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Investigation Of Sodium Layer Anisotropies For Atmospheric Tip-Tilt Retrieval Using Laser Guide Stars

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14. ABSTRACT

This project delivered results in 2 tracks of investigation to derive tip/tilt information for improved adaptive optics performance using an event-based sensor (asynchronous-read-out CCD).
1. Direct analysis of large area illumination of mesospheric sodium layer density variations.
2. Time-delay differences between upward and downward propagation to and from the mesosphere.
The results showed that the first method was possible but not practical due to spurious motions, but the second method was definitely workable. This is a significant result as it would greatly improve the performance of free-space optical communications systems with minimal additional cost or complexity.
Future work has been proposed to test the performance of the tip-tilt sensor in conjunction with a standard, higher-order WFS both in the laboratory and on-sky. I would recommend this further study if sufficient funding can be obtained.

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"Investigation of Sodium Layer Anisotropies for Atmospheric Tip-Tilt Retrieval Using Laser Guide Stars"

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Abstract:

The investigation into event-based tip-tilt retrieval on Laser Guide Stars (LGSs) explores the application of event-based sensors to measure tip-tilt on LGSs using innovative techniques. Two methods have been explored: a novel approach utilizing the distribution of the atoms in the sodium layer, and the time-delay method. The emerging event-based sensors were investigated as potential wavefront sensors capable of implementing either or both of these methods.

This report focuses on identifying the natural mechanisms within sodium dynamics that would enable tip-tilt measurement, as well as characterizing event-based detectors within this context.

Publications:

The work described in this report has been partially submitted to MRAS and Optics Express, pending revision.

Cockram, Monique and Martinez Rey, Noelia, *"To change or not to change": Exploring the potential of event-based detectors for wavefront sensing*. Adaptive Optics for Extremely Large Telescopes Conference, June 2023 (DOI 10.13009/AO4ELT7-2023-074).

Report:

Introduction

In the context of optical communications, the capability of measuring (and correcting) the entire atmosphere, including tip-tilt, with a Laser Guide Star, would increase the achievable optical data transfer by 1.5 orders of magnitude for a ground-LEO optical link. However, the challenge lies in accurately measuring the tip-tilt with an LGS, a problem that remains unsolved to date.

Two methods have been explored: a novel approach utilizing the distribution of sodium layer atoms [1], and the time-delay method proposed by Roberto Ragazzoni in the 1990s [2], but has not yet been validated due to a lack of necessary technology. Emerging event-based sensors are being investigated as potential wavefront sensors capable of demonstrating either or both of these methods.

Where traditional frame-based sensors register the overall illumination during a fixed exposure time, event-based sensors detect only local brightness changes in the scene. These sensors produce an asynchronous stream of spatial-temporal events data, outputting single pixel information as each experiences a change in illumination. The output data typically contains a stream of events labelled with spatial location on the sensor, timestamp of the event, and polarity of the change in illumination.

Figure 1a) shows that the sensor is comprised of a differencing circuit that amplifies any changes in illumination for each pixel. Subsequently, a comparator compares those changes in illumination with a set threshold value and determines the polarity of the event (i.e. an increase or decrease in illumination). For this sensing principle, the illumination level of the previous event is captured in the circuit to use as a comparison in the differencing circuit.
A faster illumination change will generate more events in a particular time-frame than a slower illumination change, as visualised in Figure 1b). Background noise and fluctuations can be filtered by appropriately choosing a threshold for what magnitude of illumination change is considered an event. Additionally, any constant background is not sensed by the detector, due to its working principle of only detecting the changes in the light within the field of view.

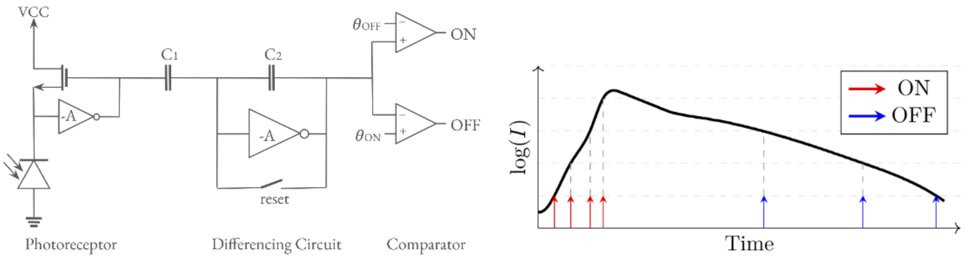


Figure 1: a) Circuit diagram of an event-based sensor. b) Demonstration of how changes in illumination are represented by ON and OFF events [3].

The particular advantages of these detectors include a high temporal resolution, ideal for sensing fast atmospheric changes (i.e. tip-tilt). Their high dynamic range allows for their application in a range of illumination levels (daytime wavefront sensing). These specifications indicate the potential advantages of event-based detectors to a wide range of wavefront sensing applications. Specifically, this research focuses on the retrieval of tip-tilt using Laser Guide Stars.

Horizontal Sodium Density Variations for LGS tip-tilt retrieval: wide field LGS

If non-uniformities existed in the sodium layer, one could illuminate them with a beam of the required width and observe the image generated by these structures using a wavefront sensor suitable for extended objects. The large illuminated area would wander in the sky due to the guide star uplink tip-tilt, while the non-uniformities within that area would exhibit different movement, reflecting the downlink tip-tilt. This would effectively isolate the atmospheric tip-tilt as if it were sensed on a natural star.

One well-studied mechanism known to cause density perturbations in the mesosphere is atmospheric gravity waves. This phenomenon was investigated for the first time in the context of LGS generation during this research project, with the aim of determining whether the stability and effects of the perturbation would be sufficient to generate a high-contrast image at the sodium layer, thereby creating a wide-field, non-uniform Laser Guide Star.

There is a lack of data at high resolution in sodium observation. However, perturbations in OH airglow can serve as an indicator of density perturbations that may also be observed in sodium density.

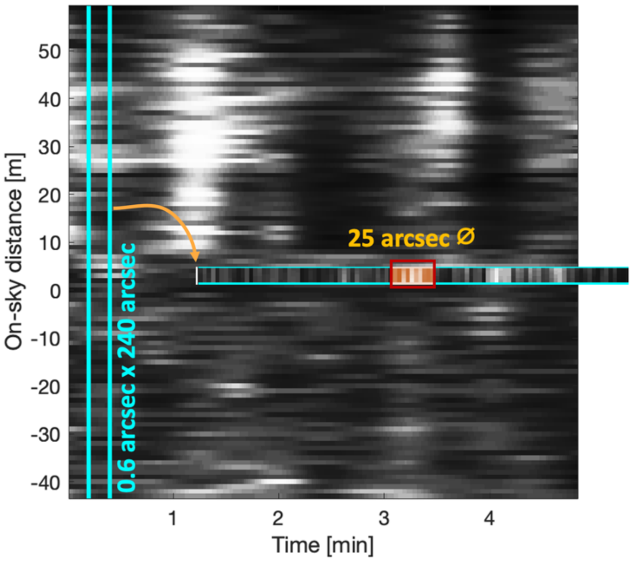


Figure 2: Based on observations of the OH airglow, the contrast typically peaks at a beam width of 25", which is taken in consideration for the generation of the wide-field LGS.

