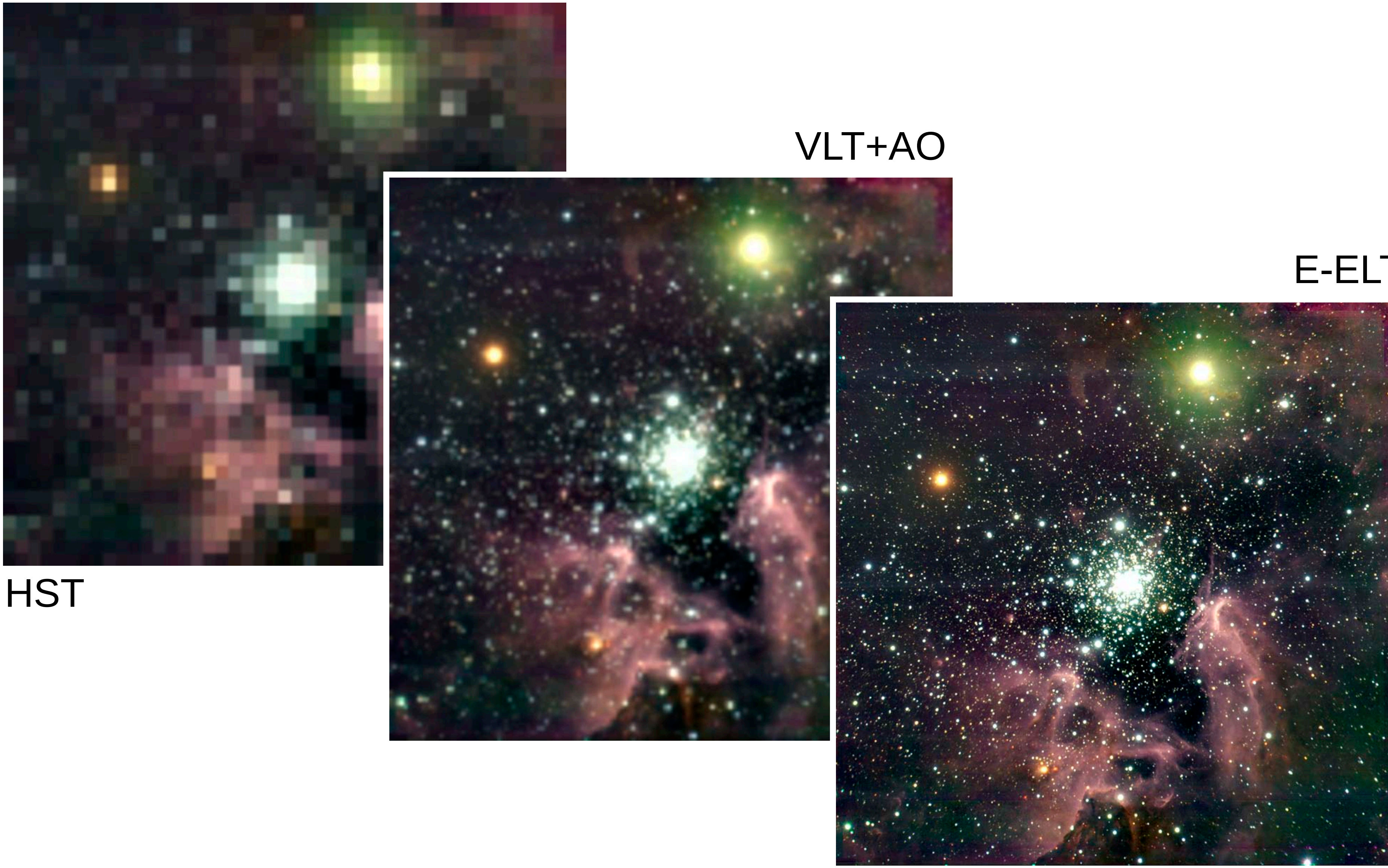
Final Antenna Delivered to ALMA— All 66 ALMA antennas now handed over to the observatory

