Athermal Laser Launch Telescopes

F. Kamphues[1,a], R. Henselmans[2], N. Rijnveld[2], M. Lemmen[2], N. Doelman[2], D. Nijkerk[3]

[1]TNO, Technical Sciences - Space Systems Engineering, Stieltjesweg 1, Delft, Netherlands

[2]TNO, Technical Sciences - Optomechatronics, Stieltjesweg 1, Delft, Netherlands

[3]TNO, Technical Sciences - Optics, Stieltjesweg 1, Delft, Netherlands

ESO has developed a concept for a compact laser guide star unit for use in future Adaptive Optics (AO) systems. A small powerful laser is combined with a telescope that launches the beam, creating a single modular unit that can be mounted directly on a large telescope. This approach solves several of the stability problems experienced with a number of first generation laser guide star systems around the world. Four of these compact laser guide stars will be used for the new VLT 4LGSF Adaptive Optics Facility (AOF), to be installed on UT4 in Paranal. The design is passively athermalized over a large temperature range as well as under the influence of thermal gradients. TNO has developed the laser launch telescopes and successfully demonstrated its performance under operational conditions. The technology will also serve as a testbed ahead of the construction of the future European Extremely Large Telescope, which will also have multiple laser guide star units.

1. Introduction

ESO has developed a concept for a compact laser guide star unit for use in future Adaptive Optics (AO) systems. A small powerful laser is combined with a telescope that launches the beam, creating a single modular unit that can be mounted directly on a large telescope.
Four of these compact laser guide stars will be used for the new Very Large Telescope Four Laser Guide Star Facility (VLT 4LGSF). The 4LGSF is part of the next-generation VLT Adaptive Optics Facility (AOF), that will make the VLT's 4th Unit Telescope Yepun (UT4) a fully adaptive telescope in 2013 (Fig. 1).

With four such artificial stars, the 4LGSF will be able to dramatically improve sharpness across the wide field of the VLT's near-infrared camera HAWK-I. The 4 LGSF consists of a high power 25 W CW 589 nm laser, a Beam Conditioning and Diagnostics System (BCDS) and an Optical Tube Assembly (OTA). TNO has developed the OTA laser launch telescopes and successfully demonstrated its performance under operational conditions. The technology will also serve as a testbed ahead of the construction of the future European Extremely Large Telescope, which will also have multiple laser guide star units.

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[a] e-mail : fred.kamphues@tno.nl

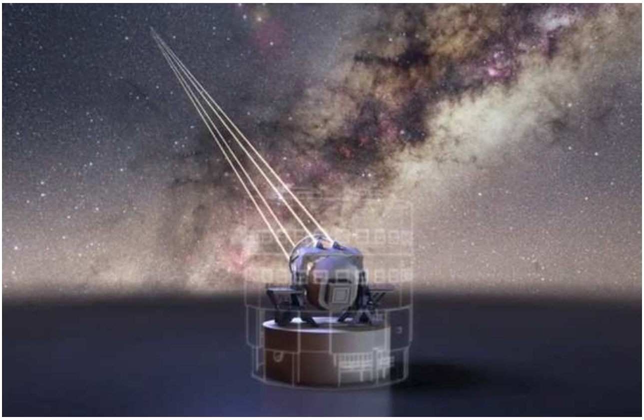

Fig. 1. Artist impression of the VLT Four Laser Guide Star AO Facility

2. OTA design

The OTAs are 20x Galilean beam expanders, consisting of an entrance lens L1, a steerable 45° mirror (Field Selector Mirror, FSM) and a large aspherical exit lens L2. They expand a ∅15 mm input beam to a ∅300 mm output beam, and operate at 589 nm with 25W of continuous laser power. The 4LGSF laser guide stars will be installed on the centerpiece of the UT4 telescope (Fig. 2).
The design is passively athermalized over a large temperature range as well as under the influence of thermal gradients.

