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Photometric reduction of data from electron-multiplying charge coupled devices (EMCCDs)

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ABSTRACT

Context. The EMCCD is a type of CCD that delivers fast readout times and negligible readout noise, making it an ideal detector for high frame rate applications which improve resolution, like lucky imaging or shift-and-add. This improvement in resolution can potentially improve the photometry of faint stars in extremely crowded fields significantly by alleviating crowding. Alleviating crowding is a prerequisite for observing gravitational microlensing in main sequence stars towards the galactic bulge. However, the photometric stability of this device has not been assessed. The EMCCD has sources of noise not found in conventional CCDs, and new methods for handling these must be developed.

Aims. We aim to investigate how the normal photometric reduction steps from conventional CCDs should be adjusted to be applicable to EMCCD data. One complication is that a bias frame cannot be obtained conventionally, as the output from an EMCCD is not normally distributed. Also, the readout process generates spurious charges in any CCD, but in EMCCD data, these charges are visible as opposed to the conventional CCD. Furthermore we aim to eliminate the photon waste associated with lucky imaging by combining this method with shift-and-add.

Methods. A simple probabilistic model for the dark output of an EMCCD is developed. Fitting this model with the expectation-maximization algorithm allows us to estimate the bias, readout noise, amplification, and spurious charge rate per pixel and thus correct for these phenomena. To investigate the stability of the photometry, corrected frames of a crowded field are reduced with a point spread function (PSF) fitting photometry package, where a lucky image is used as a reference.

Results. We find that it is possible to develop an algorithm that elegantly reduces EMCCD data and produces stable photometry at the 1% level in an extremely crowded field.

Key words. instrumentation: detectors – techniques: high angular resolution – techniques: image processing – techniques: photometric – gravitational lensing: micro-

1. Introduction

There are a number of exciting areas of astrophysical research that could benefit from accurate, precise, high time- or angular-resolution photometry in crowded fields. For instance, the search for Earth-mass exoplanets in gravitational microlensing events calls for photometry with a precision of order 1–2% in the crowded stellar fields of Baade’s window (Jørgensen 2008).

As a detector for light in the optical and UV parts of the electromagnetic spectrum, the CCD is ubiquitous in astronomy. CCDs have a high quantum efficiency and low dark current when cooled appropriately. Under optimal conditions, the dominant source of noise in the CCD itself is the readout noise. With low-noise CCDs the readout noise can be as low as 2–3 electrons, using very slow readout speeds (∼5 × 10^4 pixel per second). With higher readout speeds, above ∼10^6 pixels per second, the readout noise increases to beyond ten electrons per readout.

By recording frames at a high frame rate, one can reduce the impact of atmospheric seeing (Fried 1978), using methods such as lucky imaging (LI) and shift-and-add. But even with the very lowest readout noise achieved with a traditional CCD, readout noise is a serious hindrance for high frame rate imaging of faint targets. One possible solution is the electron multiplying CCD (EMCCD), also known under the trade name L3CCD.

The CCD used in the SONG project (astro.phys.au.dk/SONG) is an EMCCD implemented in an Andor iXionSM+ 897 camera with 16 × 16 μm pixels; it is an electron multiplying frame transfer CCD. Compared to a conventional CCD, the serial register in an EMCCD has been extended. In the extended part of the register, the voltage used to shift the captured electrons from pixel to pixel is not in the normal 5 V range, but on the order of 40 V. Consequently the probability that an electron will knock another electron out of a bound state has been dramatically increased, in a process known as impact ionization. Such an event will effectively multiply the electron similarly to the process in an avalanche diode or a photomultiplier. The details of electron multiplication in this particular camera have been described in Harpsøe et al. (2012).

Due to the stochastic nature of the impact ionization events, the number of electrons in a cascade from one photo electron is...
not constant; that is, the gain of the electron multiplying regist-
er is essentially random, in a similar way to an avalanche diode
or the dynodes in a photomultiplier. This leads to a number of
complications, but allows EMCCDs to produce images at very
high readout speeds, even at very low light levels, without being
dominated by readout noise. This makes them ideally suited for
high frame rate applications. Because the analogy between the
photomultiplier and the EMCCD, much of the statistics devel-
oped for the photomultiplier can be reused when dealing with an
EMCCD. The possibility of doing high frame rate imaging, like
luck imaging, has been explored in numerous other articles and
theses; see for instance Mackay et al. (2004); Law et al. (2006).

