# Advanced Back-Illuminated CMOS Provides an Alternative to EMCCDs for Dynamic, Faint Astronomy

## Overview

Ground-based optical astronomy investigates various objects in space, from galaxies to exoplanets, via visible light. Some of these objects are **dynamic** and move at high speed through the sky. Traditionally, observation of these dynamic objects and events has been **limited to EMCCD cameras** due to their **fast frame rates** and high sensitivity. However, EMCCD cameras are **limited by excess noise** factor when the signal is greater than a few photons.

The most recent **advancements in CMOS imaging technology** deliver **low read noise** and **high quantum efficiency** within the visible range, increasing their detection capability for ground-based optical astronomy. CMOS cameras, like EMCCDs, also have **fast frame rates** but are **not limited by excess noise factor**. Therefore, state-of-the-art CMOS cameras are now the ideal choice for observing dynamic events in space.

## Introduction

Ground-based optical astronomy is essential for many astronomical investigations. Most objects in space can be observed via **visible light (380-700 nm)**, to study, for example, supernovae remnants or how stars develop [1]. Some objects and events move in space at **high speeds**, such as near-Earth objects, requiring a **fast camera** to capture any changes [2].

One of the limitations of ground-based astronomy is image deformation caused by **atmospheric turbulence**. Techniques such as adaptive optics and lucky imaging have been developed to **counteract** the effect of the atmosphere. Lucky imaging is a technique which acquires **multiple images very quickly** so that turbulence motion is "**frozen**." Sharp images can then be collated during post-processing to **improve the overall resolution** of the image.

Adaptive optics, another technique, uses **wavefront sensing** to counteract the effects of atmospheric turbulence. A traditional camera can be transformed into a wavefront sensor by the **addition of lenslets**. These lenslets can either be located **outside of the camera** or **incorporated into the camera** so that they are close to the sensor. The lenslets measure **distortions in the wavefront**, allowing software to **feed corrections** back to the telescope to counteract atmospheric distortions. Figure 1 shows a schematic of how an adaptive optics system operates.

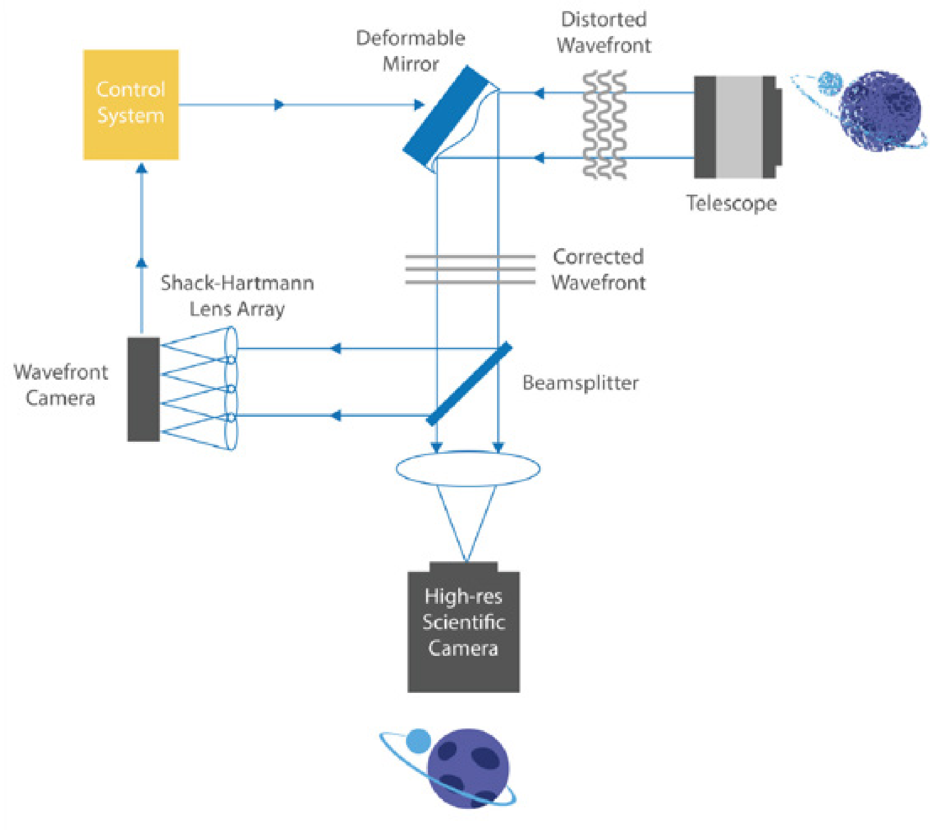


***Figure 1:*** *Schematic of an adaptive optics system in which a distorted wavefront is measured by a wavefront camera, which feeds the level of distortion into a control system. This control system counteracts the distortion via a deformable mirror which corrects the wavefront to produce a diffraction limited image.*

