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Manipulating starlight: improving detection of nearby binaries and exoplanets with an adaptive pupil mask

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Abstract. Identifying the faint reflected or even light signal from extrasolar planetary companions close to a bright star is technically challenging. The wavefront is distorted by refractive index variations in the turbulent atmosphere, resulting in a speckled point distribution function (PSF) at short exposures. When observed at long exposures, these spots combine to form a large halo around a central core, leading to a loss of astrometric information and an inability to detect close companions. If the effects of this turbulence are not corrected, the acquisition of astronomical images in large telescopes is seriously compromised. The advent of adaptive optics (AO) has offered astronomers the possibility of tackling these problems. It makes it possible to recover the maximum angular resolution of terrestrial telescopes, correcting the distortions caused by atmospheric turbulence. The technique increases the peak intensity of the PSF by concentrating the photons back into the diffraction-limited nucleus. However, every optical system, even at the diffraction limit, generates elements in the PSF that can hide a weak companion, like the rings in the Airy disk. The pupil shape manipulation technique would allow us to modify the PSF and reduce these undesirable effects. This work investigates a method to attenuate the residual phase variance using an adaptive pupillary mask (APM). It can work alone or with the AO system, improving the telescope's performance in observing close double stars whose resolution is below 0.5 seconds of arc. The system was simulated in OOMAO (Object-Oriented MATLAB Adaptive Optics) and measured the phase with a Shack-Hartmann sensor. An algorithm reconstructs the phase and sends data to the deformable mirror (DM) and the APM. The mask blocks sub-openings and the reconstruction is enhanced at the same frequency as DM.

Resumo. É tecnicamente desafiador identificar o fraco sinal refletido ou mesmo luminoso de companheiros planetários extrassolares próximos a uma estrela brilhante. A frente de onda é distorcida pelas variações do índice de refração na atmosfera turbulenta, resultando em uma função de distribuição pontual (PSF) pontilhada em exposições curtas. Quando observados a longas exposições, essas manchas se combinam para formar um grande halo em torno de um núcleo central, levando à perda de informações astrométricas e à incapacidade de detectar companheiros próximos. Se os efeitos dessa turbulência não forem corrigidos, a obtenção das imagens astronômicas em grandes telescópios fica seriamente comprometida. O advento da óptica adaptativa (AO) tem oferecido aos astrônomos a possibilidade de enfrentar esses problemas. Ela permite recuperar a resolução angular máxima dos telescópios terrestres, corrigindo as distorções causadas pela turbulência atmosférica. A técnica aumenta a intensidade de pico da PSF ao concentrar os fótons, ora espalhados pela atmosfera num halo difuso, de volta ao núcleo limitado por difração. Entretanto, todo sistema óptico, mesmo no limite de difração, gera elementos na PSF que podem ocultar uma companheira fraca, como os anéis do disco de Airy, por exemplo. A técnica de manipulação do formato da pupila nos permitiria modificar a PSF e reduzir esses efeitos indesejáveis. Este trabalho investiga um método para atenuar a variância de fase residual, utilizando uma máscara de pupila adaptativa (APM). Ela poderá trabalhar sozinha ou em conjunto com o sistema de AO, melhorando o desempenho do telescópio na observação de estrelas duplas muito próximas, cuja resolução fique abaixo de 0,5 segundo de arco. O sistema foi simulado no OOMAO (Object-Oriented MATLAB Adaptive Optics) e mede a fase com um sensor Shack-Hartmann. Um algoritmo reconstrói a fase e envia dados para o espelho deformável (DM) e a APM. A máscara bloqueia sub-aberturas e a reconstrução é aprimorada na mesma frequência que o DM.

Keywords. Atmospheric effects – Instrumentation: adaptive optics – binaries (including multiple): close

1. Introduction

Most of our knowledge about close binary stars and exoplanets has been gained from the light from space arriving at our telescopes. The information these electromagnetic waves provide us is essential in studying these astrophysical objects.

