Steele, IA, Mottram, CJ, Smith, RJ and Barnsley, RM

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I.A. Steele, C.J. Mottram, R.J. Smith, R.M.Barnsley

Astrophysics Research Institute, Liverpool JMU, ic2 Liverpool Science Park, 146 Brownlow Hill, Liverpool L3 5RF, UK

ABSTRACT

Some modern CCD designs provide a dummy readout amplifier that is designed to be operated with the same clock and bias signals as the true amplifier in order to provide a measurement of clock induced and other common-mode noise signals in the true amplifier readout. In general the dummy output signal is subtracted electronically from the true output signal in a differential input preamplifier before digitization. Here we report on an alternative approach where both signals are digitized and the subtraction done in software.

We present the results of testing this method of operation using the ARC SDSU generation III CCD controllers and an e2v CCD231 device and find it works well, allowing a noise figure of ~ 2.2 electrons to be reached in the presence of significantly higher (~ 6 electrons) pickup noise. In addition we test the effectiveness of using unused (but still genuine) readout amplifiers on the detector to provide a pseudo-dummy output, which we also find effective in cancelling common mode noise. This provides the option of implementing noise reduction on CCDs that are not equipped with dummy outputs at the expense of overall readout speed.

Keywords: charged coupled device, dummy amplifier, common mode noise, read noise

1. INTRODUCTION

Recent detectors from e2v have featured "dummy output" circuits on chip that are of identical design to the actual output amplifiers, but are not connected to the readout register of the array.[1] These are designed to be used as part of a differential input circuit to the readout electronics, allowing the cancellation of common mode noise due to clock feedthrough or electromagnetic interference. A potential downside of this approach is that the theoretical readout noise of the array will be increased by a factor of $\sqrt{2}$. Depending on the individual circumstances in which a detector is operated, the benefits of noise cancellation may or may not outweigh the read noise increase. A particular problem that can be encountered is an implementation which works perfectly in laboratory conditions, but at the noisy electrical environment of the telescope with the potential for poor and variable earthing shows additional noise components. In this paper we describe the implementation of a system allowing the dummy output signal to be subtracted in software (i.e. post data acquisition) thereby allowing the optimal solution to be adopted for any particular dataset. In addition we show that such a system may also be implemented successfully on a system with multiple readout amplifiers (but no dummy amplifiers).

2. TEST INSTRUMENT

All of the tests and data presented here were carried out as part of the development and operation of a new imaging camera (IO:O) for the Liverpool Telescope[2] (LT). The LT is a fully robotic 2.0 metre f/10 telescope at Roque de los Muchachos Observatory on La Palma. Our tests use an engineering grade E2V CCD231-84 device. This has 4096 (H) $\times$ 4112 (V) pixels. The pixel size is 15 μm. The device is equipped with 4 output amplifiers and 4 dummy output amplifiers, and has the ability to drive the clock signals to allow readout through one, two or all four of them (Figure 1).

While the device used in our experiments is engineering grade, the test data supplied by e2v on procurement shows this is solely due to cosmetic (flat field) effects below $\sim$ 4000Å rather than the noise performance of the device. The e2v test data showed a measured read noise of 4.7 electrons rms at 500 KHz pixel rate, dropping to

Further author information: (email i.a.steele@ljmu.ac.uk)

