AO4ELT7 - June 2023 - Avignon

The new LLTs for Gemini North AO: design and qualification tests

Sara Zuccon[a], Marco Girardini[a], Emanuele Piersanti[a], Enrico Marcuzzi[a], Paolo Spanò[a], Paolo Miotti[a], Enrico Tessarolo[a], Danilo Lentini[a], David Vizzoni[a], Joe D'Amato[b], Kim Tomasino-Reed[b], Manuel Lazo[b], Chas Cavedoni[b], Thomas Schneider[b], and Gaetano Sivo[b]

[a]Officina Stellare S.p.A., Via Della Tecnica, 87/89 - 36030 - Sarcedo (VI) – ITALY
[b]Gemini Observatory - AURA, NSF's National Optical-Infrared Astronomy Research Laboratory, Colina El Pino s/n, Casilla 603 La Serena, Chile

ABSTRACT

The new Gemini North AO (GNAO) Laser Guide Star Facility (LGSF) will require four Laser Launch Telescopes (LLTs) to enable wide or narrow field corrections with GLAO or LTAO. In early 2021, Officina Stellare has been awarded a contract to design and build four LLTs. Based on the current LLT designs, Officina Stellare carried out a year-long design study and started the production of an Engineering and Qualification Model (EQM) to validate this design and minimise risks in the production of the four deliverable units. Following the manufacture of the mechanical and optical parts, including the large aspherical lens, produced in-house using CNC optical polishing and tested using high-resolution interferometry, the EQM underwent a full series of mechanical and optical tests to validate its performance under representative operating conditions, including gravity, pressure and temperature. Serial production of the other four units to be installed on the telescope has begun, with all key components already manufactured.

Keywords: LLT, AO, asphere, qualification

1. INTRODUCTION

The Gemini Observatory consists of two 8-meter telescopes; the northern observatory is located on Maunakea in Hawaii, USA (Gemini North), the southern observatory is located on Cerro Pachón, Chile (Gemini South). The National Science Foundation awarded AURA funding providing support for the Gemini in the Era of Multi-Messenger Astronomy (GEMMA) program. The GEMMA program has three component projects: (i) upgrade the Gemini North Adaptive Optics system, (ii) provide new rapid-response capabilities for time-domain

---

Further author information:
S.Z.: E-mail: sara.zuccon@officinastellare.com, Telephone: +39 0445.370540

astronomy and (iii) expand community engagement. The GNAO project is one of three projects in the GEMMA program [2]. The GNAO facility consists of 4 major products: the Laser Guide Star Facility (LGSF), the Adaptive Optics System, the GNAO System Controller and the Real Time Controller System. The GNAO project includes the development of a new laser guide star facility which will consist of four side-launched laser beams supporting the two primary AO modes of GNAO: a wide-field mode providing an improved image quality over natural seeing for a 2 arcminutes circular field-of-view and a narrow-field mode providing near diffraction-limited performance over a 20 x 20 arcsecond square field-of-view. The LGSF integrates closely with the other GNAO systems and the telescope to generate the 4-LGS asterism necessary for AO corrections. In order to support both the wide field and narrow field LGS asterisms, the GNAO project requires 4 laser launch telescopes (LLTs). Each LLT shall provide two main functions: (a) receive a linearly polarized beam and project an enlarged circularly polarized beam of a 589 nm input laser on to the mesospheric sodium layer; (b) provide for steering of the beam over a patrol field large enough for both wide and narrow field asterisms. Additionally, Gemini requires to have the LLTs capable to patrol a field much larger for a future wide field GLAO system using an Adaptive Secondary Mirror. Similar facilities are being employed at ESO-Paranal and other observatories. Different LLT designs have been widely discussed in literature, Refs. [3] [1] [2]. The present design is based on them, and it has been tailored to GNAO requirements. Gemini Observatory, through AURA, has launched a Request for Proposal in early 2020. Officina Stellare was awarded the contract to study, develop and deliver four LLTs for GNAO in January 2021. The project duration is estimated at 27 months, including delivery of the LLTs and on-site testing in Hawaii in 2023. To date, all design phases, including a Preliminary Design Review (PDR) and a Critical Design Review (CDR), have been completed on schedule. The CDR took place in December 2021. In order to fully validate this LLT design, an Engineering and Qualification Model (EQM) has been produced and tested against the mechanical and optical requirements. The results of the optical tests will be here reported together with the results of the manufacture of the large spherical lens, which was produced in-house.