Still, it is technically challenging to identify the faint reflected or even luminous signal from extrasolar planetary companions near a bright star. The wavefront is distorted by variations in the index of refraction in the turbulent atmosphere, which results in a dotted point distribution function (PSF) at short exposures. When observed at long exposures, these speckles combine to form a large halo around a central nucleus, leading to a loss of astrometric information and an inability to detect close companions.

Historically, this problem has already been addressed by Newton in the second edition of his book *Opticks*:

> For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by... the twinkling of the fix'd Stars... The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds (Newton 1718, 98).

Since then, many telescopes have been installed in mountainous and inhospitable regions where the atmosphere is thinner, thus minimizing the effects of atmospheric turbulence and, consequently, better seeing. However, there are now new remedies that Newton could not have predicted, like putting a telescope in orbit around the Earth, far beyond the atmosphere[1] or correcting the dynamic jitter of ever-changing air with a flexible mirror. Something unimaginable in the 18th century, it was proposed

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[1] A reality since 1968 with the *Stargazer* orbital astronomical observatory.

in 1956 by the American astronomer Horace W. Babcock. Thus emerging, the principle of an adaptive optics system.

AO makes it possible to recover the maximum angular resolution of terrestrial telescopes, correcting the distortions caused by atmospheric turbulence. The technique increases the peak intensity of the PSF by concentrating the photons, sometimes scattered through the atmosphere in a diffuse halo, back to the diffraction-limited nucleus. However, despite using AO, there is still residual phase variation. Every optical system, even at the diffraction limit, generates elements in the PSF that can hide a weak companion, like the rings in Airy's disk, for example. The pupil shape manipulation technique would allow us to modify the PSF and reduce these undesirable effects.

This work investigates a method to attenuate the effect of this variance using an adaptive pupillary mask (APM). It can work alone or with the AO system, improving the telescope's performance in observing close double stars whose resolution is below 0.5 seconds of arc. This resolution is where Gaia presents many spurious solutions (Brown et al. 2021, 10).

We also hope this system can improve the image's contrast, enabling the detection of exoplanets and faint companions in the close orbit of these stars. Adaptive pupil masking is an extension of techniques like lucky imaging. It allows the astronomer to manipulate the PSF of the images by actively blocking the areas of the wavefront with an average phase excursion greater than a specific value limit. Removing these incoherent parts of the wavefront reduces the PSF halo.

By changing the shape of the pupil, we can change the way light is diffracted. When we change the pupil's function several times, we can smooth out the spots, but a longer exposure time may be needed to see small objects. Reducing these smears helps make it easier to identify nearby objects.

A system simulation was developed in OOMAO (Object-Oriented MATLAB Adaptive Optics), where the phase is measured using a ShackHartmann-type wavefront sensor. Then, a continuous over-relaxation reconstruction algorithm estimates the phase map and transmits the data to the deformable mirror (DM) and the APM.

In the process, the mask blocks sub-apertures that exceed a defined threshold, while the design reconstruction is enhanced at the same rate as the DM. The mask is placed on the plane telescope pupil conjugate. It is proposed to replace the DM with MEMS mirrors, an electronic device with segmented mirrors on a millimetric scale, as an option for building the system. This solution can reduce costs, since piezoelectric deformable mirrors are expensive. However, a limited alternative, using MEMS mirrors, can present a better cost-benefit for the optical project.

2. Adaptive Pupil Mask

Our research was inspired by James Osborn's work on an adaptive pupil mask (Osborn, 2012), a thin plate with important patterns or segments placed in the telescope's pupil. It acts as a controllable filter, blocking some areas of light that reach the telescope while allowing others to pass through. Adjusting the mask segments accordingly makes it possible to compensate for specific distortions in real-time. It can work alone or in conjunction with the AO system, reducing the PSF halo and thus improving monitoring performance when observing close double stars.

The functioning of the adaptive pupil mask (APM) is intrinsically linked to algorithms and sensors that monitor atmospheric aberrations in real-time. Based on this data, the system calculates the necessary adjustments to the mask, ensuring that the light collected by the telescope is as distortion-free as possible, resulting in sharper, more detailed images of astronomical objects. Adaptive pupil masking expands techniques such as *lucky imaging*[2] and can reduce residual phase variation in telescopes of any size with or without AO.

