# TACKLING ET'S THERMAL DEFORMATION CHALLENGE

**The ET Merope project addresses the challenge of improving the performance of the Einstein Telescope (ET), by measuring and correcting the optical phase errors that are induced by thermal loads. By developing advanced deformable mirrors, wavefront sensors, and automated inference algorithms, the project consortium aims to demonstrate several of the key building blocks required to actively correct such phase errors in the ET interferometer cavity. The project unites research institutes and industry partners to deliver innovative solutions, not only for enhancing sensitivity and stability in gravitational-wave detection but also enabling broader applications in astronomy, satellite communications, and other high-tech industries.**

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## Introduction

The Einstein Telescope (ET) will be the next-generation gravitational-wave detector (GWD), presenting a significant upgrade over the current Virgo and LIGO detectors. ET (see the visualisation in Figure 1) will be more than ten times


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*Visualisation of the Einstein Telescope. (Source: [1])*

more sensitive than existing GWDs, featuring measurement sensitivities better than 1/10th the size of an atom. This pushes the technological boundaries of what is currently possible, and requires cutting-edge support systems and components.

Compared to existing detectors, ET will make use of considerably more laser power to accurately measure the 10 km distance between the super-fine polished mirrors ('test masses'). To achieve the extreme sensitivities required for ET, the losses in the optical path should reach levels of tens of ppm and this puts extreme requirements on the wavefront quality of the propagating beams. The low-frequency detector (ET-LF) will operate at 18 kW laser power, while the high-frequency detector (ET-HF) operates at several MW of continuous laser power. Any residual absorption at the test masses can deform the optical surface and lead to wavefront distortions, thus limiting overall sensitivity. Any unknown or insufficiently controlled heat source in the entire beamline can have similar effects.

Mitigation is possible through active control of the wavefront quality through a closed-loop feedback system. LIGO and Virgo already make use of similar systems based on adaptive optics where the induced distortion is measured and then corrected through controlled deformation of optical elements. ET is foreseen to require novel sensors, actuators and inference algorithms given that, compared to LIGO and Virgo, there is a much higher laser power in the ET-HF arms; and a cryogenic environment in the ET-LF arms.

This is where project ET Merope (MEasuring & Rectifying Optical Phase Errors) comes in. It aims to mitigate thermal effects in two parallel ways. Firstly, by inferring the origin of the error within the system using information extracted from the laser-spot characteristics, followed by targeted resolution to individual error sources via inference-based modelling (see below). Secondly, by employing a high-power, high-stability deformable mirror (DM) to actively correct the laser-spot quality as a 'catch all' approach.

Project ET Merope will focus on advancing key technologies in areas critical to ET:
- Actuators:
  ET is expected to deploy mode-cleaners at various locations, which improve beam quality by allowing only the fundamental mode of the laser to pass through. A DM suitable for the ET environment needs to be designed, capable of handling the high laser power while preserving the overall system stability to ensure very low residual distortions.

**AUTHORS' NOTE**

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- Sensors:
  Development of wavefront sensors and control methodologies, suitable for the ET system environment, and achievement of the required sub-nanometer-level wavefront measurement sensitivities.
- Inference:
  The thermal deformations in the final GWD interferometer occur at multiple locations and are expected to have strong correlations. Inferring the actuator control from dedicated sensor measurements is complicated, currently relying heavily on human interpretation. Thus, the project intends to "take the human out of the loop" by having completely automated actuator control.