2. LLT DESIGN

This section gives an overview of the optical and mechanical design main characteristics. More details can be found in Ref. [4].

2.1 Optical design

The LLT optical tube assembly (OTA) is based on a reverse Galilean telescope configuration used as 20X beam expander. The optical layout is shown in 1. At the entrance an air-spaced, zero-order, quartz quarter-wave plate transforms the linearly polarized beam into a circular one. Then, a biconcave Fused Silica aspherical lens (L1) converts a collimated ϕ15 mm beam into a diverging $\approx$F/4 beam. A plano fold mirror (field selector mirror, FSM) at 45 degrees redirects light towards a large N-BK7 plano-convex aspherical lens (L2) that creates a ϕ300 mm collimated exit beam. The patrol field steering is obtained by moving the FSM in tip/tilt only. The object focal plane of L2 is located at the position of the image focal plane of L1. This configuration avoids a focused beam inside the system, which can represent a laser safety issue.

The main parameters of the optical design are listed in table1.

The LLT includes a quarter wave plate (QWP) which translates an input linear polarized beam into a circular polarized beam. The birefringence of the lenses and the retardance properties of the coatings has been specified in order to keep the polarization extinction ratio (PER) above 97%.

2.2 Mechanical design

The LLT mechanical design (see layout in fig.2 consists of two main sections: the lower one hosts the FSM, L1 and its focuser while implementing the interface to the Gemini telescope. The upper section is meant to give a radial constrain to L2 while its axial position is defined thanks to a set of three rods directly connected to the lower segment; a set of flexures is used to connect the lens cell to the outer structure in the radial direction while leaving the axial direction to be almost completely defined by the said rods. The material with which the rods are manufactured, and their lengths are therefore part of the athermalization process of the design while the radial displacement of the lens can be studied as a separate problem, merely depending on the outer structure and flexures lateral stiffness.

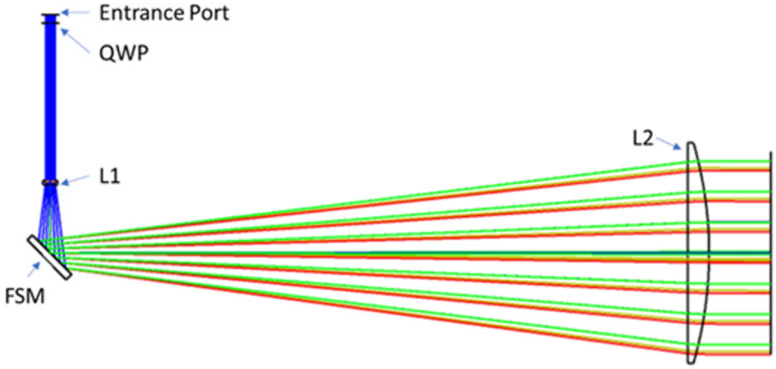


Figure 1. Optical layout of the LLT.

Table 1. Optical specifications

Requirement	**value**
Transmitted Wavefront Error	$\leq$ 75 nm RMS
Thermally induced defocus	$\leq$ 0.2 waves PV
Polarization Extinction Ratio	$\geq$ 97%
Throughput	$\geq$ 95%
Operating wavelength	589 nm
Patrol field	± 7 arcmin on sky
Operating temperature range	-10°C/+10°C
Survival temperature range	-20°C/+70°C

Plenty of FEA analyses have been run on the discussed design, assessing its static behavior (self-weight deflection and beam deviation), dynamical behavior (i.e., eigenmodes and eigenfrequencies, operative vibrations induced displacements) and survivability (thermal shock, transport vibration, shock response).

In order to avoid any focus correction during the observing night, an athermal design has been accomplished. Given the optical design already discussed, calculations gave the needed displacement to be imposed to L1 with respect to L2 to maintain the output beam collimated after a temperature change. A thermoelastic model has then been developed to tune lengths and materials of the mechanical components, pursuing the equivalent CTE of the structure. Uncertainties on lengths or CTEs have been taken into account in the thermoelastic model as well in order to produce a design sufficiently robust to efficiently work not only considering the surroundings but also to tolerate the said non-idealities.

3. LARGE ASPHERE MANUFACTURING

The large Ø360-mm aspherical L2 lens has been pre-polished to a plano-spherical shape. Next, the aspherical surface has been CNC-machined using different technologies. Final figuring corrections have been done by using the advanced fluid-jet polishing technique. The WFE has been measured with a 4" DynaFiz Zygo interferometer and a null lens. The measurement has been performed in transmission in double pass. This setup measured the transmitted WFE of the lens, directly related to the final LLT performances, including any error due to surface irregularities and the material inhomogeneity. The plano surface was measured by a beam-expander and calibrated over a large 500-mm reference flat mirror. The final WFE map is reported in 3.

