Literature Review on Adaptive Optics

Muaayed F. AL-RAWI[1], Mhnd FARHAN*,[2]

*Corresponding author
[1]Al-Mustansiriyah University, Baghdad, Iraq,
muaayed@uomustansiriyah.edu.iq
[2]Baghdad University, Iraq,
mhndfarhan@yahoo.com*

DOI: 10.13111/2066-8201.2026.18.2.17

Received: 31 March 2026/ Accepted: 11 May 2026/ Published: June 2026

Abstract: *Adaptive optics (AO) is defined as a technology developed to compensate for wavefront distortions caused by atmospheric turbulence or microscopic heterogeneities, thereby enhancing image quality in observational astronomy and biological microscopy. It utilizes devices such as deformable mirrors or spatial light modulators to detect and correct these distortions for improved imaging. In adaptive optics, a deformable mirror is incorporated into the optical system. This mirror measures wave aberration in real time to correct distortions, reducing environmental impacts and improving imaging quality. Essentially, adaptive optics actively corrects errors in optical systems, combining scientific principles with engineering applications to play a crucial role in modern optics. This paper serves as a review on adaptive optics.*

Key Words: *Adaptive optics, architecture, applications*

1. INTRODUCTION

AO is a technique that removes the atmospheric disturbance and allows a telescope to achieve diffraction-limited imaging from the ground. This is critical in achieving the maximum signal-to-noise ratio. The basic idea of AO is to first measure the amount of atmospheric disturbance, then correct for it before the light reaches the camera. A schematic of how this can be done is shown in Fig. 1 [1].

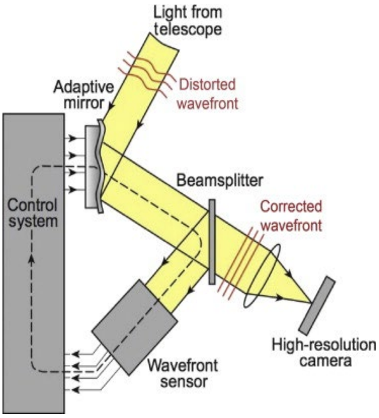

Fig. 1 Simplified diagram of an AO system

Light from the telescope is collimated and sent to an adaptive or deformable mirror. If there were no atmospheric turbulence, the wavefront of the light would be perfectly straight and parallel. The light is then reflected to a beam splitter, where part of the light is reflected to the wavefront sensor. The wavefront sensor measures the distortion of the wavefront and sends a correction signal to the adaptive mirror. The adaptive mirror is capable of changing its shape to remove the deformations in the light wave caused by the atmospheric turbulence. In this way, the light with a corrected wavefront reaches the high-resolution camera, where a diffraction-limited image is formed [1].

AO requires a star or another object that is bright enough for rapidly and accurately measuring the incoming wavefront. If the object of interest is not bright enough, then it is necessary to use a nearby bright star. This limits the sky coverage, since not every region of the sky will have a bright enough star nearby.

If there is no nearby bright star, then it is necessary to use a laser guide star. A laser is pointed in the same direction as the telescope and is used to excite a thin layer of sodium atoms in Earth's ionosphere (at an altitude of 90 km). This provides a point source that acts as an artificial star for the AO system [1].

Fig. 2 shows a dramatic photo of laser guide stars in use at the Keck and Subaru telescopes on Mauna Kea. All large telescopes now have AO and laser guide stars. The effect of using AO is striking. It is like placing the telescope into space. An impressive example of how AO can improve image quality is shown in Fig. 3. A further example of the high angular resolution provided by AO is shown in Fig. 4. Here the volcanoes on the satellite Io can be individually resolved. Such high angular resolution is impressive and rivals the images from the Voyager and Galileo spacecraft [1].

Fig. 2 Sodium laser guide stars in simultaneous use at the Keck and Subaru telescopes

The laser operates at a wavelength of 5890 Å (0.589 μm), and the laser light is propagated through a smaller telescope attached to the telescopes. It excites sodium atoms at an altitude of 90 km in Earth's atmosphere. The sodium atoms emit light at the same wavelength as the laser, and this is viewed as an artificial star by the telescope. All large telescopes employ laser guide stars to achieve diffraction-limited imaging. This is a long exposure photograph. The laser guide star is barely visible with the naked eye from this angle.

