THE AOLI NON-LINEAR CURVATURE WAVEFRONT SENSOR: HIGH SENSITIVITY RECONSTRUCTION FOR LOW-ORDER AO

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Abstract

Many adaptive optics (AO) systems in use today require bright reference objects to determine the effects of atmospheric distortions on incoming wavefronts. This requirement is because Shack-Hartmann Wavefront Sensors (SHWFS) distribute incoming light from reference objects into a large number of sub-apertures. Bright natural reference objects occur infrequently across the sky leading to the use of laser guide stars which add complexity to wavefront measurement systems. The non-linear Curvature Wavefront Sensor as described by Guyon et al. has been shown to offer a significant increase in sensitivity when compared to a SHWFS. This facilitates much greater sky coverage using natural guide stars alone. This paper describes the current status of the non-linear Curvature Wavefront Sensor being developed as part of an adaptive optics system for the Adaptive Optics Lucky Imager (AOLI) project. The sensor comprises two photon-counting EMCCD detectors from E2V Technologies, recording intensity at four near-pupil planes. These images are used with a reconstruction algorithm to determine the phase correction to be applied by an Alpao 241-element deformable mirror. The overall system is intended to provide low-order correction for a Lucky Imaging based multi-CCD imaging camera. We present the current optical design of the instrument including methods to minimise inherent optical effects, principally chromaticity. Wavefront reconstruction methods are discussed and strategies for their optimisation to run at the required real-time speeds are introduced. Finally, we discuss laboratory work with a demonstrator setup of the system.

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1. Introduction

Adaptive Optics (AO) systems used on telescopes today use many different types of wavefront sensor to determine the distortions imprinted on wavefronts as they pass through the Earth’s atmosphere. Traditionally Shack-Hartmann Wavefront Sensors (SHWFS) have been the norm, however in recent years there has been a growth in the use of Pyramid Wavefront Sensors and other methods including phase-diversity techniques.

Work by Guyon [1] simulated several different wavefront sensors to determine their sensitivity to different orders of atmospheric distortions. The most sensitive across the full range was the non-linear Curvature Wavefront Sensor (nlCWFS), a technique which has been theorised and demonstrated to low order in a laboratory setup but has never been used on-sky.

The Adaptive Optics Lucky Imager (AOLI) instrument, being developed initially for use on the William Herschel Telescope (WHT), combines the techniques of AO and Lucky Imaging (LI) together in a single instrument for the first time. The AO component employs a nlCWFS for wavefront sensing with a 241-element deformable mirror (DM) from Alpao for wavefront correction.

In this paper we present an update on the wavefront sensor development including strategies for wavefront reconstruction, managing intrinsic effects when using the nlCWFS and optical design.

2. The Non-Linear Curvature Wavefront Sensor

The non-linear Curvature Wavefront Sensor uses a set of four imaging planes around a conjugate pupil plane, two on either side of the pupil as shown in Figure 1. This differs from a conventional Curvature Wavefront Sensor (cCWFS) which uses single images on either side of a focal plane.

![Figure 1: The nlCWFS uses pairs of imaging planes, one at $\pm z_1$ and the other at $\pm z_2$ where $z$ is the distance from the pupil plane. These images are used to obtain information about the phase within the pupil through an iterative reconstruction process which propagates between the imaging planes in turn.](image)

As light enters the telescope aperture i.e. the pupil, it can be considered to have uniform illumination in amplitude but with phase distortions caused by the turbulence in the atmosphere. These distortions develop into speckles as the wavefront propagates away from the pupil. Smaller scale i.e. higher-order distortions appear closest to the pupil while lower-order distortions appear as the wavefront propagates further. By using a combination of inner and outer planes, sensitivity to both scales of distortion is possible.
Phase information in the pupil is retrieved through an iterative wavefront reconstruction process. This process is based upon the Gerchberg-Saxton method where a pupil estimate is propagated to an imaging plane before being constrained with known data and then propagated back to the pupil [2-3]. Further information about this reconstruction process can be found in Section 4.

2.1. Intrinsic effects

The nlCWFS works in the regime of Fresnel propagation. Optical propagation within this regime can be described using the standard Fresnel diffraction integral

\[
U(x_2, y_2) = \frac{\exp(i k \Delta z)}{i \Delta z} \int_{-\infty}^{\infty} U(x_1, y_1) \exp \left\{ i k \frac{1}{\Delta z} \left[ (x_2 - x_1)^2 + (y_2 - y_1)^2 \right] \right\} dx_1 dy_1
\]

where \( U \) is the complex representation of a wave at a specific plane location, \( x_1, y_1 \) is the position within the input plane for propagation, \( x_2, y_2 \) is the position in the final plane, \( \Delta z \) is the distance between the planes and \( k \) is the wavenumber.