We propose a complete AO simulation, developed in OOMAO[3], an open-source software package developed to simulate and model AO systems in a *Matlab* (*MAtrix LABoratory*) environment. The phase will be measured using a Shack-Hartmann wavefront sensor (WFS). A continuous over-relaxation reconstruction algorithm estimates the phase map and passes the data to the deformable mirror (DM) and APM. The mask blocks sub-openings that reach a certain threshold, and the piston reconstruction is updated at the same rate as the DM. In Figure 1, we show the simulated data flow and the location of the APM in the optical system with and without the DM.

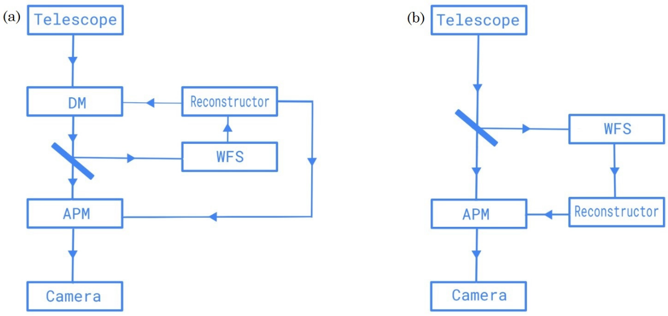

Figure 1. APM system block diagram.

It is important to note that OOMAO is a simulation tool not used directly to control adaptive optics systems on real telescopes. It is a valuable platform to study and improve understanding of adaptive optics principles and techniques before applying them to real projects.

AO systems are expensive and can reach considerable values, often in the range of millions to tens of millions of dollars. Additionally, ongoing maintenance and upgrade costs also need to be considered. Given this perspective, we propose removing the DM from the circuit to use only the APM (see Figure 1b). This APM can be built from MEMS mirrors, an electronic device with millimeter-scale mirrors, reducing costs since piezoelectric deformable mirrors are expensive. With this, we hope to present a more economical alternative, although limited, for the optical project, considering the best cost-benefit.

3. The APM simulation

The proposed simulation offers a detailed analysis of a specific Adaptive Optics (AO) system with a 4-meter telescope. Choosing this specific size directly influences the system's resolution and light collection capacity. Furthermore, the telescope mirror was divided into ten sub-apertures for wavefront system analysis.

When starting the simulation, the telescope mirror was modelled with a pupil resolution of 100 pixels, providing a detailed representation of the optical system. The field of view (FOV) was set at 30 arcseconds, representing the angular extent of the telescope. These parameters are crucial for defining the initial

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[2] Proposed by Fried (1978), this technique consists of recording many short-exposure images and selecting a fraction according to their quality. This fraction is encoded to produce sharp images.

[3] Available on the OOMAO page at GitHub.

conditions of the simulation and directly impact the quality of the images obtained.

The number of iterations was set at 15,000, representing the number of cycles the system will go through to adjust the adaptive pupil mask dynamically. This aspect is fundamental to understanding how the system adapts over time, especially in variable atmospheric conditions.

In addition to the mentioned parameters, it is relevant to consider the exposure time during the simulation, as it plays a crucial role in capturing astronomical data. The integration time, or exposure time (sampling time), defined as 1/500 seconds, can directly influence the telescope's sensitivity, impacting the quality and depth of the observations. Therefore, the choice of exposure time is an additional element to be considered when evaluating the effectiveness of the Adaptive Optics system in obtaining high-resolution astronomical images.

The OOMAO tool, implemented in the Matlab environment, allows the creation of a modular model where different components, such as the telescope, wavefront sensors, atmosphere, and deformable mirrors, can be adjusted and configured individually. This modular approach offers significant flexibility in model construction, adapting to different astronomical scenarios.

During the simulation, two telescopes were used simultaneously, allowing direct comparison between different scenarios or configurations. This specific choice highlights the model's ability to handle complex systems and provides a deeper understanding of the influences of telescope size on the overall capabilities of Adaptive Optics.

