TNO TECHNOLOGIES FOR ASTRONOMY

TNO innovation for life

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1 SUMMARY

In this brochure you will find the highlights of TNO's long history of work in Astronomy, and related space and scientific instrumentation. TNO combines four areas of expertise to reach cutting-edge levels of accuracy and control in ultra-precision opto-mechatronics. These include Optics (optical design and engineering), Mechatronics (mechanical design, mechanisms, controls, to full optical systems), Space Systems Engineering (engineering, managing and testing the finest details to ensure performance in the most challenging environments), and Optical Manufacturing (nanometer precision of complex optics, coatings, freeforms and aspheres).

2 INTRODUCTION

TNO is the Netherlands Organization for Applied Scientific Research. Some highlights of the institution are:

- TNO is the largest independent Dutch research organization for applied science.

- TNO was founded in 1932 and as of March 2018 has about 3000 employees, including more than 50 professors.

- TNO's annual turnover in 2017 was more than 500 million euro.

- TNO is structured into 9 innovative and social themes: • Buildings, Infrastructure & Maritime • Circular Economy & Environment • Defence, Safety & Security • ECN part of TNO • Healthy Living • Industry • Information & Communication Technology • Strategic Analysis & Policy • Traffic & Transport.

- TNO has > 250 researchers from different expertise groups of optics, opto-mechatronics, contamination control, and space system engineering. In addition to researchers, TNO projects are usually structured (when needed) with personnel with roles such as: Project Managers (PM), Manufacturing, Assembly, Integration and Testing (MAIT), Product Assurance (PA), Quality Assurance (QA) & system calibration engineers.

- TNO has acquired a consolidated heritage on optics manufacturing (free forms, aspheres, gratings, coating etc.).

- TNO is active in the field of advanced optical, radar and big science instrumentation that require proper functioning under extreme conditions.

- Backed with over 50 years of space heritage, we develop single-unit and prototype instrumentation for terrestrial astronomy and big science, space borne science missions, Earth observation, as well as our rapidly expanding developments for high-bandwidth laser satellite communication.

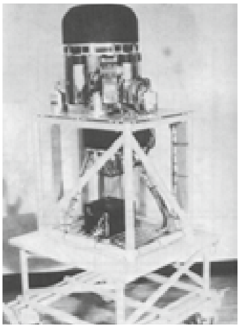
3 TNO TECHNOLOGIES FOR ASTRONOMY

When technology must be mature, precise and reliable, our organization has a 100% success rate in space and scientific instrumentation. An effective telescope system must have the highest precision components possible. From a system perspective this includes key instruments to maintain, measure and correct the wavefront. Segmented mirrors must be co-phased to sub-lambda scale accuracy. Even before the first deformable mirror, the primary and secondary mirrors must maintain near perfect surface form to preserve the quality of the incoming light, and maintain the diffraction limit. Beyond excellent component design and production, this includes calibration and actuation to counter natural forces including gravity vector (changing telescope orientation), wind loading, thermal gradients and ground movement. Of course adaptive optics is more than just deformable mirrors. Other key components, such as wave front sensors, laser guide stars, and optimized real-time control systems are key to quality scientific data from large telescopes.

4 TNO HERITAGE

Since 1964 a growing list of mainly optical instruments and modules has been designed, built and calibrated by TNO. With a heritage of over 50 years, starting with the very first scientific instrument built for ESA, TNO has a proven track record in space instruments and components. TNO has consistently delivered breakthrough technology and components, ranging from spectrometers for Earth observation and planetary exploration to high-tech mission-critical space components.

Dozens of satellites are equipped with systems that have been designed, built and tested by TNO. Our climatological models, which combine ground-based and space measurements are used on a daily basis by the Royal Netherlands Meteorological Institute. TNO works in compliance with international quality and confidentiality regulations. TNO helps to improve the quality of life on Earth and stimulates the search for signs of life beyond our planet.



Spectrometer S59

1970

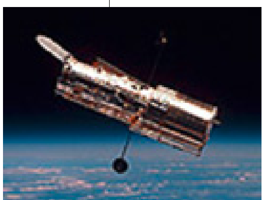
UV and soft X-ray on ANS satellite

Sun Acquisition Sensor

R7 on Skylark sounding rocket

Leinax on Terrier – Sandhawk sounding rocket

Attitude Anomaly Detector



1980

Faint Object camera on Hubble space telescope

DAX on IRAS

Short Wave Spectrometer on ISO satellite

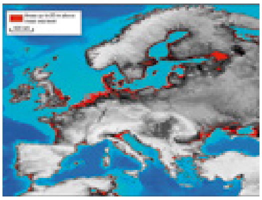
1990

Refocus mechanism on Hipparcos

Global Ozone Monitoring Experiment (GOME)

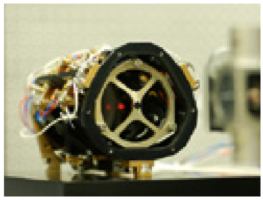
Achromatic phase shifter for DARWIN satellite

High Precision Optical Metrology for DARWIN

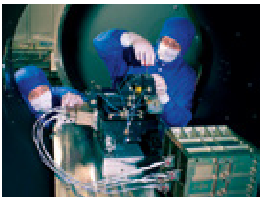


InSAR PSI

Nulling breadboard for DARWIN satellite



Optical delay Line for DARWIN



OMI

80

1990

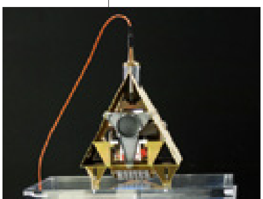
SCIAMACHY on ENVISAT

MetOp calibration

LOTUS-EUROS

A range of miniaturized sun sensors

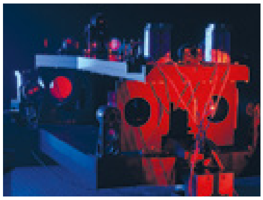
R7 on Skylark sounding rocket



Raman/LIBS spectrometer

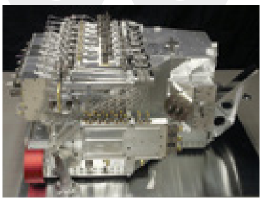
DESDEMONA

Sentinel 3 Viscal calibration unit

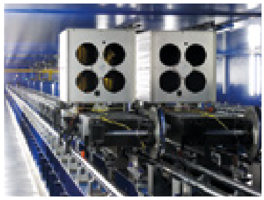


VLTI Star Seperators

2000



HERSCHEL HIFI



VLTI Delay lines

E-ELT Mirror Cell prototypes

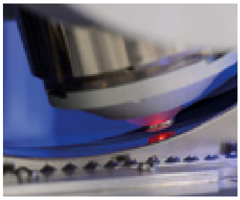
Micro-propulsion

2010

GAIA Wave Front Sensor

GAIA Auto Collimating
Flat Mirror Assembly

GAIA Basic Angle
Monitoring



NANOMEFOS freeform
optics

EARTHCARE MSI
Spectrometer

Cool Gas on PROBA-2

TROPOMI / Sentinel 5
precursor

10

2020

LISA Pathfinder

VLT Laser Launch
Telescope

5 SUPPORT STRUCTURES FOR SEGMENTED MIRRORS

5.1 INTRODUCTION

Figure 1: *E-ELT M1 Support Structure. 1.4 m mirror controlled to 25-50 nm surface form accuracy.*

Large Telescopes in particular face new challenges as a result of unprecedently large optics. Maintaining surface form and segmented mirror co-phasing requires precision actuated mirror mounts and control systems that must, in real time, utilize thousands of actuators to sub-Lambda accuracy. TNO has designed and built such systems.

After over a decade of competitive prototype and knowledge development, the TNO design solution has been adopted by ESO for the 39-m E-ELT telescope consisting of almost 798 hexagonal segments with a size of 1.4 meter. TNO and its industrial partner, VDL, were recently awarded the contract to build the full series of ELT M1 structures.

To ensure stability and high stiffness each of the parabolic shaped segments is supported on a structure (see Figure 1) with three whiffletrees providing a total of 27 support points. The three whiffletrees are supported by three actuators which are used to position the mirror segments actively. Different actuators embedded within the whiffletrees are used to compensate for the elastic gravity deformation of the telescope structure when the telescope pointing elevation is changed. This system has been proven to maintain a 25 nm surface form in any pointing angle and over a wide range of temperatures.

For the lateral support a membrane is used that is mounted inside a pocket of the mirror segment itself. This membrane is supported by the moving frame. Its position in piston and tip/tilt is also controlled by the actuators. The lateral displacement and clocking of the moving frame is controlled by three leaf springs which are connected to the fixed telescope structure. The moving frame isolates the mirror segment from the elastic loads induced by the leaf spring deflections.

5.2 KEY TECHNICAL SPECIFICATIONS

All support structures are identical while the segments all differ. The differences in surface form deformation are compensated by applying balance masses at specific locations.
Each segment assembly can be tuned such that the surface form performance is maintained passively within the specification for every possible angular position relative to a horizontal plane. Furthermore this performance is independent of temperature.

The TNO design solution allows for assembly without the necessity to align the system. That means that the support structure can be built with high production rates, and subsequent lower costs.

Segment shape	Near hexagon with size of 1.4m corner to corner.
Surface form error contribution	24 nm rms, temperature range: -15 to +25°C. (focus, astigmatism, spherical aberration and residual errors) Thermal sensitivity: 0.1nm rms/°C
Surface form correction	Passive using 6kg max. at specific places inside the structure. Active by using nine warping harnesses – Focus correction: factor >7 – Astigmatism correction: factor >18 – Trefoil correction: factor >6
Eigen frequencies	First six eigen frequencies are segment rigged body modes. – Piston: 72.1Hz (66Hz) – Tip/tilt: 56.3/56.0Hz (55/55Hz) – Lateral translation: 53.4/52.0Hz (52/52Hz) – Clocking: 30.1 (30Hz)
Mass properties	Total mass: 297 kg Mirror segment: 180 kg Segment support: 67kg Fixed frame: 50kg Position actuators: 30kg (max.)
Mechanical strength	Simultaneous accelerations of ax=±1.7g, ay=±2.1g, az=±2.4g (quasi static)
Power dissipation	8W
MTBF	>8.5 years

5.3 ROM PRICE RANGE[1]

- M1 Structures – 50K Euro per unit (assuming an order of 90-100 units)
- Flip handling tool – 25K Euro, one unit
- Transport container – 2500 Euro per unit
- Force field test tool – 250K Euro with software, data acquisition and training

5.4 REFERENCES

- Nijenhuis et al., 2010, “MEETING HIGHEST PERFORMANCE REQUIREMENTS FOR LOWEST PRICE AND MASS FOR THE M1 SEGMENT SUPPORT UNIT FOR E-ELT”. Proc. of SPIE Vol. 7732 “Ground-based and Airborne Telescopes III”, pp. 77332H

- Nijenhuis et al., 2011, “THE OPTIMIZATION OF THE OPTO-MECHANICAL PERFORMANCE OF THE MIRROR SEGMENTS FOR THE E-ELT”. Proc. of SPIE Vol. 8336 “Integrated Modeling of Complex Optomechanical Systems”, pp. 83360H

- Nijenhuis, J. & Braam, B., 2016, “THE OPTO-MECHANICAL PERFORMANCE PREDICTION OF THIN MIRROR SEGMENTS FOR E-ELT”. Proc. of SPIE Vol. 8450 “Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II”, pp. 84500A

- Bos et al., 2014, “DESIGN OF AN E-ELT M1 SEGMENT MEASUREMENT MACHINE WITH NANOMETER ACCURACY”. Proc. of SPIE Vol. 9151 “Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation”, pp. 91510X

- Bos et al., 2015, “NANOMETRE-ACCURATE FORM MEASUREMENT MACHINE FOR E-ELT M1 SEGMENTS”, Precision Engineering, 40 pp. 14

- Nijenhuis et al., 2016, “DESIGNING THE PRIMARY MIRROR SUPPORT FOR THE E-ELT”, ”. Proc. of SPIE Vol. 9906 “Ground-based and Airborne Telescopes VI” , pp. 990616.