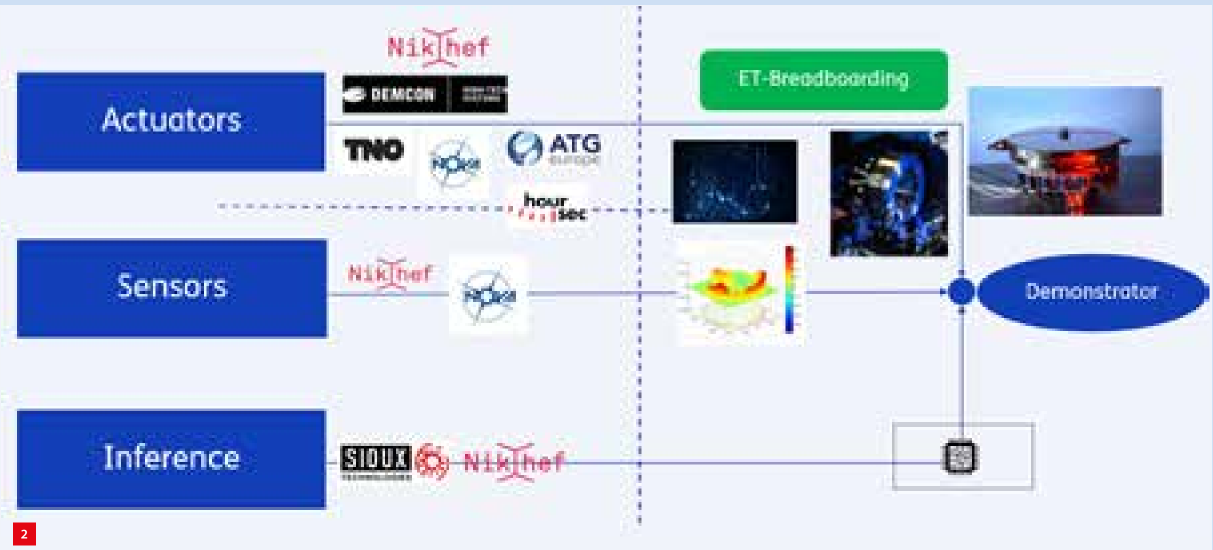
The Netherlands has a rich heritage in astronomy and plays a crucial role in building advanced instruments for both ground-based and space-based astronomy. ET presents challenges that will necessitate substantial technical and performance enhancements of these components. Besides, novel sensors, actuators and inference technologies are key enablers of adaptive optics systems used not only in astronomy but also in satellite communications, semiconductor manufacturing, and earth observations. Their development is especially exciting given the strong position of the Dutch industry in these high-tech domains.

## ET DM development

To meet the demanding optical requirements of next-generation GWDs such as ET, the consortium is exploring the use of DMs for advanced wavefront correction. Current thermal actuators used in LIGO and Virgo are limited in both amplitude and shape control, especially as laser power increases. TNO is leading the development of a new DM based on variable-reluctance actuators [2] (Figure 3), aiming to deliver high-precision correction while withstanding the intense thermal and mechanical ET environment. The mirrors are being designed for strategic locations in the interferometer, such as the input mode-cleaner and signal-recycling cavities; close by, but just outside of the most critical main cavity. There they must maintain stability under high optical power, and have minimal drift over long timescales.

## ET Merope Consortium

The ET Merope project unites research institutes, industrial partners, and innovation-driven start-ups (Figure 2). TNO (Netherlands Organisation for Applied Scientific Research) will develop a thermally stable DM. Demcon, a Dutch design and engineering firm, is creating proof-of-concept electronics for ultra-low noise and high-dynamics DM pulse-width modulation. ATG will contribute thermal-mechanical modelling and simulation code. Hoursec, an AI start-up, is developing machine learning algorithms to accelerate DM convergence and enhance control. Sioux Technologies will build inference models using simulation and measurement data. Nikhef (Dutch National Institute for Subatomic Physics) will set up a table-top experiment featuring an optical cavity and phase camera. NOVA (Netherlands Research School for Astronomy) will support wavefront correction through breadboarding.

