Scientific CMOS Optical Detectors for Orbital Debris Observations

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ABSTRACT

Ground-based optical observations of orbital debris are crucial to assess the debris population in near-Earth space. This allows to better understand and predict related collision risks with space missions and satellites. Debris can have varying sizes from meters down to millimeters, it moves at high relative velocities and can appear much fainter compared to other objects in the night sky. Therefore, detectors for orbital debris observations ideally can take extremely short exposures and have fast read out times, while simultaneously offering low noise characteristics and high quantum efficiency. In this context, scientific complementary metal-oxide semiconductors (sCMOS) are becoming increasingly recognized as leading technology solution for the detection and tracking of orbital debris. We will present Andor's newest large area sCMOS camera solution, called Balor, for ground-based orbital debris observations, discuss its key characteristics and compare it to a CCD detector of similar size (4k x 4k CCD). The Balor sCMOS camera utilizes a 16.9 Megapixel, 70mm sensor with fast ultra-low noise read out (2500x faster than a low noise 4k x 4k CCD read out). Thus, the Balor represents an ideal detector solution for large sky surveys that measure variability in the sky across timescales ranging from milliseconds to tens of seconds.

1 INTRODUCTION

Orbital debris, or space debris, is defined as any man-made, non-functional object in near-Earth space [1, 2]. The sizes of these objects range from several meters down to millimeters and are leftovers of any material launched from Earth. Debris can be found at different altitudes, such as the low Earth orbit (LEO; up to 2,000 km), the geostationary Earth orbit (GEO; at ~36,000 km) and the geostationary transfer orbits (GTOs; elliptical orbits with perigees and apogees located between the altitudes of LEOs and GEOs, respectively). Therefore, orbital debris also populates the same regions as space missions and satellites, imposing a great threat to ongoing and future space operations. Due to their high relative velocities, even impacts of small debris may lead to severe damages [3, 4]. Therefore, different observational programs, such as the Michigan Orbital Debris Survey Telescope (MODEST) [5], the NASA CCD Deris Telescope (CDT) [6] and the Rapid Action Telescope for Transient Objects (TAROT) [7] are in place to detect, monitor and characterize orbital debris to continuously assess collision risks.

One technique to investigate the space debris population is through passive optical observations from the ground [8]. This method is based on observing the reflected light of orbital debris, as these objects are illuminated by the Sun. This allows to detect unknown objects and to track and refine the orbits of already known debris. However, this technique does not yield direct information about the object's distance from Earth. For the latter parameter, active optical observations through, for example, illuminating a space debris object with a strong, pulsed leaser beam (called 'laser ranging', as in CDT) are used.

Orbital debris can appear as faint, small and fast-moving objects with respect to the stellar background. The following list highlights some of the key requirements, which need to be fulfilled by a ground-based optical imaging detector for successful debris observations, as in [4]:

- low read noise and low dark current (especially important when observing faint objects)
- short exposure times of less than 1s (e.g., crucial when observing debris in LEOs)
- short read out times (should be negligible compared to exposure time; improves duty cycle)
- electronic shutters (e.g., more reliable than mechanical shutters)
- high full-well capacity
- high quantum efficiency (ideal for detection of photon starved signals)
- large field of view (FOV) (e.g., more sky can be investigated during a single exposure)

- low number of dark and hot pixels

With respect to these requirements, scientific complementary metal-oxide semiconductors [9] offer a broad range of advantages in comparison to charge-coupled devices (CCDs). sCMOS detectors provide fast imaging and fast read out capabilities, while also featuring low noise characteristics. These key features arise from the sCMOS specific sensor architecture, with each pixel utilizing its own read out electronics and amplifier. The main differences between sCMOS and CCD detectors will be discussed in Section 2. In Section 3, we will explore the key characteristics of Andor's large area sCMOS camera (Balor) and its CCD equivalent (4k x 4k CCD) with special attention to their application toward orbital debris observations.