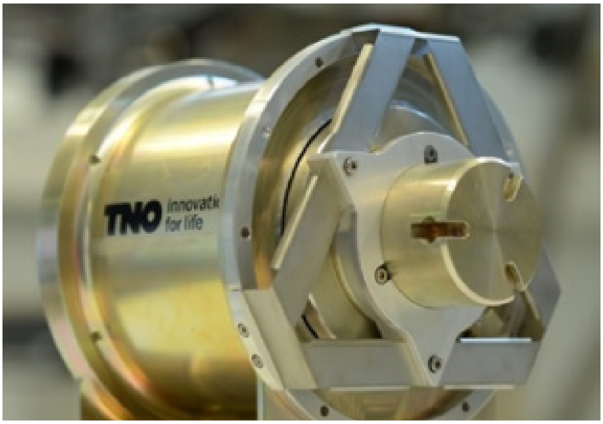
- Nijenhuis, J. & Braam, B., 2016, “THE OPTO-MECHANICAL PERFORMANCE PREDICTION OF THIN MIRROR SEGMENTS FOR E-ELT”. Proc. of SPIE Vol. 10012 “Integrated Modeling of Complex Optomechanical Systems II” pp. 1001203

1 Price estimate includes adjusting the design for a different telescope size, building and testing the units. Any price indications herein are not binding, but rough estimations, and also subject to pricing revisions of suppliers and partners.

6 PRECISION ACTUATORS

6.1 INTRODUCTION

Extremely high precision actuators are often required in astronomy and space science. In particular, segmented primary mirror telescopes require dedicated piston-tip-tilt actuators for control of mirror surface positions in order to ensure optimal optical performance. The accuracy of these precision actuators can also benefit other fields such as in space science and laser communications to nanometer accuracy.



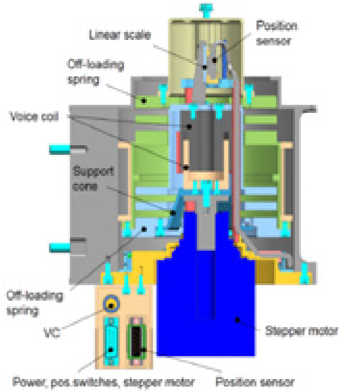


Figure 2: *Position Actuators for Segmented Mirrors*

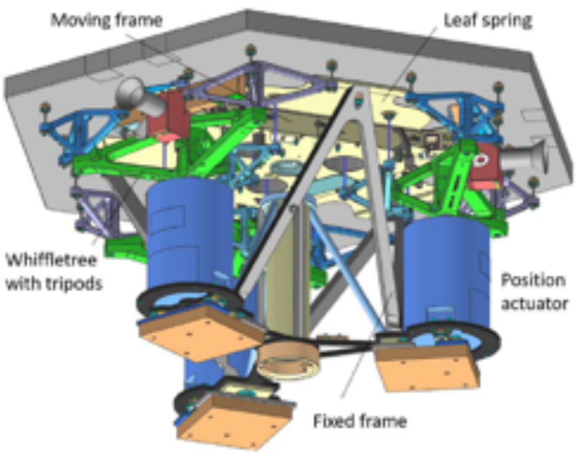


Figure 3: *PACTs are well matched to be used with the M1 segment support structures.*

6.2 KEY TECHNICAL SPECIFICATIONS

- Used in 3-acutator configuration with M1 support structures (see Section 5).
- Large stroke capability: 5-15 mm stroke.
- 1.4 nm RMS accuracy with simple control.
- < 1nm RMS accuracy with adaptive control.
- More reliable and lower cost voice coil precision stage compared to piezo actuators.
- Up to 1.2 μm/s proven tracking speed.
- Low voltage, with power dissipation less than 1.0 W.
- Design allows range from low to high stiffness (‘soft’ or ‘hard’ characteristics).

6.3 ROM PRICE RANGE

- 5 k€ per actuator: assuming an order of 250-300 units. Note that 3 actuators are needed for each segment (e.g. when using with M1 support structures as in Section 5).
- This ROM cost includes minor adjustments to the design for stiffness, stroke & interfaces.

6.4 REFERENCES

- Kamphues et al., 2008, “PACT: THE ACTUATOR TO SUPPORT THE PRIMARY MIRROR OF THE ELT”. Proc. of SPIE Vol. 7018 “Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation”, pp. 70180Z.

- Witvoet et al., 2014, “HIGH PERFORMANCE CONTROL OF MIRROR SEGMENT ACTUATORS FOR THE EUROPEAN EXTREMELY LARGE TELESCOPE”. Proc. of SPIE Vol. 9145 “Ground-based and Airborne Telescopes V”, pp. 91451S.

- Witvoet et al., 2015, “DYNAMIC ANALYSIS AND CONTROL OF MIRROR SEGMENT ACTUATORS FOR THE EUROPEAN EXTREMELY LARGE TELESCOPE”. Journal of Astronomical Telescopes, Instruments, and Systems 1(1), 019003.

- Witvoet et al., 2016, “PRIMARY MIRROR CONTROL FOR LARGE SEGMENTED TELESCOPES:COMBINING HIGH PERFORMANCE WITH ROBUSTNESS”. Proc. of SPIE Vol. 9906 “Ground-based and Airborne Telescopes VI” , pp. 990611.

- Actuators for the E-ELT, Nanometer accuracy with centimeter stroke http://www.e-elt.nl/index.php?v=actuators-e-elt

7 CO-PHASING SENSORS FOR SEGMENTED MIRRORS

7.1 INTRODUCTION

Co-phasing of dozens to hundreds of segmented mirrors requires feedback from thousands of edge sensors, each of which must be placed properly and calibrated to a known position.

TNO has developed a fast, time domain white light interferometer (Optical Coherence Tomography or OCT) for industrial height profiling applications, which could be adapted to fulfil the needs of segment mirror alignment metrology system.

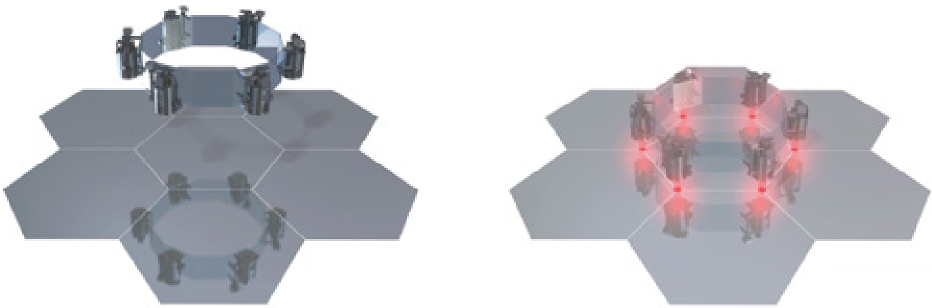


Figure 4: *proposed co-phasing sensor based on TNO developed Optical Coherence Tomography 3-D mirror alignment.*

The TNO OCT sensor has been developed as a commercial product and is currently in use within industrial metrology systems, therefore a full Technology Readiness Level (TRL) of 9 is guaranteed. The current applications for the system are for the inline inspection of manufactured components where nanometer to sub-micrometer profile accuracy is required.

A low-risk modification of the OCT concept could easily result in a co-phasing sensor for segmented mirrors to use in ELTs providing a 3-dimensional image map of segment intersections in full daylight within a short measurement time (less than 0.25 secs per segment intersection). This sensor would be used for edge sensor calibration, initial co-phasing of the array, and co-phasing of mirrors replaced after servicing. Daytime operation avoids the risk of losing expensive evening observation time.

7.2 CONCEPTUAL SPECIFICATIONS AND EXPECTED PERFORMANCE

TNO is currently investigating the feasibility to modify the successful concept of the OCT sensor. From discussions with various telescope builders, the following high level requirements have been considered and acknowledged as feasible to meet by the TNO OCT-based co-phasing approach:

Lateral surface range:	50 mm x 50 mm
Lateral surface grid:	280 x 290 pix (expandable to 512 x 560 pix)
Depth of scanning range:	2 mm
Stand-off distance:	~ 150-500mm (for mirror safety)
Height accuracy:	~1 nm (< 1 nm with pixel averaging algorithm)
Measurement duration:	< 0.25 sec (per mirror intersection)
Measurement repetition interval:	< 0.5 sec
Daylight operation:	Yes
Handling 4 mm gaps:	Yes
Sensor mass:	25 kg
Heat dissipation at the mirror:	1 Joule
Electrical dissipation:	< 250 Watt

The key characteristics making an OCT-based co-phasing sensor are:
- High TRL. The OCT is already a patented system working in industry.
- Simple system based on well-known principles.
- Insensitive to vibrations and ambient light: OCT has proven to be able to work in harsh industrial environments.
- Accurate system. While industrial needs involve sub-micron accuracies, a feasibility study of the OCT as a co-phasing sensor indicates nm or even sub-nm can be achieved.

7.3 NEXT STEPS

We are in continuous discussions with potential users, to further refine the concept and develop hardware specific to telescope needs. Please contact us to discuss further developments.

7.4 REFERENCES

- Crowconbe et al, 2016, “OCT System for Segmented Mirror Co-Phasing”, TNO-MEMO-OCT_WP (Internal document; Available upon request).

- Snel et al., 2017, “IN-LINE HEIGHT PROFILING METROLOGY SENSOR FOR ZERO DEFECT PRODUCTION CONTROL”, Proc. of SPIE Vol. 10329 “Optical Measurement Systems for Industrial Inspection X”, pp. 1032933.

8 SUPPORTS AND WHIFFLE TREES FOR SECONDARY AND TERTIARY MIRRORS

8.1 INTRODUCTION

Based on design studies and the experience and lessons learned by TNO on the successful implementation of support structures for large mirrors segment support structures (see Section 5) we are in position to offer similar support structures for secondary (M2) and tertiary (M3) mirrors. The basic expertise needed for the TNO deliverables in this development is nearly identical to our involvement in the EELT M1 cell, but with larger scale components (4-meter vs. 1.4-meter).

TNO developed designs meeting requirements for the M2 and M3 support for the E-ELT. TNO's technical proposal included the design, manufacture, verification and supply of the Qualification and Verification models for the E-ELT M2 and M3.

Figure 5: *Designs for the M2 & M3 units at the E-ELT*

The key advantage of TNO's conceptual M2/M3 cell design is an isostatic design with predictable performance and good dynamic behavior and control, built on heritage from the segment support structure for the E-ELT M1 design. Another important feature of TNO's design is the limited amount of parts by smart integration of functionalities of the warping harness, mass balancing and struts. As with the M1 segment support structure in Section 5, the M2/M3 structures are well matched to be used in combination with the Position Actuators (PACTS) in Section 6.

Closely related to these developments, TNO is currently working on the development of an Adaptive Secondary Mirror up to 3 m diameter (see Section 10).

8.2 KEY TECHNICAL SPECIFICATIONS

- Active Support Structures for large circular telescope mirrors.
- Actuatable Warping-Harness and Whiffle-Tree designs allowing surface deformation control with accuracies within 50-100 nm over 2-4 meter diameter mirrors.
- Design studies have included positioning hexapod interfaces.
- Design is tunable to different radii of curvature.
- Tools for transportation, handling, storage and testing are also available for future quotation.

8.3 ROM PRICE RANGE

Rough estimated prices per mirror support structure, including positioning actuation systems:

- ~4 meter diameter with 75-100 nm accuracy: ~8-10 million Euro[2].
- ~3 meter diameter with 50-75 nm accuracy: ~6-7.5 million Euro[2].

8.4 REFERENCES

- Nijenhuis, 2016, “M2_M3 CELL for E-ELT. Technical proposal. TNO-OFF-2016-9213378”, M2_M3-TNO-DER-0001 (Available upon request).

- Fritz, 2016, “M2_M3 CELL for E-ELT. Management proposal. TNO-OFF-2016-9213378”, M2_M3-TNO-PLA-0001 (Available upon request).

- Kuiper et al, 2018, “TMT Adaptive Secondary. Report on initial concept design”, TNO-TMT-AM2-report-2018-941363 (Available upon request).

2 Prices are for single units, with minor design changes. Different sizes are also possible. Significantly lower prices are possible for additional units.

9 FINE STEERING MIRRORS (FSM)

9.1 INTRODUCTION

Adaptive optics for use in ground-based astronomy and free space optics laser communications with satellites/ground vehicles/aerial vehicles impose strong requirements on aiming and positioning devices in terms of accuracy, fast response and large tip/tilt range.

