FOUNDATIONS AND HIGHLIGHTS

The Netherlands plays a prominent and long-standing role in astronomy. This is due in part to the Dutch expertise in systems engineering, precision optomechanics, mechatronics and control engineering. Dutch high-tech engineering companies and research institutes are active in the ongoing developments involved for each step in bringing an electromagnetic signal (photon, radio wave, etc.) from outer space to a detector. This article presents an overview and concludes with a number of highlights.

WOUTER JONKER AND RAMON NAVARRO

"Preserving knowledge is easy. Transferring knowledge is also easy. But making new knowledge is neither easy nor profitable in the short term. Fundamental research proves profitable in the long run, and, as importantly, it is a force that enriches the culture of any society with reason and basic truth."
Ahmed Zewali, winner of the Nobel Prize in Chemistry (1999)

Introduction

The development of instruments for astronomy is an inspiring subject where science and society meet engineering and business. The science of astronomy addresses important societal topics, seeking to address big questions about our understanding of the Universe and our place in it, such as the hunt for exoplanets where life might be possible. It fosters international collaboration and advances human knowledge in the broad sense.

At the same time, it offers goals for the high-tech industry: astronomy requires the development of optical and optomechanical instruments for ultimate precision, which boosts the expertise of the involved companies, creating visibility on the world stage and offering potential for series production. The development of such instruments brings deep technical knowledge and conceptual solutions that also find their application in neighbouring domains such as aerospace, optical satellite communication, medical instruments, defence and ICT.

For such a relatively small country, the Netherlands plays a prominent and long-standing role in astronomy (Figure 1). Dutch inventors and astronomers are credited with such achievements as: the invention of the microscope and the telescope; the discovery of Saturn's rings and its largest moon, Titan, and the Oort Cloud and Kuiper Belt structures in the solar system; finding the first hints of the existence of dark matter; and major new insights in cosmology. Frits Zernike was awarded the Nobel prize in the field of Optics and, as recently as 2018, Dutch astronomer Ewine van Dishoeck won the prestigious Norwegian Kavli Prize for astrophysics for her work on the origin of stars and planets (Figure 2).


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Professor Jan Hendrik Oort, the Dutch pioneer in the field of radio astronomy, and H.M. Queen Juliana at the opening of the radio telescope in Dwingeloo (NL) in 1956. (Image credit: Oort archives)

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Professor Ewine van Dishoeck receiving the Kavli Prize for astrophysics from H.M. King Harald V of Norway. (Image credit: Fredrik Hagen / NTB scanpix)

The Dutch precision engineering industry is solidly world class in areas of expertise such as systems engineering, precision optomechanics, mechatronics and control engineering. As it stands, the Netherlands is ideally positioned to both benefit from, and contribute to, the science of astronomy (Figure 3).

From starlight to signals

In its path from outer space to a photon detector in a telescope, light is reflected off several optical surfaces to collect it and bring it into focus. The blurring effect of the atmosphere is corrected before the light is fed into the main science instruments that measure the desired properties. Dutch high-tech engineering companies and research institutes are active with the ongoing developments for each of these steps. Below is a quick overview of the steps in going from starlight to signals, followed by a few illustrative highlights.

Mirrors and support structures

The first component that starlight encounters in a big astronomical telescope is the primary mirror. Polished and finished down to an accuracy of single-digit nanometers, the mirrors are kept in that near-perfect shape using statically determined mirror support structures. Active mechanisms in these can compensate for the known, relatively slow effects of the temperature gradients that occur throughout the night, and for the changing gravity vector as the telescope pointing angle varies between horizon and zenith. The largest modern telescopes (Figure 4) have segmented primary mirrors, while the secondary, tertiary and further mirrors in the optical train can also be actively positioned, pointed and often 'warped'.

Turbulence

The only remaining significant disturbances to the image then come from outside the observatory dome, in the form of atmospheric turbulence. Turbulence varies depending on the time of day, the location on Earth and the altitude in the sky. The turbulent mixing of air layers with different temperatures distorts the optical wavefront. The typical distance over which the wavefront can still be considered 'flat' is called the Fried parameter R0 ('R-naught'), which can range from 5 cm on a typical day in the Netherlands to 20 cm on a clear night on Mauna Kea (Hawai'i, USA), one of the world's most favourable observational locations.

A small telescope with a diameter comparable to R0 will always see a more-or-less flat wavefront and so its image will be relatively unaffected. However, a large mirror can fit many times this R0 distance across its diameter. Despite the increased resolution that theoretically comes from having a larger mirror ('diffraction limit'), the practical resolution of a telescope is therefore still limited to that of a ~20-centimeter telescope due to turbulence ('seeing limit').

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The Milky Way rises over the BlackGEM telescope array in La Silla, Chile. A joint project by NOVA (Netherlands Research School for Astronomy), Radboud University (NL) and KU Leuven (Belgium), it is designed to observe the optical counterpart to neutron-star and black-hole mergers. (Image credit: Zdeněk Bardon / ESO).

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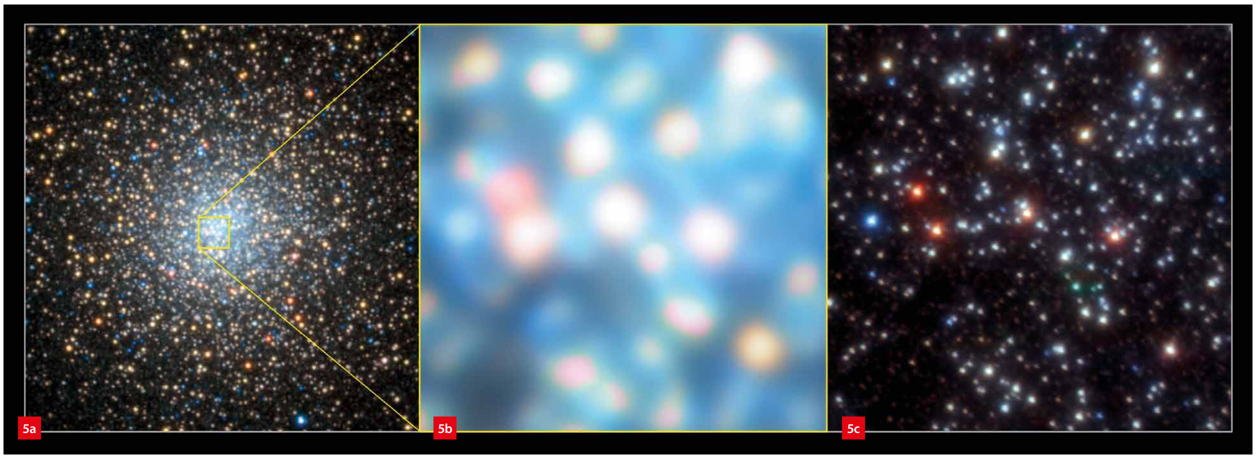
Artist's rendering of the completed Extremely Large Telescope at Cerro Armazones, Chile; red truck for scale. (Image credit: ESO)



