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Centroiding Search for a Wavefront Sensor Robust to Truncation.

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Abstract. Adaptive optics systems require a reference star for proper operation, commonly an artificial star (laser guide star). The image of this star, observed by the wavefront sensor, appears as an elongated spot with light intensity dependent on the sodium layer density profile. Processing wavefront sensor data with elongated stars is not trivial, especially in the presence of truncation—an error caused by turbulence-induced movement in the wavefront, resulting in the star's elongated spot "spilling out" of the sub-aperture. This effect will be present in the future E-ELT telescope. The central objective of the project is to determine the star's centroid even in the presence of truncation. This research aims to translate the theoretical work of Pires, 2024, into a practical confirmatory experiment on an Adaptive Optics (AO) platform built in the LASSIP laboratory. For this purpose, an integrated table is being constructed with a set of optical instruments, including a monochromatic camera (CCD, CMO), a deformable mirror, a Shack-Hartmann wavefront sensor, lenses, a laser light source, an LED light source, a control drive, and a turbulence generator. This setup will test the centroiding technique even in the presence of laser guide star truncation. To achieve satisfactory results in testing the centroiding technique, a high-quality sensor and camera will be used to capture images of the guide star, simulated by the laser generator (Faes et al, 2018). A robust centroid detection algorithm will be implemented to determine the star's centroid position. Centroid detection involves precisely locating the geometric center of the guide star, which is crucial for the accuracy of the entire adaptive optics system.

Resumo. Os sistemas de óptica adaptativa requerem uma estrela de referência para operar corretamente, geralmente uma estrela artificial (estrela guia a laser). A imagem dessa estrela, observada pelo sensor de frente de onda, aparece como uma mancha alongada, com intensidade de luz dependente do perfil de densidade da camada de sódio. O processamento dos dados do sensor de frente de onda com estrelas alongadas não é trivial, especialmente na presença de truncamento — um erro causado pelo movimento induzido por turbulência na frente de onda, resultando na "transbordo" da mancha alongada da estrela para fora da subabertura. Esse efeito estará presente no futuro telescópio E-ELT. O objetivo central do projeto é determinar o centróide da estrela mesmo na presença de truncamento. Esta pesquisa visa traduzir o trabalho teórico de Pires, 2024, em um experimento prático confirmatório em uma plataforma de Óptica Adaptativa (AO) construída no laboratório LASSIP. Para isso, está sendo construída uma bancada integrada com um conjunto de instrumentos ópticos, incluindo uma câmera monocromática (CCD, CMOS), um espelho deformável, um sensor de frente de onda de Shack-Hartmann, lentes, uma fonte de luz laser, uma fonte de luz LED, um sistema de controle e um gerador de turbulência. Este conjunto testará a técnica de determinação do centróide mesmo na presença de truncamento da estrela guia a laser. Para alcançar resultados satisfatórios no teste da técnica de determinação do centróide, será utilizado um sensor e uma câmera de alta qualidade para capturar imagens da estrela guia, simulada pelo gerador de laser (Faes et al., 2018). Um algoritmo robusto de detecção de centróide será implementado para determinar a posição do centróide da estrela. A detecção do centróide envolve localizar com precisão o centro geométrico da estrela guia, o que é crucial para a precisão de todo o sistema de óptica adaptativa.

Keywords. first keyword – second keyword – third keyword

1. Introduction

Today, adaptive optics systems have become indispensable for equipping large ground-based telescopes, as they allow the elimination of atmospheric turbulence effects, which are responsible for distorting images reaching the telescopes, making them blurred and of low resolution. These systems typically use artificial laser guide stars for proper operation. However, the image observed by the wavefront sensor in large-scale telescopes presents critical challenges due to the size of the mirrors, increasing the system's complexity. The laser image becomes elongated and susceptible to truncation, with light intensity dependent on the sodium layer density profile. This issue will be present in the European Extremely Large Telescope (E-ELT) (Neichel et al, 2016), motivating contingency studies such as the experiments included in this practical work, based on the search tool proposed by (Pires, 2024).

2. Laser Star

Lasers used in telescopes to create artificial guide stars, interact with the sodium layer located at an altitude of 80 to 100 km above Earth's surface. The sodium concentration in this layer is sufficient to reflect the laser light, creating an artificial guide star visible to telescopes (Mello & Pipa, 2016). With this method, the guide star for adaptive optics is generated; however, one of the challenges is the elongation of this star on the Wave Front Sensor.

3. Truncation in the Wavefront Sensor

Truncation occurs when the elongated image of the guide star is shifted by atmospheric turbulence outside the field of view, causing truncation and preventing it from being fully captured by the wavefront sensor, as ilustrated in fig. 1. This results in the guide star image extending beyond the sensor's effective area, surpassing the limits of its sub-apertures, leading to inaccurate centroid and wavefront measurements (Hardy, 1998).