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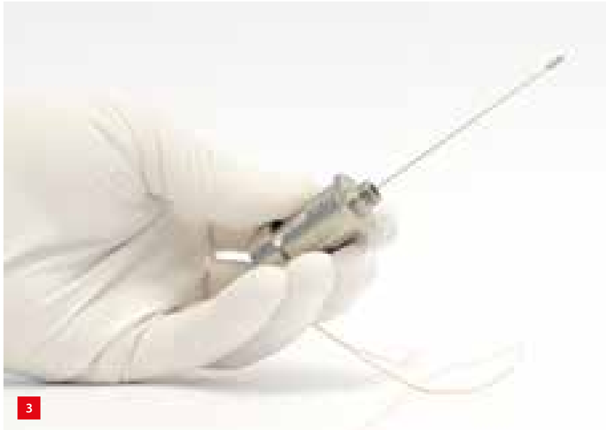
*Partner contributions within the ET Merope project consortium.*

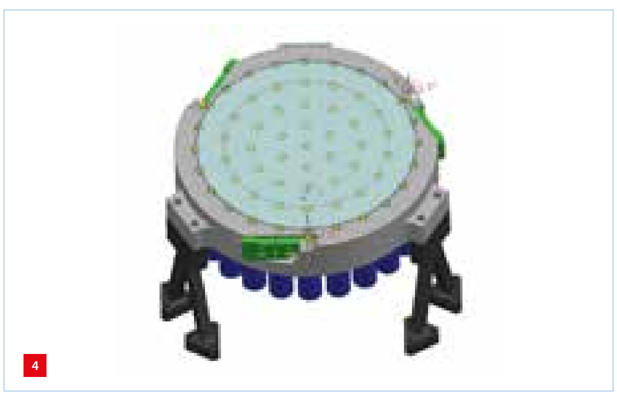


3 Hybrid variable reluctance actuator.

A key challenge lies in managing the thermal effects caused by even minimal absorption of high-power laser light, which can lead to mirror deformation and optical turbulence. In contrast to astronomical systems that rely on high-frequency wavefront sensing, ET requires DMs and electronics with exceptional shape stability due to its inherently slower control-loop dynamics. To address this, the project is also developing low-noise, low-drift drive electronics and investigating the mirror's dynamic thermal behaviour.

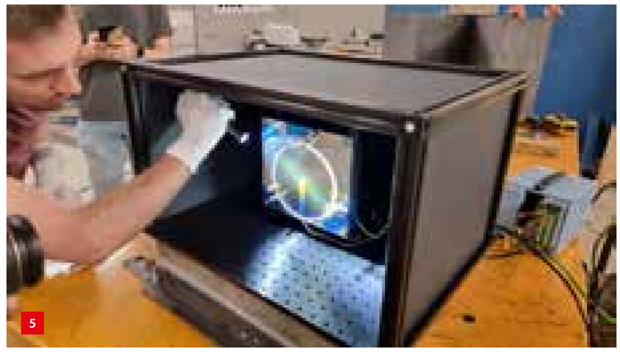
Since traditional high-speed wavefront sensors are impractical in ET, the team is exploring machine-learning techniques to optimise DM control using lower-order sensor feedback. This approach could enable effective, high-order correction with slower, more robust feedback loops paving the way for more sensitive GWDs.

The latest design iteration builds on earlier concept work and focuses on three core capabilities: resilience to high optical power; ultra-high mechanical stability; and low-noise, high-stability electronics. The current baseline features a flat deformable mirror shell with a 100-mm optical aperture, actuated by 61 precision-controlled elements (Figure 4). Advanced materials, such as silicon carbide and hybrid structures combining metal with carbon-fibre reinforced polymer, are being considered to achieve the required thermal and dynamic performance.



4 Current ET DM concept baseline.

A mock-up of the DM thin mirror shell and a supporting mechanical structure were built. A successful 2-day test campaign was carried out over the summer of 2025 using TNO's 30-kW high-power laser (Figure 5). Several test parameters were varied, including exposure times, spot sizes and details of the hardware configuration. The recorded temperature profiles were matched with a thermomechanical model, to experimentally validate the assumptions behind the eventual DM's cooling strategy.