The E-ELT

Spectacular Resolution

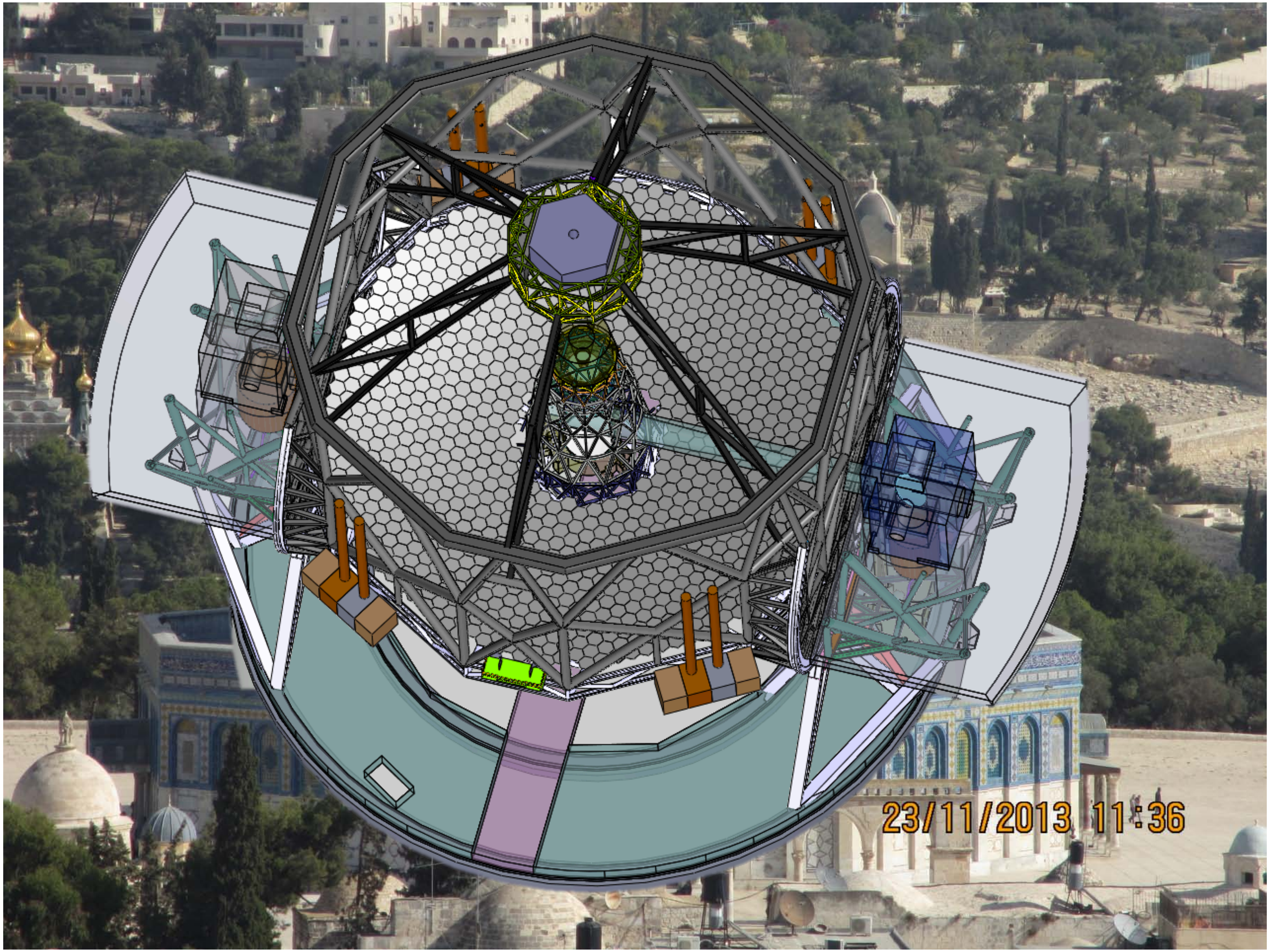
VLT+AO

E-ELT



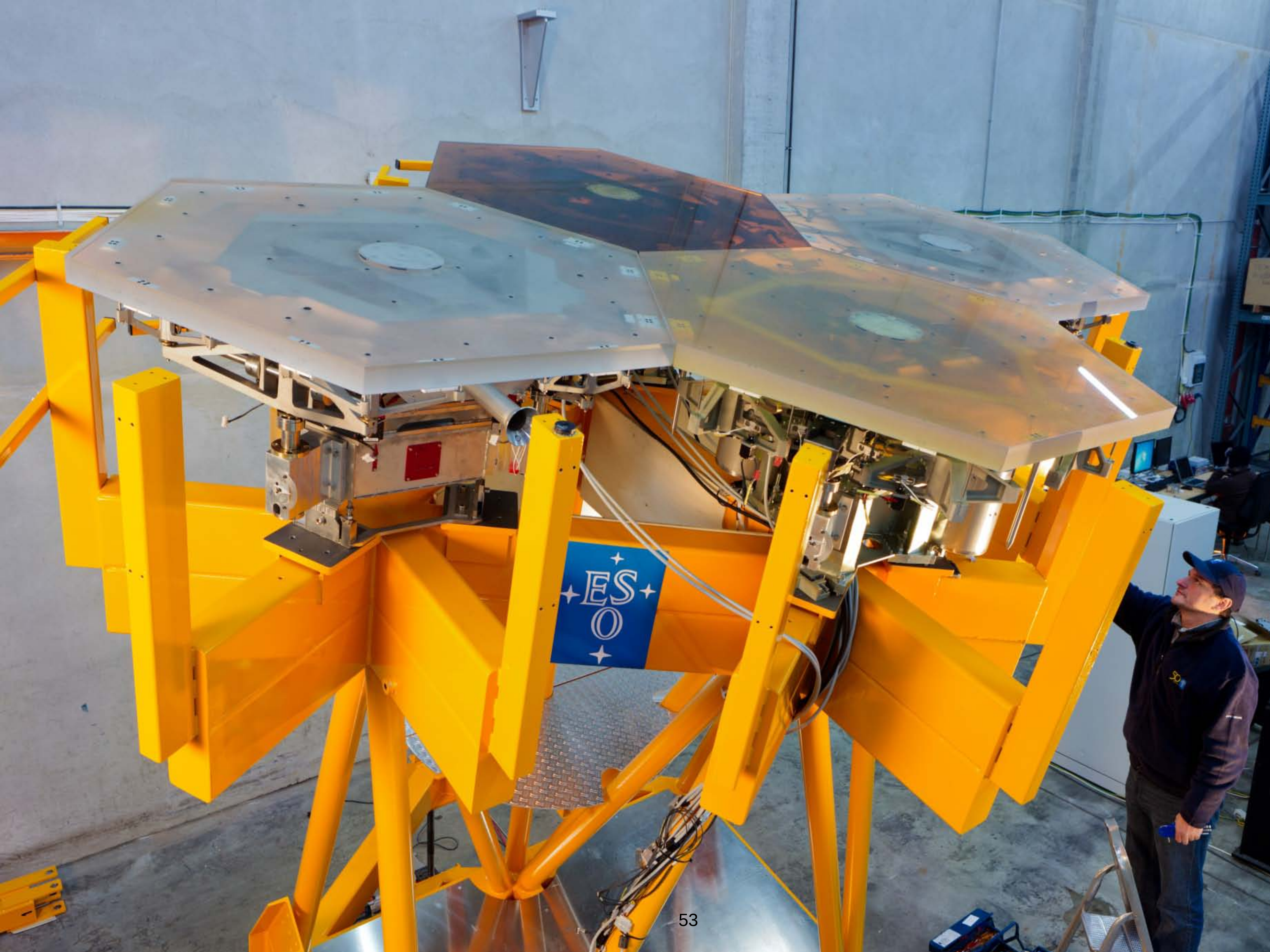
HST

To put it in perspective…



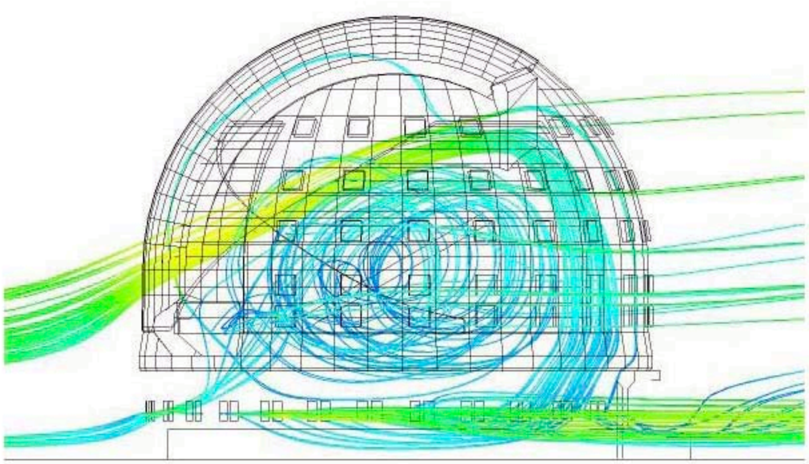