The beneficial effect of adaptive optics (AO). (Image credit: ESO)
(a) Image of the globular star cluster NGC6388, taken with the MUSE (Multi Unit Spectroscopic Explore) instrument of the VLT (Very Large Telescope) at Cerro Paranal, Chile.
(a) A zoomed-in section without AO.
(a) The same section with AO engaged.

Wavefront sensing and natural guide stars

The optical effects of turbulence can be measured with a wavefront sensor. To determine the amount of disturbance, the nature of the undisturbed wavefront must be known. In practice this is done by observing a bright star ('guide star') that acts as a beacon/reference. Under ideal conditions, due to their incredible distance, stars are point sources of light. After the image has been distorted by the atmosphere, this is no longer the case, and this distortion of the wavefront can be measured.

One way to do this is to divide the image of a star into many sections using a lenslet array in the pupil plane that focuses the light in many points on a detector array, and then observe how the image from each lenslet shifts in position on the detector. This in turn provides an estimate of how the wavefront can be approximated locally with a tilted plane. The integration of all these locally tilted planes gives a good approximation of the total global wavefront error, and hence of the correction needed to 'flatten' the wavefront and once again show the star as a point source.

Laser guide stars

Most of the world's large telescopes look towards such small portions of the sky that a bright-enough natural guide star is often unavailable in the field of view. In addition, the nature of the atmospheric disturbance varies over the field of view, while measurement of one natural guide star will only provide information on the image distortion in one point.
To solve these problems, astronomers have developed the concept of artificial 'laser guide stars'. Using a laser at a precisely tuned wavelength, it is possible to excite the sodium atoms in the upper layer of the atmosphere at 90 km altitude. The laser kicks the electrons in the outer electron shell to a higher energy state, and as they fall back to their ground state, they emit a photon. By focusing the laser on a small enough spot, it is possible to create a near-point source of light that can act as a beacon/reference. By projecting several such laser guide stars around the object of interest, the state of the atmosphere in the entire region of interest can be reconstructed.

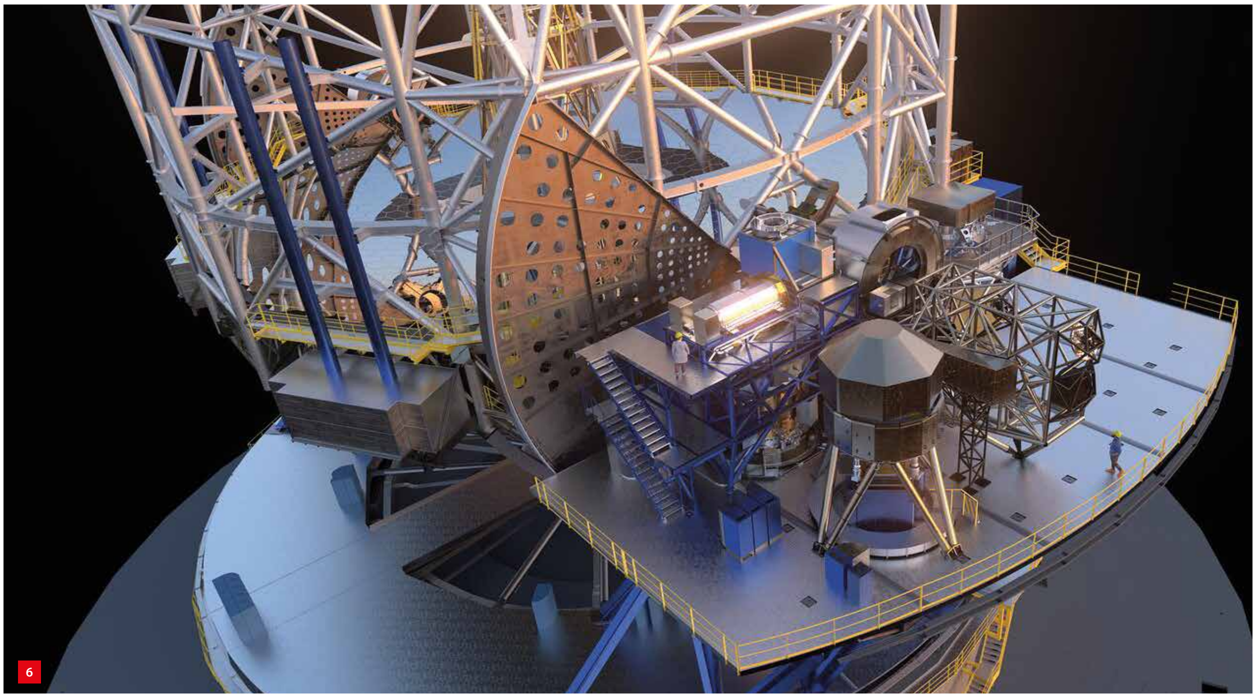
Deformable mirrors

Once the wavefront disturbance has been characterised, it can be largely corrected with adaptive optics (AO), using an adaptive deformable mirror (DM). Such a DM consists of a thin mirror shell suspended on a grid of actuators. The actuators manipulate the shape of the mirror shell in real time (≥ 100 Hz) to 'flatten' the wavefront of the incoming light. In this way it is possible to achieve better-than-Hubble-Space-Telescope image quality with a telescope on the ground (Figure 5).

Science instruments

When all the light has been gathered and its wavefront properly corrected, it is then fed into the detector – the actual science instrument. There are several types of instruments (Figure 6).

- Imager
  An imager is the most basic scientific instrument on a telescope. It simply creates an image of a patch of the sky. Unlike a photo camera, which uses three colour filters (red, green and blue), an astronomical camera can have many more filters, such as broadband filters as well as narrowband filters to look for specific chemical elements. The wavelengths for ground-based telescopes cover the extremes from ultraviolet, visible and infrared light to sub-millimeter radiation. For more extreme wavelengths, the atmosphere is opaque and telescopes need to be launched into space.