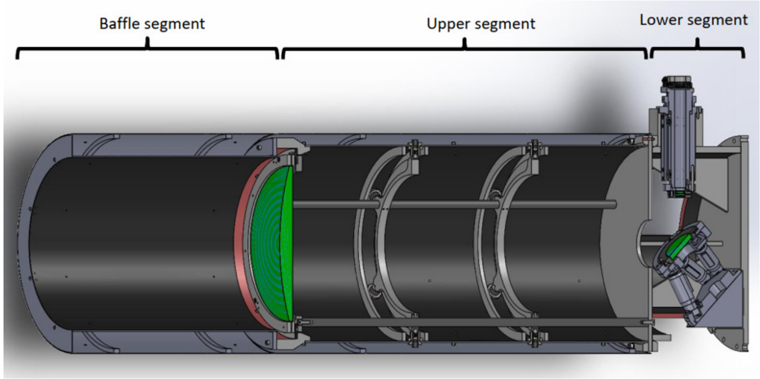


Figure 2. Mechanical layout of the LLT.

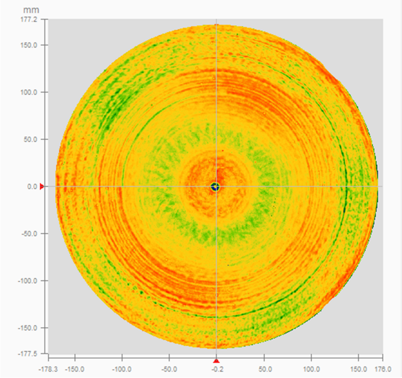


Figure 3. Final TWFE of L2.

4. EQM OPTICAL TEST

The EQM was subjected to a series of tests to verify that all mechanical and optical requirements were met. The first tests, after completion of the alignment procedure, were the optical quality and the polarisation extinction ratio (PER); these measurements were then repeated at different inclinations to verify that they were not dependent on gravity. The second part was aimed at verifying the athermalisation of the system. The Hexpod which moves the FSM is the only mechanism in the system. Its operation at low pressure has been verified by chacking its movement when in vacuum chamber.

4.1 Optical quality

The UUT (Unit Under Test), after being integrated and aligned, is mounted on the ”tilting table” (see fig. 5). This GSE allows the measurement of WFE and PER at 0, +60 and -60 degrees from the zenith. The alignment was performed with a Twymann-Green interferometer operating at a wavelength of 633 nm. The subsequent tests were carried out at the operating wavelength of 589 nm. A Shack-Hartmann setup was therefore designed. This allows flexibility in the choice of wavelength and physical test conditions. In fact, it can be mounted on the side of the table to take measurements at different inclinations. Figure 4 shows a general view of the SH setup. A couple of lenses act as a beam expander to produce the 15mm probe beam. The two folding mirrors allow the input beam to be centred and aligned with respect to the UUT reference. The tilting table is equipped with a flat reference mirror to close the cavity for the double-pass measurement of the WFE. Analyses have been carried out to optimise its support in order to avoid the contribution of the gravitational deformation of the mirror to the overall WFE budget.

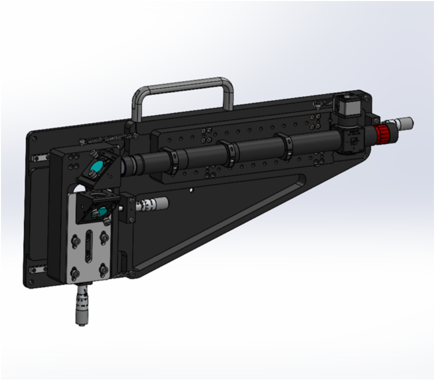


Figure 4. general view of the SH set-up.

