Technological Development and Needs at ESO

Industry Day, São Paulo, 16-November-2015

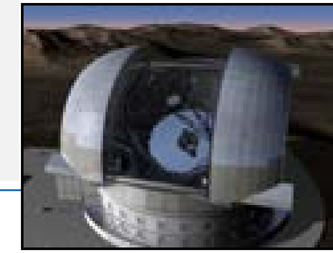
Gerald Hechenblaikner

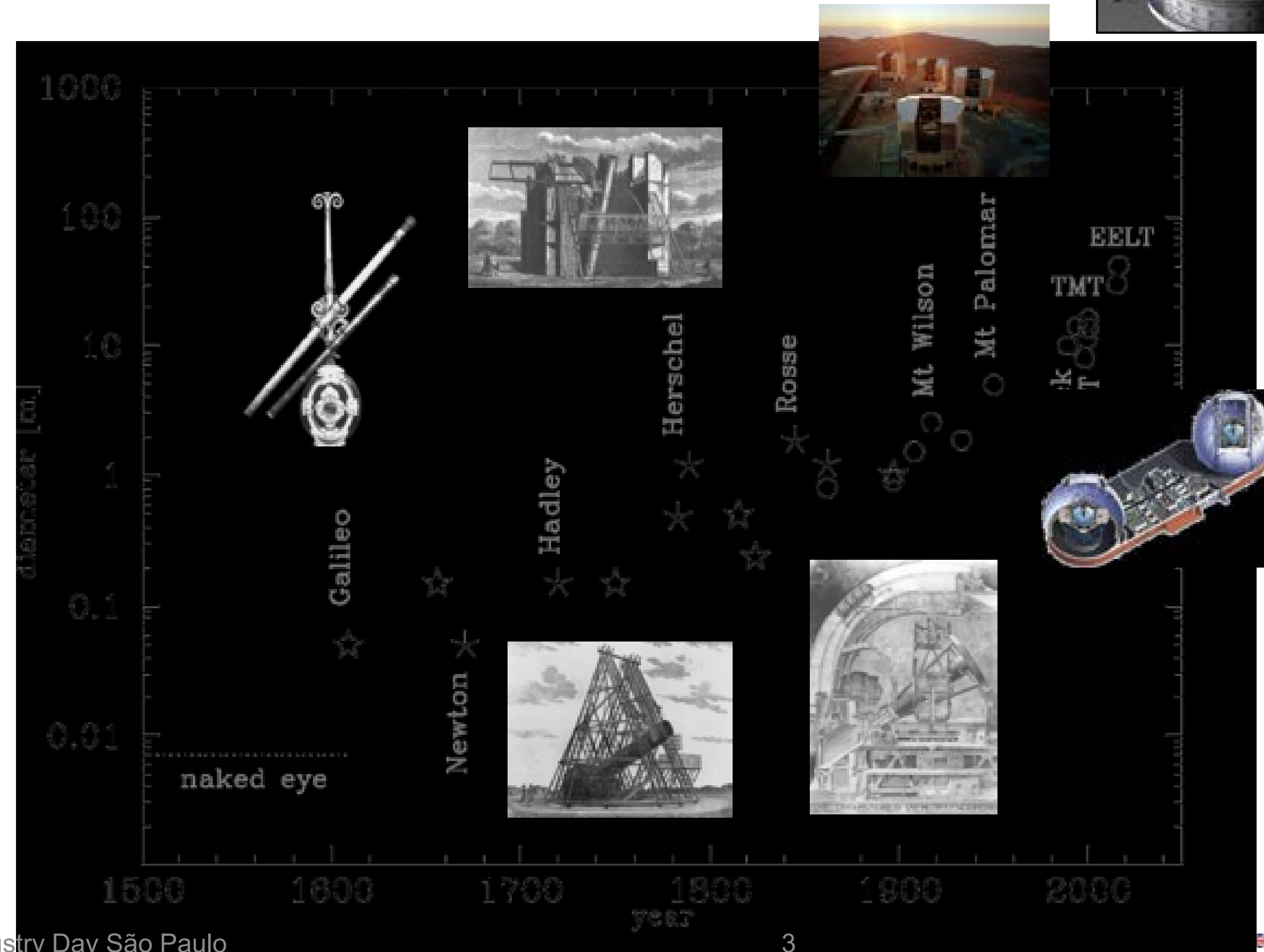
Deputy Director of Engineering, ESO

Technology in Astronomy

- From a small, manually pointed device for visual observations (around 400 years ago)
  ➡ large, sophisticated, computer-controlled instrument with fully 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 objects)
  - the image sharpness, or angular resolution (allowing more detail 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 with similarly complex instrumentation

Historical Evolution





Key-Technology in Astronomy

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

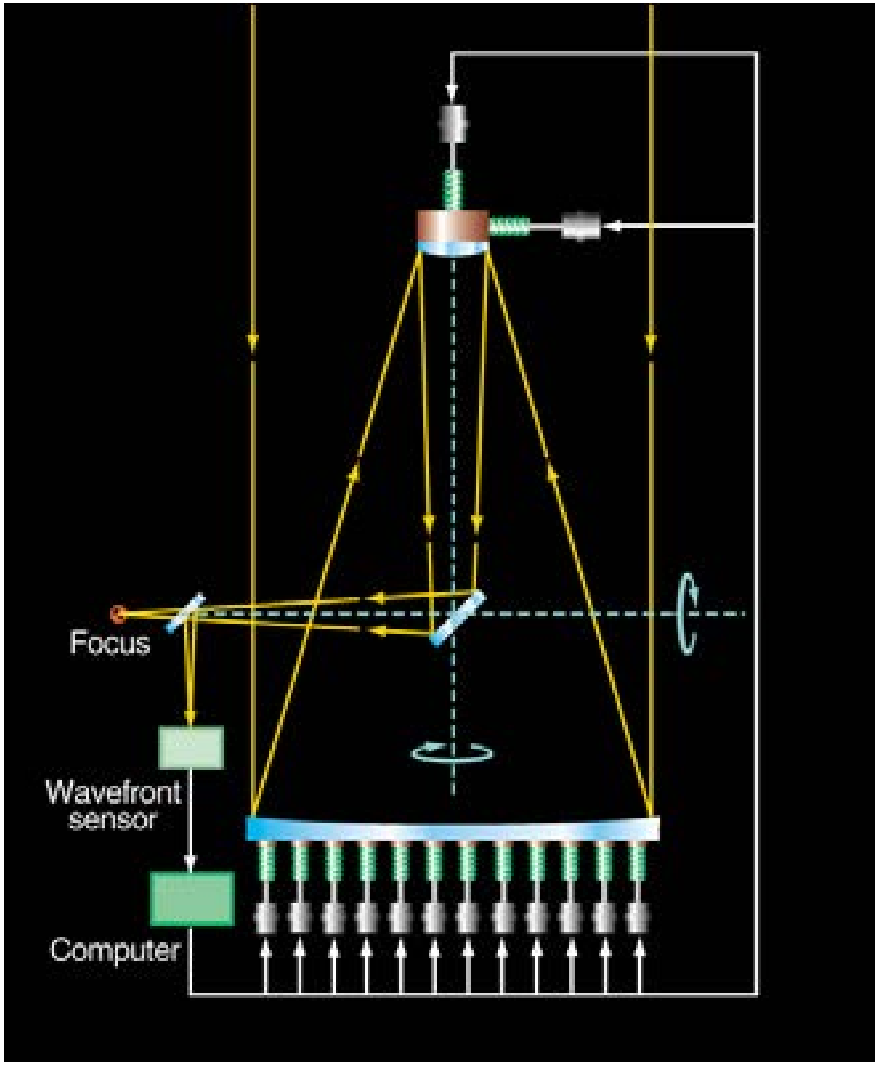
- ACTIVE OPTICS
  - Preserves optimal image quality by adjusting a “flexible” mirror’s shape with actuators during observations (i.e. corrects telescope flexure)
  - In use in most modern medium and large telescopes
- ADAPTIVE OPTICS
  - Technology to reduce distortions introduced by atmospheric turbulence
  - 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 boosts the angular resolution beyond that of a single telescope
  - ESO has been a pioneer in this field with the Very Large Telescope Interferometer (VLTI) at Paranal

Principle of Active Optics

Closed control loop with:

1. Measurement of wave front error generated by the telescope itself
   - Integration times of ~30 sec
   - 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

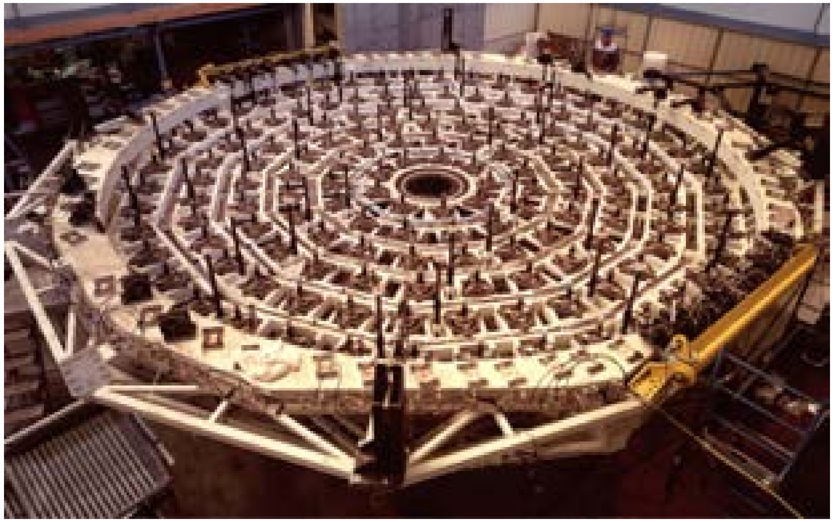
From the NTT to the VLT

A computer-controlled **active** optics system was first developed by 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