We analysed archive observations of the OH airglow using the NOTCam instrument at the Nordic Observatory Telescope. In these observations, the contrast typically peaks at a beam width of 25", which is approximately 10 times larger than a typical LGS beam. At the highest resolution, the contrast curve plateaus at values between 1.4% and 2.1%, with a median value of 1.9%. Due to a lack of dedicated observations, we are forced to assume that similar contrast values would be measured in the sodium distribution. As the next step to understand the factors influencing the return LGS flux, this system was simulated using the Mathematica *LGSBloch* code.

The LGS flux was simulated using the parameters shown in Table 1. The laser power at 589nm was specifically chosen based on the latest advancements in guidestar technology. The maximum flux return that was found was 6e10^{7} ph/s/m^{2} at Teide Observatory (Spain). This simulation was repeated with the same set-up but at Mauna Kea and Paranal and similar results were found, having maximum flux returns of 5.96e10^{7} ph/s/m^{2} and 5.64e10^{7} ph/s/m^{2} respectively. These photon return values were then combined with the contrast derived from the OH airglow data to determine the signal-to-noise ratio at which these perturbations could be detected using a LGS.

Variable Name	Symbol	Standard Value
Laser Launch Power	P_{launch}	70 W
LGS Spot FWHM in Mesosphere	r_{LGS}	25 $''$
Polarisation Ellipticity Angle	χ	$\pi/4$ (circular)
Laser FWHM Linewidth	Δf_{ab}	0
Telescope Diameter	D	1 m

Table 1. Simulation parameters which were constant throughout all simulations.

To achieve a SNR of 10 for the tip-tilt measurement, a LGS flux of 3.02e10^{7} ph/s/m^{2} is required. In all sites, simulated return flux would meet this requirement (SNR >12) for the considered laser power. To achieve SNR values of above 10, the contrast in the non-uniform image of sodium can go down to roughly 1.5%.

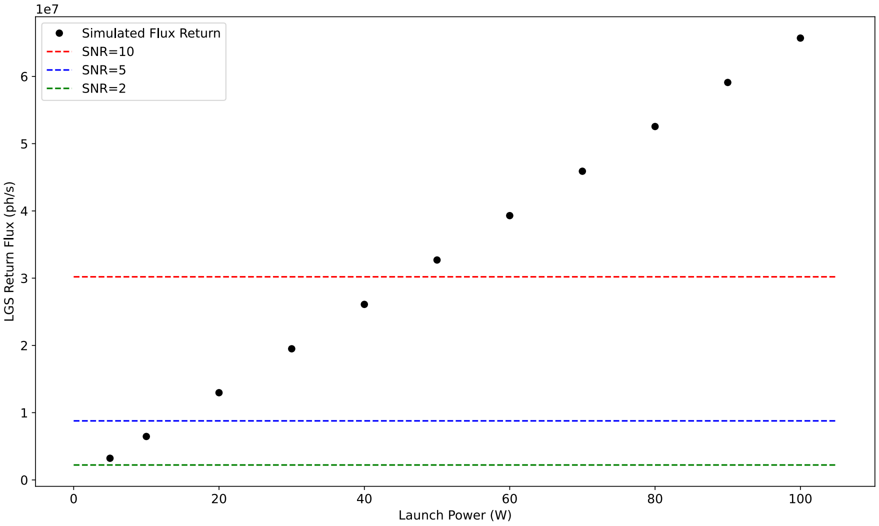


Figure 3: Simulated return flux from a LGS at Teide Observatory (Spain) compared to the LGS flux required to get a particular SNR for a 1m telescope and perturbation with a 1.9% contrast.

The LGS return flux requirement to see perturbations with a 1.9% contrast is shown in Figure 3. This figure shows that for a laser power greater than approximately 55W perturbations of 1.9% would be detectable with a SNR of 10, 15W for a SNR of 5 and 5W for a SNR of 2.

Simulation in [2] show the expected error using this technique on a 1m class telescope with a SNR of 10 gives an RMS error of less than 20nm. This capability would enable Adaptive Optics to achieve full sky coverage using existing laser technology. While this technology is not yet commercially available, it is expected to be so within the next two to three years.

Point Source Laser Guide Star and the Time-delay Method

Another method for LGS tip-tilt retrieval utilizes conventional point source laser guide stars. Based on the time-delay method proposed by Ragazzoni in 1996 [2], the error signal derived from the apparent tilt on the LGS caused by the propagation delay to and from the mesosphere can be utilized to retrieve the absolute tilt.

The differential tip-tilt between the upwards and downwards propagation of an LGS is small, typically on the order of less than 10-20 milliarcsec for a 1-m telescope. Detecting such level of perturbance, requires a highly sensitive device to distinguish it from noise levels, which is currently limited by frame-based detector technology.

Event-based Wavefront Sensor for LGS tip-tilt retrieval: Experiment

This research aimed to assess the feasibility of event-based sensor technology for detecting and measuring differential tip-tilt on LGSs, aiming to eliminate the need for natural guide stars in Adaptive Optics systems. We investigated the two previously described methods to achieve this goal.

The simulations and initial experimental work of this project were presented at the Adaptive Optics for Extremely Large Telescopes (AO4ELT) Conference in June 2023 and the publication of the conference proceeding (attached, DOI still pending).

At the Advanced Instrumentation and Technology Centre (AITC) at the Australian National University (ANU), a test bench was set up to characterise this type of sensor. A CenturyArks SilkyEvCam VGA event-based camera (containing the Prophesee PPS3MVCD sensor) was purchased for testing. The Thorlabs DMP40 deformable mirror was used as a tip-tilt mirror in combination with a 589nm low-power laser source. The deformable mirror (DM) was used to only actuate the tilt, and was controlled to introduce ranges of angle and speed of tilt in order to test the capabilities of the event-based detector. A lens with focal length 200mm was included to set a plate scale of 15 arcsec/pixel. The experimental set-up is demonstrated in Figure 4 and Table 2.