Within the context of current developments in laser communications at TNO, a Fine Steering Mirror (FSM) was developed based on the same variable reluctance actuators used in the TNO Deformable Mirrors: (see Section 7).

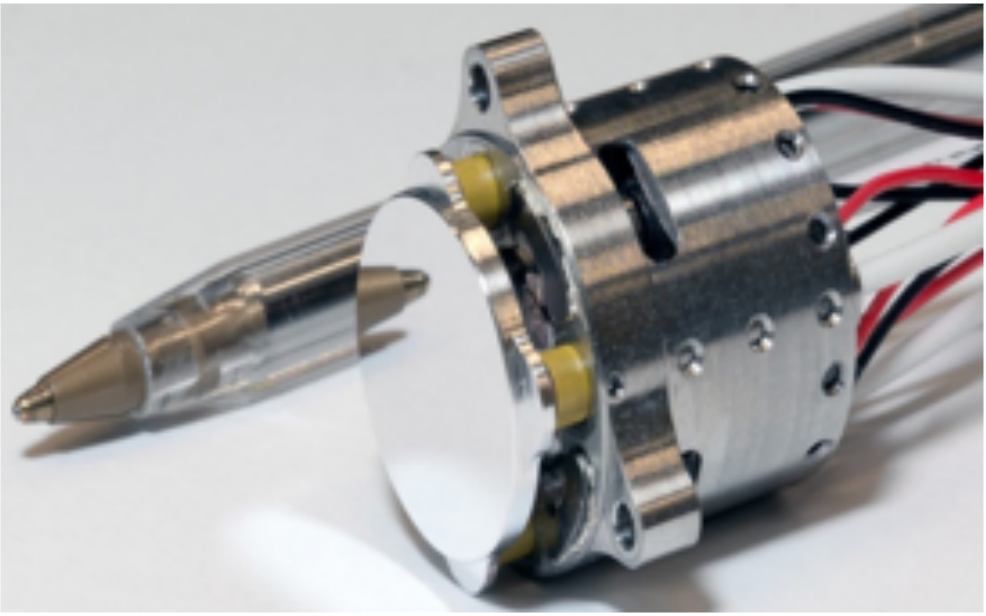


Figure 6: *FSM at TNO, which is high-precision, low-power, compact, high-frequency (fast), and vacuum-compatible.*

The TNO FSM exhibits desired features in terms of low size, volume, mass, power consumption as required in satellite platforms. For astronomy applications the tip-tilt range and fast response make TNO FSM an interesting alternative to bulky tip-tilt mirrors/mounts.

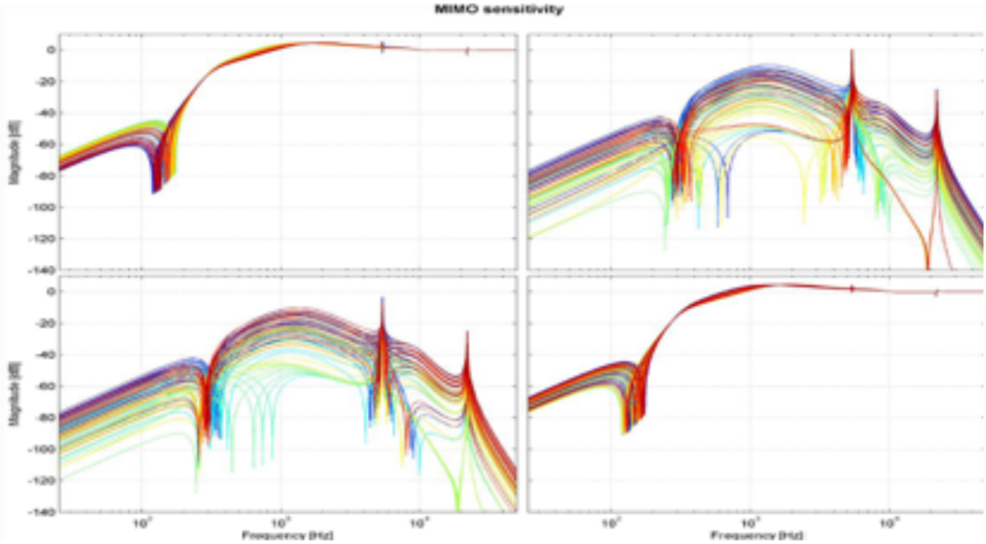


Figure 7: *Bode sensitivity amplitude plot of the feedback controlled FSM showing disturbance rejection bandwidth of around 800 Hz in both axes.*

9.2 KEY TECHNICAL SPECIFICATIONS

Mirror clear aperture:	Ø 20 mm.
Volume:	Ø 24x30 mm.
Large Tip/Tilt Range:	±2° (optical).
Low jitter:	< 1 µrad (optical).
High Bandwidth (-3 dB):	> 1kHz (see Figure 4).
Optical coating[3]:	Enhanced gold with > 98% reflectivity @ 1550 nm.
Wavefront Error (@1550nm):	λ/60 (rms).
Admissible Optical power[4]:	~10 Watts.
Operating temperature regime:	-20 to +50° C.
Lifetime:	> 15 years.

9.3 PRICING

The FSM can be a mature and cost competitive instrument for the demanding needs of scientific instrumentation. Please contact us for a quotation based on your requirements.

9.4 REFERENCES

- Kuiper et al., 2016, “ELECTROMAGNETIC DEFORMABLE MIRROR DEVELOPMENT AT TNO”. In Proc. of SPIE Vol. 9912 “Astronomical Telescopes+ Instrumentation” (pp. 991204- 991204).

- Kuiper et al., 2017, “HIGH-BANDWIDTH AND COMPACT FINE STEERING MIRROR DEVELOPMENTFOR LASER COMMUNICATIONS”, Proc. ESMATS 2017.

3 Coating can be tailored for specific applications.
4 This refers to the incident power on the surface assuming a ~2% absorption and resulting into a shape deformation of 3 nm rms.

10 DEFORMABLE MIRRORS (DMS)

10.1 INTRODUCTION

Deformable Mirrors (DMs) are key components in Adaptive Optics (AO) systems employed in astronomy and laser satellite communications to compensate for the effects of the degradation in the imaging or signal reception caused by propagation through atmospheric turbulence. Within the context of space-based astronomical programs AO systems are also a key player to achieve high contrast imaging capabilities (e.g. exoplanet science) and compensate imperfections of the optics due to manufacturing flaws, misalignments, gravitational release and stress during launching and deploying phases.

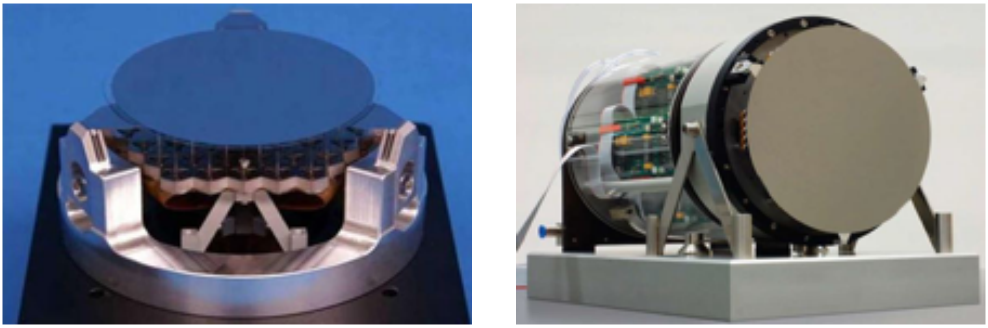


Figure 8: *First DM prototypes by TNO with 61 and 427 actuators (left and right, respectively).*

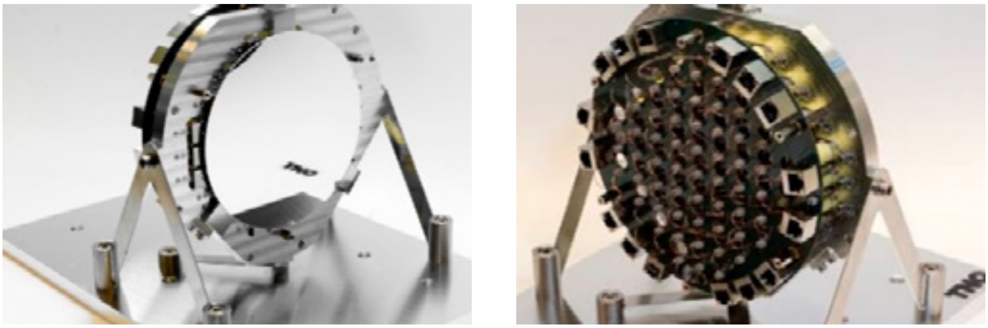


Figure 9: *DM developed for ESA TRP with emphasis on reduced mass & volume and high reliability.*

10.2 KEY TECHNICAL SPECIFICATIONS[5]

Traditionally, DMs have suffered from a lack of actuator reliability and inability to service components. While deformable mirror technology for ground based applications is already widely available and reasonably mature; accuracy, reliability, serviceability and tunable performance are often lacking. For space applications several development steps needed to be made to comply with the different set of requirements. As a result, within the frame of the ESA technology readiness program (TRP) TNO has further developed an actuator technology which is reliable, modular, scalable and serviceable as needed to be used in an AO system on-board future space missions. TNO's DM concept is based on variable reluctance actuators (the same principle is used on TNO FSMs, see Section 7) which has several important advantages, including: high reliability, highly linear actuator response, high scalability to large apertures sizes and low power consumption. These advantages also benefit AO systems to be deployed on ground-based telescopes for astronomy.

The following specifications correspond to the prototype for the ESO TRP program and can be scaled up to larger values depending on the specific application:

Mirror diameter:	Ø 160mm (TNO currently considering scalability to 3m).
Number of actuators:	57 (extendable to several > 1000).
Actuator pitch:	18 mm (scalable down to 4 mm).
Free Actuator stroke[6]:	40 µm (optical surface, wavefront is 2x this value).
Inter-actuator stroke:	10 µm (optical surface, wavefront is 2x this value).
Linearity:	> 99%.
Maximum Power dissipation:	< 30 mW per actuator.

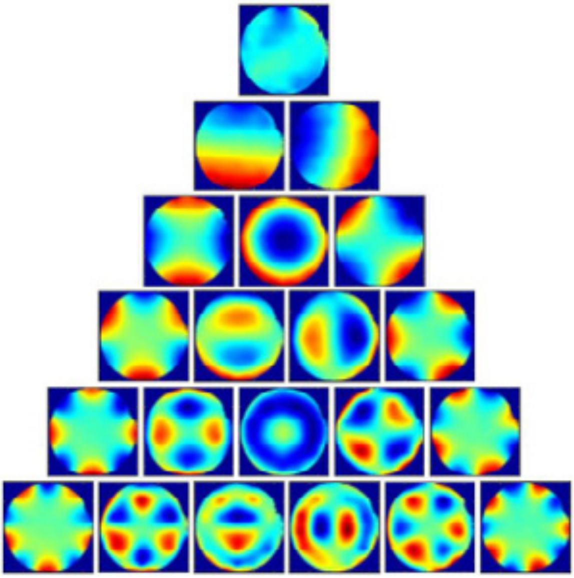


Figure 10: *Zernike mode generation with TNO DM for ESA AO/DM system.*

5 These specifications are based on our most recent prototype within the context of ESA TRP program.
6 This refers to total piston built upon acting on all actuators at the same time.

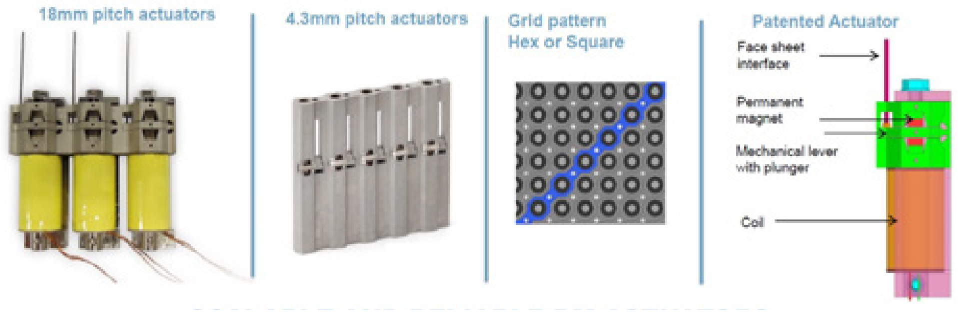


Figure 11: *Scalable and reliable DM actuators.*

10.3 NEXT STEPS

We are also planning to grow our deformable mirror technology to the 1, 2 and 3 meter scale. We are in continuous discussions with potential partners and users to further refine the concept and develop hardware specific to telescope and instrument needs. Initial design studies have already been performed in the range of 1 and 2 meter diameters. Please contact us to discuss further developments.

