Using EMCCD's to improve the photometric precision of ground-based astronomical observations

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Abstract. We report on a novel data reduction technique that uses the fast, low-noise operation of EMCCD’s to provide improvements in ground-based astronomical photometry of up to 48% by removing much of the incoherent wavelength-dependent absorption of the atmosphere. The technique has significant application potential in multicolour photometry where inter-colour short-timescale variability are particularly prone to atmospheric effects. We comment on a two-colour photometer we have developed to take advantage of the technique.

1. The importance of precision photometry in astronomy

Variability is a defining characteristic of many astrophysical phenomena, and timescales can range from milliseconds to years. Measuring variability enables competing theoretical models to be assessed and compared. In some cases the variability is periodic in nature; in others it is stochastic. Variability which is stochastic in nature is the most difficult to reliably quantify and characterize because the observer has only one chance to measure it. The data cannot be epoch-folded nor analysed using periodicity techniques. Having precise, reliable photometry is most crucial in such circumstances. In other instances, such as exoplanet transit-hunting, the variability amplitude gets smaller as the transiting planet gets smaller. Since the holy grail of exoplanet hunting is to find an earth-sized planet, the motivation to reach ever-increasing photometric precision is obvious.

In optical astronomy flux from a source is now typically measured using a Charge Coupled Device (CCD) which provides both intensity and spatial information. A well documented advantage of using CCDs for photometry is that, along with the target, the flux from a number of reference sources can be measured simultaneously which allows for the technique of differential photometry to be performed. Differential photometry measures the difference between the target source and a number of nearby reference sources (usually stars) to provide a potentially high precision differential measurement. Inherent in this technique is the assumption that objects that are spatially close to one another are similarly affected by variations in the atmosphere. The approach has long been recognized as the most effective technique for achieving the highest precision photometry [1],[2].
2. EMCCD’s as the recording mechanism in photometry

Characterising low-amplitude variability which occurs on timescales of minutes or less necessitates the use of integrations which are substantially shorter than that. Electron Multiplying CCD’s (EMCCDs) have the potential to provide such a capability because their onboard gain effectively reduces the otherwise catastrophic readnoise that accompanies high-speed readouts in conventional CCD’s. EMCCD’s offer the opportunity to increase both the S/N in individual frames and the frame rates themselves.

2.1. Photometric Precision of EMCCD’s

We performed laboratory tests to determine the limiting photometric precision that is achievable with EMCCDs to ascertain whether they are suitable detectors for our work. Tests were carried out on Andor Technology’s iXon DV887-BI (512x512 pixels) and DU88E (1kx1k pixels). The tests employed an artificial starfield and consisted of taking approximately 100,000 images of 0.1s duration. We rebinned the data into successively longer time bins, equivalent to longer integrations per data-bin, and calculated the associated photometric error using differential photometry. The corresponding graphs (an example of which is shown in figure 1) indicate the limiting precision achievable and are consistent with an rms value of ~0.04%.

![Fig 1. Scatter plots showing the instrument limiting precision of 0.4mmag (0.04%).](image)

2.1.1. Gain, linearity and CIC.

While this limiting photometric precision is acceptable for our work, it is worth noting that the use of EMCCD’s is not as straightforward as that of conventional CCD’s. We performed gain measurements on the DV887-BI using the technique described by Newberry [3] and found the gain to range from 1 to 2600 which requires careful choosing of the exposure/gain combination so as not to enter the non-linear region of the device. Non-linearity starts occurring at about 85% of full-well capacity. Using a technique described by Tubbs [4] we also measured the clock induced charge (CIC), which is actually the dominant source of instrument noise in EMCCD’s. The result of 0.4% noise per frame suggests that CIC is not generally problematical for our application.
3. Using EMCCD’s to remove atmospheric extinction – Selective Photometry

While the photometric precision achievable is ultimately limited by photon statistics, the observed precision from real data often deviates largely from laboratory experiments [5]. This suggests that factors other than the imaging instrumentation are responsible for limiting the photometric precision observed.

Many factors are known to effect photometry [1], however, short-timescale turbulent atmospheric conditions that occur on timescales of 0.01 – 0.1s are considered to be a dominant factor that are rarely, if ever, corrected for. Pockets of heterogeneous air temperatures combine to distort incoming light (variously referred to as scintillation and seeing). The effects are incoherent, wavelength-dependent, and cannot be completely corrected for by differential techniques. Indeed the photometric limitations imposed by atmospheric effects are a large driver in the development of spaceborne telescopes such as the Kepler planet-search spacecraft [6]. The cost associated with such systems, however, limits the accessibility to many leaving terrestrial based observations the only option.