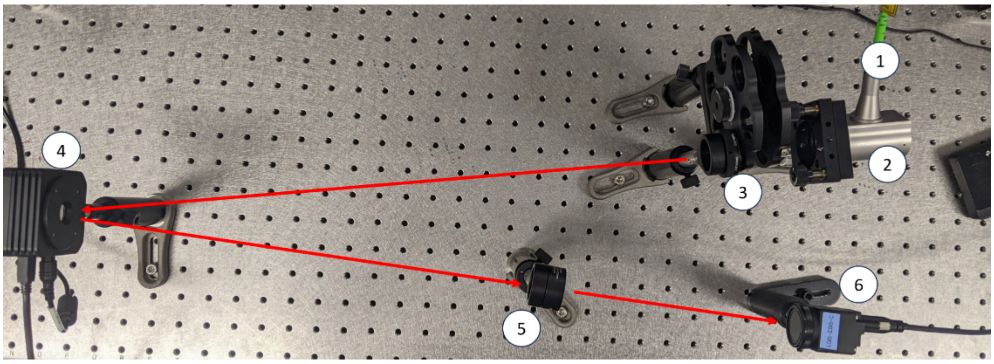


Figure 4: Photo of standard lab set-up, labelled as in Table 1.

Component	**Part Number**	**Label (as in Figure 2)**
Laser (589nm)	MSL-U-589-5mW	1
Collimator	Thorlabs RC12APC-P01	2
Iris	Thorlabs SM1D12CZ	3
Deformable mirror	Thorlabs DMP40	4
Lens	Thorlabs AC154-200-A-ML	5
Event-based detector	CenturyArks SilkyEvCam (VGA)	6

Table 2: Components used in testing, as in Figure 2.

The tilt was calculated by using an average position tracker algorithm [1] on the event-based data, recording the changes in movement of the laser spot on the detector. This algorithm, outlined in the equation below, updated the average position $\hat{x}_{ti}$, $\hat{y}_{ti}$ at the event timestamp every time an increase (or ON) event $e_i = [x_i, y_i, t_i]$ was generated by the detector. The weighting parameter m can be used to control how quickly the position changes as each new event is acquired.

$$\hat{x}_{ti} = m\hat{x}_{ti-1} + (1-m)x_i$$
$$\hat{y}_{ti} = m\hat{y}_{ti-1} + (1-m)y_i$$

Results

To verify the detector's high temporal resolution, its performance under increasing tip-tilt frequency was tested. The amplitude of the tip-tilt introduced by the DM remained constant whilst increasing the frequency of the changes. Measurements were taken at 1, 2, and 4kHz tip-tilt frequencies, with 4kHz being the limiting frequency of the DM.

The results in Figure 5 demonstrate that the measurements and their error were consistent as frequency increased. The time intervals between detected events were at a higher frequency than the tilt, at approximately 10kHz. This confirmed the high frequency capability of the detector.

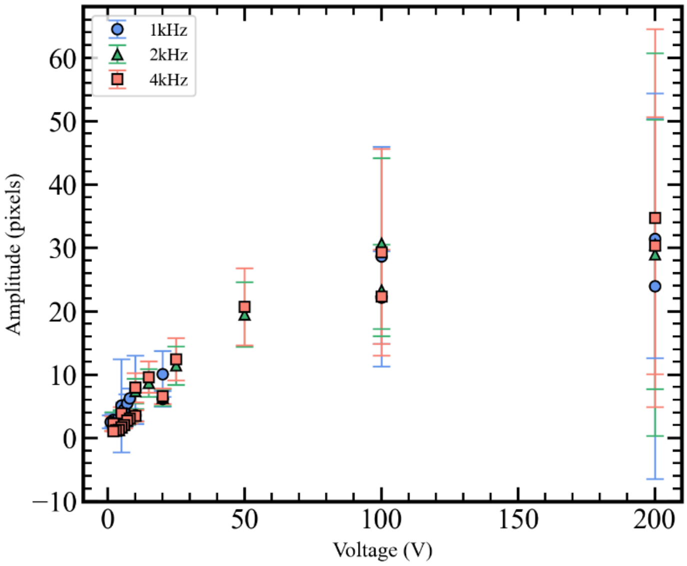


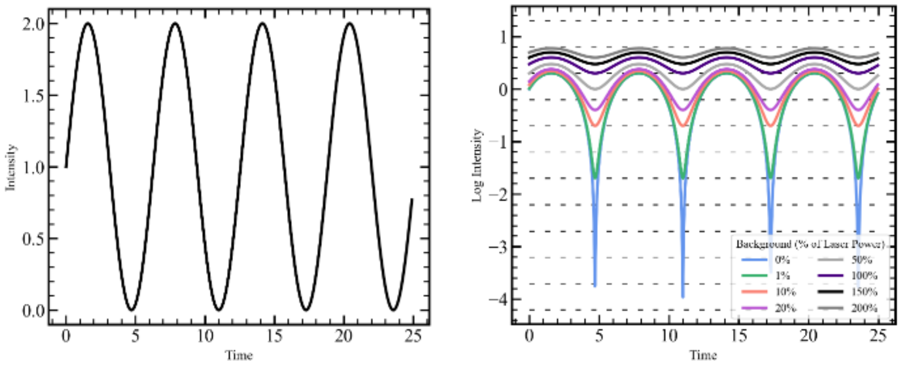
Figure 5: Measurements taken of tilt movements with frequencies of 1kHz, 2kHz, and 4kHz at different tilt voltages applied to the deformable mirror.

The full temporal resolution of the detector of $1\mu s$ (1MHz) was not able to be tested in this set up, due to the limited frequency at which the DM could operate. However, these results do demonstrate the ability of the event-based detector to sense at significantly higher frequencies than traditional frame-based detectors with the same errors as in lower frequency measurements.

Logarithmic Intensity Response

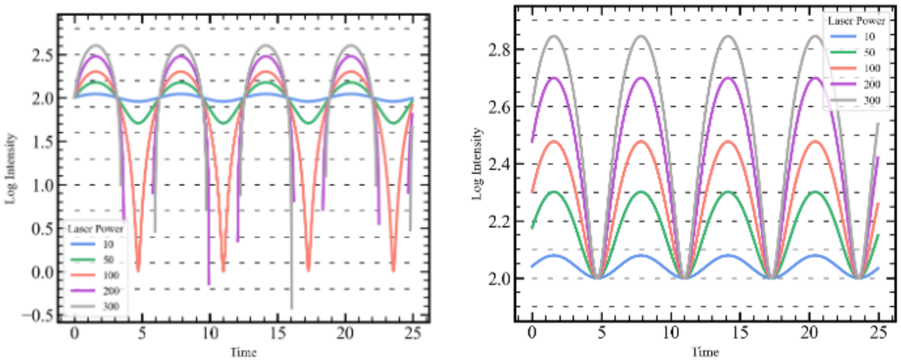
Theoretical Background:

The circuitry of the event-based detector takes the logarithm of the light intensity of the photodetector, notably before the differencing circuit. This means that the differencing process that enables the event-based sensor's immunity to sky background is not the very first process. As a result, even a constant background does have an effect on the response of the detector. This is displayed in Figure 6 which plots the theoretical response of an event-based detector (Figures b to d) to a sinusoidal signal (Figure a). From Figure 6b), it is clear that the regions with the lower laser signal strength generate many more events when the background illumination is also low. As the background level increases, this asymmetrical response to different laser source intensities is dampened, eventually returning to the same sinusoidal pattern of intensity as the signal input into the detector. The dotted lines that represent a threshold value of the event-based sensor can be used to visualise how each curve triggers an event (i.e. crosses to the next integer multiple of threshold value) at different rates. As a result, lower background illumination levels result in more events being triggered, particularly for low signal strength. If the threshold value is increased, the separation of the dotted lines would increase, and the intensity curves would cross these thresholds less often for a similar change in illumination.



a) Sinusoidal intensity input signal.

b) Increasing background as a percentage of (constant) laser power. Legend shows background intensity as a percentage of laser power.



c) Increasing the magnitude of change in laser power. Background level (100 units) and average laser power is kept constant. Legend shows amplitude of sinusoidal laser signal.

d) Increasing the magnitude of change in laser power as well as the average laser power. Background level is kept constant at 100 units. Legend shows amplitude of change and average laser power.

Figure 6: Theoretical plots of the response of the event-based sensor to different input intensities and background levels. The dashed lines are used to represent a threshold for triggering an event, where the spaces between the lines are set to the threshold value. Plots are depicted as intensity in arbitrary units.

Figure 6c) shows a similar effect. Here, the behaviour of the sensor remains relatively sinusoidal until the magnitude of the change of the laser power reaches and exceeds that of the background value of 100 units. In these conditions (low level power), the signal triggers many more events. This is also observable in Figure 6d), with the addition of an increase in average laser power. Here, the increased laser power results in the intensity curve crossing the threshold lines more times.

These theoretical representations of the event-based sensor's response to different conditions indicate that its performance in a dynamic scene, such as this sinusoidal signal, is best when the background illumination is greater than the signal illumination level. These plots show that it is the relative intensity between background and signal that is important to consider, rather than the absolute intensity.

This behaviour due to the logarithmic intensity signal results in an uneven response of the detector, making it difficult to choose an appropriate threshold value across laser powers. If a signal is being detected only in a small section of the dynamic range of the detector, this effect is less significant. However, making use of the full dynamic range of the detector in a single measurement results in this uneven response.

<u>Experimental</u>:

The following experiment aimed to verify the theoretical behaviour described above. This was done by changing the background illumination level of the set-up by introducing external light sources, placed next to the focusing lens. At the same time, the laser power was attenuated using ND filters to also investigate the effect of this. The behaviour of the detector was thereby analysed for a range of illumination levels for both signal and background. The same tilt experimental and analysis procedure was followed as with all previous experiments; in this case, the key information was the number of events recorded.

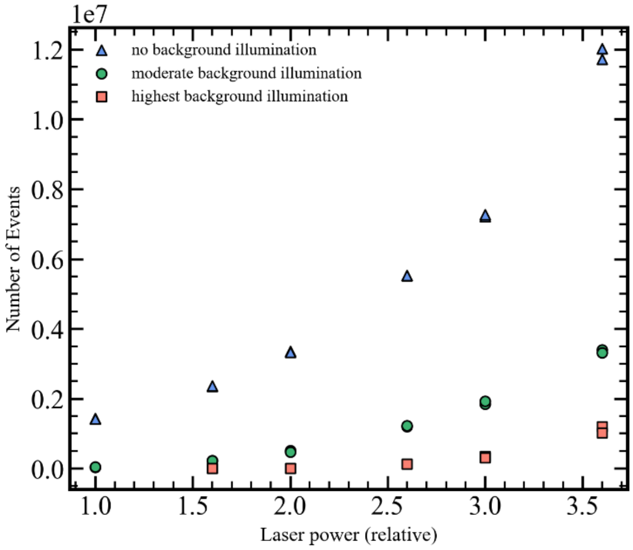


Figure 7: The number of events registered during a run of tilt measurements, showing the different number of events recorded as the laser power is attenuated for three background illumination levels. Laser power was attenuated using ND filters, and different backgrounds were introduced using external light sources.

Figure 7 displays the results of this experiment. It is clear that measurements made under higher background levels output less events than the equivalent test under lower background levels. This agrees with the theory in Figure 6b), which shows how the detector response became more uniform across the laser power levels as the background level increased. Also consistent with the theoretical analysis, the lower background levels produced more events across all laser powers. Results were indeed comparable to the logarithmic intensity plots, which show the detector response curve crossing the marked event threshold (and thus producing an event) more times for lower background levels.

Furthermore, the behaviour of the detector when the background is kept constant was also verified in each of the three experimental data sets. As laser power increases, so does the number of events recorded. This is comparable to the theoretical plots c) and d).

An additional experiment was undertaken to investigate how the threshold values affect the detector response to these different conditions. This aimed to test the detector's capability to have the same response even for different background illumination levels by appropriately tuning the threshold values. By repeating the same tilt measurements with three background illumination levels, the responses of the detector at different threshold values can be compared. Figure 8 shows how conditions of a high background with threshold value of 30 matches approximately with the moderate background level with threshold value 100, and no background conditions with a threshold value of 130. The error in the second plot in Figure 6 is on the order of the plate scale, and can also be matched across different background illumination conditions.

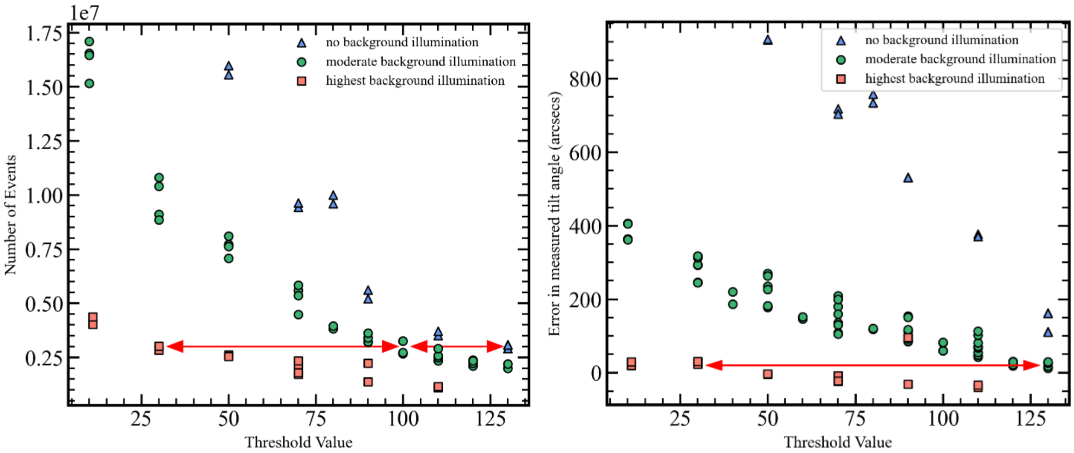


Figure 8: Left: The number of events registered during a run of tilt measurements. Right: The error in measured tilt from the set tilt angle (true value) during a run of measurements. This shows how conditions can be matched across multiple different background illumination levels using threshold values. More than one combination results in matching conditions, one of which is demonstrated by the red horizontal arrows between three different conditions of background illumination. Different backgrounds were introduced using external light sources, and the threshold value of the event-based detector was set to a range of values.