10.4 REFERENCES

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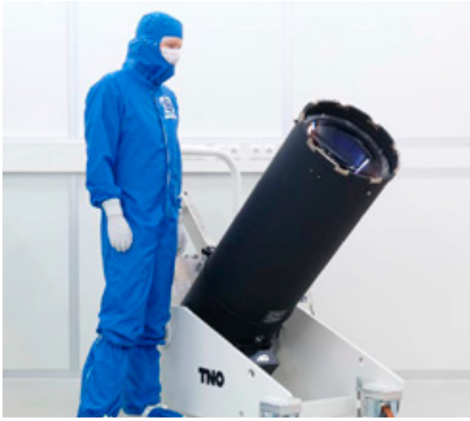
11 LASER LAUNCH TELESCOPES

11.1 INTRODUCTION



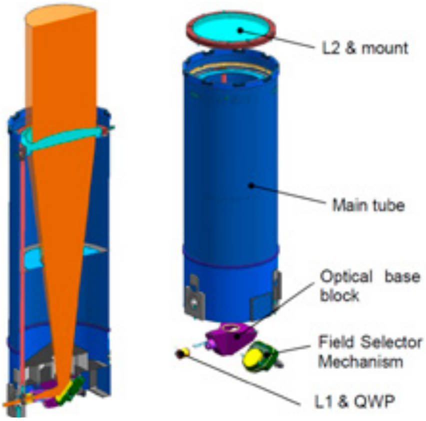


Figure 12. Left: *laser launch telescope assembly ready for delivery to ESO (for VLT).* ***Right:*** *schematic overview showing the main components.*

Laser launch telescopes must maintain spectral quality while expanding and collimating the sodium vapor frequency beam. TNO has delivered 5 launchers with a thermally insensitive design, currently in operation at the VLT. The combination of large FOV and small wavefront error (< 50 nm) led to the use of a large size (Ø 380 mm) convex aspherical L2 lens. L2 is particularly difficult to manufacture and measure, but TNO provided an L2 meeting and exceeding requirements thanks to the use of the in-house NANOMEFOS machine which uniquely allows for measuring the surface form directly, giving feedback to computer controlled deterministic polishing at TNO.

11.2 KEY TECHNICAL SPECIFICATIONS

Athermal design to minimize defocus due to thermal effects.	
Input source beam diameter:	15 mm (source provided by ESO).
Beam expander ratio:	20x (300 mm diameter collimated output beam).
Transmitted wavefront[7] error:	17-23 nm rms (required < 50 nm rms).
Thermally induced defocus:	0.15 waves PV (required <0.2 waves rms).
Pointing accuracy on-sky:	< 0.2” at 3x rms (required 0.3” at 3x rms).
Polarization extinction ratio:	> 99.5 % (required > 98 %).
Throughput:	97.7 % (required > 95 %).
Field selector mechanism:	4.8 arcmin radius FOV.

7 Excluding tip-tilt and focus terms.

11.3 ROM PRICE RANGE

Single unit costs can be significantly reduced based on the heritage achieved by TNO with the units developed for ESO VLT. Prices are significantly reduced by means of spreading project costs over multiple units, and by ordering units to be concurrently developed during production of a series for other customers.

11.4 REFERENCES

- Rijnveld et al., 2011, “A TIP/TILT MIRROR WITH LARGE DYNAMIC RANGE FOR THE ESO VLT FOUR LASER GUIDE STAR FACILITY”, Proc. of SPIE Vol. 8125 “Optomechanics 2011: Innovations and Solutions”, pp. 812503.

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- VLT FOUR LASER GUIDE STAR OPTICAL TUBE ASSEMBLY, https://www.tno.nl/en/focus-areas/industry/roadmaps/space-scientific-instrumentation/space-science/vlt-four-laser-guide-star-optical-tube-assembly/

12 PRECISION INSTRUMENTS AND OPTIMIZED CONTROL

12.1 INTRODUCTION

The demands placed by instruments for aerospace, ground-based astronomy and scientific research are challenging the limits of technology. Creating such instruments therefore calls for a thorough project organization, in which experts in the fields of optics, mechatronics, manufacturing and testing work together in a multidisciplinary setting to achieve the desired result.

These extremely high precision astronomy and space instruments require optimized, real-time control systems. With joint professorships at Leiden and Eindhoven Universities, TNO stays on the cutting edge of control systems. TNO can engineer real-time systems for the most demanding angle accuracies, dimensions and shape controls, including closed-loop feedback from various optical sensors.

12.2 EXAMPLES

12.2.1 Control of primary mirrors for large segmented telescopes

The pioneering work on the Keck telescopes paved the way for the use of segmented primary mirrors for optical telescopes. Keck telescopes example has later been followed by the Gran Telescopio Canarias (GTC), the Hobby-Eberly Telescope (HET) and the Southern African Large Telescope (SALT).

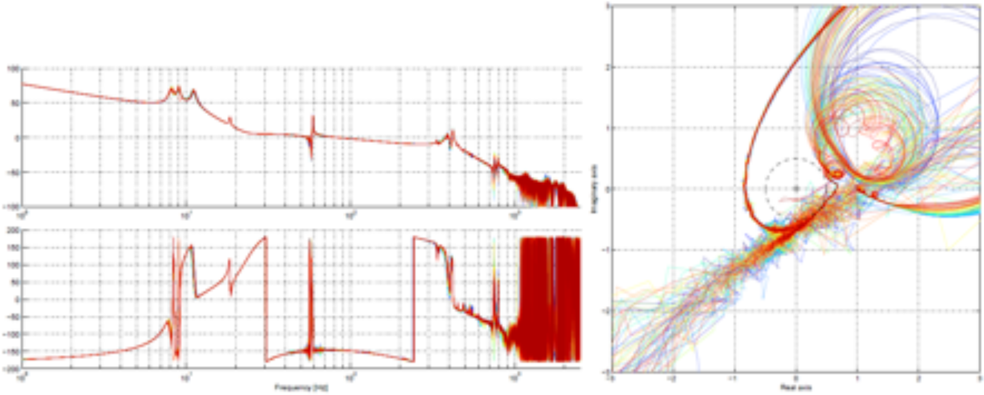

Figure 13: *Open loop responses of PACT (Sect 6, above) with an optimized control strategy for M1 segments.*

The enormous sizes of tomorrow's most prominent telescopes, such as the Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (E-ELT), requires them to use a similar segmented primary mirror concept but over a significantly larger number of mirror segments to be controlled: E-ELT and TMT will need feedback control of the thousands of actuators underneath their segmented primary mirrors (M1), while existing Keck and GTC telescopes need to control only 36 segments. Differences in actuator dynamics and spatially and temporally changing disturbances make it extremely difficult to formulate classical controllers which are both sufficiently robust and high performing.

TNO has developed and tested a control approach, in which the actual system response is quickly measured, disturbances are continuously estimated and the controller is adapted in real-time. The TNO algorithm has been tested on an actual M1-relevant setup, in which it converges to a sub-nm optimum within a few minutes, keeps track of changing disturbances and shows its reliability over multiple days.

12.2.2 GAIA Basic Angle Monitoring (BAM) system

TNO has developed the Basic Angle Monitoring Opto-Mechanical Assembly (BAM OMA). This is a picometer metrology system aimed at guaranteeing the constant angle between the two telescopes on board Gaia.

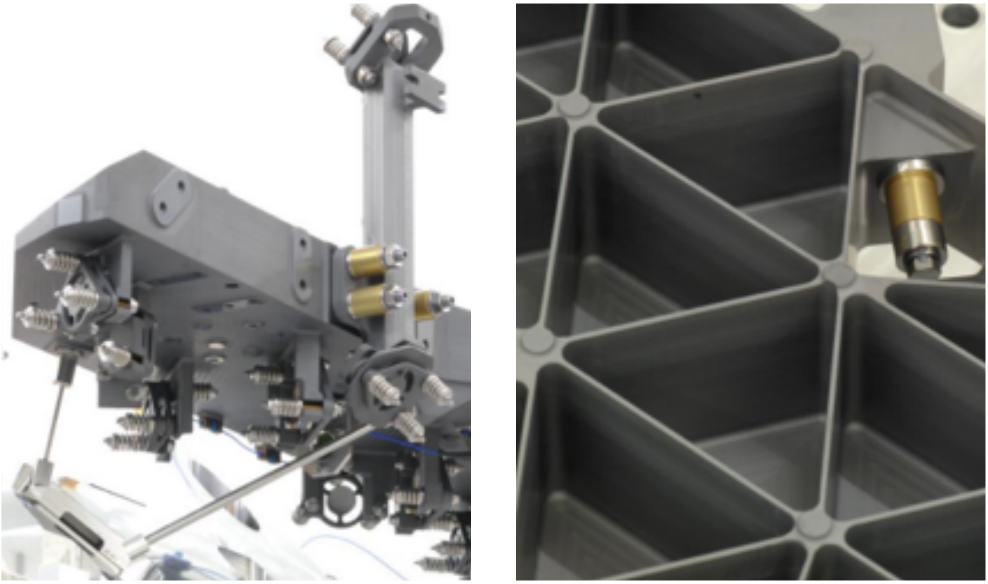

Figure 14. Left: *details of Sintered Silicon Carbide (SSiC) BAM bar 2 with optics, periscope and Invar iso-static mount.* ***Right:*** *open backside structure of SSic baseplate.*

BAM consists of two laser interferometers: two pairs of parallel laser bundles are sent to the two telescopes, which create two interference patterns on a detector. If the basic angle varies, the interference patterns will shift. The Basic Angle variation is measured within a precision of 0.5 microarcsec, during an observation period of 5 minutes, which equals an Optical Path Difference (OPD) as small as 1.5 picometers.

The BAM OMA consists of two optical benches, a number of flat mirrors, beam splitters, fibre collimators and periscopes. In order to fulfil the stability requirements for such accurate OPD measurements, the entire BAM OMA is constructed from Silicon Carbide.

12.2.3 LISA In-Field Pointing Mechanism (IFPM)

An active mirror mechanism to correct for seasonal alignment errors of the evolved Laser Interferometer Space Antenna (LISA), a future ESA space mission meant to accurately detect gravitational waves, has been designed, realized and tested by TNO. The mechanism is designed to move ±2.5° in a whole year with extreme accuracy. The design utilizes Haberland hinges and piezo stepper actuators and yields satisfactory frequency-domain open-loop performance. Apart from relatively low DC-gain variations, the resulting dynamics are nearly constant over a full actuator cycle. A closed-loop controller design based on the measured dynamics complies with the requirement of just 5 nrad/VHz of jitter on the mirror angle.