Artist's rendering of the ELT science platform showing the first-light instruments: an integral-field spectrograph, a diffraction-limited near-infrared imager and a thermal infrared imager-spectrograph; human for scale. (Image credit: ESO)

Even these simple imagers have several technical challenges: the images need to be crisp (sharp and rich in contrast) to the very edge of the field. The atmospheric dispersion (prismatic effect closer to the horizon) needs to be corrected with special optics. Infrared instruments need to be cooled to cryogenic temperatures. Astrometry requires the recording of the position of stars with such accuracy that you can see them move over a number of years. Imagers can be made sufficiently stable and sensitive so as to be able to detect the dimming of a star when an exoplanet temporarily crosses in front of it, thereby measuring the diameter of the planet.

- Spectrometer
  After making an image of a patch of the sky, a star can be selected for further investigation. This is done with spectroscopy: disentangling the light into many wavelength components. The resulting spectrum can provide information on chemical elements and processes in a star, or between the star and Earth. Using the Doppler effect, the velocities of celestial objects can be measured. The most accurate spectrometers can even detect the decimeter/second motion of a star, when an Earth-like planet is orbiting that star. This is used to determine the mass of a planet.

  A multi-object spectrometer can measure spectra of up to thousands of stars at the same time, with robots positioning optical fibres at the locations of stars of interest. Integral field spectrometers create a data cube of a piece of sky, for instance a galaxy. This means that a spectrum is taken for each pixel of the image, measuring 3D velocities in spiralling galaxies.

- Polarimeter
  When driving a car, you can wear sunglasses with polarised lenses to suppress glare on the road. Similarly, polarisation is used in scientific instruments to increase the contrast between a star and the exoplanet around it. An Earth-like planet at the Earth-Sun distance only reflects one photon for every 10 billion photons emitted by the star. Coronagraphy and polarisation are used to suppress the starlight by a factor of a billion in order to be able to detect and characterise the exoplanet. Polarisation is also used to measure magnetic fields in space.

- Interferometer
  An interferometer combines the light of multiple telescopes in order to achieve a higher spatial resolution than is possible with just one telescope. In radio astrometry this is relatively simple, since you can sample the electrical field, timestamp the signals and later compare these with recorded signals from other telescopes. As there are much higher frequencies in the optical domain, only intensities can be measured. This means that we have to physically combine the optical paths from different telescopes in order to create an interferogram. This is achieved in underground tunnels, with optical trains correcting the path distance between the telescopes real time to sub-micrometer accuracy. The achieved resolution for the VLT-interferometer is complementary to a telescope of nearly 200 m in diameter.

Highlight 1: ELT M1 mirror support structure

The primary mirror (M1) of the Extremely Large Telescope (ELT) is one of the most impressive and challenging aspects of the entire ELT project. Too large to be made from a single piece of glass, the 39-meter-diameter mirror will consist of 798 segments, each about 5 cm thick, measuring close to 1.5 m across and weighing 250 kg, including its support. Since the segments have to work together as a single mirror, they require specific infrastructure and control schemes. This is extremely challenging, as the full structure will be moving constantly during an observation and will be affected by wind and thermal changes. To achieve the required scientific performance, the mirror needs to be maintained in position and in shape to an accuracy of tens of nanometers across its entire 39-meter diameter.

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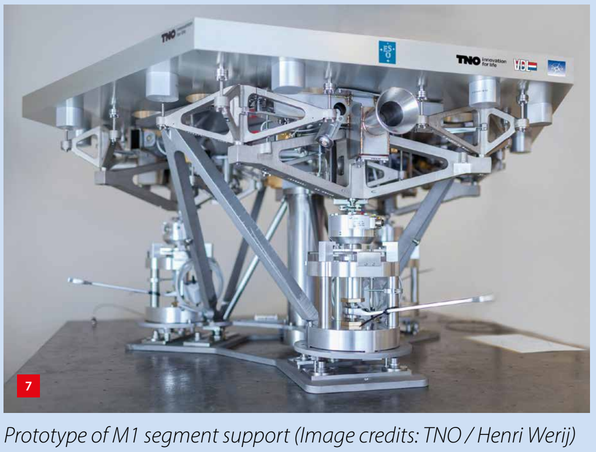
Close-up of one of three 9-point whiffletrees. (Image credits: VDL ETG)

Segment manufacturing

M1 segments (Figure 7) begin their life at German glass manufacturer Schott as blanks made of Zerodur, a glass-ceramic material that has very low thermal expansion. After the casting and machining of the blanks to their approximate shape, the segments are delivered to Safran Reosc, in France, who are responsible for shaping the segments and mounting them on their support systems, as well as for polishing and testing. VDL ETG in the Netherlands is responsible for the production and testing of the segment supports, which act as the backbone of the mirror.

Segment support

Each segment support includes axial and lateral supports and a clocking restraint, all attached to a moving frame. The axial support is a 27-point isostatic support, made of three 9-point whiffletrees (Figure 8). Each M1 segment assembly comprises a warping harness, made of nine shape actuators, which allows correction of three segment deformation modes: curvature, astigmatism and trefoil. The actuators modify the axial support forces by applying a torque at the location of the axial support tripod pivots. The load on the whiffletree can be adjusted in this way to slightly change the shape of the mirror to compensate for optical aberrations induced by gravity and thermal effects. The warping harness has a micron-range stroke and it is a 'slow' actuator (1.5 s full stroke). The segment support also includes adjustable counterweights to compensate for the shape variation of the 133 segment types.



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Prototype of M1 segment support (Image credits: TNO / Henri Werij)

The segment support materials and components have been selected to minimise outgassing under vacuum; the entire segment assembly is loaded in vacuum vessels for ion beam figuring (fabrication) and optical surface coating (operational maintenance). On the telescope, the segment assembly will be mounted with a fixed frame that provides local stiffness to the M1 subunit and accurate reference position to the mirror assembly. A total of seven prototypes were developed jointly by VDL ETG and TNO, and successfully delivered to ESO in 2018, after which VDL ETG was awarded the contract for volume manufacturing.