Cameras employing wavefront sensors must have **sufficient frame rate** to react to the **rapidly changing atmosphere**, especially when it is unstable. These cameras also require low read noise alongside **high sensitivity** so that faint reference stars can be used for atmospheric correction. It is not always guaranteed that a bright reference star is **located near the scientific object of interest**, in which case a faint reference star within close proximity must be used. Therefore, wavefront cameras with higher sensitivity and lower noise are **advantageous** to capture these **fainter** reference stars [3].

Although the majority of visible ground-based astronomy utilizes silicon-based **CCDs**, these sensors are **limited** when it comes to **high-speed** astronomy observations. Standard **CCD detectors** have **relatively high read noise** and read out at a slow rate, preventing fainter, dynamic objects from being investigated.

Electron multiplying CCDs (**EMCCDs**), are a variant of silicon-based CCDs that are able to **overcome** these limitations through the use of an **extended serial register** called the **electron multiplier register (EM register)**, on the sensor [4,5]. The EM register uses **electron multiplication** to elevate electron signal greatly **above** the read noise floor. This allows for **higher sensitivity** during low-light acquisition.

When dynamic objects are observed they require **faster acquisition** in order to capture any changes, however this results in a **lower exposure time** and therefore **minimal photon detection**. By using an EM register, EMCCDs are able to **amplify** any detected photoelectrons before they are read out, making the read noise **effectively negligible** and allowing for the observation of dynamic, faint objects.

In this EM register, photoelectrons are **accelerated** via an increased voltage along each stage of the register, with secondary electrons generated via the **impact-ionization process** (Figure 2). The quantity of secondary electrons can be controlled by **altering the clock voltages** within the EM register. As this amplification of electrons elevates the signal **far above read noise**, the read noise can be very high at the point of measurement. This means that the readout process can be driven at a **much faster rate** than on a regular CCD, achieving higher frame rates.

EMCCD sensors also have **frame-transfer architecture** in which the sensor is divided into an **imaging capture area** which captures any incident photons, and the **storage area** onto which any detected photons are rapidly transferred after acquisition (Figure 2). While the storage area is being read out by the system electronics, the image array can be **exposed to light again** allowing for continuous operation at high frame rates. This allows EMCCDs to operate at a **much faster rate** than 'Full Frame' CCDs which require a mechanical shutter to close during readout.

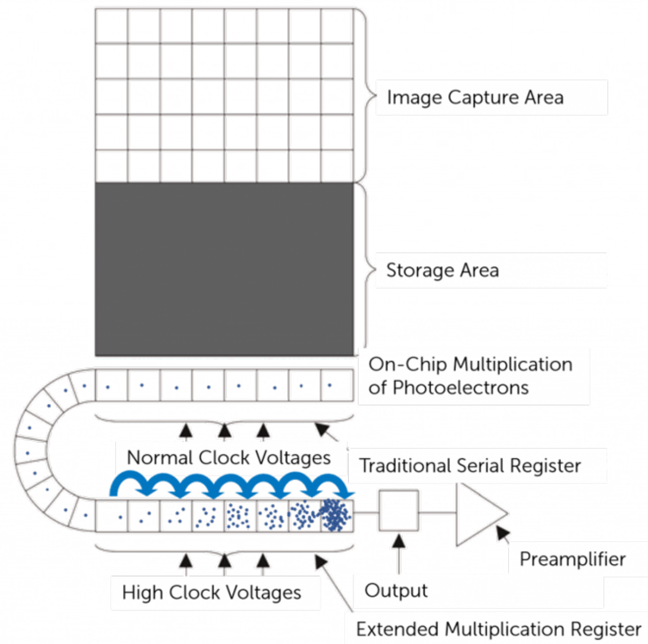


***Figure 2:*** *Schematic showing the architecture of an EMCCD sensor, with an image capture area and storage area for short frame times and an EM register with on-chip multiplication.*

The combination of both **negligible read noise** and **fast readout** makes an EMCCD camera a good option for imaging faint, high-speed objects. However, while EMCCDs are **an improvement** on CCD technology for dynamic observations, they come with their own **limitations**.

### EMCCD Limitations

EMCCDs are ideal for amplifying single-photon signal due to the EM register; however, this advantage breaks down when the signal is **greater than a few** photons.

