OBSERVATIONAL EVALUATION OF EVENT CAMERAS PERFORMANCE IN OPTICAL SPACE SURVEILLANCE

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ABSTRACT

Dynamic vision sensor (DVS) event cameras possess a unique feature of outputting only sparse and asynchronous brightness changes rather than the conventional image sensor measurement of average intensity level during a fixed exposure time. This new technology opens a window of opportunity for SST, especially for survey observations, where users are mostly interested in detecting objects moving within the telescope's field of view. In this work we present a comparison between a regular global-shutter CMOS camera (QHY174-GPS) and several DVS-based DAVIS cameras, which can concurrently output standard frames and DVS events. The measurements include new sensors, so far uncharacterized for space surveillance, specifically the first back illuminated DAVIS (BSIDAVIS) and a DAVIS with more sensitive temporal contrast threshold (SDAVIS). The sensors were observationally tested during stellar observing runs with varying telescope tracking speed to simulate SST targets on different orbits, using identical optics and under the same weather conditions. Observations included daytime sky targets with high sky brightness. The minimum detectable object magnitudes and maximum object speeds were quantitatively assessed. The potential of existing event-based sensors is evaluated and future upgrades to DVS designs to fully utilize this technology in SST are discussed.

1. INTRODUCTION

Space surveillance and tracking (**SST**) is of increasing importance because of the growing number of active satellites and space debris which increases the risks of collision, and the threat of the Kessler phenomenon, which could make low earth orbits (**LEO**) inaccessible. SST optical methods are traditionally considered primary source of tracking and surveillance data for higher orbits due to satellites low proper motions and relaxed image timing requirements which are possible to fulfill using regular astronomical CCD and CMOS image sensor (CIS) cameras [1]. Optical surveillance in the LEO region has been developing rapidly in recent years because of the emergence of low cost and high spatial resolution cameras delivering high lateral position precision [2]. It is an interesting supplement, or even alternative, to expensive radar installations that provide precise orbit altitude, but poor lateral precision. By contrast, optical SST can use mount encoder readings or fixed stars as known reference points to compute precise astrometric positions.

1.1 Standard camera optical SST

Optical SST observations are divided into two main categories: survey and tracking. The principle of optical survey is to watch the sky to detect and identify any moving object in the sensor field of view, and to add new objects identified as Earth satellites to a catalog. In tracking observations, the aim is to follow up already known objects to improve their orbital parameters, characterise maneuvers, and to update close pass predictions for collision avoidance. In both cases camera image timing is of critical importance. For higher orbits it is sufficient to time images with accuracy at the level of tens of milliseconds, but for LEO sub-millisecond accuracy is required to obtain 1 arcsec astrometric accuracy. It is obviously very hard to obtain such an accuracy with mechanical shutter and large CCD array. Moreover short exposure times translates to read noise dominated images. Therefore low-noise CMOS image sensor (**CIS**) with global electronic shutter is recently becoming a standard detector for low orbit tracking and survey.

LEO objects move rapidly across the image; for example a satellite in 500km orbit moves at an apparent speed of 0.9 deg/s at zenith. It crosses the field of view (**FOV**) of the CIS camera we used for this study in only 1.4s in zenith. Assuming diffraction size of 2arcsec, it spends only 0.7ms over each pixel. If the object moves too quickly, the time spent by it over each pixel

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becomes too small and the signal is lost in the noise.

SST observations could benefit from recently developed dynamic vision sensors (DVS) event cameras in the following areas. Day-time observations thanks to high dynamic range, data flow reduction due to the nature of these cameras and possible astrometric accuracy improvement due to separate time records from each pixel.

1.2 Dynamic vision sensor (DVS) event cameras

Fig. 1 shows the recorded output of a “dynamic and active pixel vision sensor” (DAVIS) event camera [3], [4]. A DAVIS concurrently outputs conventional global shutter frames and DVS brightness change events. The brightness change events are in the form of timestamped address-events (x,y,p,t), where x and y are the pixel coordinates, p is the sign (*ON* or *OFF*) of the brightness change, and t is the time of the event in microseconds.

The DVS output is attractive for various applications because of its low latency, sparsity, and high dynamic range. It allows applications to only process the changing pixels and to do so with sub millisecond latency.

Event camera prototypes are now commercially available, although the most advanced types are still laboratory objects. A main aim of this paper was to evaluate new event camera prototypes for SST applications.