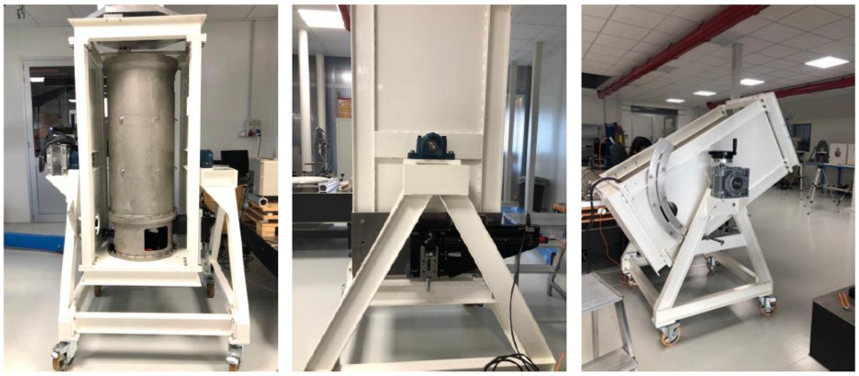


Figure 5. UUT installed on the tilting table (left), SH set-up on its interface (center), tilted table ato 60 degrees (right).

After the completion of the UUT preparation and the setup characterization activities the focuser has been installed and the WFE has been measured. The results in the vertical position are reported in figure 6.

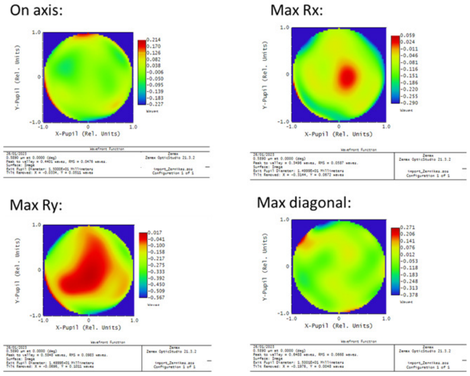
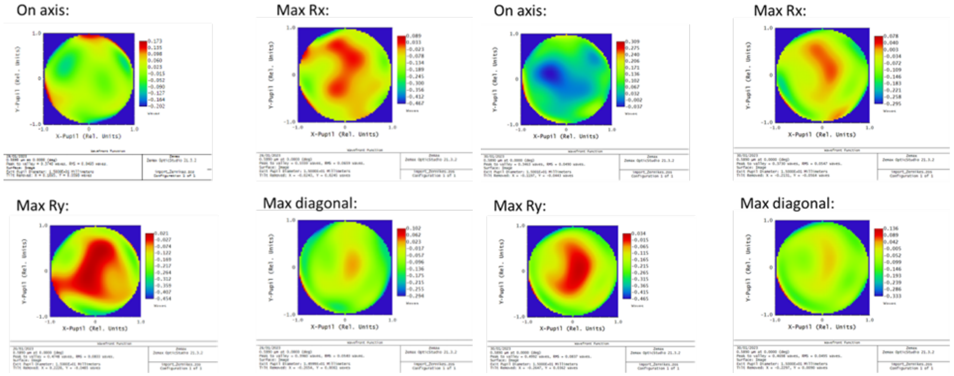


Figure 6. WFE measurement at Zenith.

The UUT has then been tilted at 60 deg and at -60 deg and the same measurements on axis and off axis have been performed (figure 7. It is clear that the results don't seem to be affected by the tilt of the structure, given the repeatability of the measurement. As can be seen in the table 2, there is only one point that exceeds the allocated budget (50 nm RMS). However, this doesn't affect the overall budget, which is still within the requirements.


On axis:

Max Rx:

On axis:

Max Rx:

Max Ry:

Max diagonal:

Max Ry:

Max diagonal:

Figure 7. WFE measurement at +60 degrees (left) and -60 degrees (right) of inclination.

Table 2. WFE as function of FOV position and tilt of the structure

	WFE 0 deg (nm RMS)	**WFE +60 deg** (nm RMS)	**WFE -60 deg** (nm RMS)
on axis	29	30	30
Rx	36	39	33
Ry	58	49	49
Rx Ry	40	33	30

4.2 Polarization measurement

Given a linear input polarisation, the LLT shall project a circularly polarised beam with a polarisation extinction ratio of $\geq 97\%$. The circularly polarised beam is achieved by the use of a quarter-wave plate. The polarisation can be altered by the retardance of the coating and the birefringence of the material. The purpose of the test is to quantify the polarisation effects of the system without the QWP. his requirement can be in fact translated as, when the incoming beam is linearly polarized and its polarization is rotated over 180 deg, the output degree of linear polarization (in case the QWP is still not present) shall not vary more than 3%. In order to estimate this, we evaluated the LPS (linear polarization sensitivity).