Although EMCCDs are able to amplify the signal above the read noise, they are limited by the **excess noise factor**. When photoelectrons enter the EM register there is a **small chance** that a photoelectron will be multiplied at each step. As an EM register is comprised of **numerous multiplication steps**, the number of photoelectrons **exponentially** increases. This process is **stochastic in nature**, meaning that small variations in number of photoelectrons multiplied in each step will result in a **wide spread** of multiplied photoelectrons at the end of the EM register. This spread is described as the **excess noise factor**, and for any signal above a single photoelectron, the **larger the signal** that enters the EM register, the **larger the excess noise**. Therefore, even with low read noise, multiplication can contribute **more total noise** rather than less at typical signal levels [6,7].

EMCCDs are also limited by **EM gain decay**, whereby with use, the ability of the EM register to multiply signals **diminishes**. Although not fully understood, it is thought that **charge builds up** in the silicon sensor **reducing the effect** of the EM gain. The EM gain will decay at a **faster rate** both if a **high EM gain** is used and if there is a **high signal intensity**. This means that the EM gain will **not remain consistent** over long periods of time, limiting quantitative analysis. This **reduces the lifespan** of an EMCCD, requiring **regular calibration** and **limitation of the EM gain** to preserve camera longevity [6].

To find out more about EMCCD sensor technology, please refer to **EMCCDs: The Basics**.

**CMOS for High-Speed Observation**

Complementary metal-oxide-semiconductor, (**CMOS**), sensors are also silicon-based sensors that are able to capture photons within the visible range. Although CMOS sensors have frame times **shorter than EMCCDs** despite higher pixel counts, and are therefore able to **more rapidly acquire data**, the traditional **front-illuminated** sensors were not considered for high-speed astronomical observation due to **high read noise** and **low quantum efficiency**.

Advancements in CMOS technology have **improved the QE** and **lowered the read noise** to match that of a typical EMCCD, **without** the presence of the **excess noise factor**. For example, the Teledyne Princeton Instruments COSMOS™ camera offers **0.7 e- read noise** due to advanced electronics, with **back-illuminated** technology providing a **peak QE of >90%**, as shown in Figure 3.

Front-illuminated CMOS technology illuminates the sensor with incident light **from the front**, meaning that the **miniaturized electronics** on each sensor **interact** with any incoming light first. This **reduces the area** of the pixel which is sensitive to light. To correct for this, front-illuminated CMOS sensors use **microlenses** to improve the light-collection efficiency of each pixel, however these microlenses **limit the sensor's peak quantum efficiency**, with the quantum efficiency **reducing** with the incidence angle of incoming light (see Figure 3).

In comparison, **back-illuminated CMOS sensors** illuminate the sensor from behind, meaning that the incident light interacts with the **light-sensitive silicon first**. This allows the **entire pixel** to be light-sensitive and removes the need for microlenses. This change in illumination technology allows for an **increase in peak quantum efficiency** [8].

