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

Monique Cockram[a] and Noelia Martinez[a]

[a]Advanced Instrumentation and Technology Centre, Research School of Astronomy and Astrophysics, Australian National University, Canberra, Australia

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

Further author information: (Send correspondence to M.C.)
M.C.: E-mail: monique.cockram@anu.edu.au

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.

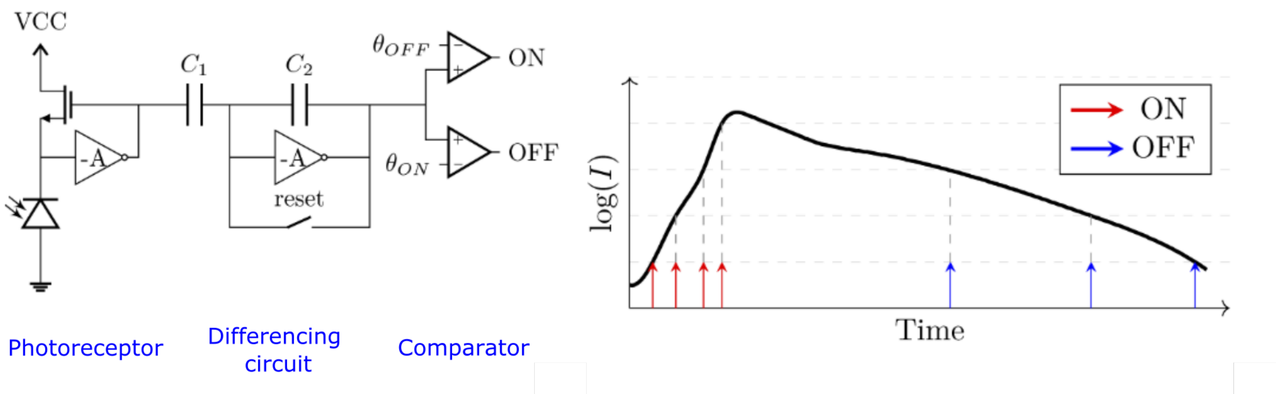


Figure 1: Left: Circuit diagram of an event-based sensor. Right: Demonstration of how changes in illumination are represented by On and Off events. [1]

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.

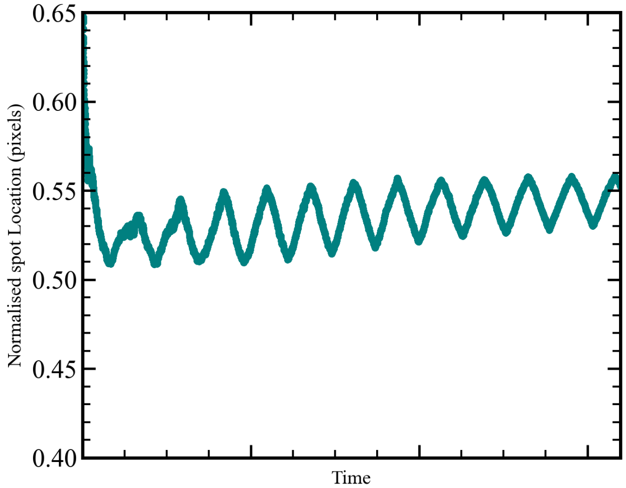
Throughout these preliminary analyses, some limitations of using simulations of event-based detectors were faced. In particular, the response to the movements of the Shack-Hartmann spots were not entirely as expected. Whilst it provided some preliminary results, it had some limitations preventing a full 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.

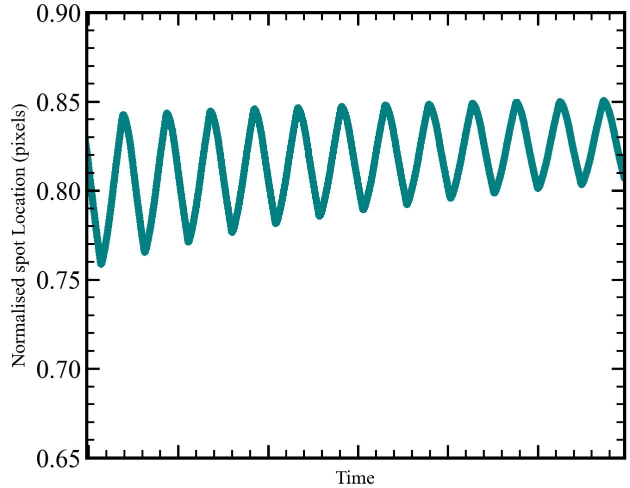
4. EXPERIMENTAL RESULTS

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.

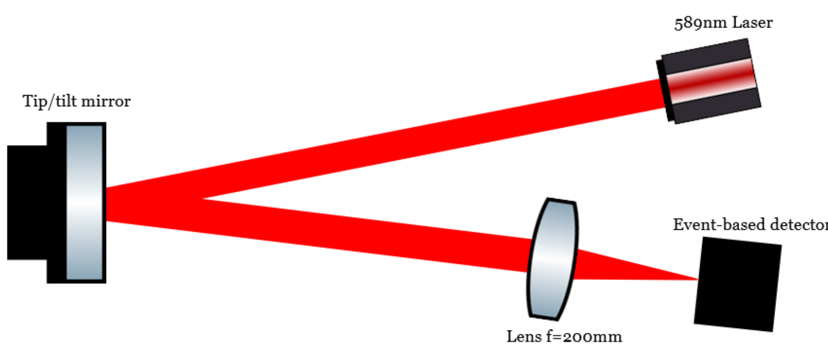


Figure 3: Schematic of laboratory testing setup.