While the groundbreaking improvements achieved in spatial
resolution by use of high frame rate techniques is thoroughly
described in the scientific literature, little work has been devoted
to the aspect of photometric capability, in terms of accuracy and
stability of EMCCDs and high frame rate imaging.

In the application of EMCCD cameras to follow-up observa-
tions of gravitational microlensing events in the search for ex-
oplanets, both spatial resolution and photometric accuracy is of
paramount importance for results. In the following we therefore
present our first results from analysis of the photometric qual-
ity of sequences of shifted and added EMCCD images of a very
crowded stellar field.

2. Determination of bias and spurious charge

The bias of a CCD is usually assumed to be composed of a fixed
bias pattern over the pixel coordinates and a bias DC level which
is common to all pixels. The DC level is usually some function of
time. With a conventional CCD camera, we may normally
assume that over a set of bias frames, corrected for bias DC level
drift, the ADU values for each individual pixel will be normally
distributed around the bias. We can therefore apply the mean of
a set of bias frames as a good estimate of the true bias. This is not
the case with our EMCCD camera because of the EM cascade
amplifier. Also, in a conventional CCD the bias DC level will
usually only be weakly variable, because the temperature of the
cooled CCD and on-chip readout amplifier is under servo control
and therefore stable. Due to the readout speed and comparable
large current through the electron multiplication (EM) cascade
stages, there is a significant on-chip heat dissipation. One may
therefore expect to see an appreciable bias DC level drift in an
EMCCD camera, once the readout is initiated.

2.1. Exponentially distributed output from the EM amplifier

Figure 1 shows the histogram of 2000 dark frames from our
high speed EMCCD camera, corrected for bias as described be-
low. Here we see a classical Gaussian peak, corresponding to
the well-known classical readout noise. Furthermore we see an
exponentially decreasing tail to the right. This tail arises from
the EM cascade stages. Spurious electrons will arise randomly
in the image array, even without exposure to light, as an effect of
the parallel shifts and serial shifts in the EM register. They do
also occur in a conventional CCD, but here they are undetectable
because of the readout noise. But in an EMCCD spurious elec-
trons will be cascade-amplified in the EM stage, giving rise to
the exponential tail. Because of this peculiar distribution, the tra-
ditional mean value is not useful for determining the bias, which
is the mode of the distribution in Fig. 1. Because the distribu-
tion is asymmetric, the mean is not an accurate estimator of the
mode. Also, bias is not an integer, which implies that we cannot
simply select the most common value in a histogram as the bias.

![Histogram of 2000 images](image)

**Fig. 1.** The histogram of 2000 dark images on a log scale. The exponen-
tial tail from the spurious charge can easily be seen. For this particular
example the sum of the number of counts of the blue columns is approxi-
ately 4% of the sum of the red columns. The scale length of the tail is
related to the electron multiplication gain, in accordance with Eq. (3).

But by appropriate truncation we can make the distribution ap-
proximately symmetric, hence we can use a truncated mean as an
estimator of the mode.

The truncated mean of a set of numbers is defined as the
ordinary mean of the set where some percentage of the high-
est and/or lowest values has been discarded. Approximately
5–10%, depending on the gain and timing settings, of the pix-
els are affected by spurious charge and the affected pixels always
have higher counts than the true bias. We will therefore for our
purposes define the truncated mean as the mean of a set in which
the 5% highest values have been discarded, as this will exclude
all amplified spurious electrons, assuming the rate of spurious
electrons is constant. Furthermore, a significant benefit of this
method is that it is computationally fast.

2.2. Bias DC level drift

The CCD used in this experiment consists of an image area
and two overscan regions, so that the first 20 pixels and the last 6 pix-
els of the 538 pixels in each row on the CCD are overscan re-
geons, where no light reaches the CCD. In Fig. 2, the truncated
mean of the overscan and the image area in a time series of
10000 images is shown. It can be seen that there is consider-
able bias DC level drift over the course of the series for which
one ought to correct. It can also be seen that the truncated mean
of the overscan and image area varies in almost perfect uni-
son. The truncated mean is needed as the overscan regions also
have cascade amplified spurious electrons. The correlation co-
efficient between the two curves is 0.9995. Altogether, the trun-
cated mean of the overscan appears to be a good estimator for
the bias DC level of the image area, albeit with a constant offset
of approximately 2.75.