Volume production

In the transition from the prototype project to the volume manufacturing project, which started in 2018, VDL and ESO joined to further refine all technical documentation. A lean production area was set up with a main assembly line, which is fed with parts and sub-assemblies from sub-lines. Each work place has dedicated tooling available, clear work instructions, and personnel receives dedicated training to work at that particular place. Every completed support structure goes through a rigorous and largely automated test sequence to ensure every single one meets the specifications (Figure 9).

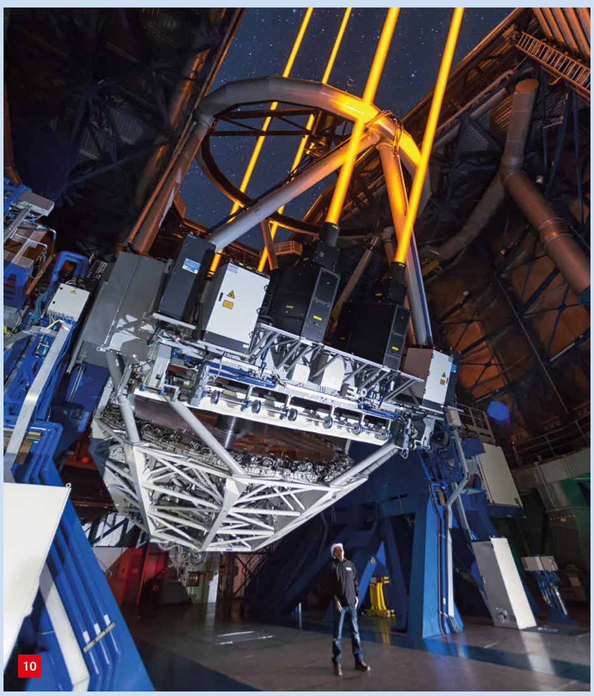
Performance testing of each unit during volume production. (Image credit: VDL ETG)

In setting up the supply chain, VDL worked closely with suppliers to define standards; suppliers were audited, and quality control plans were put in place. The most critical parts are dual-sourced to assure availability at all times. Delivery quantities of parts are optimised with suppliers for cost and operational efficiency. Since the full project lasts for four to five years, long-term agreements have been made to ensure the supply chain's continuity.
The volume production of this complex product for ESO (European Southern Observatory), and the advanced supply chain that was put in place for it, have attracted other interested parties, including the US-based Thirty Meter Telescope, the Mauna Kea Spectroscopic Explorer, and NASA's Jet Propulsion Laboratory.

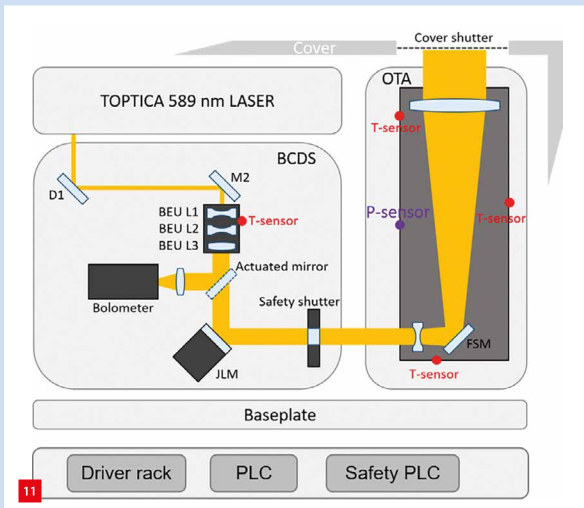
(adapted from elt.eso.org/mirror/M1)

Highlight 2: Laser guide stars

ESO's Very Large Telescope (VLT) facility at Cerro Paranal, Chile, consists of four 8.2-meter Unit Telescopes (UTs). Since 2016, one of these (UT4) has been equipped with laser launch telescopes provided by TNO. Combined with other instruments in VLT's adaptive optics facility, these allow astronomers to correct for the blurring effect of the Earth's atmosphere in real time and create images of unprecedented sharpness.



VLT UT4 with the laser guide stars in operation. The VLT LPS units are the black boxes from which the laser beam is emitted. (Image credit: ESO / Fred Kamphues)



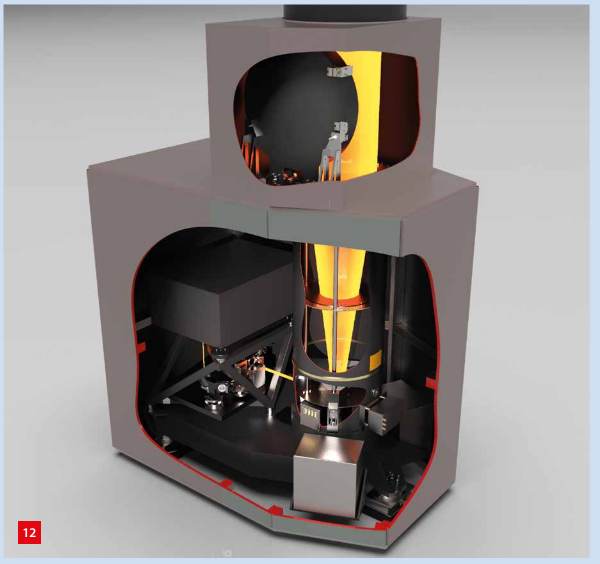
Schematic optomechanical layout of the laser projection sub-unit. (Image credit: Demcon / Ralph Pohl)

For the development of the next-generation system for the upcoming Extremely Large Telescope (ELT), ESO has once more turned to the Netherlands. Since January 2021, Demcon Focal and TNO have been working on the preliminary and detailed design of the ELT Laser Projection System (LPS).

Subsystems

The ELT LPS is an evolution of ESO's VLT reference design and consists of several major subsystems. The Beam Conditioning and Diagnostics System (BCDS) receives a Ø4.2-mm Gaussian laser input beam from the external 589-nm, 22-W continuous-wave laser. The BCDS contains a custom variable beam expander that expands the beam to Ø15 mm and controls focus, and a fast tip/tilt mirror to correct for jitter. The BCDS also performs beam diagnostics, and its propagation shutter can send the laser beam to a calibrated bolometer for absolute power measurements.