This has become a standard technology for all major new telescopes

VLT Mirror



VLT Cell

Adaptive Optics

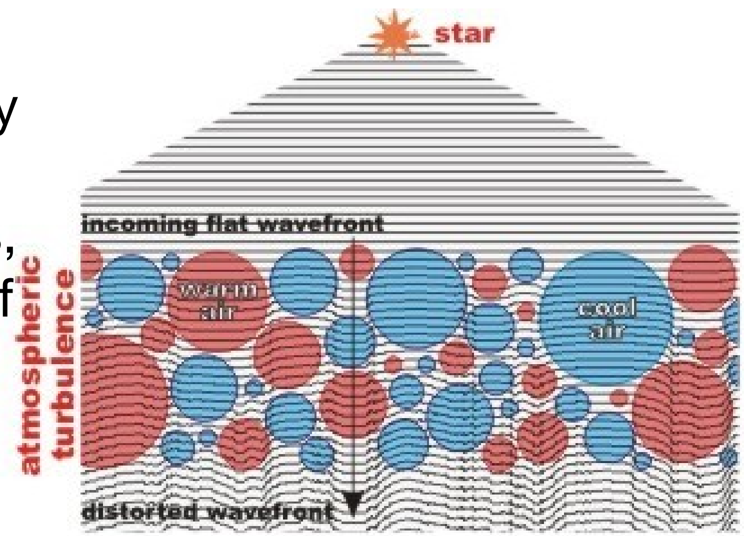
An adaptive optics system (AO) corrects turbulence in the atmosphere (loop frequency in kHz range), which is much faster than corrigible by the active optics

- Active optics:

  Shape of the primary mirror adjusted by stiff actuators to compensate slowly changing disturbances (gravity flexures, thermal deformations) on a timescale of tens of seconds

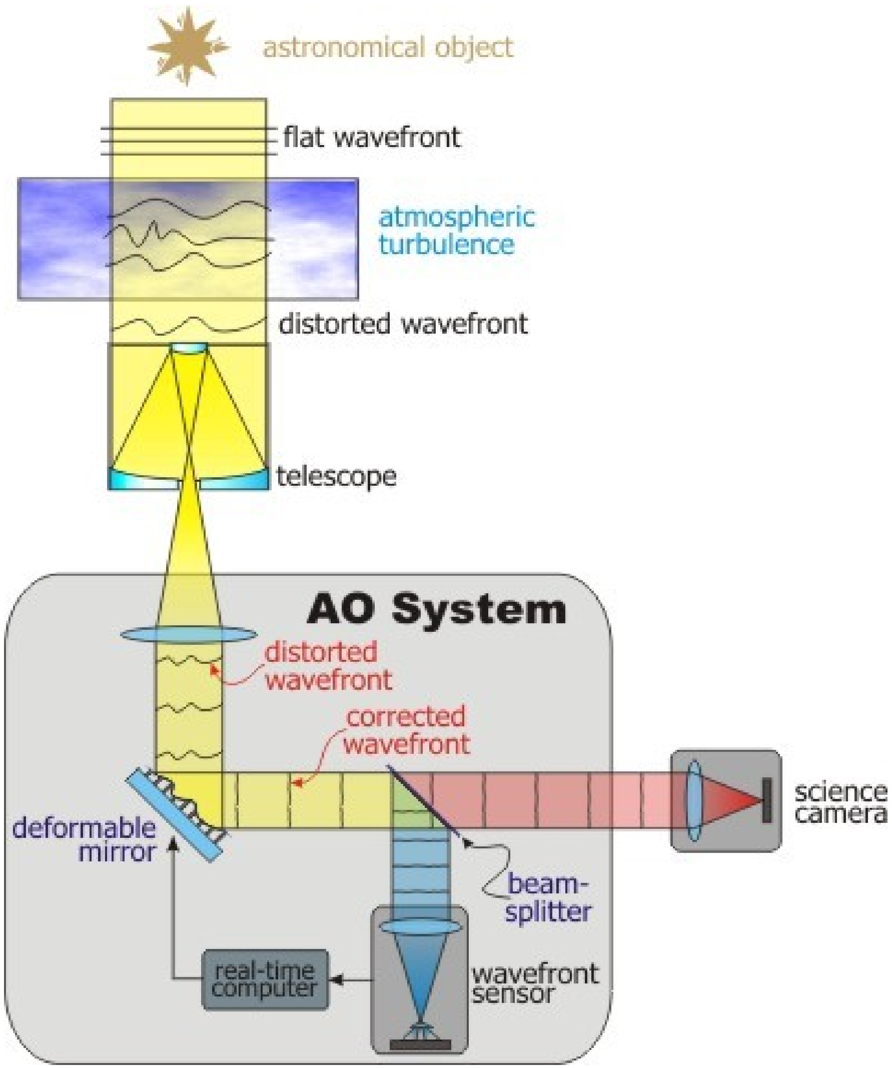
- Adaptive optics:

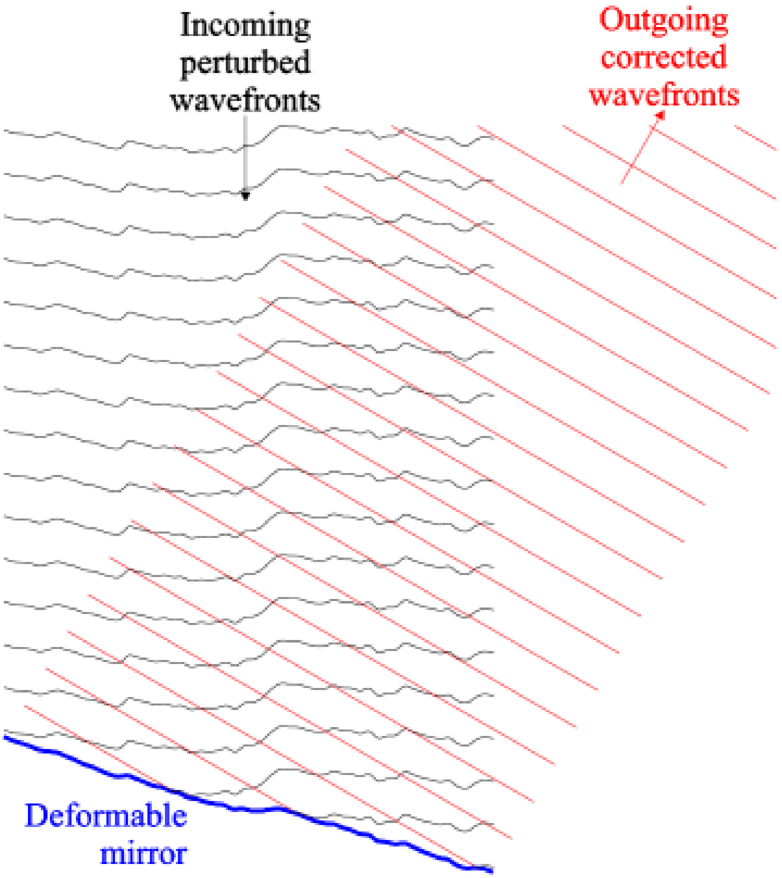
  Shape of a smaller and thinner deformable mirror adjusted (typically second Cassegrain mirror "M2" or a subsequent mirror conjugate to pupil plane)



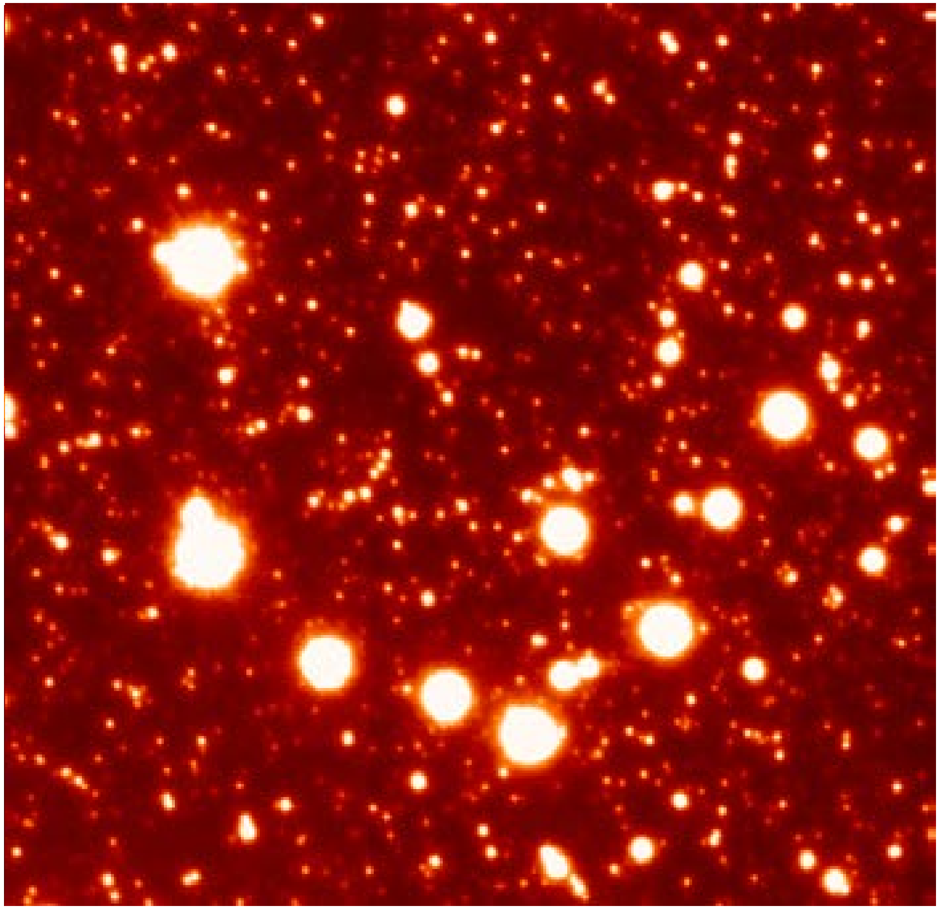
Turbulence in the earth atmosphere: Warm (red) and cool (blue) air cells (~10 cm) distort the incoming wavefront from the star.

