Technology in Astronomy VLT / VLTI as showcase

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ESO

What is ESO

ESO is the European Southern Observatory, builds and operates a suite of the world's most advanced ground-based astronomical telescopes

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 several advanced technologies that have enabled the construction of ever larger telescope mirrors, while maintaining optical accuracy.

Technology in Astronomy

ESO has developed and / or participated 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.

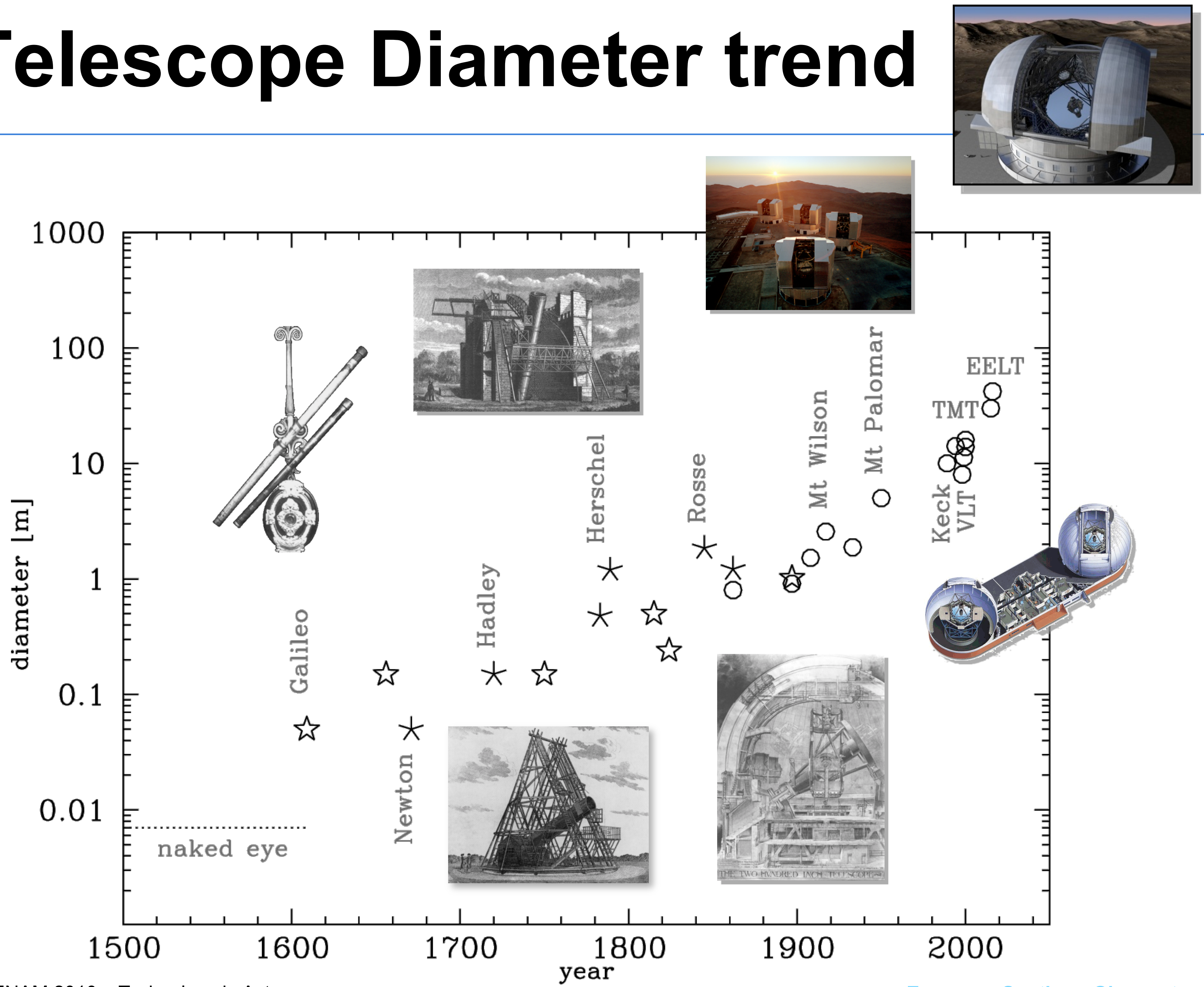
Technology in Astronomy

- In addition the telescopes themselves can introduce errors into astronomical observations. Manufacturing errors and irregularities in equipment, ranging from mirrors to structural components, can disturb views of the cosmos. Over the years, engineers have made a series of improvements to minimise wear-and-tear errors caused by the mechanical movement of the telescope and heat damage. Mirror figuring and polishing have improved, along with the design of stiffer support structures and mirrors to reduce deformations. Low expansion glass has also reduced mirror distortions when temperatures vary. To reduce the small, but noticeable, turbulence inside the telescope dome, heat loss from motors and electronic equipment is curtailed during the night, and the dome that shields the telescope from the wind is cooled during the day.
- ESO has substantially contributed in abating several of these disturbances and/or in improving their control.

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.

Telescope Diameter trend



Active Optics

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.

Telescope	Dia/thkn	year
ESO 3.6	6	1960s
ESO NTT	15	1970s
ESO VLT	47	1990s
ESO E-ELT	840	2010s

Active Optics

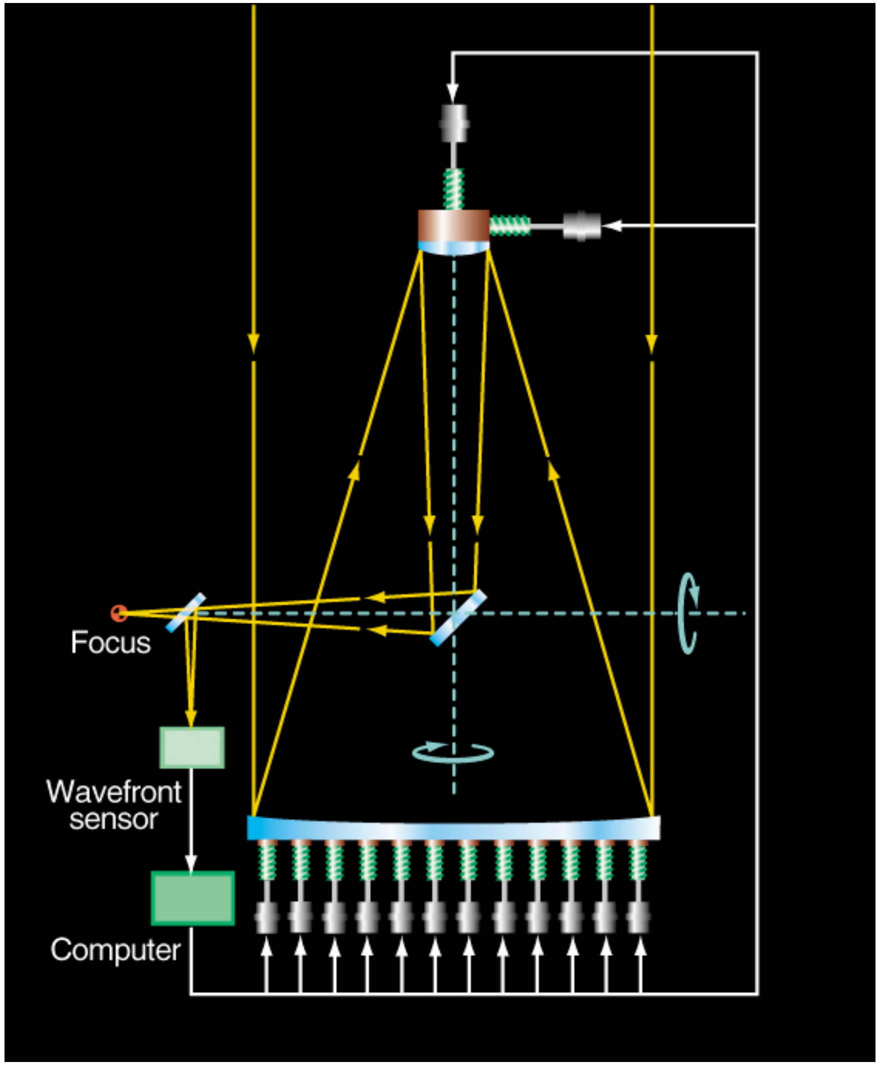
The combination of actuators, a quality-of-image detector, and a real-time computer program to move the actuators to obtain the best possible image, is termed “active optics”, a technology developed by ESO.

The “activeness” in their name means that the system keeps the primary mirror in its optimal shape against all environmental factors such as gravity (at different telescope inclinations), wind, telescope axis deformations, thermal disturbances, etc.

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



Measurement of the wavefront errors

Standard method for the measurement of wavefront errors:

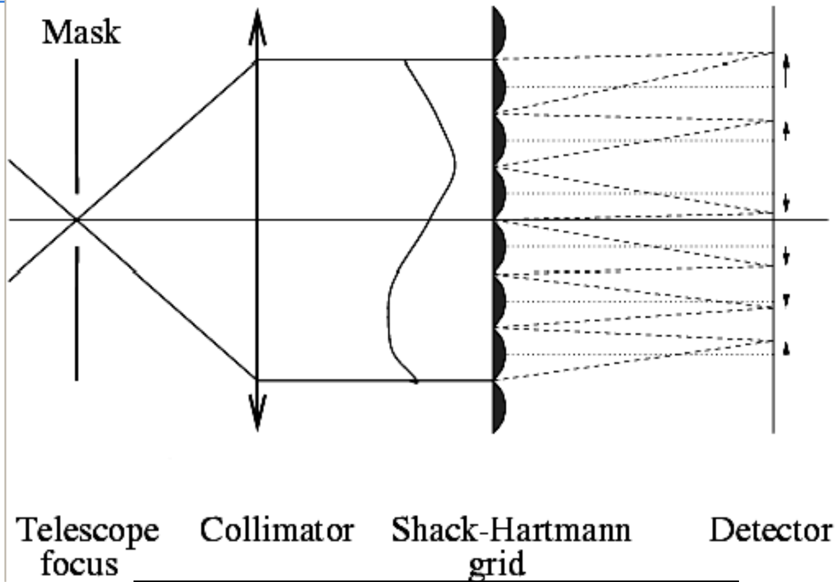
• Use of Shack-Hartmann lenslet array

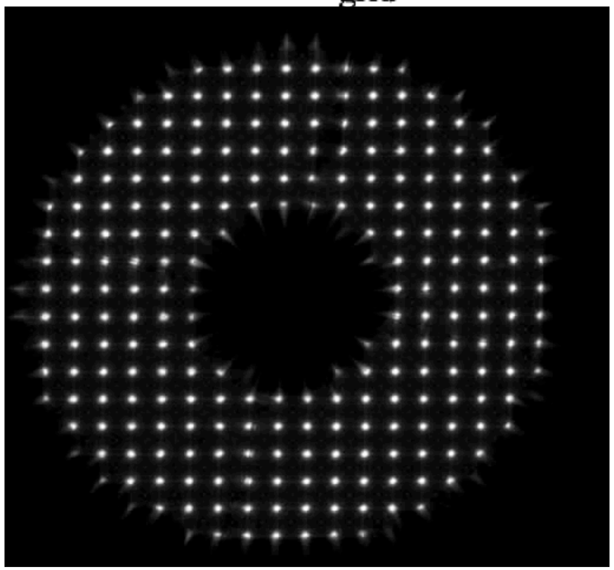
• Measurements are done in a pupil

• Method measures the local tilts of the wavefront

• Measurements during astronomical observations became possible with the invention of computers and CCDs

• With 30 seconds integration time one can find sufficiently bright stars in every field





Active Optics=>The NTT

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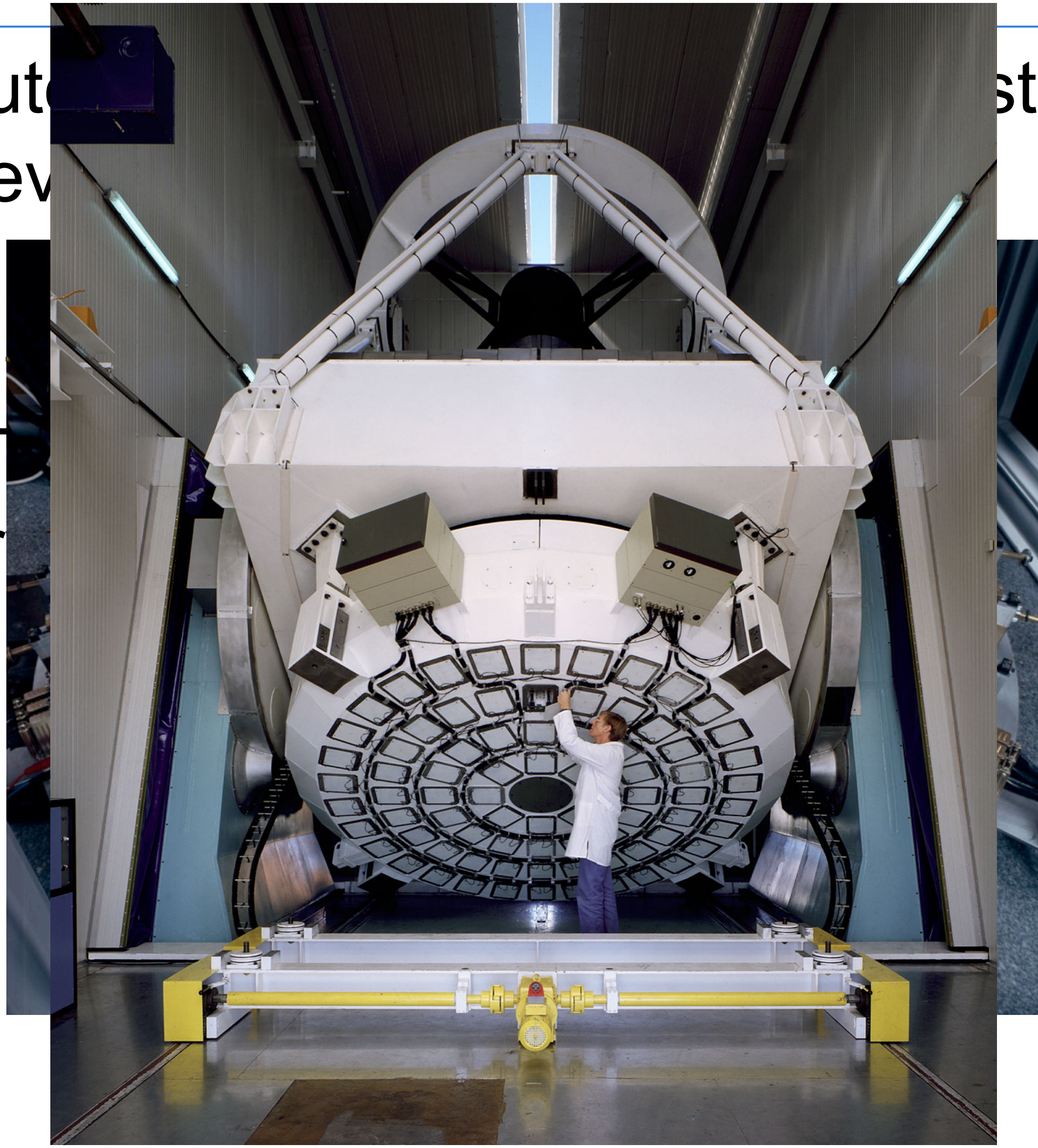
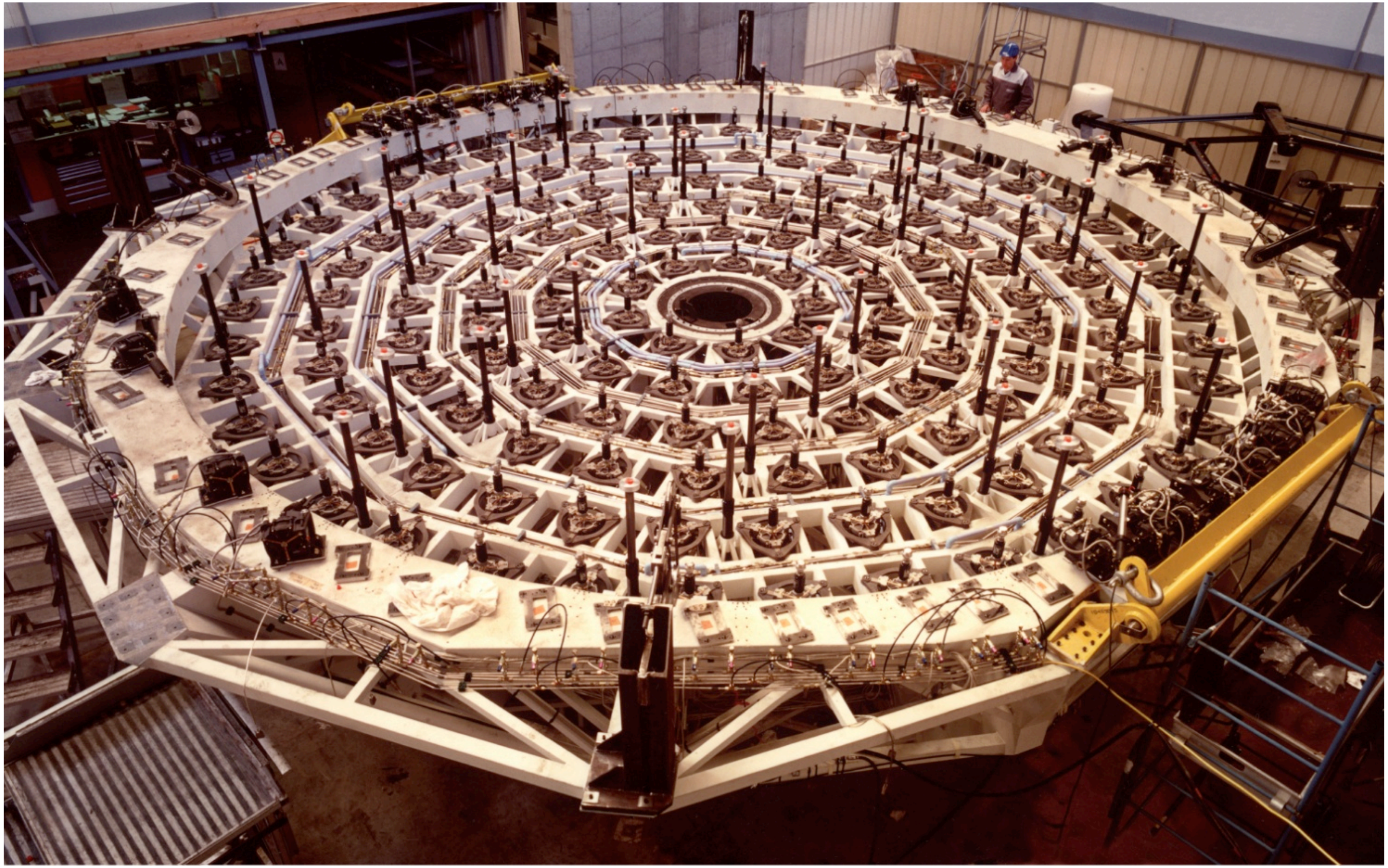


From NTT to VLT

Since the NTT began operating in 1990, the 75 adjustable supports below its 3.58-metre primary mirror, coupled with advanced image analysis and control software, have made this telescope one of the best in the world. Active optics technology is now applied to all modern major telescopes, including ESO's VLT. Each of the four VLT Unit Telescopes is equipped with the best active optics systems constructed to date. The systems control the primary 8.2-metre Zerodur mirror (22 Tonnes) as well as the secondary 1.1-metre lightweight beryllium mirror at the top of the telescope structure.

