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AiLoV ET ADVANCED OPTICS LAB @ TOR VERGATA FOR ET

Optimizing Hartmann Wavefront Sensor performances for direct measurement of optical aberrations

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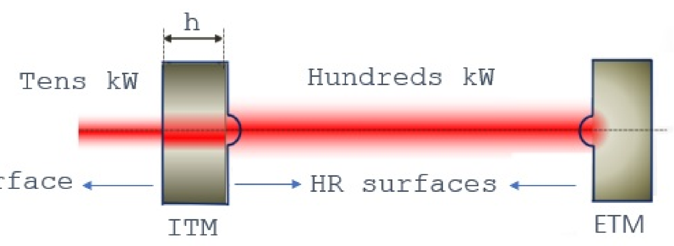
Future gravitational wave observatories – like the Einstein Telescope (ET) – are expected to operate with higher circulating power (ET-HF) with respect to the current detectors. The resulting thermal load introduced by the main laser beam – that is absorbed in the mirror coating and substrate – induces wavefront aberrations that must be actively corrected to restore the detector's nominal optical configuration. The ET research group in Roma Tor Vergata is contributing to the development of Wavefront Sensing and Control techniques needed to mitigate thermally-induced optical distortions. The system relies on the Hartmann Wavefront Sensors (HWS) – a differential measurement devices developed in collaboration with the LIGO group at the University of Adelaide (AU) [1] – to monitor wavefront aberrations in the interferometer's optical components. Although the DALSA CCD sensor currently used in the HWS of Advanced Virgo Plus has proven effective for wavefront reconstruction, its discontinuation by the manufacturer required to search for a suitable replacement. Preliminary testing of the Ximea MQ042MG-CM CMOS sensor has demonstrated excellent performances, achieving a wavefront reconstruction accuracy better than 0.4 nm RMS – thereby, establishing it as a reliable candidate for future deployment in the ET-HF.

Thermally-induced Wavefront Distortions

Absorption - mainly in the TMs coatings - of a small fraction of the circulating power (order of a few ppm)



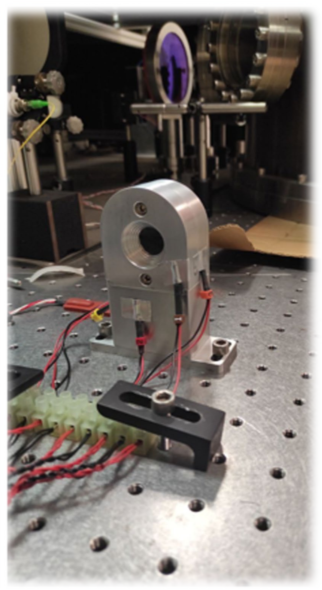
Temperature gradient and Optical Path Length variation

$$\Delta W(r,\theta) \approx \beta \int_0^h \Delta T(r,\theta,z)dz \qquad \beta \approx \frac{dn}{dT} + \alpha(1+\sigma_P)(n-1)$$

It affects the interferometer controllability and its performances

- n: refractive index;
- α: thermal expansion coefficient;
- σ_P: Poisson's ratio.

The New CMOS-based HWS



After being mounted in a custom-made aluminum housing, the Ximea MQ042MG-CM CMOS sensor has been tested and validated at the laboratories of the University of Rome "Tor Vergata", achieving a wavefront reconstruction accuracy better than 0.4 nm RMS.

Parameter		Ximea	DALSA
Pixel array size (H × V)	[pixel]	2048 × 2048	1024 × 1024
Active area size (H × V)	[mm]	11.27 × 11.27	11.27 × 11.27
Pixel size (H × V)	[μm]	5.5 × 5.5	12 × 12
Full Well Capacity (FWC)	[ke⁻]	13.5	350
Amplifier noise	[e⁻]	12 (RMS)	1.2 (RMS)
Dark current	[e⁻/s]	125 (25° C)	813 (45° C)
Digitization	[bit]	10	12
Framerate	[fps]	90	60