Adaptive Optics Principle





An AO Milestone: MAD



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

Multi-conjugate adaptive optics demonstrator (MAD) installed on Nasmyth A of UT3

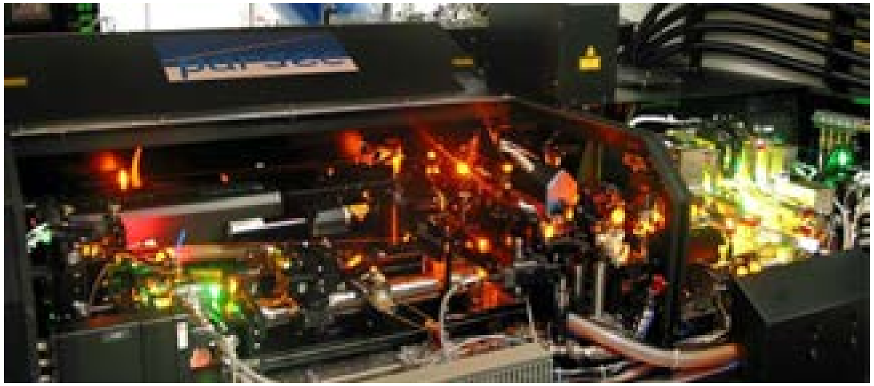
Laser for Adaptive Optics

LASER GUIDE STARS

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

LASER DEVELOPMENT

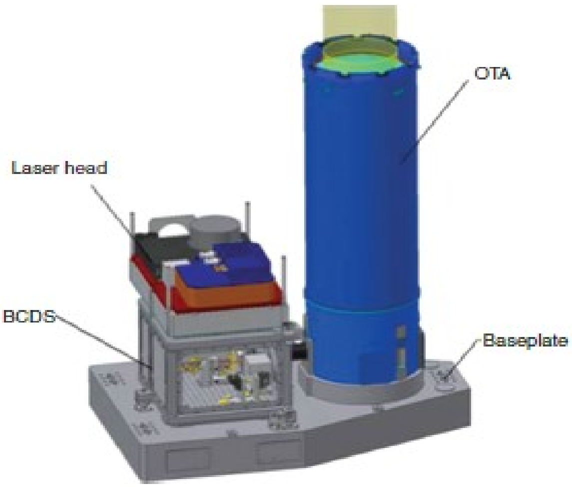
- In 2009 ESO demonstrated continuous output power >50 W at 589nm in a narrow spectral line
- Optical fibre Raman amplifier technology developed at ESO and licensed to industry
- Milestone industrial demonstrator of 20W using technology developed by ESO



Laser Guide Star Development

4LGSF LGSU1 Installation Tests

4LGSF Laser Launch Telescope



4LGSF Laser Guide Star Unit

Field Selector Beam Steering Mirror

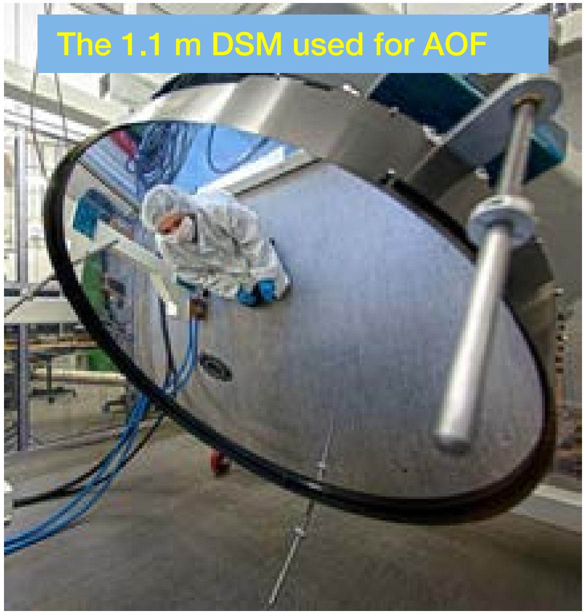
Adaptive Optics Facility

Adaptive Optics Facility (AOF):

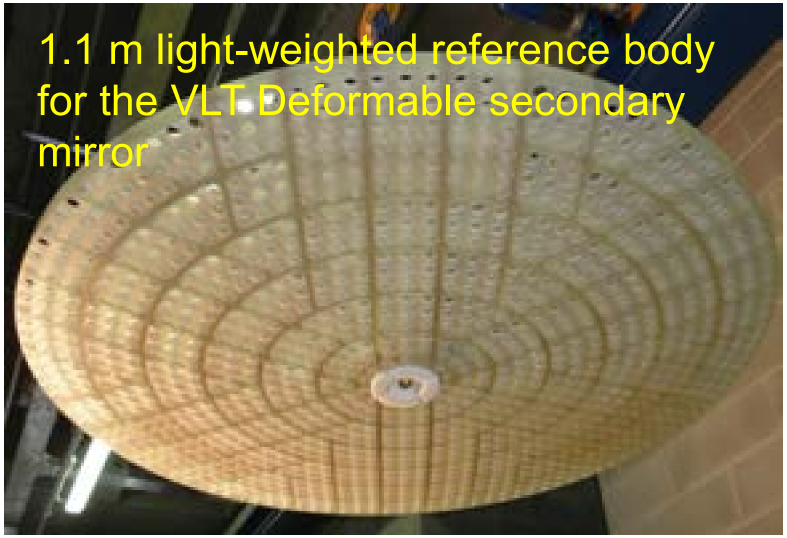
- 2nd generation AO System on UT4
- Uses 4LGSF, deformable M2, and 2 WFS modules:
  - GALACSI for MUSE
  - GRAAL for Hawk-I
- Commissioning in 2015/16

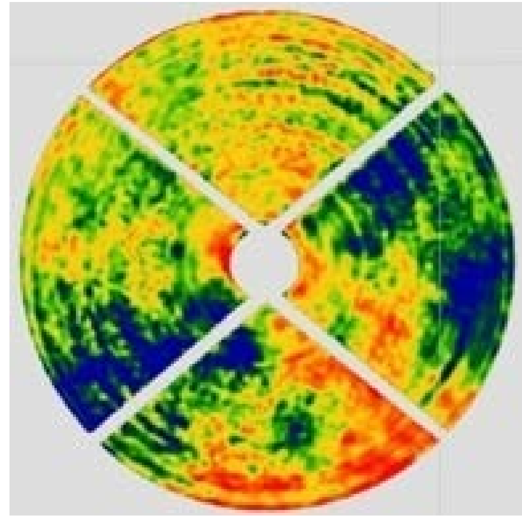
Technical Data of 4LGSF:

- 4 LGS, off axis up to 330”
- 2.5-5 Mphot/sec/m^2
- LGS FWHM <1.2“ on WFS
- 4 LGSs fixed on pupil

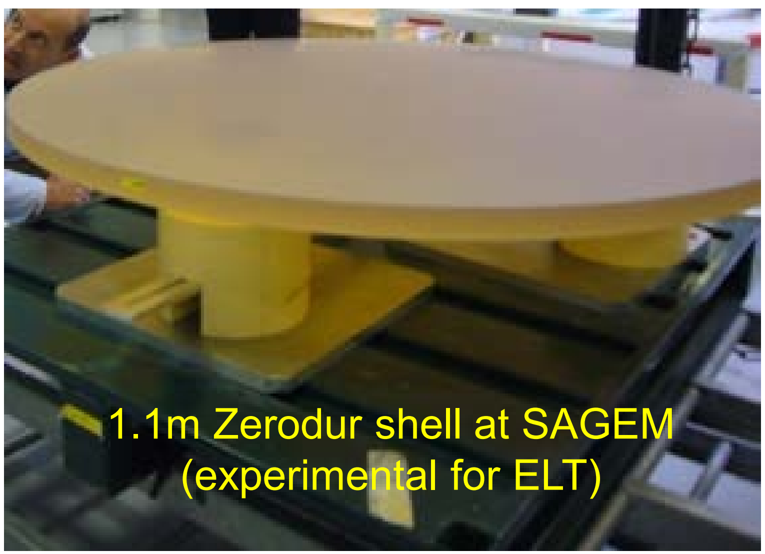


Special Optics for AO


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



Wave front map for the VLT DSM, best figure: <10 nm RMS

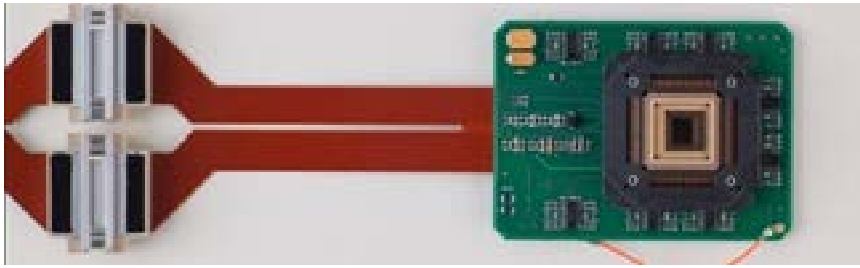

1.1m Zerodur shell at SAGEM (experimental for ELT)


2.6m glass shell, 2 mm thick at SAGEM (experimental for ELT)

Detector Development

Near infrared high speed wavefront sensor: eAPD array

- HgCdTe Electron Avalanche PhotoDiode array: 320x256 pixel
- Avalanche effect offers noiseless amplification → sensitivity larger by factor 100
- first time worldwide NIR subelectron readout noise at 5Mpix/s/output
- Technology only available in Europe: SELEX, SOFRADIR funded by ESO & NSF
- Needed for IR wavefront sensing and fringe tracking in interferometry (GRAVITY)