2 ARCHITECTURE OF SCMOS AND CCD DETECTORS

2.1 CMOS versus CCD detector technology

Complimentary metal-oxide semiconductor (CMOS) detector technology shares many of the same detection principles as more the more traditional CCD technology. Incoming photons that fall within the bandgap of the photosensitive material generate an electron-hole pair, which in turn are converted into digital counts by some sequence of amplifiers and analog-to-digital circuitry (ADC). However, a significant difference exists between the two technologies when considering architecture of each pixel and the readout process. Photoelectrons generated on a CCD sensor are restricted to specific spatial locations by the biased placed on the surrounding readout electrodes, until the readout process begins. At this stage the charge is clocked vertically through adjacent pixels into a masked "readout" register and then clocked horizontally to the amplifier and ADC. Because every pixel is read serially, this process can give rise to many of the unwanted artifacts associated with CCDs such as blooming, clock-induced-charge, and long readout times for large area CCDs. In contrast, CMOS technology places the readout circuitry predominantly on each pixel (Fig. 1).

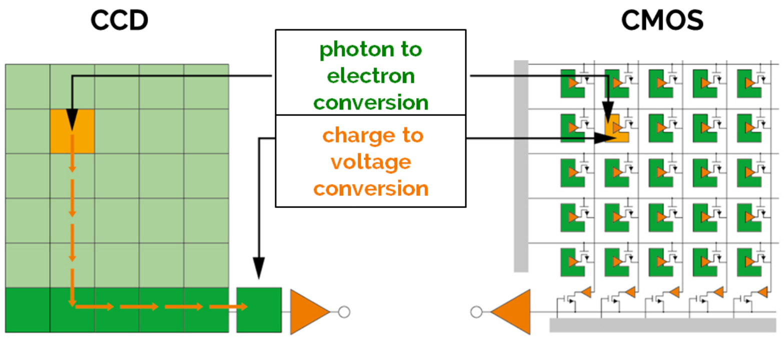

Fig. 1. Readout Architecture of CCD vs CMOS.

In the Active Pixel Sensor (APS) pixel scheme, each pixel is independent from the adjacent pixel and converts its charge into an amplified voltage, and each column has additional amplifiers and ADCs controlling the analog signal processing. The most noticeable result of this architectural difference between CMOS and CCDs is the decreased readout time associated with this parallelized readout with CMOS sensors having charge transfer times that can approach 2 us in comparison to the millisecond to second time scales associated with the serial readout of CCDs [10].

2.2 CMOS vs sCMOS

CCDs have dominated the fields of scientific imaging for the last several decades due to many of the advantages they carried over CMOS imaging technology. The most significant of these advantages being that of the much lower read noise and thus higher dynamic range associated with the readout of CCD technology. Other differences include the better performance of CCDs with respect to the dark current levels and the linearity of photo-response with intensity. Scientific-CMOS (sCMOS) represent a significant leap forward in the control of these parameters.

The APS pixel architecture along with correlated double sampling has reduced the read noise of sCMOS sensors to as low as 1 e- rms (or 2.9 e- for Balor). This is substantially lower than conventional CCDs, which tend to hover around the 10-40 e- for reasonable readout rates. Consequently, the decreased well depth associated with the lower fill factor of sCMOS sensors does not necessarily result in a significant decrease in dynamic range. For example, a traditional large area 4k x 4k CCD has a 350,000 e- active area well depth. However, this is over a ~10 e- read noise floor resulting in a dynamic range of ~35700:1. In contrast, the Balor large are sCMOS camera has a well depth of only 80,000 e-, however this is over a read noise floor of only 2.9 e- resulting in a dynamic range of 27,600:1 for only a 1.3x decrease in dynamic range.

Aside from the read noise consideration, sCMOS sensors all maintain high linearity (Fig. 2) of photo-response across the dynamic range of the sensor, which is crucial for quantitative imaging.