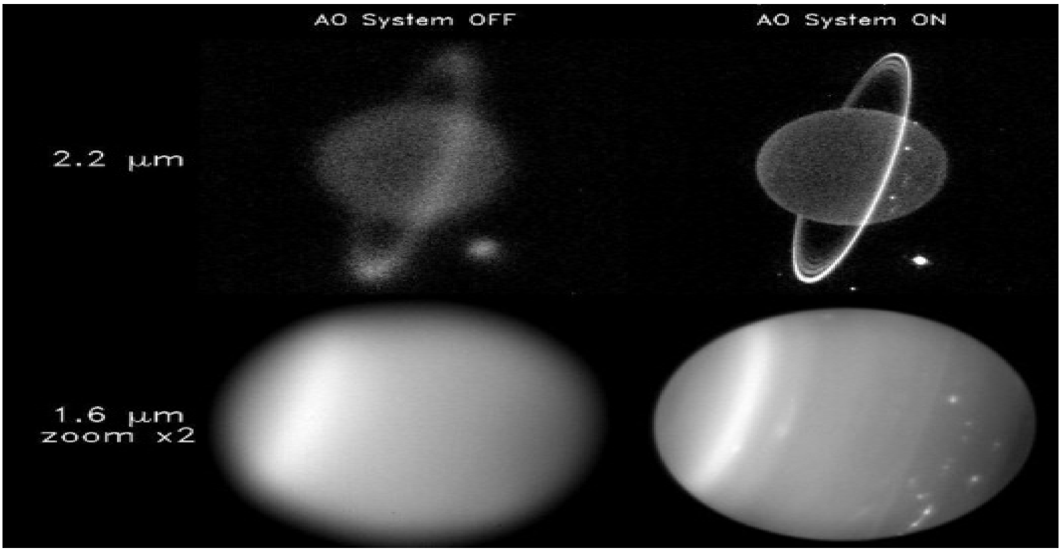

Fig. 3 Images of Uranus with and without adaptive optics

This is a striking demonstration of the effectiveness of AO in removing atmospheric turbulence. One can also see that the signal-to-noise ratio is greatly enhanced because light is concentrated into a diffraction-limited image with AO, thus greatly increasing the ability to detect faint spots and cloud structure.

At a wavelength of 1.6 µm, we are seeing reflected light from low-altitude clouds, while at 2.2 µm the high-altitude clouds are revealed. The planet is much darker at 2.2 µm because of absorption of methane gas in the atmosphere. This allows a much longer exposure and for the rings to be seen clearly.

The point-like cloud features at 2.2 µm show that in certain places turbulence is very strong, and it is pushing material from lower altitudes into the stratosphere [1].

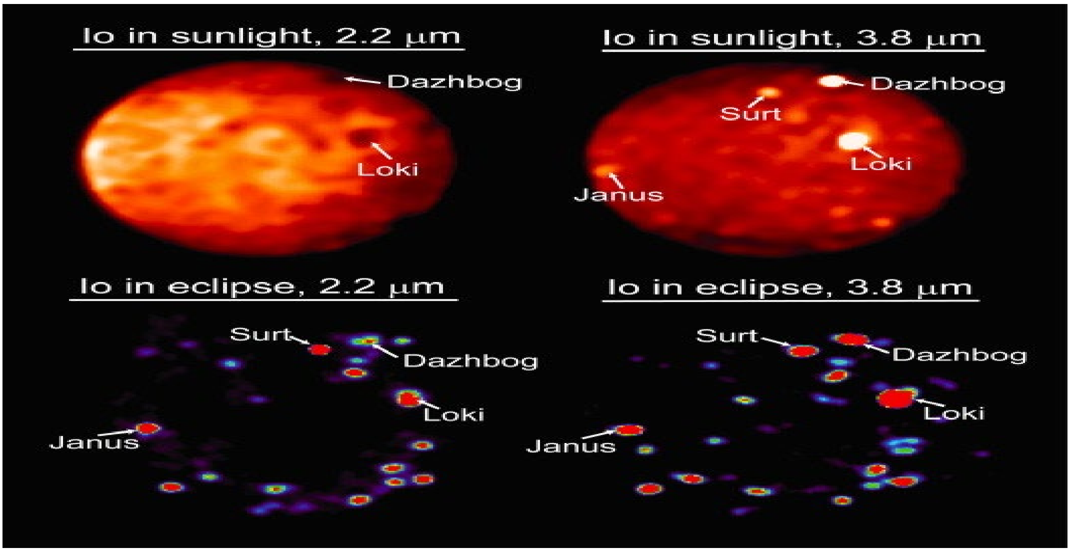

Fig. 4 Adaptive optics images of Jupiter's satellite Io obtained with the Keck Observatory.