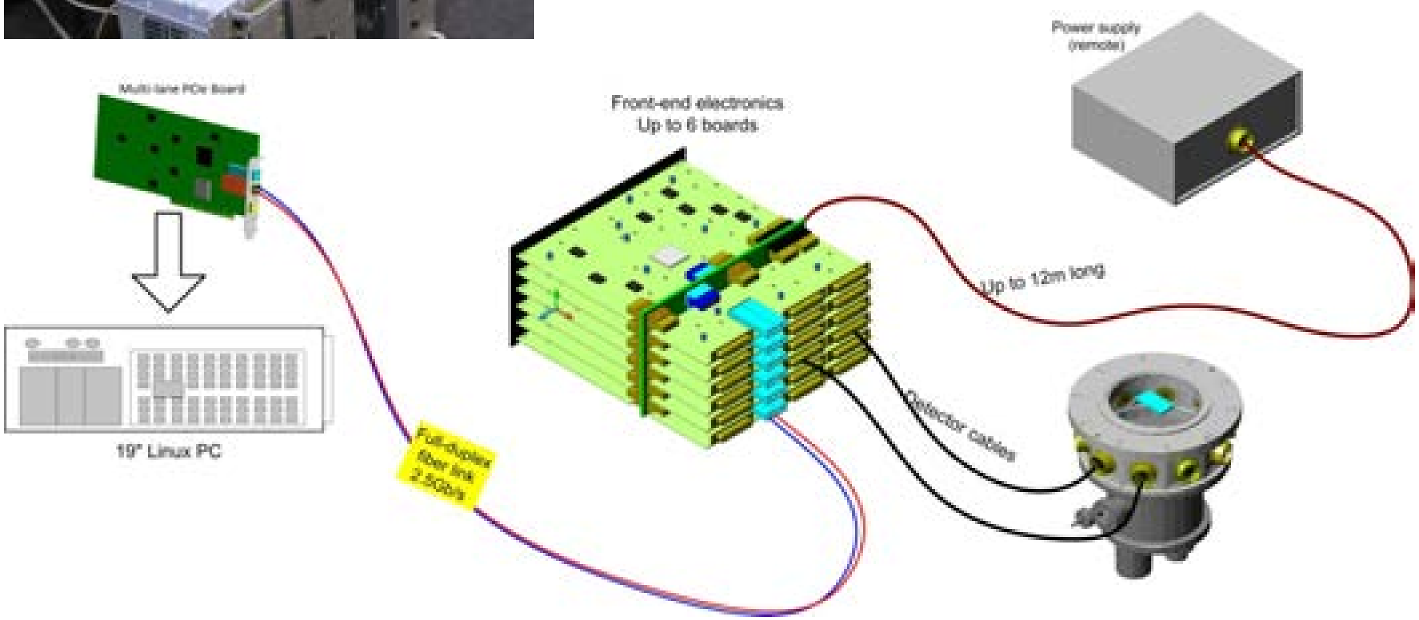


Mid infrared detector (3-28 μm): AQUARIUS

- Arsenic doped Silicon detector (Raytheon)
- 1024 x 1024 pixels, 30 μm pixel-pitch
- Hybridized construction: silicon MUX + indium bumps
- 64 outputs with 150 Hz frame rate

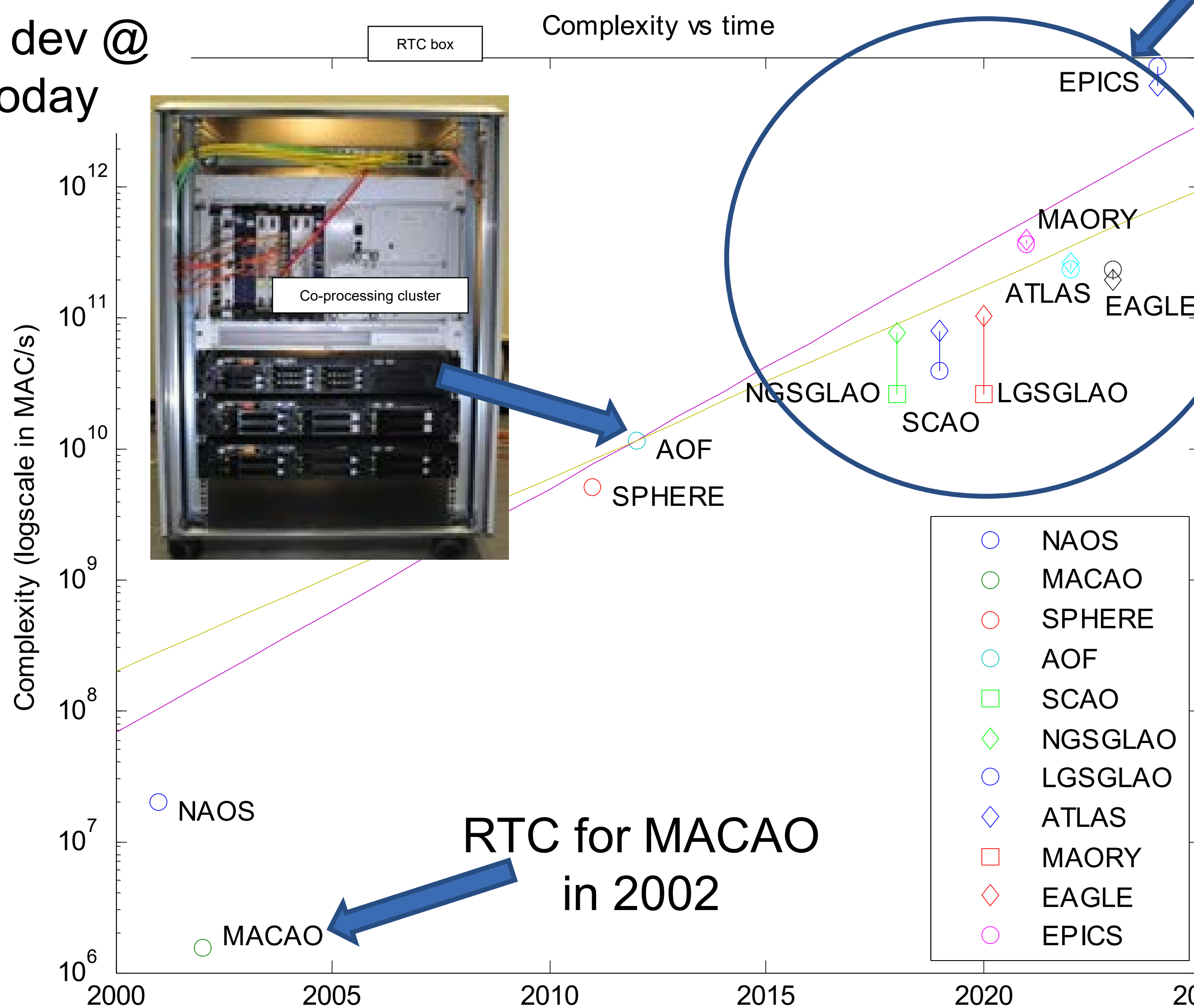
NGC: Generic Control Electronics

- Controller platform NGC is the result of three decades of development at ESO
- NGC is a state-of-the art controller for all detectors at the observatory
- high speed (10MHz) low noise (sub-electron) AO wavefront sensors
- large format mosaic (VISTA: 256 channels)