Figure 8 displays how the same range of threshold values has less of an effect on the number of events recorded for conditions where the background is higher. Where there was no background illumination, even small changes to the threshold value significantly changed the number of events recorded. This demonstrates that the response to the chosen threshold values also depends on the background illumination level.

Discussion

Error Budget for Event-Based Tip-Tilt Sensing:

When detecting tip-tilt using an event-based wavefront sensor, the error budget consists of three main areas; the deformable mirror, the background illumination level, and the event camera noise. Many of these are discussed in the attached conference proceedings.

The average position tracker algorithm was able to update the tilt measurements with each event (unlike previous iterations) making full use of the high speed measurement capabilities. The algorithm was optimised for its implementation in a real-time system. The implementation of this algorithm into the tilt measurement code was a significant improvement to the error, as compared to previous iterations of this research which implemented an approach similar to that of frame-based detectors. This enabled the measurement of tilt down to an error of approximately 1 pixel, once the event threshold values were appropriately chosen.

As demonstrated in the experimental results, the behaviour of an event-based sensor changes depends on the level of background illumination. Ideally, the background illumination will have a higher illumination relative to the tip-tilt signal level in order to minimise extra events being triggered from dim light around the signal source. If this is not the case, then a constant background illumination can still contribute to the error budget. Appropriate adjusting of the event-based detector's threshold values can minimise this.

Feasibility of Tip-Tilt Retrieval:

The use of event-based detectors has been explored in the context of retrieving tip-tilt on Laser Guide Stars through two methodologies: the wide-field LGS and the time-delay method. The wide-field LGS technique is probably not the best application for this technology due to several movements involved (uplink tip-tilt and downlink tip-tilt from non-uniformities).

However, it has proved to be very adequate for techniques like the time-delay method, where detecting very small movements is crucial and current sensors are not able to do so.

The event-based detector's immunity to a constant sky background allows it to sense small movements despite some noise levels. This is of particular use for laser communications applications which make use of adaptive optics in the daytime. The characterisation of the detector outlined in this report demonstrate how this can be achieved through appropriate choice of event threshold values.

The outcomes of this work suggest that the event-based sensor is a strong contender to enable retrieving atmospheric tip-tilt information using laser guide stars with the time-delay method, which otherwise might not be possible with current technology.

Conclusion

Event-based detectors have been tested to demonstrate the effect of key characteristics in the application of tip-tilt retrieval. Preliminary analysis through simulation provided some insight into the behaviour of the detectors, but the implementation of such a function into a simulation proved limiting.

A test bench was set up with a CenturyArks event-based detector. The testing confirmed the sensor's ability to measure tilt down to the plate scale of the camera, and demonstrated its capability of detecting tilt at very high frequencies. Whilst the detector was indeed immune to a constant background, the exact response of the detector in these conditions was analysed. This allows for a more informed choice when tuning the event threshold values.

This study offered a comprehensive characterization of the capabilities of the event-based detector and its response under various conditions. It showcased the potential applicability of event-based detectors in scenarios requiring the detection of small, rapid movements, such as those encountered in the tip-tilt retrieval problem.

Additionally, this research presented highly promising findings regarding the wide-field Laser Guide Star (LGS) technique, which leverages non-uniformities in the sodium layer to detect tip-tilt. This was achieved through the analysis of high-resolution OH observations assumed to represent the sodium distribution.

Future work

In future phases of this project, we plan to integrate an event-based detector into a complete wavefront sensor setup on our established test bench. This step will facilitate a comprehensive study of feasibility and capabilities, especially in comparison to traditional frame-based wavefront sensors. Subsequently, on-sky testing will be conducted to assess its ability to measure wavefront error caused by turbulence under both daytime and nighttime conditions in observatory or optical ground station settings, with the application of the time-delay technique to the observations.

Regarding sodium dynamics, our future work will involve observing the sodium layer at high resolution, building upon the promising results obtained from OH observations. These findings will require verification in the sodium context.

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“To change or not to change”: Exploring the potential of event-based detectors for wavefront sensing

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“To change or not to change”: Exploring the potential of event-based detectors for wavefront sensing

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ABSTRACT

Event-based image sensors respond to the brightness changes in the scene; they operate differently than traditional frame-based sensors, as they only detect changes rather than registering the overall illumination during a fixed exposure time. These sensors produce an asynchronous stream of spatial-temporal events data, which includes information on the location, timestamp, and polarity of triggered events (positive vs negative change). Compared to frame-based sensors, event-based sensors offer benefits such as high temporal resolution, low latency, high dynamic range, and low power consumption. The use of event-based cameras has been explored in the fields of computer vision, navigation, and space situational awareness applications; however, their potential in Adaptive Optics and wavefront sensing has not been thoroughly investigated. We will present the modelling and preliminary experimental results of a Shack-Hartmann tip-tilt wavefront sensor equipped with an event-based detector, demonstrating its ability to estimate spot displacement with remarkable speed and sensitivity in low-light conditions.

Keywords: wavefront sensing, event-based detector, tip-tilt, laser guide star

1. INTRODUCTION

Where traditional frame-based sensors register the overall illumination during a fixed exposure time, event-based sensors detect only local brightness changes in the scene. These sensors produce an asynchronous stream of spatial-temporal events data, outputting single pixel information as each experiences a change in illumination. The output data typically contains events labeled with spatial location on the sensor, timestamp of the event, and polarity of the change in illumination.

Figure 1 shows the electronics circuit of a pixel: the sensor comprises of a differencing circuit that amplifies any changes in illumination for each pixel; subsequently, a comparator compares those changes in illumination with a set threshold value and determines the polarity of the event. For this sensing principle, the illumination level of the previous event is captured in the circuit to use as a comparison in the differencing circuit. A faster illumination change will generate more events in a certain time-frame than a slower illumination change, as

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visualised in Figure 1. Background noise and fluctuations can be filtered by appropriately choosing an illumination threshold for what is considered an event. Additionally, any constant background is not sensed by the detector, due to its working principle of only detecting light changes within the field of view.