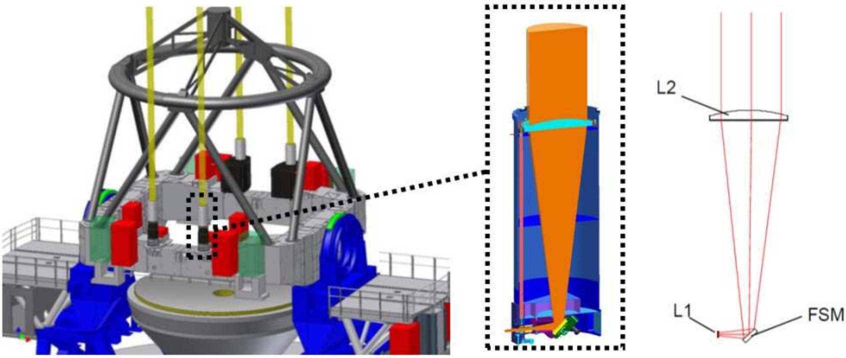

Fig. 2. The OTA location on the telescope, and the optical design

The main OTA requirements are shown in Table 1, together with the achieved performance.

Table 1. OTA main requirements and achieved results

Requirement	***Value***	***Achieved***
Transmitted wavefront error (excl focus and tilt)	< 50 nm rms	17-23 nm rms
Thermally induced defocus	< 0.2 waves PV	~ 0.15 waves PV
Pointing accuracy on-sky	< 0.3" (3σ)	0.07" (3σ)
Polarization extinction ratio (PER)	> 97%	99.7%
Throughput	> 95%	97.7%

The OTA must achieve this performance under the operational conditions. The operational temperature is 0 - 15°C with 10°C average, with a maximum gradient of -0.7°C/hr for 8 hours. The pointing can vary between 0 - 60° Zenith angle. The air pressure varies between the locations: 1013 mbar in Delft (TNO), 960 mbar in Garching (ESO) and 750 mbar in Paranal (VLT). Extensive verification testing was done at TNO and ESO Garching to demonstrate the performance under the operational conditions (Fig. 3).

Fig. 3. High power laser testing in ESO thermal chamber in Garching

2.1. Athermalization

Two concepts were evaluated. In the first, a Carbon Fibre Reinforced Plastic (CFRP) tube with a tuned CTE is used to determine the spacing between L1 and L2 (Fig. 4). This tube also constrains the L2 in lateral direction. This design is light and stiff, but has a relatively high uncertainty for the CTE and CME (Coefficient of Moisture Expansion). It has a low thermal time constant, making the tube (and the internal air) much faster than L2. The carbon design is expected to be relatively difficult and costly to manufacture.

The second concept creates the desired CTE by combining about 0.2 m stainless steel with 1 m Invar (Fig. 5). The Invar is implemented as 3 rods constraining piston, tip and tilt of the L2. A steel tube constrains the L2 in lateral direction. This design has similar stiffness as the carbon design, but with higher mass. The uncertainty on the expansion coefficient is smaller, and the time constant is much larger. This slows down the internal air, keeping the defocus determining components better in pace. It is also expected to be easier and less costly to manufacture.

Carbon tube with tuned α

- Carbon tube does 6 DOF of L2
- Tuned to 3.2 µm/m/K

- Light, stiff
- α uncertain (~0.5 µm/m/K)
- Small thermal time constant
- Difficult to manufacture
- Higher cost (interfaces)

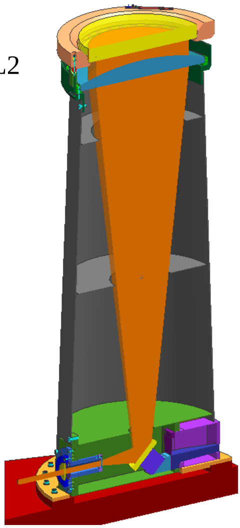

Fig. 4. Concept 1 – CFRP tube

Steel tube with Invar struts

- 3 Invar struts do piston & tilt of L2
- Steel tube does lateral DOFs
- 1 m Invar + 0.2 m steel ≈ 3.2 μm/m/K

