Electron-Multiplying CCD Imaging: Effectiveness for Stellar Occultations by Faint Objects

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Abstract: Our Portable Occultation, Eclipse, and Transit Systems (POETS; Souza *et al.* 2006, PASP 118, 1550) have been successfully employed for multiple stellar occultation observations: (i) four systems obtained data in South America during the 2005 July 11 occultation of C313.2 (2UCAC 26257135) by Charon (Gulbis *et al.* 2006, Nature 439, 48; Person *et al.* 2006, AJ 132 1575); (ii) four systems obtained data in Australia during the 2006 June 12 occultation of P384.2 (2UCAC 26039859) by Pluto (Elliot *et al.* 2007, AJ 134, 1), and (iii) three systems were utilized in the Southwestern U.S. for the 2007 March 18 occultation of P445.2 (2UCAC 25823784) by Pluto (Pasachoff *et al.* 2007 & Person *et al.* 2007, this meeting).

Pluto and Charon have apparent *V* magnitudes of ~14 and ~16, and the stars for these events had UCAC magnitudes of 14.99 to 15.25. These events were bright enough to achieve fair to excellent signal-to-noise ratios (SNRs) at cadences between 2 and 10 Hz by using "conventional" camera modes. POETS also possess electron-multiplying (EM) readout modes, which we have not yet employed for occultation observations because conventional modes have been more than adequate. Here, we present an exploration of conventional versus EM mode as applied to observations of stellar occultations by faint objects and stars – a relevant situation for occultations of USNO-B stars by Kuiper Belt objects (KBOs). Although dependent on specifics of the observaton, such as telescope size, integration time, and image quality, we find that EM mode can be effectively utilized to provide data of higher SNR for KBO occultation observations.

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Overview: Conventional vs. Electron-Multiplying (EM)

The POETS camera, an Andor iXon (e2v CCD97), has two modes: conventional and electron-multiplying (EM). Conventional mode functions as a standard, frame-transfer CCD. In EM mode, charge is moved through an additional multiplication register, where it is amplified prior to the e~/ADU conversion in the standard output amplifier (see Figures 1a and 1 b).While the EM process effectively increases signal without increasing read noise (see Figure 2), the drawbacks are (i) dynamic range is limited at high gain (see Figure 1c), (ii) an excess noise factor is incurred due to impact ionization statistics (see Figure 3), and (iii) spurious (or clock-induced) charge becomes a significant factor.

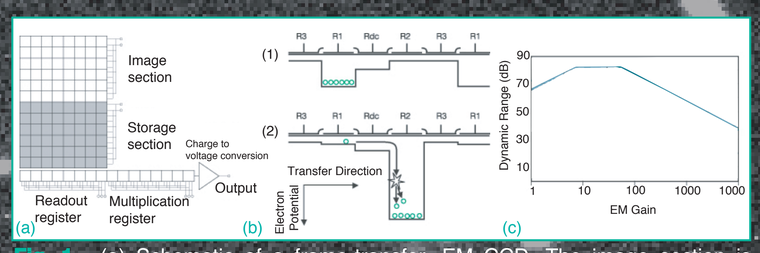


Fig. 1. (a) Schematic of a frame-transfer, EM CCD. The image section is exposed, and accumulated charge is rapidly transferred to the masked storage section. Transfer times for the iXon are a few µsec per row. Charge then proceeds through a standard readout register as well as a multiplication register. (b) Schematic of electron amplification in the multiplication register. Charges are clocked with a high enough voltage, at a low enough temperature, to induce impact ionization. The probability of amplification in any one cell is low; however, ~1000x signal amplification can be achieved over hundreds of register cells. (c) Dynamic range as a funcion of EM gain. In EM mode, the read noise is reduced, increasing dynamic range, until the register can no longer accomodate the amplified signal, When read noise falls below sihgle photon levels, the dynamic range falls off. (figures from Robbins and Hadwen 2003 and http://www.andor.com)