The BCDS feeds the laser beam into the Optical Tube Assembly (OTA), a 20x a-focal beam expander that expands the input beam to a Ø300-mm collimated Gaussian output beam. A Field Selector Mirror (FSM) is placed in the expanding beam between OTA's L1 and L2 lenses, and can be actuated in tip and tilt to point the output beam over a ±7-arcmin field of view within 10 arcsec absolute pointing error.
The Cover Assembly shields the LPS from dust and contamination and provides an extra layer of laser safety. The Cover Assembly has a number of access hatches to allow for easy maintenance. All motor drivers, controllers and sensor read-out electronics are housed in a separate electronics cabinet and commanded through an industrial PLC that connects to the overall ELT PLC.



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Artist impression of the completed ELT Laser Projection System. (Image credit: TNO / Bert Dekker)

Requirements

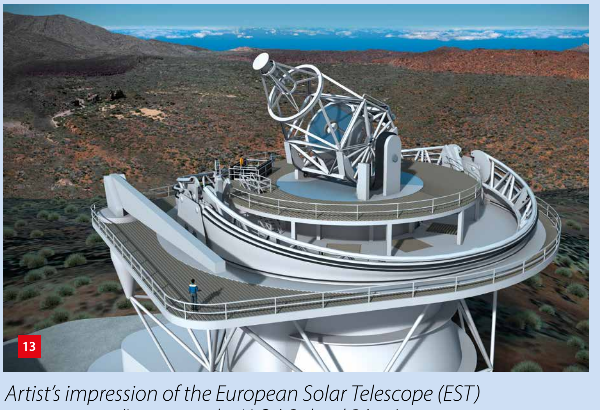
The LPS (Figure 12) will have a total transmission wavefront error of < 65 nm rms, excluding tip/tilt and focus, over the full field of view and under all operational conditions. The requirements on pointing accuracy and stability are equally challenging. During operation, the LPS experiences a temperature gradient of up to 0.55 °C/hr. The thermal time constants of all OTA components will be precisely tuned to athermalise the design for these gradients. Repeatable focus errors of the LPS can be modelled, characterised and compensated using the variable beam expander. Due to the optical design, any pointing angle variations at the LPS input are demagnified by a factor of 72; lateral offsets, however, are magnified by the same factor. This requires a system-level approach for handling thermal and gravity loads.

Planning

The manufacturing, integration and testing of the first LPS is planned for 2022. Eventually, ELT will be equipped with at least four, potentially six, laser guide stars. ESO now expects ELT to achieve technical 'first light' in 2027, with scientific verification to begin shortly after.

Highlight 3: EST adaptive mirror

While the Adaptive Secondary Mirror development for the University of Hawai'i 2.2-meter telescope (UH2.2) has entered the manufacturing and integration phase (see the article on page 28 ff.), the involved partners are taking the next step. An international team of scientific institutes, coordinated by the Instituto Astrofísica de Canarias (IAC), is working on the development of the European Solar Telescope (EST, Figure 13), planned to be the largest solar telescope in the world when it becomes operational in 2027 on La Palma.



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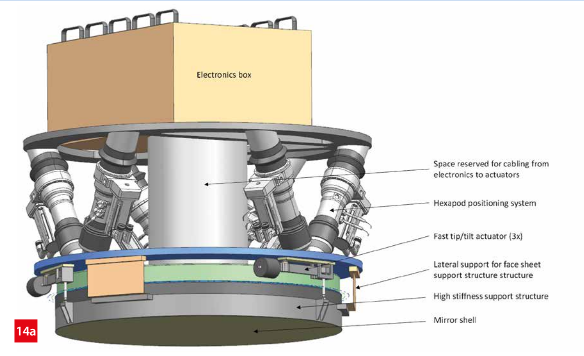
Artist's impression of the European Solar Telescope (EST) in operation. (Image credit: IAC / Gabriel Pérez)

The EST project, partially funded by the EU, will enable Europe to remain at the forefront of knowledge about our Sun and its influence on Earth. The field of view of EST will be 1.5 arcminutes, and with the Sun's apparent diameter of 30 arcminutes this means it will see only 1/400th of the Sun's surface at a time. EST will, however, be able to see this part in enormous detail, which is why some have nicknamed it the 'solar microscope'.

While the initial concept study of the EST considered a classical approach of having a passive secondary mirror and all deformable mirrors further downstream, the EST team found in their concept studies that having an Adaptive Secondary Mirror (ASM) could reduce the total number of mirrors in their system from 14 to only 6. This in turn would lower the overall cost and complexity of the telescope and



The EST adaptive mirror.
(a) Conceptual layout. (Image credit: TNO / Arjo Bos)
(b) Artist impression of the complete design. (Image credit: TNO / Bert Dekker)

would increase the optical throughput by nearly 50%. Building on the design and success of the UH2.2 technology demonstrator, TNO was recently awarded the contract for the preliminary design of this adaptive mirror, to be completed by late 2022.

System layout

The EST ASM (Figure 14) will have an 800-mm-diameter concave aspheric mirror shell that defines the telescope pupil. The mirror shell is supported on potentially as many as 2,000 hybrid variable-reluctance (HVR) actuators for providing corrections. The actuators require a high-stiffness mounting frame, and the investigation of design concepts and materials choices is just one of many trade-offs to be performed as part of the preliminary design study.

Next to the HVR actuators, a separate mechanism will provide fast tip/tilt and piston corrections to compensate for vibrations produced by the wind. This is especially important since EST, contrary to most telescopes, will not be protected by a dome during observations and thus will be fully exposed to the wind. While this approach produces vibrations throughout the structure and optics that need to be compensated, it also provides natural cooling and reduces turbulence in the atmospheric ground layer.

Finally, the entire assembly is mounted on a hexapod for slow, coarse positioning and alignment. If the global corrections provided by the deformable mirror (DM) actuators are nearing the end of their stroke, part of that stroke can be off-loaded to the fast tip/tilt subsystem, which can in turn be off-loaded to the hexapod.

Cooling

The solar constant, the solar energy received by the Earth, is approximately 1,360 W/m^2 and about 56% of this energy actually reaches the surface. Considering the 4.2-meter primary mirror of EST, this means the ASM will receive roughly 10 kW of light. A large portion of that optical power is taken out by a heat stop located at the intermediate focus between the primary and the secondary mirror, which only transmit the light over a small field of view. As a result, the maximum irradiance at the ASM is around 250 W.

