Advanced CMOS Detectors: Enabling the Future of Astronomical Observation

Introduction

Ground based astronomy provides an **accessible way** to image objects in space. As most of the objects in space can be observed within the **visible wavelength range** (380-700 nm), optical astronomy has been at the forefront of astronomical observation. Many objects in space are **very faint**, requiring a camera with high sensitivity and minimal noise to detect their weak signal.

For decades, **back-illuminated CCDs**, with **>95% quantum efficiency** (QE) in the visible, have been the go-to detector choice for astronomical observation. The faint signal of objects within space often requires **long exposure times** to ensure detection. Figure 1 shows two images, one of the Pleiades and the other of the Milky Way taken by CCD cameras.

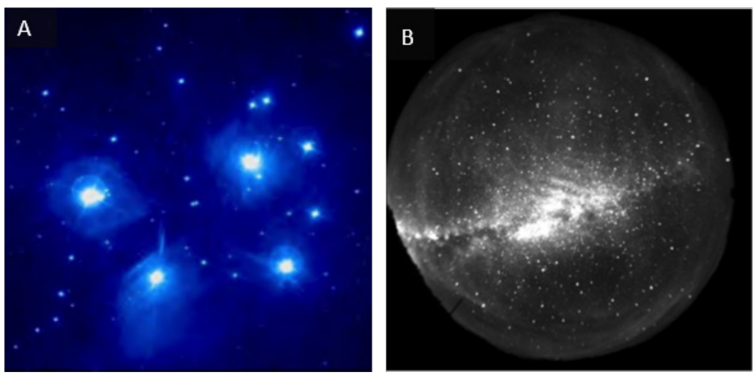

Figure 1: *Images of A) the Pleiades and B) gravity waves and the Milky Way taken using a CCD camera. Images courtesy of Rozhen National Astronomical Observatory and Korea Polar Research Group respectively.*

The ability to detect this signal is constrained by **various noise sources**, and this limitation is typically defined by the signal to noise ratio, or SNR. Typically, the **higher** the SNR, the **better** the image. There are **several noise sources**, including shot noise from the source and background noise from the sky, which are inherent to ground based observation [1].

Two **additional noise sources** are native to the camera, read out noise and thermal noise. Read noise is essentially the **"noise floor"** of the image and is reduced by proper electronic design. Thermal noise, or **dark current**, is the noise generated from thermal sources and is directly correlated to **temperature and exposure**. Dark current **increases** with long exposures (minutes and longer) regardless of camera technology. To significantly reduce dark current, and improve SNR, back-illuminated CCDs are **deeply cooled** to reduce the amount of thermal noise contributing to the signal [2]. For these reasons, when **very long exposures** are needed to capture **faint signals**, CCD cameras have been the best option.

There are other applications in ground-based astronomy for which CCD's are **not the best solution**. One of these is the requirement to operate imaging sensors at **faster time scales**. Applications, such as time domain astronomy and space debris tracking, require **faster times scales** to capture as much information about **dynamic objects or events**.

Faster time scales are determined by the combination of **exposure** and **readout speed**. For CCD's photons are **converted into photoelectrons**, and during readout, the detected photoelectrons need to be **shifted** to one (or sometimes a few) readout nodes, causing a **bottleneck that slows readout**. Fast readout on CCDs requires **very fast measurement of signals** at these readout nodes, performed by analog-to-digital convertors (ADCs). This high-speed measurement **reduces signal quality** through introducing a **high level of read noise** [3]. Detectors with large sensor areas and high number of pixels (4k x 4k or greater) have **long readout times** where **no signal** can be acquired, ranging from seconds to tens of seconds even at higher ADC rates.

Full frame CCDs, typically used within astronomy, require **mechanical shutters** to completely **block** any incident light during readout [4]. Mechanical shutters have **finite lifetimes** and often need to be **replaced frequently** when the camera is in heavy use. This can be problematic for observatories in **remote locations** where maintenance can be challenging. Additionally, opening and closing a mechanical shutter is **relatively slow**, leading to **slower frame rates** and **quantitative errors** for shorter exposure times.