The main test parameters and steps have been:

- Input polarization: linear (DOLP/DOP=1), rotated over 180 deg (step 20 deg)
- The test has been performed without the QWP
- Output: DOLP/DOP
- For each position we then had a set of measurement as function of the linear polarization angle. The average, maximum and minimum value have been computed (see Figure 5 4). From this the LPS has been computed as:

$$LPS = \frac{MAX - min}{MAX + min}$$

In the following graphs the average and LPS results are reported for each aperture. The right side corresponds to the entrance port side, therefore to lower angles of incidence on the dielectric mirror, where the Rs/Rp difference is lower meaning less polarization effects.

The results show that in each condition and at each position the LPS is $< 2.3\%$ and the average polarization is $> 98\%$, therefore the specifications are met.

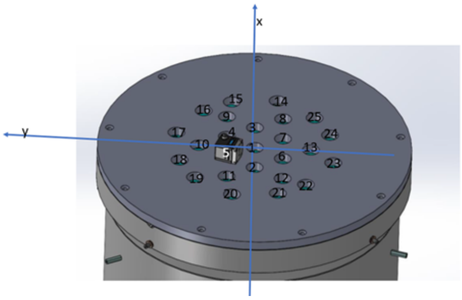
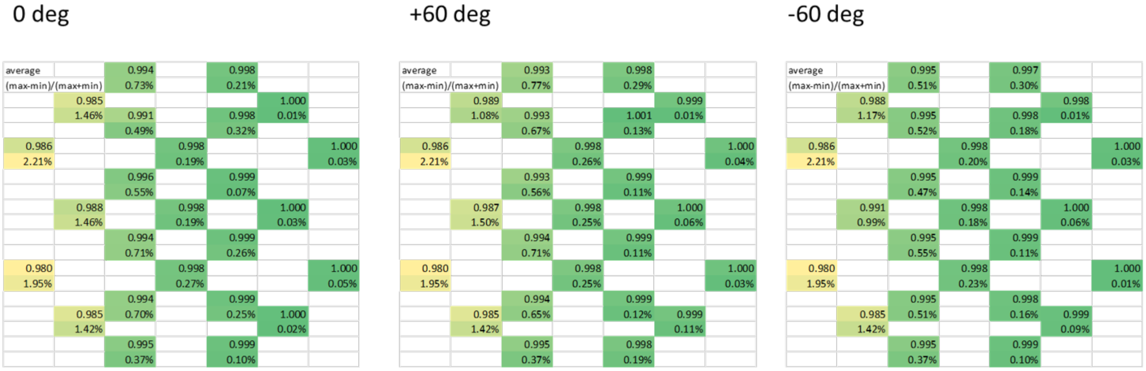


Figure 8. Mask with apertures, properly numbered during the test.



0 deg

average		0.994		0.998		
(max-min)/(max+min)		0.73%		0.21%		
	0.985				1.000	
	1.46%	0.991		0.998	0.01%	
		0.49%		0.32%		
0.986			0.998			1.000
2.21%			0.19%			0.03%
		0.996		0.999		
		0.55%		0.07%		
	0.988		0.998		1.000	
	1.46%		0.19%		0.03%	
		0.994		0.999		
		0.71%		0.26%		
0.980			0.998			1.000
1.95%			0.27%			0.05%
		0.994		0.999		
	0.985	0.70%		0.25%	1.000	
	1.42%				0.02%	
		0.995		0.999		
		0.37%		0.10%		

+60 deg

average		0.993		0.998		
(max-min)/(max+min)		0.77%		0.29%		
	0.989				0.999	
	1.08%	0.993		1.001	0.01%	
		0.67%		0.13%		
0.986			0.998			1.000
2.21%			0.26%			0.04%
		0.993		0.999		
		0.56%		0.11%		
	0.987		0.998		1.000	
	1.50%		0.25%		0.06%	
		0.994		0.999		
		0.71%		0.11%		
0.980			0.998			1.000
1.95%			0.25%			0.03%
		0.994		0.999		
	0.985	0.65%		0.12%	0.999	
	1.42%				0.11%	
		0.995		0.998		
		0.37%		0.19%		

-60 deg

average		0.995		0.997		
(max-min)/(max+min)		0.51%		0.30%		
	0.988				0.998	
	1.17%	0.995		0.998	0.01%	
		0.52%		0.18%		
0.986			0.998			1.000
2.21%			0.20%			0.03%
		0.995		0.999		
		0.47%		0.14%		
	0.991		0.998		1.000	
	0.99%		0.18%		0.06%	
		0.995		0.999		
		0.55%		0.11%		
0.980			0.998			1.000
1.95%			0.23%			0.01%
		0.995		0.998		
	0.985	0.51%		0.16%	0.999	
	1.42%				0.09%	
		0.995		0.999		
		0.37%		0.10%		

Figure 9. Average DLP/DOP and LPS results for each position when the UUT at 0 deg (left), +60 deg (center) and at -60 deg tilt (right).