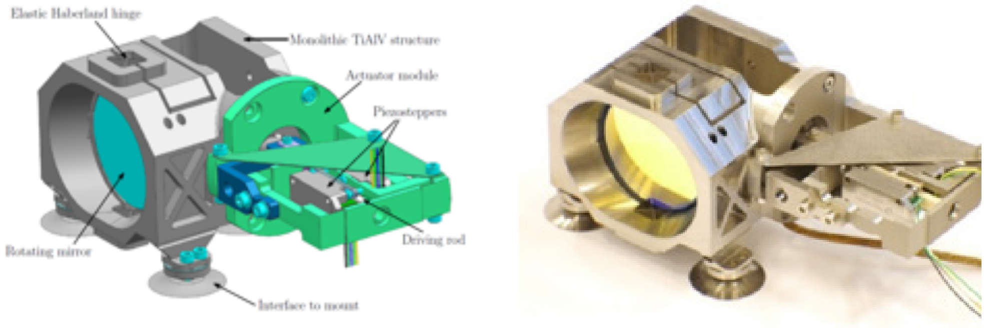

Figure 15. Left: *CAD version of the latest IFPM design showing the most relevant parts.* ***Right:*** *the realized IFPM at TNO able to achieve milliarcsecond angular pointing accuracy.*

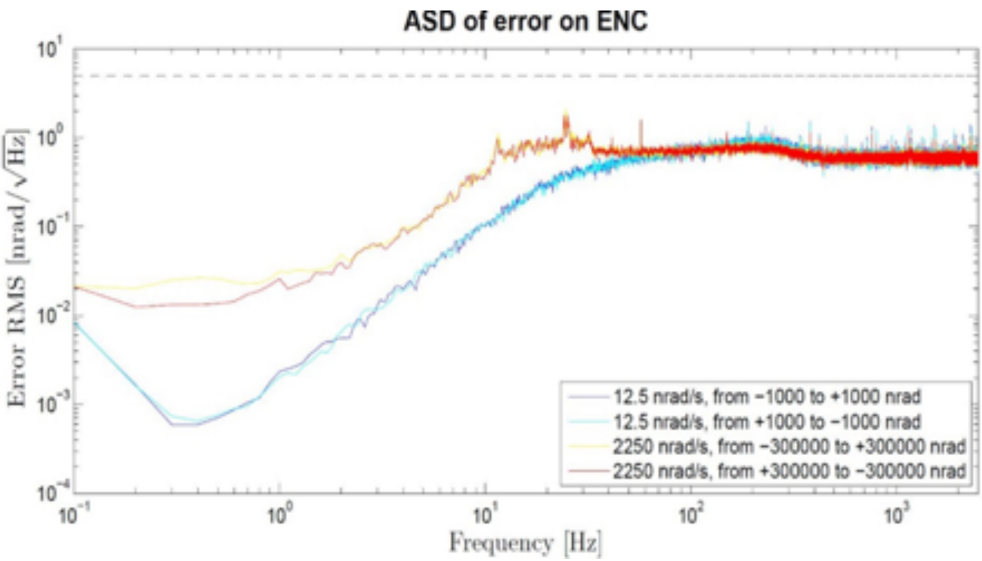

Figure 16: *Actual performance for a series of loads (color lines) vs requirement (horizonal dash line).*

13 OPTICS MANUFACTURING

13.1 INTRODUCTION

TNO's Centre for Optics Manufacturing is specialized in the development of application-specific optical elements and coatings. Optics Manufacturing also provides advice on the manufacturability and costs of products, and conducts production process research for industry.

We focus on the manufacturing of sophisticated optical components and instruments. TNO's advice and products are commonly applied in space instruments, astronomy, scientific research, Semicon and high-tech industries. Maintaining the ability to make unique and extremely accurate optics enables TNO's cutting-edge designs for opto-mechatronic instruments.

Optics Manufacturing of TNO houses a multitude of experts and professionals, whose knowledge and experience is directed towards a large diversity of processes. TNO has a full range of in-house facilities for optics manufacturing including asphere and freeform optics:

- Optics Design and Engineering.
- Classic manufacturing: polishing and grinding technology for the production of spherical optics.
- Computer controlled polishing for the finishing of aspheric and freeform optics.
- MRF polishing for the polishing of aspheric optics.
- Ion Beam Figuring for correction to higher surface accuracies.
- Ultra-precision processing for diamond turning, milling and grinding of optical components made of metal, plastic, glass, crystal and ceramic materials.
- Processing and application of standard and special optical materials (glass, crystal, metal and plastic) Optical measurement for 2D/3D geometry and optical performance: Nanomefos absolute metrology (see Section 16).
- The design and application of optical thin films for (anti)reflective custom coatings and interference filters.
- Enhanced UV silver coatings (see Section 14).
- The assembly of optical systems including gluing and optical contacting.
- Precise alignment of optics.
- Verification and qualification.

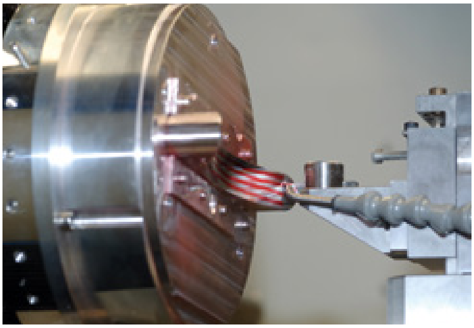

Figure 19. *Left: bonnet polishing.* ***Right:*** *ultra-precision diamond turning.*

13.2 EXAMPLES

SOFIA M2:

- Light weight (2.03 kg) Aluminum mirror.
- Convex hyperbolic mirror. Ø350mm.
- Curvature radius: 954.78 mm.
- Surface error: 121 nm RMS.
- Surface roughness: 3.5 nm RMS.
- Diffraction limited at 3.6 µm.

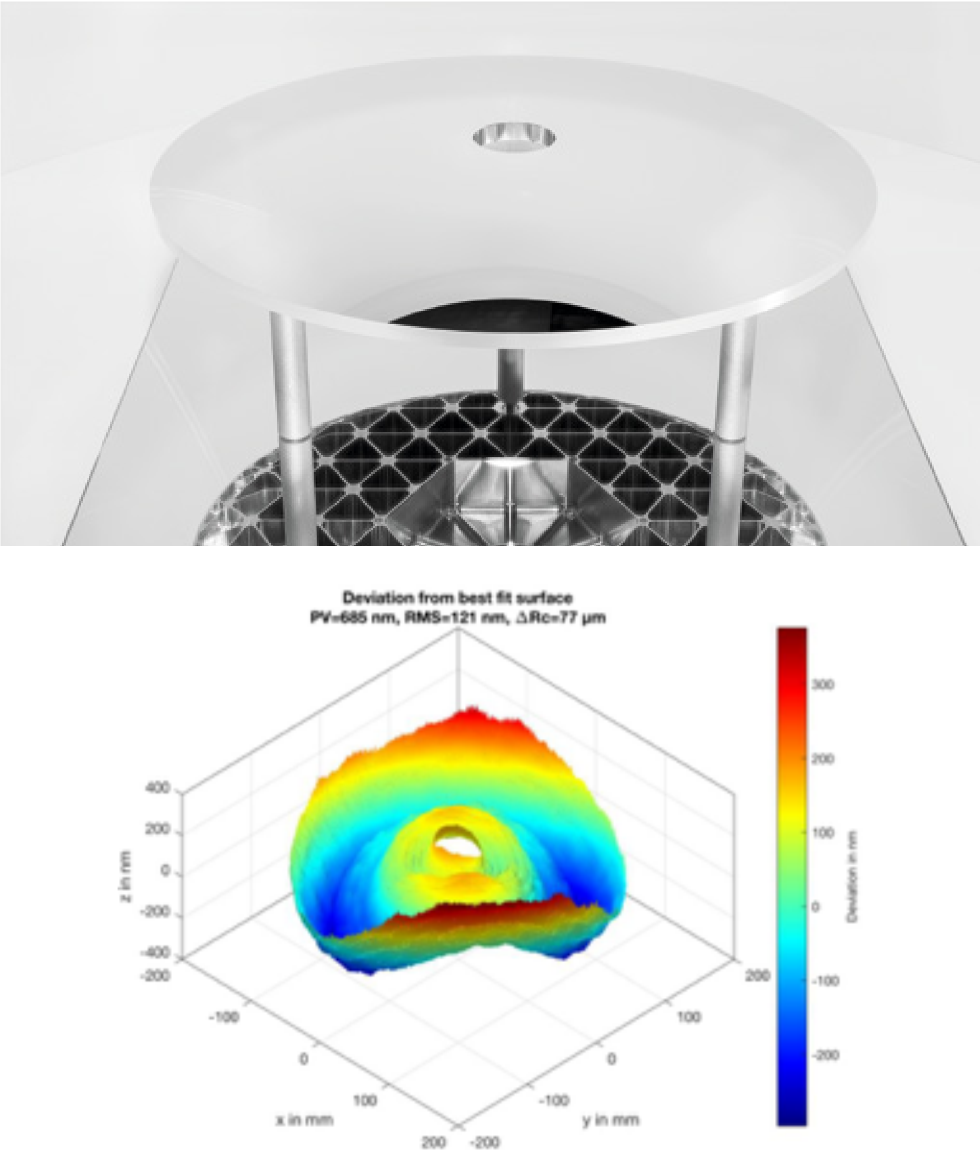

Figure 20. Top: *SOFIA M2 realized by TNO.* ***Bottom:*** *surface error map as measured on final unit.*

L2 lens in Laser Launch Telescope for LGS AO in VLT (see Section 11):
- Large refractive optics: Ø 380 mm.
- Convex aspherical side:
  - radius of curvature 637.381 mm.
  - conic constant -0.447.
  - Departure from best-fit-sphere: 320 µm.
  - Surface error: 24 nm rms (after six polishing runs starting at 5 µm PV).
  - Final contribution to wavefront error: 7 nm rms.

Concave spherical side:
- radius of curvature 6876.981 mm.
- Surface error: 18 nm rms.
- Final contribution to wavefront error: 7 nm rms.

Custom 589 nm coating with measured reflectivity 0.2% for both sides.

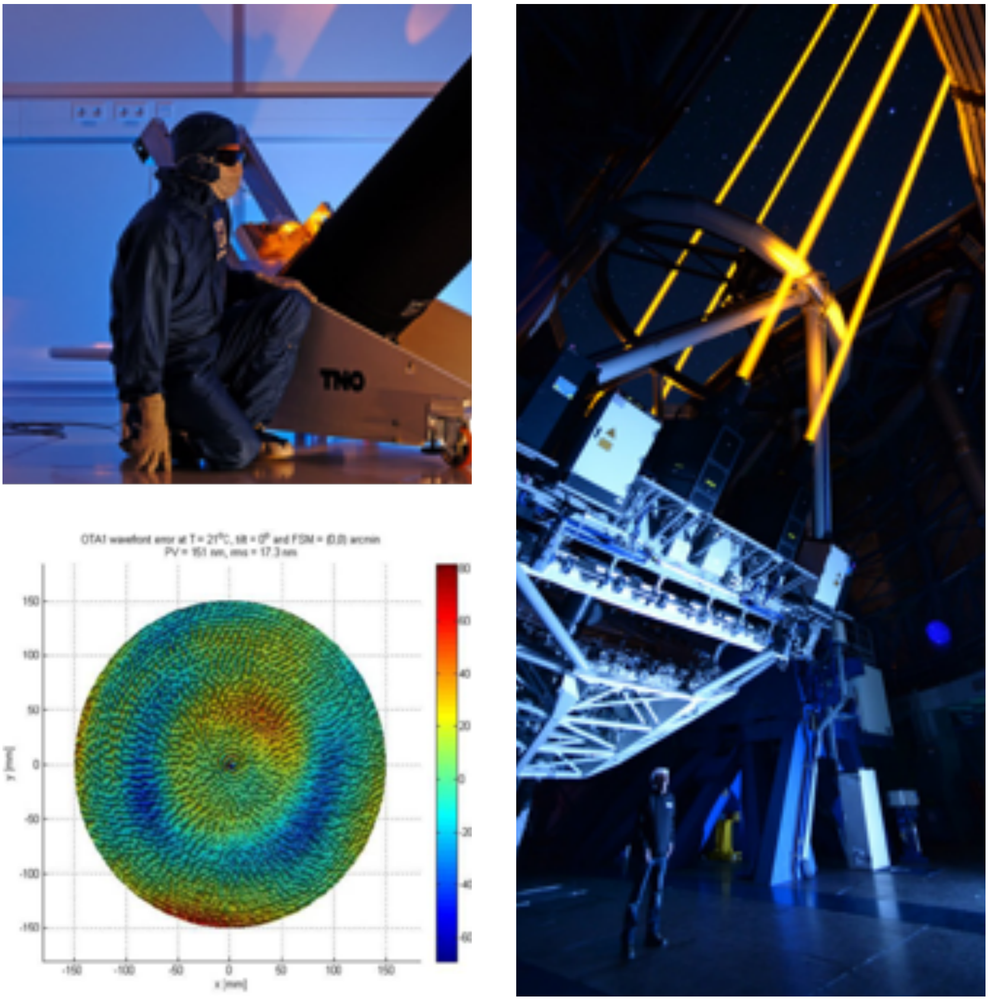

Figure 21. Top Left: *realized lauser launch system.* ***Bottom Left:*** *wavefront error as measured on realized unit.* ***Right:*** *commissioning of 4 units at VLT.*

13.3 REFERENCES

- Optics Manufacturing:
  https://www.tno.nl/en/focus-areas/industry/roadmaps/semiconductor-equipment/industrial-instrumentation/optics-manufacturing/

- Ultra-Precision Diamond Turning:
  https://www.tno.nl/en/focus-areas/industry/roadmaps/semiconductor-equipment/industrial-instrumentation/ultra-precision-diamond-turning/

- NANOMEFOS: NON-CONTACT MEASUREMENT MACHINE FREEFORM OPTICS,
  https://www.tno.nl/en/focus-areas/industry/roadmaps/semiconductor-equipment/industrial-instrumentation/nanomefos/

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- Henselmans et al., 2012, “DESIGN, ANALYSIS AND TESTING OF THE OPTICAL TUBE ASSEMBLIES FOR THE ESO VLT FOUR LASER GUIDE STAR FACILITY”; Proc. of SPIE Vol. 8447 “Adaptive Optics Systems III”, pp. 84474N.

