Development of ML for AO and Bench Validation

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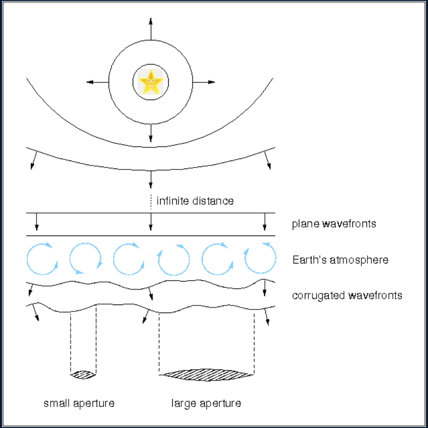
III ICTEA Research Days · 1–2 June 2026

1. The atmosphere as the main limitation

- Ground-based telescopes receive light after it has crossed a **dynamic turbulent medium**.
- The incoming wavefront is no longer flat when it reaches the pupil.
- The result is a loss of angular resolution, contrast and photometric stability.
- The same physical limitation affects **free-space optical communications**.



Atmospheric turbulence degrades image quality

2. Physics of wavefront degradation

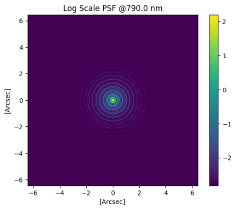
Atmospheric turbulence produces local fluctuations of the refractive index:

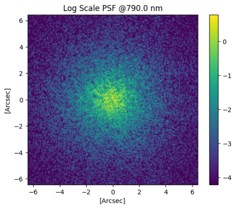
$$n(\mathbf{r}, t) = n_0 + \delta n(\mathbf{r}, t)$$

These fluctuations introduce phase delays across the pupil:

$$\phi(\mathbf{r}, t) = \frac{2\pi}{\lambda} \int \delta n(\mathbf{r}, z, t)\, dz$$

The telescope then forms an image limited not by diffraction, but by **seeing**.





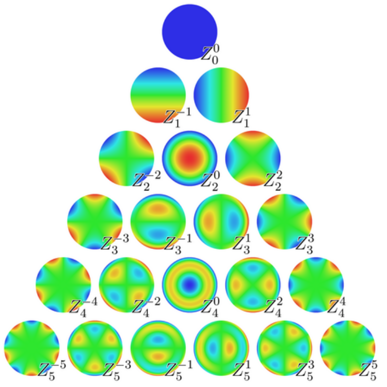
3. Representing atmospheric aberrations

Zernike polynomials

- Orthogonal basis defined over a circular pupil.
- Low-order modes correspond to familiar distortions:

Kolmogorov turbulence

- Statistical model of atmospheric turbulence.
- Characterized by parameters such as r_0 and L_0.



Examples of low-order Zernike modes

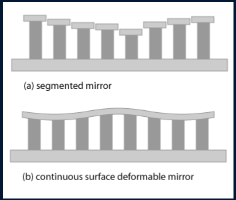
4. Main Components of an AO system (I)

Natural Guide Star

A bright astronomical source used as a reference to measure atmospheric distortion.

Laser Guide Star

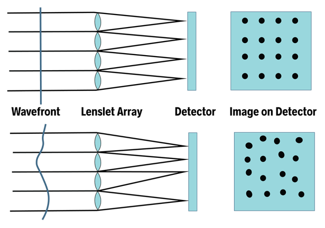
An artificial reference created by projecting a laser into the upper atmosphere.

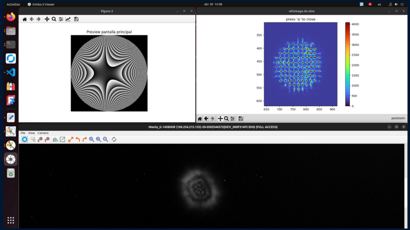


Deformable Mirror

A controllable mirror that reshapes the wavefront to compensate atmospheric aberrations.

5. Main Components of an AO system (II)





WFS (Shack–Hartmann + Camera)

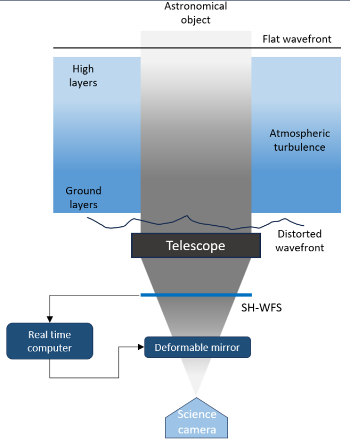
A microlens array splits the incoming wavefront into subapertures. The camera records the spot displacement pattern, from which local wavefront slopes are estimated.