EMCCDs, an alternative sensor technology, are typically used for more challenging, **dynamic observations**. EMCCDs use **on chip amplification** to elevate the signal relative to the read noise. With this low or **negligible effective read noise**, EMCCDs can operate at much **higher frame rates** more suitable to capture the evolution of dynamic events while **maintaining** the required SNR. Figure 2 shows a schematic of EMCCD sensor architecture, showing how the on chip amplification elevates the signal above read noise.

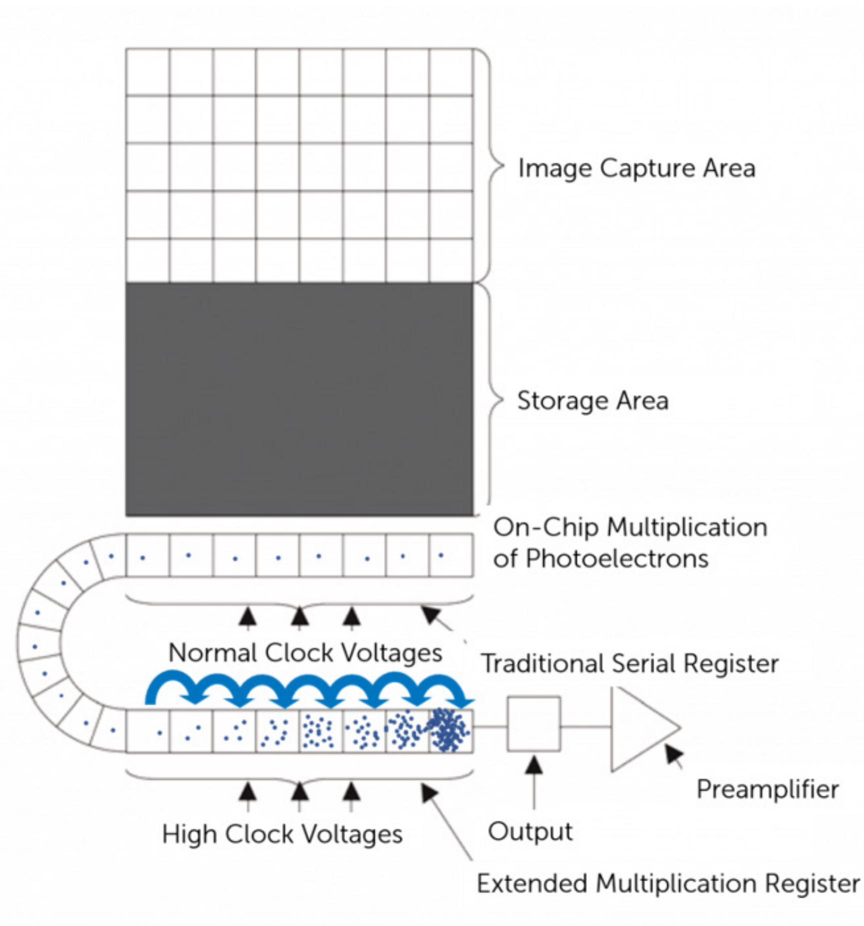

Figure 2: *Schematic showing an EMCCD sensor. Photons are collected and converted into photoelectrons within the image capture area which are then transferred to the storage area. These electrons are then amplified in the extended multiplication register which increases the signal produced without increasing any read noise.*

Many EMCCDs have a fast, **electronic shutter** where exposure is stopped by shifting detected photoelectrons into a **frame storage** area before readout. The electronic shutter is not only **more precise** than mechanical shutters, but also leads to **lower dead time** of the detector during which the camera is not exposing to light, as subsequent exposures can already start as signal is readout from the storage area. This is referred to as '**High duty cycle**'.

