

Study of the parameters for a polar coordinate CCD using laser guide stars

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Abstract: A study of different centroid estimation is given for elongated spot in the context of laser guide star adaptive optics. The framework is a new CCD development with a special geometry, aligned with the elongation. © 2007 Optical Society of America

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1. Introduction

The next generation of adaptive optics (AO) systems will make extensive use of laser guide stars (LGS). Due to the finite range of the mesospheric sodium layer, perspective elongation of the LGS image will occur, leading to elongated spots in the subapertures of Shack-Hartmann wavefront sensors (SHWFS) commonly used for high order wavefront sensing in AO systems. As telescope apertures increase, such as the 30 m TMT, LGS image elongation will become an even more important factor in LGS AO system performance. The consequence will be the presence of more noise in the measurement of the centroids and thus in the reconstruction of the phase. An optimization and comparison of different centroid estimation methods has been done in the case of a symmetric round spot [1]. This work extends the study to the elongated spot. The difficulties introduced by elongation are that the spot will not be radially symmetric, the orientation of the elongation will make an angle with respect to the direction of the pixels on a rectilinear grid and the signal to noise ratio will drop for a given magnitude. The second problem will be overcome or at least reduced by the use of a polar coordinate CCD [2], where pixels are aligned to a polar rather than rectilinear grid. In this paper, we will present the consequences of the other limitations and study several centroider methods to define some parameters of the polar CCD design.

The methods considered are center of gravity (COG), which can be weighted (WCOG) [1,3], correlation tracking (CORR) [4], quad cell (QC) [5] and the weighted least square (WLS) method introduced by Luc Gilles and Brent Ellerbroek [6]. The framework here is the development of a new CCD with a special geometry, aligned to the LGS elongation. The parameters of interest are the pixel size and the size of the array in each subaperture considering both open and closed loop operation of the wavefront sensor. We also want to study the linearity of each method for the open loop purpose.

2. The polar coordinate detector

The polar coordinate detector is the second phase of development in an Adaptive Optics Development Program¹(AODP) supported project titled "Development of the Next Generation Optical Detectors for Wavefront Sensing". The goal is to develop new detectors for wavefront sensing in two steps [2]: the first phase consists in making a very low readout noise detector for SHWFS. The test device, CCID-56 from Lincoln Laboratories, was measured to have a readout noise of less than $1e^{-}$ [2]. The second phase is to develop the same detector with pixels aligned in polar coordinates, appropriate for elongated spots and thus optimized for laser guide star AO SHWFS, especially on Extremely Large Telescope (ELT) for which the elongation is higher. Indeed, it is made of rectangular "pixel islands" in each subaperture, where each major axis of the rectangle is aligned with the axis of elongation in that subaperture. This geometry allows us to get a good sampling of the spot along the elongated axis when using a continuous wave LGS as well as permits tracking of the spot if we use a pulsed laser. To get the final parameters of the CCD, such as the number of pixels, the pixel size, the dynamic range and so on, it is important to first simulate its performance considering those different requirements.

We can separate this work into two levels: the subaperture level and the system level. The first one takes into account the error made only on the position of the spot in one subaperture while the second level gives the error made on the wavefront reconstruction and the global performance of the system. To

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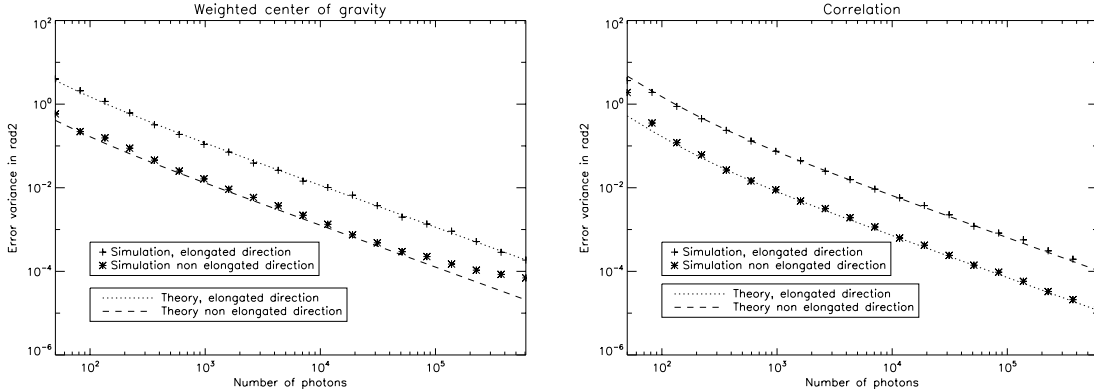


Fig. 1. Comparison between simulation and theory for the WCOG (left) and CORR (right). The elongation ratio is equal to 3 and the readout noise is $1e^-$. The dashed line is the non-elongated direction and the dotted line the elongated direction.

correctly simulate the spot at the focus of the lenslet and the system performance, it is important to consider all possible perturbations that will occur: laser performance, laser launch telescope and uplink performance, Rayleigh scattering, sodium layer variability, non-common path errors. Finally we do want to consider open and closed loop situations, and thus linearity issues.

Here, we are presenting the first results of this study concerning Monte-Carlo simulations of the spot at the focus plane of one subaperture only, with a derivation of theoretical formulae. This work is done in the context of the Thirty Meter Telescope (TMT) and Keck Next Generation Adaptive Optics (NGAO) systems, but can be generalized to other AO systems using LGS. The strategy was to add the elongation and sodium layer variability to existing simulations conducted by Thomas et al. [1]. In this first step, we mostly focused on generalizing the formulae given in Thomas et al. [1] and verifying the optimal sampling as well as the dynamic range of different algorithms.