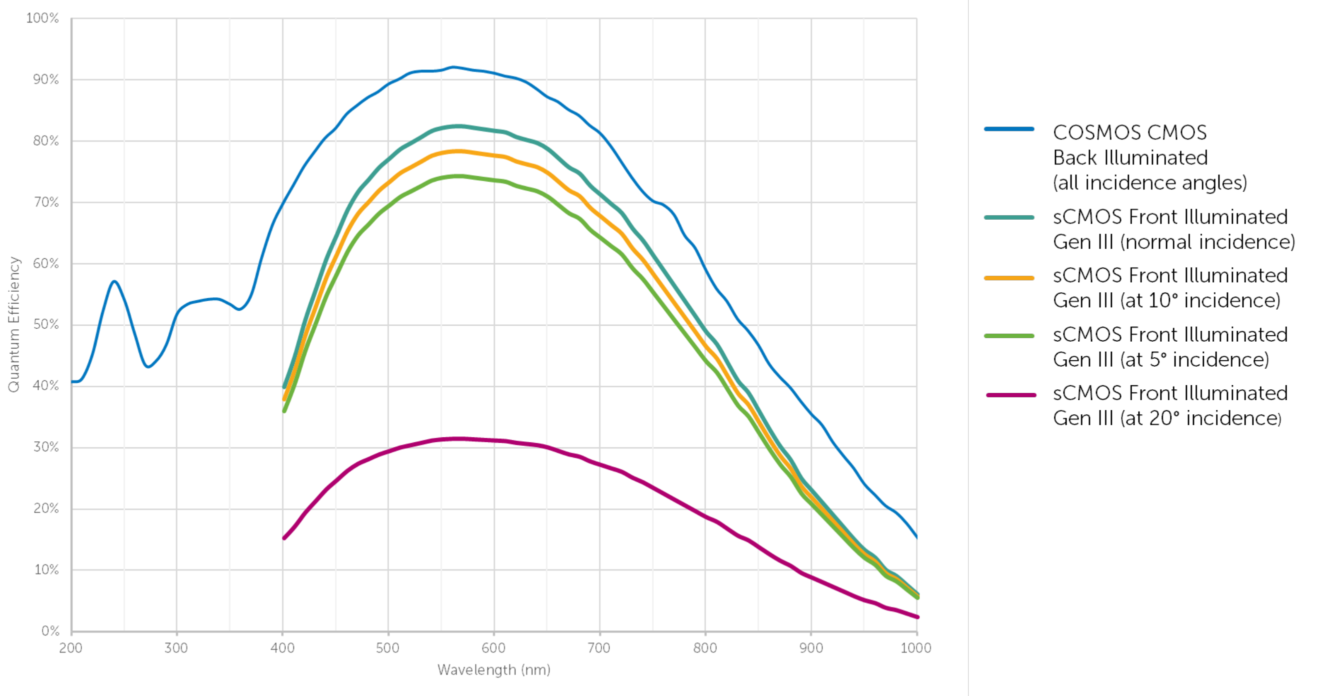


***Figure 3:*** *Quantum efficiency (QE) of the COSMOS with respect to wavelength, showing 90% peak quantum efficiency, and a typical front illuminated sCMOS Gen III sensor at normal incidence, 10° incidence, 5° incidence and 20° incidence showing how QE drastically decreases in front illuminated with angle of incidence.*

Not only does advanced CMOS technology, such as that of the COSMOS camera, match the **essential parameters** required from EMCCDs when detecting high-speed objects, it **does not suffer** the same **sensitivity limitations** of the EMCCD with regards to **excess noise** factor. CMOS sensors don't have an EM register, meaning that they do not suffer from excess noise due to the stochastic nature of the multiplication steps. Removing this **limitation of EMCCDs** allows low-noise CMOS sensors to **far exceed EMCCD sensitivity** when greater than a few photons are detected. Minimizing read noise is still of the utmost importance, but the **0.7 e- read noise** of the COSMOS allows **low-light signal** to be detected with a high signal-to-noise ratio.

Due to the **architecture** of CMOS sensors, data can be processed **much faster** than both EMCCDs and CCDs. CMOS sensors have a **miniaturized capacitor and amplifier** on each individual pixel, allowing the CMOS sensor to **work in parallel**, with each converted photoelectron being **immediately converted** into a voltage while **still on the pixel**.

CMOS sensors also have an analogue-to-digital-converter (ADC) for **each column**, rather than a single ADC as with EMCCD sensors. ADCs **convert** the voltage of electrons into a **digital signal** which is used to display data. Having an **ADC per column** means that each ADC has **less data to process**, therefore the whole sensor is able to process all of the acquired data at a much **faster rate**. Figure 4 shows a typical schematic of CMOS readout architecture in comparison to that of an EMCCD. This allows CMOS detectors to run at **very high frame rates** – ideal for dynamic imaging.