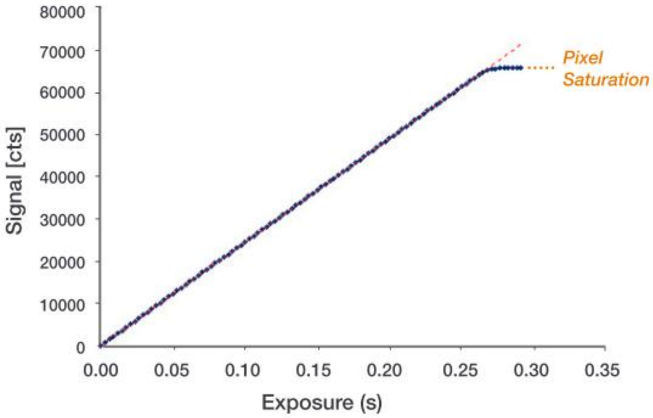

Figure 2. Signal vs. Exposure Time of a sCMOS sensor.

With the predominant noise, dynamic range and linearity issues inherent to older generation CMOS detections resolved, scientific-CMOS sensors are now a viable option as sensors in quantitative scienfic imaging.

3 LARGE AREA SCMOS FOR ORBITAL DEBRIS OBSERVATION

Apart from the already treated consideration between CCD and sCMOS detector technology, orbital debris observations bring an additional set of requirements for image detectors. These requirements have been delineated in previous works [e.g., 4] and include fast readout for large FOVs, low readout noise and dark current, short exposure times and electronic shuttering. Recently, Andor Technology has developed a large FOV (70 mm diagonal) sCMOS detector called Balor. In the following sections, the camera will be characterized with respect to these key parameters for orbital debris observations and compared with a similar sized 4k x 4k CCD camera.

3.1 Readout rate and FOV

The Balor sCMOS camera has a FOV approaching that of the 4k x 4k large area CCD sensor. The Balor sensor is a 4128(w) x 4104(h) sensor with a 12 μm pixel pitch resulting in a 69.8 mm diagonal FOV. This is in contrast to the 4k x 4k CCD at 15 um pixels which has an 87 mm diagonal FOV. The parallelized readout architecture of the Balor sCMOS camera allows the camera to operate at 54 fps for rolling shutter mode at the full FOV which is ~100x faster than the 4k x 4k CCD at its fastest readout. The readout rates comparison for the 4k x 4k CCD and the Balor are summarized in Table 1.

Table 1. Balor readout rates compared to a 4k x 4k CCD camera.

	Balor	**4k x 4k CCD (100 kHz Readout)**	**4k x 4k CCD (500 kHz Readout)**	**4k x 4k CCD (1 MHz Readout)**	**4k x 4k CCD (3 MHz Readout)**
Frame Rate at full FOV (Hz)	54	0.022	0.11	0.21	0.5

Apart from the overall readout rate, duty cycle might be an even more relevant parameter to orbital debris observation. Many LEO objects can exhibit high angular velocities necessitating short readout times relative to the exposure time (i.e. near 100% duty cycles). The electronic shutter (rolling and global) of sCMOS cameras can operate in what is known as an "overlap" lap mode. In this mode, the readout of the previous frame is performed during the exposure of the current frame. This minimizes the interframe gap normally associated with a CCD readout time, to be only the time necessary for charge transfer into the readout node (microsecond timescale). In this fashion the camera can operate with essentially 100% duty cycle [11] (Fig. 3).

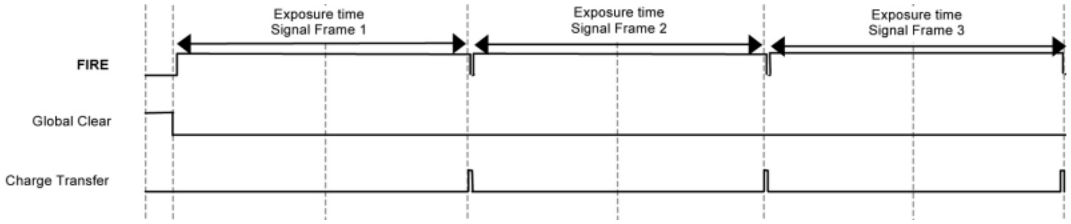

Figure 3. Timing illustration of the Balor operating with 100% cycle.