2.3. Fitting fixed pattern bias and spurious charge rates

In a CCD camera there is usually some fixed bias pattern in the
image; this is also the case for this camera. Traditionally one
takes the mean over several bias frames to obtain a good esti-
mate of this bias pattern. Because of the bias drift and the spuri-
ous charges in the particular case, things have to be done a little
differently. In long series, one would also like to be able to cor-
rect for the systematic background from the spurious charges.
where there is at most one spurious electron per pixel per readout in a μ where the truncated mean of the overscan region. Red is the difference between the two curves. An absolute variation in bias of about ±3 ADU is seen over time (image index) for both the image area and the overscan region, whereas the variance of difference between them (red curve) is only about ±0.05 ADU.

We therefore assume that the instantaneous bias $b_{\text{inst}}$ in the images can be written as

$$b_{\text{inst}}(x, y, t) = b(x, y) + b_o(t),$$

That is, the instantaneous bias is composed of a fixed bias pattern $b$ that depends on the image coordinates, and a DC level $b_o$ that depends on time. For a set of bias frames $\{b_{\text{inst}}(x, y, t_i)\}$, a new set of bias frames is generated, where the DC bias level is normalised to zero.

$$b_k(x, y, t_i) = [b_{\text{inst}}(x, y, t_i) - \mu(5\%)(b_{\text{inst}}(x, y, t_i))]_{(x,y)}$$

where $\mu(5\%)$ is the 5\% truncated mean from above, over the pixel coordinates $x$ and $y$. To estimate $b$ it will be assumed that there is at most one spurious electron per pixel per readout in a series of bias frames. It is also assumed that the size of the electron cascade arising from one electron through the EM multiplier $X$ is given by an exponential distribution:

$$P(X = x) = ye^{-\gamma x}H(x)$$

where $H$ is a Heaviside function and $y$ is the EM amplification. In the case that no electron entered the EM multiplier we assume a constant bias reading; that is, the probability distribution of a bias $B$ is given by

$$P(B = x) = \delta(x).$$

An EMCCD still has conventional additive Gaussian readout noise, but this noise is added after the EM multipying. We will define $R$ as a random variable representing Gaussian readout noise around the bias value $b$, the numerical value of $b$ being a property of the readout electronics. That is,

$$P(R = x) = N(x - b, \sigma)$$

where $N$ is the normal distribution probability density function (PDF):

$$N(x, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}}.$$
It can be seen that there is a clear structure in the spurious charge probability distribution. This pattern is a logical consequence of the way this CCD is clocked. As the clocking pulse travels over the array of pixels, the rate of spurious electrons, which carry information about the gain, is higher at the edges. The rate of spurious electrons is due to less variance in the gain determination at the edges, as the rate of spurious electrons, which carry information about the gain, is higher at the edges.

For a given raw science image \( c(x,y,t) \), composed of the real image \( c_b \) and the bias \( b \) we can then calculate the DC level as

\[
b_b(t) = \mu[5\%](c(x,y,t) - b(x,y))
\]

where \( x_o \) and \( y_o \) is the pixel coordinates of the overscan region, because the DC level \( b_b(t) \) is only a function of time, not \( x \) and \( y \). Note that the offset between the overscan region and the image area has been absorbed into \( b \). Finally we can correct the image as

\[
c_b(x,y,t) = c(x,y,t) - [b(x,y) + b_b(t)] - (1/\gamma)s(x,y)
\]

\( s = 1 - p \) is the probability of a spurious charge and \( 1/\gamma \) is the average EM gain. Strictly the correction term \( s \) will only correct for background from parallel clock induced charge and not clock induced charge in the serial registers, but as the serial register is common to all pixels, this background contribution is not expected to be a function of the pixel coordinates and therefore not important to correct for.

As a check on the consistency of the procedure outlined above, the average of 10 000 bias frames is presented in Fig. 4. As it can be seen from the spurious charge map, the rate of spurious charges per pixel per readout changes systematically over the image from about 2\% to about 8\%. Furthermore, with the applied settings on the camera we found the average EM gain \((1/\gamma)\) to be 20.9 ADU/e\(^-\). Over many frames this will average to a systematic background with a peak to valley range of approximately \((8\%–2\%)(1/\gamma) = 1.3\) ADU per frame. Reducing the frames as outlined above, by subtracting the spurious charge rate map suitably scaled as in Eq. (16), should remove this background. As there is no structure in the \( y \) direction of the spurious charge rate map, this map was smoothed by averaging in the \( y \) direction. The average of these images is shown in Fig. 4: the procedure seems consistent, the image is flat, and the mean value is close to zero. The variance of the image area is approximately 0.06 ADU. Over 10 000 frames, the expected variance given Eq. (19) would be approximately 0.004 ADU. This suggests that the noise is dominated by systematics. In fact, the noise in sums of more than about 1000 empty frames seems to be dominated by systematic noise.