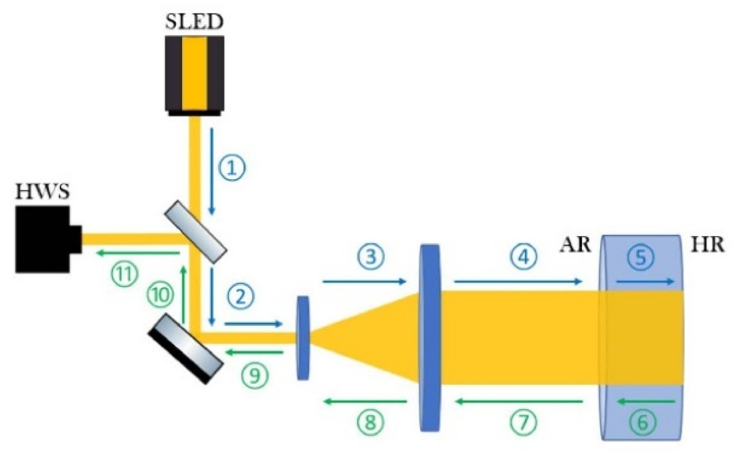
Required Sensitivity: $2\frac{\langle \Delta W_{max} \rangle}{10} \sim 0.4\, nm$

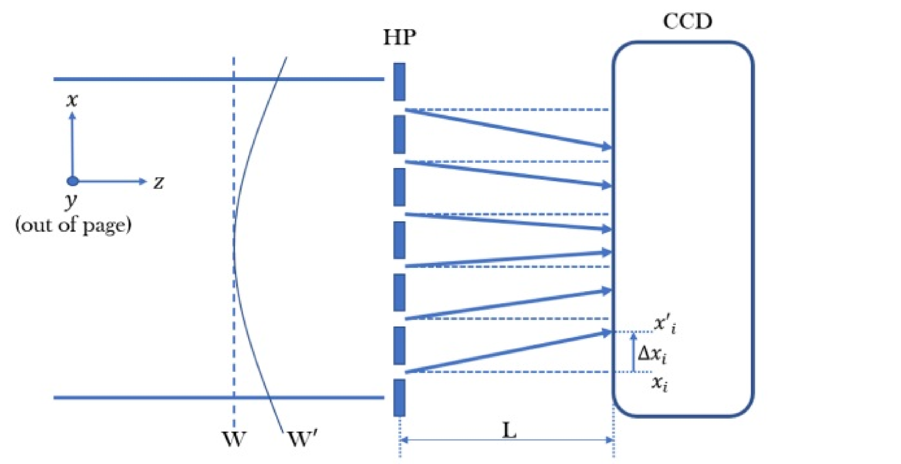
Wavefront RMS [nm]

N_{img}	Ximea	Dalsa
1	1.18	0.57
100	0.17	0.12
1000	0.10	0.05

The Hartmann Wavefront Sensor

The HWS is the **only** sensor capable of directly measuring variations in the wavefront. It operates in a **differential mode** by comparing the wavefront of a probe beam against that of a reference one.



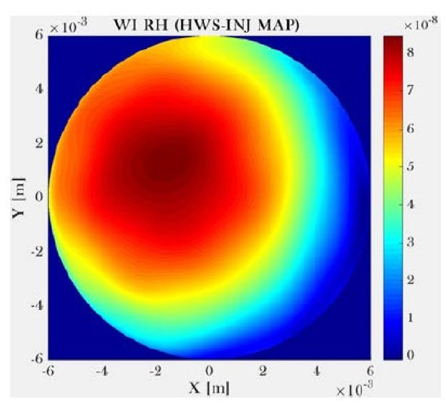


Numerical integration

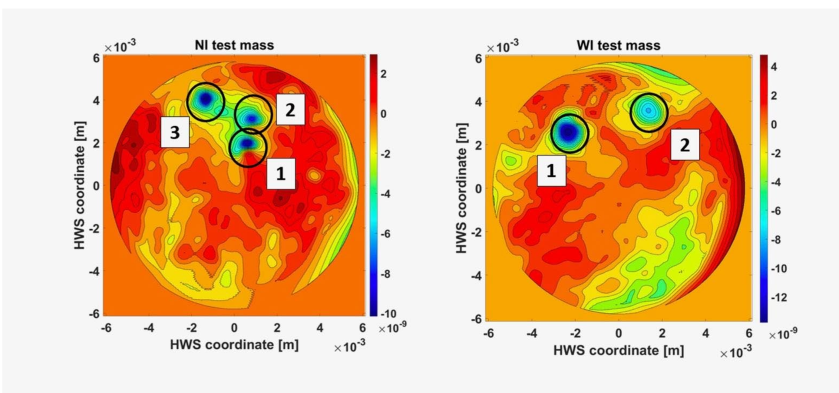
$$\frac{\partial \Delta W}{\partial x} = \frac{\Delta x_i}{L} \longrightarrow \Delta W$$