3.2 Read noise and dark current

Read noise originates from the electronic processes within the camera during the image read out. Due to the individual sensor architecture of CCD and sCMOS detectors, the corresponding read noise values are determined differently [12]. For CCD cameras, the read noise can be described by a single value. This is because during a CCD read out process, the charges are passed from pixel to pixel and then converted by a single analog-to-digital converter. In the case of sCMOS sensors, each individual pixel has its own associated amplifier circuit to convert electrons to a voltage signal. This results in every pixel having a slightly different read noise, thus, the read noise of a sCMOS detector is represented by a noise distribution (Fig. 4). The median or RMS of this distribution is then taken and is the typical value reported for read noise. The Balor is an active pixel scientific sCMOS sensor which employs correlated double sampling to shift this noise distribution to very low values. Figure 4 shows the noise distribution for the Balor plotted alongside the distribution of the 4k x 4k CCD sensor. As is demonstrated, the Balor has a ~3.4x reduction in read noise while maintaining a greater than 100x the frame rate.

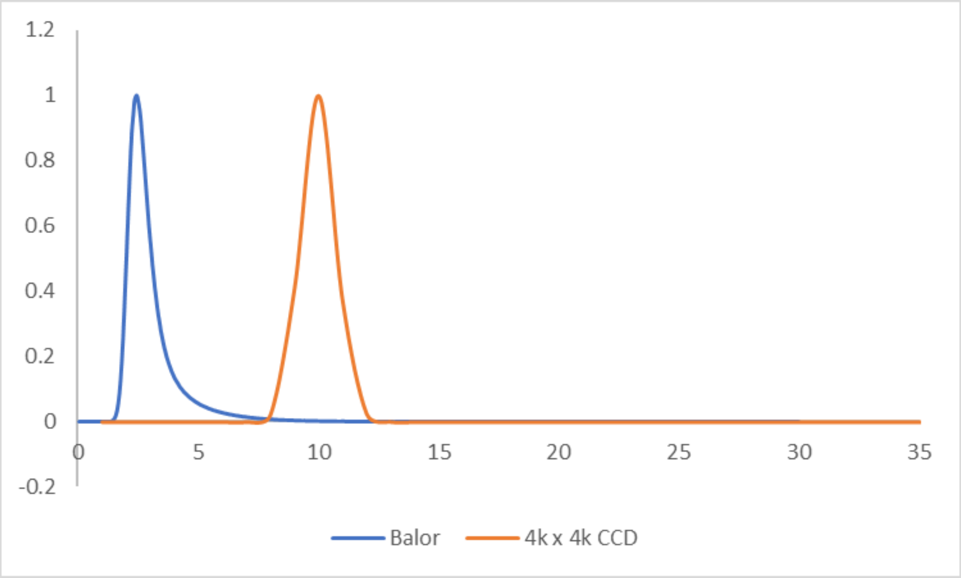

Figure 4. Normalized read noise distribution of the Balor front-illuminated sCMOS camera in rolling shutter mode and 4k x 4k CCD camera showing a read noise median value of 2.7 electrons and 9.8 electrons, respectively.

3.3 Electronic shutter modes

The electronic shutters in sCMOS cameras consist of rolling shutter and global shutter. The shutter modes are more precisely described as the timing associated with the exposure (photo-collection) phase and readout phase of the camera on a per row basis. In rolling shutter, the exposure time setting is defined as the "per row" exposure time. However, the exposure of each row is offset from the adjacent rows by some time which is a multiple of the readout clock speed. This means that every row starts and ends its exposure slightly offset to its neighboring row ("rolling wave effect"). The Balor sensor operates on 4 rows simultaneously, thus the rolling wave consists of 4 rows. Each set of 4 rows can be initialized/reset in ~18 us thus requiring only ~18.5 ms for readout of the full array. This is in contrast to the ~2 s required by the 4k x 4k CCD at its fastest readout rate and the 45s required in its lowest noise mode [13] (Fig. 5).