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 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.

Adaptive Optics

It's a frustrating fact that photons coming from an astronomical object are severely disturbed by turbulence in Earth's atmosphere in the last few kilometers on their way to the observer after an essentially undisturbed journey of up to several billion light-years. Earth's atmosphere consists of small cells (~10cm diameter), which are slightly warmer or cooler than the average. The result is that when a plane light-wave from a star passes through the atmosphere, the light is distorted.

When observed with a telescope, the image of this star is not sharp, but rather it is dissociated into many small bright spots, so-called speckles. These speckles evolve rapidly, resulting in a smeared image with a typical diameter of 1 arcsec, as soon as the exposure time is longer than a few milli-seconds. The size of this so-called seeing-disk is the limit for the angular resolution, which can be achieved with a telescope from the ground. For large optical telescopes, the angular resolution is thus ~100 times worse than what could be achieved without the influence of the atmosphere.

Adaptive Optics

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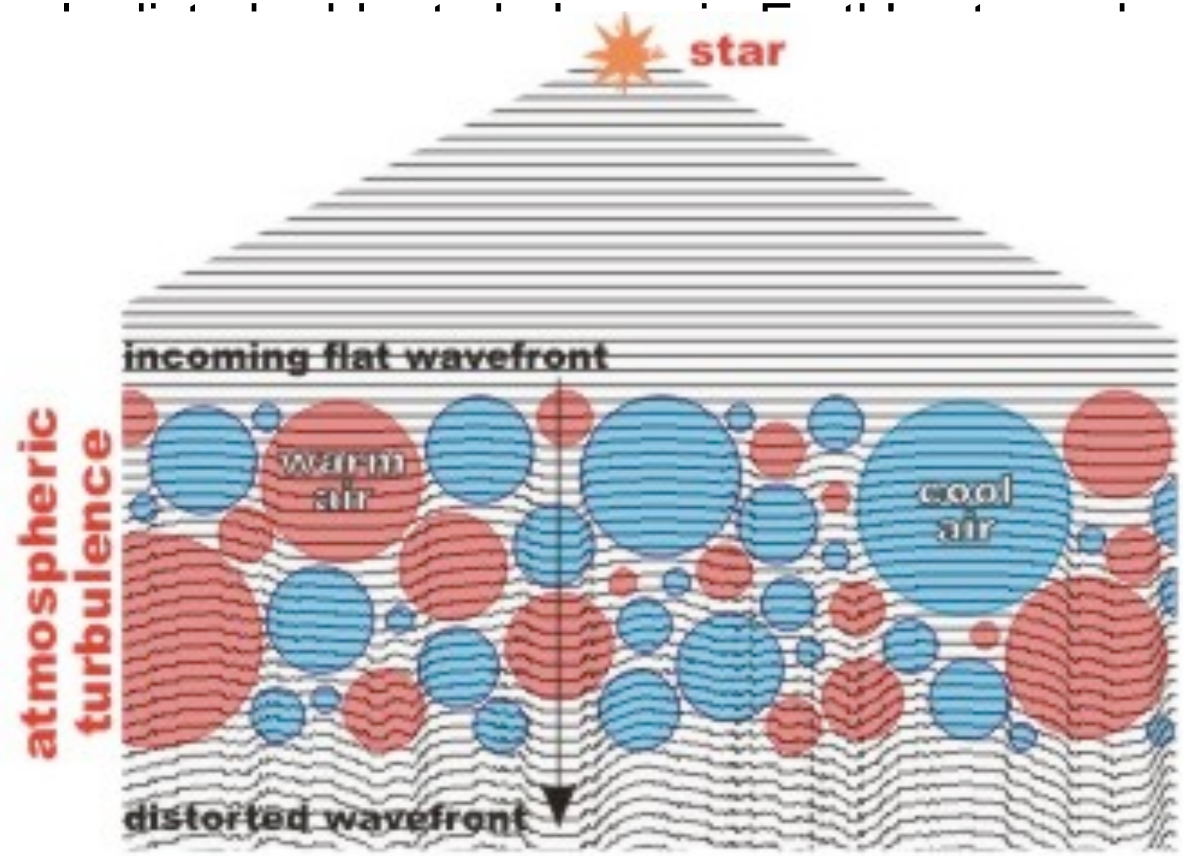

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resolution is thus ~100 times worse than what could be achieved
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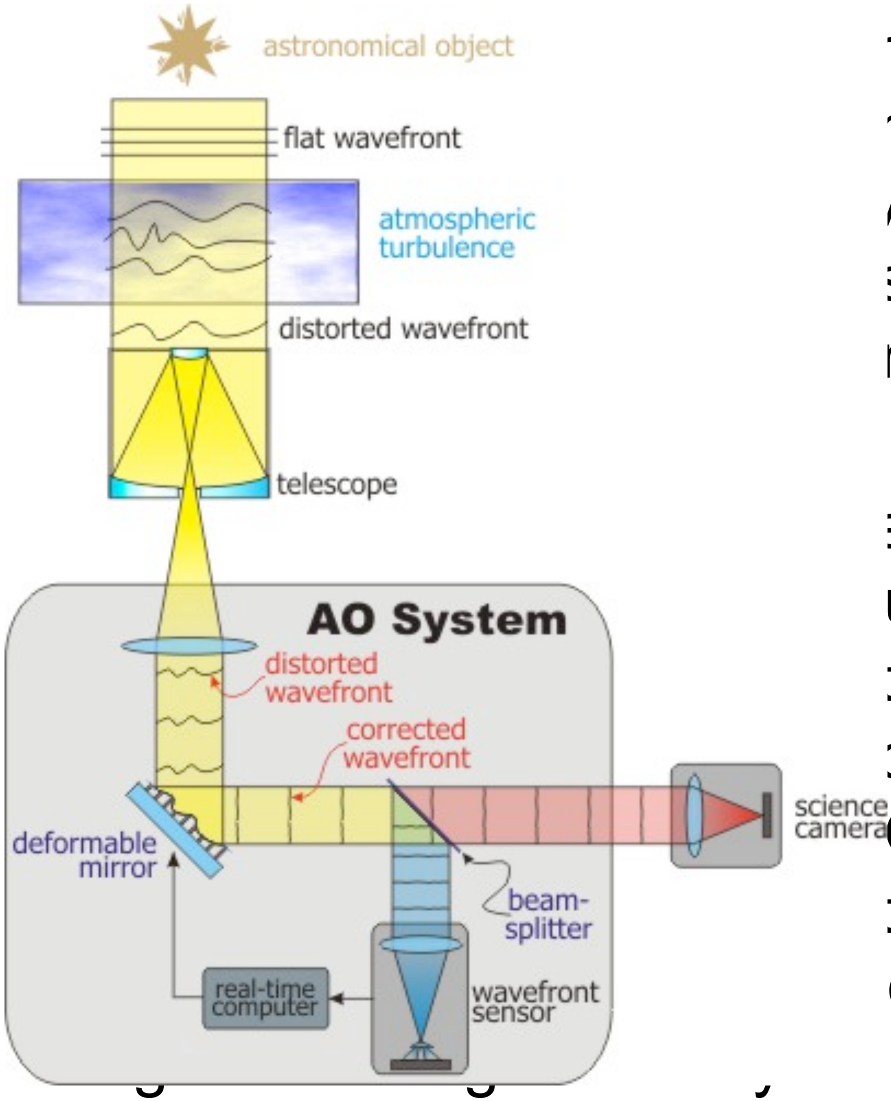
Adaptive Optics principle

One approach to improve the image quality is to correct the induced distortions of the light before imaging it with a detector. The idea of Adaptive Optics (AO) is to use a guide star to measure the distortions of the star-light with a wavefront sensor (WFS) and to compensate them with a Deformable Mirror (DM).

This has to be done in real-time, and the shape of the DM has to be adjusted several hundred times per second to follow the rapid evolution of the atmosphere. In the case that a suitable guide star is located close to the interesting science-object, AO systems can currently deliver nearly diffraction-limited images at large optical telescopes for wavelengths longer than ~1μm at a very high observing efficiency.

Adaptive Optics principle



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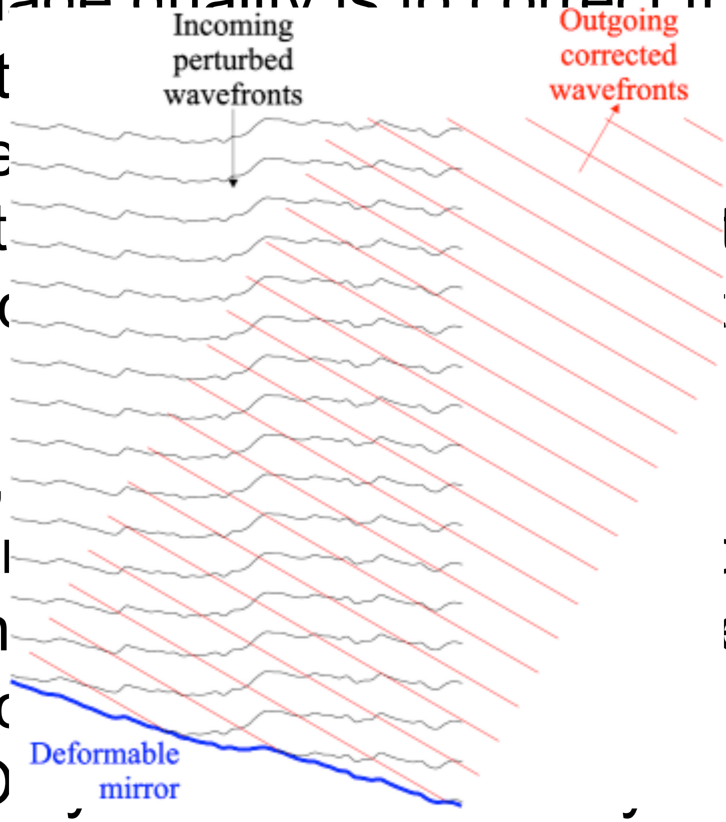


From classical Adaptive Optics…

- Classical AO systems use one natural guide star to measure the deformations of the incoming wavefront with a wavefront-sensor and correct them with the help of a Deformable Mirror (DM).
- However, since light originating from objects other than the guide star experiences different deformations by the turbulent atmosphere, the correction by such an AO system degrades rapidly with the distance from the guide star.

…to MCAO and MAD

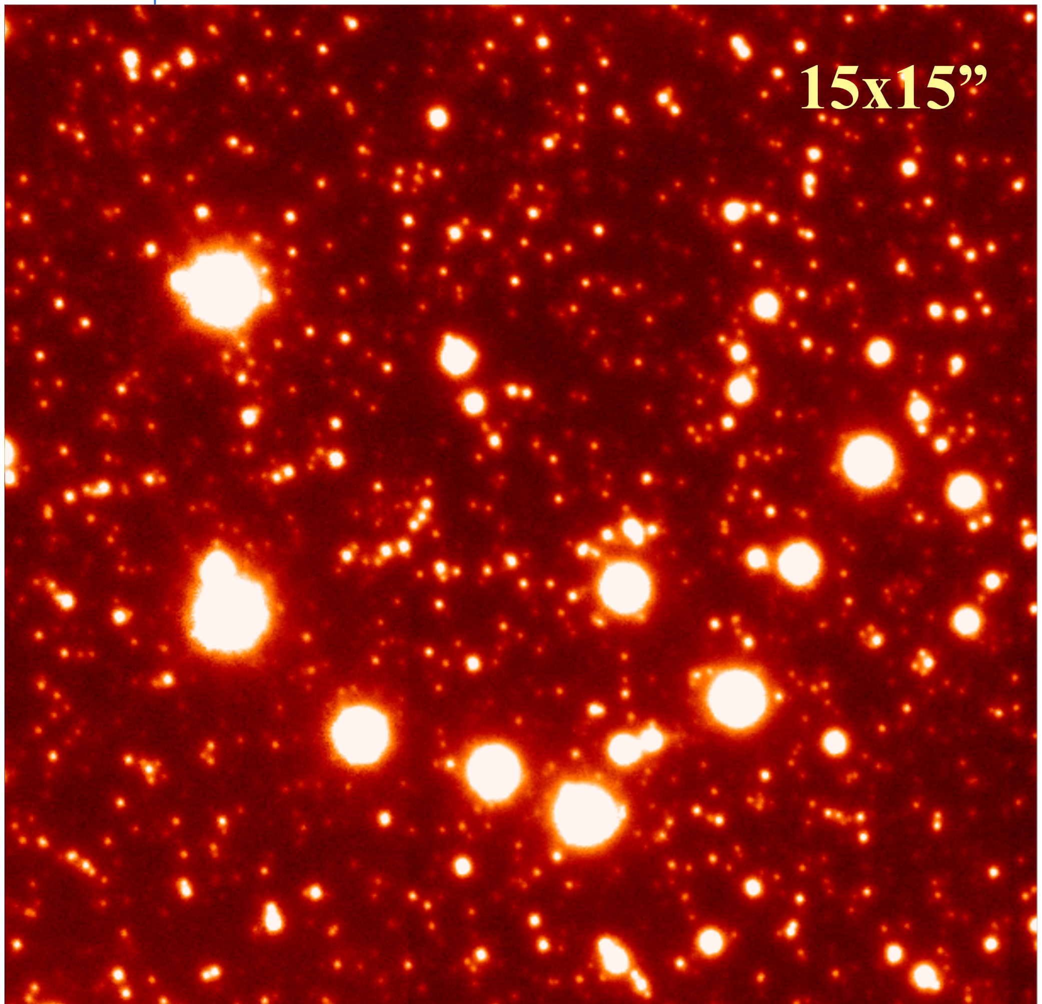
- To increase the area of homogenous correction, the concept of Multi-Conjugate Adaptive Optics (MCAO) has been introduced. Several guide stars are used to measure the vertical structure of the turbulence in the complete volume above the telescope. Several DMs are in place to optically compensate the turbulence in individual layers and no longer in a single direction. The result is that the correction is much more uniform over the significantly increased .

- Measurements of the vertical distribution of the atmospheric turbulence show at various sites that the optical active turbulence is strongly concentrated near the ground. Typically 75% are within the first 2 km above the ground. A significant improvement of the image quality could thus be already achieved, if only the turbulence near the ground is corrected. F. Rigaut thus proposed a ``MCAO-light'' system, i.e. to measure and correct only the ground-layer turbulence, thus called Ground-Layer Adaptive Optics (GLAO).