Multiple Diagnostics Instrument

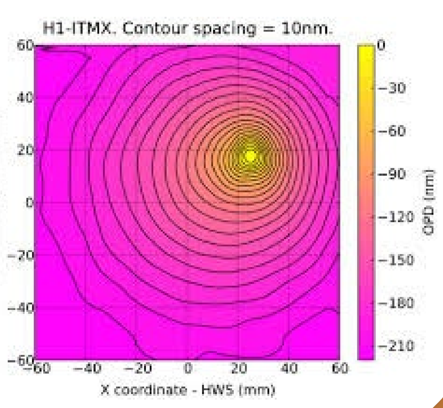
Centering of Thermal Actuators



Identification of Point Absorber

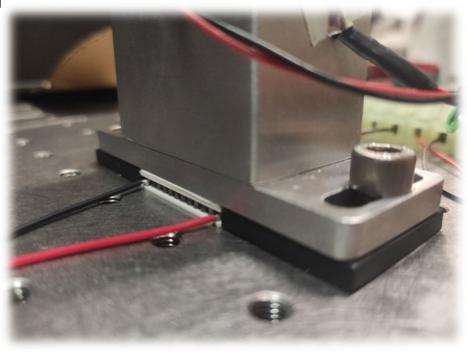


Coating Absorption Measurements



The New HWS Temperature Control

Temperature fluctuations induce thermal defocus, limiting the sensor's performance [2].

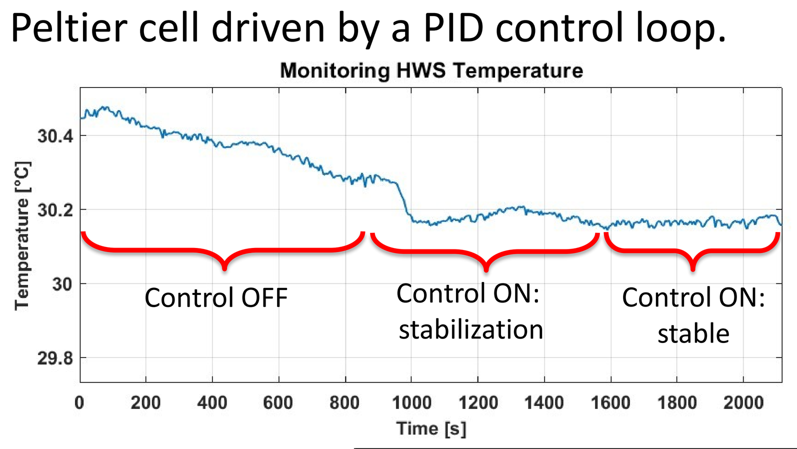


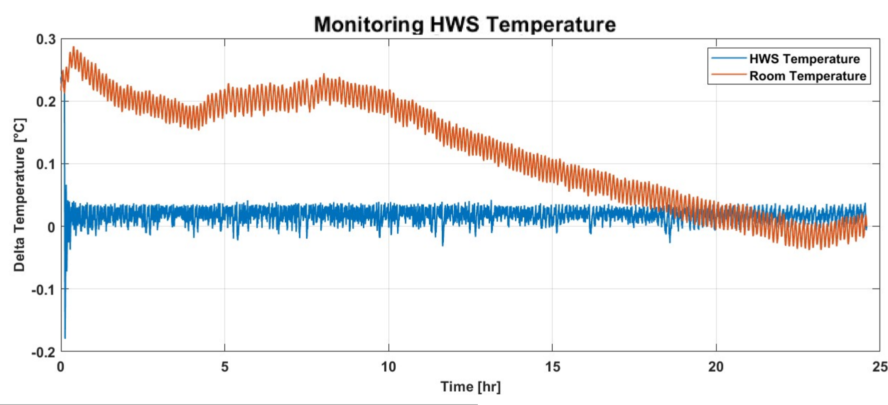
$$\Delta T_{max} = \frac{24}{\sqrt{3}}\frac{L}{\alpha D^2}\langle \Delta W_{max} \rangle$$

- L: lever arm;
- α: thermal expansion coefficient;
- D: distance between holes in the Hartman Plate.

Assuming a wavefront reconstruction requirement of 0.4 nm RMS. → $\Delta T_{max} \sim 37\, mK$ → **Temperature control required**

Temperatures are monitored using PT1000 sensors, while the thermal actuation is performed via a Peltier cell driven by a PID control loop.