4.3 Thermal behaviour test

Aim of the test is to validate the athermal design of the LLT. The following equipment has been used to perform the test campaign:

- Climatic chamber: Criotecna custom climatic chamber, range -30°C/+70°C equipped with an optical window to monitor the WFE from the outside (pre-calibration performed).
- Thermocouples on key locations of the LLT and acquisition system.
- Shack-Hartmann setup aligned to the LLT reference thanks to a hexapod, see fig.10.
- Flat reference mirror with tip/tilt support.

After a complete thermalization to dwells at different temperatures within the operative range (- 10°C/+10°C) is reached, a WFE measure at 589 nm is acquired through the Shack-Hartmann setup (double-pass measurement) to assess the power term amplitude and to verify the compliancy to the requirement (0.2 waves PV).

From the experimental results (fig. 11) it can be inferred that by properly performing the very first focusing of the system during the installation of the summit (after 6/7 hours, at around 0°C), then the LLT will satisfy the requirement in all operative conditions.

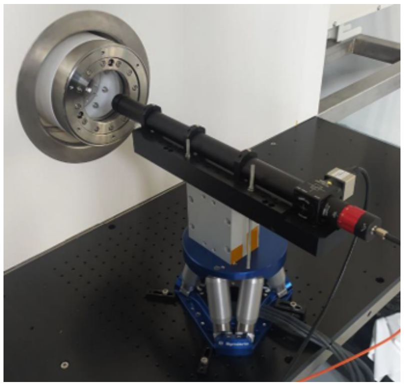


Figure 10. Shack-Hartmann set-up monitoring WFE change from the outside of the climatic chamber through an optical window.

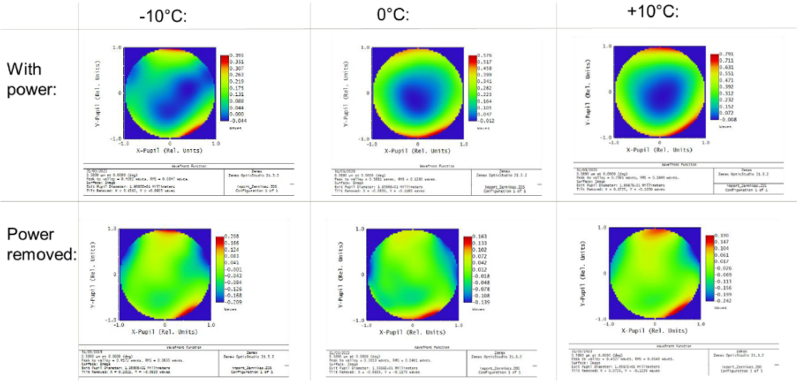


Figure 11. WFE map as temperature changes.

5. CONCLUSIONS

The qualification test campaign is considered successful. It proved that the system meets the requirements and suggests the best practice to follow for the first initial focusing on the summit.

References

[1] W. Hackenberg et al. "Assembly and test results of the AOF laser guide star units at ESO". In: *Adaptive Optics Systems IV*. Ed. by Enrico Marchetti, Laird M. Close, and Jean-Pierre Véran. Vol. 9148. International Society for Optics and Photonics. SPIE, 2014, 91483O. DOI: 10.1117/12.2057167. URL: https://doi.org/10.1117/12.2057167.

[2] Rens Henselmans et al. "Athermal design of the Optical Tube Assemblies for the ESO VLT Four Laser Guidestar Facility". In: (Sept. 2011). DOI: 10.1117/12.893845.

[3] Rens Henselmans et al. "Design, analysis and testing of the Optical Tube Assemblies for the ESO VLT Four Laser Guide Star Facility". In: (July 2012). DOI: 10.1117/12.926484.

[4] Sara Zuccon et al. "The new Laser Launch Telescopes for Gemini North AO: design and status update". In: *Adaptive Optics Systems VIII*. Ed. by Laura Schreiber, Dirk Schmidt, and Elise Vernet. Vol. 12185. International Society for Optics and Photonics. SPIE, 2022, p. 121857C. DOI: 10.1117/12.2629191. URL: https://doi.org/10.1117/12.2629191.