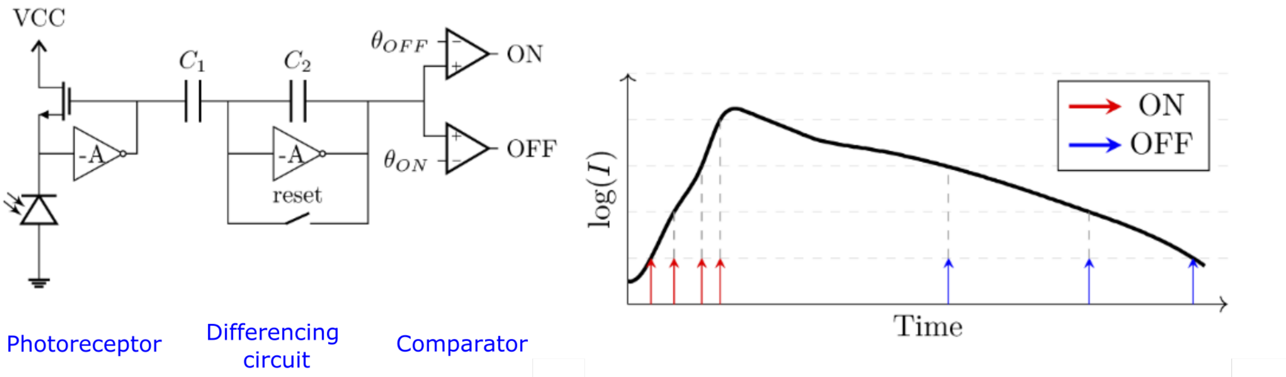


Figure 1: Left: Circuit diagram of an event-based sensor. Right: Demonstration of how changes in illumination are represented by On and Off events. [1]

The particular advantages of these detectors include a high temporal resolution, ideal for sensing fast atmospheric changes (i.e. tip/tilt). Their high dynamic range allows their application in a range of illumination levels. These specifications are discussed further in Section 2, and indicate the potential advantages of event-based detectors to a wide range of wavefront sensing applications.

1.1 Motivation

The use of conventional adaptive optics techniques with a laser guide star (LGS) restricts the measurement of tip/tilt aberrations. This is a result of the laser propagation paths upwards and downwards travelling through regions of the atmosphere within the tip/tilt isoplanatic angle. As a result, any tip or tilt in the beam path caused by the atmospheric turbulence is cancelled out by its return propagation.

However, based on the time-delay method [2], the error signal derived from the apparent tilt on the LGS caused by the propagation delay to and from the mesosphere can be used to retrieve the absolute tilt. This enables retrieval of tip/tilt information without the need for a nearby natural guide star (NGS). This differential tip/tilt between the upwards and downwards propagation of a LGS is small, on the order of <10-20 mas for a 1-m telescope. This requires a very sensitive device to sense it above noise levels, which, at present, is limited by the current frame-based detector technology. This research aims to study the feasibility of a new approach, with potential to detect and measure differential tip/tilt on LGSs and remove the need of having natural guide stars for this purpose in the Adaptive Optics system.

2. DETECTOR SPECIFICATIONS

The nature of event-based detectors only recording pixels that have changed illumination results in a data stream of reduced size. This can greatly improve computational speeds. Furthermore, the temporal resolution is significantly greater than that of a frame based camera, as single pixels can be quickly and asynchronously read out. For measuring fast changes (atmospheric tilt), this detector does not need additional electronics to achieve the same or even higher performance than conventional detectors with dedicated and complex readout systems.

The event-based detector model CenturyArks SilkyEvCam VGA was selected to investigate the feasibility of this application. The specifications of this detector are summarised in Table 1.

Table 1: CenturyArks SilkyEvCam VGA event-based detector specifications.

Minimum temporal resolution	1μs
Latency	200μs
Dynamic Range	> 200dB
Max readout throughput	50Mevents/s
Pixels	640×480
Pixel size	15μm

3. PRELIMINARY STUDIES: SIMULATED EVENT-BASED WAVEFRONT SENSOR

For a preliminary evaluation of this concept, a Shack-Hartmann event-based wavefront sensor was simulated using Conan and Correia's [3] Object-Oriented Matlab Adaptive Optics (OOMAO) toolbox along with Hu and Delbruck's [4] Video2Events (v2e) event-based camera simulator. A spot tracking algorithm was developed to enable the calculation of local slopes due to tip/tilt effects. This algorithm was a weighted centroid of all pixels in the spot.

These simulations were repeated with a wide range of different strength tip/tilt coefficients. The results clearly showed th at higher values of tip/tilt strength coefficients result in higher magnitude movement of the spot, as in Figure 2. However, there was no clear or linear correlation between the known input tip/tilt strength and the detected tip/tilt to enable a measurement of its magnitude. In some simulations, unexpected behaviour was observed out of the event-based detector, such as decreased tip/tilt magnitude over time, when no such behaviour was actually being produced by the Shack-Hartmann array. This effect is visible in Figure 2(b).

Additionally, different strength backgrounds were applied to the Shack-Hartmann simulator, to verify the immunity of event-based detectors to sky background. The results were highly comparable to that of simulations without backgrounds added, except where the strength resulted in significant reduction in contrast, affecting the clear definition of peaks. This suggests that the immunity of event-based detectors to a constant background is not effectively implemented into the simulator. The subsequent experimental tests in Section 4 were used to corroborate the initial hypothesis.

A key feature of event-based detectors is their high temporal resolution. This was tested by increasing the frequency of the tip/tilt movements being simulated, which did not impact the accuracy of the simulated measurement of tip/tilt. It was observed, however, that the simulated event-based detector was unable to accurately detect tip/tilt down to 100μs period of oscillation. This is well below the specified temporal resolution of 1μs. This was a key factor in determining the use of these simulation results as only a preliminary analysis.

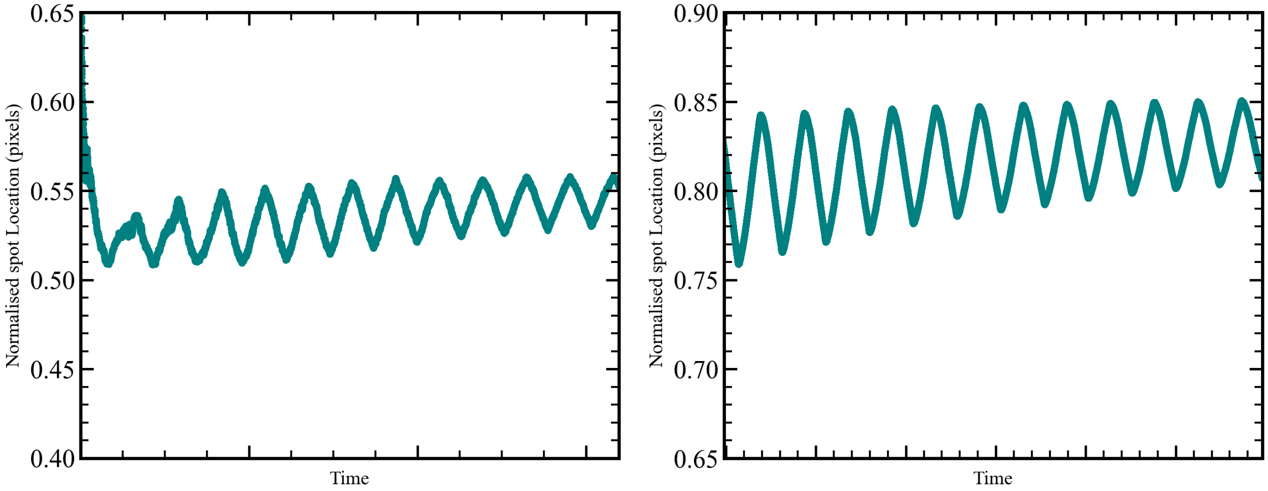
Throughout these preliminary analyses, some limitations of using simulations of event-based detectors were faced. In particular, the response to the movements of the Shack-Hartmann spots were not entirely as expected. Whilst it provided some preliminary results, it had some limitations preventing a full analysis. The v2e simulation expected inputs more analogous to real-life imaging, where the motion of the Shack-Hartmann spots is smooth and continuous. However, the simulated Shack-Hartmann produced discontinuous movements at each timestamp. This affected how the simulated event-based detector tracked changes in illuminated pixels over time.