Real Time Computer & Control

SPARTA dev @ ESO today



Future E-ELT needs

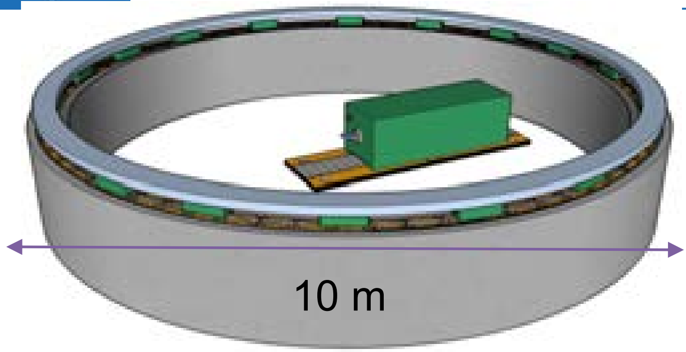
RTC for MACAO in 2002

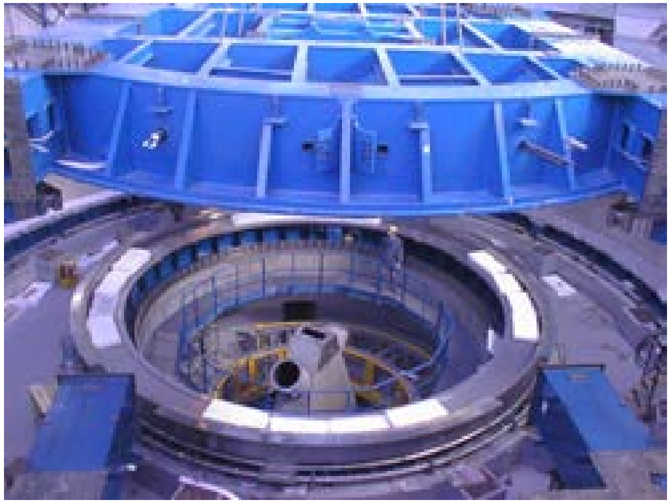
VLT – Main-Axes Drive System

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

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

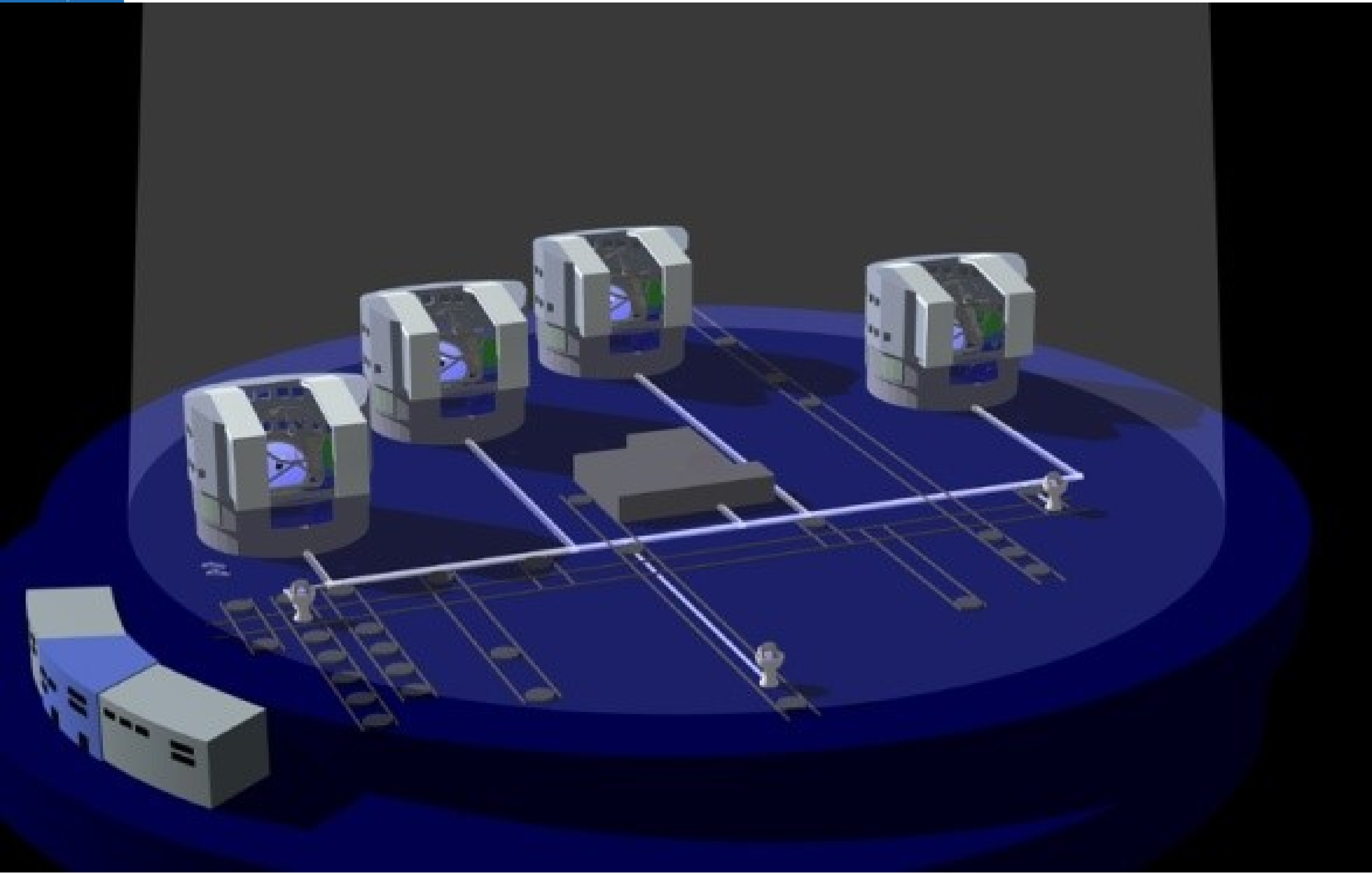
VLT – Technologies



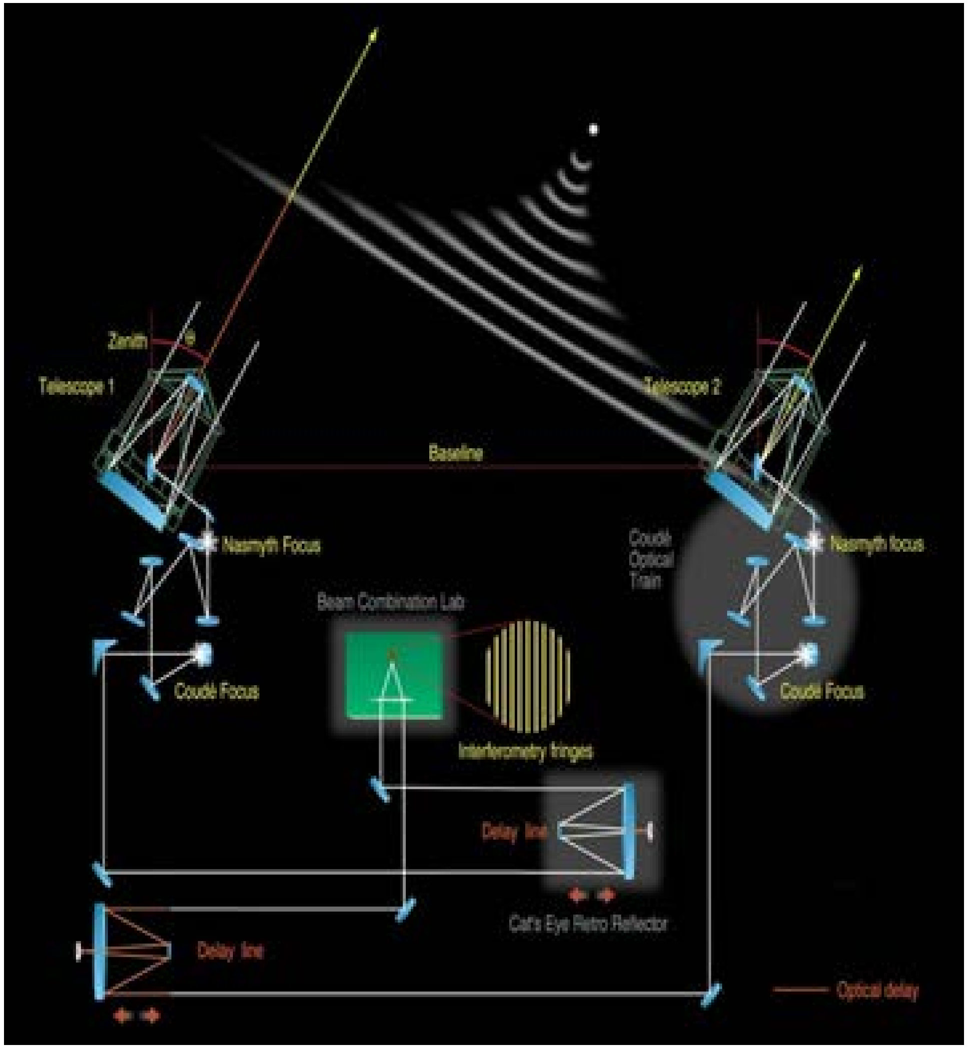


- VLT was the first telescope to use large diameter **direct drive motors** (early 90s)
  → outperform traditional gear or friction coupled drives due to high stiffness and no backlash
  → little wear and maintenance
- Direct drive motors offer possibility of using **collocated encoders**
  → optimal for control engineering
  → VLT encoders are high quality tape encoders with same diameter as the motors.
  → mounted together on the same structure, accuracy ~0.1”
- VLT main axis uses **hydrostatic bearing system**
  → telescope structure floats on an oil film of thickness 50 μm.
  → very low friction (one person can move it)
  → absence of stick-slip friction make the system practically linear.
  → huge advantage for the control system
- First telescope with entire control system implemented in software

VLTI = VLT & Interferometry



VLTI Scheme



Very Large Telescope Interferometer (VLTI)

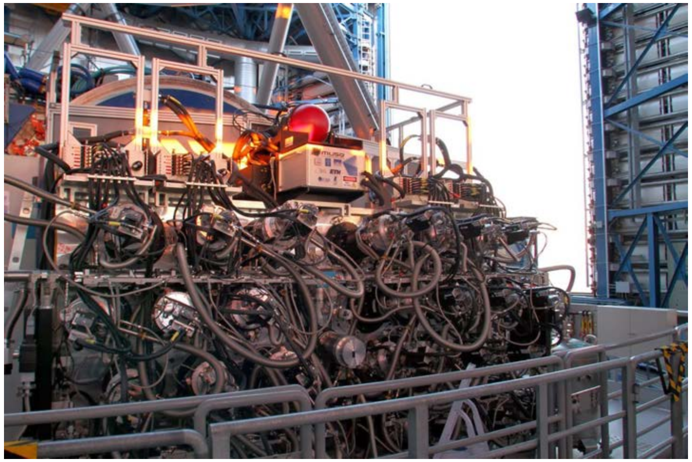
- Combines light from the 8-m UTs and several moveable 1.8-m ATs, separated by up to 200 m
- Inside a130-m long underground tunnel the light beams pass through **delay lines** to balance the optical path length from each telescope
- The resulting interference fringes provide information needed to reconstruct an image with unprecedented detail
- The angular resolution is increased according to telescope distance, i.e. 10-20 times better than individual telescope → opens door to milli-arcsec resolutions

Instrumentation Technologies

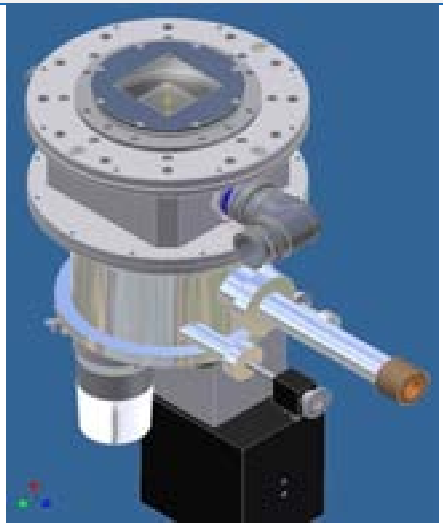
Selected Technology Examples

Cryogenic Systems & Lines

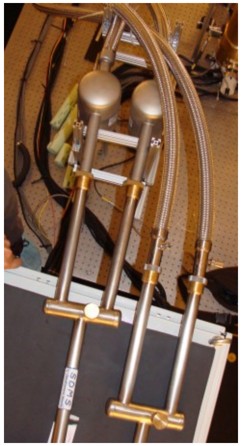
Cooling systems and cryostats down to 3 Kelvin, small and large scale



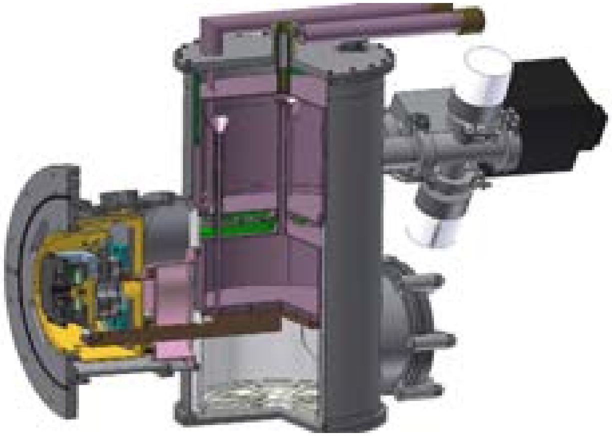
VLT MUSE cooling system with 24 identical CCD cryostats



Single detector head cryostat for MUSE



Manufacturing and testing qualification of transfer and distribution lines for liquid nitrogen



Wave front sensor cryostat for GRAVITY

Manufacturing

small and large structures

- Manufacturing of small accurate parts

- Materials: Aluminum, martensitic and austenitic stainless steels, copper…

Custom gears and worm gear systems

- Final machining of large structures including in some case in-situ metrology for accurate references