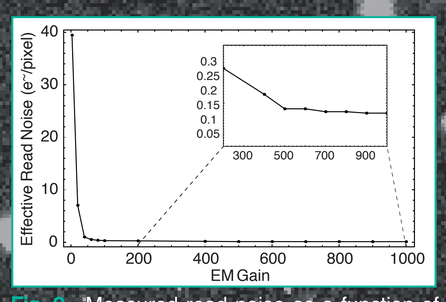
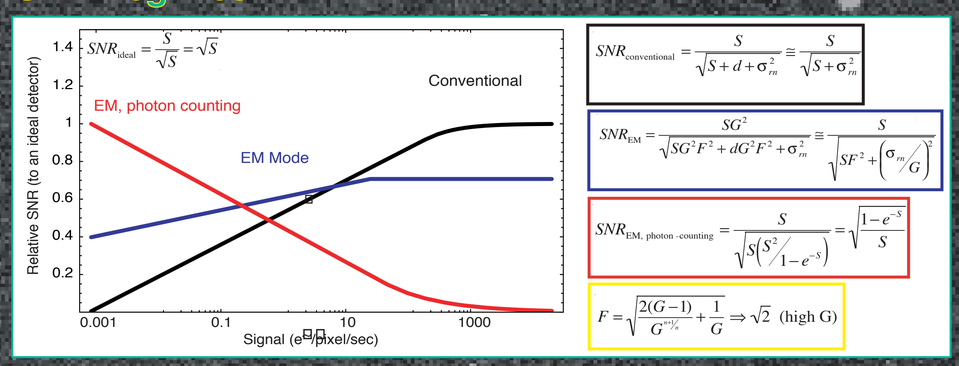


Fig. 2. Measured read noise as a function of EM gain. These data were taken using Andor iXon X-3020 in 3MHz mode, with 2.4x preamp gain (3.89 e~/ADU), at –70° C. For this camera, the read noise is less than one electron at EM gain settings greater than approximately 40.

SNR Regimes



S = signal in electrons per pixel per second
d = dark current per pixel
σ_{rn} = read noise per pixel
G = electron multiplication gain
F = excess noise factor
n = number of mult. register cells (~536 for the iXon)

Fig. 3. The signal-to-noise ratio (SNR) as a function of signal for three different regimes, relative to an ideal, noiseless detector. The black line of "conventional" represents data taken in the conventional mode. The blue "EM mode" line represents data that are read out through the electron-multiplying register. The red "EM, photon counting" line represents data taken in the EM mode and analyzed using a photon-counting (i.e. threshold) method. Optimal modes for the given signal levels are as follows: conventional >10e~, EM ~0.2e~ – 10e~, EM photon-counting < 0.2e~. The transition between EM and conventional is dependent on read noise. Here, we have assumed the POETS read noise of 6e~ conventional (1 MHz) and 60e~ EM (10 MHz).