This preliminary analysis provided a starting point for establishing an experimental setup to test event-based wavefront sensing concepts.

4. EXPERIMENTAL RESULTS

4.1 Experimental Setup

Laboratory testing of an event-based Shack-Hartmann wavefront sensor began in July 2023. The experiments used the CenturyArks SilkyEvCam VGA event-based camera, which contains the Prophesee PPS3MVCD sensor. Its specifications are outlined in Section 2.



(a) Tilt coefficient ×1

(b) Tilt coefficient ×3

Figure 2: Simulation results of tilt aberrations for an event-based Shack-Hartmann wavefront sensor.

The Thorlabs DMP40 deformable mirror was utilised as a tip/tilt mirror to introduce tilt (i.e. only one axis of movement) into the 589nm laser source. The deformable mirror (DM) was used to only actuate the tilt, and was controlled to introduce a range of angles and speed of tilt in order to test the capabilities of the event-based detector. Several plate scales were tested; results presented in subsequent subsections correspond to a configuration where a lens with focal length 200mm was included to achieve a plate scale of 15 arcsec/pixel. The same spot tracking algorithm as in Section 3 was used to measure the magnitude of the tilt.

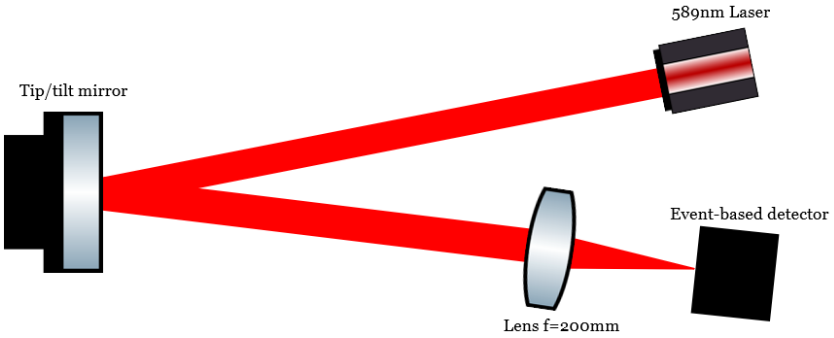


Figure 3: Schematic of laboratory testing setup.

The experiment was split into sections to test key specifications of the event-based detector. These tests focused on (1) increasing the frequency of the tilt signal and (2) attenuating the brightness of the source.

All of the tests were performed with the ambient lights in the laboratory turned on, to demonstrate the event-based detector's immunity to sky background. None of the data contained illuminated pixels outside of the laser source.

4.2 Results

The capability of the event-based detector to measure tilt of high frequencies was tested, up to the limiting frequency of the DM of 4kHz. The results in Figure 4 demonstrate that the measurements and their error were consistent as frequency increased from 1kHz up to 4kHz. The time intervals between detected events were at a higher frequency than the tilt, at approximately 10kHz. This confirmed the high frequency capability of the detector.

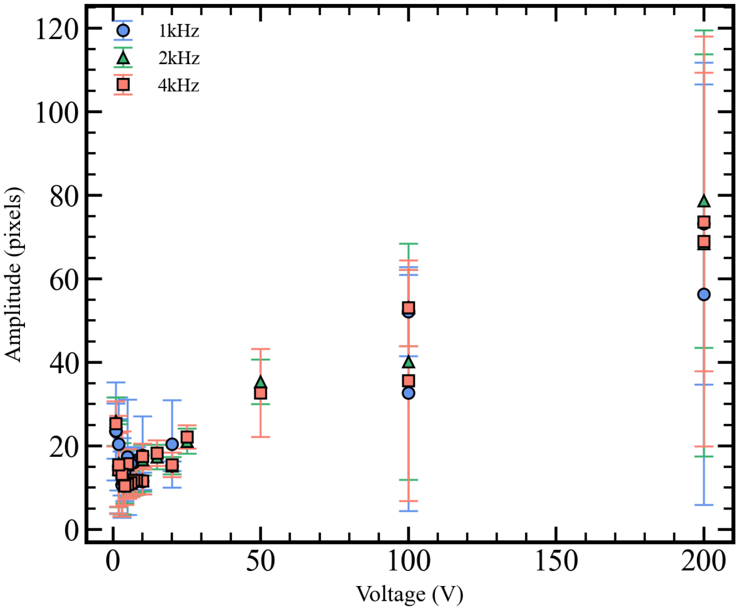


Figure 4: Measurements taken of tilt movements with frequencies of 1kHz, 2kHz, and 4kHz at different tilt voltages applied to the deformable mirror. The voltage range corresponds to the full tilt amplitude of the Thorlabs DMP40.

Additionally, the brightness of the laser source was gradually attenuated in order to investigate the capabilities of the detector at different levels of contrast between the signal and background. This was achieved using neutral density (ND) filters of values 0.4, 1, 1.4, and 2, which resulted in transmission percentages of 40%, 10%, 4%, and 1% respectively. Figure 5 demonstrates that when greater attenuation was applied to the source, the measured tilt amplitude decreased. However, the error over all the measurements taken remained stable across the different tests demonstrating that decreasing the source brightness does not increase the error measuring tilt.

Missing events would translate into an effective reduction in frequency at which the sensor can be utilised, as it would require slower operation to capture the same information. Since there are large numbers of tilt movements being recorded, the tilt is still detected without a change in error. This would not be the case for rapidly changing tilt amplitudes. To further investigate the impact this has on the error, an experiment was designed to change the tilt amplitude every 5ms within a range from 12” to 60”.