14 PROTECTED SILVER COATINGS

There is an ongoing demand for increasing throughput in high-end optical systems. Silver based coatings show the highest reflection across the visible spectrum. However, the performance in the UV range is poor and they tarnish quickly as result of the exposure to uncontrolled environments (e.g. high humidity, Sulphur, etc.).

14.1 INTRODUCTION

TNO Centre for Optics Manufacturing has designed and developed a silver based coating using e-beam evaporation in a clean room that shows stable performance over a broad spectral range (extending down to 350nm, see Figure 14), even when exposed to harsh environments. TNO silver coated mirrors offer the highest reflection from near Ultra Violet to Infrared and are suitable for demanding applications such as Space, Astronomy and other high technology instrumentation.

Figure 22: *Aluminum collimating mirror with silver coating.*

In order to ensure the durability, the coating has been submitted to a demanding qualification program containing tests that are performed according to the ISO 9211 standard. Performance wise the TNO silver coating offers an interesting and reliable alternative for aluminum-based coatings, which so far have been the standard for telescopes and other high-end optics. The projected extended life (> 5 years) of TNO protected silver coatings over traditional aluminum-based coating translates directly into a better efficiency, therefore optimizing scientific output and a significant savings in operational costs.

14.2 KEY TECHNICAL SPECIFICATIONS

TNO is specialized in the development of application specific coatings. TNO routinely develops coatings that have specific requirements on reflection or transmission in various spectral bands. TNO's UV enhanced silver coatings deliver:

- High reflectivity (see Figure 14):~95% in λ in [350, 800] nm, >97% in [800, 2400] nm.
- Coating on following substrate materials: Aluminum, phosphorous nickel plated aluminum, fused silica and zerodur.
- Standard treated surface up to Ø 350 mm. Larger diameters can be discussed.
- Durability specifications in Table 1.
- Extended coating life (> 5 years) which optimizes science output and reduces operational costs.

Durability	Method	Standard
Abrasion	50 Strokes with cheesecloth and 5N force	ISO9211-3-1-01
Adhesion	Slow tape removal	ISO9211-3-2-01
Solvent solubility	15 min. immersion in acetone and ethanol	ISO9211-3-12-3-02
Damp heat	16 hours exposure at 55°C and 95% relative humidity	ISO9211-3-5-07
Thermal cycling	Thermal cycling from -50°C – +70°C – 20 cycles under ambient pressure – 5 cycles under vacuum	ISO9211-3-8-07
Radiation hardness	6.2kGy(Si), using 10 MeV protons	

Table 1: *Durability specification for TNO protected silver coatings.*

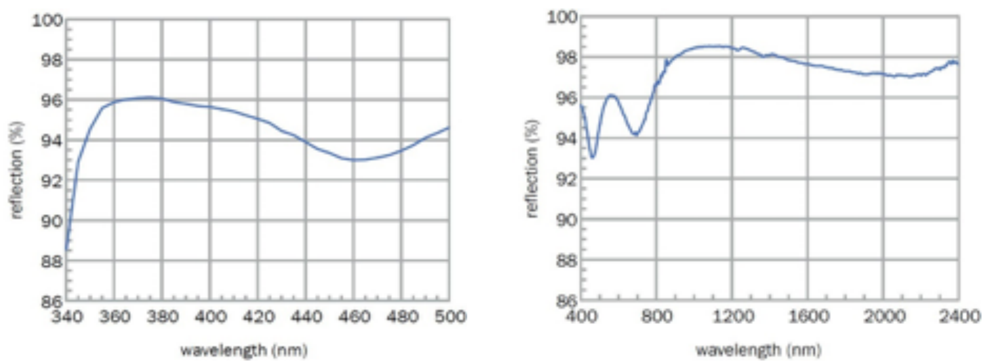

Figure 23: *Coating performance from Visible to Near Infrared in near normal incidence.*

14.3 NEXT STEPS

We are in continuous discussions with potential users, to further refine the concept and develop hardware specific to telescope needs. Please contact us to discuss further developments.

15 NON-CONTACT FREEFORM OPTICAL SURFACE MEASUREMENT (NANOFEMOS)

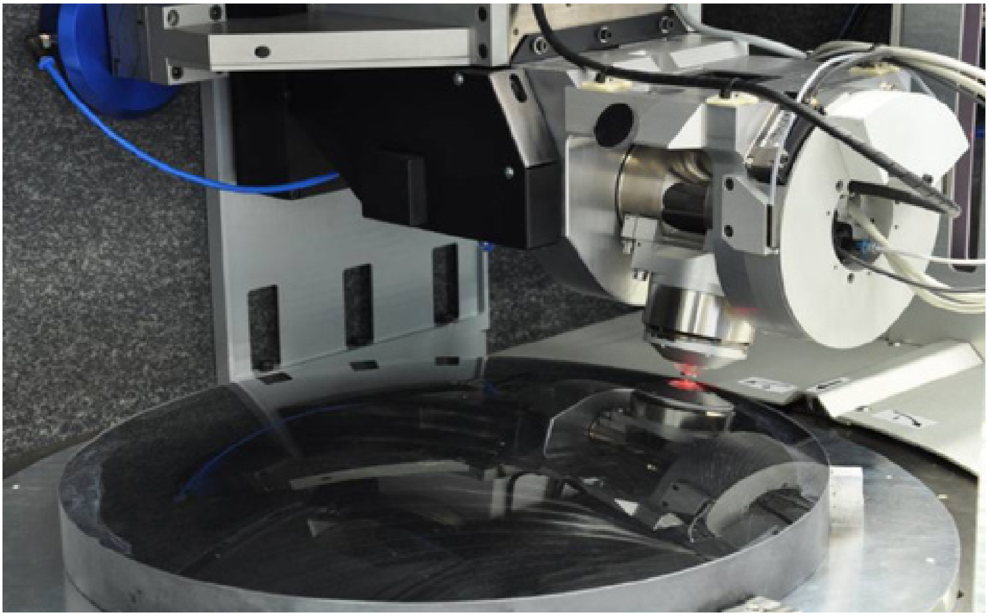

Figure 25: *Metrology laser launch L2 lens (in Section 11).*

15.1 INTRODUCTION

Nanofemos is a fast, non-contact measurement system which is capable of measuring convex and concave optics including flat, spherical, aspherical and freeform surfaces down to nm range with diameters up to 0.5 meter (with designs for a 2m in diameter system in the future).

The concept of a non-contact autofocus sensor, combined with a highly accurate metrology system to obtain absolute surface measurements is a scalable concept.

Nanomefos will be commercialized by the Dutch company Dutch United Instrument and a range of products will be developed: Nanomefos 500 with upgraded functionalities, Nanomefos 300, Nanomefos 800 and Megamefos (for diameters of up to 2m).

Within the context of this brochure, the main application areas of nanomefos is the measurement and high-precision characterization of optical surfaces for spectrometric and imaging applications in the fields of scientific research, astronomy, lithography and space-based instrumentation. Nanomefos enabled the TROPOMI free form telescope which allowed ten times better performance than conventional design used in OMI within the same volume.

15.2 KEY TECHNICAL & PROVEN SPECIFICATIONS

- Non-contact.
- Measurable shapes: convex concave, flat, aspherical, freeform.
- Measurement volume: 500 × 100 mm.
- Maximum slope: +900 to –450 (radial); +50 to –50 (tangential).
- Measurement uncertainty: <15 nm RMS.
- Typical measurement setup time: <1 h.
- Typical measurement time: < 15 min.

15.3 EXAMPLES USING NANOMEFOS

Nanomefos have been widely used at TNO during manufacturing and testing of highly specialized systems. Some of the systems described elsewhere in this document are:

- SOFIA M2 mirror: used to determine aberration on original M2 and need for a new M2 (built by TNO. See section 13.2).
- GAIA Basic Angle Monitoring System: picometer metrology system guaranteeing the constant angle between the two telescopes on-board ESA GAIA mission (Section 12.2.2).
- Large size (Ø 380 mm) convex aspherical L2 lens in Laser Launch Telescope for LGS AO in VLT (see Section 11).
- Proposal for a design of metrology system for the E-ELT M1 segments when mounted on M1 Support Segment Support structure (see Section 5).
- Design & characterization of freeform mirrors in TROPOMI instrument (see Section 15.2.1).

15.4 NEXT STEPS

We are developing a product line with industrial partners. Contact us for more details.

15.5 REFERENCES

- Henselmans et al., 2009, “NANOMETER LEVEL FREEFORM SURFACE MEASUREMENTS WITH THE NANOMEFOS NON-CONTACT MEASUREMENT MACHINE”. Proc. of SPIE Vol. 7426 “Optical Manufacturing and Testing VIII”, pp. 742606.
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- NANOMEFOS: NON-CONTACT MEASUREMENT MACHINE FREEFORM OPTICS: https://www.tno.nl/en/focus-areas/industry/roadmaps/semiconductor-equipment/industrial-instrumentation/nanomefos/

16 ASTRONOMICAL & SPACE INSTRUMENTS

16.1 INTRODUCTION

Ever since its foundation, TNO has been active in the field of advanced optical instruments, and for over 50 years has been developing instruments for use in space, astronomy, scientific research and manufacturing industry.

TNO has developed a broad range of optical instruments from ground science to satellite deployment. Our scientists and engineers have integrated knowledge of optics, mechanics, electronics and controls (ultra-precision opto-mechatronics), to design and deliver the most challenging instruments to the most challenging environments.

TNO's Scientific instruments (spectrometers, imagers, polarimeters, endoscopes, on-board calibration, etc.) have been developed for ESA, NASA, ESO, ITER, Airbus, Thales, General Atomics and other key customers around the world. Examples of this work include the development of instruments and wavefront sensors on board the GAIA space telescope and instruments for measuring the ozone layer (GOME and TROPOMI).

16.2 EXAMPLES

16.2.1 TROPOMI

The satellite instrument TROPOMI is the most sophisticated and accurate instrument ever to carry out measurements from space for the purposes of climate and air pollution research. TROPOMI has been conceived and designed by experts in optics and mechanics at TNO and Dutch Space and has been built largely by the Dutch manufacturing industry. On 13 October 2017 this instrument, which is incorporated in the European satellite Sentinel-5 Precursor, was launched by the European Space Agency (ESA) and has since been orbiting the Earth at an altitude of 824 kilometres collecting data.

Figure 23: *Coating performance from Visible to Near Infrared in near normal incidence.*

The TROPOMI Instrument (Sentinel 5 Precursor), designed and built by TNO.
See: Nijkerk et al., “THE TROPOMI TELESCOPE,” in Proceedings of International Conference on Space Optics ICSO (2012), pp. 19

16.2.2 GAIA wavefront sensor (WFS)

The Gaia mission was launched on 19 December 2013 and is already delivering spectacular data to scientists: approximately around the year 2022 Gaia will provide us with a very accurate three-dimensional map of our Galaxy.