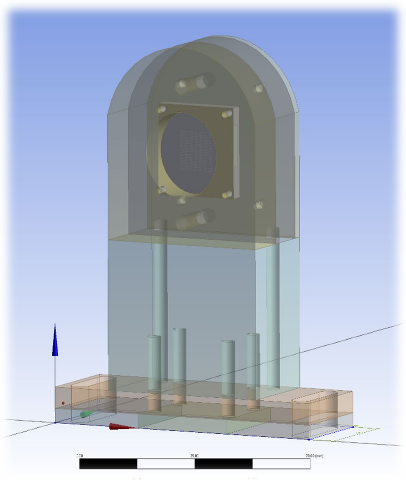




	Temperature Control OFF	Temperature Control ON
ΔT [°C]	0.07	0.02
RMS 1 img [nm]	1.18	1.02
RMS 100 img [nm]	0.17	0.13
RMS 1000 img [nm]	0.10	0.05

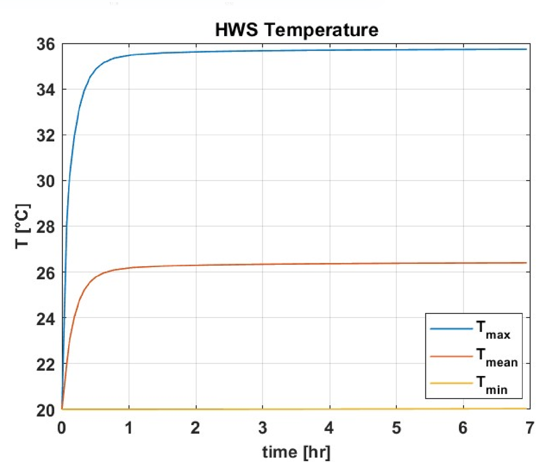
The New HWS Case Optimization

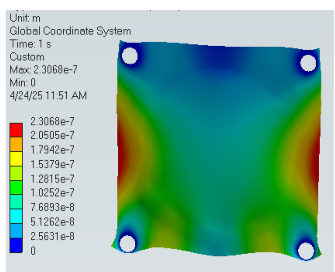
Material selection for the HWS housing is crucial to **optimize the heat transfer** between the HWS and the optical bench, to enhance the CMOS heat dissipation and to improve the temperature control.

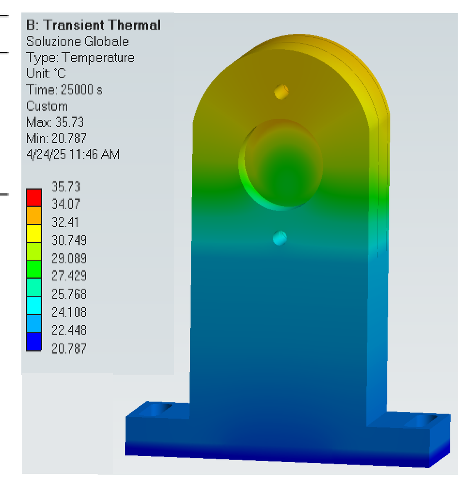


A 3D model of the HWS housing was developed and used for thermal and structural FEA simulations in ANSYS. Several design solutions have been compared.

	Max T [°C]	Mean T [°C]	Deformation RMS [μm]
Alluminium Case	25.25	23.70	0.72
Invar HP Retainer	25.31	23.70	0.68
Full-Invar Case	47.14	35.41	10^{-11}
Top-Invar Case	35.73	26.41	0.11
Bottom-Invar Case	37.38	31.50	2.36







The two-component case – with an Invar top and an aluminum base – proved to offer the best tradeoff between thermal stability and minimal deformation of the Hartmann plate.

Conclusions and Future Perspectives

The prototype of the new Hartmann Wavefront Sensor has been fully characterized, confirming its capability to achieve sub-nanometric wavefront reconstruction accuracy. The implemented temperature control system is in operation and has proven effective in minimizing thermally-induced defocus – thereby preserving sensor performance. Thermal and structural simulations guided the optimization of the sensor housing, revealing that a two-component design – with an Invar top and an aluminum base – results in the best tradeoff between thermal stability and minimal deformation of the Hartmann plate. This improved case design will be manufactured and tested at the AiLoV_ET facility (PNRR_ETIC) in Roma Tor Vergata to further validate its performance under more realistic operational conditions. This development marks a significant step toward delivering a suitable wavefront sensor for the next-generation gravitational wave detectors.

References

[1] *A. F. Brooks. "Hartmann Wavefront Sensors for Advanced Gravitational Wave Interferometers." PhD thesis. University of Adelaide, School of Chemistry and Physics, 2007*

[2] *L. Aiello et al. "Thermal defocus-free Hartmann Wavefront Sensors for monitoring aberrations in Advanced Virgo". In: Classical and Quantum Gravity 41.12 (May 2024), p. 125001.*