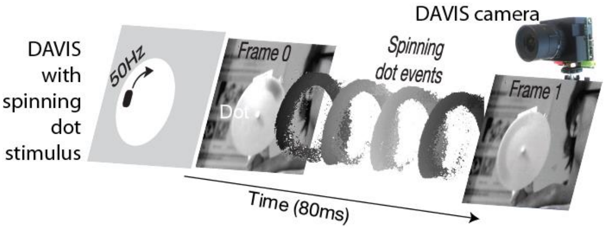

Figure 1. In response to the spinning dot, a DAVIS outputs frames (on demand) and a concurrent stream of brightness change events (adapted from Delbruck, 2018, unpublished).

1.3 Optical SST with DVS

Using DVS for SST, was first proposed in [1]. The results reported in that paper stimulated the current study, which aimed for a quantitative comparison of star magnitude and speed detection limits from CIS and DAVIS.

Fig. 2 shows an example of BSIDAVIS (see Sec. 2) data collected for this study from a GlobalStar M008 satellite flyby event at altitude 1530km. The satellite transited about 350 pixels in 3s (~100 pixels/s). For clarity, the raw data was filtered using jAER[1] software noise reduction filters using parameters listed in the figure caption, which removed about 96% of the events.

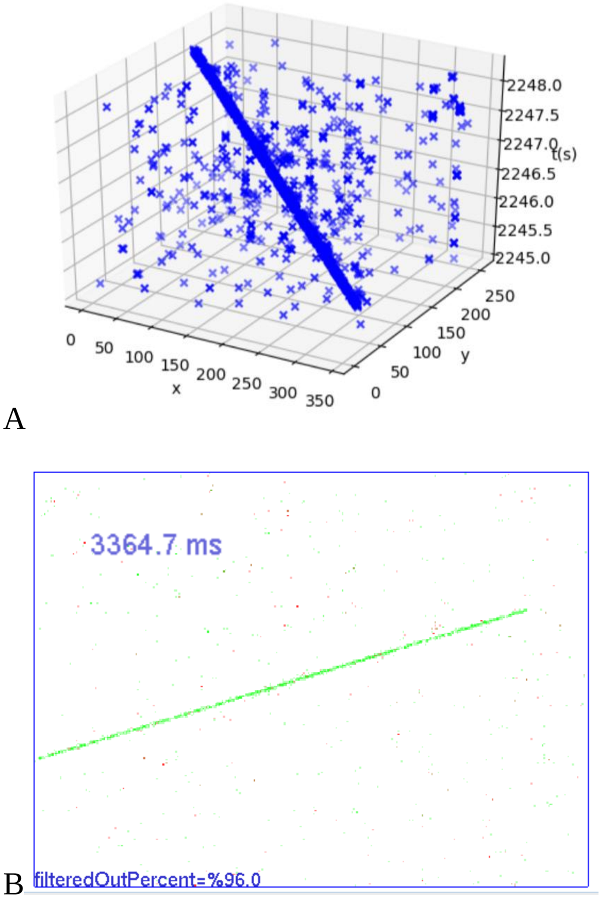

Figure 2. Spacetime data from flyby of GlobalStar 25309. Approximately 96% of the raw data was filtered out using SpatioTemporalCorrelationFilter and HotPixelFilter with the criterion of at least 3 active neighbours of the closest 36 pixels during the past 10ms. ***A:*** *spacetime plot.* ***B:*** *accumulated events over 3.4s. Speed: 101 pix/s. Green: ON events. Red: OFF events.*

2, EQUIPMENT and METHODOLOGY

Cameras: Tab. 1 compares the cameras used in this study. The global-shutter CIS camera (QHY174-GPS[2]) used in this paper is the first commercially available astronomical camera which is integrated by its manufacturer with a GPS receiver. The camera is specifically designed for time resolved astronomy and provides exposure time with a precision claimed to be at the level of 10^{-6}s. It also includes electronic cooling which was not used for this study due to short exposure times.

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[1] http://jaerproject.net

[2] http://www.qhyccd.com

The two DAVIS sensors used in this study are the first back illuminated DAVIS (**BSIDAVIS**) [5] and the first sensitive-DVS DAVIS camera (**SDAVIS**) [6]. These are experimental cameras developed by the Sensors Group at the Institute of Neuroinformatics. The BSIDAVIS has higher quantum efficiency from its 100% effective fill factor, and the SDAVIS is sensitive to smaller brightness changes from the increased gain in its preamplifier.