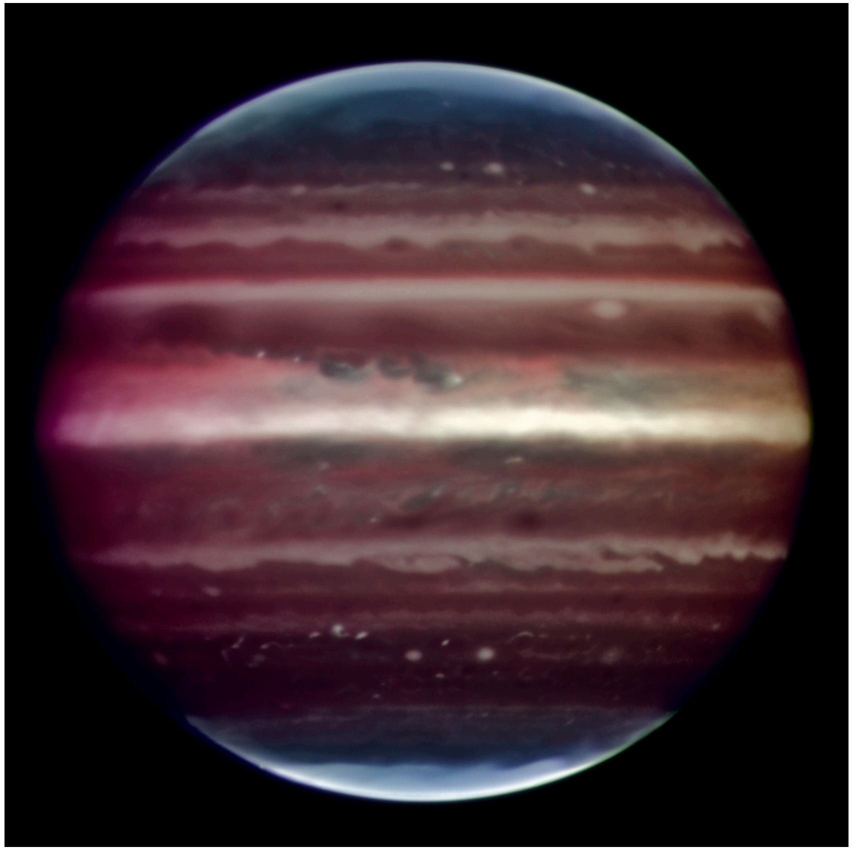
MAD (McAoDemonstrator) on Nasmyth A UT3 (Melipal)

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



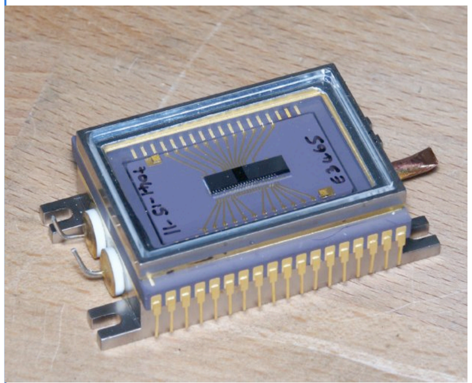
MCAO: 3 Guide stars at 2'
K-band, FWHM: 100-120mas, Sr: >20%
0.7" seeing, Exposure 360 s

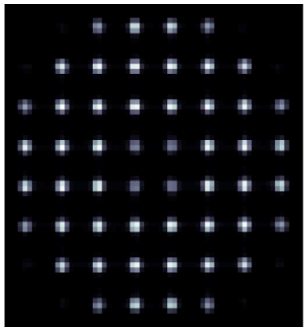


MCAO: 2 Guide "stars" (satellites Europa and Io)
2.14µm + 2.16µm filters
90 mas resolution (300 km at Jupiter)

WFS for AO

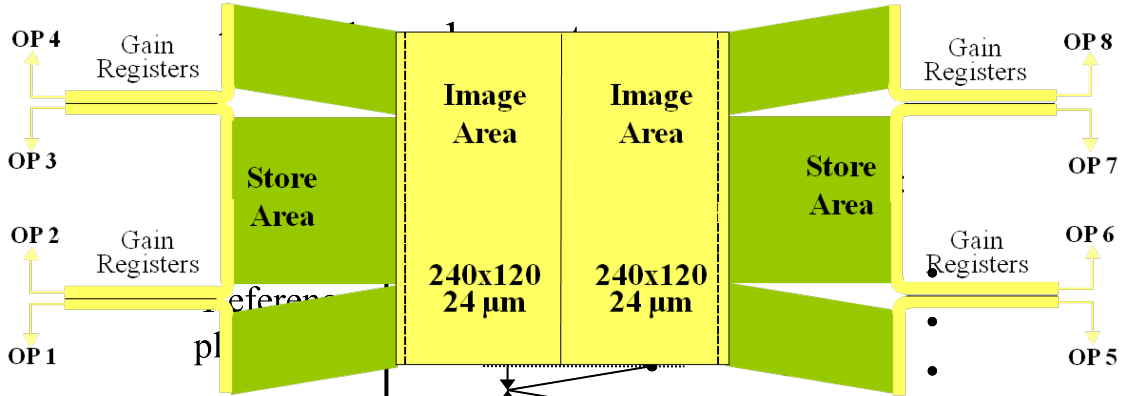
Existing system ("MAD"):
8x8 sub-apertures on an e2v CCD39

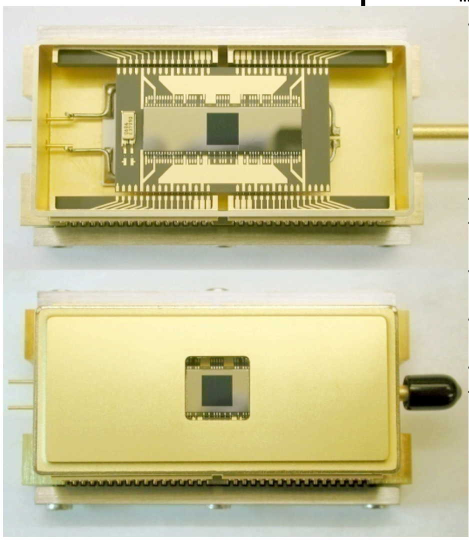


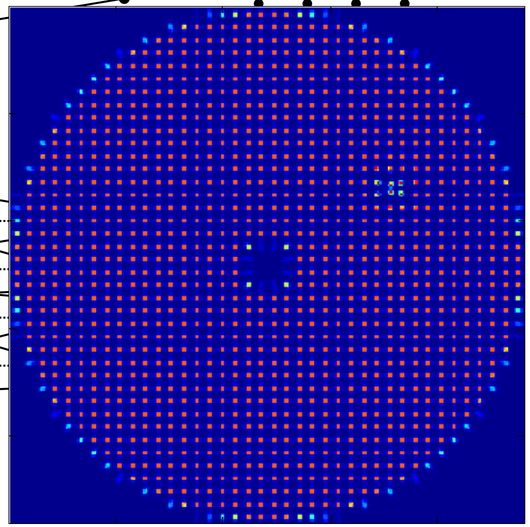


In development ("AO Facility"):
40x40 sub-apertures on an e2v CCD220

Shack-Hartmann WFS: measure



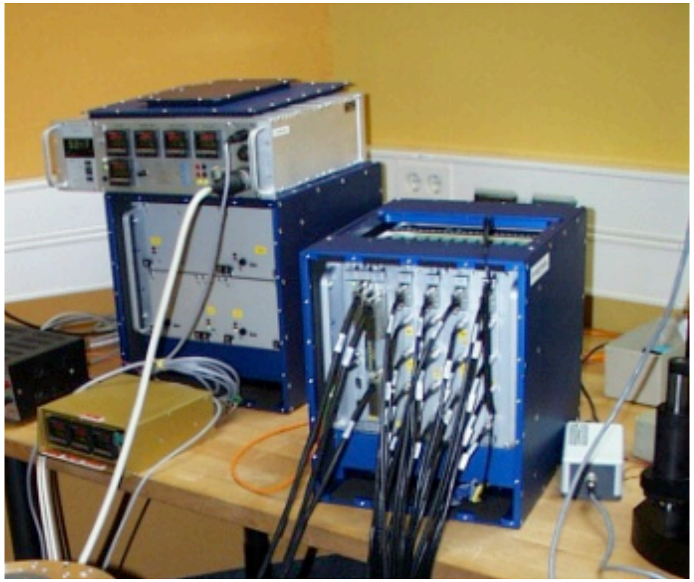




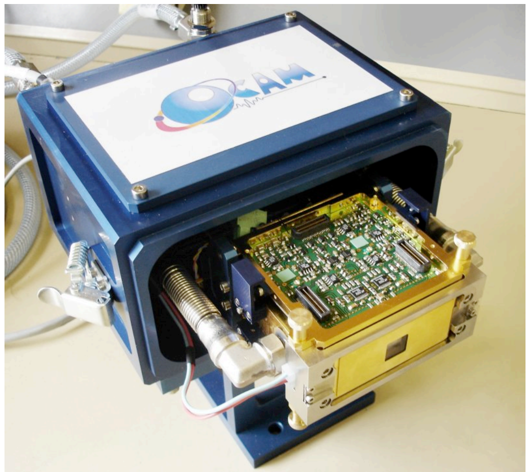
Road Map of WFS Detectors

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

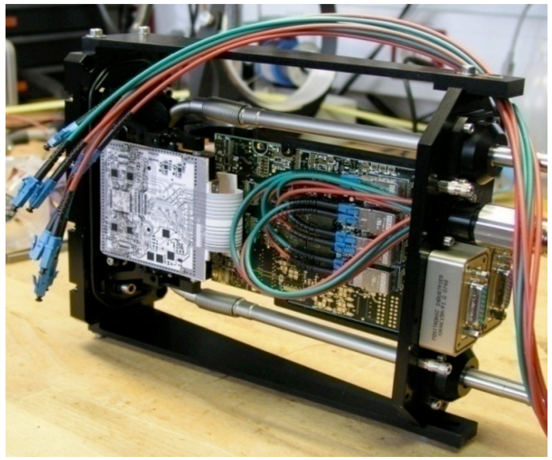
AO detector controllers



FIERA controller with 16 outputs
600Hz; 128x128 pixels

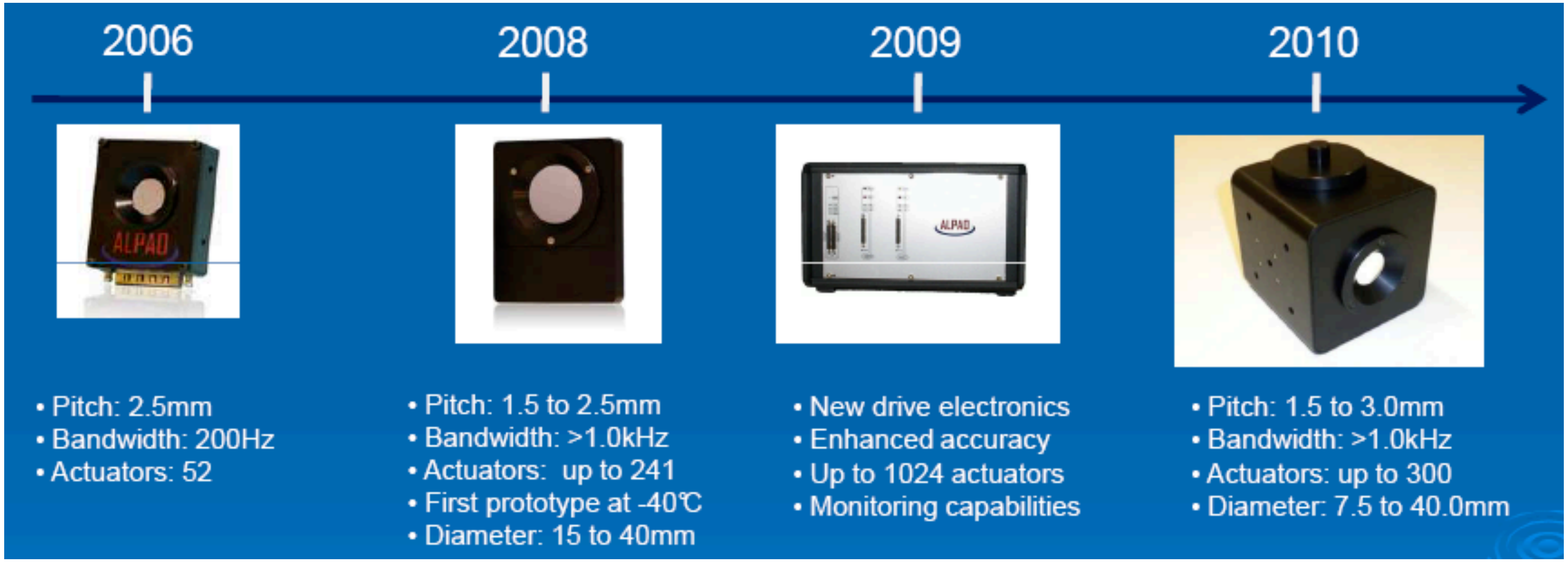


OCAM prototype and ESO NGC controller; 1.2-1.5kHz with 8 outputs; 600Hz; 128x128 pixels

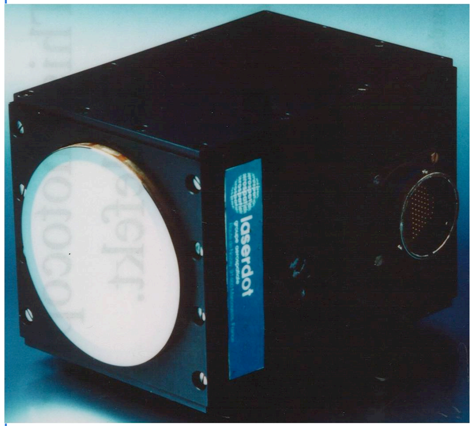


Electromagnetic DM

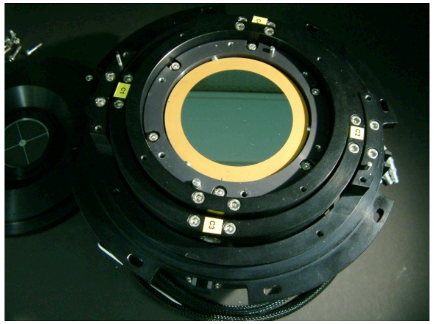
- Technology partially funded by OPTICON-JRA1 & ESO
- Large mechanical stroke: 50 microns
- Next step: 64x64 act. DM with surface position control



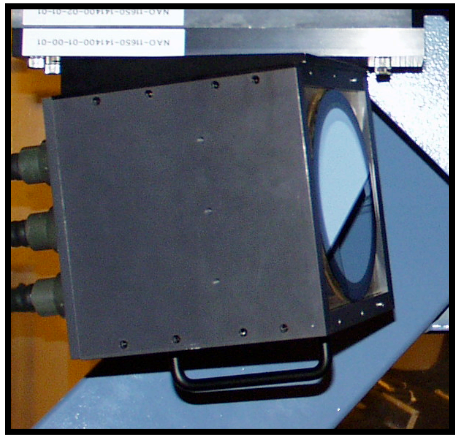
Development of Piezo DM technology



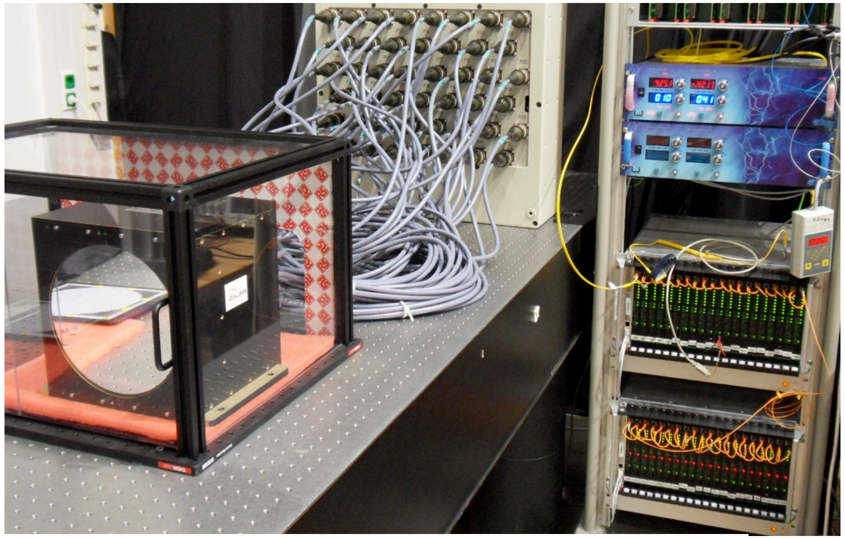
52 actuator piezo DM
COME-ON-PLUS



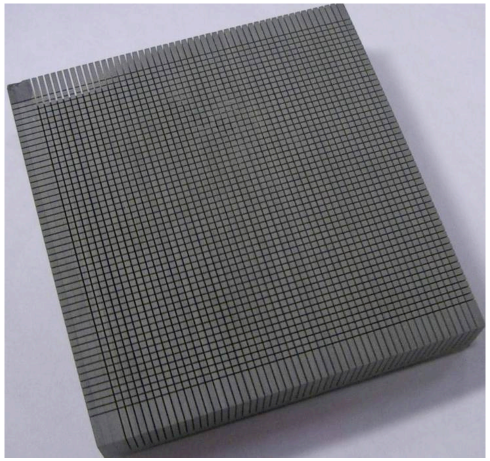
60 actuator bimorph
piezo DM: MACAO



189 act. Piezo DM for NAOS



1377 act. Piezo DM for SPHERE
with its drive electronics



50x50 actuator matrix of
1mm pitch

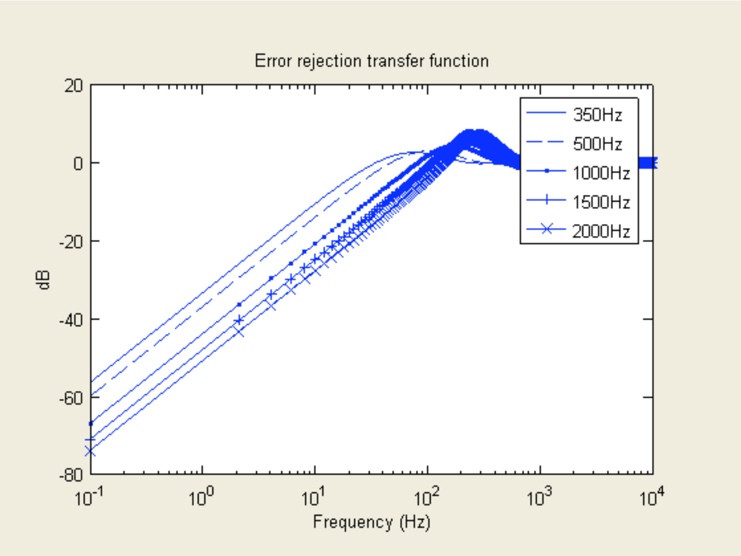
Adaptive Optics Time Constant

- How fast an AO control loop need to be?
  - Quick answer: the faster the better
  - Detailed answer: Even an infinitely fine mirror (infinite number of actuators) and a perfect measurement of the wavefront sensor would not be enough because the atmosphere evolves. The coherence time of the atmosphere is:

$$\tau_0 = 0.31 \frac{r_0}{\bar{v}}$$

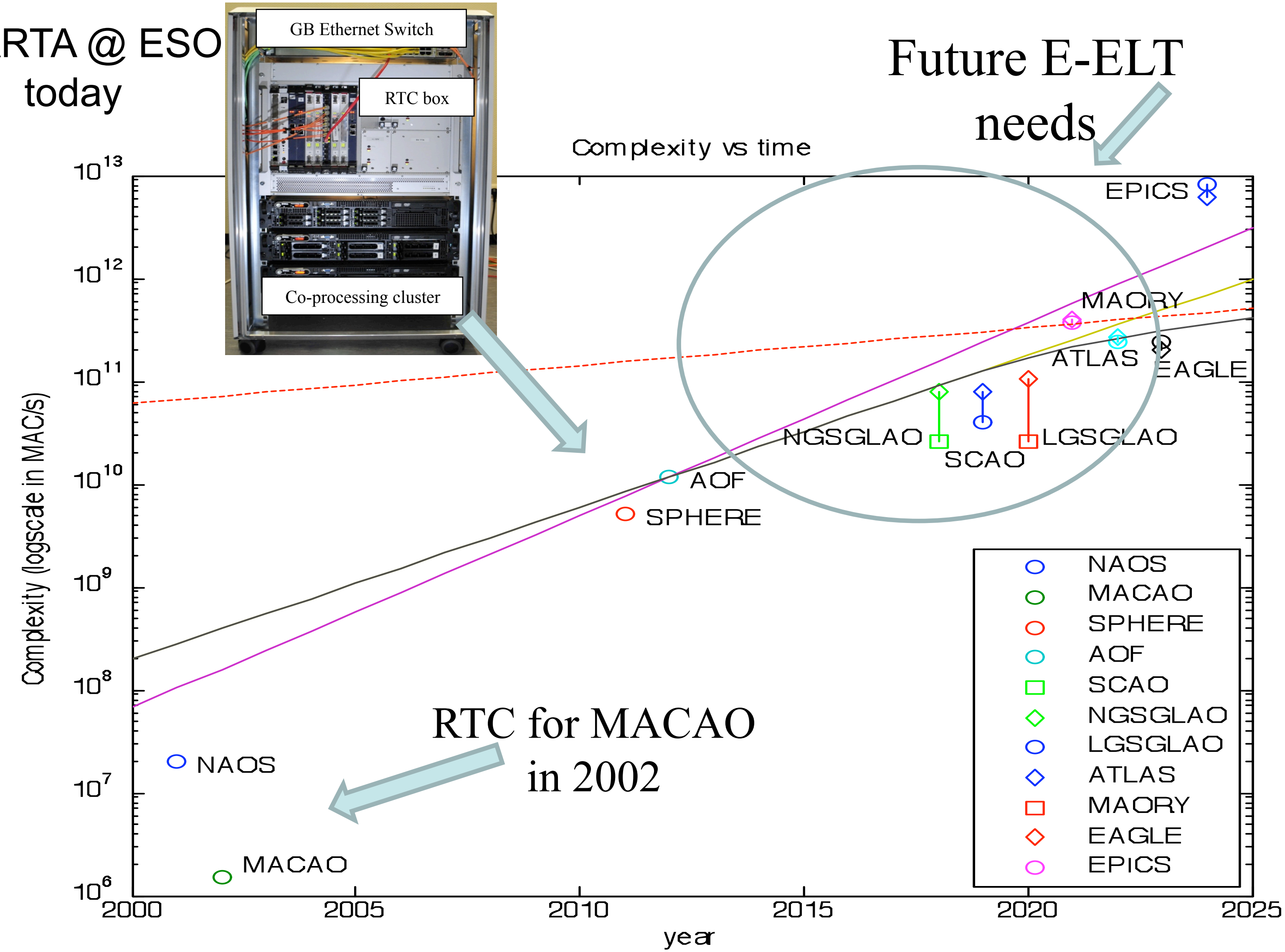
and it is between 1 and 4 milliseconds. Therefore an update rate of 500Hz to 2KHz is required.

  - Faster loops are needed for special applications like planet finders: running faster allows for correcting more details since the "error rejection transfer function" removes more errors.



Real Time Computer/control

SPARTA @ ESO today

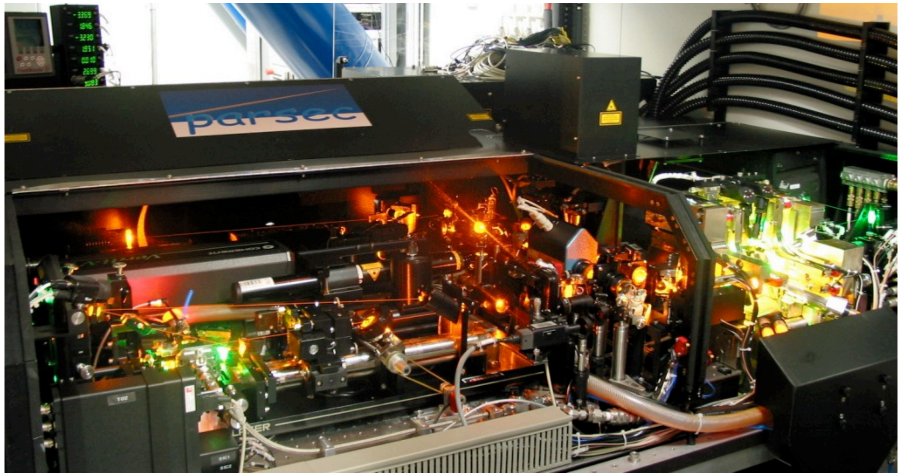


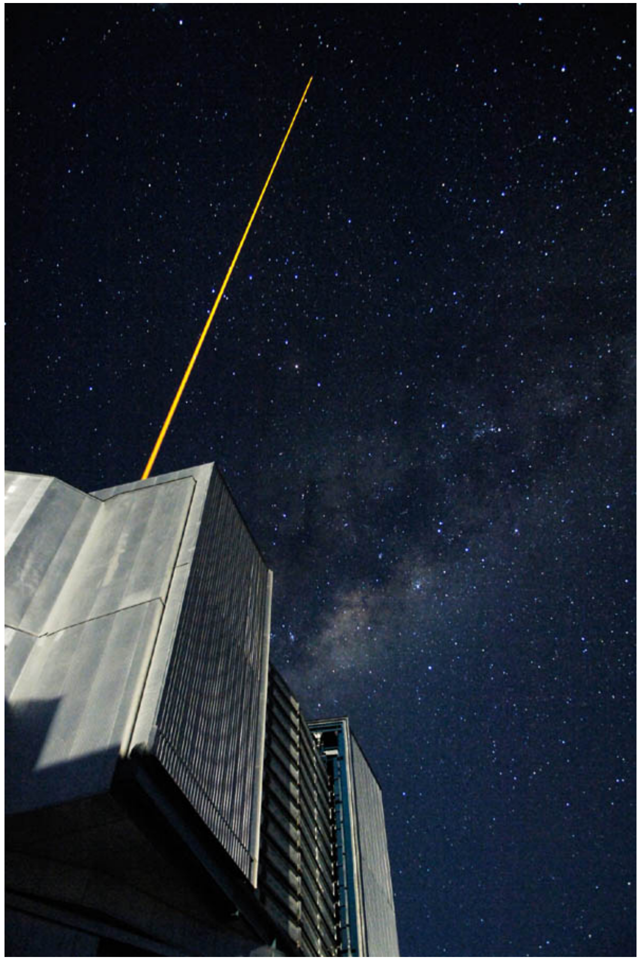
Laser Guide Star Facility

- ESO has also developed and deployed Laser Guide Stars projectors on the VLT, to study novel LGS-AO sensing schemes and to pursue related technologies. The, by now classical approach, is to use a narrow-line laser emitting at a sodium resonance line wavelength to create a yellow artificial “star” in the ~ 95 km altitude sodium cloud around the Earth. When working with an Adaptive Optics system, this beacon provides a bright reference source to correct atmospheric turbulence in real time in fields devoid of bright enough natural stars; note however that a moderately bright natural star is still needed to correct global image motion in the field.
- The ESO first LGSF was installed in Paranal on the VLT Unit Telescope #4 (Yepun) in 2005. It uses the PARSEC dye laser developed by MPE-Garching and MPIA-Heidelberg. Two adaptive optics assisted instruments, also installed at Yepun, use that facility, viz. the NACO IR imager and the SINFONI near-IR 3-dimensional spectrometer.

Laser for Adaptive Optics

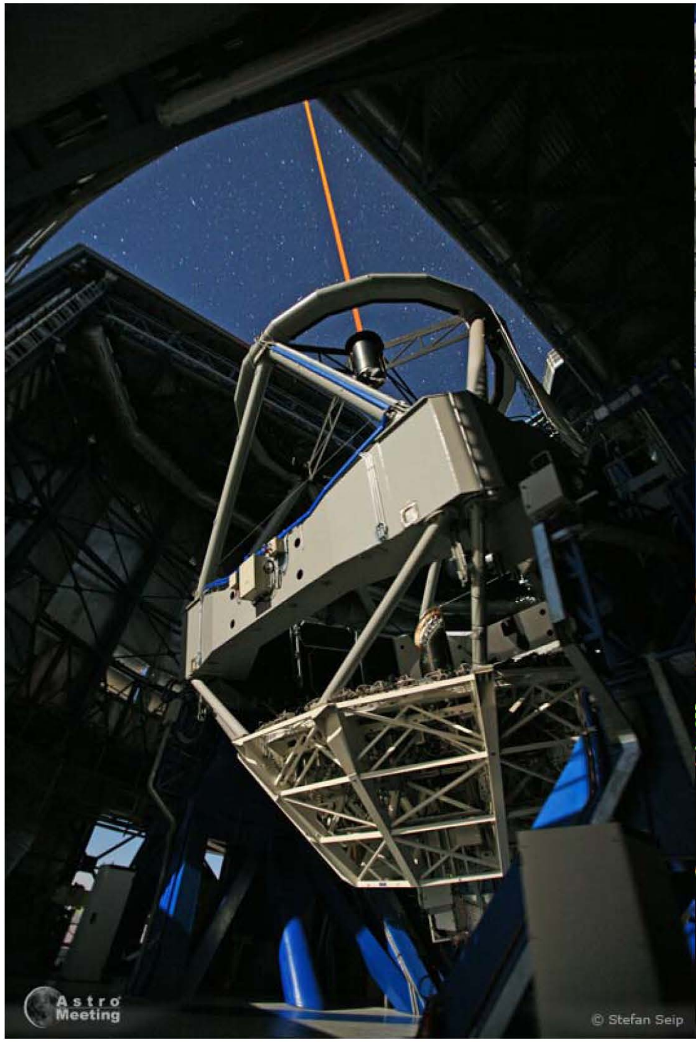
- Laser guide stars are artificial stars generated by exciting atomic sodium in the mesosphere at a height of 90km
- This requires a powerful laser beam launched from the telescope
- The yellow wavelength (589nm) is the colour of a sodium street lamp





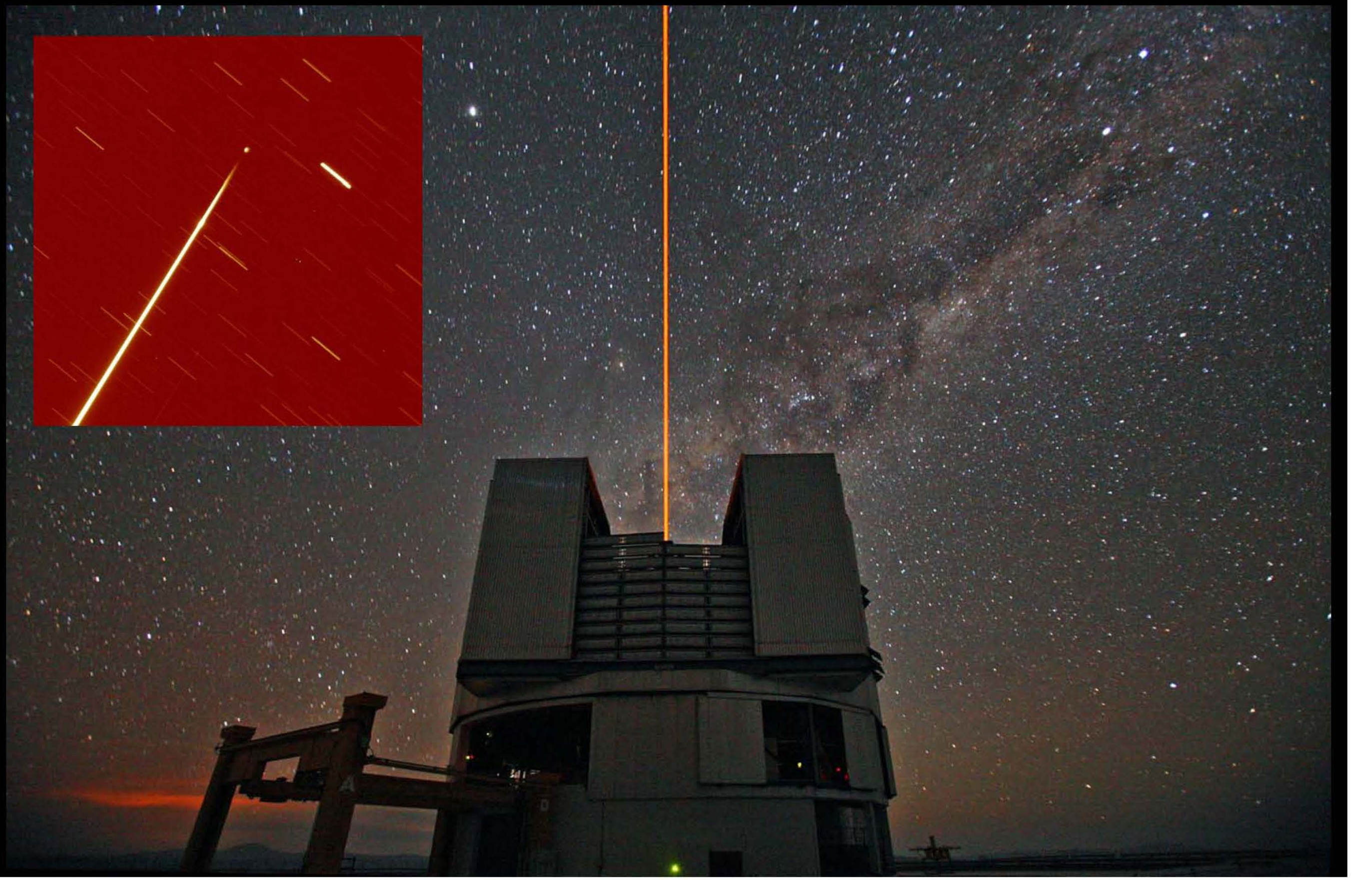
VLT Laser Clean Room

The LGSF at UT4



The VLT LGSF at UT4

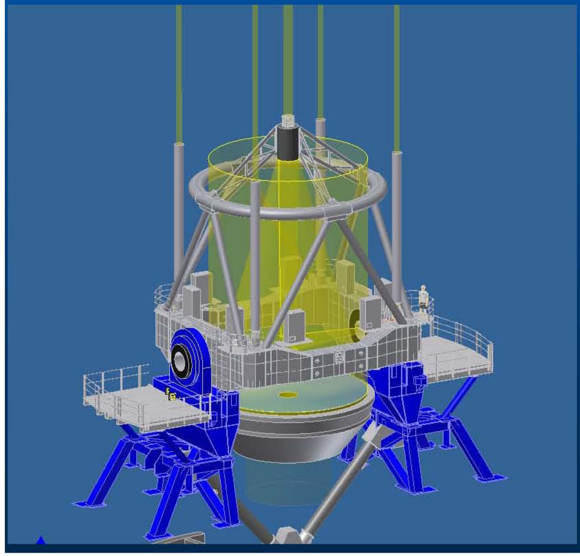
One LGS-AO system is operational at VLT now

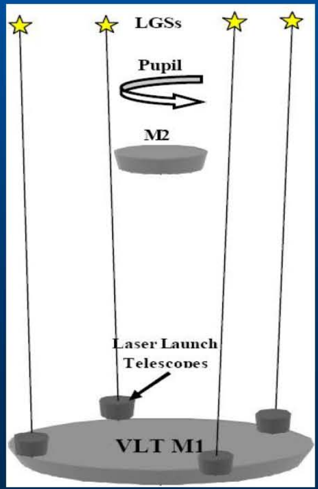


4 Laser Guide Stars Facility

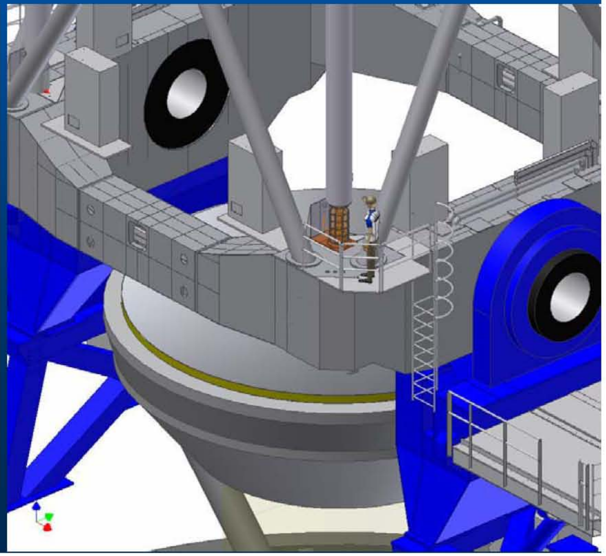
- 4 LGS, off axis up to 330″
- 2.5–5 Mphot/sec/m^2
- LGS FWHM <1.2″ on WFS
- Central LGS also operational