5 Post-test inspection of the borofloat glass mirror of the high-power DM mock-up.

Recent collaboration between Demcon, TNO and Nikhef has led to a preliminary definition of requirements for the DM's control electronics, with a focus on low-noise, low-power amplifier technologies, an area currently under review. In parallel, Hoursec has been evaluating optimisation strategies for DM control, initially applying the existing Nelder-Mead algorithm to this new wavefront-sending use case within a newly developed simulation environment. These early results are shaping the next phase of algorithm development, which will explore more advanced techniques. Meanwhile, ATG Europe has delivered the first iteration of a thermal model and is progressing on a structural model, starting with a single-actuator set-up designed for scalability. While the thermal model remains simplified, the structural detail is prioritised due to the dominant thermoelastic effects.

## Laser cavity set-up and inference

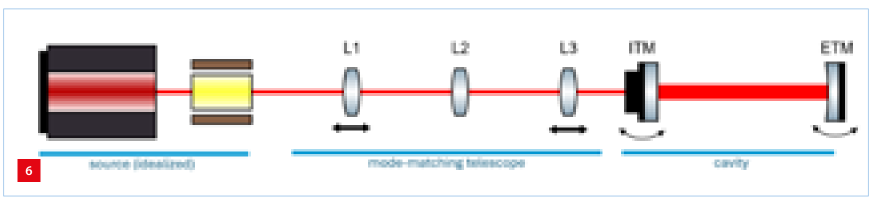
GWDs are among the most sensitive instruments ever built, and their performance hinges on precise control of optical systems. One of the key challenges is managing thermal deformations that occur across various components of the interferometer. These deformations are often interdependent and difficult to isolate. Traditionally, corrections have relied on manual tuning of actuators such as ring heaters, guided by expert interpretation of sensor data.

The ET Merope project aims to revolutionise this process towards a highly automated control loop, where sensor data is systematically interpreted to infer deformation parameters and drive actuators accordingly. This approach promises to enhance stability and precision, and is of direct relevance to future detectors such as ET.

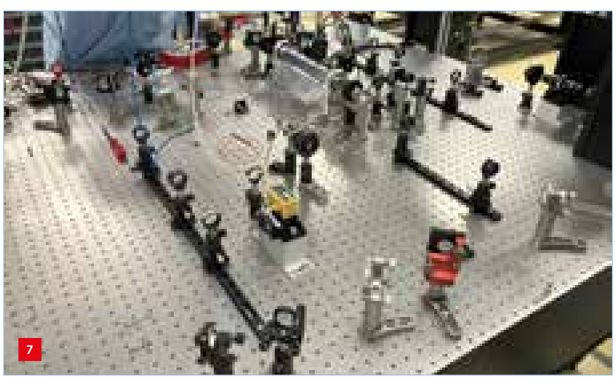
To tackle this complex problem, the project is structured into three progressive phases. It begins with using a suspended cavity set-up at Nikhef to develop and validate an inference framework based on simulated data. Sioux Technologies leads the simulation and algorithm development, while Nikhef prepares the experimental set-up. Then, the cavity is enhanced with controlled optical defects to study correlated deformations, using a Michelson-Morley interferometer configuration. Finally, a deformable mirror is integrated into a more advanced experimental set-up, pushing the framework to handle a large number of actuators. Throughout, the software is designed to be implementation-agnostic, ensuring broad applicability across different detector architectures.

Sioux Technologies has made significant progress in simulating the suspended optical cavity system using Finesse3 [3], specialised software for modelling interferometric set-ups. The simulations included tip-tilt alignment mirrors and a mode-matching telescope, with photodiodes used to monitor the optical signals (Figure 6). By analysing how these signals change with mirror adjustments, Sioux developed an algorithm that precisely aligns the cavity's optical axis.

The set-up was then enhanced with a model of a phase camera, which captures both the amplitude and phase of the light across its sensor. This richer data enabled even more accurate alignment, demonstrating the added value of phase-based sensing. Improvements were also made to the signal-analysis algorithms, particularly in decomposing complex optical modes, which is crucial for identifying subtle distortions.