Observatory: We compared the cameras using an experimental observatory located in Krakow during the months of September and December 2018. The observatory is equipped with a Takahashi Sky90 (90mm aperture, f/5.5) and a star+satellite tracking motorized mount Bisque Paramount MX.

Table 1. Camera specifications.

	QHY174-GPS	BSIDAVIS [5]	SDAVIS [6]
Type	CIS, global shutter	DAVIS	DAVIS
Pixel array	1920x1200	346x260	188x192
Pixel size (um)	5.86	18.5	18.5
/Active area(mm)	11.3x7.0	6.4x4.8	3.5x3.6
Peak QE (%)	78	92	~20
Fill factor (%)	NA	~100	21.2
APS Dark current @25°C (e/s)	~37	~16k	16k
CIS DR (dB)	43-75*	53	53
CIS read noise (e)	1.6-5.3*	60	60
CIS conv gain (uV/e)	NA	22	22
DVS min threshold (%)	NA	15*	3.5*
DVS DR (dB)	NA	>120	>100
Pixel image scale [arcsec]☩	2.39	7.70	7.70
FoV [arcmin]☩	76x49	44x33	25x25

* - depending on gain settings;
☩ - using 90mm f/5.5 telescope.

In this paper we simplified the problem of detection to visually observing image streaks in the CIS and accumulated-event DVS images, as explained below.

2.1 Nighttime observations

The goal was to assess the minimum magnitude object that each sensor could detect. The BSIDAVIS has about 4X higher QE than the equivalent front-side illuminated DAVIS [5] and about 12X higher QE than the DAVIS240C used in [7]. Therefore we were interested in whether this higher QE allows detecting fainter and faster moving objects compared with the CIS.

We used the Pleiades constellation as a collection of stars with known magnitude that we could easily identify in a star catalog. The goal here was to traverse the stars with speeds ranging from 7 arcsec/s to 3.5 deg/s (DAVIS 1.8 pix/s to 1800 pix/s, CIS 5.7 pix/s to 5700 pix/s). We use sidereal (fixed mount) for the slowest speed and the telescope drive motor for faster speeds. We captured data with 1X, 10X, 100X, and 300X sidereal speeds.

2.2 Daytime observations

The BSIDAVIS minimum temporal contrast threshold is about 15% change in intensity, so it is not suitable for detecting low contrast objects such as those expected in daytime observation against a bright sky. The SDAVIS QE is only about 20%, and the circuit design does not function well at very low photocurrents. However, it's photoreceptor preamplifier provides it a higher temporal contrast sensitivity (down to 3.5%). Therefore we were particularly interested in exploring whether it allowed observation of daytime or evening/dawn satellite tracking.

To assess this possibility, using the SDAVIS, we imaged several brighter stars during daytime (Vega and Deneb) using the same apparent motion methods as for nighttime observations. Cloudy winter weather and difficulty adjusting the prototype's sensor parameters severely limited observational time so these results are very preliminary.

2.3 Pixel transit time considerations

CIS: During any finite CIS exposure, the satellite may pass over many pixels, resulting in a streak in the image. The detection limits for CIS SST are mainly from the limited time that a satellite spends over each pixel. The increased light exposure resulting from the satellite is inversely proportional to the speed of the satellite. The faster the satellite moves, the less time it spends over the pixel, and the dimmer is the resulting streak. The entire image is also exposed to dark current, which increases the value of each pixel according to the product of dark current and exposure time.

DVS: Since pixels continuously monitor the photocurrent, a satellite is only detected if the momentary increase in photocurrent caused by the transit is detected as an event, i.e. if it causes a relative change of the filtered photocurrent exceeding the temporal contrast threshold. [8] analyzed this case in the context of particle tracking velocimetry. It found that the required pixel bandwidth is proportional to the inverse of the pixel transit time, i.e. if the object produces a Gaussian deflection of photocurrent and the full width at half maximum of this deflection is 1ms, then the required bandwidth to produce a full-contrast response is a few times $1/(2\pi \times 1ms) = 159Hz$. The

DVS pixel bandwidth is a linearly increasing function of the photocurrent [3]. It means that the brighter the star, the faster the bandwidth. However, the bandwidth of the pixel is also controlled by the analog bias currents for the photoreceptor and source follower buffers. By settings these bias currents small, the front end circuit can limit its bandwidth and hence increase its integration time, as well as reducing the shot noise. However, the quantitative value of the bandwidth produced by a particular magnitude is difficult to estimate, and has only been measured under particular bias conditions for some DVS [3], [6]. As for CIS, the situation is complicated by the dark current, which in the case of DVS decreases the photocurrent contrast. In the case of a dim star, the contrast of the star is reduced by the background dark current.