The process

- 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

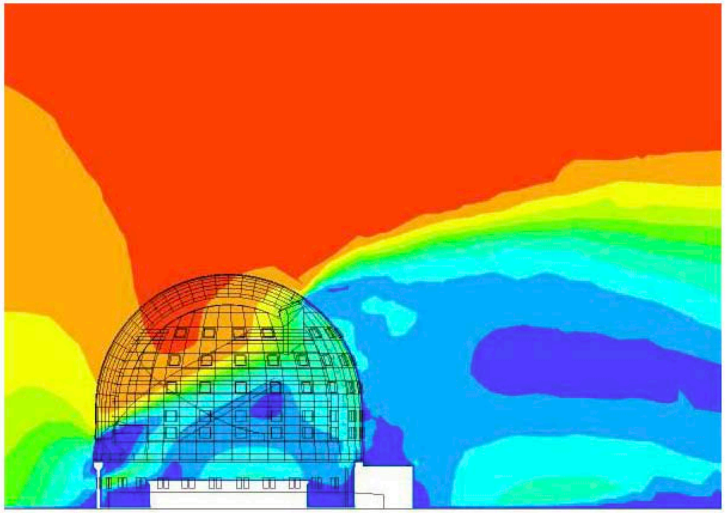

ESO

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



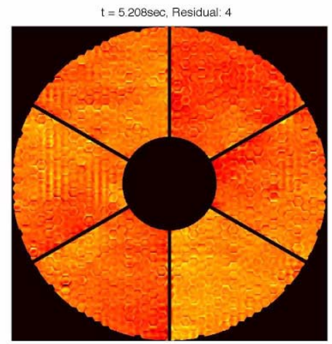
Streamlines distribution in the E-ELT Dome structure

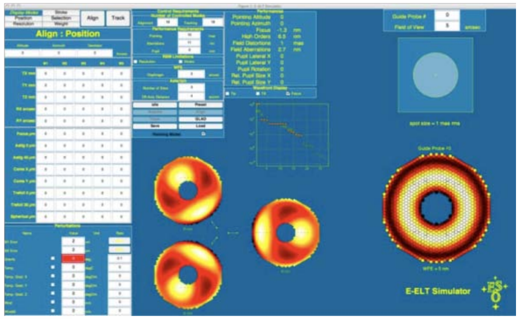


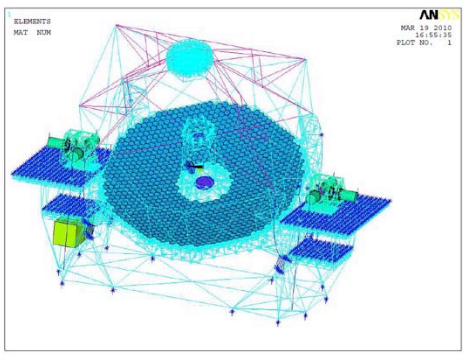
Velocity distribution in the E-ELT Dome at the symmetry plane.