- Manufacturing of stainless steel structures

Manufacturing

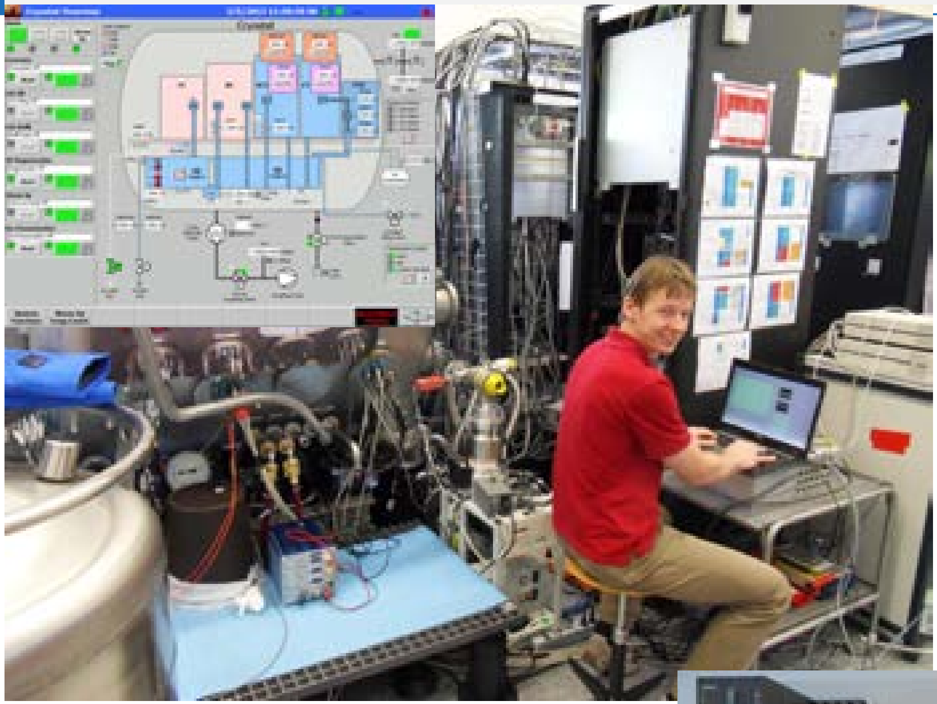
Cryostats and vacuum chambers

- Aluminum structures: Manufacturing Techniques
  - Forming of aluminum
  - TIG welding
  - Thermal treatments
  - Machining.

- Aluminum structures: Cryogenic applications
  - intermediate treatment
  - temperature ageing

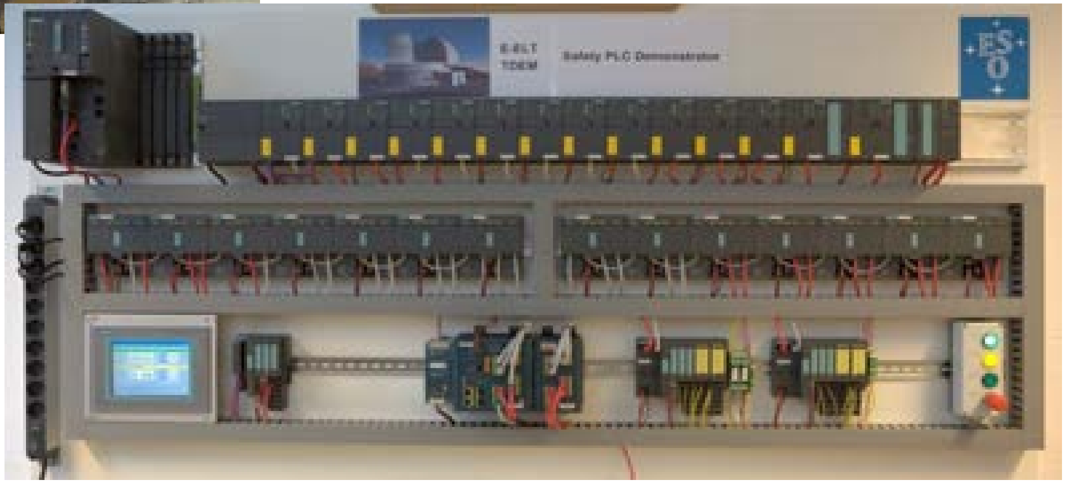
- Manufacturing & testing
  - vacuum chambers
  - LN2 cryostats (including intermediate thermal shocks)

Control Systems on PLC-basis



Cryogenic and Vacuum Control System for Scientific Instruments:
X-Shooter, Gravity, MUSE, MATISSE

- Interlock and Safety Systems for telescopes and instruments ELT, VLT, 4LGSF
- UT Dome control system upgrade
- From the shelves components standardized SIEMENS, WAGOO, MAXON, PI, etc



Obsolescence management

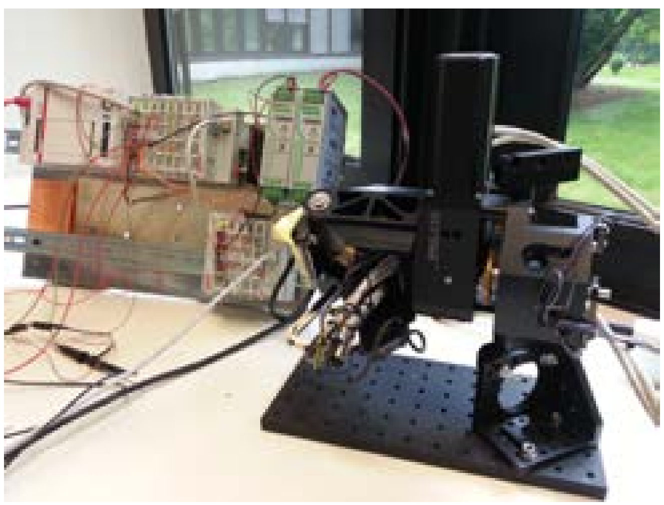
- **HW Virtualization: keep HW and SW interfaces untouched**
  - **Today Design and back engineering made by ESO**
  - **Shall be outsourced → FPGA and schematic design, Layouting, production, tests**

Control Software at ESO

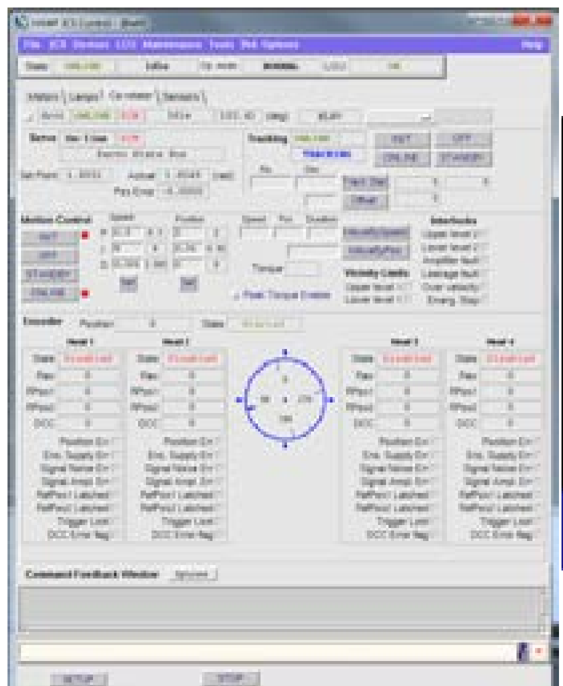
At ESO, we develop control software for telescopes, antennae and astronomical instruments over the full lifecycle

VLT Software: All current ESO telescopes and their instruments are based on the VLT Common Software and on the VLT Instrumentation Software

Real time HW control



Graphical user interfaces



VLT Software

The ALMA Observatory

Selected Technology Developments

The ALMA Observatory

- ALMA=**A**tacama **L**arge **M**illimeter / sub-millimeter **A**rray:
  - Giant array of 66 radio antennas at 5000m altitude
  - 54 x 12-m antennas which can be configured to achieve baselines up to 16 km for highest angular resolution, plus a compact array of 12 x 7-m antennas
- ALMA is a joint project between ESO, North America (USA, Canada), and East Asia (Japan, Taiwan, Korea)

Some challenges:

- Continuous operation at the Array Operations Site (AOS) at 5000m
- Operation up to 18 m/s wind
- Temperature extremes of -20C to +20C and large temporal gradients
- Seismically active region

ALMA Technologies

ALMA uses state-of-the-art technologies in many areas including

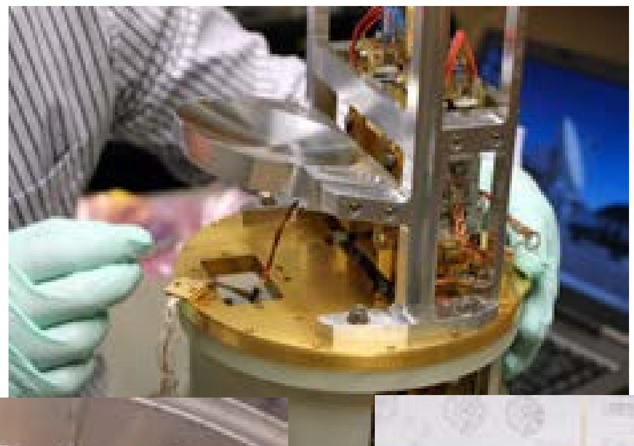
- Antennas
- Antenna transporters
- Cryogenic receivers (30-1000 GHz)
- Digital electronics & transmission
- Digital supercomputer
- Photonics
- Software

ALMA Antennas

- Demanding specifications, leading to
  - Direct drive system
  - Advanced metrology
  - New materials (CFRP)
- Receiver cabin in CFRP technology: Low inertia, no need for insulation
- Back Up Structure out of 16 CFRP slices glued together
- High-res tilt-meter (sub-arcsec) to correct pointing errors due to wind-induced structural deformations.