CIS: For the measurements reported here that start with the slowest transit speed of 1X sidereal, we determined an optimal time of exposure of 500ms, as follows. We estimate star point spread function (**PSF**) FWHM is 1.9 pixels, or 4.5 arcsec, and the CIS pixel resolution is 2.39 arcsec.

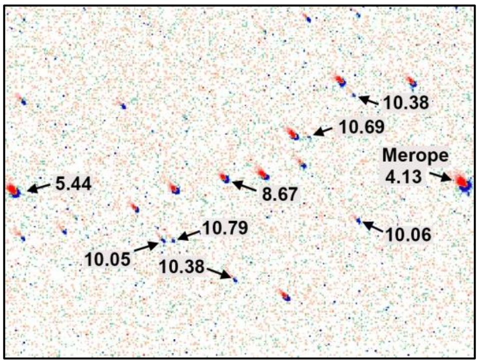
With the speed 1X sidereal, star travels 15 arcsec/s, or 6.28 pixels/s. In 200ms, a star travels only 1.26 pixels, which is less than its own PSF. But in 500ms, it travels 3.14 pixels, which is about 150% of its diameter. Therefore with a 500ms exposure, we are assured that any star will cross at least several pixels, causing a full exposure of the pixel to the star.

DVS: Since the DVS has no exposure time, we simply recorded continuous DVS output during the constellation transit. When possible by sufficient observation time, we varied the photoreceptor and source follower bias currents to study the effect of front end bandwidth on maximum transit speed and noise and used the subjectively optimal parameters for the results reported here.

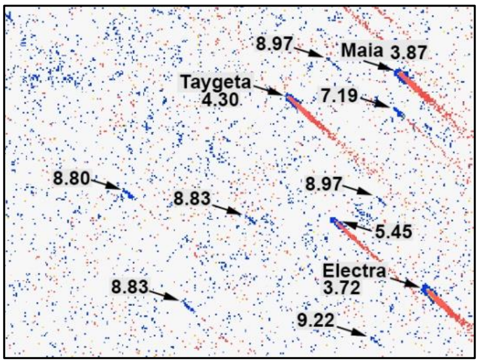
Detection: We determined the limiting magnitude star by visual inspection of the DVS accumulated event image and the single CIS image. We considered the dimmest track with clearly detectable start and end points as the limiting magnitude.

3. RESULTS

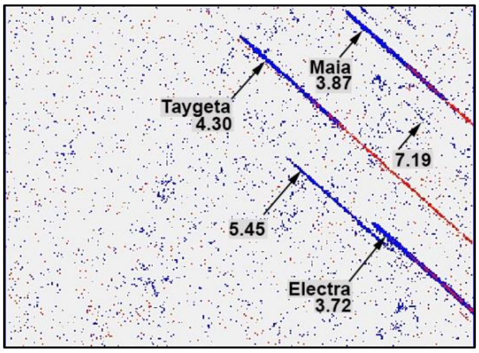
3.1 Limiting magnitude (night)



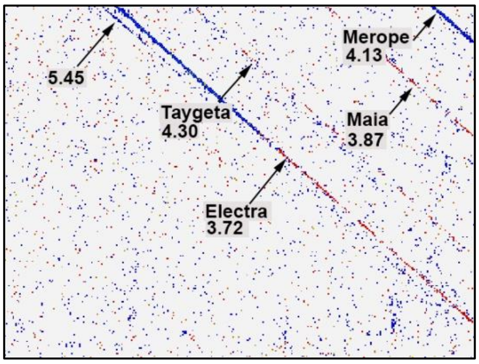
telescope speed: 1x sidereal



telescope speed: 10x sidereal



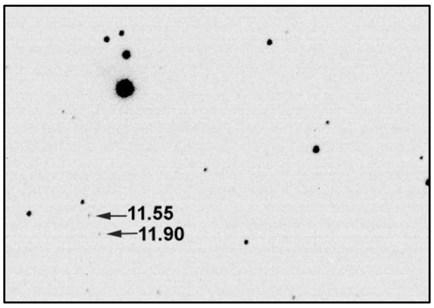
telescope speed: 100x sidereal



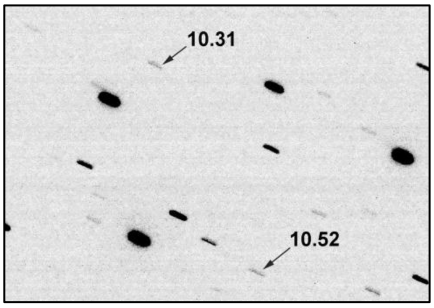
telescope speed: 300x sidereal

Figure 3. BSIDAVIS events accumulated during 320ms for Pleiades transits at different speeds. V magnitudes are overplotted for selected stars.