Flat fielding with EMCCDs is foreseen to be analogous to conventional CCDs; it corrects for differences in sensitivity between pixels and dust in the optical train. These effects affect an EMCCD in the same way as a conventional CCD.

2.4. Noise scaling

The standard noise model for conventional CCDs does not apply to EMCCDs. In most cases the readout noise can be ignored, but the cascade amplifier effectively doubles the photon noise, which is equivalent to cutting the quantum efficiency in half, if photon counting is not performed.
Specifically, if the cascade amplifier is viewed as a linear amplifier, the signal is the mean value of a mixture distribution like Eq. (9), which is simply the weighted average, i.e. the mean value of Eq. (9) is
\[ E(Z) = b + \frac{1-p}{\gamma} \] (17)

in general the \( j \)th central moment of a mixture distribution is given by (Frühwirth-Schnatter 2006, p. 11):

\[ E((Z - \mu)^j) = \sum_{i=0}^{j} \binom{j}{k} \mu_i^{j-k} p_i E(X_i - \mu_i)^k \] (18)

where \( \mu \) is the mean value of the mixture distribution and the \( \mu_i \) are the mean values of the component distributions. Knowing the variance and mean of the exponential and normal distributions, one can then calculate the variance or second central moment of Eq. (9). Assuming a bias of \( b = 0 \), the expression simplifies to

\[ E((Z - E(Z))^2) = p\sigma^2 + \frac{1-p}{\gamma^2} \] (19)

In deriving Eq. (9) we have explicitly assumed that at most one electron gets cascade amplified. In the more general case of higher fluxes, one cannot ignore coincident photoelectrons. According to Harpsøe et al. (2012), the distribution of the output can be generalized to

\[ P(Z = n) = p_0 N(n, \sigma) + \sum_{i=1}^{\infty} p_i \frac{\gamma n^{i-1} e^{-\gamma n}}{(i-1)!} \] (20)

assuming \( b = 0 \). The rightmost term is the PDF of the Erlang distribution and the \( p_i \)'s are given by the Poisson PMF

\[ p_i = \frac{\beta e^{-\beta}}{i!}. \] (21)

One sees that the approximation in Eq. (9) is adequate when \( \beta \) is small so that \( p_i \approx 0 \) for \( i > 1 \), because the Erlang distribution for \( i = 1 \) is the exponential distribution. Formally the factor \( 1-p \) in Eq. (9) refers to the spurious charge rate, but spurious charges will be Poisson distributed, hence they can be viewed as constant addition to the rate parameter for any photon flux. Thus, in this limit, the noise is given by Eq. (19). The S/N ratio in this limit can be approximated as

\[ \frac{S}{N} = \frac{\beta + \alpha}{\sqrt{\beta^2 + 2(\beta + \alpha)}} \] (22)

where \( \alpha \) is the rate of the spurious charges.

If \( \beta \) is large then \( p_0 \approx 0 \) and one obtains a different scaling for the noise. Specifically because the mean variance of the Erlang distribution for a given \( i \) is \( i/\gamma \) and \( i/\gamma^2 \), one finds that

\[ E(Z) = \sum_{i=1}^{\infty} p_i \frac{i}{\gamma} = \frac{\beta}{\gamma} \] (23)

because the mean value of the Poisson distribution is exactly \( \beta \). Further one can calculate the variance according to Eq. (18)

\[ E((Z - E(Z))^2) = \frac{1}{\gamma^2} \left( \sum_{i=1}^{\infty} p_i (i-\beta)^2 + \sum_{i=1}^{\infty} p_i i \right) \] (24)

\[ = \frac{1}{\gamma^2} (\beta + \beta) = \frac{2\beta}{\gamma^2} \]

the first term in the sum evaluates to \( \beta \) because the variance of the Poisson distribution is \( \beta \), and this term is by definition the variance. Calculating the S/N ratio in this limit we find that

\[ \frac{S}{N} = \frac{\beta/\gamma}{\sqrt{2\beta/\gamma^2}} = \frac{\beta}{\sqrt{2\beta}} \] (25)

3. The image registration algorithm

In an astronomical image taken through a Kolmogorov atmosphere, the dominant seeing aberrations in terms of Zernike polynomials are piston, tip and tilt. For imaging purposes the zeroth term piston (i.e. an overall phase delay) is of no importance. We will therefore try to design the algorithm to correct for tip and tilt as fast, efficiently and accurately as possible.