As shown in equation 1, the wavenumber generates an intrinsic wavelength variation when propagating in the Fresnel regime. As such, when using a polychromatic source such as a natural guide star, it is vital these effects are minimised when using a wavelength insensitive detector e.g. CCD. It is however important to note that to maximise the wavefront sensor sensitivity, broadband imaging should be used which leads to conflicting requirements between intrinsic effects and sensitivity.

Without correction for this chromaticity, at each imaging plane, brighter regions of one wavelength overlap with dark regions of another leading to blurring and a failure in accurate wavefront reconstruction. This is a particular problem in the higher-order region where the scale of speckle structure is small.

3. Optical Design

3.1. From simulation to implementation

In previous simulation work [4-5], optical beams are propagated from the pupil of the telescope without any image scaling i.e. focussing optics. In this regime, the distances between imaging planes for the 4.2m William Herschel Telescope are ~100km or greater from the pupil and over 5 metres in diameter. For any practical implementation, these imaging planes need to be rescaled to a more manageable size however to do this, the characteristics of Fresnel propagation must be maintained.

The diffraction effects seen within an optical system can be described by the Fresnel Number

\[
F = \frac{a^2}{2\lambda}
\]

where \( a \) is a characteristic size of the aperture in the system e.g. pupil diameter, \( z \) is the distance from the aperture to the imaging plane and \( \lambda \) is the wavelength. To provide scaling between the simulations and optical implementation, the Fresnel number must be conserved between the two systems. For the WHT, simulation imaging planes were chosen to be at 200km and 650km with a beam diameter of 4.2m and an assumed wavelength of 700nm. Within the AOLI optical design, this beam diameter has been rescaled through the use of the telescope and re-imaging optics to 2mm providing equivalent plane distances of 45mm and 147mm respectively at the same wavelength.
3.2. Minimising chromatic effects

As described in Section 2.1, it is vital that the chromatic effects which are intrinsic to the nlCWFS are managed effectively. AOLI does this through the use of three dichroics in the wavefront optics providing four imaging planes, each at a different wavelength. The four imaging planes, each approximately 100nm in bandwidth, are centred at 550nm, 650nm, 750nm and 875nm. This allows the reconstruction process to be treated as monochromatic with the appropriate conservation of Fresnel Number.

3.3. Optical layout

The AOLI instrument features a set of common optics followed by both a science detector (located after the pickoff mirror) and the nlCWFS. The optical layout of the instrument can be seen in Figure 2 where the common optics and dichroic beam splitting are shown.

Figure 2: The AOLI optical layout. The diagram on the left shows the common optics path from the WHT focus through a 375mm focal length collimating lens onto a 241-element DM from Alpao. The beam is brought to a focus at the pickoff mirror where a reference object is selected before being reimaged to a conjugate pupil plane in the nlCWFS optics. The right hand diagram shows the proposed dichroic splitting of the beam to provide the four imaging planes.

The common optics includes a 241-element deformable mirror from Alpao to provide wavefront correction for ground layer distortions. The DM provides up to 25 microns of tip-tilt stroke negating the requirement for a separate woofer-tweeter configuration.

The four imaging planes for the nlCWFS are imaged onto two separate detectors. Each detector has a pair of images at approximately equal distances either side of the pupil plane. The beam reflected off the dichroic in each arm provides the post-pupil plane image with the straight through beam being pre-pupil.

3.4. Detectors

The imaging planes are recorded using back-illuminated EMCCDs from E2V Technologies (CCD 201). Readout is done using custom electronics developed in Cambridge providing up to 25 frames per second when reading the full 1024x1024 imaging region of the detector. To increase the frequency of reconstruction however, a limited region of 1024x256 is read out from each device delivering frame rates of approximately 100Hz and providing two wavefront images per CCD of 256x256 pixels.
4. Wavefront Reconstruction

The method of determining the pupil wavefront from imaging plane data is through an iterative reconstruction algorithm based upon the Gerchberg-Saxton method. This method propagates an estimate of the pupil wavefront to the different imaging planes in turn while known information is used to constrain the wavefront estimate at each stage. The algorithm is shown in Figure 3.

When propagating the estimated wavefront to an imaging plane, the wavefront can be separated into amplitude and phase components. There is no data available to constrain the phase and as such this remains unchanged however, the recorded image data provides information about the intensity (i.e. amplitude squared). The estimated amplitude component is discarded and replaced with the measured data. The amplitude and phase components are then recombined to form the new wavefront estimate which is propagated to the next imaging plane.

When propagating between planes, there are times when the wavefront estimate passes through the pupil plane e.g. from $p_1$ to $p_2$. Although no data is directly recorded at this location, the shape of the pupil is known i.e. the aperture mask. Work by Aisher et al. [6] has shown that when propagating between planes it is optimal to maximise the number of propagations through the pupil. This allows the aperture mask to be imposed, constraining the spatial extent of both the amplitude and phase and significantly aiding the convergence of the reconstruction process.