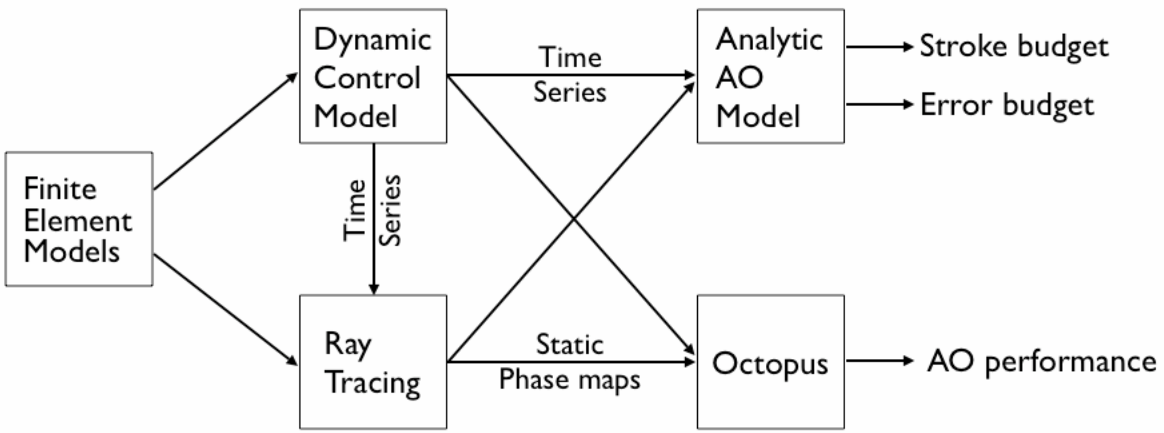
Analysis and simulation crucial

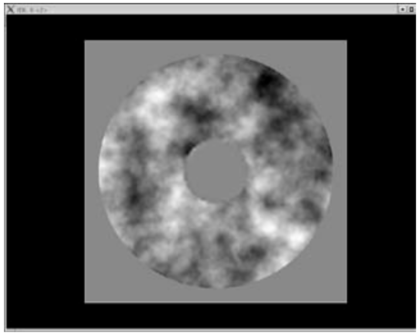
Optical performance analyses of the E-ELT were carried out to simulate the propagation of numerous error sources and the impact on System Engineering aspects. This is supported by instantiations of the telescope's ray tracing models with temporal and spatial resolutions adapted to the spectral properties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