- 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)



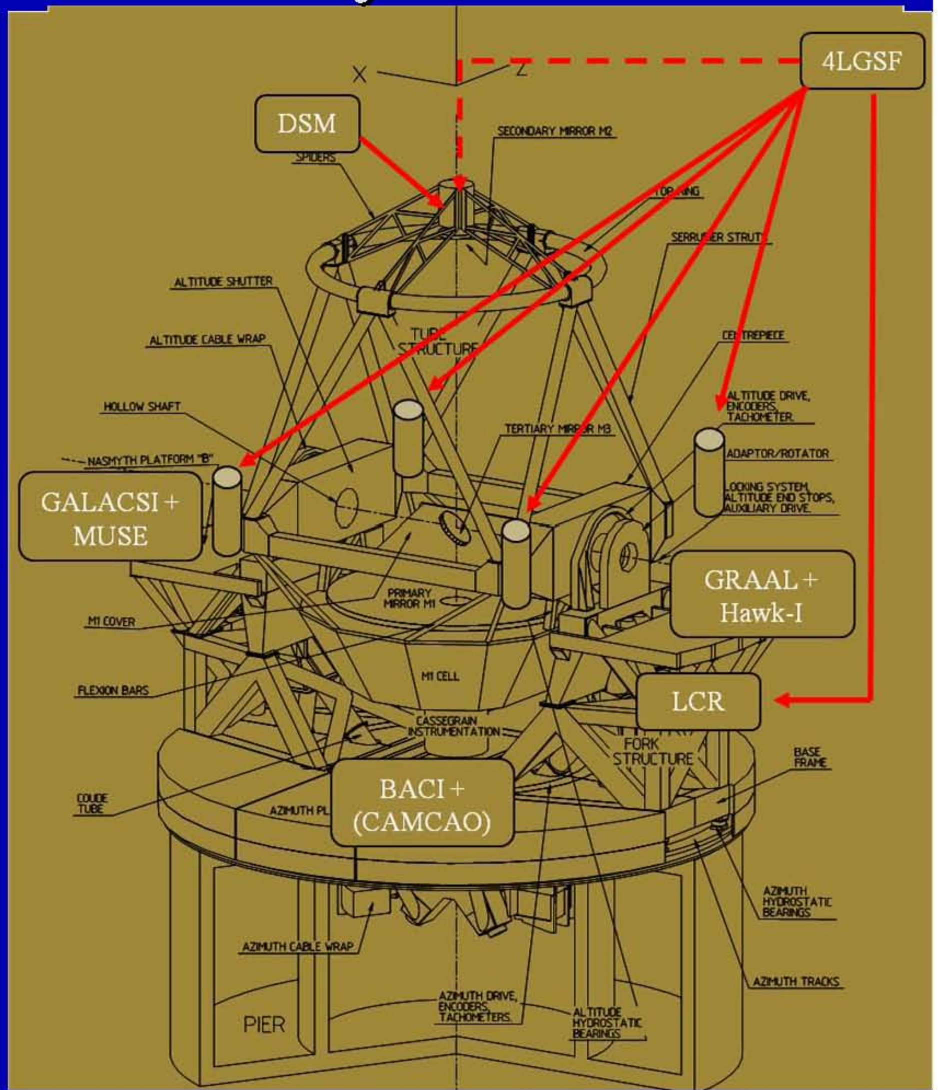


LGS fixed on pupil



VLT AO Facility

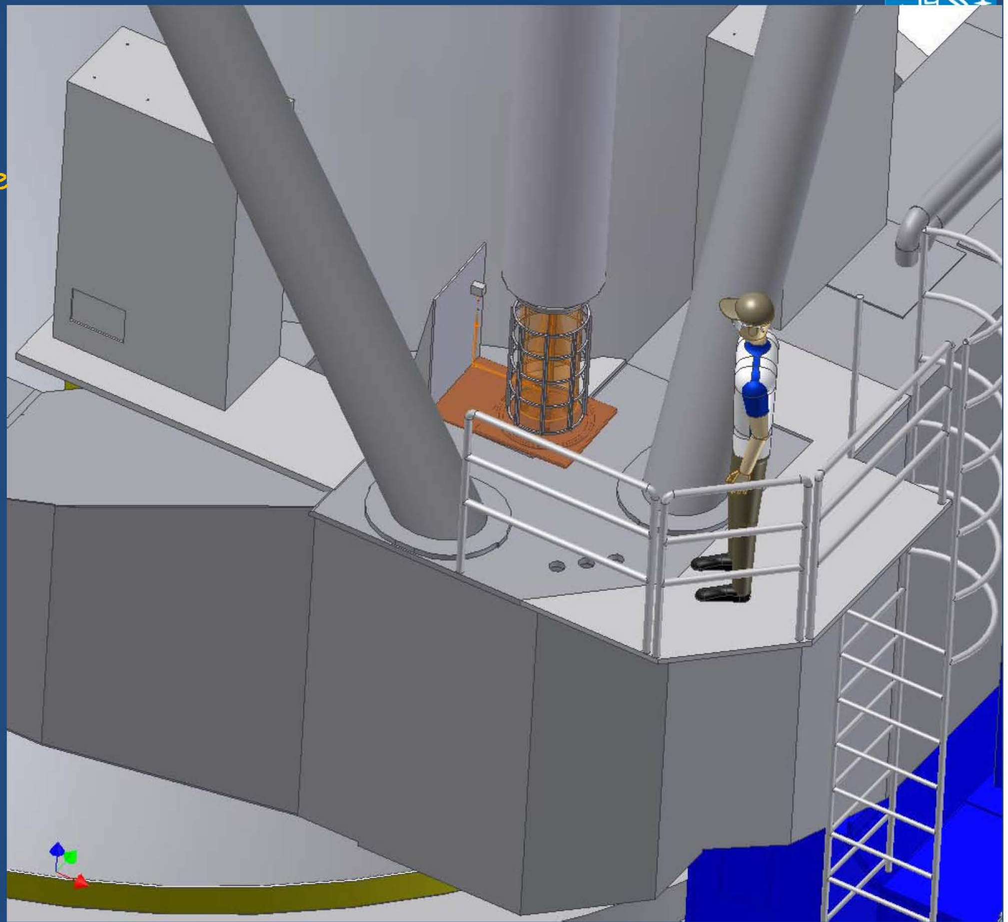
- 1170 actuators in DSM
- GRAAL/Hawk-I 7' FOV imager, 0.1"/pxl, near IR / GLAO correction
- GALACSI/MUSE integral field visible spectrometer. GLAO (60" field) or MCAO (15" field)
- CASIS
- LGS assisted



Launching Telescope of 4LGSF

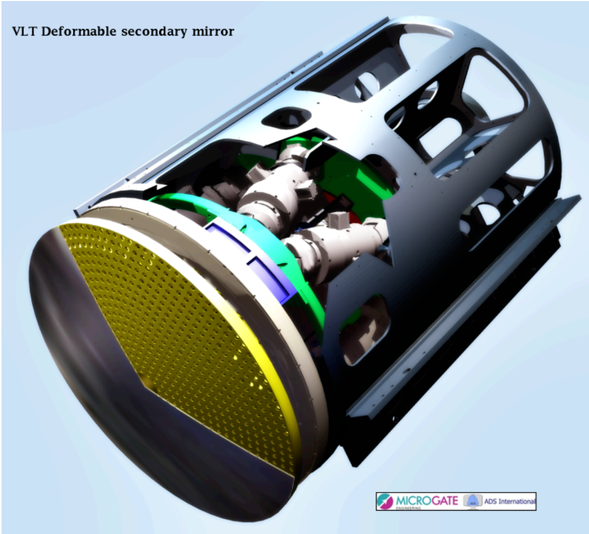
Unique design aspects of 4LGSF:

- Rack-mounted 15-W fiber laser systems in the direct vicinity of each laser launch telescope
- 6' field selection by tilting the 30-cm laser launch telescope
- Shield of scattering up to the top ring
- LTS units modular
- Service mostly in the integration room
- LRU concept for LTS (line replacement)



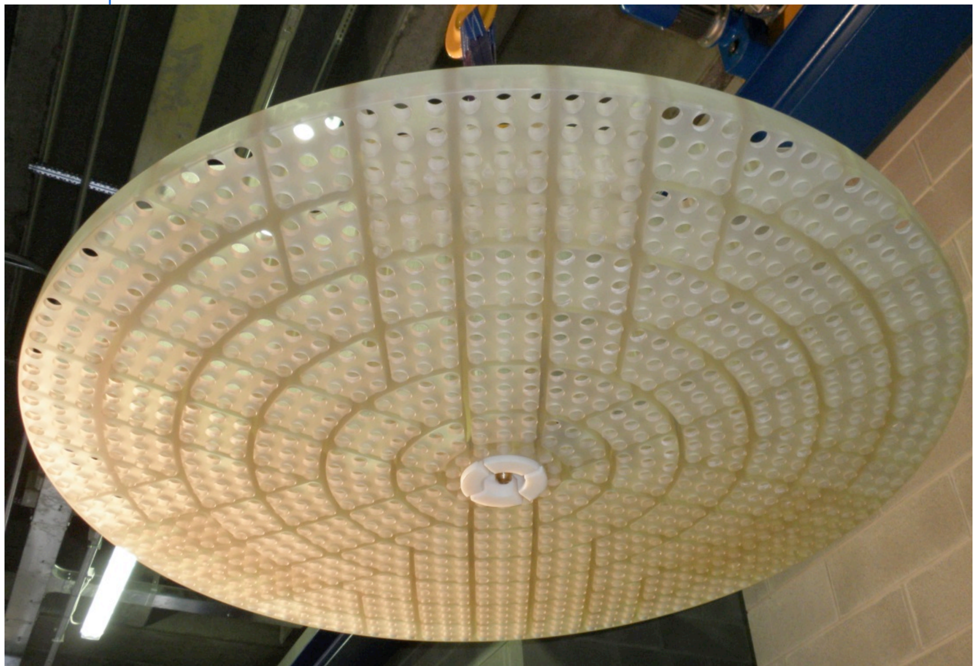
Fiber Laser demo

VLT Deformable Secondary Mirror

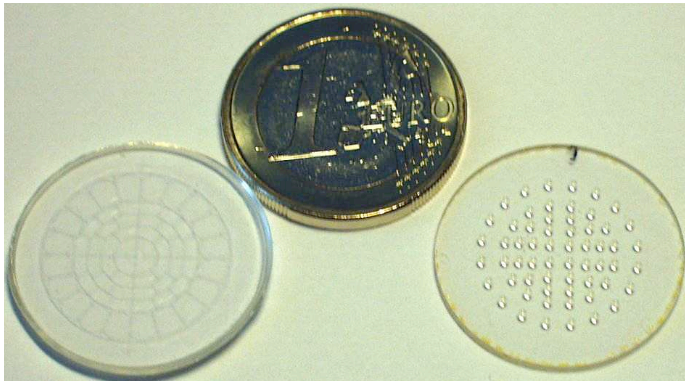


- 1170 actuators
- Shell diameter: 1.12m
- Shell thickness: 1.95mm
- 75 16ch DSP control boards, 3 double-crates
- 150 floating point DSPs, 150 GMACs/s FP
- ✓ EL+Mech components manufacturing completed
- Optical components manufacturing ongoing:
  - SESO → reference body
  - SAGEM → thin shell
- Mechanical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

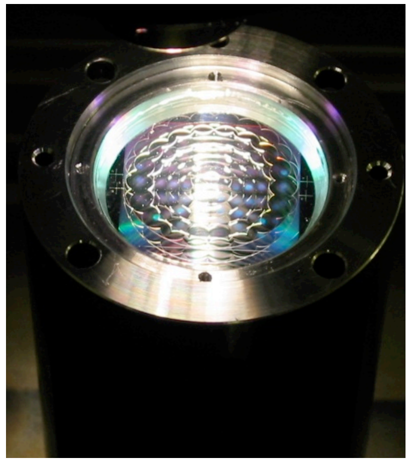
Special optics for AO



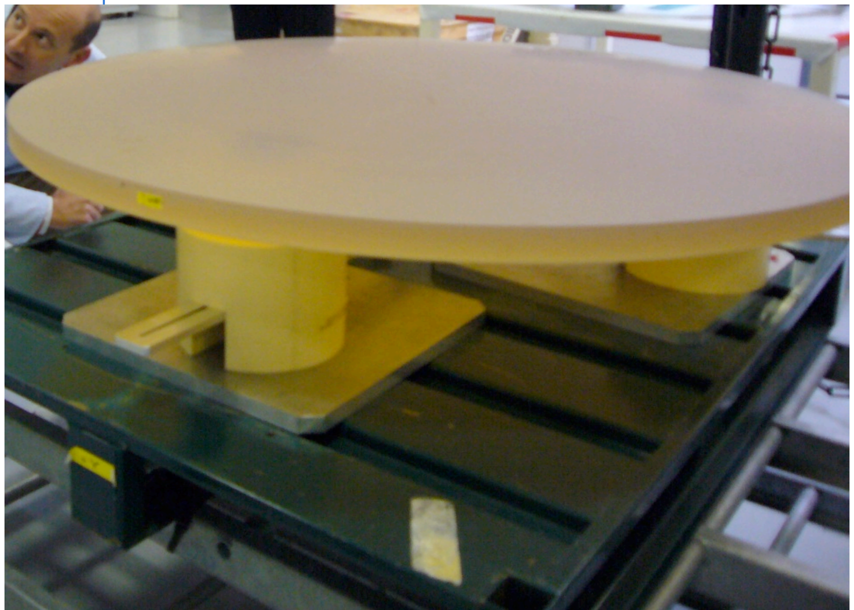
1.1 m light-weighted reference body
for the VLT Deformable secondary mirror



Custom lenslet arrays for MACAO



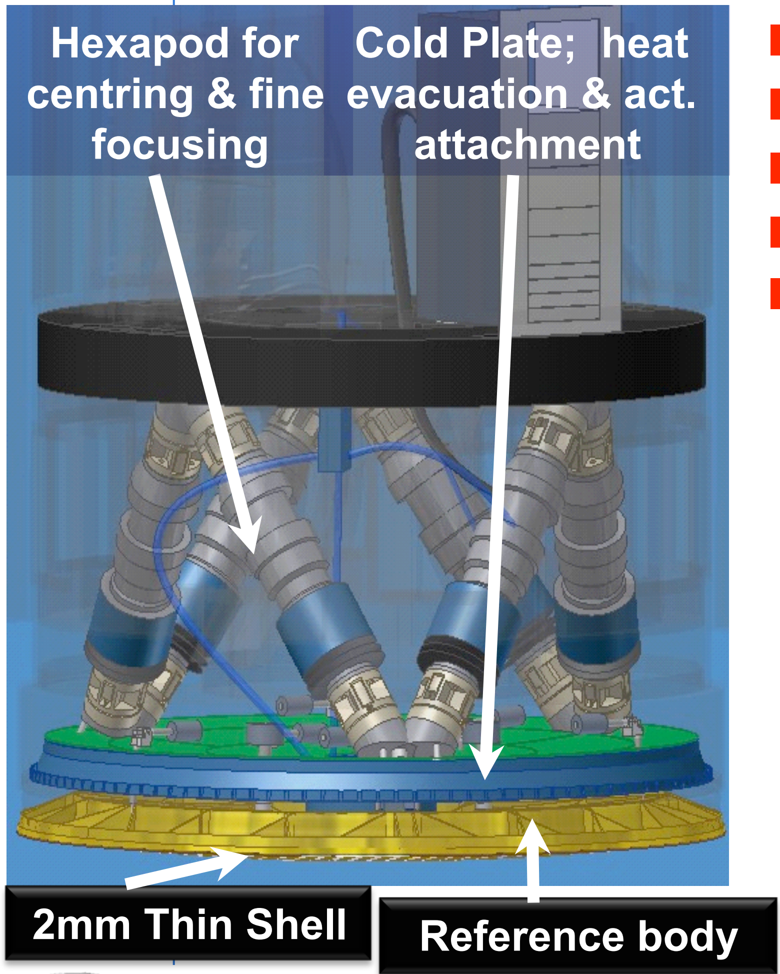
Thin shells



1.1m Zerodur shell, in manufacturing at SAGEM

2.6m glass shell, 2 mm thick at SAGEM

Large Deformable mirrors: from VLT to ELT



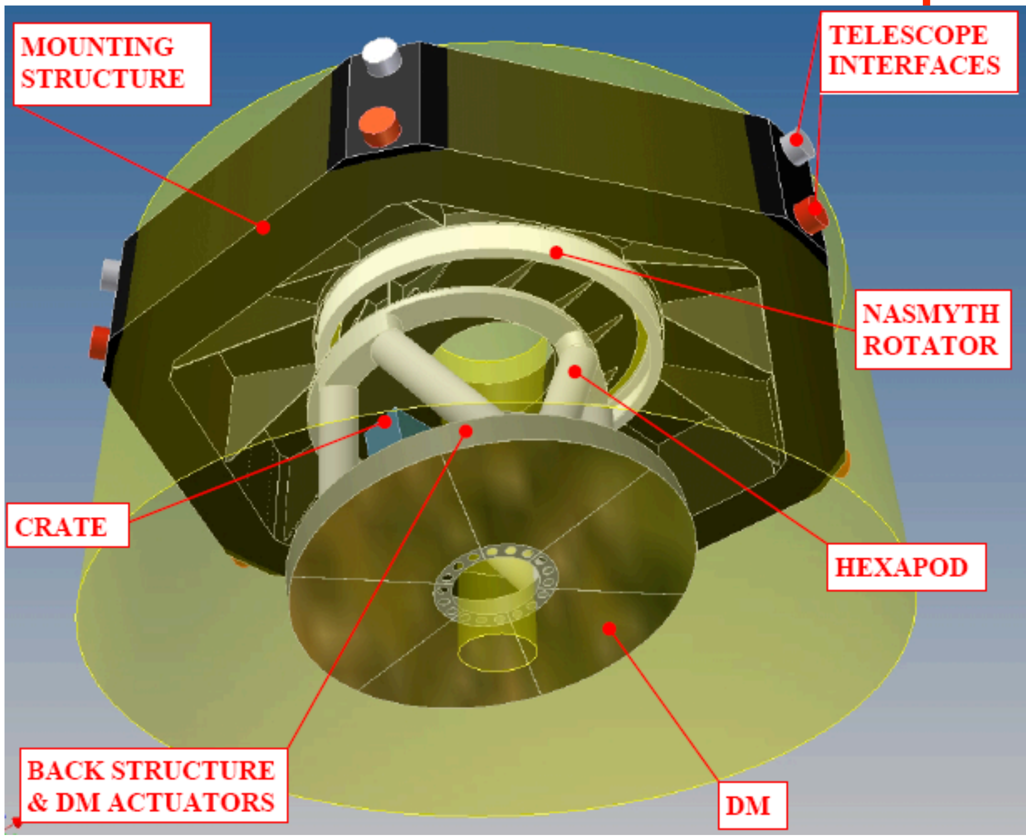
ADS International

VLT Deformable M2

- Ø 1.1m convex
- 1170 actuators
- 29 mm pitch
- 1 ms response
- Stroke 50 / 1.5 μm