Figure 6(a) shows some preliminary results of the variable tilt experiment, operating the tilt mirror at 2kHz, with amplitude changes at 200Hz, and the event-based data stream accumulated at 400Hz. When varying the tilt amplitude, the error increases by a factor of 3 with respect to the fixed amplitude test (see discussion on error sources in 5). These are preliminary results, and this ×3 increase in error requires further investigation. The offset between the known tilt amplitude and the measured tilt amplitude suggests a calibration error.

5. DISCUSSION ON ERROR SOURCES

Notably, on all the results, the error in tilt measurement increased with its magnitude. This error was on average 20% of the tilt magnitude. This is comparable to the expected error of the DM, which the vendor outlines to be typically 15%.

Error from other sources increased when small movements, on the limit of the plate scale, were measured. In these tests, not all tilt movements were detected, hence reducing the number of correct measurements taken over the same amount of time by, on average, 80%. When the measurement time period was increased (and

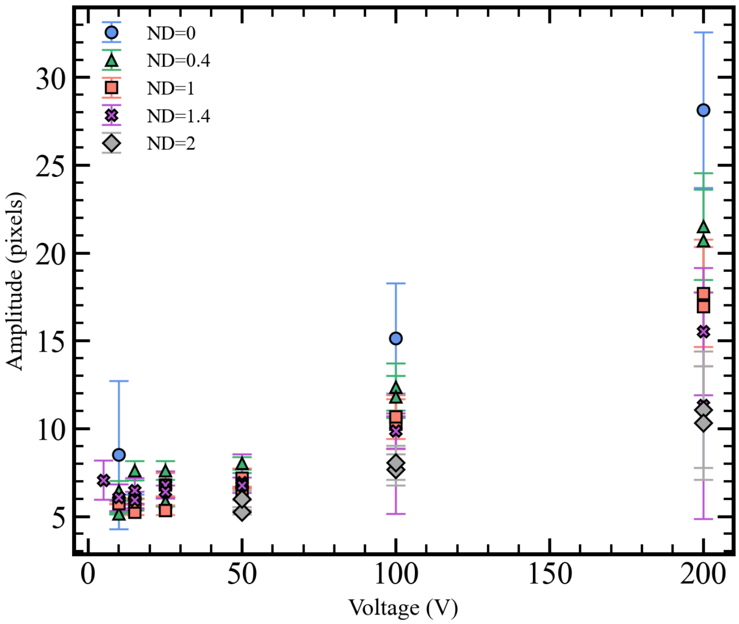
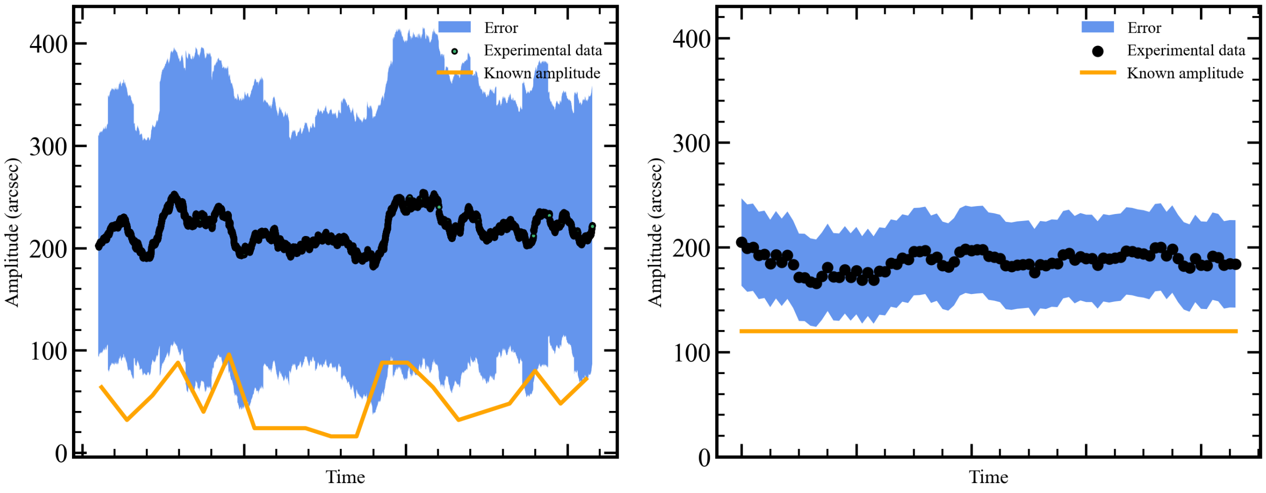


Figure 5: Tilt measurements taken with decreasing source brightness using neutral density (ND) filters at different tilt voltages applied to the deformable mirror.



(a) Varying tilt amplitude every 5ms.

(b) Constant tilt amplitude.

Figure 6: Experimental results demonstrating the increased error when the tilt amplitude is changed every 5ms (a), compared to remaining constant (b). Both experiments demonstrate 2kHz tilt oscillation frequency. Dark yellow line indicates the true tilt amplitude; black circles are the experimentally measured tilt amplitudes; blue shaded region denotes the standard deviation of the measurements.

therefore also the number of successful measurements increased), no reduction in error was detected with a fixed tilt amplitude. This highlights that, despite some measurements being missed, the small tilt movements were detected without significantly increased error. However, when the tilt amplitude was changed every 5ms, a ×3 increase in error was observed in the preliminary results. This is likely due to the smaller amount of data going into each measurement of tilt, however further investigation is required. Results suggest that the small tilt movements were still detected without further error due to the fact that the amplitude was constant, which does not necessarily represent the atmospheric tip-tilt in a realistic scenario.

A limitation on these tests emerges from the spot tracking algorithm used to extract tilt information from the event data. The sensitivity of the algorithm to small changes could differ from that of the event-based detector, despite all care being taken to avoid it.

Another key consideration of the analysis of event data is the choice of how many events should be included in each step for the algorithm to extract the measured tilt. Ideally, the tilt measurements could be updated with every new event, however that is computationally heavy and could hinder the ability for real-time calculations. As a result, a number of events can be combined into one "frame". This number needs to be optimised for each application. Across all the tests in Section 4, each "frame" contained 500 events. This relates to the earlier discussion on errors increasing when smaller amounts of data are used to take each measurement. The amount of error can be minimised by appropriately controlling the sampling rate of the tip/tilt.

6. CONCLUSION

Event-based detectors were tested to demonstrate the effect of key characteristics in the application of tip/tilt retrieval. Preliminary analysis through simulation provided some insight into the behaviour of the detectors, but the implementation of such a function into a simulation proved limiting. From this, laboratory tests were undertaken using a CenturyArks event-based detector. These tests demonstrated the immunity of the detector to background illumination, its ability to detect high frequency changes, and the effect of different contrast levels between signal and background.

This work demonstrated the potential suitability of event-based detectors in applications where rapid, small movements need to be detected, such as that of the tip/tilt retrieval problem.

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