Although EMCCDs can operate at **higher frame rates**, duty cycles and are ideal for the detection of **ultra-weak signals**, they are limited by excess noise. This additional noise source is caused by the **random nature of the on-chip amplification process** and causes a **sacrifice in overall sensitivity** for signals larger than a few photons per pixel. For more information on these limitations, please refer to our article **Types of Camera Sensor** [5].

The Advantages of Advanced CMOS Technology

Traditional **CMOS sensors** have not been widely considered for astronomical observation as they are front illuminated, typically having **low QE** and operating at **higher read noise** and **poorer linearity** (proportionality between detected signal and digital signal) compared to CCD and EMCCD sensors. However, **advancements** in CMOS technology now allow CMOS to not only **match these parameters** of CCD and EMCCD sensors, but to also **overcome the common limitations** of these technologies.

Back-Illuminated CMOS Technology

The introduction of **back-illuminated CMOS sensors** has significantly increased QE, achieving **>90% for visible wavelengths**. In addition, advanced CMOS sensor design, such as Teledyne Imaging's **LACera™ technology**, shows **increased sensitivity** in the UV with respect to a typical CCD (see Figure 3). This makes advanced CMOS detectors not only ideal for observations in the visible wavelength range, but also for those which utilize the **UV spectrum**.

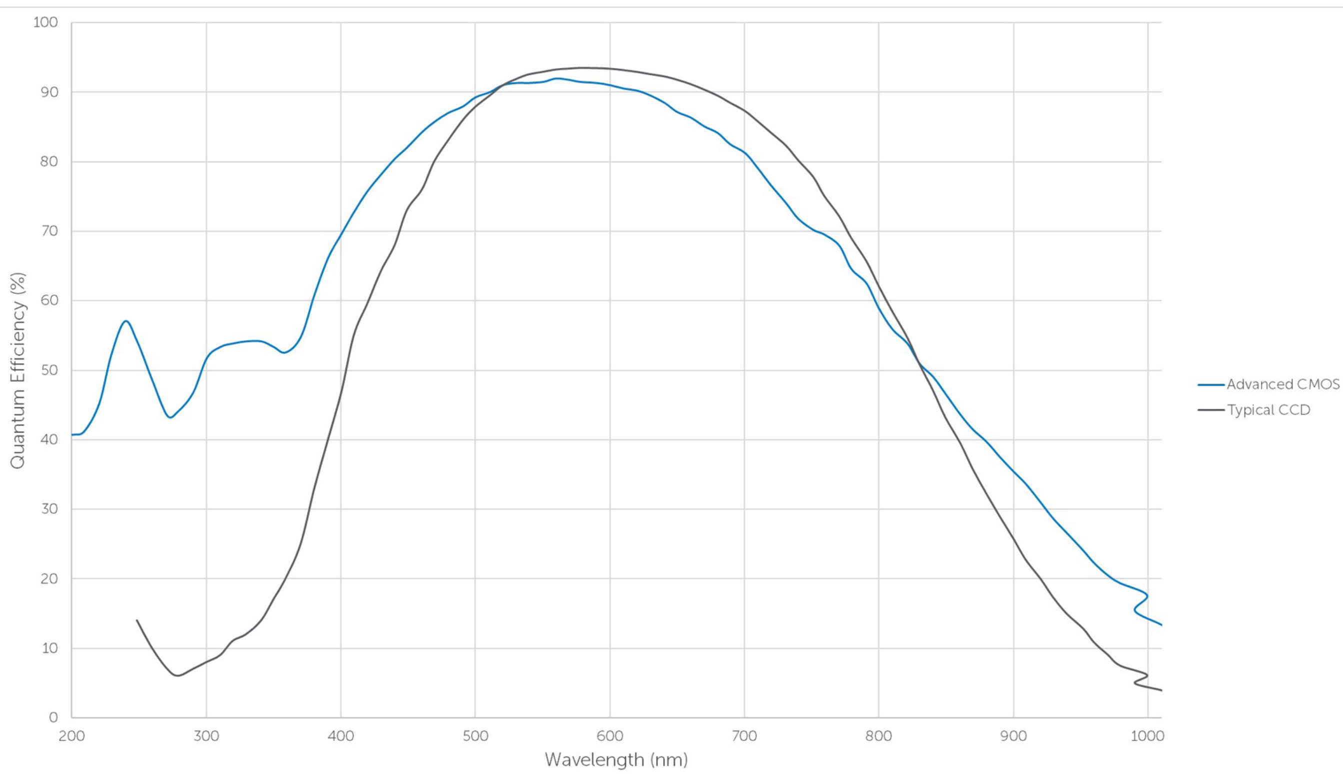

Figure 3: *Quantum efficiency curve of an advanced CMOS sensor and a typical back-illuminated CCD sensor.*

CMOS Sensor Architecture

Unlike CCD sensors, the **charge to voltage conversion** on CMOS sensors takes place in every **pixel individually** (see Figure 4), with the readout nodes on **every column** of the sensor operating **simultaneously**. This parallel readout architecture provides a **tremendous speed advantage**, allowing CMOS sensors to process acquired data at a **much faster rate** while achieving **lower read noise than CCDs**, and **without the excess noise of EMCCDs**.

Fast readout is not only important for **dynamic astronomical imaging**, but also for **quick decision making** and analysis such as in adaptive optics systems for **correction of atmospheric turbulence**. CMOS sensors also use precise electronic shutters allowing for **continuous imaging** without loss of data.