The angular size of Io is 1.2 arcseconds. (Top): Io in sunlight. At 2.2 µm the reflected light from the Sun dominates, while at 3.8 µm thermal emission (heat) from the volcanoes can be observed. Some volcanoes (Loki, Dazhbog) show up as hot spots at 3.8 µm, but as low-albedo features at 2.2 µm. (Bottom): Io in eclipse. Images of Io taken 2 h later, after the satellite had entered Jupiter's shadow.

Without sunlight reflecting off the satellite, even the faintest hot spots can be discerned. The difference in brightness between the two wavelengths gives an indication of the temperature of the spot. Dazhbog, very bright at 3.8 µm, is a low-temperature (500 K) hot spot. Janus, on the other hand, is very bright at both 3.8 and 2.2 µm, indicative of higher temperatures (800 K) [1].

2. ADAPTIVE OPTICS APPLICATIONS

Besides its use for improving nighttime astronomical imaging and retinal imaging, adaptive optics technology has also been used in other settings. Adaptive optics is used for solar astronomy at observatories such as the Swedish 1-m Solar Telescope, Dunn Solar Telescope, and Big Bear Solar Observatory. It is also expected to play a military role by allowing ground-based and airborne laser weapons to reach and destroy targets at a distance including satellites in orbit. The Missile Defense Agency Airborne Laser program is the principal example of this.

Adaptive optics has been used to enhance the performance of classical and quantum free-space optical communication systems, and to control the spatial output of optical fibers.

Medical applications include imaging of the retina, where it has been combined with optical coherence tomography. Also the development of Adaptive Optics Scanning Laser Ophthalmoscope (AOSLO) has enabled correcting for the aberrations of the wavefront that is reflected from the human retina and to take diffraction limited images of the human rods and cones [2]. Adaptive and active optics are also being developed for use in glasses to achieve better than 20/20 vision, initially for military applications.

After propagation of a wavefront, parts of it may overlap leading to interference and preventing adaptive optics from correcting it. Propagation of a curved wavefront always leads to amplitude variation. This needs to be considered if a good beam profile is to be achieved in laser applications.

In material processing using lasers, adjustments can be made on the fly to allow for variation of focus-depth during piercing for changes in focal length across the working surface. Beam width can also be adjusted to switch between piercing and cutting mode. This eliminates the need for optic of the laser head to be switched, cutting down on overall processing time for more dynamic modifications.

Adaptive optics, especially wavefront-coding spatial light modulators, are frequently used in optical trapping applications to multiplex and dynamically reconfigure laser foci that are used to micro-manipulate biological specimens.

3. LITERATURE REVIEW

In [2], the optical scintillation is mitigated by the adaptive optics technique and its corresponding effect on the channel capacity of the UOWC link is studied. In this respect, the channel capacity of the UOWC link employing a Gaussian beam and operating in weak oceanic turbulence is evaluated. The related entities for the evaluation such as the received signal intensity is derived by the help of the Huygens-Fresnel principle, and the scintillation index with and without adaptive optics compensation is obtained by the Rytov method. Low-order Zernike filter functions, namely, tilt, defocus, astigmatism, and coma are used to represent the turbulence-induced.

In [3], adaptive optics (AO) has the potential to mitigate the effect of atmospheric turbulence and improve the performance of orbital angular momentum (OAM)-based optical wireless communication (OAM-OWC) links. Here, the authors propose a single-intensity-measurement phase retrieval algorithm (SPRA)-based AO technique of compensating for the distortion of the OAM beam. The only parameter required by the SPRA wave-front sensor is the intensity of the probe beam in the Fourier domain, which substantially simplifies the AO system. Authors first derive an analytical expression to characterize the expansion of probe beam in OAM-OWC links and then determine the diameter constraints as the apriori information of the SPRA required for guaranteeing a certain compensation performance. The simulation results illustrate that the SPRA-AO approach can indeed correct a distorted OAM beam both in a single-channel scenario and in multiplexed OAM-OWC systems. The bit error rate can be improved by orders of magnitude with the aid of SPRA-AO compensation. Furthermore, authors establish noise models of AO-based OAM-OWC systems and analyze the robustness of the SPRA-AO technique. In a nutshell, this paper provides new insights for the applications of AO and forms the theoretical basis of employing probe beams in OAM-OWC systems.