The centroid refers to the calculation of the geometric center of an image, representing the center of the image in terms of the light intensity distribution of a laser guide star on a wavefront sensor. Precisely measuring the centroid is essential for determining the wavefront of the light and correcting atmospheric distortions (Hardy, 1998).

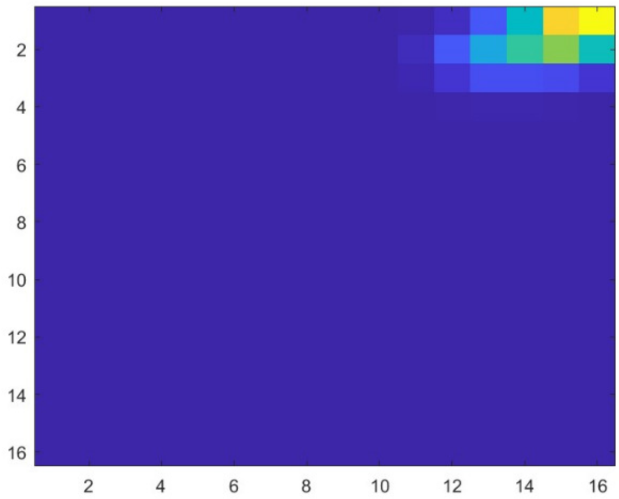

Figure 1. Wavefront sensor simulation showing the elongueited truncation effect.

To calculate the centroid under truncation, we will apply the method proposed by Pires (Pires, 2024), which estimates the central position using knowledge of the sodium layer profile, showing in the figure 2. This numerical optimization method searches for the x,y position values that minimize the Poisson noise distribution function, given the observed image probability for the sodium layer, where the operator represents the optical image acquisition process.

4. Optical Bench

An adaptive optics setup was built in the LASSIP (Laboratory of Statistical Signal Processing & Inverse Problems) laboratory at the central unit of UTFPR (Universidade Tecnológica Federal do Paraná) for the validating experiment of centroid detection. The arrangement of instruments on this platform was designed to ensure the correct and efficient positioning of each component, including a Shack-Hartmann wavefront sensor encapsulated with a monochromatic camera, a deformable mirror, a set of lenses, a laser light source, and a slit array with an LED light source, the figure 2 show the bench mounted.

The objective of this experiment is to replicate what will be observed in a wavefront sensor applied to the E-ELT (European Extremely Large Telescope), validating in the laboratory the simulation results of Pires (Pires, 2024). The system is being executed with the necessary corrections to reposition the guide star centroid at the desired center. This is simulated by an LED assisted by a slit and lenses acting as the guide star, with turbulence simulated by a deformable mirror.

In this work, we obtained preliminary results through simulations that included various truncation conditions caused by elongation to test the robustness of the technique.

For each image, the real or expected geometric center is established by alternating a point-like image with an elongated one under the same turbulence, keeping the deformable mirror static. This approach provides a reference for error assessment.

We compared the centroid determined by the technique with the reference geometric center, calculating error metrics such as the Euclidean distance between the determined centroid and the reference center indicated by the laser. This evaluation assesses the method's performance under different levels of elongation and truncation, including an analysis of its precision, convergence, and computational efficiency.

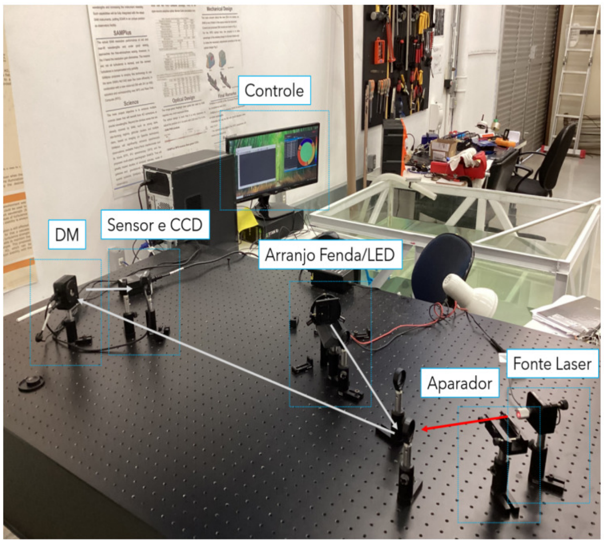

Figure 2. Monochromatic camera, a deformable mirror, a set of lenses, a laser light source, and a slit array with an LED light source and controler bench.

5. Conclusion

The setup has already been assembled, and we have obtained images consistent with what is expected for the E-ELT.

The next steps include obtaining a wider range of position and elongation angle scenarios to represent the full wavefront sensor operation. Algorithmic adjustments to the centroid detection method are expected based on the results to fine-tune the method's configurations, aiming to improve accuracy and reduce error. Additionally, statistical analyses will be conducted to determine the significance of the results. Further testing routines will be developed to validate the robustness of the optimized technique under various atmospheric or imaging conditions.

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