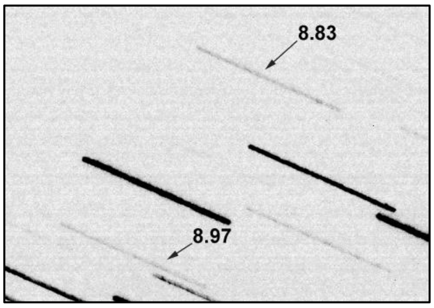
Fig. 3 shows raw BSIDAVIS DVS event data for the tracking experiment. Each panel is a 2D histogram of accumulated DVS events during part of the scan. Stars are visible as streaks. Identified stars are labelled with their magnitudes for each experiment. At 1X sidereal, many more stars are visible than at 300X. For each speed, the faintest visible streak was identified by eye.



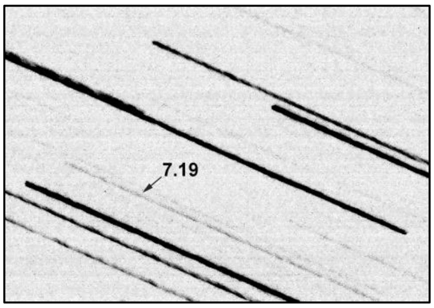
telescope speed: 1x sidereal



telescope speed: 10x sidereal



telescope speed: 100x sidereal



telescope speed: 300x sidereal

Figure 4. 500ms CIS frames for Pleiades transits at different speeds. V magnitudes are overplotted for selected stars.

Fig. 4 shows the same type of data but for the CIS.

Tab. 2 and Fig. 5 show the lower limiting magnitude for DVS and CIS versus speed. For each sensor, the faster the movement, the brighter must be the star to observe a track. The CIS can detect stars that are dimmer on average by about 1.6 magnitude than the DVS (a factor of about 4.3).

Table 2. Limiting V magnitude

Speed (x sidereal)	DAVIS (mag.)	CIS (mag.)	diff.
1x	10,38	11,9	1,52
10x	9,22	10,52	1,30
100x	7,19	8,97	1,78
300x	5,45	7,19	1,74

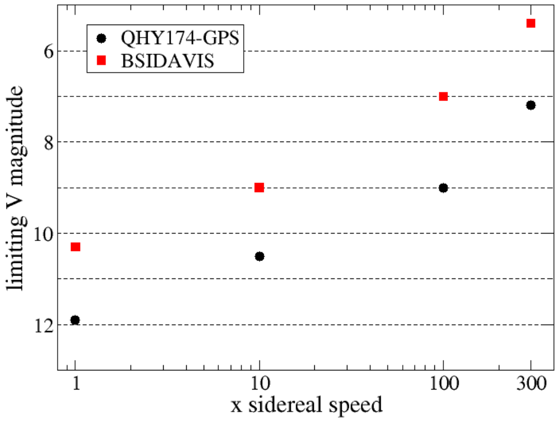


Figure 5. Estimated nighttime limiting magnitude versus relative sidereal speed.

3.2 Limiting magnitude (daytime)

We repeated the experiment during daytime using the SDAVIS, although we were not able to compare with the QHY CIS. As mentioned, observation time was limited to a single session with clear weather and daytime conditions. At about 11:00 on a slightly overcast November day in Krakow with high cirrus clouds, we located and recorded observations of Vega (mag 0). Vega could be observed by eye in the telescope. Using the APS mode of SDAVIS, we observed that the sky brightness was 2.2e4 DN/s[3]. Vega produced 2.75e4 DN/s and thus had a contrast of about 1.25X against the sky.

A caveat on the data presented here is that the SDAVIS

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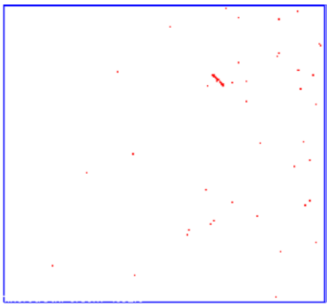
[3] DN is digital number; 1 DN=1.23mV=56e$^-$.