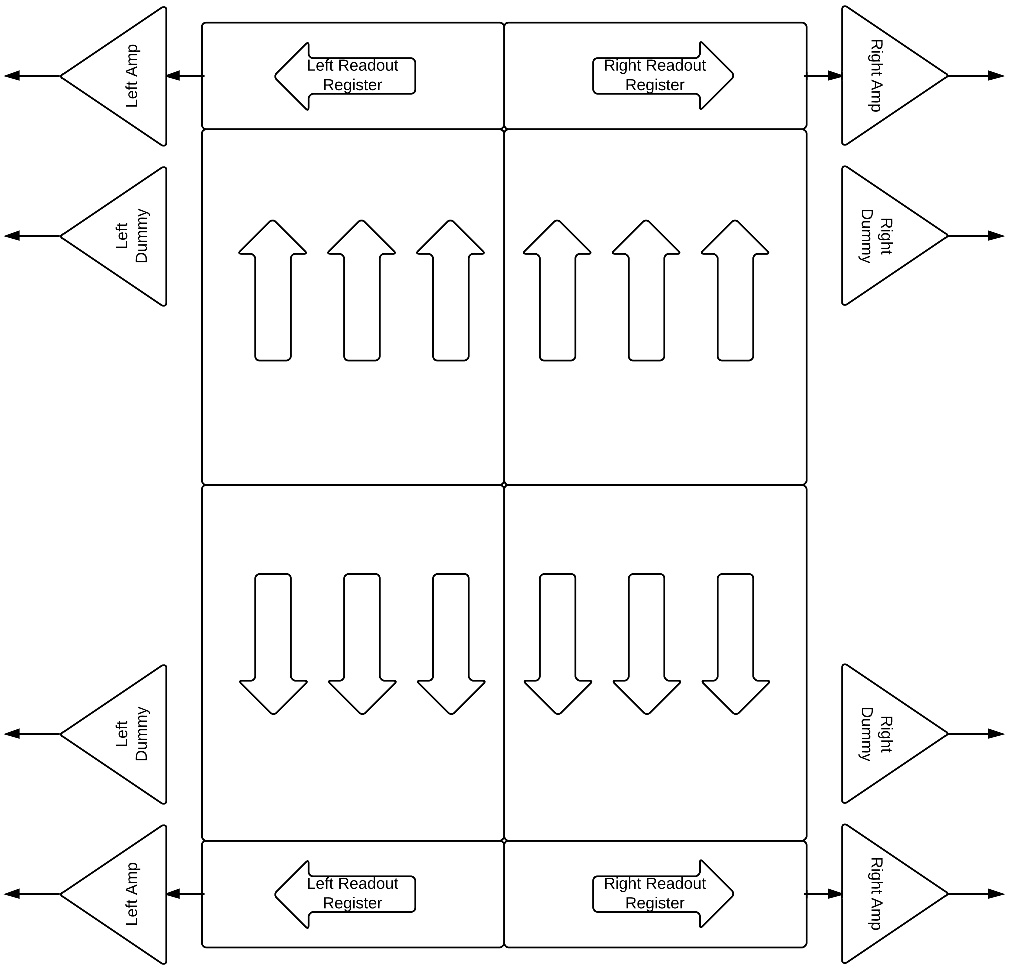

Figure 1. E2V CCD231 readout architecture. The array is split into four quadrants, each of which can be clocked individually. By this means, the entire array can be readout in single, dual or quad mode. Dummy amplifiers are also provided which are not connected to the readout registers.

2.1 electrons rms at 50 kHz, in line with the e2v specification. We determined experimentally that best linearity performance for this device was obtained when the array was operated in inverted mode, with an equivalent substrate potential of +7V.

To read the device out we use the AstroCam (SDSU) Generation III control electronics[3] equipped with a pair of ARC-45 dual readout CCD video boards with our custom DSP code derived from the example code supplied with the controller. The ARC readout system uses a classical dual slope integrator approach to implement double correlated sampling. Laboratory testing of this controller with no detector connected and open circuit inputs showed a typical controller read noise of 1.3 electrons rms at the readout speeds typically used here.

3. PSEUDO-DUMMY OUTPUT TESTS

Our initial wiring of the detector to the CCD controller simply connected the four normal outputs to the four inputs of the ARC-45 boards in single ended mode. The CCD dummy outputs were left unpowered and unconnected, and DSP code developed to read out in either a single, dual or quad fashion. While testing in the laboratory was unproblematic, once the instrument was tested on the telescope, medium level ($\sim 6-7$ electron rms) pickup noise became apparent. The usual mitigation techniques of earthing modifications, power supply decoupling etc. proved ineffective. Inspired by the "dummy output" idea, we therefore modified our DSP code to a dual readout mode, where the entire array would be clocked out of the left hand amplifiers (i.e. both halves of the readout register were clocked in the same direction). However, the signal from the right hand amplifiers was still read out to act as a "pseudo-dummy" readout (Figure 2). Both the true and pseudo-dummy outputs signals were combined into the same FITS file, with the true output as the primary image and the pseudo-dummy output as an image extension. By retaining both images, subtraction can then be carried out in software to produce a final image.