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.

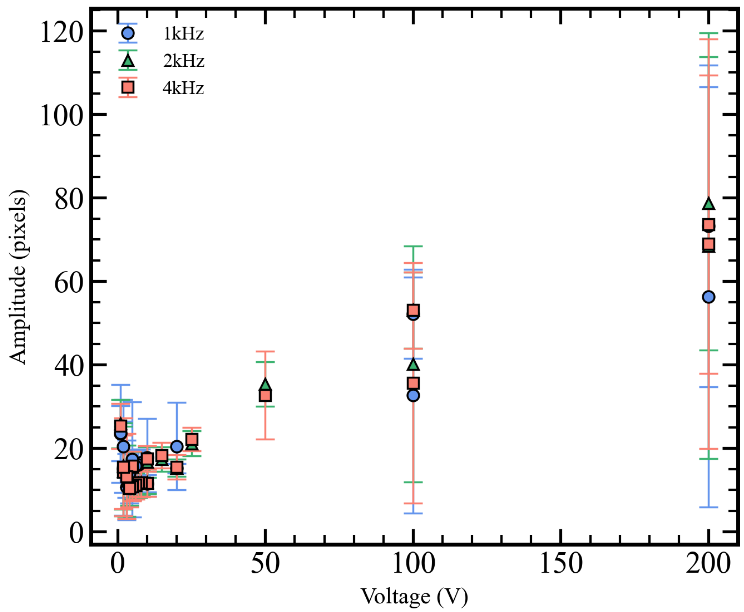


Figure 4: Measurements taken of tilt movements with frequencies of 1kHz, 2kHz, and 4kHz at different tilt voltages applied to the deformable mirror. The voltage range corresponds to the full tilt amplitude of the Thorlabs DMP40.

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 $\times 3$ 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

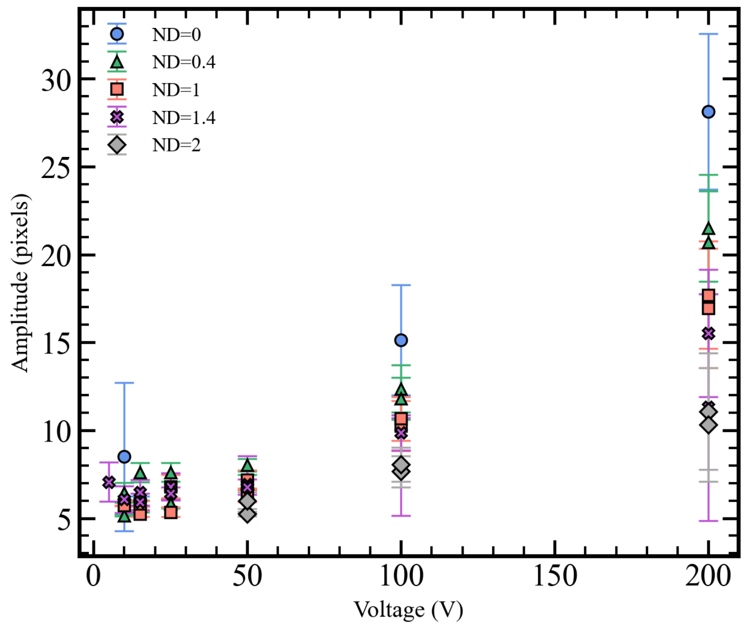
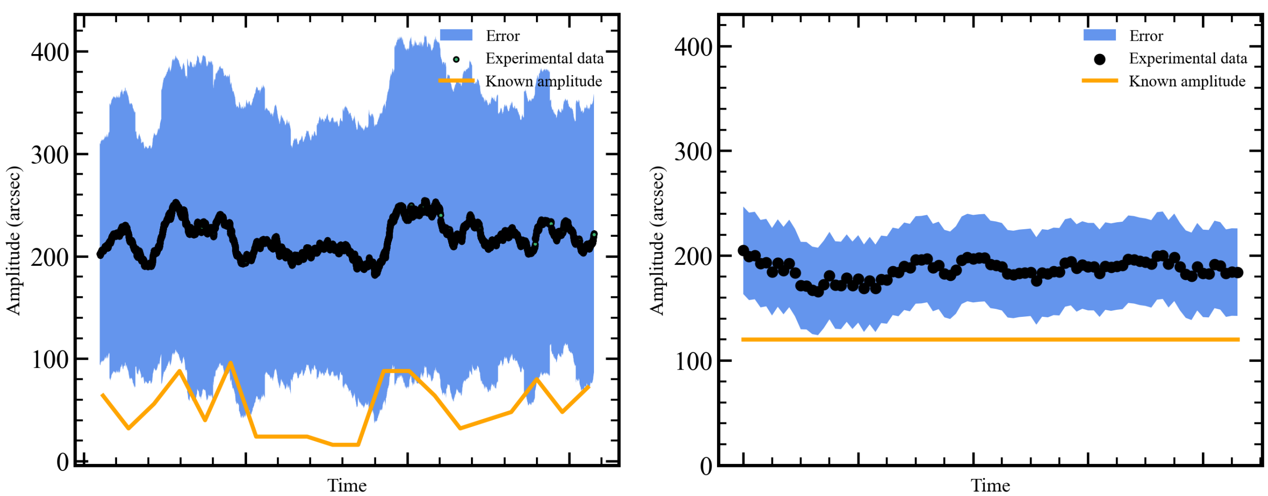


Figure 5: Tilt measurements taken with decreasing source brightness using neutral density (ND) filters at different tilt voltages applied to the deformable mirror.



(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 $\times 3$ 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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