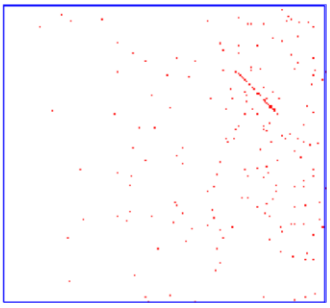
was not optimally configured owing to a lack of understanding of the rather complex controls. It means that the background activity rate (of noise OFF events) was very high and the sensitivity was not optimized. There was also a periodic oscillation of the activity probably caused by power supply load positive feedback. This periodic pulsation at a frequency of about 1.7Hz somewhat obscured the star tracks.

We observed Vega using the telescope drive to create transits. Fig. 6 shows traces from two of the recordings. We could easily track Vega for transits up to 0.6 deg/s (270 pix/s).

We did not succeed to catch any daytime satellites in this session. Subsequently we were able to adjust the SDAVIS biases for better performance but cloudy skies prevented any further observations.



Vega at 0.04 deg/s



Vega at 0.6 deg/s

Figure 6. Daytime tracks of DVS events from SDAVIS. showing only ON events. Tracks of Vega at two speeds: 318ms at 0.04deg/s and 80ms at 0.6deg/s. No noise filtering was applied.

4. DISCUSSION

The results of this comparative study show that for nighttime observation, the current state of the art DVS sensor (BSIDAVIS) offers about 1.6 mag worse limiting magnitude compared to the QHY CIS camera. Current prototype DVS sensors do not offer superior absolute detection capability, despite its larger pixel size and higher QE peak. It is however worth noting that the FWHM of CIS images was significantly lower (~5 arcsec compared to ~15 arcsec), which was caused partially due to DVS charge leakage between pixels and partially due to focusing errors.

From the DVS event tracks, although we have not demonstrated it in this paper, we believe it would be possible in real time to precisely estimate the satellite location, with precision down to sub-millisecond and system latency of a few milliseconds.

From the CIS streaks, it should also be possible to accurately determine object speed. From the CIS start and end frame times it should also be possible to determine absolute sky position with the timing precision of the known shutter times.

Therefore, both cameras appear to offer roughly comparable capability of survey and tracking, although the CIS sensor clearly offers higher spatial resolution.

The data volume from DVS especially after noise filtering is much lower than from CIS, even at low CIS frame rate. At 2Hz (500ms exposure time) CIS frame rate, a QHY sensor output data rate is 4.6M pixel/s. A CIS sensor of same spatial resolution to the BSIDAVIS would output a data rate of about 346x260x2=180k pixels/s. This data rate is still much higher than the raw BSIDAVIS data rate of about 30k events/s. After modest correlation and hot pixel noise filtering of BSIDAVIS, the data rate drops to less than 5k events/s, which is a factor of 36 smaller than from the downscaled CIS sensor. This low rate puts real time analysis of the DVS data in reach of small embedded platforms like Raspberry Pi.

Therefore, the main results of this study are the following:

1. For nighttime observation, the prototype BSIDAVIS offers 4X lower sensitivity and timing resolution than the QHY CIS sensor, but at factors of 10s or 100s less data rate.
2. For daytime observation, the prototype SDAVIS can detect Vega in noonday northern latitude conditions at speeds up at least 0.6 deg/s (450 pix/s).

A sensor with higher pixel count that combines the higher event sensitivity of the SDAVIS pixel circuit with the high quantum efficiency of the BSIDAVIS back illumination process technology would appear to offer useful capabilities for survey and tracking applications, for both nighttime and perhaps daytime observation of LEO objects.

A DVS camera outputs pixel position and time for every event on each pixel while CIS outputs only two times (beginning and end of exposure) for all pixels. A single image from CIS is usually transformed using tools such as sextractor[4] to a target's single pixel position at a single time of mid-exposure. DVS data creates an opportunity to develop a dedicated astrometric procedure that would utilize additional timing information and analyze satellite positions at much higher rate than possible from CIS images. It is possible that for bright targets, such a procedure would produce a superior astrometric accuracy compared to regular CIS measurements. The shorter latency of these measurements could also enable real time telescope drive control to track new objects. These capabilities of course require verification with future observational tests of DVS cameras.

Acknowledgments

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