Suspended cavity set-up simulation. ITM and ETM are the input- and end-test masses, respectively: the mirrors that make up the main Fabry-Perot arm cavities.




Early suspended cavity breadboard set-up at Nikhef. The metal tube near the top-middle of the figure is the ITM-ETM cavity.

Meanwhile, Nikhef has prepared the physical experimental set-up (see Figure 7) for the first phase with measurements starting in Q3 2025. For the second phase, Sioux and Nikhef have jointly designed a more complex interferometer based on a Michelson-Morley configuration. This set-up introduces controlled optical imperfections to study how distortions in different components interact. The goal is to test whether the inference framework can correctly identify the source of these distortions using only sensor data. Simulation work for this configuration has begun in Q3 2025, to be followed by experimental validation by the end of Q4 2025.

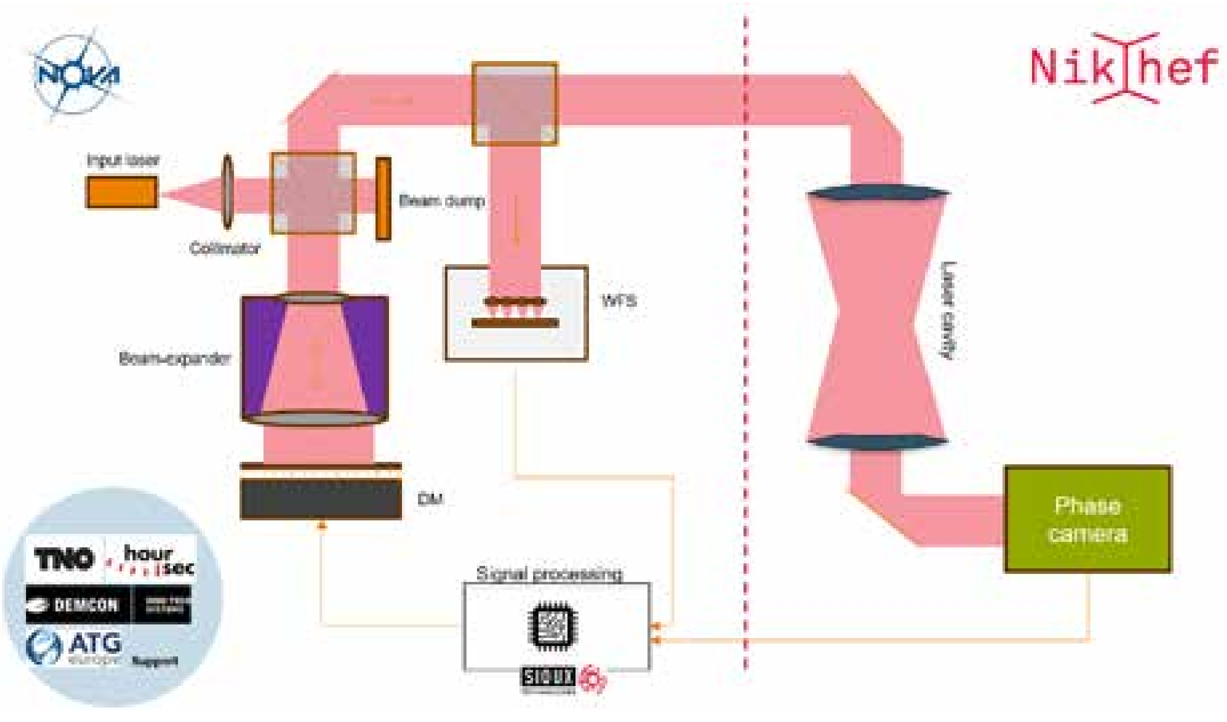
## Thermal deformation breadboarding

The goal of the thermal deformation breadboarding effort is to integrate a range of advanced technologies into a unified, functional set-up. This integration is far from trivial; it requires careful coordination between wavefront sensors, control algorithms, DM actuators, and low-noise electronics. The breadboard serves as a testbed to ensure these components can interface correctly and operate together with the precision needed for ET.