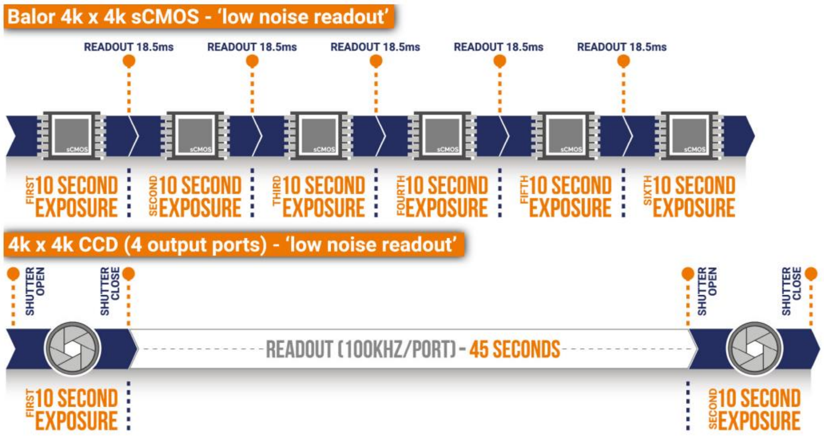

Figure 5. Illustration of readout time comparison for the Balor with a large area CCD, as in [13].

Performing observations in rolling shutter mode has the advantage of maximizing read out speeds while minimizing noise. However, this mode can cause spatial distortion on the image especially when observing fast moving objects. Consequently, space debris observations for objects moving fast with respect to the "rolling wave" require cameras with true global shutter [4]. True global shutter represents a “snapshot” mode, which means that every pixel on the sensor is exposed and read simultaneously and with the same length of exposure. While this mode decreases the frame rate (54 fps rolling vs 34 fps global shutter) it ensures that all events across the entirety of the sensor are correlated in time.

Furthermore, as was previously explained, the Balor can operate in an overlap mode which effectively makes the duty cycle 100%. As a consequence of this mode, the fast charge transfer of the photoelectrons to the readout nodes also acts as a fast, high-contrast optical shutter. Because no charge is physically clocked vertically or horizontally though the silicon material during readout, a mechanical shutter is not required to shield the sensor from light during the readout phase to avoid streaking. It also avoids the exposure gradient effects associated with a large mechanical iris shutter.

3.4 Sensitivity and linearity

The quantum efficiency is one of the few parameters where the Balor large area sCMOS lags behind the CCD equivalents (Fig. 6).

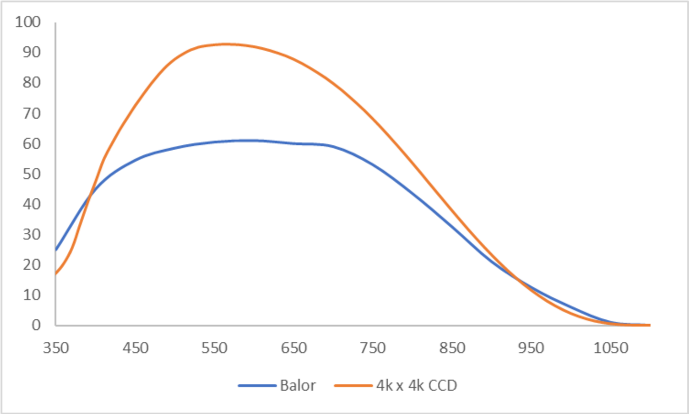

Figure 6. Quantum efficiency of the Balor sCMOS and 4k x 4k back-illuminated CCD with mid-band AR coating.

This is predominantly due to the front-illuminated geometry of the sCMOS coupled with the lower fill factor resulting from the readout circuitry on each pixel. In contrast, CCDs generally have a back-illuminated geometry with a 100% fill factor (Fig. 7).