Cryogenic Receivers

- Specialized heterodyne receivers, operated at 2.5 K
- Superconducting detector elements
- Each antennas has one cryostat with 10 bands



ALMA Correlator

- Specialized Supercomputer
- Operates at 5000m (Cosmic Rays tolerant)
- Key Technologies: high speed digital electronics CMOS ASICs (2^{12} units), FPGAs
- ~10^{16} multiply/accumulate fixed point operations/s
- 32 full size cabinets, ~3000 printed circuit boards, ~5000 cables, ~20 million solder joints, 170 kW

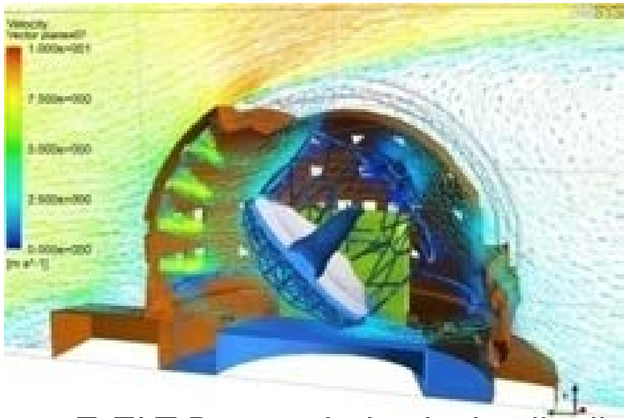
Industrial Opportunities

- Contributions to new developments
  - Radio astronomy instrumentation
  - Scientific software
  - Digital electronics
  - Machining of parts
- Maintenance of high-tech systems in Chile
  - Mechanical (incl. CFRP repairs)
  - Electronic
  - Direct drive
  - Sensor equipment
  - Radio frequency equipment

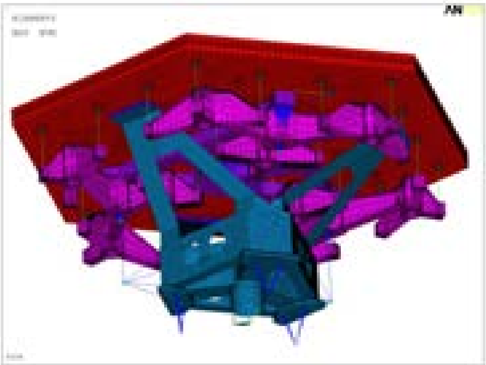
The E-ELT

Selected Technology Developments

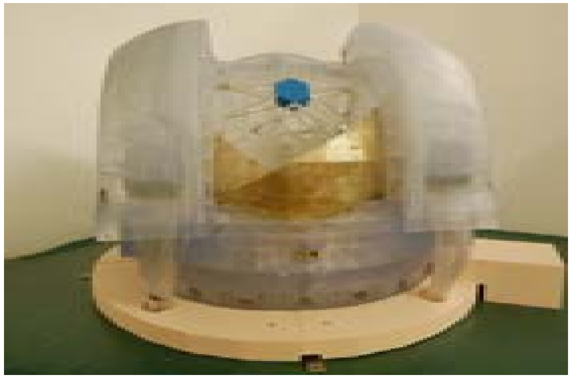
FEA and CFD Analyses



E-ELT Dome wind velocity distribution

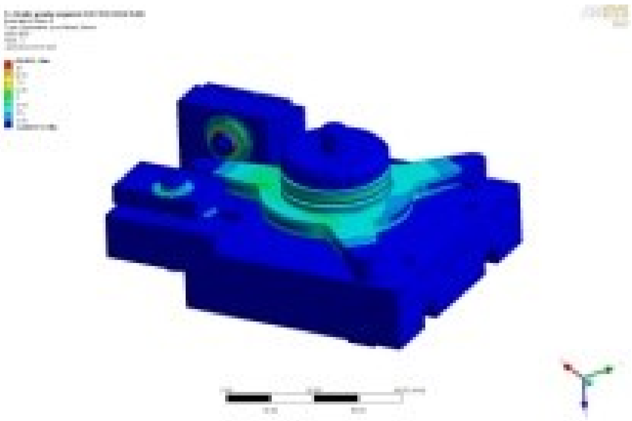


M1 Segment subunit detailed FE model



Wind Tunnel Tests for Dome and Main Structure

- Validation of in-house CFD analyses
- Input to specification requirements

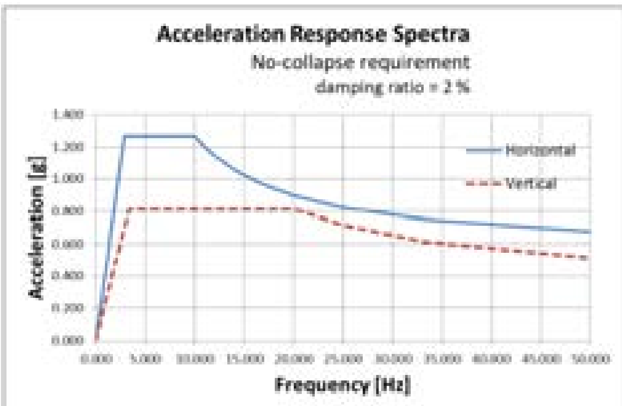


M1 Edge Sensor stresses

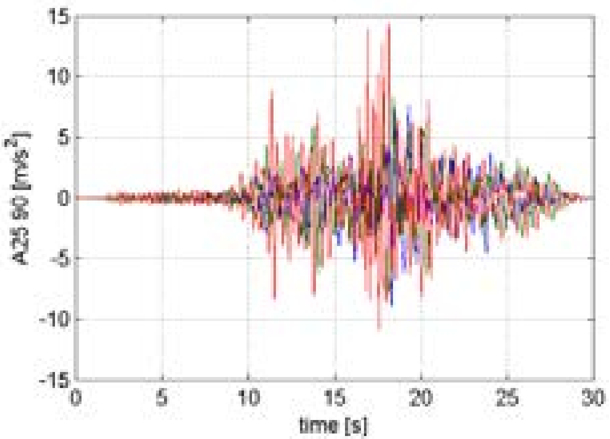
Earthquake Analysis

Evaluation of seismic design loads

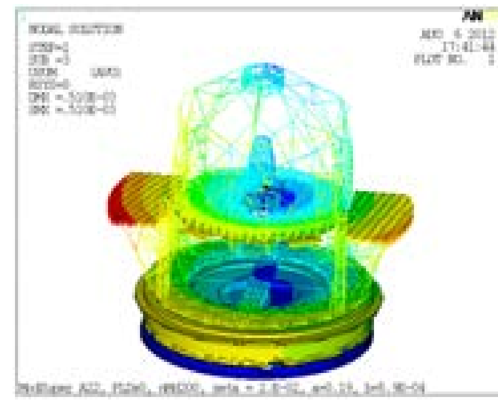
- Define seismic Acceleration Response Spectra and ground motion time histories for E-ELT specifications



Seismic acceleration response (M2)



Seismic isolation 3rd mode shape

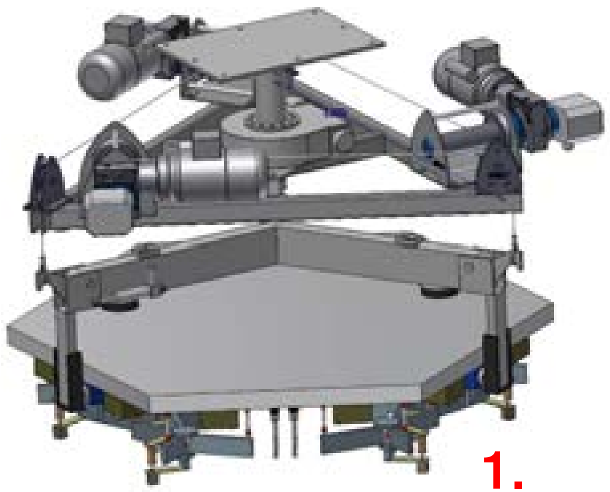


Seismic devices & isolation

- system prototype testing
- Verification of seismic isolation analyses by testing

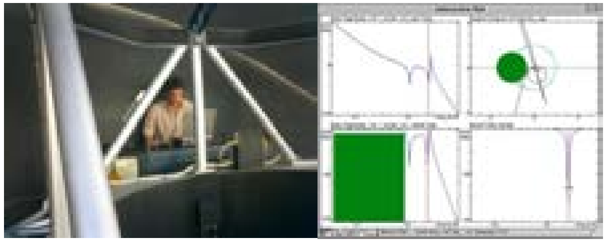
E-ELT mirror handling

handling & treating large mirrors



1. E-ELT segment handling system for M1
2. E-ELT large mirror handling system for M2, M3: gantry with 5 DoF, precision movement, force control
3. Mirror cleaning and washing facilities
4. Coating tank with infrastructure for applying y multi-layer coatings on glass-ceramic substrates (ca 4m diameter)

Control System Design



VLT - Model-based controller design based on frequency models

ALMA - Model-based non-linear damping system design

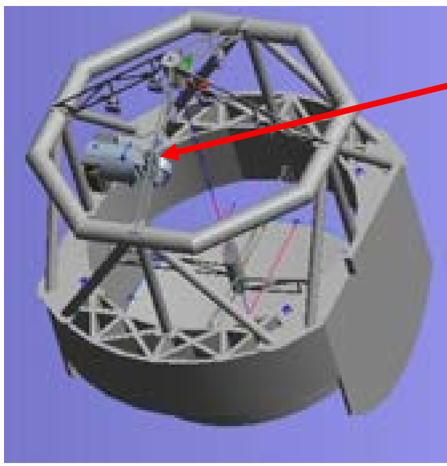
EELT - Prototyping and design of M1 and M5 control systems

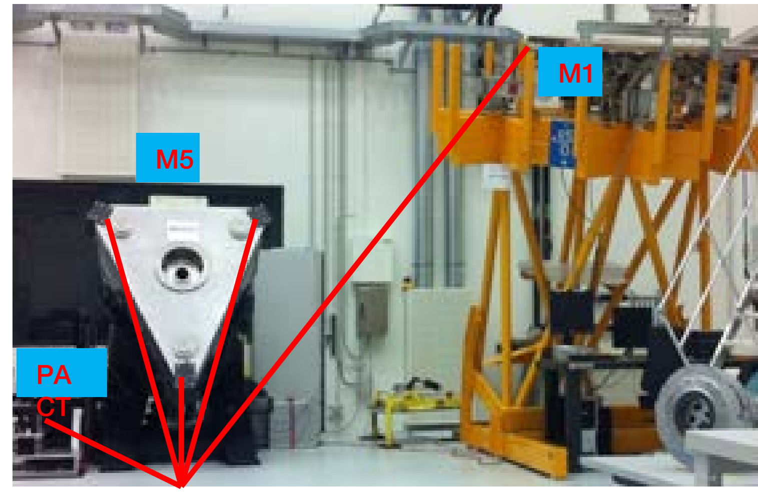
Presentation of EELT technical concepts to the public