ELT voice coilDM

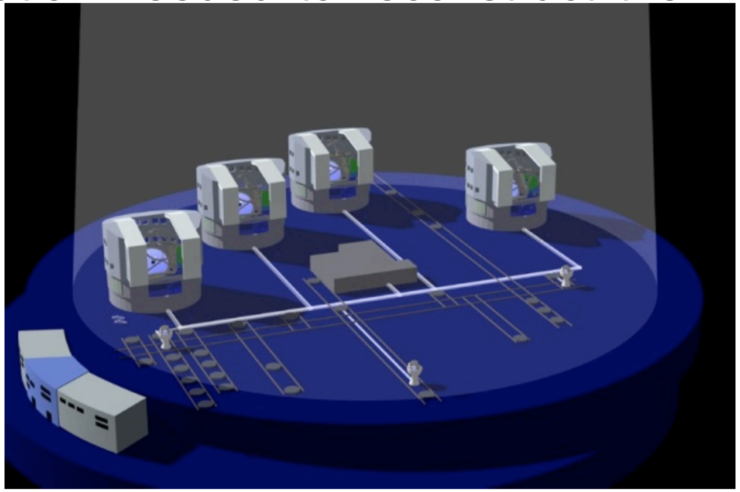
- ~2.6 m flat
- >6000 actuators
- 30 mm pitch
- 0.5ms response
- Stroke 120μm
- Inter act: 2-3μm



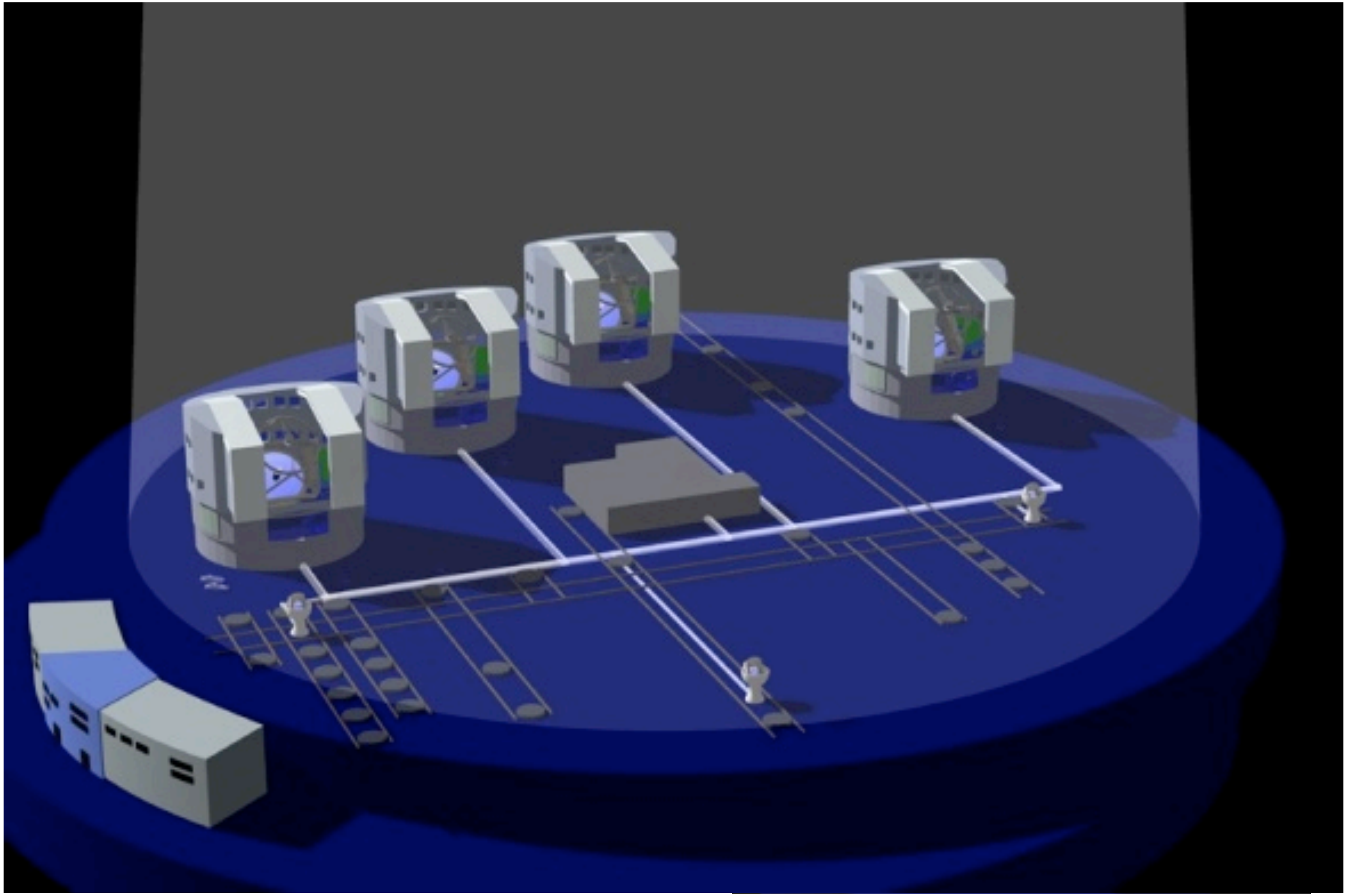
What is the VLTI

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.

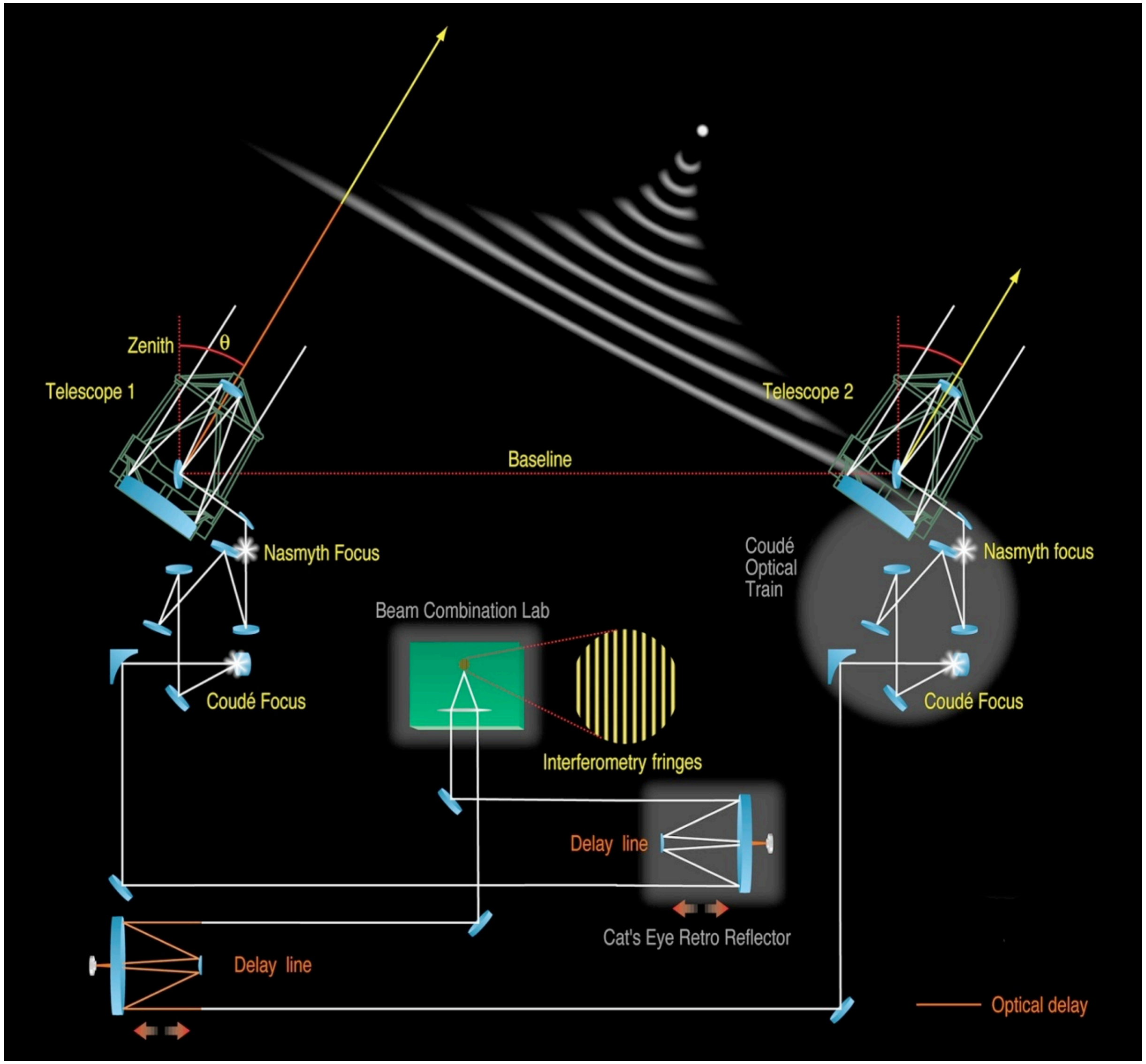
The delay lines help to synchronize the beams, before redirecting them to a central laboratory. The interference fringes produced when the beams are finally recombined provide the information needed to reconstruct the original image in unprecedented detail, giving a picture as sharp as if it had come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



What is the VLTI



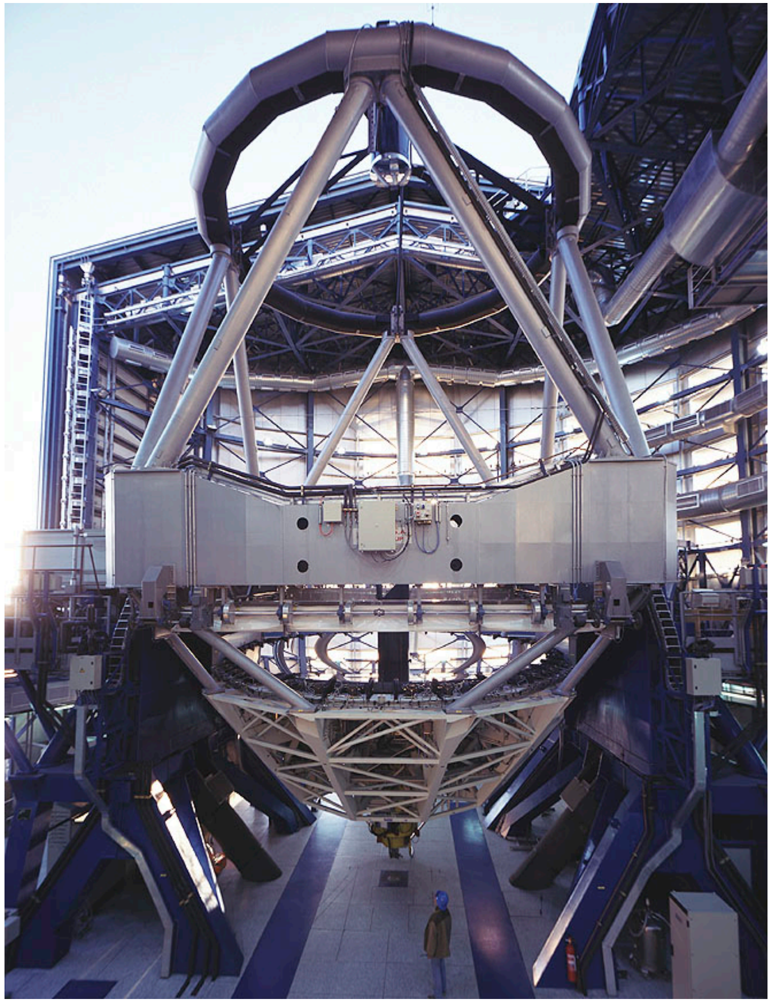
VLTI Scheme - Subsystems



A brief history of VLTI

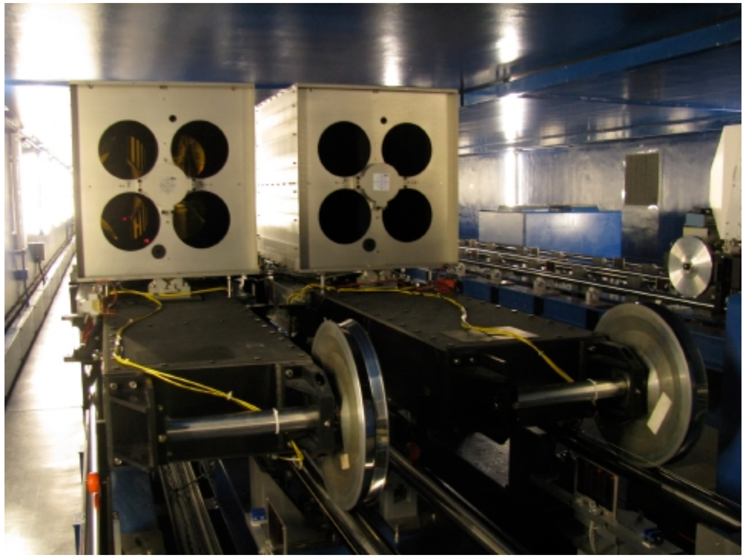
- 1980s - Interferometry integral part of the VLT project, early linear array design for UTs goes to trapezium structure
- Early 1990s - engineering of the general layout
- 1993 - council stalls the VLTI, but infrastructure implementation (light ducts, tunnel, lab) continues
- 1996 - MPG/CNRS/ESO tri-partite agreement for third AT
- 1997 - MIDI and AMBER proposed by community
- 1998 - contracts for ATs and Delay Lines awarded, MIDI and AMBER instruments started
- 2000 - start of implementation on Paranal (siderostats and delay lines)
- March 2001 - first fringes with VINCI on siderostats

The VLTI Telescopes

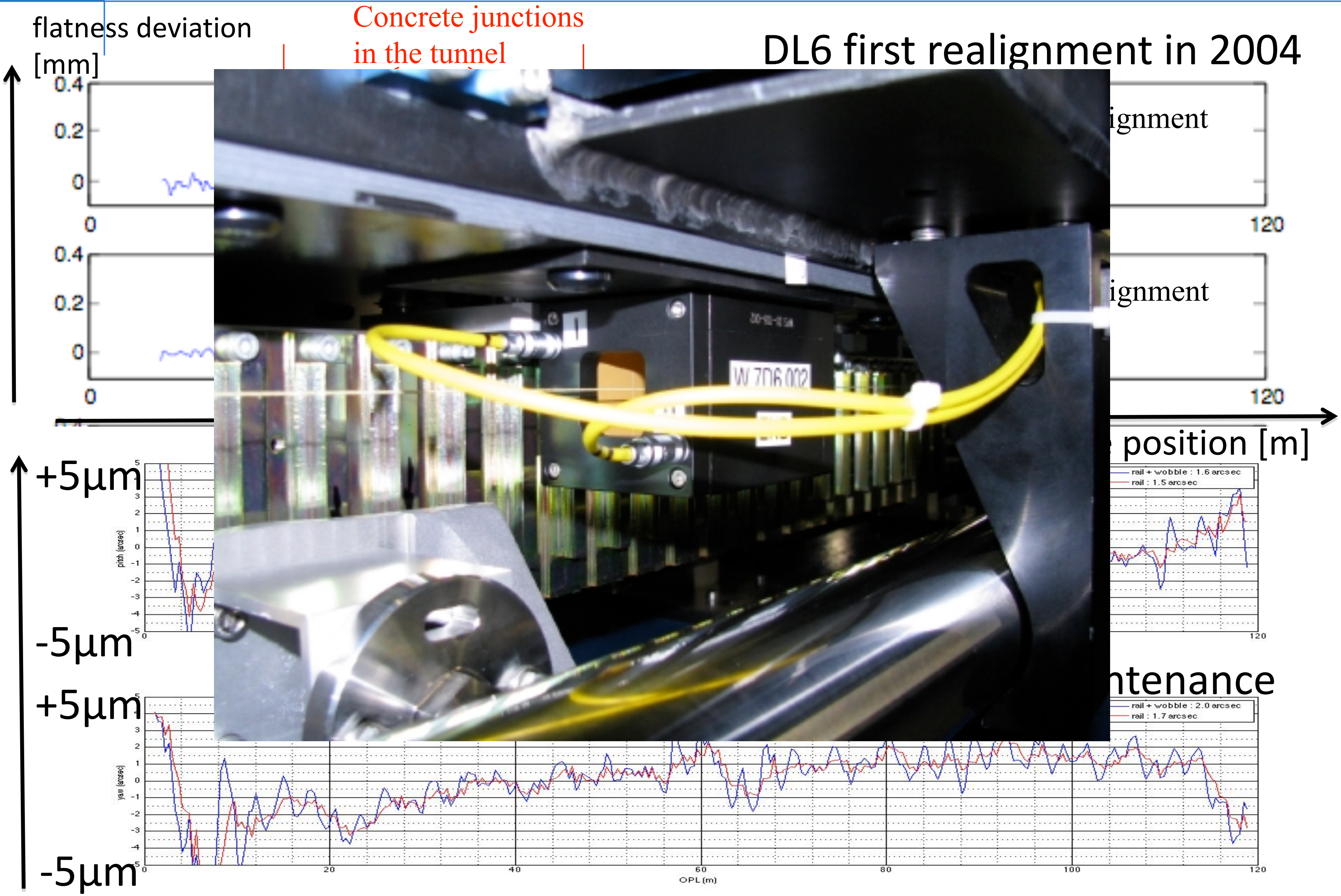


VLTI - Delay Lines (DL)