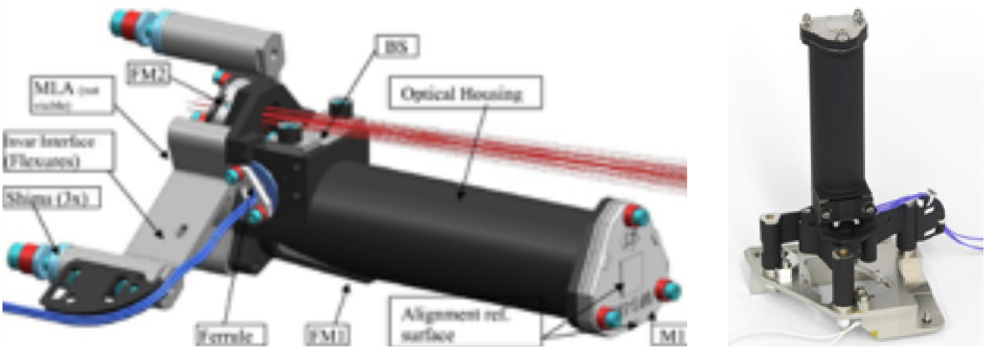

Figure 24: *Overview of the GAIA WFS mechanical design showing (left) the qualification model.*

TNO developed, built, assembled and tested the two Gaia Shack-Hartmann-type wavefront sensors (WFS; one WFS per telescope on board of Gaia). The WFSs are used for diagnostics, metrology and re-aligning the two telescopes on board Gaia, to cancel errors due to mirror microsettings and gravity release. The required accuracy for the WFSs is λ/1000! Gaia is active over a broad wavelength (450 to 900 nm) and in cryogenic conditions (130 to 200 K).

See: Vosteen et al., 2009, “WAVEFRONT SENSOT FOR THE ESA-GIAIA MISSION”, Proc. of SPIE Vol. 7439 “Astronomical and Space Optical Systems”, pp. 743914

16.2.3 GAIA Auto-collimating Flat Mirror Assembly (AFMA)

As part of the Optical Ground Support Equipment (OGSE) for the ESA GAIA mission, TNO designed and developed the Auto-collimating Flat Mirror Assembly (AFMA) system. The main goal of the AFMA system was to simulate the rotation of the GAIA satellite around its vertical axis. The accuracy of the important scanning direction is very high: 3.2 nrad per 4.4 s. As such, it was one of the most important ground support equipment tools to test the payload performance of the GAIA mission.

Figure 25. Left: *realization of one of the AFMA modules without mirrors mounted.* ***Right:*** *GAIA payload with two realized AFMAs (one in the top right corner, one at the bottom right).*

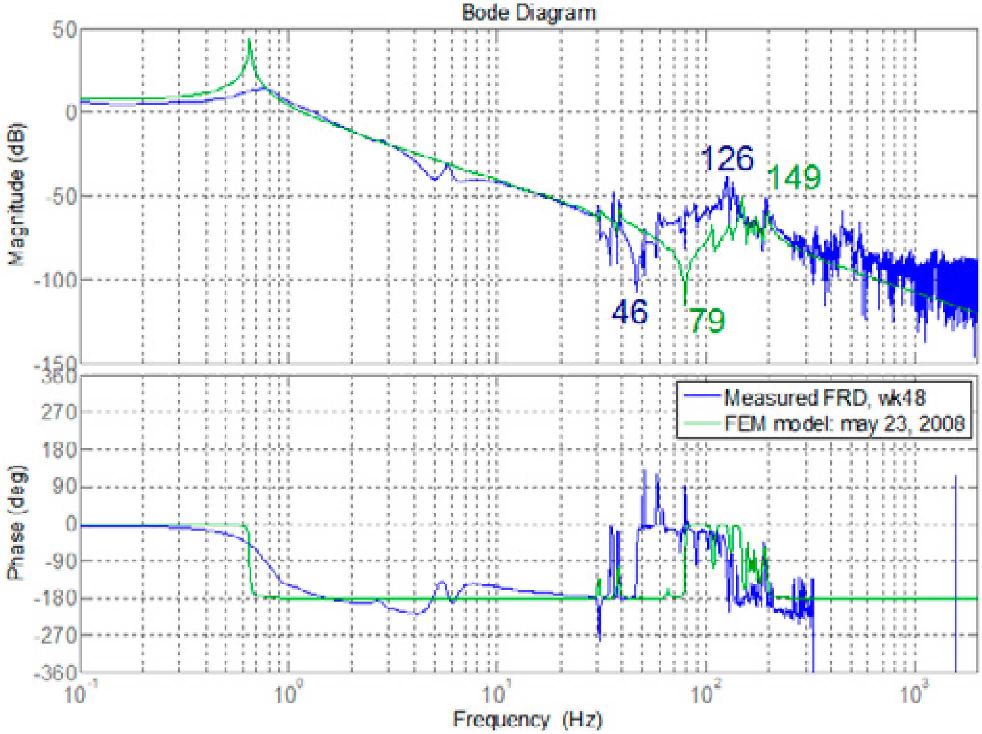

Figure 26: *comparison of predicted open-loop frequency response function (FRF) from model and measurement. A post-flight re-analysis improved the dynamic behavior of AFMA. The performance of TNO's design during commissioning was excellent with full accomplishment of all requirements. One of the challenges of the AFMA design and realization has proven to be the prediction of the dynamic behavior of AFMA and the accurate prediction of its performance given the required nrad stability and the need to control ground vibrations during on-ground testing.*

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- https://www.tno.nl/en/about-tno/news/2018/1/lisa-mission-passes-successfully-the-mission-definition-review/

- Bos et al, 2016, “ON THE PERFORMANE OF THE GAIA AUTO-COLLIMATING FLAT MIRROR ASSEMBLY: COULD IT BE EVEN BETTER?”, Proc. of SPIE Vol. 9904 “Space Telescopes and Instrumentation 2016: Optical, Infrared and Millimeter Wave”, pp. 99044F.

16.3 TNO, EXPERTISE AREA SPACE SYSTEMS ENGINEERING

In the context of space programmes, since 1964 TNO has been delivering innovative and complete solutions for large companies, SMEs and governmental organisations. TNO has specialised in instrumentation for science missions, for Earth observation, for attitude measurement, and in space mechanisms. The TNO capabilities cover all phases of space projects, ranging from feasibility studies to detailed design studies and from prototyping to development, production, test and calibration of flight hardware.

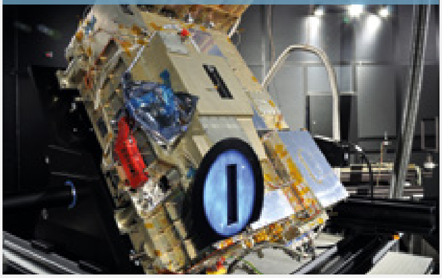
The TNO space department covers the following heritage in the specific fields as described below.

16.3.1 TNO general experience in Optical instruments for Earth observation

- Atmospheric science in environmental missions (ozone detection). Examples: GOME (ERS-2), SCIAMACHY (for ENVISAT), the Ozone Monitoring Imaging Spectrometer OMI (for NASA mission EOS-CHEM), GOME-2 (Metop), MSI VNS (EarthCare);
- Focal plane assemblies, such as for MIPAS (ENVISAT);
- TROPOMI for the Sentinel 5 precursor mission;
- Sentinel 5 UV1 and TSBOA;
- Pre-phase A study for NO2 Compact Spectrometers;
- ASPIM design concept for a single wavelength band wide angle polarimeter (with SRON, own funding);
- SPEXLite design concept for polarimetric imaging spectrometer (with ADSN, and SRON, proposal concept for NASA);
- Spectrolight instrument concept for a compact hyper-spectral imager to measure NO2 and suitable for CubeSat’s (with ADSN, ISIS and SRON, on EFRO contract).

Examples of high-end optical instruments for space developed by TNO.

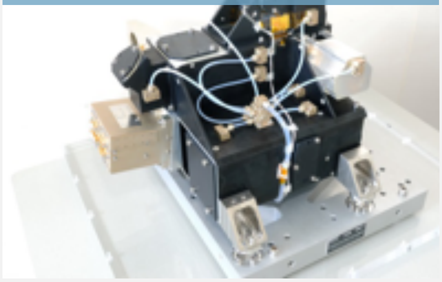
GOME-2 (METOP)



SCIAMACHY (ENVISAT)

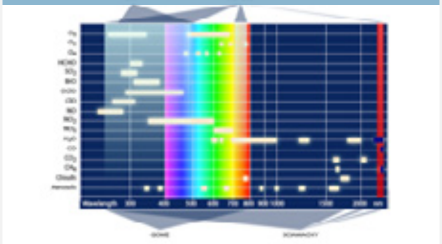
GOME-2 (METOP)

OMI (NASA-AURA)



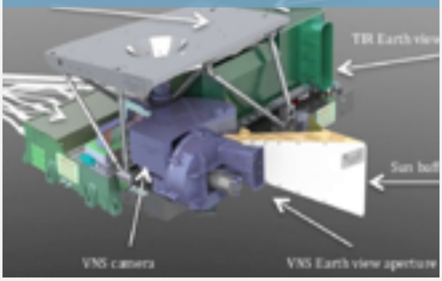
TROPOMI OBM

WAVELENGTH RANGE AND PRODUCTS



TROPOMI (Tropospheric Ozone-Monitoring Instrument) is a five-channel UV/VIS/NIR/SWIR non-scanning nadir viewing imaging spectrometer that combines a wide swath (114°) with high spatial resolution (10 × 10 km2). The instrument heritage consists of GOME on ERS-2, SCIAMACHY on Envisat, GOME-2 on Metop and, especially, OMI on EOS-Aura. TROPOMI has even smaller ground pixels than OMI-Aura but still exceeds OMI's signal-to-noise performance. These improvements optimise the possibility to retrieve tropospheric trace gases. In addition, the SWIR capabilities of TROPOMI are far better than SCIAMACHY's both in terms of spatial resolution and signal to noise performance. TROPOMI covers the OMI wavelengths to measure O3, NO2, HCHO, SO2 and aerosols and adds a NIR channel and a SWIR module for improved cloud detection, aerosol height distribution and CO and CH4 measurements.

MSI VNS (EARTHCARE)



The EarthCARE satellite mission objective is the observation of clouds and aerosols from low Earth orbit. The EarthCARE Multispectral Imager (MSI) is a radiometric imager that is intended to remotely determine cloud cover and cloud top surface temperature. MSI will image the Earth atmosphere in 7 spectral bands. The MSI instrument consists of two parts: the Visible, Near infrared and Short wave infrared (VNS) unit and the Thermal InfraRed (TIR) unit. VNS is a Nadir viewing push broom imager instrument with a swath width of 150 km. TNO is building the VNS module.

VNS shall provide images of the ground scene in four wavelength bands:

VNS channel	Central wavelength [nm]	Spectral width [nm]
VIS	670	20
NIR	865	20
SWIR1	1650	50
SWIR2	2210	100

16.3.2 More examples of TNO Space heritage

Precision engineering & mechanisms:
- High accuracy mechanisms in space, e.g. refocusing mechanisms, such as for HIPPARCOS and Meteosat Second Generation SEVIRI, and for LISA.
- Interferometry equipment such as delay lines and nulling technology for DARWIN.
- High-stability opto-mechanical equipment such as the GAIA Basic Angle Monitoring system, the GAIA WaveFront Sensor and LISA mechanisms.

Scientific optical instruments for astronomy and astrometry:
- Spectrometers from UV to far Infrared, flown on TD-1A, ANS, IRAS, ISO and HIFI space missions.
- Photometers, flown on IRAS.
- Focal plane assemblies, such as for HIPPARCOS and for the Faint Object Camera (FOC) in Hubble Space Telescope (HST).

Optical Attitude Sensors:
- Analog Coarse and Fine Sun sensors, flown on various telecommunication, earth observation and scientific missions (Globalstar, Spacebus4000, O3B).
- Digital Sun Sensor (maiden flight on ESA's PROBA-2 S/C).
- Mini- and Micro-Sun sensor technology developments.

Cleanliness and Contamination control:
- For various space projects very demanding contamination requirements have been met. This has led to a strong knowledge position of cleanliness and contamination control, e.g. OMI, S5P, GAIAI BAM, BepiColombo Fine Sun Sensor.

Some highlights of the TNO heritage, relevant for this proposal, are shown below.

Some examples of high stability optics and opto-mechatronics developed by TNO.

EUCLID THERMAL STABLE OPTICS MOUNT

For the ESA TRP EUCLID mirrors, TNO has performed research to highly stable and stress free mounting of medium sized optics cooled to low temperatures.

The mounts are based on flexures, resulting in a very stiff system without hysteresis. The wavefront distortion due to cooling down to 140 K is less than 34nm over 125mm beam.