3.1. Correcting tip and tilt

To utilize the signal in the whole image, we propose using the Fourier cross correlation theorem for correcting tip and tilt, which translates to an overall solid body translation of the image. This method is different from the more common method of registering the frames based on one or more centroids (Mackay et al. 2004; Law et al. 2006).

Given a set of bias- and flat field- corrected images \( I_i(x, y) \), as described earlier, we will generate a reference image \( R \) by taking the average

\[ R(x, y) = \frac{\sum_{i=1}^{N} I_i(x, y)}{N} \] (26)

The mean image represents the mean position of the image, and we will then shift all the individual images to this position and co-add them. A method for finding the shift between two images using fast Fourier transforms (FFT) has been described by Araiza (2008). It can be shown that the shift between two images where

\[ I_i(x, y) = R(x + \Delta x_i, y + \Delta y_i) \] (27)

can be found using the following expression for the cross correlation between the images:

\[ P_i(x, y) = |FFT^{-1}[FFT(R) \cdot FFT(I_i)]| \] (28)

This expression will have a global maximum at \( (\Delta x_i, \Delta y_i) \). The appropriate shift can be found by looking for the position of the global maximum in \( P_i \).

Using the Fourier cross correlation theorem implicitly assumes that the images are circularly shifted. This is obviously not the case and some sort of apodisation of the images is called for to avoid edge effects. Furthermore, in the field of adaptive optics, the size of the typical isoplanar patch is on the order of 10’. One would therefore expect the size of a “lucky” patch to be similar. Surprisingly experience shows that the “lucky” patch size, where we do not see differential image motion, is significantly larger. The patch size is on the order of 35’, which is slightly smaller than the field of view in our camera. We can therefore solve both the apodisation problem and the problem with differential image motion by multiplying by an appropriate apodising Hamming window.
3.2. Instantaneous image quality

The most widely used measure of instantaneous image quality in lucky imaging is simply the maximum value of the pixel values in the frame (Smith et al. 2009). Over long time scales this measure suffers undue interference with fluctuations in atmospheric extinction and scintillation, simply because the maximum value scales with a multiplicative constant:

$$\text{max}(aI_i + b) = a \text{max}(I_i) + b.$$  \hfill (29)

We have therefore adopted another measure for instantaneous image quality based on $P_i$. Because the FFT is linear we have that

$$P_i'(x, y) = |\text{FFT}^{-1}[\text{FFT}(R) \cdot \text{FFT}(aI_i + b)]|$$  \hfill (30)

$$= aP_i + b|R|.$$  \hfill (31)

If we therefore adopt the maximum of $P_i$ scaled with its surroundings as a quality measure

$$q_i = \frac{P_i(\text{max}, y_{\text{max}})}{\sum_{(x,y)|x<\text{max},y<\text{max}} P_i(x, y)},$$  \hfill (32)

any scaling factor $a$ will cancel out. This measure is sensitive to any offset $b$. It is therefore important to accurately calibrate out any offsets. This is also true for the more common maximum value measure.

This expression is a proxy for the breadth of the maximum correlation peak. Intuitively if a frame has high image quality it will fit (correlate) well in very narrow range of offsets, and if a frame has low image quality it will correlate less well over a broader range of offsets.

In Staley et al. (2010) it is proposed that a LI PSF is a convex linear combination of a diffraction limited core and a diffuse halo in the form of a Moffat function akin to the conventional seeing disk. Consequently it would be rational to measure the instantaneous image quality as the relative weighting between these two components as a form of pseudo Strehl ratio.

We have therefore tested whether the instantaneous image quality measure proposed here is a reasonable proxy for the relative weighting of the two PSF components. To this end we generated a 100 pixel 1D reference image with two PSFs consisting of a Gaussian core with a FWHM of 2 pixels and a Moffat halo with a FWHM of 10 pixels. The weight of the two components was 50%:50%. We then calculated the proposed image quality with respect to images where the weighting was varied from 100%:0% to 0%:100%, and found that the proposed quality measure was a monotonous approximately linear function of the relative weighting. We also found that if the reference was sharper, i.e. more weighted towards the Gaussian core, the relation between the quality measure and the weight ratio was steeper. This indicates that the image quality measure is more discriminatory when given a sharper reference image.