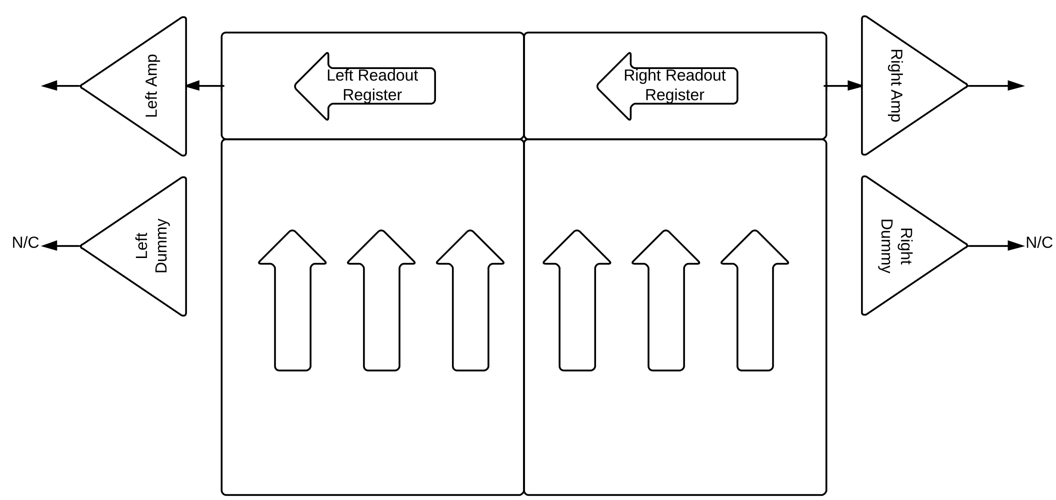

Figure 2. Top half of CCD 231 architecture in Pseudo Dummy configuration. The charge is clocked to the left in both readout registers. The left hand amplifier therefore reads out the entire top half of the image. The right hand amplifier has no charge clocked into it, and therefore acts as a pseudo dummy output creating a pseudo dummy image that is also read out. The true dummy outputs were not used in this configuration.

Some simple experiments with bias frames immediately showed this technique has value. A typical bias frame readout with a dual slope integration of 400 ns per slope (corresponding roughly to a 700 kHz pixel rate) showed a noise level of 7.2 electrons rms. The dummy image had an rms of 7.9 electrons rms. The subtraction of the two however yields a final difference image with a reduced noise level of 5.9 electrons, close to the predicted e2V value. Increasing the dual slope integrator time to 1600 ns per slope, the final read noise is 2.8 electrons rms.

Increasing the time beyond this does not yield any improvement, indicating the additional expected noise factor of $\sqrt{2}$ as we approached the detector limit of 2.0 electrons rms (Figure 3).

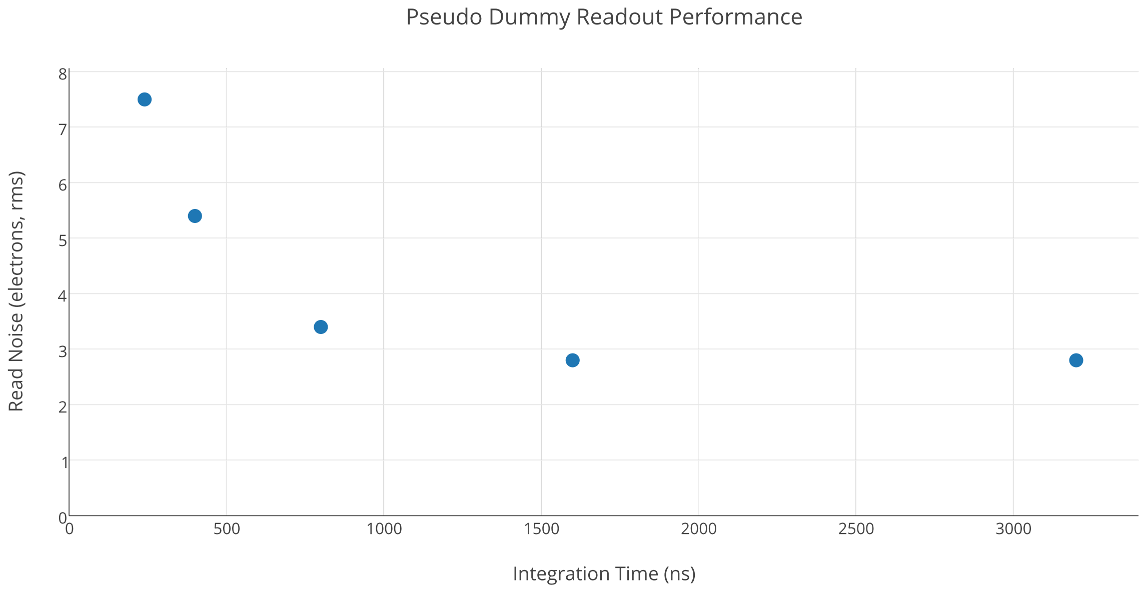

Figure 3. Measured read noise in the difference image constructed by subtraction of the real and pseudo-dummy image at different dual slope integration times. The noise reaches a limit at around 2.8 electrons.