GAIA BAM BAR #2

GAIA BAM TV TEST

Gaia is equipped with a Basic Angle Monitoring (BAM) system. This SiC metrology system consists of two laser interferometers and is able to measure an Optical Path Difference (OPD) as small as 1.5 picometers rms.

Gaia BAM performance over the entire operational range (including shock and vibration environment):
Beam pointing (deviation from nominal angle): <100 μrad
Differential beam tilt (angle between A and A' or C and C'): <50 μrad
OPD (path diff. between A and A' or C and C'): <8.5 μm

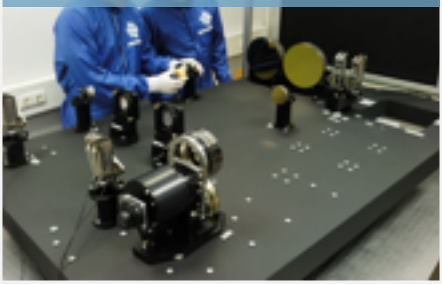
Stability of individual components:
Mirrors/beamsplitters: < 1 μrad tip/tilt
Collimator fibre-tip position stability:
< 1 μm (radial) /< 2 μm (axial)
WFE mirrors/beamsplitters:< 3 nm rms

tno.nl/gaiabam

VLT 4LGSF OTA

TNO has developed the Laser Launch Telescopes for the ESO VLT Four Laser Guide Star Facility (4LGSF). The 4LGSF is part of the new ESO Adaptive Optics Facility (AOF) on Unit Telescope 4 (UT4). The Laser Launch Telescope launches a 300 mm laser beam into the sky and has the following performance:
Defocus during thermal transients: <90 nm
On sky pointing accuracy: < 0.1" (3σ) over 4.8' range
WFE <25 nm rms WFE (large aspherical optics)
tno.nl/vlt4lgsf

VLTI PRIMA UT STAR SEPARATOR



VLT PRIMA AT STAR SEPARATOR

ESO is building the Phase Referenced Imaging and Microarcsecond Astronomy (PRIMA) facility for the VLTI in Chile. PRIMA will enable interferometric imaging of very faint objects and high precision astrometry with both Unit (UT) and Auxiliary (AT) telescopes.

TNO has developed the PRIMA Star Separator (STS) subsystems for both the UT and AT telescopes.

The STS separates the light of two astronomical objects and feeds it into the long stroke delay line. The STS compensates for field rotation (UT only), stabilises the beam tip tilt and adjust the lateral and axial alignment of the pupil.

Star Separator performance:
Pointing range 149"(vertical), 130"(horizontal) Pointing accuracy ±0.01"
Pointing resolution ±0.002"
Pointing correction freq. 100 Hz
Chopping frequency 63 Hz

E-ELT M1 PROTOTYPE MIRROR SUPPORT AND POSITION ACTUATORS

The Primary Mirror (M1) of the E-ELT will have a diameter of 42m and consists of 984 quasi-hexagonal segments with a circumscribed diameter of 1.4 m. Each segment is connected to the back structure by means of an axial support system consisting of three whiffle trees and three position actuators (PACT). The PACTs are used to control the out-of-plane motions piston, tip and tilt under wind loading with a position accuracy of <3 nm rms. The segment assembly includes 9 shape actuators, the warping harness, which allow correction of three aberrations: curvature, astigmatism, and trefoil.

Relevance: demonstrating TNO experience in high accuracy/high stability optics and opto-mechatronics

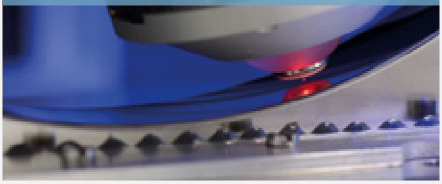
Some examples of advanced optics developed by TNO.

ROBOTIC POLISHING OF LARGE ASPHERIC LENS

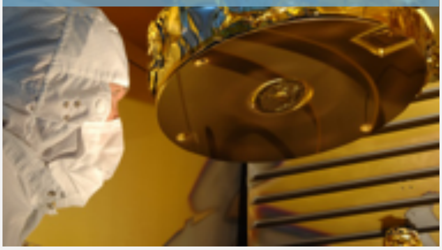
DIAMOND TURNING OF LARGE FREEFORM MIRROR

SURFACE ERROR MEASUREMENT OF LARGE ASPHERE WITH NANOMEFOS; TNO.NL/NANOMEFOS

SURFACE ERROR MEASUREMENT OF STRONGLY CURVED DIAMOND TURNED FREEFORM MIRROR ON NANOMEFOS



GOLD COATING ON OFF-AXIS PARABOLIC ZERODUR MIRROR



AR COATING ON ASPHERIC LENS

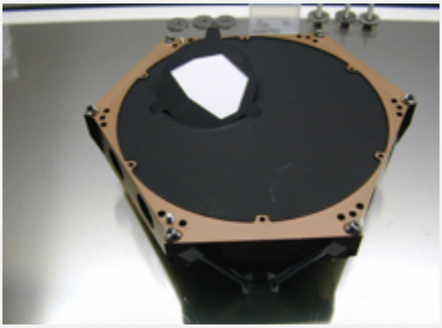
Relevance: demonstrating TNO experience in advanced optics manufacturing

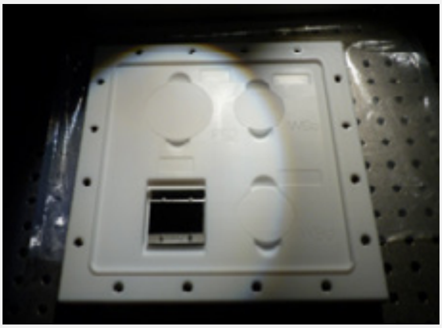
16.3.3 TNO specific experience in calibration

TNO has a leading position in calibration technologies for earth observation instruments. Many of the instrument characteristics depend on the environment in which the instrument is operated. In case of space instruments this means in vacuum, within a certain temperature range and zero gravity. Calibration is performed in dedicated Thermal Vacuum facilities at the Van Leeuwenhoek Laboratory of TNO in Delft.

TNO has been responsible for the calibration of the following Earth observation instruments: GOME, SCIAMACHY, OMI, GOME-2 and MSI-VNS. Currently, within the Sentinel-5 Airbus DS core-team, TNO is responsible for the Calibration Engineering, which comprises the definition of the overall calibration approach, the specification of the equipment, development of the SW to calculate the KDP, responsibility for the proper execution of the calibration test campaign and delivery of the CCDB.

Activity	**Calibration Unit Viscal for Sentinel 3 with calibrated Zenith Diffusers**
Customers	**Jenoptronik, Leonardo, Thales and others**
TNO Role	**Design, development and verification**
Partners	**-**



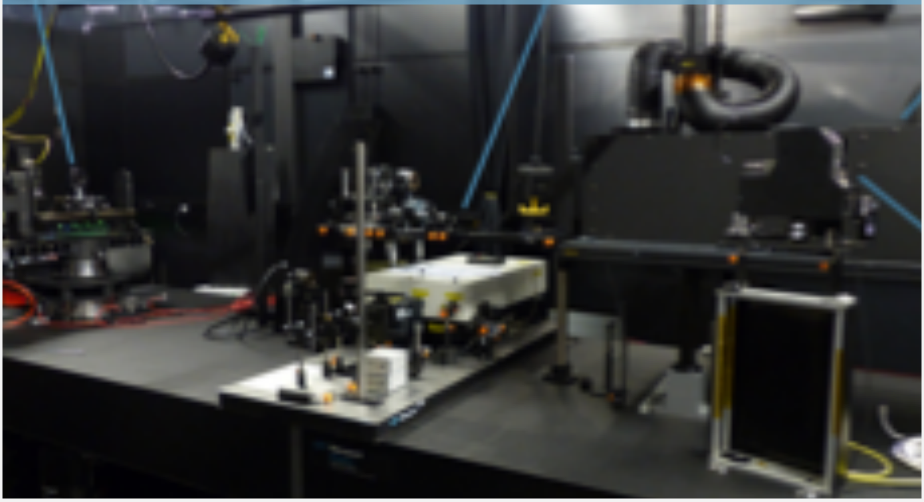


Viscal (Calibration Unit for the SLSTR instrument on Sentinel-3)
Showing the diffuser mounted on its base (up-right)
The Viscal unit (up-right)
The Zenith diffuser + witness samples

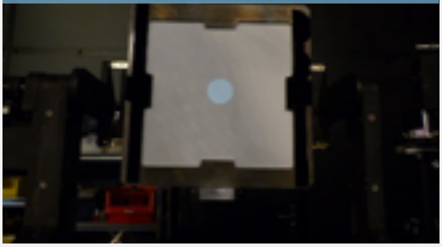
Relevance: Design, development and verification of in-flight diffusers.

Activity	**Characterization and Calibration of diffusers**
Customers	**Leonardo (Gome2), Jenoptronik (Viscal), Tropomi, OMI, Sentinel 4 diffusers**
TNO Role	**BRDF measurements in the ARCF**
Partners	**-**

THE ARCF FACILITY (ISO5) IN TNO'S VAN LEEUWENHOEK LABORATORY

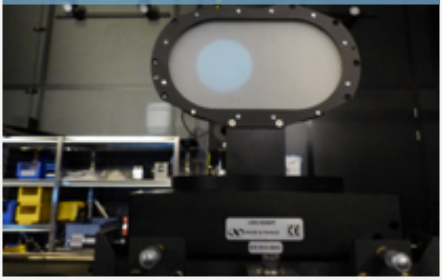


GOME2 EXTERNAL DIFFUSER IN ARCF FOR CALIBRATION (2017)

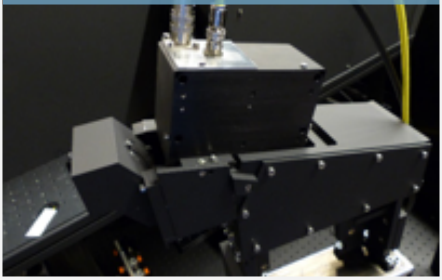


AB10 DIFFUSER SAMPLE IN ARCF (=CALIBRATION REFERENCE TO NPL)

SENTINEL 4 DIFFUSER IN ARCF

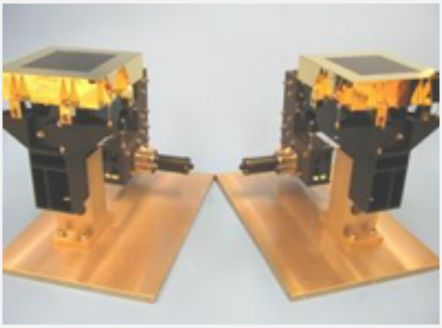


ARCF'S SWIR DETECTOR



Relevance: (Absolute) radiometric calibration BRDF with high accuracy.

Activity	**HIFI Alignment Camera System (HACS)**
Customer	**ASTRIUM**
TNO Role	**Design, development and verification**
Partners	**-**



TNO developed the HACS, covering the opto-mechanical and thermal design.
The HACS is an Optical Ground Support Equipment (OGSE) that is specifically developed to verify proper alignment of different modules of the HIFI instrument during on-ground thermal (vacuum) testing of the ESA Herschel Space Observatory.
Alignment of the Focal Plane Unit (FPU) located in cryostat (10K) and the Local Oscillator Unit (LOU) mounted exterior of cryostat (120K).
Realised accuracies at 0.1 mm and 10 arcsec level.

Relevance: Successful development of OGSE for use in vacuum

17 CONCLUSION

TNO Space and Scientific Instrumentation is proud of its 100% success rate in the field of Astronomy and other scientific applications, and will continue to strive to maintain that track record. TNO is always interested in the most demanding technical performance and conditions. When there are difficult challenges in opto-mechatronic systems, we are only bound by the laws of physics. If we can be of any service to you on your opto-mechatronic system or instrumentation for astronomy, we are happy to arrange a technical team to discuss your needs.

With this booklet, we hope we have given you an overview of our available technology, our development programs as well as our competencies in the area of Astronomy. We look forward to working together with you to build the highest quality scientific instrumentation.

Matthew Maniscalco, MSc, JD, LLM.
Senior Business Developer
TNO Space & Scientific Instrumentation
matthew.maniscalco@tno.nl

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