- Function separation
- Larger mass
- α less uncertain
- Larger thermal time constant
- Easier to manufacture
- Lower cost

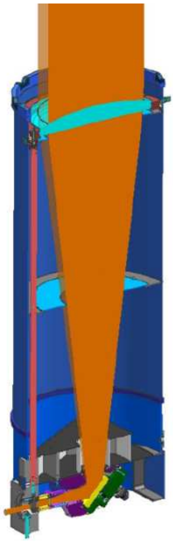

Fig. 5. Concept 2 – Steel tube with Invar metering rods

A lumped mass model was made of both concepts, with which the defocus performance was simulated. In the steel and invar concept, the time-constants are better matched, resulting in less defocus. By making some components heavier than necessary from a strength point of view, the thermal matching was optimized. Fig. 6. shows the final expected behavior (temperature difference from external temperature shown), with -0.013 waves defocus after 6 hours.

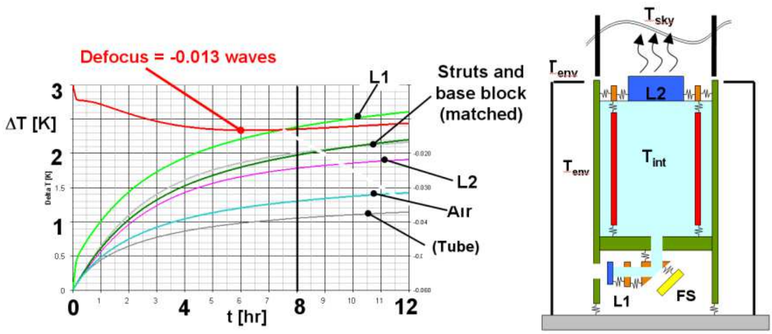

Fig. 6. Lumped mass model defocus simulation

FEM analysis was also performed to calculate the gradients in the lenses. All combined, a nominal defocus of nearly zero was expected, with a model uncertainty of 0.122 waves PV.

However, the lumped mass model did not completely correlate with the initial test results. Further detailed modeling was done on the L2 and its mount to calculate the radial gradient in the L2 lens during cool down and warmup. This allowed a much more accurate prediction of the defocus under transient conditions. Final verification testing in the ESO climatic chamber with high power laser and under transient thermal conditions showed an excellent correlation with the model [2].

2.2. Field Selector Mechanism

The FSM design and testing is described in more detail in [3], a summary is given here. To achieve 4.8 arcmin radius field of view on-sky, the FSM has to tilt up to ±6.1 mrad, in combination with less than 1.5 µrad RMS absolute accuracy. The maximum settling time for a 1 arcsec step on-sky is 0.2 sec. The FSM design (Fig. 7) consists of a Zerodur mirror, bonded to a membrane spring and strut combination to allow only tip and tilt. Since the range is too large for piezos, two (self-locking) spindle drives actuate the mirror, using a stiffness based transmission to increase resolution. Absolute accuracy is achieved with two differential inductive sensor pairs. A prototype of the FSM is realized to optimize the control configuration and measure its performance. Friction in the spindle drive is overcome by creating a local velocity control loop between the spindle drives and the shaft encoders. Accuracy is achieved by using a cascaded low bandwidth control loop with feedback from the inductive sensors.

Fig. 7. Field Selector Mechanism

The pointing jitter and settling time of the FSM are measured with an autocollimator. The amplitude spectral densities of the pointing jitter of the FSM mirror, show that the jitter of the mirror is only increased below the inductive sensor feedback loop, as can be expected. Integration of these spectra shows that the RMS of the pointing jitter down to 0.2 Hz is below 0.4 µrad rms. An additional measurement is performed to show the behaviour of the pointing jitter towards lower frequencies, up to 0.07” in worst case. All step responses are within 0.2 seconds. The FSM therefore meets its requirements.