The simulation results are evaluated based on the Strehl metric, which reflects the quality of the image corrected by Adaptive Optics. The implementation of the Adaptive Optics closed loop is a central point in the simulation, where the adaptive pupil mask is dynamically adjusted based on wavefront sensor measurements, demonstrating the system's ability to adapt in real-time to changing atmospheric conditions.

This model was used to simulate APM in OOMAO; the resulting adaptive pupil mask is then applied to the primary telescope pupil, defining which sub-apertures will be used in the adaptive optics closed loop. This selection of sub-apertures is updated with each iteration of the control loop, allowing only the sub-apertures most useful for correction to be used, which improves the efficiency of the adaptive optics system.

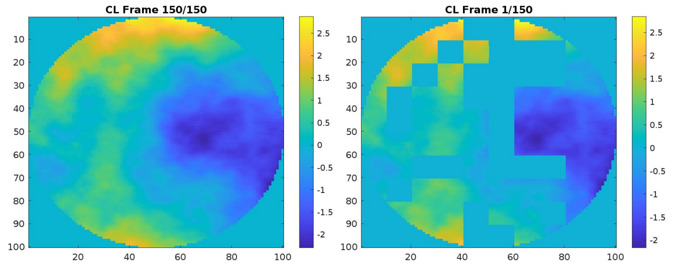

FIGURE 2. APM acting on atmospheric turbulence.

The turbulence images (figure 2) are generated from data from the object `ngs` (light source, in this case, the guide star) and `ngs2` (another light source) after propagation through the telescope and wavefront sensor. They represent the atmospheric distortions present in the sub-apertures of the wavefront sensor and are used to visualize the effect of atmospheric turbulence on images. They are identical; however, the mask only works on the image on the right. This routine allows observing the temporal evolution of the APM during the simulation.

4. Application results

Simulations were carried out with the APM in 4-meter aperture telescopes, observing its response to the evolution of turbulence. The cut parameter was modified 35 times in a range of values ($1 < \texttt{cut} < 5$) with 15,000 interactions per value, which enabled a comparative study between systems with and without APM. The results show a significant improvement in *Strehl* for the system that used APM, as can be seen in the comparative graph (figure 3):

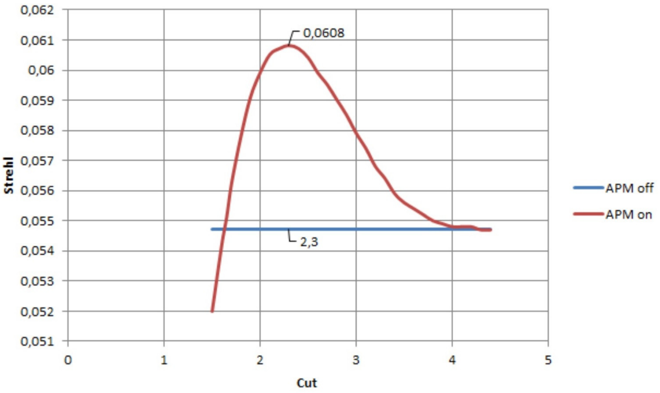

FIGURE 3. *Strehl* variation of telescopes with and without APM.

By increasing the value of `cut` beyond 1.65, the mask allows a higher *Strehl* ratio in telescope 2. This is considered a good result, as it indicates that the system is more aggressively correcting the atmospheric distortions. This can be beneficial in specific scenarios, especially if the goal is to maximize the quality of images obtained by telescope 2.

By setting the cut-off variable with an upper limit, such as 1.65, to delineate the regions where APM will be applied, we select the sub-apertures of the WFS that will be used for adaptive correction. If a specific sub-aperture has slopes that exceed this limit, it may indicate an area of the atmosphere with more intense turbulence or significant variations. In these regions, adaptive correction may be more effective or beneficial, as correcting these steep slopes may result in a gain in image quality.

Therefore, adjusting the APM based on the slopes measured by the WFS is logically valid. This approach helps optimize adaptive correction by focusing on points where correction will positively impact image quality. Allowing telescope 2 to have a higher *Strehl* ratio in these areas can result in a sharper, higher-quality final image.