4. The implementation

4.1. The camera and optical setup

The lucky imaging system has been implemented on the Danish 1.54 m Telescope at the ESO La Silla Observatory in Chile. The camera used for the implementation is an Andor Technology iXon+ model 897 EMCCD camera. This camera has an image area of $512 \times 512$ $16 \mu m$ pixels, corresponding to a pixel scale of $0.079$ on sky. The average seeing at La Silla is around 1".

This system is intended as a testbed for the lucky imaging system of the SONG telescope network (Grundahl et al. 2011), and the specifications are therefore identical to SONG. The firmware of the camera was specially modified by Andor to also read out the overscan regions: 20 columns to the left and 6 columns to the right of the image area. The camera is equipped with two readout amplifiers, one conventional and one electron multiplying. For the lucky imaging experiments the camera is read out using the electron multiplying readout amplifier at a rate of 10 MHz. In this mode the gain of the readout amplifier is $25.8 \text{ e}_{\text{ADU}}$ with a readout noise of $6.8 \text{ e}_{\text{ADU}}$ but this conversion takes place after electron multiplication stages, which, in this experiment, amplifies one photoelectron into approximately 300 electrons on average. Thus the formal readout noise is sub-electron, on the order of $6.8 \text{ e}_{\text{ADU}}/300 = 0.2 \text{ e}_{\text{ADU}}$. The notation with $\text{e}_{\text{phot}}$ and $\text{e}_{\text{EM}}$ is to highlight the difference between electrons before and after the cascade amplifier, respectively.

One has to keep in mind that the output distribution of the electron multiplier is exponential, not normal, as this leads to the extra photon noise described previously. This particular setup translates one photoelectron to $300 \text{ e}_{\text{ADU}}/25.8 \text{ e}_{\text{ADU}} = 11.6 \text{ ADU}$ photons. Most photometry packages take a gain input parameter, and assume that the noise is $\sqrt{\text{signal/gain}}$. One can take the extra photon noise into account by defining a new fictitious gain, $\text{emgain} = \text{gain}/2$. Inputting this gain will make the noise assumption read $\sqrt{\text{signal/emgain}} = \sqrt{2} \cdot \text{signal/gain}$.

To communicate with the camera we used a dual core 3 GHz PC with 2GB of memory and an iSCSI 600GB RAID0 array for intermediate data storage. On the PC we ran Ubuntu 9.10 as Andor delivers a Linux driver in the form of a.so shared library.

4.2. Software implementation

The software for handling the camera and reducing the data was written using Python, representing the images as NumPy arrays. The camera was controlled from Python using the andor.py project (http://code.google.com/p/pyandor/). This project wraps the .so driver via the Python extension ctypes, which makes it possible to control the camera and load the images directly from the camera as NumPy arrays. The driver implements a spool function that should be able to spool series of images as three dimensional FITS files directly to a disk, but this function was found to be non-functional when called from Python, for unknown reasons. Also the way a FITS cube is represented in a FITS file as a continuous binary blob without any indexing hampers performance and caching when manipulating such files.

Instead, a spool function was implemented using the PyTables (Francesc Alted et al. 2002–2011) project, thereby enabling the spooling of data directly to disk in the form of HDF5 files at a satisfactory rate. The FFT for the lucky imaging reduction was done using functions from the FFTW3 library (Frigo & Johnson 2005), linked into Python via the PyFFTW project, to get a satisfactory processing speed. For our purposes the FFTW3 FFT implementation proved to be some 20 times faster than the stock FFT from NumPy.

To be able to handle the data reduction and the data acquisition simultaneously, the software was designed to be multithreaded using the Python extension multiprocessing. The software runs a thread for handling the graphical user interface, a thread for controlling the camera and acquiring data, and threads for reducing data.
When the camera handling thread gets an order to acquire a lucky image, it creates an HDF5 (The HDF Group 2000–2010) file, and saves the current bias frame, flat frame, and the data about the setup into the file. It then spoils the image data into the file. When done it starts an independent reductions thread with the name of the created HDF5 file as a parameter. The HDF5 file contains all the information the reduction process needs to create a reduced image.

The output from the reduction is a FITS file with 10 images in it. The header of the file contains standard information about the reduction, and the camera setup. The first image in the FITS file is the shifted sum of the original images in the image quality reduction, and the camera setup. The first image in the FITS file, and saves the current bias frame, flat frame, and the data about the setup into the file. It then spoils the image data into the file. When done it starts an independent reductions thread with the name of the created HDF5 file as a parameter. The HDF5 file contains all the information the reduction process needs to create a reduced image.