In [4], authors design a modified phase diversity algorithm (MPDA)-based wavefront sensor to enhance the reconstruction accuracy of distorted OAM wavefront information. Aiming to further strike a compelling trade-off between AO system complexity and compensation accuracy, authors first construct a novel AO system that applies a quickly and electronically controlled focus-tunable lens (FTL).

It decontaminates distorted OAM signaling beams while having a low systemic complexity and superior convergence performance. Furthermore, authors propose the 3-modified phase diversity algorithm (3-MPDA) AO scheme relying upon a Fourier intensity and two defocused intensities as the prior information, which beneficially balances the compensation effect and the number of defocused intensities and exhibits good noise robustness against charge-coupled device (CCD) detectors. In summary, this paper provides new insight for designing AO schemes with high compensation performance in communication links.

In [5], synthetic aperture lidar (SAL) is a widely used radar system, and the quality of its imaging is greatly affected by atmospheric turbulence during transmission. The use of adaptive optics (AO) systems can effectively improve the imaging quality. In this paper, authors constructed a SAL simulation system based on wavefront sensing (WFS) and studied its imaging quality.

The simulation results show that the adaptive optics system with WFS can effectively improve the imaging signal-to-noise ratio (SNR) of the system, and has almost no negative impact on its imaging resolution.

In [6], the development of laser communication technology between satellites and ground stations has been paid attention recently. On the other hand, the laser communication between satellites and ground stations is always affected by the atmospheric condition. Authors can compensate this effect by applying the technology of Adaptive Optics that is used for astronomical observation. We started the development of Adaptive Optics for laser communication in NICT from 2019 and completed the manufacture of Adaptive Optics for Koganei 1-m telescope in 2021 fiscal year.

Authors performed the initial inspection of the performance of this system in March 2022. Although it was just simulation using artificial light source in our inspection, we can confirm the performance of AO of Koganei 1-m telescope is enough to improve the fiber coupling efficiency. In this study, authors describe the detail of Adaptive Optics for laser communication in NICT.

In [7], the paper presents a direct data-driven control scheme to compute an optimal controller using the frequency-domain representation of the disturbance and the system model. Numerical simulations of the AO system demonstrate performance improvement compared to standard AO control schemes, and resilience to the variance in atmospheric turbulence and internal vibrations.

In [8], the paper presents the design and laboratory prototyping of a high-order AO system intended for the University of Canterbury's 0.61 m Boller & Chivens (B&C) Telescope. The AO system incorporates a 12×12 actuator Micro-Electro-Mechanical Systems Deformable Mirror to simulate atmospheric conditions and static aberration screens, and a Thorlabs DM and Shack-Hartmann Wavefront Sensor for closed loop correction. The system was tested in the laboratory under simulated atmospheric conditions, with a focus on correcting higher-order aberrations, such as defocus and astigmatism.

Experimental results demonstrate significant improvements in the Full Width at Half Maximum of the Point Spread Function, indicating the system's potential for improving image quality. The prototype's design allows for simple integration with the B&C Telescope, paving the way for its future implementation at the University of Canterbury's Mount John Observatory.

In [9], the paper introduces a straightforward and efficient decoupling control algorithm that is based on mode-voltage constraints. The proposed algorithm utilizes the mode method to decompose the control voltage mode, constructs a transition matrix to avoid piston and tip/tilt aberrations, and combines this matrix with the response matrix of the deformable mirror to generate a new reconstruction matrix.

The direct slope algorithm is used to obtain the mode coefficient of the control voltage, which is then followed by obtaining the constrained control voltage through the proportional-integral controller and transition matrix. Simulation results demonstrate that this algorithm outperforms both the traditional vector project-constraint algorithm and the projection-based decoupling algorithm.

The experimental results demonstrate the effective suppression of coupling between the deformable mirror and tip/tilt mirror by this algorithm, leading to a higher Strehl Ratio and improved correction for first 44-order Zernike mode aberrations.

In [10], the paper combines preprocessing techniques with sparse matrix multiplication techniques to reduce the computational complexity of the algorithm. And the convergence and wavefront control stability of the iterative algorithm are optimized. For an adaptive optical system with 1201 actuators, the computational efficiency of the proposed algorithm is increased by 5 times. And the larger the scale of the adaptive optics system, the more significant the improvement in efficiency compared to the direct gradient wavefront control algorithm.