In case of a high-power laser that emits monochromatic light, a coating can be designed to achieve 99.99% reflectance at that one particular wavelength, and hence to have minimum absorption. Over the broad spectrum emitted by the Sun such optimisation is not possible, and the broadband coating of the ASM will reflect only about 90%, resulting in a heat absorption of 25 W. To avoid generating local turbulence, an integrated cooling system is needed to keep the mirror temperature within 0.5 °C with respect to the environment. Investigation and breadboarding of cooling concepts are therefore another important activity in the preliminary design phase.

Actuator adaptations

TNO and VDL ETG together have developed, manufactured and tested several HVR generations. The lessons learned from the UH2.2 actuator development are implemented in the new High Density Actuator (Figure 15), which is also the baseline for use on EST. This latest version is rotationally symmetric to make more efficient use of the available space for the generation of actuator force, has vastly increased

Artist impression of the latest-generation High Density Actuator. (Image credit: TNO / Bert Dekker) stiffness for higher AO-correction bandwidth, and removes the need for wire-erosion machining, which lowers manufacturing cost. Due to the 'lasagna'-style layered structure, the actuators are also easier to assemble.

The design is scalable down to an actuator pitch of around 5 mm and is also suitable for use at instrument level, where DMs need much tighter actuator spacings. Modelling predicts a force range of ±1 N in an actuator volume of Ø5 mm x 10 mm, which yields a stroke of more than 30 µm peak-to-valley at an actuator resonance of around 3 kHz.

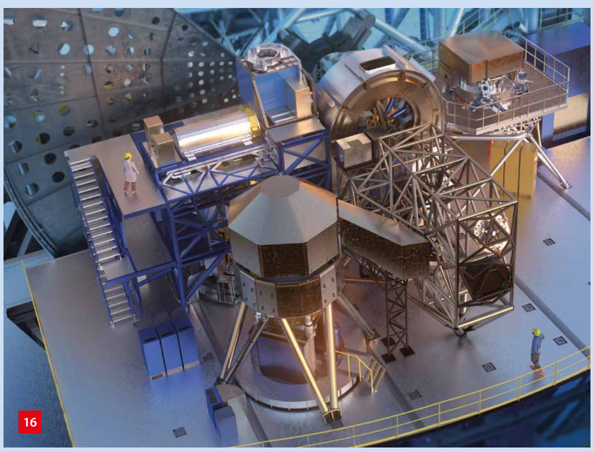
Several prototypes were recently manufactured, and at the time of writing, functionality and performance testing is ongoing.

The preliminary design study for the EST ASM will be concluded near the end of 2022, after which the EST consortium will prepare for the detailed design and realisation phase, which will take several years. This could provide an exciting opportunity for the current and new partners involved in precision engineering and electronics development.

Highlight 4: ELT instruments

The mirrors of the ELT collect, correct and stabilise the light from astronomical objects. The scientific instruments attached to the telescope analyse the light in detail. The ELT instrument suite includes cameras to capture images, and spectrographs to disperse light into its component colours. They can be combined with other functions, such as coronagraphs that block the light from a star in order to reveal its planets. Each of these instruments will allow astronomers to observe and study the cosmos in a unique way.

For a gigantic telescope, its science instruments will inevitably also be large. The instruments are located on the Nasmyth platform (Figure 16), about 25 meter above ground level. The optical beam from the telescope is 6 meter above the platform, which measures 15 m by 30 m. Three instruments will start to operate shortly after ELT achieves first light, while others will be added at a later stage. Throughout the telescope's lifetime, additional instruments will be developed to study the Universe in ever more detail.



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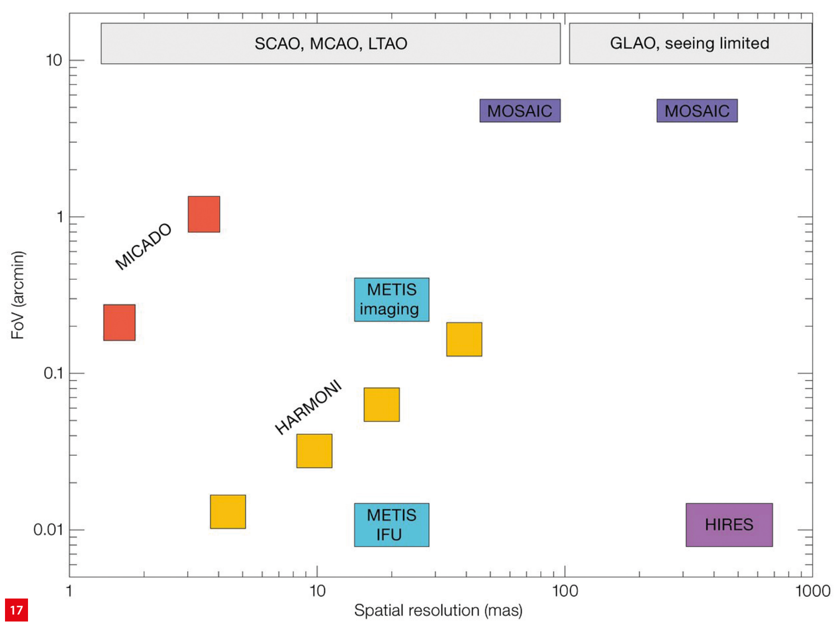
Render of the ELT and the Nasmyth platform, showing, from left to right, the instruments HARMONI, MICADO, MAORY and METIS. The platform is the same size as a basketball court. (Image credit: ESO)



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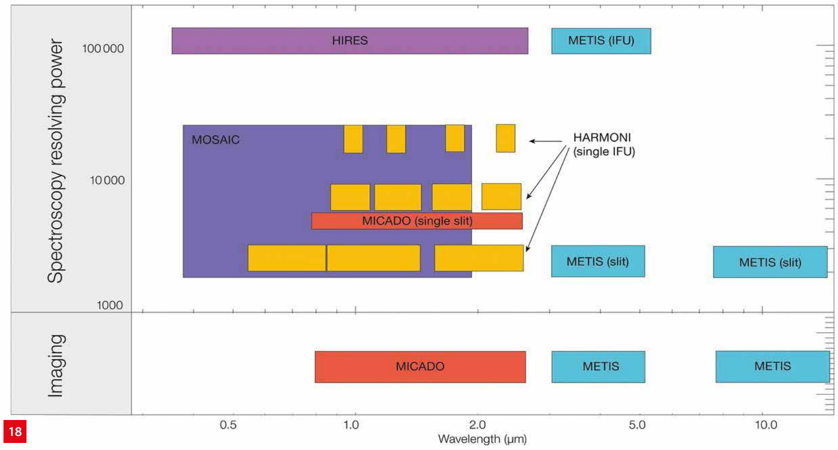
Field of view (FoV) versus resolution for various instruments, spanning several orders of magnitude. The maximum resolution of the ELT is 1.5 milliarcsec (7 nrad), which compares to being able to separate two objects that are the thickness of a human hair apart, viewed from 10 km distance. Their location (the centre of those objects) must be known with an accuracy that is even 100 times better. The maximum FoV is limited by the 2-meter diameter size of the ELT focus. There are various adaptive optics (AO) modes to combat the turbulence of the atmosphere: single-conjugate AO works great in the vicinity of a single bright star, whereas multi-conjugate AO works well in a small area between multiple bright stars. Laser tomography AO uses lasers to create artificial stars anywhere in the sky. Ground layer AO only corrects for turbulence close to the telescope. (Image credit: ESO)