4.1. Numerical wavefront propagation

The nlCWFS reconstruction algorithm works in the regime of Fresnel propagation as described in Section 2.1. The propagation in equation 1 can be thought of as the Fourier transform of the input wavefront multiplied by an exponential term. As with all Fourier transforms, the pixel scale of the output is the inverse of the input pixel scale. As such, if the imaging plane pixel scale is fixed i.e. limited to the pixel scale on the nlCWFS detectors, a single Fourier transform is unable to propagate between imaging planes and choose an arbitrary input pixel scale. To counter this effect, the propagation between planes requires two propagations; the first to an intermediate plane chosen to
provide the correct pixel scaling between the initial and final planes and the second, from the intermediate to the final plane [7].

The numerical Fourier transforms in the wavefront reconstruction have been implemented using standard Fast Fourier Transform (FFT) methods. A significant speed up is seen in using graphics processor unit (GPU) implementations over CPU when using the CUDA libraries and FFTW respectively.

4.2. Phase unwrapping

As the reconstruction algorithm uses numerical FFT methods for propagation, the complex wavefront has a phase which is wrapped between ±π. While this phase wrapping is not a problem while attempting to determine the pupil wavefront, to apply a correction to the incoming wavefront the surface must be continuous and therefore unwrapped.

To aid in the phase unwrapping process, the recovered phase is assumed to be dominated by the lowest-order wavefront distortions, in particular tip-tilt terms. By taking the cross-correlation of either the inner or outer pair of imaging planes, it is possible to determine the tip-tilt term of the wavefront to the first-order. This measurement can then be used to constrain the phase value when unwrapping.

4.3. Using prior information

One of the key challenges facing the nlCWFS is its ability to work at sufficiently high speeds for wavefront correction. Initially there is no prior knowledge about the wavefront distortion entering the system and as such, a flat wavefront is assumed as the first estimate for propagation. This estimate however requires several iterations of the reconstruction algorithm to be completed before an accurate wavefront is recovered leading to a delay in wavefront correction. This can be seen after each iteration of the algorithm where the wavefront estimate gradually converges towards the tip-tilt term in a step like fashion prior to any higher-order effects being accurately reconstructed. If the timescale of this process is sufficiently long, there will be no correlation between the wavefront passing through the system and that being corrected.

One possible solution to this problem is through the cross-correlation method for phase unwrapping as described in Section 4.2. The cross-correlation is a rapid numerical process and can be used to provide a tip-tilt value which can be used as the initial estimate for the reconstruction process. This circumvents the gradually stepping towards the tip-tilt value and reduces any delay in convergence.

Once an accurate wavefront has been measured, it is expected that there should be a strong correlation, at least to low-order, between it and the next wavefront. As such, once this regime has been reached, using the previous wavefront solution as a prior should minimise the number of reconstruction loops required.

4.4. Parallelisation

Currently the nlCWFS algorithm works in serial, performing propagations to planes in order. It is possible to consider parallelising this method and propagating to all planes concurrently, constraining before returning to the pupil and then combining these four estimates together to produce the new wavefront estimate. The challenge with this method however is that to combine, the phase in the pupil will need to be unwrapped which in the initial stages of reconstruction is unreliable. Further investigation of this method is currently being undertaken.
5. nlCWFS Demonstrator

As part of the AOLI instrument, a demonstration system has been developed at Cambridge to further understand the nlCWFS. The system comprises a turbulent phase plate from Lexitek to provide wavefront distortions, the instrument common optics and the wavefront sensor optics as shown in Figure 4.

![Image of nlCWFS Demonstrator](image_url)

Figure 4: A laboratory setup of the non-linear Curvature Wavefront Sensor and common path optics for AOLI. The system uses a fibre feed and rotating phase plate to simulate effects of the atmosphere. The beam from this setup is then fed into a set of common optics. The nlCWFS can be seen in the centre of the bench with two arms separating different wavelengths to minimise chromatic effects.

6. Conclusions

The development of the non-linear Curvature Wavefront Sensor as part of the AOLI instrument will facilitate much greater sky coverage using natural guide stars through the use of EMCCDs. The intrinsic chromatic effects have been identified within the system and their effects mitigated through the use of dichroics, producing four imaging planes each at a different wavelength band.

The success of the wavefront sensor requires the development of algorithms to work at the required speeds for wavefront correction. Work to date has focussed on the development using variants of the Gerchberg-Saxton method however work is continuing to explore improved methods including parallelisation. It has been identified however that for sufficient speed, GPU units will be required.

Once developed, the AOLI nlCWFS will be tested on sky with the rest of the instrument in September 2013 on the William Herschel Telescope. This will be the first on-sky test for this type of wavefront sensor and will allow a further understanding of the best strategies for optical design and wavefront reconstruction.

7. References


7. J.D. Schmidt, Numerical simulation of optical wave propagation with examples in MATLAB. SPIE. (2010)