3. Simulation of an elongated spot

For this paper, we consider photon noise, readout noise of $1e^-$ and a Gaussian spot with a FWHM N_d equal to 2 pixels. We tested the Full Width Half Maximum (FWHM) of the spot N_d from 0.5 to 3 pixels and we are confident that $N_d = 2$ pixels gives a good compromise between the size of the array and the performance for elongation ratio equal to 1 to 3, especially at good SNR. The array was sufficiently large (32×32) compared to N_d to neglect any truncation effect. The readout noise N_r is equal to 0 to 4 electrons rms and the number of photons N_{ph} is such that the Signal to Noise Ratio (SNR) is greater than 10. This corresponds to N_{ph} greater than about 10 when N_r is equal to 1. We usually do Monte Carlo simulations over 500 iterations.

We have derived the theoretical formulae for the different methods [7]. In this section are shown plots of the theory versus the simulation. We took the tilt estimation error variance σ^2 as a performance metric which we plot against the number of photons, equivalent to the SNR in the photon limited case. The error variance is given in rad^2 and represents the wavefront error. It is equivalent to the error variance on the CCD in arcsec multiplied by $2\pi/(\lambda/d)$ (with (λ/d) in arcsec). Fig.1 shows the comparison between Gaussian theory and Monte Carlo simulation for an elongated spot for the weighted CoG (left) and the correlation method (right), giving a good agreement between theory and simulation for different elongation ratios (3 on the plots). The reference function for CORR and WCOG is elongated with the same ratio as the LGS.

In the following we are showing results concerning the WCOG. One important parameter for this algorithm is N_w the FWHM of the reference function (like CORR or WLS). Fig.2-left shows σ^2 as a function of N_w as a function of the guide star brightness. The highest curves represent the lower number of photons. It shows that a minimum exists and that this minimum depends on the SNR. The elongation ratio in this example is 3. It is possible to study the optimal size, which will slightly vary depending on the elongation of the spot as shown on Fig.2-right. The optimal reference size is never much larger than the spot size even when the number of photons is large for AO purposes. Increasing the size of the reference function is not helpful, especially at low SNR, limiting the size of the islands.

As mentioned in the introduction, it is necessary to simulate the real spot resulting of the laser guide star with its structure and time variability. Intuitively, this tells us that the WLS and CORR are the algorithms

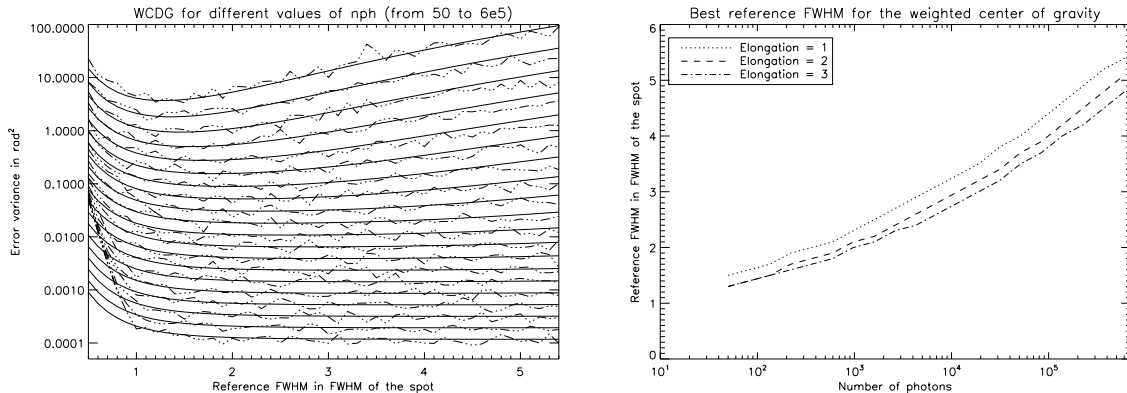


Fig. 2. Influence of the size of the reference function needed in the case of the WCOG. The elongation ratio is equal to 3, the readout noise is $1e^-$. On the left is σ as a function of the FWHM of the reference N_w in values of N_d for different number of photons. The highest curves represent the lower number of photons. Also for this graph the number of iteration was 100, which explains the higher noise on the curves. On the right is a plot of the optimal N_w as a function of the number of photons.

to consider. For more details on WLS, the reader can look at Gilles [6]. In that case, we would use a real image to create the reference. The current study is to generalize those results to a real sodium spot. The spots are computed from linear sodium profiles obtained at Gemini by Celine D'orgeville [8], by convolving the telescope PSF by those profiles projected on the subaperture. The structure will become more and more significant as we consider subapertures further from the center. A preliminary study shows that the behavior of the algorithms are similar to the one presented above. This implies there may be a lot to gain from correlation tracking but this will require more study with additional sodium profiles.

4. Conclusion and future work

Laser guide stars and extremely large telescope introduce some challenges in the concept of adaptive optics. We presented one of them, the elongated spot in a Shack-Hartmann wavefront sensor, and show how theoretical formulae and simulations have been used to understand the behavior of the system and to define CCD parameters and predict the system performances. In our future work, we will need to focus on the impact of the structure and time variability of the sodium spot on the error variance. We will also look at potential benefits of pulsed laser with spot tracking compared to continuous wave laser.

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