Technologies under evaluation include Shack-Hartmann sensors, phase cameras, and the novel Vector Zernike Wavefront Sensor [4], originally developed for space telescopes and a candidate for NASA's Habitable World Observatory (HWO), which will be searching for Earth-like exoplanets in the future. These sensors feed into control algorithms that translate optical distortions into actuator commands, which are then executed by DMs driven by precision electronics.

The breadboard set-up is designed to address several critical research questions (Figure 8). Achieving sub-nanometer, and potentially picometer, wavefront sensing accuracy is essential for ET's stringent optical requirements. The consortium is investigating the conditions under which such sensitivity is achievable, including sensor wavelength, light-intensity thresholds, and system stability. The performance of wavefront control algorithms is also under scrutiny, with metrics such as error convergence, settling time, and spectral stability being evaluated.

Furthermore, the DM's behaviour, especially in combination with a laser cavity, is being tested to understand how adaptive optics can minimise spurious mode coupling and improve cavity finesse (the ability to resolve closely spaced spectral features). This work directly links wavefront control to key performance indicators for gravitational-wave detection.

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*ET-breadboarding description.*

The breadboarding activities follow a phased approach. Breadboard 1.0 uses existing components from consortium partners, such as an existing DM from TNO, to enable rapid integration and early functional testing. This version provides a platform for validating technologies currently under development. Breadboard 2.0 will push the sensitivity limits further, incorporating new elements such as the Vector Zernike sensor and distortion-inducing components such as spatial light modulators and turbulence generators. Nikhef's laser cavity will be added to study interactions between wavefront control and cavity dynamics. The ultimate goal is to demonstrate a thermally compensated DM system that overcomes the limitations of traditional fixed optics, paving the way for high-power, high-precision interferometry.

NOVA has initiated consultations with Leiden University to evaluate the most suitable wavefront sensors for the breadboard set-up, focusing on their compatibility with ET's requirements. These discussions are helping to shape the final design of the breadboard system. Detailed planning for the integration phase is underway, with incremental implementation scheduled in the coming months. The demonstrator will be built up step-by-step in NOVA's optical lab, gradually incorporating technologies from across the consortium.

## Outlook

At the time of writing (October 2025), the project is nine months into its planned 30-month duration. The insights gained from TNO's first high-power-laser experiments are highly valuable for other domains, such as defence applications and beam combination for optical feeder links in laser-satellite communications. Similar valorisation opportunities also exist for the low-noise actuators under development by Demcon and the novel wavefront sensing technologies being pursued by NOVA, with potential applications in future space-based astronomy, satellite imaging, and related fields.

Next year will be particularly significant, with the Netherlands hosting the Big Science Business Forum in Maastricht [5], followed by the expected site selection for ET the year after. The expertise developed through the ET Merope project will not only strengthen the bid to select the Euregio Meuse-Rhine as the site for ET, but also help to position the Netherlands for its most ambitious big-science project to date.

### REFERENCES

[1] *www.einsteintelescopeforbusiness.nl/deelnemen/technologie-domeinen/Thermische-deformaties*
[2] Zhang, R., *et al.*, "In-lab and on-sky closed-loop results of adaptive secondary mirrors with TNO's hybrid variable reluctance actuators", *Proc. SPIE 13097, Adaptive Optics Systems IX,* 130975K, 27 August 2024, *doi.org/10.1117/12.3019167*
[3] *git.ligo.org/finesse/finesse3*
[4] Wang, X., Shi, F., and Kent Wallace, J., "Zernike wavefront sensor (ZWFS) development for Low Order Wavefront Sensing (LOWFS)", *Proc. SPIE 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave,* 990463, 29 July 2016, *doi.org/10.1117/12.2231252*
[5] *www.bsbf2026.org*