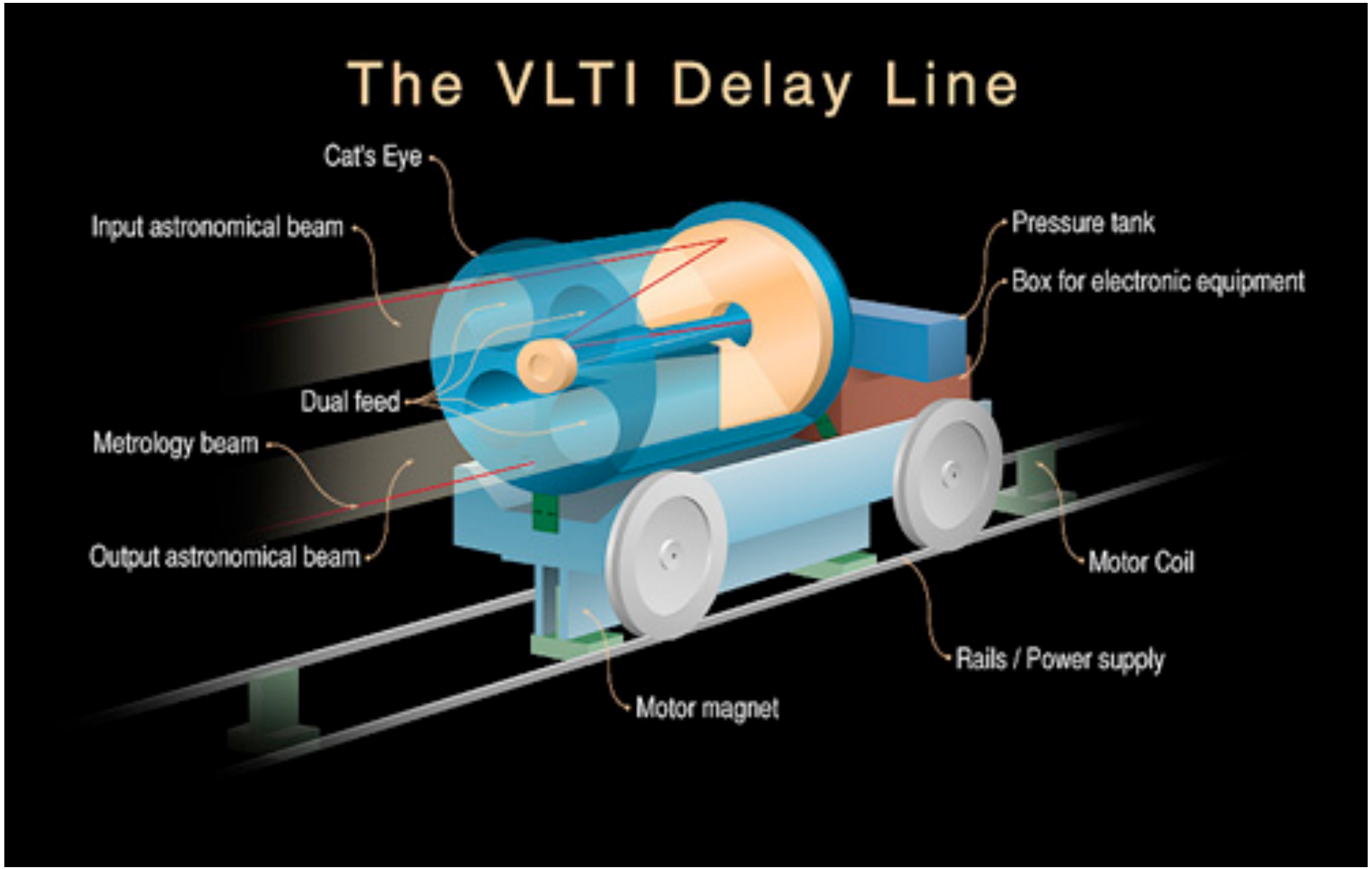
- Compensate for
  - Earth rotation => slow (5mm/s), large amplitude (length=60m)
  - atmospheric turbulence => fast (corrections at > 100Hz) and small (20µm) but with high accuracy (15nm) => needs a laser metrology
- Cat's eye => beams are stable in tip-tilt but not in lateral position =>
  - Rails 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.



Rail maintenance



The ESO VLTI Delay Line

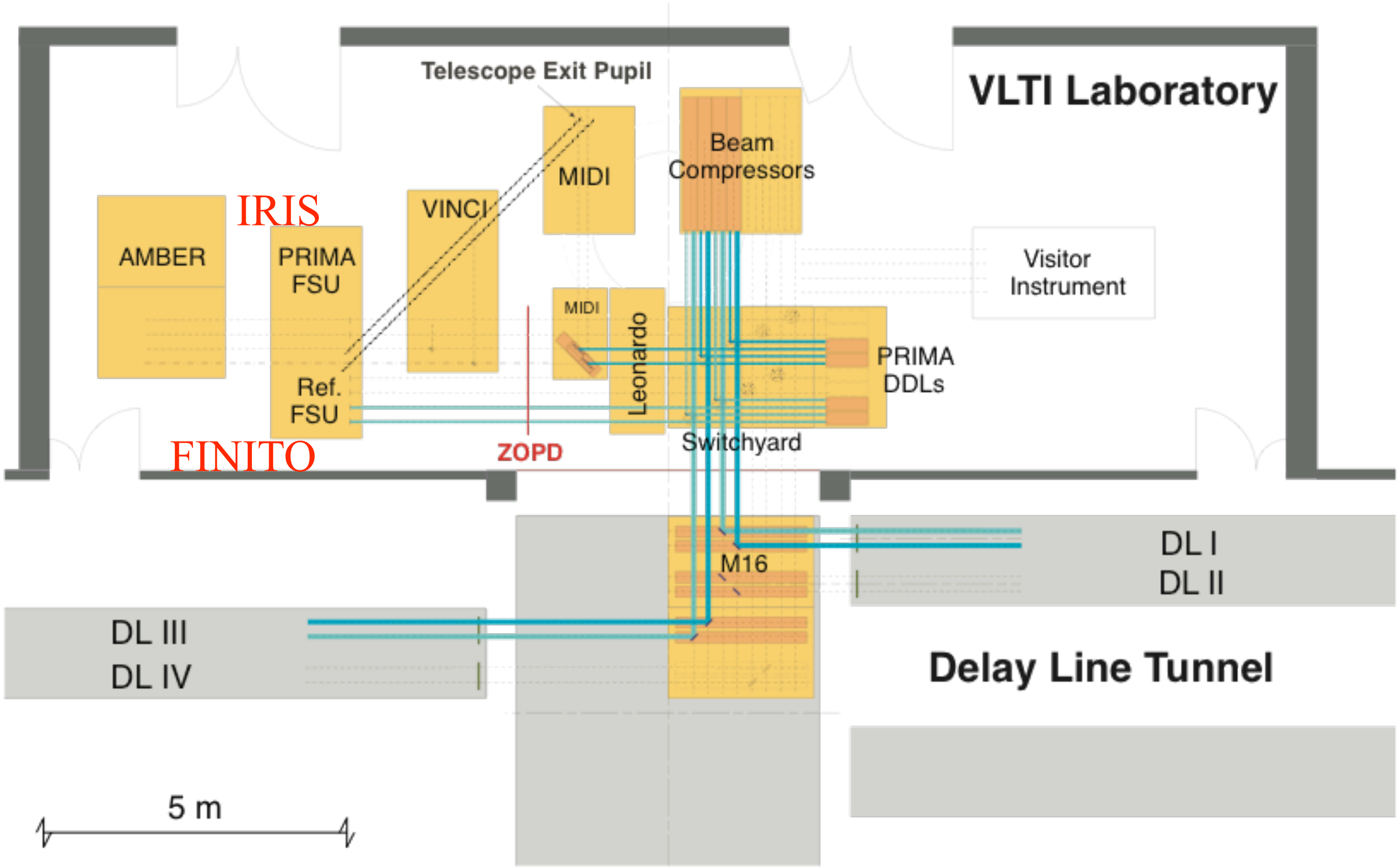


Schematic representation of the VLTI Delay Line, showing the retro-reflector on its moving base.