SelPhot (Selective Photometry) is a new technique which we have developed that utilises the low-noise, high frame rates achievable with EMCCD technology to improve the photometric precision. The SelPhot technique is an automated analysis routine which is deployed on reduced (flux extracted) photometric data. Using stars as reference targets, the SelPhot technique searches for segments within the data where the effect of the atmosphere on the photometric data is ‘most similar’. The underlying principal of the technique is that for short time intervals, differentially, the atmosphere has little effect on photometric measurements. Finding these intervals through an informed selection process allows the effect of the varying atmosphere to be removed.

An example of the application of the technique to real astronomical data is presented in Fig 2. The data was acquired during an engineering observing session at Calar Alto Observatory (altitude of 2168m) in February 2003 using an Andor iXon back-illuminated CCD97 (512 x 512 pixels) under what would be classed as good/excellent photometric conditions. Fig 2a shows the results of the standard analysis technique and the SelPhot analysis technique. It is evident that the error on each data point is significant reduced (average 32% reduction in error) using the latter. Fig 2b highlights the effect of the technique through plotting only the errors of the original technique and SelPhot technique. The optimised selection process is seen to have the effect of both homogenising and reducing the errors. Importantly, some of the suggestive short-timescale structure in the original data has been removed, suggesting its origin is extrinsic to the source.

Analysis of each reference star after the SelPhot technique has been applied shows an average reduction in rms error of 48% confirming that the technique reduces scatter in the data. A detailed discussion of the SelPhot technique is reported in [7].
Fig 2a. Photometric light curve from the active galaxy S5 0716+714. The upper plot shows the light curve obtained using the standard approach and all the data. The lower plot shows the light curve obtained when the data has been processed using the SelPhot technique. The post-SelPhot data shows a significant reduction in error across the entire light curve validating the technique.

Fig 2b. Error-only plot. This figure shows a direct comparison between the original error and the error following the SelPhot technique.

4. Simultaneous Multi-Colour Photometry
The ability to discriminate between competing models of time-variable phenomena is significantly increased if photometry is performed in more than one colour simultaneously. The major problem with two-channel photometers to date has been the wavelength dependent incoherent effects of the atmosphere which can introduce apparent variability between colours that are not intrinsic to the source. Using the SelPhot technique we are able to significantly reduce such effects as long as the photometer records data sufficiently fast. TOΦCAM (Two Channel Optical Photometric Imaging Camera, pronounced toffee-cam) is a Science Foundation Ireland funded instrument that we have developed at Blackrock Castle Observatory to do just that. It utilizes two Andor Technologies iXon+ DU88E 1K EMCCDs which sample two colour bands simultaneously and is briefly described here.

4.1 Opto-Mechanical Layout of TOΦCAM
The system has been designed in a modular fashion to allow the instrument to be used on telescopes of different types and focal lengths whilst maintaining optimal pixel sampling. The front section of the instrument consists of a 3” Crayford focuser which is used for primary
focusing of the instrument and is independent of the telescope focusing mechanism. The focuser can also house focal reducers, tele-compressors or field flatteners to optimise the system on different telescopes.

![Graphical representation of the TOΦCAM system](image)

**Fig 3. Graphical representation of the TOΦCAM system**

The main body of the instrument houses a changeable beam splitter. This beam splitter can be chosen to suit different applications. For example, for non-polarising sources dichroic beam splitters can be used to split the incident light into two colour paths. Alternatively, for sources which show variations in polarisation angle, an optically inactive dielectric beam splitter can be used. This negates the effects on the photometry of the optically active dichroics.

### 4.2 Camera Control and Data Acquisition

To support the short-timescale integrations necessary to apply the *SelPhot* technique, TOΦCAM has been designed to be capable of recording up to 1TB of data per night. Our data acquisition and control system can simultaneously acquire, timestamp and stream data to disk storage, whilst running both EMCCD’s at their maximum frame full rates.

The system has been designed to be highly fault tolerant through buffering of data, teamed network interfaces and redundant arrays of disks. The data acquisition system has been successfully tested and is capable of running for extended periods (days) of time at data rates of up to 64MB per second.
Fig 4: Architecture of TOΦCAM.

Fig 4 shows the general layout of the data acquisition system developed for TOΦCAM. Both cameras are controlled by a single PC running a customised version of Windows XP. Each science frame is time stamped via GPS to millisecond accuracy and then buffered in 4GB of onboard RAM. The data is then asynchronously streamed to a 4 Disk RAID 0 array via ISCSI to the Storage Area Network. The SAN is attached via a teamed Gigabit Ethernet connection. Once the acquisition is completed the data is moved to a more fault tolerant RAID 5 array on the same SAN where it is stored before data reduction.

TOΦCAM is currently undergoing observational tests at Blackrock Castle Observatory, Cork, Ireland.

5 Conclusion
The use of low-noise EMCCD’s operated with short integrations allows much of the wavelength-dependent atmospheric extinction to be removed, improving the quality of single- and multi-colour ground-based photometry by substantial amounts. The tradeoff is the generation of large quantities of data. Future possibilities include improving the photometry further by employing faster imagers, approaching precisions heretofore requiring spaceborne instrumentation.

References
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