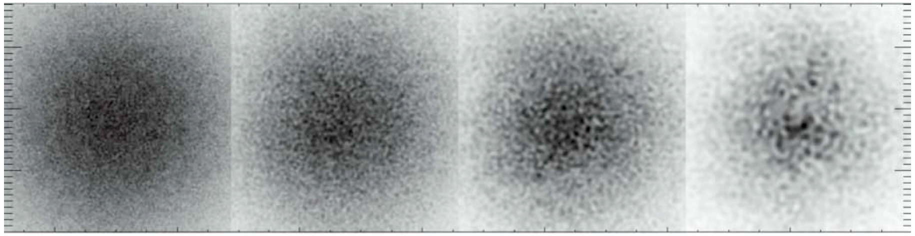






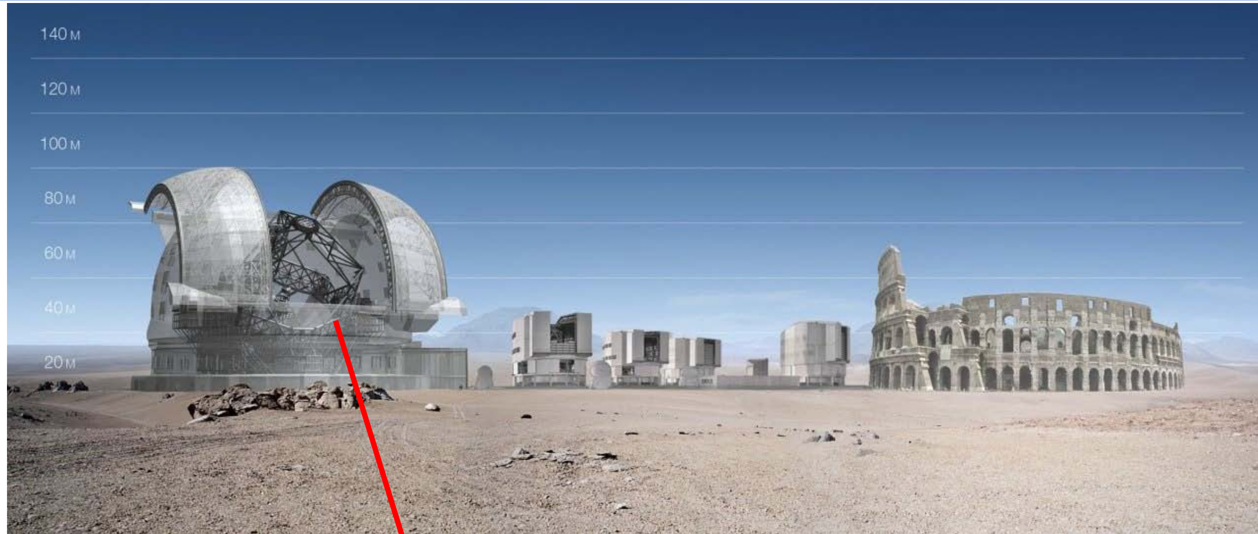




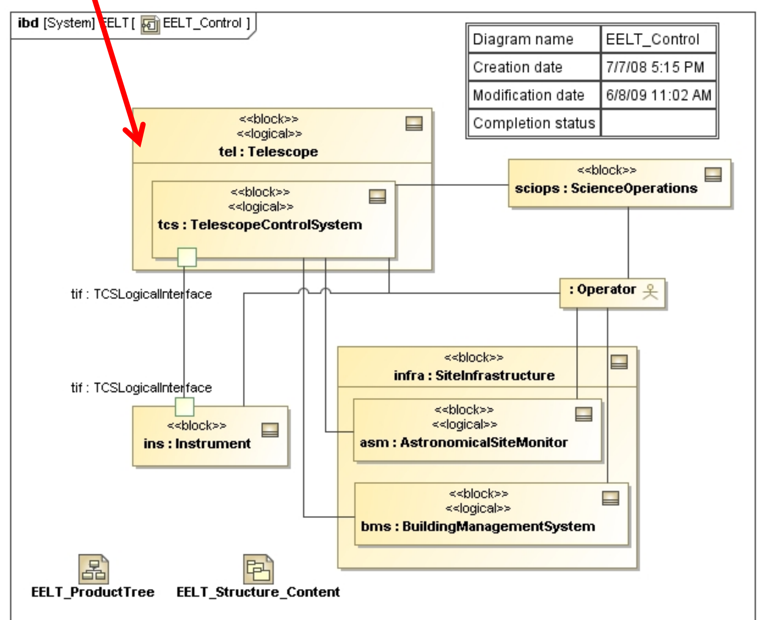


Control System

- The Control System includes all hardware, software and communication infrastructure required to control the System.
- Provides access to the opto-mechanical components.

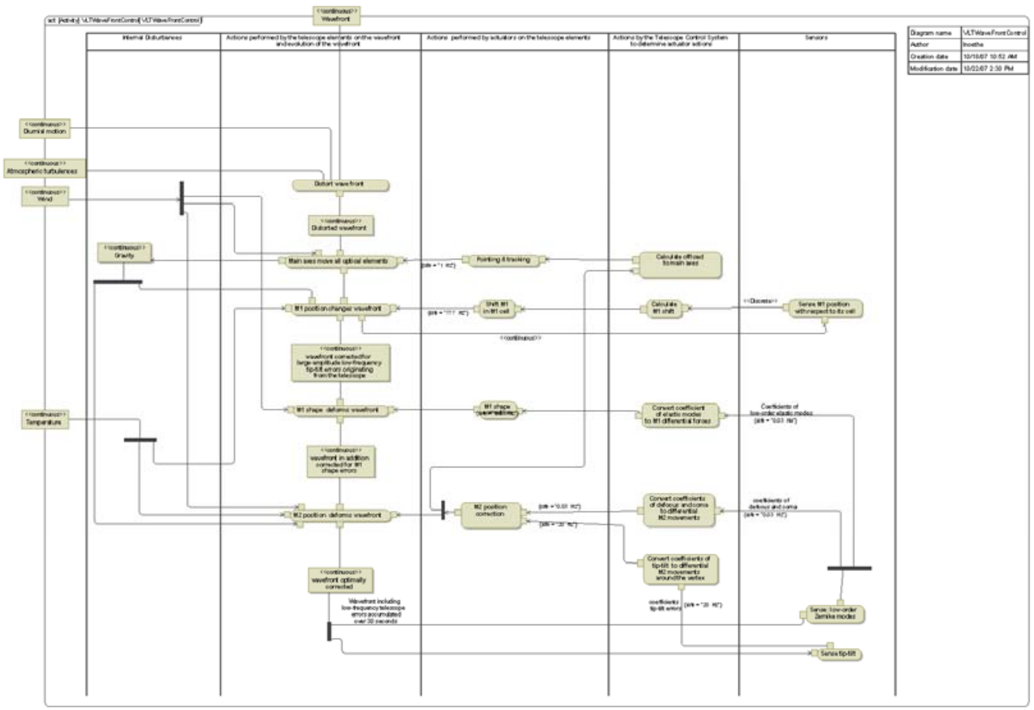


- Manages and coordinates system resources (subsyst., sensors, actuators, etc…)
- Performs fault detection and recovery
- Based on Control, Software and Electrical Engineering