2.3. L2 manufacturing

The fabrication of L2 is described in more detail in [4], a summary is given here. The aspherical L2 lenses were manufactured using TNO’s unique manufacturing facilities for aspherical and freeform optics. The process was hereto optimized for minimal mid-spatial content and low roughness (1 nm Rq achieved). The asphere was polished from 5µm PV to 24 nm rms in 6 runs. Fig. 9 shows the final result as measured with the NANOMEFOS measurement machine (Fig. 8) [5]. This non-contact measurement machine typically obtains 2k x 2k points in about 15 minutes, giving interferometric resolution with nm level accuracy. The resulting form error is about 24 nm rms, of which 14 nm rms is mid-spatial content. This contributes about 7 nm rms to the wavefront error. A custom hardened AR coating was applied with less than 0.2% reflectivity (Fig. 9.).

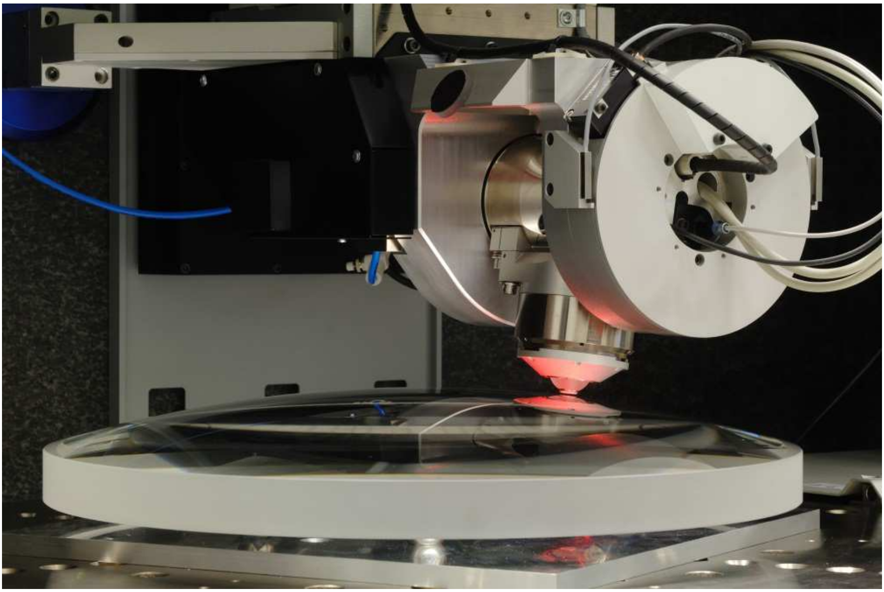

Fig. 8. Measurement of L2 asphere on NANOMEFOS

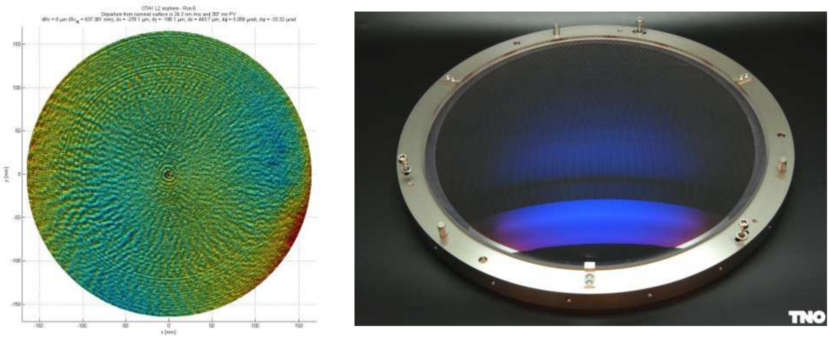

Fig. 9. L2 asphere final result and coated lens in mount

3. Conclusions and future activities

The design of the OTAs was described. A passively athermalized design was made by optimizing the CTE and time-constants of the system's components. The design and realization of the other two main components, the FSM and L2, was also described. After final testing in the ESO climate chamber, the OTA meets its requirements. The achieved performance compared to the requirements is shown in Table 1.

TNO has delivered all four Optical Tube Assemblies to ESO and will support the system level testing where necessary. The OTA design can also be applied for other laser guide star facilities for 10 meter class telescopes or ELTs.

4. References

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