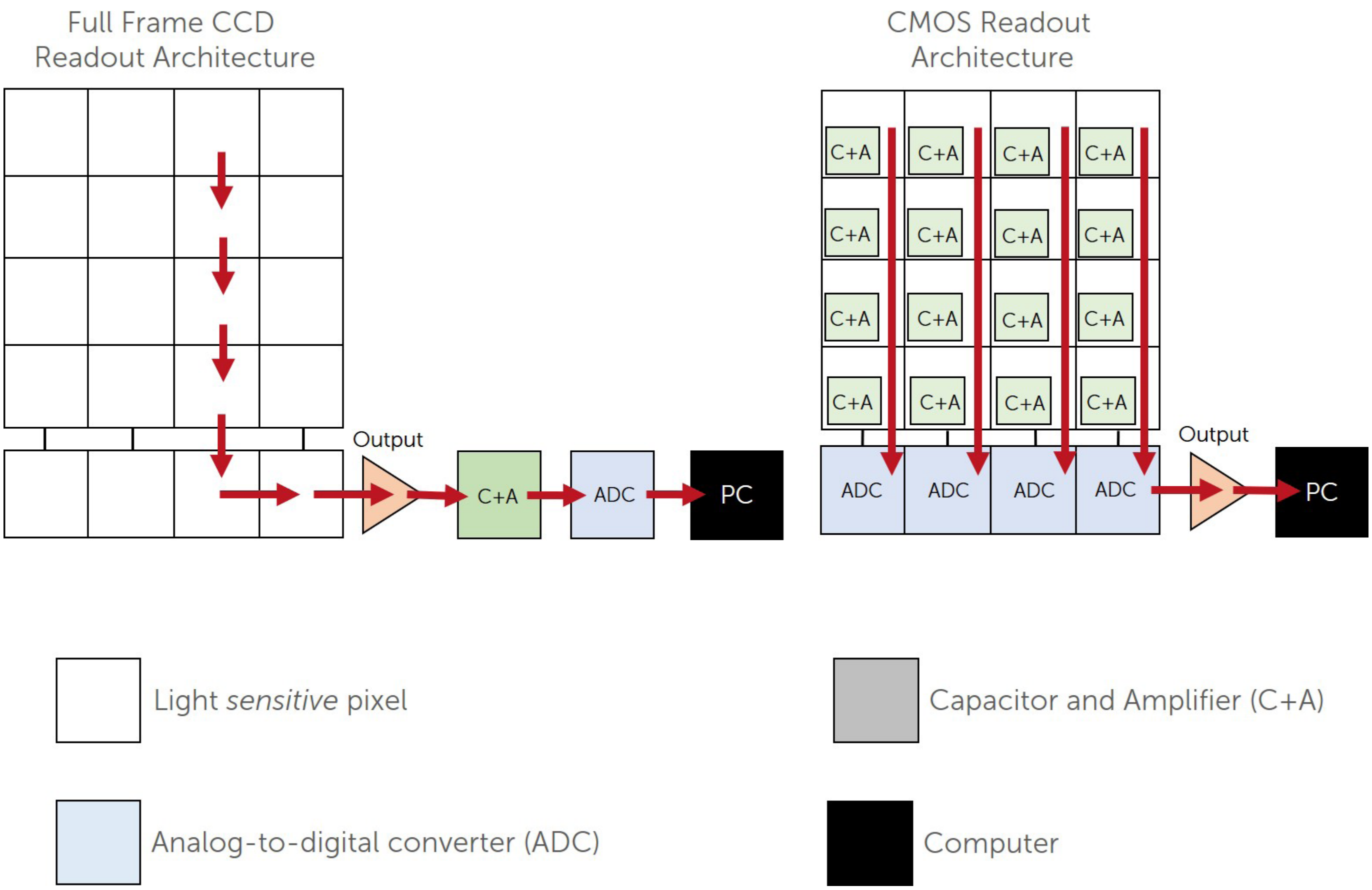

Figure 4: *Schematic showing a full frame CCD readout architecture in comparison to a CMOS readout architecture. Pixels on the full frame CCD are shifted vertically down the sensor until they read the readout array. They then shift horizontally, pixel-by-pixel, until they are read out by an Analog-to-Digital Converter (ADC). In comparison, CMOS architecture has an individual ADC per column, increasing the speed of readout while maintaining a low read noise.*

High Dynamic Range

Within astronomy, it is not uncommon to have both **bright and faint objects** within the same field of view. High dynamic range (HDR) makes the **detection of faint** astronomical objects possible **without saturating the detector** with light from surrounding brighter objects. HDR operation depends on **linearity, ADC bit-depth and gain**. CMOS cameras can extend dynamic range through **multiple sampling** of the signal with high and low gain. However, **artifacts in the cross-over** between high and low gain readouts can limit measurement precision.

Advanced CMOS designs, such as Teledyne Imaging **LACera™ technology**, ensure **precise cross-over** between both ADCs for operation with **low noise and high linearity**. Combined with **higher bit-depth ADCs**, LACera™ technology provides unsurpassed dynamic range. More details about HDR operation of LACera™ technology can be found in our article **New Era in High Dynamic Range CMOS** [6].

True Global Shutter

CMOS sensors typically begin exposure, read out and clear the sensor row-by-row, via a process called a **rolling shutter**. Although this process is **very fast**, it can introduce distortions to fast-moving objects, **potential delays** between frames, and **difficulties with synchronization** which would be detrimental for many astronomy applications (see Figure 5).