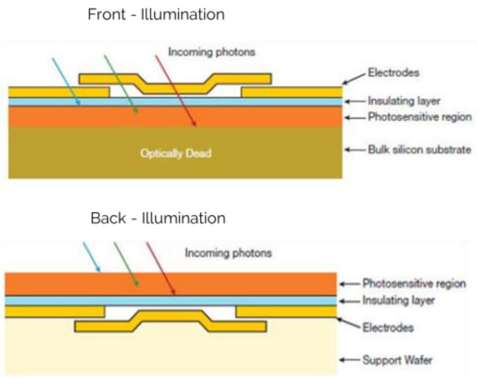

Figure 7. Illustration of front- vs. back side illumination detector geometry.

3.5 Linearity and dynamic range

Finally, the linearity of the photo-response with intensity of a scientific imaging detector is crucial to its ability to perform quantitative imaging. The linearity of CMOS detectors has been traditionally a difficult parameter to control due to the inherent variations in the sensitives of each pixel level amplifier, and the multiple column level ADCs across the sensor. Maintaining this linearity across the entire dynamic range of the camera compounds this difficulty. The Balor scientific-CMOS technology has circumvented this problem though a combination of simultaneous sampling through multiple amplifiers and on-chip FPGA intelligence which combines the readout from each amplifier. The signal from each pixel is sampled through a high, medium, and low gain amplifier and the output of all three amplifiers is scaled and reconstructed in the final image. This allows for the preservation of >99.7% linearity across the entire dynamic range of the camera [14] (Fig. 8).

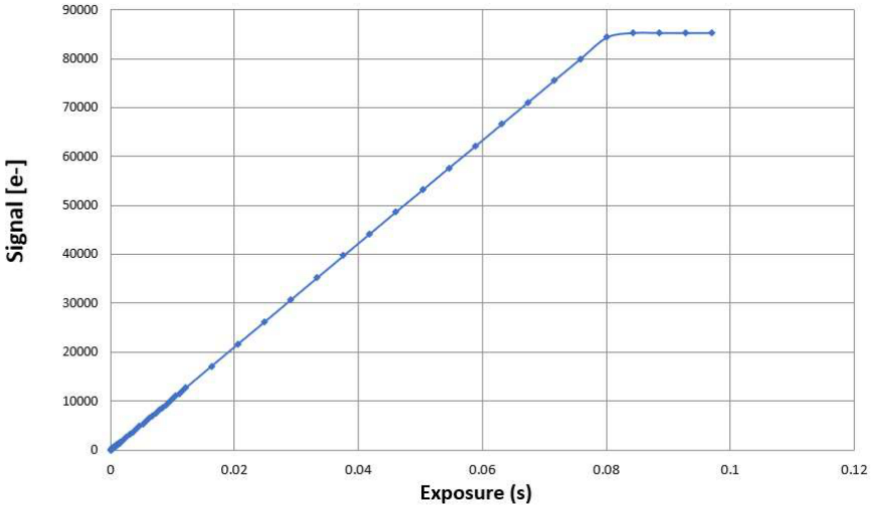

Figure 8. Signal level vs. exposure time of the Balor sCMOS camera.

In contrast, a traditional 4k x 4k CCDs only provide access to a single amplifier at a time. Typically, a high gain and low gain amplifier exist, however, only one can be digitized for any given image. Thus, one must choose whether to optimize for low noise or maximum well depth, with each setting having a different influence on the true dynamic range of the camera.

4 CONCLUSION

Scientific-CMOS detector technology has made great strides recently in improving parameters such as read noise, dynamic range and linearity. These improvements have made them viable alternatives to traditional CCDs for scientific imaging. Other benefits afforded by sCMOS imaging sensors such as fast readout (100% duty cycle), fast frame rates, and large FOV also make them very compelling as detectors for orbital debris observations. For observations of this kind, Andor recommends its recently developed large area sCMOS camera called Balor. When compared with a traditional 4k x 4k CCD sensor, the Balor is superior in many regards, providing >100x frame rate improvement and duty cycle improvement, while maintaining a low noise floor and high dynamic range.

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