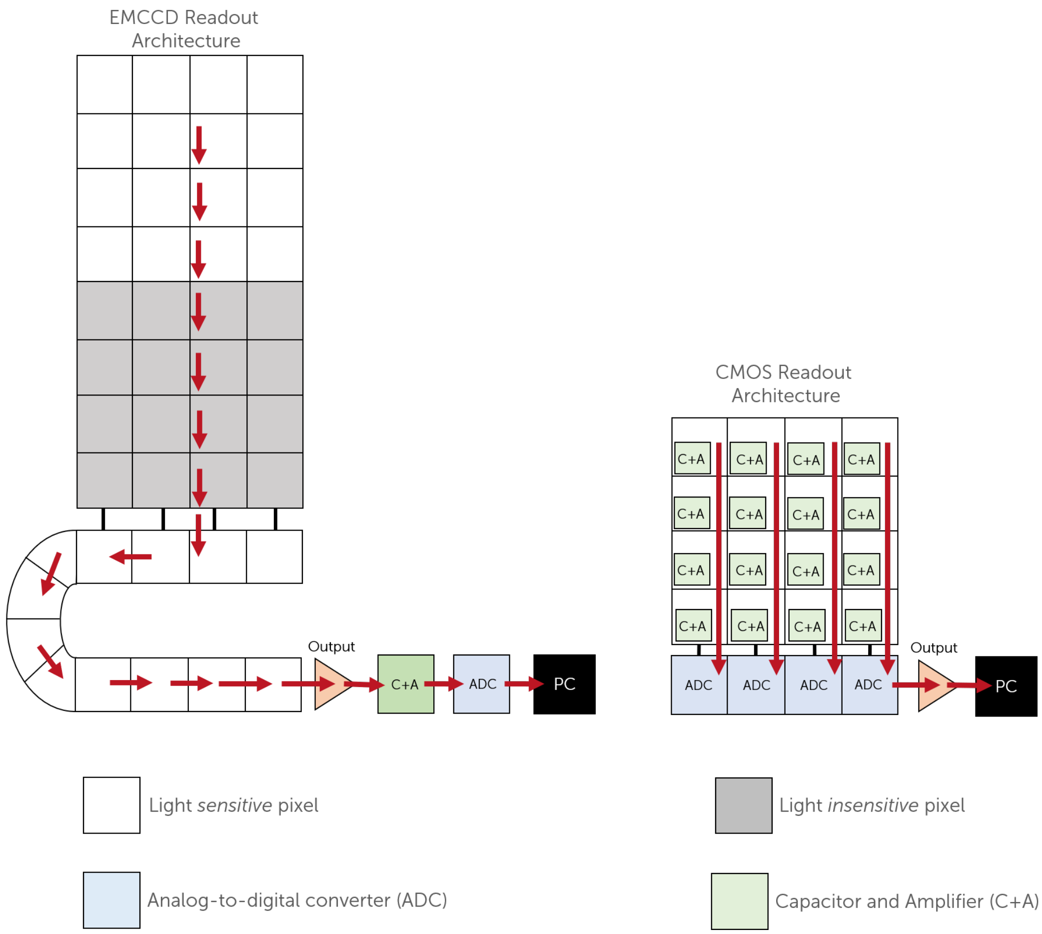


***Figure 4:*** *Sensor readout architecture of a typical EMCCD and a typical CMOS. The individual electronics on each pixel, and the ADC for each column greatly increases the speed at which acquired data can be processed.*

High-speed, ground-based space science applications often require a **large field of view** in order to sample large areas of the sky. For example, space debris, in particular **low-Earth orbit debris**, moves **quickly** across a field of view (in the order of seconds). These objects can be tracked either by leap-frog tracking, in which the object **moves across the field of view** creating an object arc, or by continuous tracking, in which the **object is point like** and background stars appear as arcs. Both of these tracking methods rely on the telescope **accurately moving** either with the object (as with continuous tracking) or predicting the position of the object once it passes the field of view (as with leap-frog tracking) [9].

A camera with a **larger field** of view can be advantageous for both methods. For example, leapfrog tracking a larger camera FOV results in the object taking **longer to traverse** across the sensor. This means that **fewer telescope movements** will be required for imaging the **full object trajectory**, increasing the accuracy of tracking.

For continuous tracking, a larger camera FOV will result in **more background stars** for reference, aiding in **predictions** of object parameters. The COSMOS is one of the **largest format CMOS sensors**, with sensor sizes of **6k x 6k and above** (see Figure 5). In combination with **lower read noise** and **high QE**, the COSMOS allows for precise tracking of **fainter**, and **smaller**, objects such as low Earth orbital space debris [9].

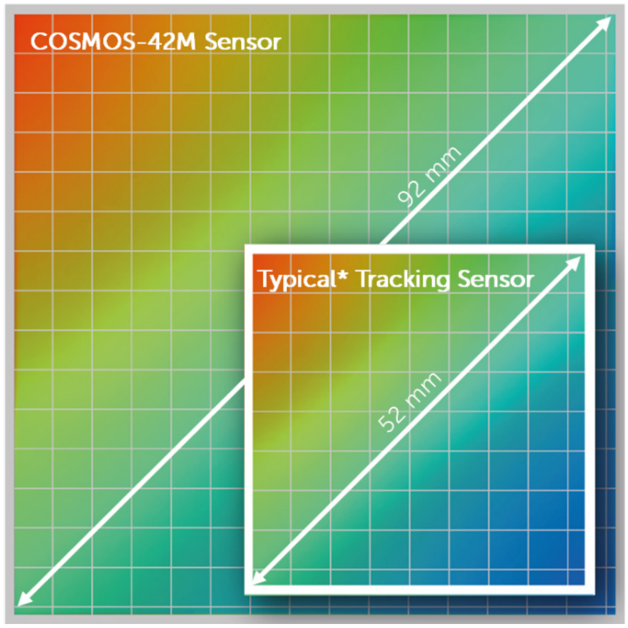


***Figure 5:*** *Graphical representation of the physical size of the COSMOS-42M (6496 x 6496) sensor verses a typical tracking sensor. *Typical sensor based on a 9-micron pixel, 4096 x 4096 CCD sensor.*

## Summary

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.

## References


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