Figure 4 illustrates an example of this correction, with (*a*) and (*c*) the images associated with the telescope without APM while (*b*) and (*d*) with the telescope with active APM. Using the logarithm can highlight details in low-contrast areas or highlight significant differences in light intensity levels in images. For this reason, (*c*) and (*d*) represent the logarithm of the camera's image buffers.

However, it is essential to consider some nuances when setting the value of `cut`:

- **The extent of Corrections:** Larger values of `cut` can allow the mask to include more significant pupil regions, resulting in more extensive corrections. This can improve the Strehl ratio but also limit the effective area and cause the inclusion of atmospheric influences further away from the center of the pupil, which may not be completely corrected.

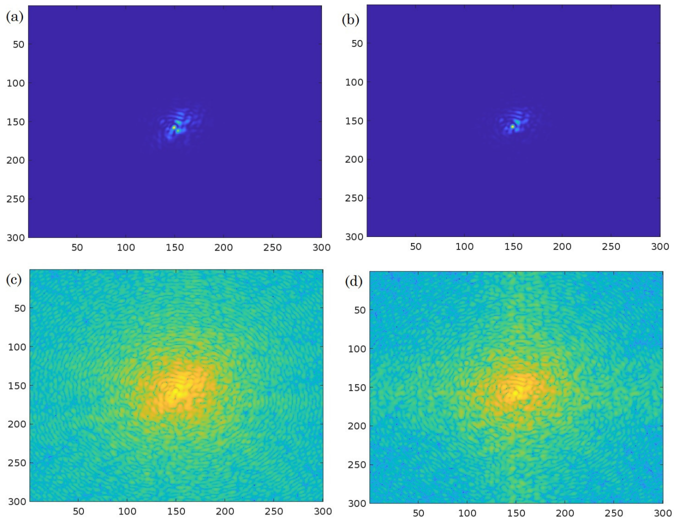

Figure 4. Image buffers captured by cameras. The images on the left were generated without AO correction, while those on the right using APM.

- **The trade-off between Brightness and Quality:** a higher `cut` value may allow for greater light intensity in telescope 2, resulting in brighter images. However, this may be at the expense of lower overall quality due to less aggressive corrections.
- **Variable turbulence:** the atmosphere is variable, and a very low `cut` value can lead to excessive corrections in moments of less turbulence, harming the quality of the images in situations with a good atmosphere.
- **System Dependency:** The response of the optical system, wavefront sensors, and APM processing may vary with your specific system configurations and the nature of atmospheric distortions.

Therefore, choosing the value of `cut` is a decision that must be based on the specific needs of your application, the observation objectives, and the system's characteristics. Carrying out simulations and analyses is a significant step to evaluate the system's performance in different scenarios and choose the value that best suits your objectives. Controlling adaptive optics is a delicate balance between aggressive corrections and practical system limitations. Significant improvements in the *Strehl* ratio may indicate a positive adjustment if the above trade-offs are considered.

Another information that we can extract from the data is that the higher the cut value, the less area is cut by the mask, in such a way that from `cut` > 4, we no longer have a difference between the *Strehl* of the two telescopes, that is, the mask no longer blocks anything.

Our analysis highlighted a vital finding: there is a specific range of `cut` values where the correction efficiency is most effective, resulting in sharper images of stars. This range is 2.1 < `cut` < 2.5 (see Figure 3). The Adaptive Pupil Mask can achieve an ideal balance between correcting atmospheric distortions and preserving image fidelity during this range of values.

As `cut` moves within the range of efficient values, we see an increase in the quality of atmospheric corrections. `cut` values in this range allow the mask to act more focused on problem areas of the pupil, resulting in more precise corrections and improvements in the Strehl ratio. This directly reflects the sharpness and clarity of the stars in the captured images.