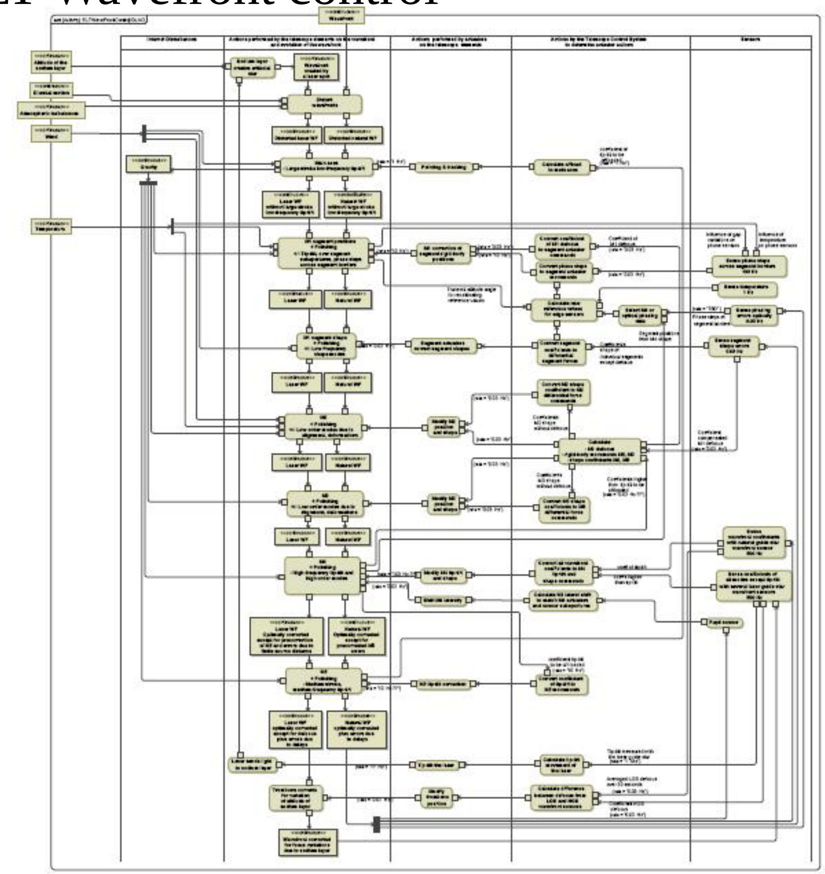


E-ELT
Telescope Control System (cont)

VLT Wavefront control

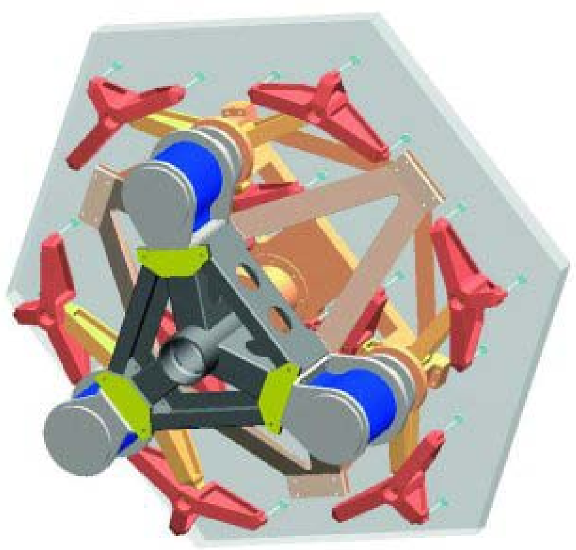


E-ELT Wavefront control



- 5000 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 ~800 mirrors must be coordinated to deliver a continuous surface with an error < 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

Technology needs in Astronomy

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

Thank you!