Capabilities

To erect the telescope, ESO contracts industrial partners to build the various components. The scientific instruments are developed in a completely different way. International consortia of research institutes collaborate to develop the necessary technology and realise the equipment, including their calibration strategies and data-processing pipelines. These instruments have imaginative names, based on abbreviations, describing their purpose and technology. Their capabilities can be visualised in plots (Figures 17 and 18), showing the following properties:

- Spatial resolution: the crispness of the image, or how far you can zoom in.
- Field of view: the size of the image; sometimes it is just a single spec on the sky.
- Spectral resolution: how many colours can be distinguished; this is how chemical elements are found, or how the Doppler shift is used to determine velocity differences.
- Wavelength range: which colour ranges can be detected; the ultraviolet shows hot stars and violent mergers, while with infrared wavelengths you can peer in dust clouds, observing planets being formed.
- Coronagraphy: the technology to suppress the light of the star, while observing the much fainter planet right next to it; for an Earth-like planet at the Earth-Sun distance, only 1 out of every 10 billion photons is from the planet.



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Spectral resolving power versus wavelength range for various instruments. The spectral resolving power R is defined as λ/Δλ. A higher number means that the light is split into more individually distinguishable colours: R = 100,000 at λ = 1 μm means that 10-pm wavelength variations are detected. A resolution of R = 2,000 is sufficient to study the rotation speed of galaxies. At R = 5,000 it is possible to study the chemical composition of individual stars. More chemical components can be found at R = 20,000. R = 100,000 is needed to measure speeds very accurately, e.g. to see stars wobble because a planet is rotating around it. In imaging mode, dozens of filters are used, corresponding to, e.g., spectral lines of specific chemical substances. METIS is the only instrument observing wavelengths longer than 2.5 μm. (Image credit: ESO)

Overview

HARMONI (High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph)
This workhorse 3D spectrograph will transform the visible and near-infrared astronomy landscape. 3D spectroscopy means that from small portions of the sky a spectrum is generated for each pixel. This enables, e.g., measurement of the rotation of galaxies, as derived from Doppler shifts.

MICADO (Multi-AO Imaging Camera for Deep Observations)
This high-resolution camera will offer astronomers the ability to take images of the Universe at an unprecedented depth. MICADO will create the sharpest images ever taken of faint targets. The Netherlands contributes with the unit that provides all the (colour) filters and corrects for atmospheric diffraction, as well as the data processing software.

MAORY (Multi-conjugate Adaptive Optics RelaY)
This unique instrument will not make observations itself, but will enable, by correcting for the blurring effect of the Earth's atmosphere, other instruments to take exceptional images. MAORY will use two additional deformable mirrors with thousands of actuators, in order to correct for turbulence at different altitudes in the atmosphere.

METIS (Mid-infrared ELT Imager and Spectrograph)
With a powerful spectrograph and high-contrast imager operating in the thermal infrared, this two-in-one instrument will allow to unravel some of the most pressing mysteries about the Universe. The range of METIS science is broad, from Solar System objects to active galactic nuclei. METIS is ideally suited to study the lifecycle of stars, from baby stars and their planet-forming discs to older stars nearing the end of their lives.

HIRES (HIgh REsolution Spectrograph)
This high-resolution spectrograph will allow astronomers to study astronomical objects that require highly sensitive observations. Large gratings unravel the light into a million colours, using the Doppler shift to detect minute variations in the velocities of stars and planets.

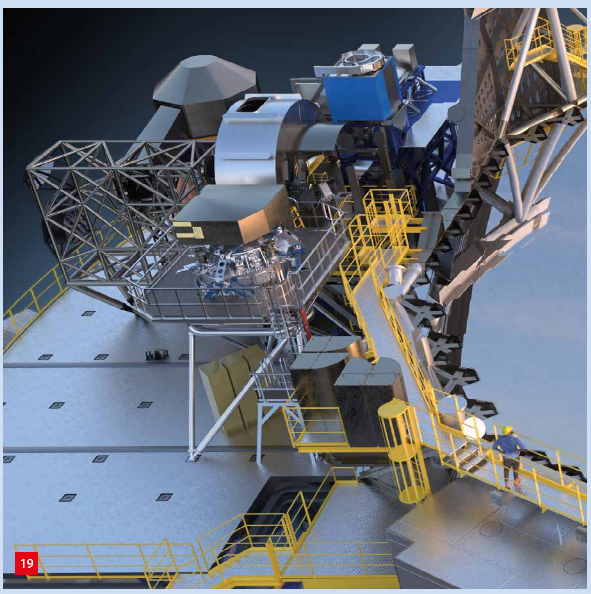
MOSAIC (Multi-Object Spectrograph for Astrophysics, Intergalactic medium studies and Cosmology)
This multitasking instrument will allow astronomers to measure the light from many objects at the same time, enabling them to quickly survey a multitude of stars and galaxies in the Universe. The Netherlands will contribute the visible spectrograph, capable of measuring the spectra of 200 objects simultaneously.

One of the highest scientific priorities for the ELT is to characterise exoplanets and, specifically, to take images of Earth-like planets. Such a giant leap from the capabilities we have today, requires significant research into new technologies over several years. Therefore, an ambitious and powerful planetary camera and spectrograph is included in the instrumentation plan. The research and development for specific components required to build it is ongoing. This project will start when the technology is ready. If the full potential of the ELT is achieved, global weather on exoplanets could be observed.