Occultation SNR: Conventional vs. EM

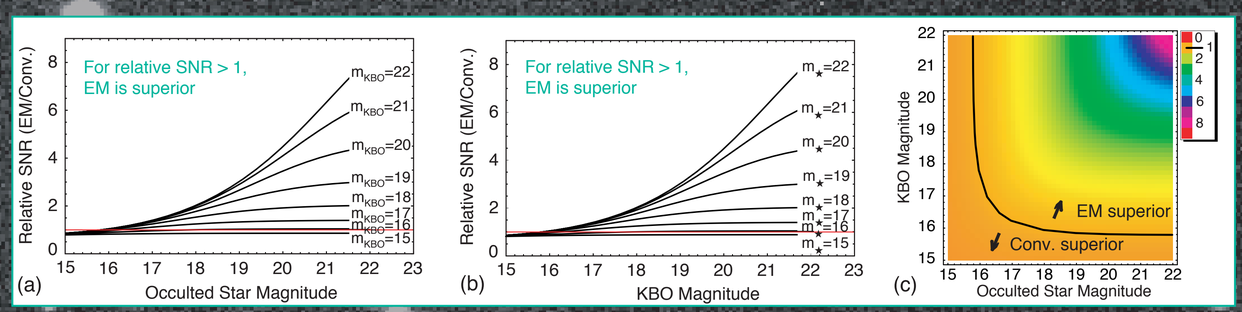


Fig. 4. Theoretical SNRs for EM mode (EM gain = 100) relative to conventional mode, as functions of the magnitude of an occulted star and an occulting KBO. These calculations are for POETS on the IRTF (anticipated in spring 2008), assuming 1 s integration time, system QE of 50%, 1 arcsec seeing, a 2-arcsec-radius photometry aperture, no filter, and sky background of 21 mag. Actual SNR values range from a few hundred (16 mag. star and KBO) to a few tens (20 mag. star and KBO). (a, b) Plots of the relative SNR as separate functions of star and KBO magnitudes. The red lines denote where the modes are equivalent. At fainter magnitudes, the EM mode clearly returns higher SNR data. (c) A density plot of the relative SNRs over a range of magnitudes. The black line denotes 1, where conventional and EM modes are equivalent. At fainter magnitudes, roughly > 16.5 mag. KBO and star, the EM mode provides higher SNR. Photon-counting analysis is not applied, since the signal is > 0.1 e~ for the considered magnitudes.