In [11], authors derive a simple, physical, closed-form expression for the optical-path difference (OPD) of a two-wavelength adaptive-optics (AO) system. Starting from Hogge and Butts' classic OPD variance integral expression, authors apply Mellin transform techniques to obtain series and asymptotic solutions to the integral.

For realistic two-wavelength AO systems, the former converges slowly and has limited utility. The latter, on the other hand, is a simple formula in terms of the separation between the AO sensing (i.e., the beacon) and compensation (or observation) wavelengths. Authors validate this formula by comparing it to the OPD variances obtained from the aforementioned series and direct numerical evaluation of Hogge and Butts' integral. Their simple asymptotic expression is shown to be in excellent agreement with these exact solutions. The work presented in this study will be useful in the design and characterization of two-wavelength AO systems.

In [12], a new filter-based off-policy policy iteration (FB-OPPI) control scheme is proposed and experimentally verified in this study to provide AO systems with a flexible beam stabilization method. The FB-OPPI is based on the policy iteration, a model-free controller design principle. To address the challenges such as convergence speed, data requirements and control stability that it faces in practice, we have proposed an implicit state reconstruction method based on the Kalman filter and introduced the adaptive transverse filter technology. Additionally, the off-policy learning mechanism is deployed to simplify the optimization process. An AO beam stabilization system was constructed to verify the effectiveness of the proposed method.

Experimental results show that the FB-OPPI method features simple design and fast training, releases the requirement for additional sensors or model recognition. The FB-OPPI method is superior to traditional integral controllers, effectively handling high-frequency narrowband and complex beam jitters. Despite not requiring model identification, it is on par with the advanced Linear Quadratic Gaussian (LQG) control.

In [13], authors derive Rytov variance of Adaptive optics (AO) applied to atmospheric turbulence. Authors chose the modified von-Karman power spectrum, which covers the atmosphere's inner and outer scales. After analytical derivations, authors plot Rytov variance against propagation distance and spatial frequency.

We organize the plots to see the effect of atmospheric turbulence, scaling factor, and type of correction. Rytov variance is directly proportional to the propagation distance. On the other hand, it has an inverse relation between the ratio of spatial frequencies. Our results show that Rytov variance in adaptive optics corrected spectrum is low for a low turbulent regime. Moreover, authors calculate the scintillation index using derived Rytov variance. We believe our results will be used to model adaptive optics corrected random phase screen approach, a model for turbulent channels in wave optics. This way, performance measurements for adaptive optics corrections could be more accurate.

In [14], the paper investigates the latest advancements in wavefront reconstruction technology within the adaptive optics system, with a particular focus on image-based wavefront sensing techniques. In satellite-to-ground laser communication, the impact of atmospheric turbulence on beam transmission can be mitigated through adaptive optics techniques. Traditional wavefront recovery methods rely on iterative operations, but the development of Deep Neural Networks (DNN) has provided new solutions for wavefront reconstruction in recent years.

This paper proposes an improved pix2pix architecture that utilizes Generative Adversarial Networks (GAN) to reconstruct wavefront images from the received intensity images. By introducing a peak-to-valley (PV) value loss function, our model can handle the issue of variable wavefront differences and demonstrates robustness under different strengths of atmospheric turbulence.

Experimental results show that compared to the U-Net model, the proposed model can more accurately reconstruct the wavefront, with higher Mean Structural Similarity (MSSIM) and Strehl Ratio (SR). Moreover, the model has an average wavefront reconstruction speed of 0.03 seconds per image on actual hardware, showing the advantage of easy implementation. Future research will explore the application of more GAN network architectures in wavefront reconstruction.

4. CONCLUSIONS

Adaptive Optics (AO) is a powerful technology that corrects light distortions from the atmosphere or within optical systems, enabling clearer, sharper images in astronomy, medicine, and microscopy by using wavefront sensors and deformable mirrors to rapidly reshape light in real-time, essentially giving ground-based telescopes "eyes" as good as space telescopes

REFERENCES

[1] T. Tokunaga, "New Generation Ground-Based Optical/Infrared Telescopes", *Encyclopedia of the Solar System* (Third Edition), chapter 51, 2014, doi: 10.1016/B978-0-12-415845-0.00051-7.