5. APM construction materials

The effectiveness of Adaptive Pupil Masking (APM) is closely tied to the choice of material for constructing the APM. Our research suggests that Digital Micromirror Devices (DMDs), being microelectromechanical optical components (MEMS), offer a promising solution. DMDs consist of thousands or even millions of individual micro mirrors, each electronically adjustable. These micro mirrors, with dimensions on the order of micrometers, can be tilted in two distinct positions: "on", reflecting light, and "off", not reflecting light (see Figure 5). The versatility provided by DMDs stands out as an innovative and efficient approach to enhancing the performance of APM in observational environments.

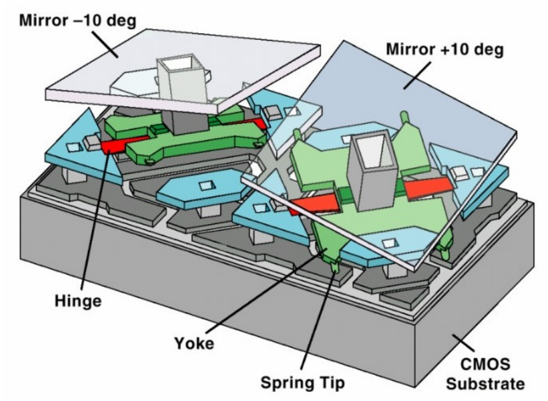

Figure 5. Two DMD pixels (mirrors appear transparent).

In the context of adaptive optics and Adaptive Pupil Masking, DMDs can be used similarly to create adaptive masks that can be adjusted to modify the light phase. Each micromirror is a phase control element that can be individually adjusted, allowing real-time correction of atmospheric distortions.

The ability to control each micromirror precisely and quickly makes DMDs an attractive option for adaptive optics systems, as they enable dynamic correction of atmospheric distortions in astronomical observations and other imaging applications that require high precision.

In comparative terms, DMD chips can easily be found for sale on the internet for prices ranging from 55 to 225 dollars. This accessibility makes DMD a desirable option for adaptive optics designs, especially considering the cost-benefit ratio. While correcting optical aberrations using DMDs may have limitations relative to other more expensive technologies, such as deformable mirrors, it is essential to note that DMDs still offer a cost-effective solution.

On the other hand, piezoelectric deformable mirrors, although undeniably effective for adaptive optics applications, have a significant disparity in cost. Prices for these mirrors generally start at around $4,000, and higher-end models can cost more than $20,000. This substantial price difference makes DMDs an economically viable option for projects with a limited budget, as in the case of APM.

An APM comprised of DMDs effectively balances remediation quality and project cost management. Although its correction may not achieve the highest possible level of quality, it still provides satisfactory adaptive correction for many applications. This approach allows us to optimize available financial resources, making DMDs a viable choice for our adaptive optics research, considering both economics and effectiveness.

Successful implementation of these devices in APMs is challenging. Future research will focus on mask assembly, developing more efficient materials, and optimizing APM systems to achieve optimal performance

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References

Brown, A. G. A. et al. *Gaia Early Data Release 3. Summary of the contents and survey properties*, A&A, 2021, .

Conan, R., Correia, C. *Object-oriented Matlab adaptive optics toolbox*, *Adaptive Optics Systems IV*, eds. E. Marchetti, L. M. Close, J.-P. Vran, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 9148, Aug. 2014, pp. 91486C.

Hecht, E. 2017. *Optics*. 5. ed. Global ed. Boston: Pearson Education.

Newton, I. *Opticks: Or, A Treatise of the Reflections, Inflections and Colours of Light*. 2. ed. London, England: W. and J. Innys, 1718.

Osborn, J. Adaptive pupil masking for quasi-static speckle suppression. *Monthly Notices of the Royal Astronomical Society*, v. 424, n. 3, pp. 2284-2291, Aug. 2012.

Osborn, J., Myers, R. M., Love, G. D. Reducing PSF halo with adaptive pupil masking. *Proc. SPIE 7736*, Adaptive Optics Systems II, 77362T, Jul. 2010.

Osborn, J.; Myers, R. M.; Love, G. D. PSF halo reduction in adaptive optics using dynamic pupil masking. *Optics Express*, vol. 17, n. 20, p. 17279, Sep. 2009.