5. Lucky imaging photometry

There is still much confusion about what the term lucky imaging implies. The original definition of lucky imaging (Fried 1978) is when, out of a stack of high frame rate images, only a small fraction of images that are diffraction-limited, or near-diffraction-limited are kept. Depending on seeing conditions, wavelength and telescope aperture, only on the order of 1% of the images are kept. These images are then shifted to correct for the most dominant atmospheric aberration modes, tip and tilt, as these modes impart a solid-body shift that can be corrected trivially. Finally the images are added to improve the signal.

This method will produce near-diffraction-limited images on 1–2 m class telescopes, albeit at the cost of a high photon waste, which is in principle bad for time-resolved photometry. It is important to note that the shifting and adding can be done for any image, regardless of the instantaneous image quality. Simply shifting and adding all images in a high frame rate stack will usually improve the seeing by a factor of approximately two, without any loss of photons. This method is known as shift-and-add.

5.1. Strategies for photometry in crowded fields

The problem of extracting photometry from an image is an archetypical inverse problem in the sense that it is easy to construct the image given the positions of the sources and the PSFs. But it is hard to extract the position of the sources and the PSFs given an image, especially in a crowded field. However, given the positions of all the sources in the image, the condition number of the inverse problem drops dramatically. One could therefore imagine a procedure for extracting time-resolved photometry where the positions of all the point sources in the image are extracted from a lucky image, but the time series of images is constructed from frames that are only shift-and-added, thus preserving all the photons with an improved resolution.

Another most interesting approach is differential image analysis (DIA), in which a high resolution reference image is blurred to the seeing and shift of images in the time series, and then subtracted. This method utilises information about the source distribution from the high resolution image. A lucky image constructed from a time series of observations seems ideally suited as a reference image in this respect. In particular, DIsAs utilizing numerical kernels, such as DanDIA (Bramich 2008), seem well-suited because a lucky imaging PSF in general seems to be peculiar and variable with a near diffraction limited core and an extended halo, comparable to the conventional seeing limit (Baldwin et al. 2008). In the vein of not wasting photons and cleverly including the high resolution information, another interesting technique is online deconvolution (Hirsch et al. 2011). These approaches will be pursued in future work.

5.2. Photometric stability

To test the stability of the photometry obtained from an EMCCD, along with the outlined reduction procedure, a 1.5 h sequence of the center of the of the globular cluster ω Cen at the coordinates 13h26m47s, +47°28′41″0 I2000 was acquired at a rate of 10 images per second. The images were then reduced, registered and had their image quality determined as outlined above. The observations were started at an hour angle of 1h33m and an airmass of 1.1. This field centered on ω Cen was chosen to simulate the crowded conditions of microlensing observations towards the galactic bulge, and because there are extensive observations from the Hubble Space Telescope for comparison.

This field is extremely crowded, and the improved resolution is a major virtue in finding the source positions in such a field. Hence the source positions were extracted with the standard PSF-fitting photometry package DaophotII (Stetson 1987) from a lucky image composed of the 1% sharpest images. This image has been reproduced in Fig. 5. It is evident that the resolution has been significantly improved when compared with Fig. 6.

Unfortunately the Danish telescope, commissioned in 1979, was never designed for imaging below the seeing limit. Hence, the image is limited by triangular coma from the telescope at the 0′3 level, leading to peculiar triangular PSFs; see Fig. 5. It has proven to be difficult to extract an accurate PSF with DaophotII from this lucky image. L1 PSFs generally have very extensive halos due to higher order atmospheric aberrations not corrected by lucky imaging. These very broad halos and the crowded field makes it very difficult not to pollute the wings of the DaophotII PSF with faints stars. The diffraction limit for a 1.5 m telescope
in I is 0″11, but the intrinsic aberrations of the telescope imply that the images are not undersampled.

The inaccurate PSF determination leads to a less than optimal subtraction in DaoPhotII. But it should be noted that this image is only used to extract the positions of the stars, and it is still possible to extract accurate positions of even very faint stars from this image.

To extract time series photometry, a sequence of 100 images were generated by shifting and adding 500 consecutive frames for an effective exposure time of 50 s. The list of positions from the lucky image was then projected onto the 100 images with the DaoPhotII program daomaster, and the full time-resolved photometry of 2523 stars was extracted simultaneously with the program allframe (Stetson 1994).

In these 100 images, which have only been shift-and-added, the PSF is more conventional and the result of the subtraction is satisfactory, as seen in Fig. 6.