Laboratory Data

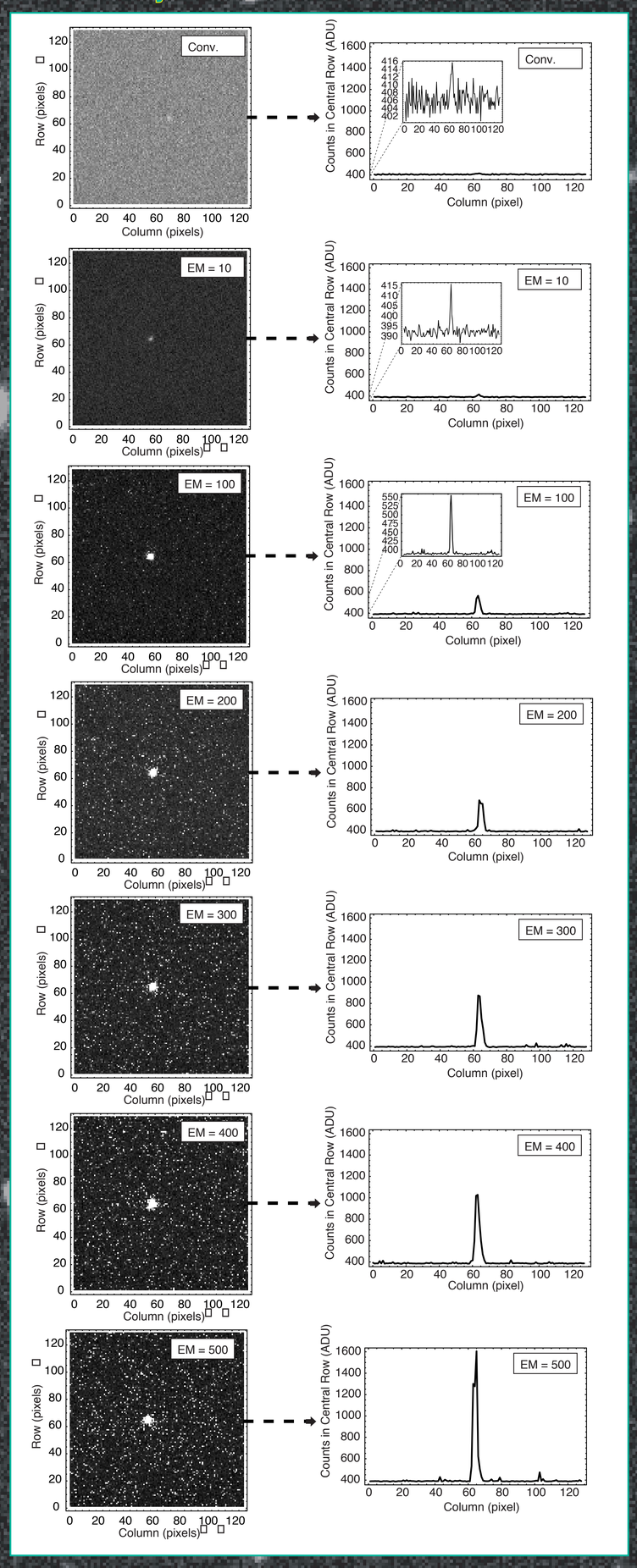


Fig. 5. Data of a high-precision, red LED behind a 50 µm pinhole. Subframe images (128 x 128) are dispayed in the lefthand column, over identical count ranges. All data were taken with the iXon X-3020, in 3 MHz readout, with the minimum cycle time of 0.0027 s. From top to bottom, data modes are conventional, EM = 10, 100, 200, 300, 400, and 500. Data from a row slice across each frame, centered on the LED, are plotted in the righthand column. The background noise that increases with increasing EM gain is due to spurious (or clock-induced) charge – the transfer of charge between rows during readout. Because this signal is also multiplied in the EM mode, the SNRs of these data are highest for frames EM= 10 and EM =100. Thus, an optimal EM setting for occultation observations would be in this range, where read noise is sufficiently supressed and spurious charge is relatively low.

Observations

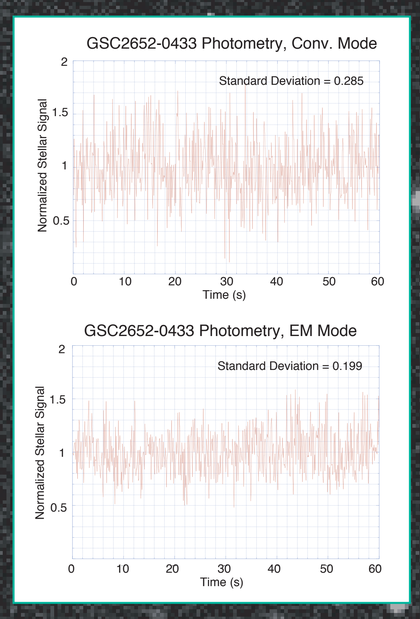


Fig. 6. Data from POETS on the Hopkins Observatory 0.6-m telescope of a 13th-magnitude star located just east of M57. Observations were made using a Bessel *V* filter in ~3 arcsec seeing. Conventional mode was 3 MHz, 4.7x preamp gain, at an exposure time of 0.09942 s. EM mode was 10 MHz, EM gain = 16 (σ_{rn} = 0.52 e~), preamp gain 4.7x, at an exposure time of 0.0982 s. These observations represent an extreme of detectability. 600 frames were taken in each mode, and the normalized counts from aperture photometry are plotted versus time. Both datasets exhibit Gaussian histograms. The standard deviation is significantly larger in conventional mode. This indicates an improved sensitivity, and at least 50% higher SNR, in EM mode for fainter occultation stars.

Conclusions

- For observing occultations with POETS iXon cameras (e2v CCD97), the optimal EM gain setting is a few tens to one hundred. These EM gain settings allow low read noise, high dynamic range and fairly low spurious charge.
- Theoretically, EM mode should return higher SNRs than conventional mode for stellar occultations of faint stars by faint objects. The transitional magnitudes depend on many factors: for POETS on the IRTF with 1 s exposures, our results indicate that EM mode will perform better than conventional for KBO occultations with star magnitudes fainter than approximately 16.5.
- Time-series photometry of a star near the detectability limit (~0.1 s exposures of a 13 mag. star on a 0.6-m telescope; taken in the manner of an occultation observation), demonstrates that EM mode returns higher SNR for a faint star in practice.

References

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Image of Eris taken on the 42" Hall telescope at Lowell Observatory on 25 August 2006 by then-MIT-undergraduate Rosemary Pike.