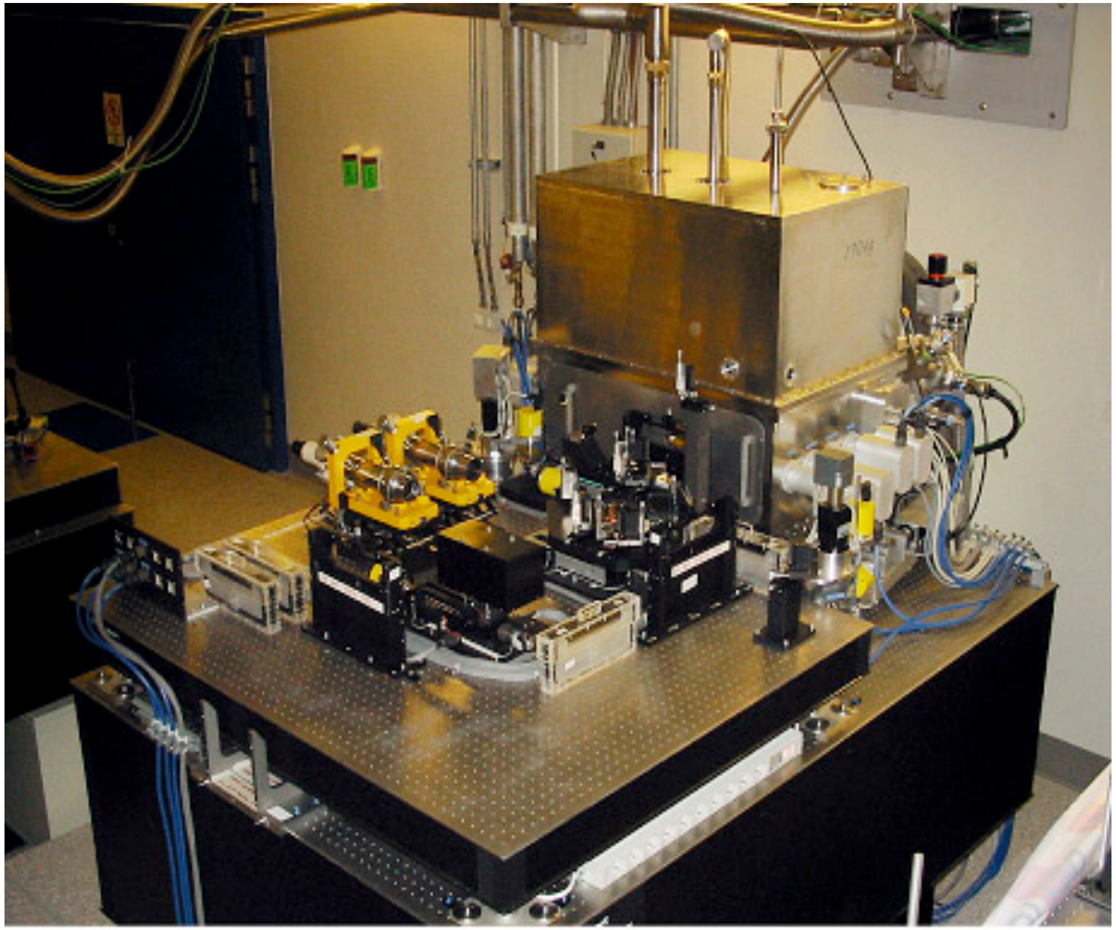
The challenge of VLTI control

- 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

The interferometric laboratory



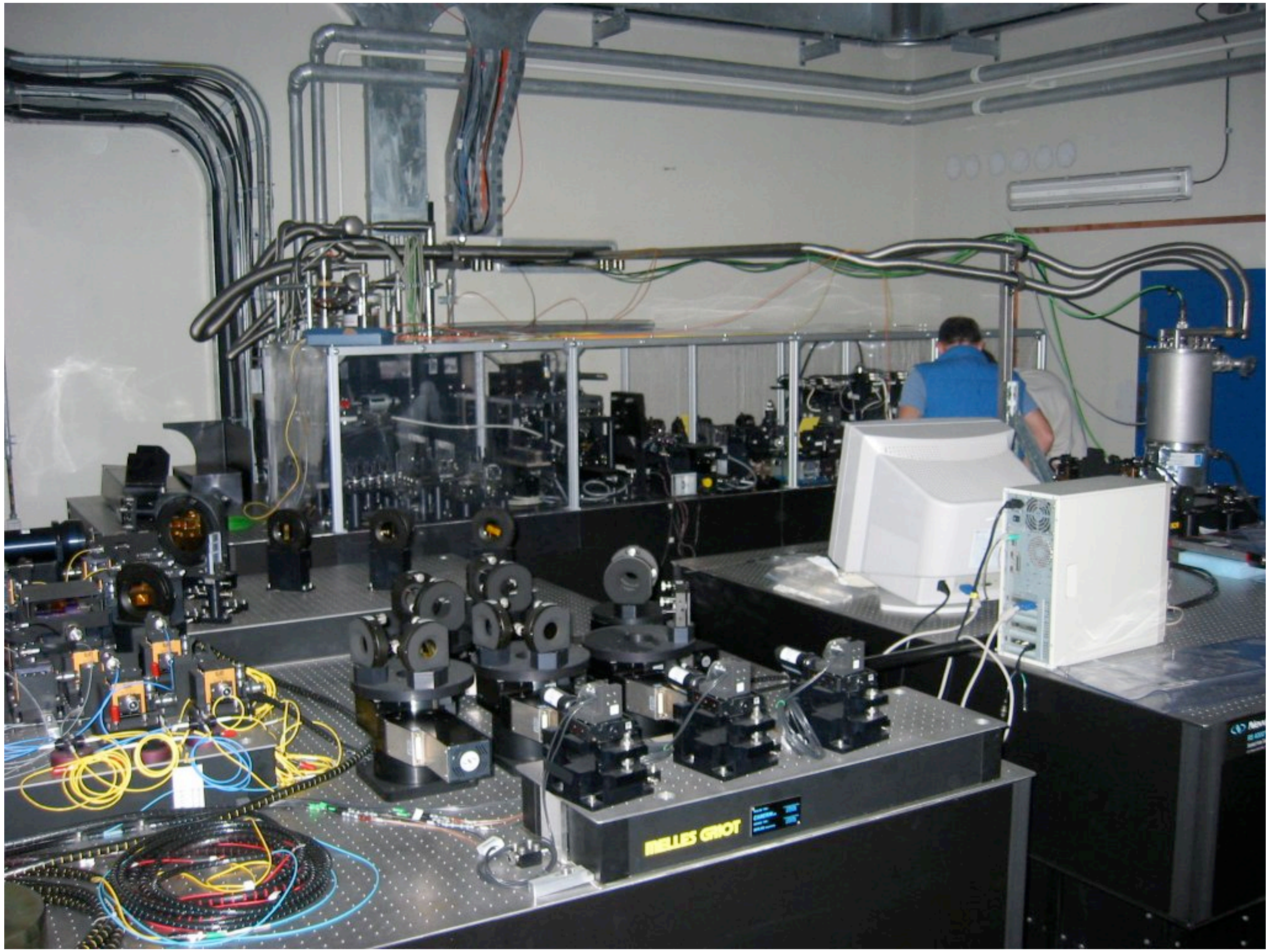
MIDI in the VLTI lab



The MIDI Instrument at the VLT Interferometric Laboratory on Paranal

ESO PR Photo 30c/02 (18 December 2002) ©European Southern Observatory

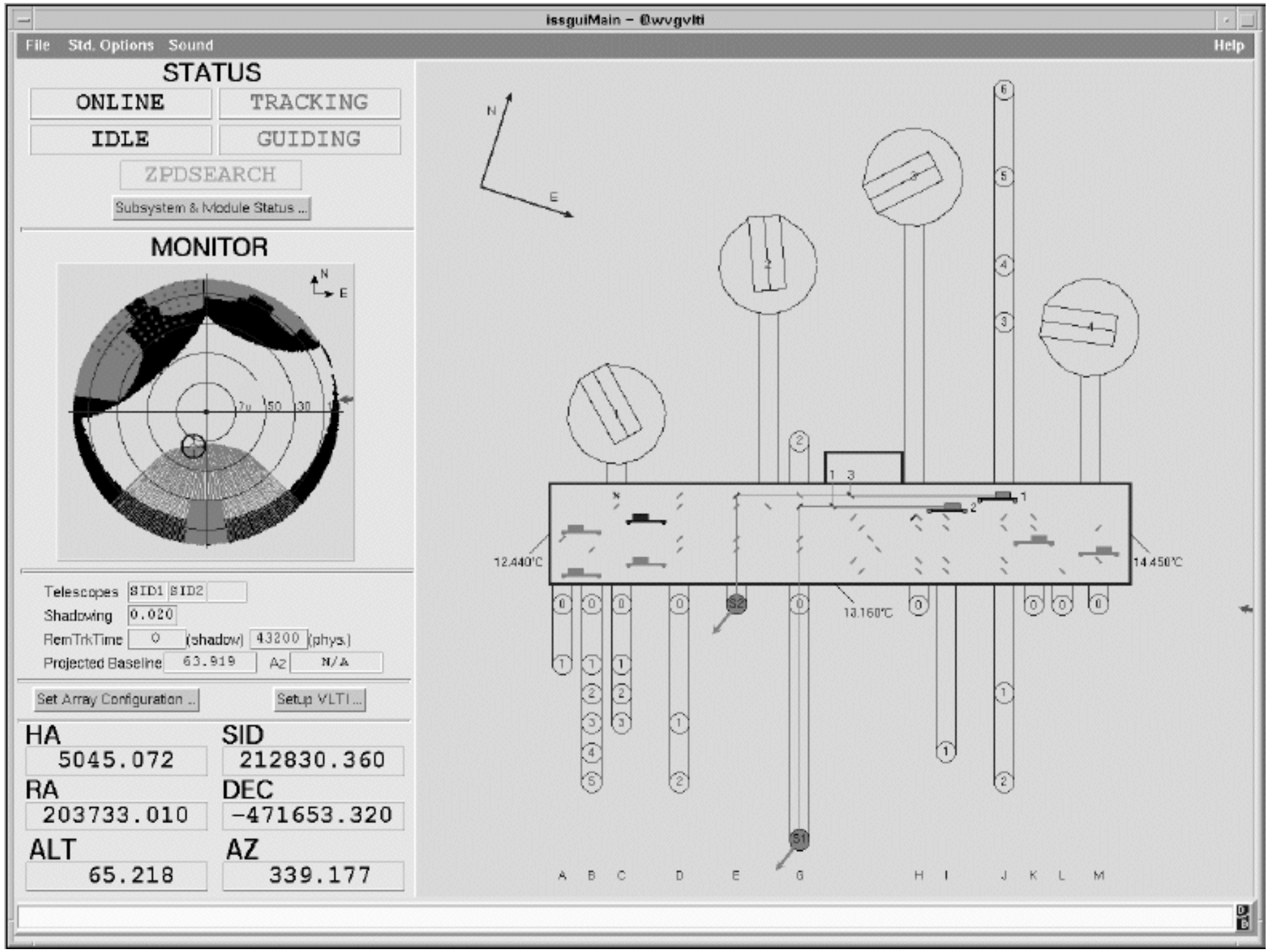
AMBER in the VLTI Lab



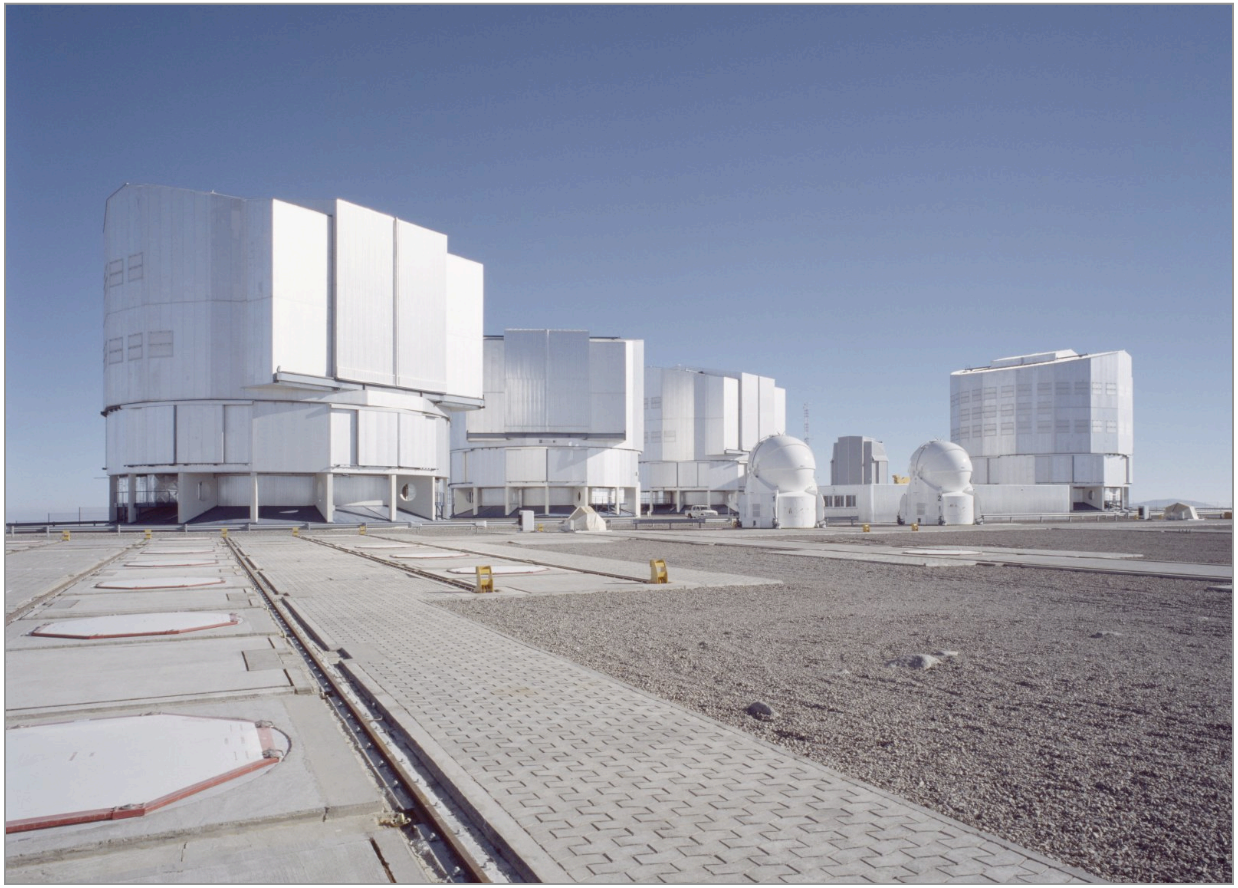
How does VLTI do it?

- Each UT has a MACAO system that concentrates the bulk of the photons within the Airy ring.
- The beam is propagated via the relay optics to the delay lines
- The delay lines correct in 'open loop' geometric OPD (telescope and star locations)
- The VCMs on the delay lines move the pupil in the 'axial' direction.
- IRIS corrects for drifts in the conjugation between the MACAO reference and the lab reference
- FINITO corrects for atmospheric OPD variations through the delay lines

Interferometer Supervisor Software



Further prospects



- Commissioning of PRIMA ongoing
- 2nd gen instruments (MATISSE and Gravity) still in Preliminary Design Phase

VLT – Main axes drive system

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

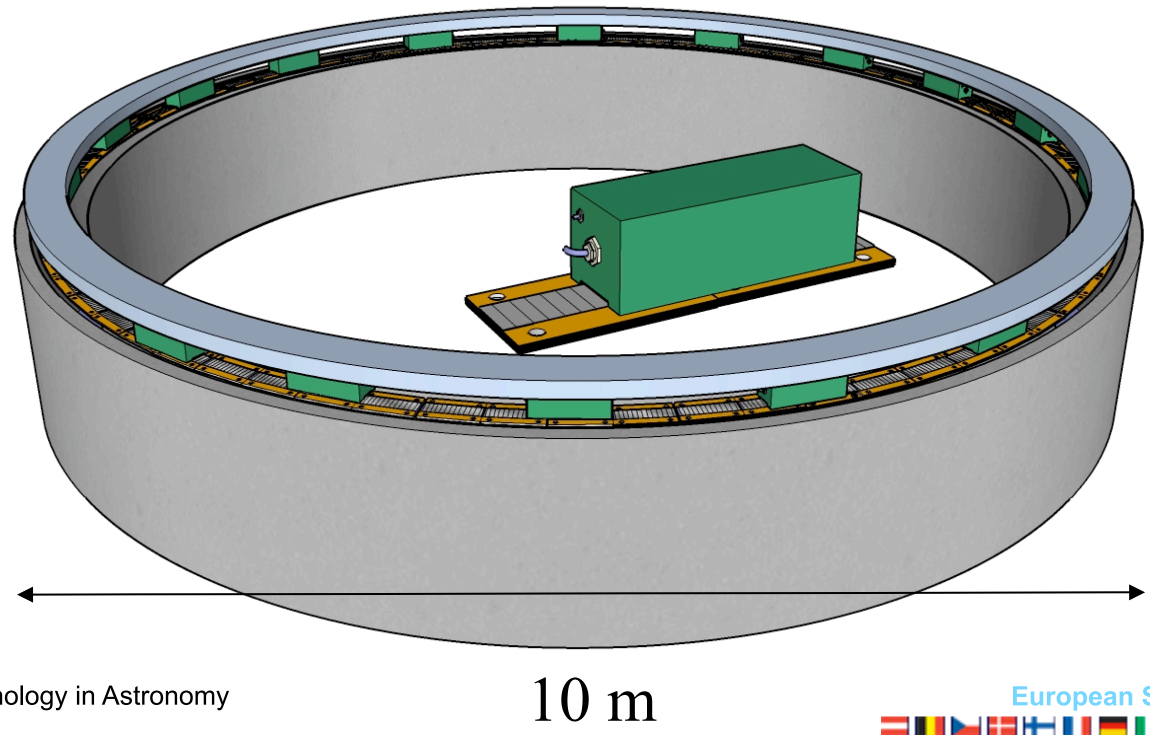
1. Direct drive motors
2. Collocated encoders
3. Hydrostatic bearing system
4. Innovative control algorithms

VLT – Direct drive motors

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

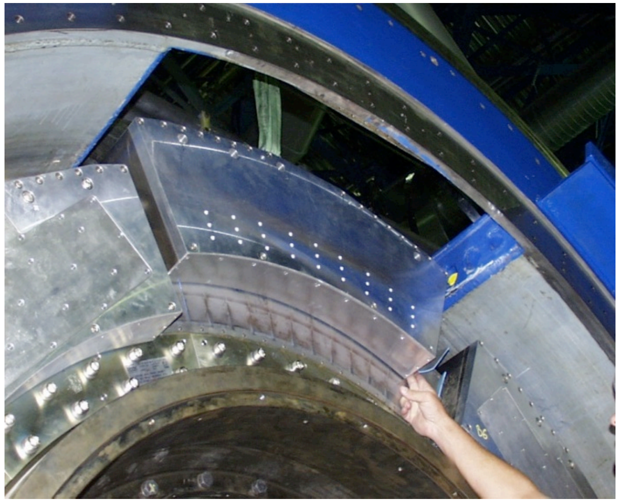
When designed in the beginning of the 1990s, this was a relatively new technology.

Such large motors have to be assembled by segments



VLT – Direct drive motors

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



VLT altitude motor

VLT - encoders

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

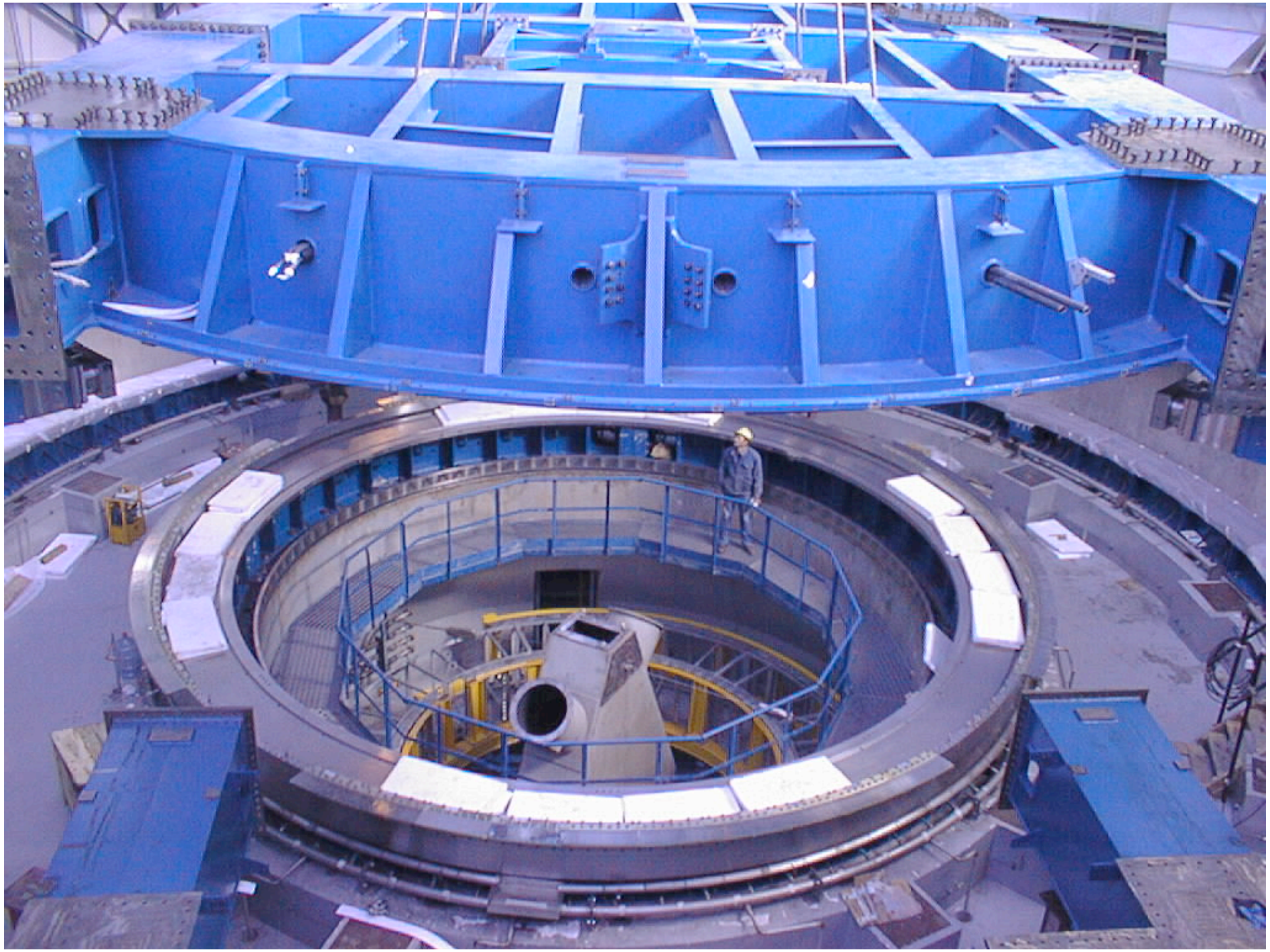
VLT - Hydrostatic bearing system

The VLT main axis use hydrostatic bearing systems.

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

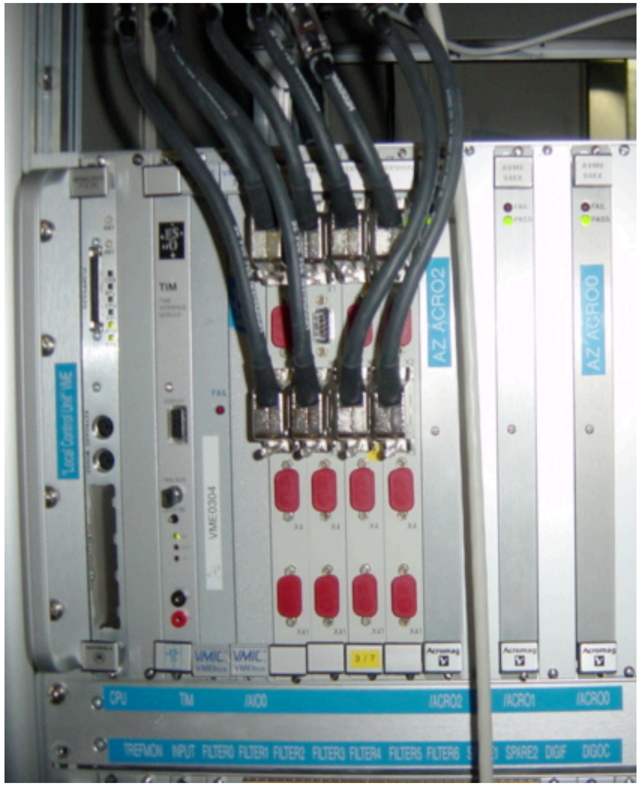
The result is not only very low friction (one person can move it) but also the fact that the absence of stick-slip friction make the system practically linear. Again a huge advantage for the control.

VLT - Hydrostatic bearing system



VLT - Control

First telescope with entire control system implemented in software



Real-time computer platform

High tech drive technology

Thank you !