To obtain relative photometry, the mean of an ensemble of 10 carefully selected stars was subtracted from the photometry at each time step. Further, for each of the 2523 light curves the RMS scatter was robustly estimated with the function biweightScale, from the astLib Python module. A plot of the relative error in this photometry is plotted in Fig. 8. The magnitudes are the instrumental magnitudes reported by DaoPhotII. To simulate a SONG telescope a special longpass filter with a cut-on wavelength of 650 nm (Thorlabs FEL0650) was used, hence the magnitudes are not directly translatable to the Johnson BVRI system.

We found that the field we have investigated was observed from the Hubble Space Telescope in 1997 with the WFPC2 camera in the F675W filter. From this we extracted the aperture photometry of three stars that were faint enough not to be saturated and reasonably isolated. The photometry extracted from the three stars in Fig. 7 has been summarised in Table 1.

<table>
<thead>
<tr>
<th>Index</th>
<th>STMAG</th>
<th>Johnson R</th>
<th>$m_{\text{inst}}$</th>
<th>$R - m_{\text{inst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.24</td>
<td>15.94</td>
<td>15.36</td>
<td>0.58</td>
</tr>
<tr>
<td>2</td>
<td>15.66</td>
<td>16.36</td>
<td>15.95</td>
<td>0.41</td>
</tr>
<tr>
<td>3</td>
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<tr>
<td>avg</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.63</td>
</tr>
</tbody>
</table>
We had to adjust the conventional procedure for photometric data extraction to take account for the exponentially distributed EMCCD output and the bias variation, but concerns about whether the stochastic nature of the EM amplification itself hinders accurate photometry over long time scales have been rebutted. In fact, the photometric scatter is close to the theoretical limits over most of the explored range of magnitudes.

For stars fainter than 19th magnitude, we get a lower bound on the photometric scatter, which is worse than predicted from photon noise, plausibly due to crowding. We believe that this can be remedied to an extent by the virtue of being able to produce high resolution references from the data set and cleverly including this information via differential image analysis, DIA, or online deconvolution.

Finally we have demonstrated a very fast and robust implementation of the lucky imaging technique, based on cross-correlation calculated in Fourier space. It is fast because it is based on FFTs and robust in the sense that no explicit reference stars have to be established, the algorithm is hands-off, and the whole image with all its information is utilised. This is most important in a robotic telescope network that is designed to observe microlensing events autonomously. Unfortunately it is difficult to find subpixel shifts with this method, but it is feasible and will be investigated in future work. Because of intrinsic aberrations in the Danish telescope at present, the images are not undersampled, but they would have been if the telescope had been diffraction limited. In this case there will be information at high spatial frequencies that can be extracted by finding subpixel shifts and applying a dithering method. But even in the well-sampled case, super sampling, subpixel shifts, and dithering would produce more smooth PSFs which are potentially more easily handled with PSF fitting photometry software, hence potentially leading to more accurate photometry.

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Fig. 8. The rms scatter of the photometry of 2523 stars in the time series consisting of 100 images stacked from 500 0.1 s exposures each. The photon noise limit and the excess noise limit has been plotted for comparison. Due to the stochastic amplification in the EM stages, an EMCCD will, when regarded as a conventional linear amplifier, effectively multiply the photon noise by a factor of 2. The robust rms is estimated with the function biweightScale from the Python module astLib.

Fig. 9. For reference, two examples of constant light curves and two variable light curves extracted from the dataset have been plotted. Each image has a cumulated exposure time of 50 s.

converted to the STMAG system for the F675W filter, and approximated to Johnson R according to the instructions in the WFPC2 Photometry Cookbook.

For stars brighter than approximately $m_{\text{inst}} = 16$, we see photometric scatter at a level consistent with scintillation. The scintillation level in Fig. 8 has been calculated according to Eq. (10) in Dravins et al. (1998), assuming a telescope diameter of 154 cm, a telescope altitude of 2340 m and an airmass of 1.1.

For stars fainter than 16th magnitude but brighter than approximately 18th magnitude, the scatter seems to be bounded by photon noise to within 50%.

Finally, for stars fainter than 18th magnitude we find a lower bound which rises more sharply than photon noise, plausibly due to crowding. We believe that this can be remedied to an extent by the virtue of being able to produce high resolution references from the data set and cleverly including this information via differential image analysis, DIA, or online deconvolution.

6. Conclusions

In this paper we have demonstrated that photometry in very crowded fields with high frame rate EMCCD data is indeed feasible.