Optical Metrology Technologies

Monitoring telescope’s inter-mirror positions

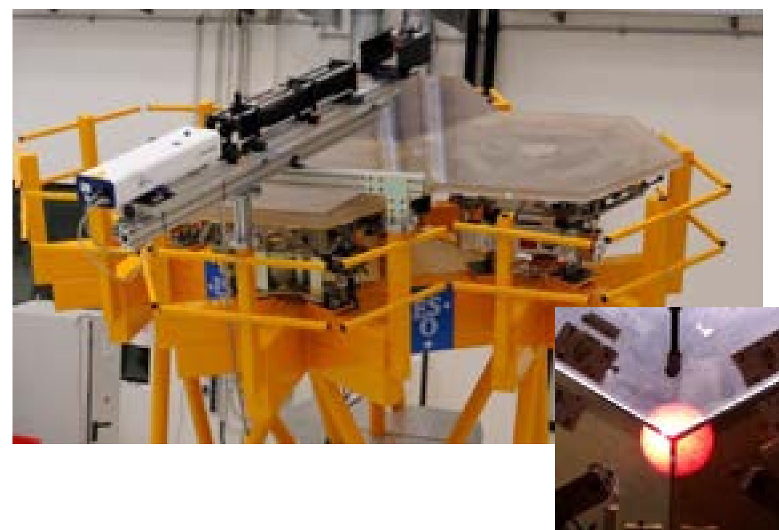
- *Laser trackers (5μm/m):*
- *Multiline frequency scanning laser interferometry (0.5μm/m)*





Segment phasing during day time

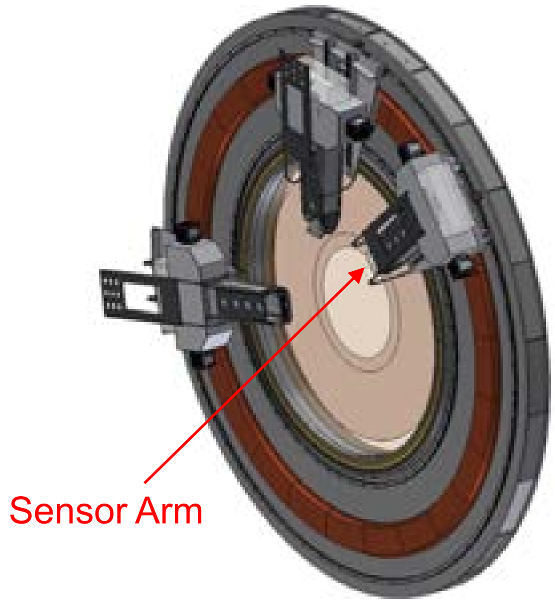
- *Instantaneous Multiwavelength shearing interferometry (10nm, 1 arcsec sensitivity):*
- *Multiwavelength fiber interferometry (nm resolution over 1.2mm)*



Prefocal Station Technologies

PFS lateral mode

Cable wrap system and adapter module



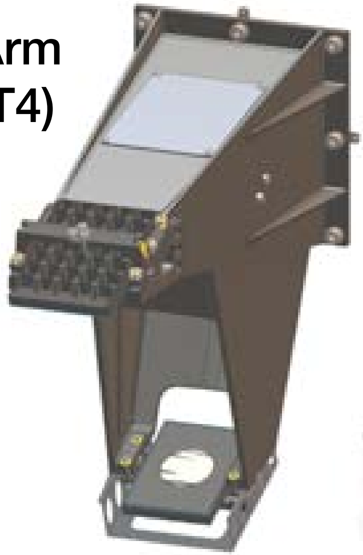
Telescope Wavefront Sensor module (TWFS) with sensor arms

Prefocal Station (PFS): Interface between telescope and instruments,

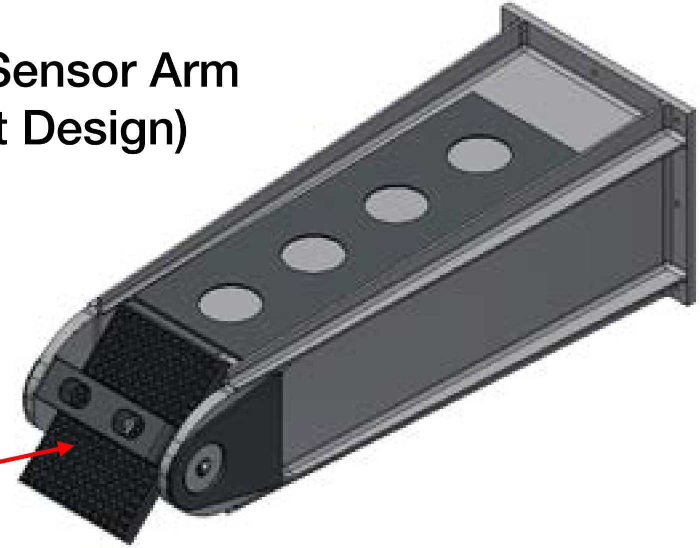
- light can be directed to 3 different locations on and 1 below Nasmyth platform
- Contains sensor arms with wavefront sensors and cameras → active optics correction and telescope control

Prefocal Station (PFS) Technologies

VLT Sensor Arm
(System @ UT4)



ELT Sensor Arm
(Draft Design)



Pick-off
mirror from CESIC

PMMA → create mould

unfinished aluminium castings

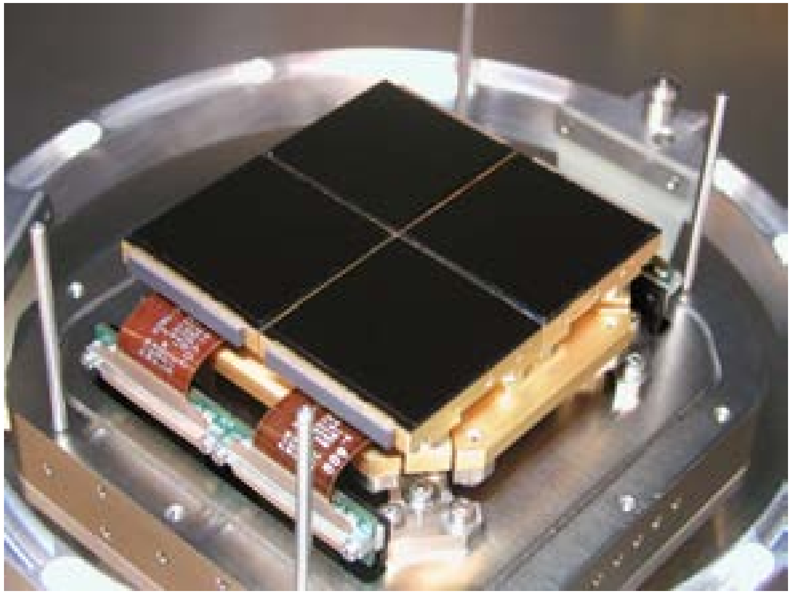
Final milling

Installation at Nasmyth Adapter

Detector Arrays

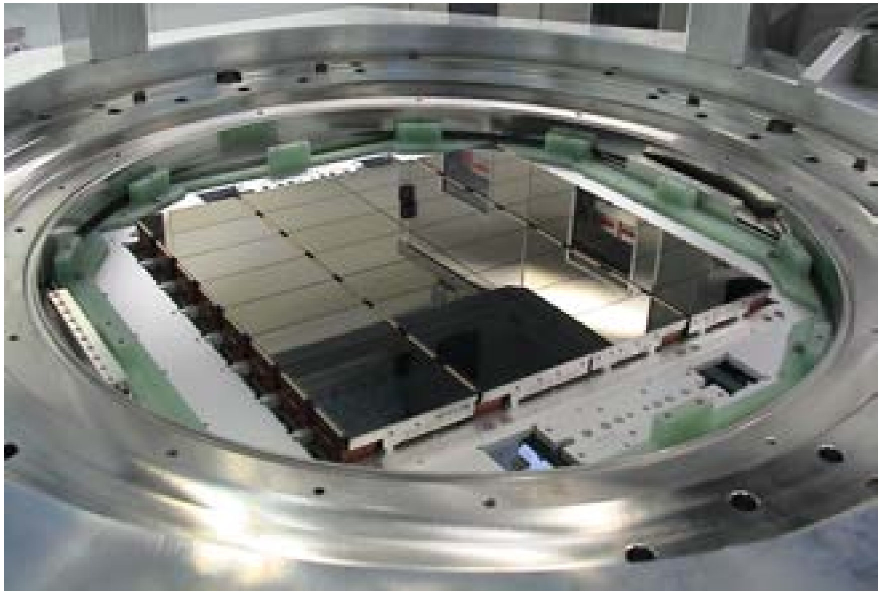
(for instrument ELT instrument focal planes)

Near infrared



HAWK-I near infrared mosaic
4 x 2Kx2K HgCdeTe Hawaii2RG arrays
Cutoff wavelength $\lambda_c = 2.5\ \mu m$
128 parallel video outputs
cryogenic preamplifiers
MICADO **(ELT Instrument):** mosaic of 16x4Kx4K Hawaii-4RG-15 arrays

Optical



OmegaCAM CCD mosaic
268 M Pixel, 32 CCDs,

NEW: 9Kx9K e2v CCDs for ESPRESSO
Also to be used in **ELT instruments**

General Technology Needs

- Optics
- Detectors (Infrared, Visible)
- Mechanical structures
- Integration support and facilities
- Cooling and chiller system
- Heating, Ventilation, and Air conditioning (HVAC)
- Cranes and handling equipments
- Mirror coating facilities
- Actuators & Controllers
- Software
- Power generation and distribution systems
- Waste and chemicals treatment
- Laser systems at specific wavelengsth
- Consultancy (RAMS, PA, QA)
- And many more …….

Questions?