Development of METIS

The METIS instrument (Figure 19) is developed by a global consortium under the leadership of the Dutch Research School for Astronomy (NOVA). This Dutch team has to ensure that all the contributions from different partners around the world will integrate and work together seamlessly, forming an operational system with optimal capabilities to harvest science from observations. In the design phase, this involves breaking down the top-level requirements into subsystem requirements. In the realisation phase, this involves combining all hardware subsystems with electronics and software deliverables into a fully-tested functional system. This entire process takes about 20 years: ten years for technology and concept development and ten years to design, build and test the instrument.

METIS will pick up the optical beam from the telescope and process it in several major subsystems, to create the spectra and images that scientists can use for their research. The common fore-optics subsystem formats the beam for injection into the scientific cameras, and includes important functionalities such as atmospheric dispersion compensation, derotation, pupil stabilisation, chopping, and coronagraphy.
The single-conjugate adaptive optics (SCAO) subsystem, which implements an infrared pyramid wavefront sensor, is used to control the shape of the ELT-M4 deformable mirror. Because of the SCAO subsystem, all science modes



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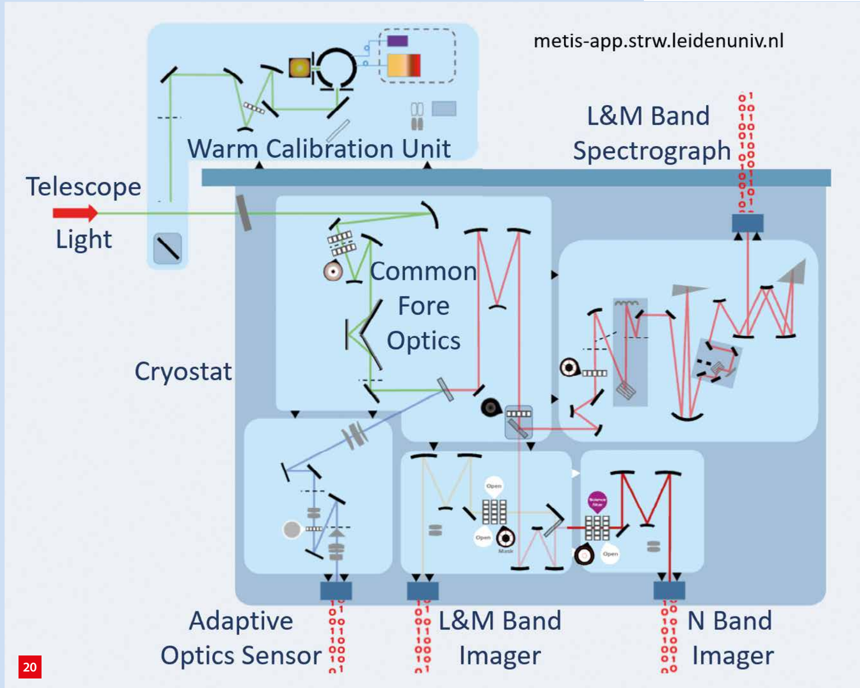
Render of the METIS instrument, together with other science instruments, on the ELT Nasmyth Platform. (Image credit: ESO)



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Layout of the METIS instrument and its most important subsystems. Due to the thermal infrared wavelengths, most of its components are located in a cryogenic vacuum environment. Many of its dozens of optical components are adjustable, some even with extreme accuracies during observations. The Adaptive Optics Sensor produces data that is used to control deformable mirrors real time. (Image credit: NOVA; still image from live simulation at: metis-app.strw.leidenuniv.nl)

observe at the diffraction limit of the ELT, yielding angular resolutions of a few tens of milliarcseconds.

A pair of diffraction-limited imaging cameras operate at two distinct wavelength bands in the 3-13-µm range with an 11-arcsec field of view, and include coronagraphy and medium-resolution long-slit spectroscopy. The integral-field high-resolution spectrograph operates from 2.9 to 5.2 µm and includes coronagraphic capabilities. A warm calibration unit sits on top of the cryostat, providing carefully calibrated light sources to finetune the instrument stability and sensitivity.

METIS detects thermal infrared wavelengths; this is heat radiation emitted by any material at ambient temperatures. This is perfect to detect the radiation of exoplanets. The downside it that everything on Earth also emits in the infrared, including the Earth's atmosphere, the telescope itself and any optical component in the beam. The signal is drowned in these bright background emissions, which significantly reduces the sensitivity. In order to eliminate emissions from the instrument itself, most of METIS is placed in a cryogenic vacuum environment and cooled to extreme temperatures. Liquid nitrogen is used to cool a thermal shield to 80 K, while helium pulse-tube coolers bring detectors and part of the optics down to temperatures of around 35 K.

At infrared wavelengths, very accurate subtraction of the spatially and temporally varying background is also essential. This is usually done by 'beam chopping': quickly alternating pointing between the science target and a nearby reference location. This differential measurement allows both the sky background and detector noise to be eliminated from the observation. This functionality is provided by means of a tip/tilt mirror, able to move very fast and then hold the image perfectly stable. For the development of the Metis Cold Chopper, NOVA collaborated closely with JPE, which handled the design, and with SRON and Delft University of Technology, which worked on the required advanced control strategies. A prototype of this mechanism has been described in *Mikroniek* [1].

Two other challenging subsystems and components deserve to be mentioned. The Image Derotator in the common fore-optics; a set of three flat mirrors that rotate very slowly with variable direction and speed to counteract the rotation of the Earth, thus keeping images still on the detector. This module is a challenging puzzle of tight tolerances in more than 20 degrees of freedom, with very limited alignment options, because of the operation in a cryogenic vacuum environment.

The Spectrograph contains an immersed grating. By creating the grating inside germanium with its high index of refraction of 4.2, the Spectrograph can effectively shrink in all directions by this same factor, which is a huge saving in volume, mass and cost. The downside is that the wavefront errors (position errors of the grating lines) must be tighter by the same factor, reaching single-nanometer manufacturing accuracies. This magnificent piece of engineering has been manufactured and the required tolerances have been achieved.

The METIS design is being finalised and will be reviewed and frozen in 2022. Then the period of manufacturing, assembly, integration and performance verification will start. The schedule of METIS, like that of ELT, was impacted by Covid-19. The plan is to be on sky in 2027.

REFERENCE

[1] M. Dekker, "Cold chopping of baby star light", *Mikroniek* 54 (5), pp. 19-23, 2014.