[2] M. C. Gökçe, "Effect of Adaptive Optics on Average Channel Capacity of Underwater Optical Wireless Communication System", *2020 Innovations in Intelligent Systems and Applications Conference (ASYU)*, Istanbul, Turkey, 2020, pp. 1-5, doi: 10.1109/ASYU50717.2020.9259866.

[3] H. Chang et al., "Low-Complexity Adaptive Optics Aided Orbital Angular Momentum Based Wireless Communications," in *IEEE Transactions on Vehicular Technology*, vol. **70**, no. 8, pp. 7812-7824, Aug. 2021, doi: 10.1109/TVT.2021.3092791.

[4] H. Chang et al., "Adaptive Optics Compensation for Orbital Angular Momentum Optical Wireless Communications", in *IEEE Transactions on Wireless Communications*, vol. **2**1, no. 12, pp. 11151-11163, Dec. 2022, doi: 10.1109/TWC.2022.3190329.

[5] C. Chen, Y. Li, H. Song, X. Hong, H. Guo and J. Wu, "Performance Analysis of Adaptive Optics in Turbulence Compensation with WFS for Synthetic Aperture Lidar Imaging", *2023 Asia Communications and Photonics Conference/2023 International Photonics and Optoelectronics Meetings (ACP/POEM)*, Wuhan, China, 2023, pp. 01-05, doi: 10.1109/ACP/POEM59049.2023.10369303.

[6] Y. Saito, D. Kolev, J. Nakazono, Y. Abe and M. Toyoshima, "Adaptive Optics for Satellite Laser Communications", *2023 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2023, pp. 1-3, doi: 10.1364/OFC.2023.Th1H.3.

[7] V. Gupta, A. Karimi, F. Wildi and J. -P. Véran, "Direct Data-Driven Vibration Control for Adaptive Optics", *2023 62nd IEEE Conference on Decision and Control (CDC)*, Singapore, Singapore, 2023, pp. 8521-8526, doi: 10.1109/CDC49753.2023.10383356.

[8] E. Johnson, S. J. Weddell, J. Chen and R. Clare, "Design and Prototype of a High Order Adaptive Optics System for University of Canterbury's 0.61m Boller & Chivens Telescope", *2024 39th International Conference on Image and Vision Computing New Zealand (IVCNZ)*, Christchurch, New Zealand, 2024, pp. 1-6, doi: 10.1109/IVCNZ64857.2024.10794467.

[9] Y. Zuo, J. Guo, N. Gao, Y. Zhu, S. Jin and X. Li, "A Survey of Blockchain and Artificial Intelligence for 6G Wireless Communications", in *IEEE Communications Surveys & Tutorials*, vol. **25**, no. 4, pp. 2494-2528, Fourthquarter 2023, doi: 10.1109/COMST.2023.3315374.

[10] S. Liu et al., "Optimization of Iterative Control Algorithms for High-Resolution Adaptive Optics Systems", in *IEEE Photonics Journal*, vol. **16**, no. 5, pp. 1-10, Oct. 2024, Art no. 6802810, doi: 10.1109/JPHOT.2024.3383792.

[11] M. W. Hyde, M. Kalensky and M. F. Spencer, "Phase Error Scaling Law in Two-Wavelength Adaptive Optic"s, in *IEEE Photonics Technology Letters*, vol. **36**, no. 12, pp. 779-782, 15 June15, 2024, doi: 10.1109/LPT.2024.3399777.

[12] S. Guo et al., "Design and Experimental Validation of a Model-Free Controller for Beam Stabilization in Adaptive Optics Systems", in *IEEE Photonics Journal*, vol. **16**, no. 6, pp. 1-12, Dec. 2024, Art no. 8600712, doi: 10.1109/JPHOT.2024.3471827.

[13] M. Bayraktar, L. M. Garces-Socarras, J. C. M. Duncan and S. Chatzinotas, "Rytov Variance of Adaptive Optics Applied Modified Von-Karman Spectrum", *2024 IEEE Wireless Communications and Networking Conference (WCNC)*, Dubai, United Arab Emirates, 2024, pp. 1-5, doi: 10.1109/WCNC57260.2024.10570868.

[14] Q. Zhao, A. Nauman, K. Guo, Z. Lin, R. Ma and Y. Wang, "Adaptive Optics Wavefront Reconstruction Based on the Improved Pix2Pix Architecture", *IEEE INFOCOM 2025 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, London, United Kingdom, 2025, pp. 1-5, doi: 10.1109/INFOCOMWKSHPS65812.2025.11152912.