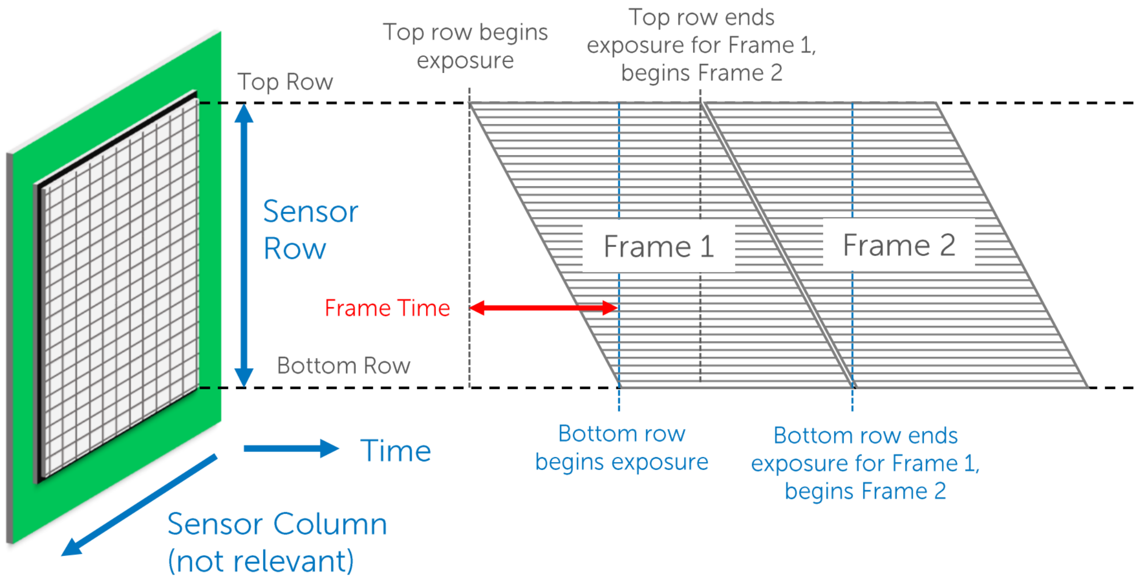

Figure 5: *The camera sensor is shown on the left, with rolling shutter architecture meaning that exposure does not begin for the entire sensor at the same time, but exposure and readout move from the top to the bottom of the sensor. The time dimension is shown from left to right, with which rows are reading out indicated on the vertical axis. The timescale of the rolling behaviour is the camera's Frame Time, typically around 20ms.*

Alternatively, **global shutter**, which reads and resets all detector pixels **simultaneously**, is challenging to engineer for back-illuminated CMOS sensors. For global shutter devices, to end an exposure, photoelectrons need to be **moved immediately into a storage area**. This storage area is typically **light-sensitive**, meaning that artifacts can arise from **unwanted photons** interacting with it.

The storage area can be **hidden** under sensor components for **front-illuminated CMOS sensors**; however, this is **more challenging** with back-illuminated technology. Advanced back-illuminated CMOS technology, like that of **LACera technology**, **redesigns the storage area** to achieve true global shutter operation **without artifacts**. Find out more about this process in our article: **Achieving a True Global Shutter with Large Format, Back-Illuminated CMOS** [7].

Large Field of View

Ground-based, high-speed astronomical observations require cameras with **high frame rates, fast read-out, and low read noise**. Although EMCCDs are traditionally used, they are **severely limited** when detecting a signal **greater than single-photon** due to the **excess noise** generated within the multiplication step.

Previously, CMOS detectors were **disregarded** for high-speed observations. Although they had **fast frame rates** and **low frame times**, they had considerably **higher read noise** and **lower QE** than EMCCDs. Advancements in CMOS technology have now allowed for **back-illuminated CMOS detectors**, such as the COSMOS camera, to provide **equivalent read noise and QE** to EMCCDs **without the sensitivity limitation**. The COSMOS incorporates a **large format sensor** which allows more of the sky to be sampled, something which is advantageous in **high-speed applications** such as space debris tracking.

Summary

Although CCD and EMCCD technologies have their advantages within ground based astronomical imaging, back-illuminated CMOS camera technology **matches their specifications while overcoming their limitations** on speed, duty cycle and noise performance.

CMOS designs feature a combination of **high QE, high dynamic range, short readout times** and **low noise** making them a competitive alternative for a wide range of astronomy applications. If you would like to find out more about our **future CMOS capabilities within astronomy**, download our webinar **Enabling the Next Generation of Astronomy**.

References

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