Science camera

After correction by the deformable mirror, the science channel records the improved astronomical image.

6. Classical Adaptive Optics loop

1. **Shack–Hartmann WFS**: measures local wavefront slopes.
2. **Reconstructor**: converts slopes into mirror commands.
3. **Deformable Mirror**: applies the inverse optical correction.
4. **Closed loop**: iterates continuously in real time.



Closed-loop Adaptive Optics system

7. Matrix reconstruction and scalability

Classical reconstruction is often written as:

$$\mathbf{a} = \mathbf{R}\,\mathbf{s}$$

where:

- $\mathbf{s}$ are WFS slopes,
- $\mathbf{R}$ is the reconstruction matrix,
- $\mathbf{a}$ are deformable mirror actuator commands.

Bottleneck

For future extremely large telescopes, the number of actuators and sensor measurements grows dramatically.

Problem

The system must remain accurate, scalable and fast enough for real-time atmospheric correction.

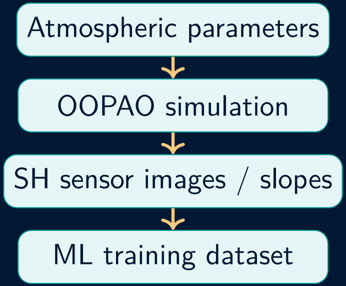
8. ML as an adaptive reconstruction strategy

	Classical AO	Deep Learning AO
Nature	Linear reconstruction	Non-linear inference
Computation	Matrix operations	Fixed trained network
Behaviour	Reactive	Potentially predictive
Scaling	Hardware pressure	Parallelizable inference

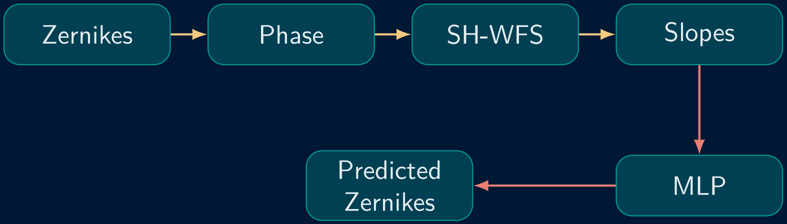
Goal: learn the mapping from sensor information to wavefront correction under realistic turbulent conditions.

9. From simulation to training data

- The project is currently focused on **numerical simulation**.
- OOPAO is used to generate controlled atmospheric turbulence.
- Synthetic datasets provide labelled examples for supervised learning.
- The target is to reconstruct or predict the distorted wavefront.

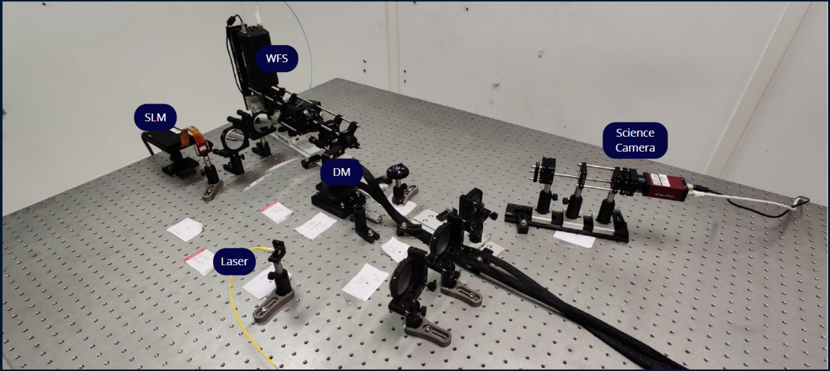


10. Dataset generation and training pipeline



- Synthetic Zernike coefficients are generated.
- OOPAO converts them into phase screens and SH-WFS measurements.
- Slopes are extracted and used as network inputs.
- The network is trained to reconstruct the original Zernike coefficients.

11. Experimental validation on the optical bench



- The ICTEA bench provides a controlled environment for turbulence injection and correction.

12. Expected impact

Astronomy

More scalable AO systems for future large-aperture telescopes, improving angular resolution and sensitivity.

Optical communications

Predictive turbulence correction for more stable free-space optical links.

- Robust real-time correction.
- Reduced computational bottlenecks.
- Better adaptation to complex turbulence.
- Bridge between simulation and experimental AO hardware.

13. Conclusions

- Atmospheric turbulence remains a fundamental limitation for ground-based observation.
- Classical AO works, but scalability and latency become critical for next-generation systems.
- Machine Learning offers a promising route for fast, non-linear and potentially predictive reconstruction.
- The current work focuses on synthetic dataset generation, model evaluation and optical bench validation.

Thank you for your attention

Questions?