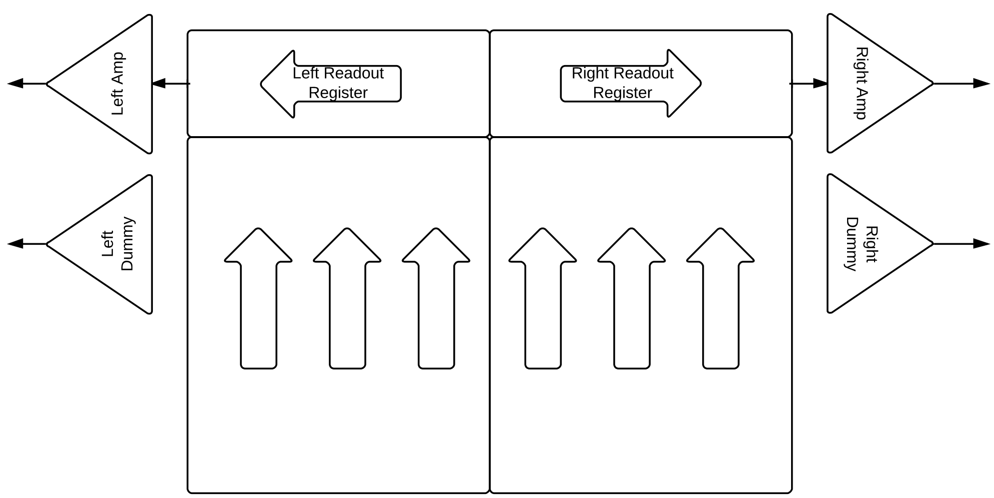

Figure 4. Readout configuration using true dummy and genuine outputs.

4. DUMMY OUTPUT TESTS

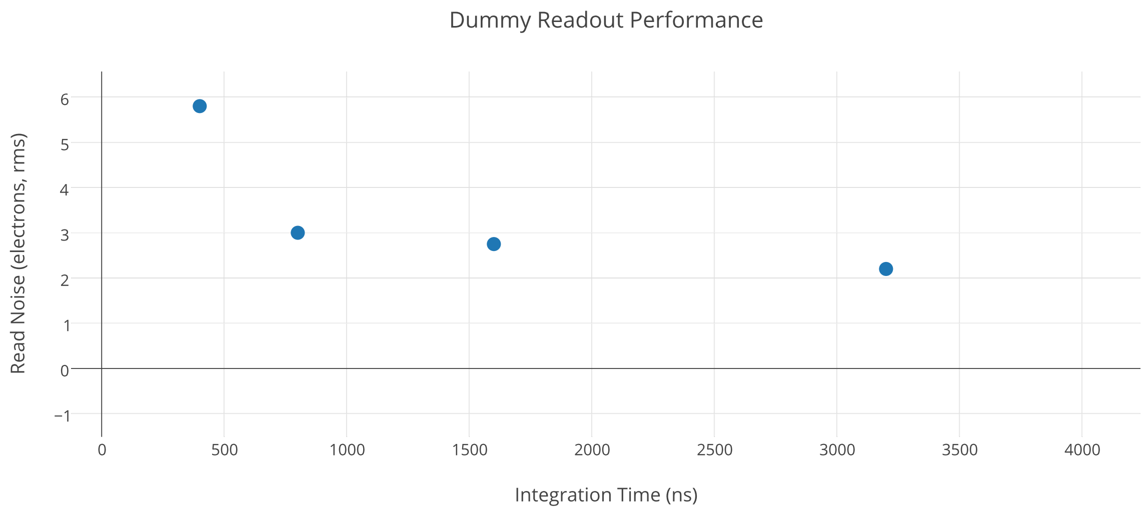

Figure 5. Measured read noise in the difference image constructed by subtraction of the real and dummy image at different dual slope integration times. At slow readout speeds, the noise is approaching the limit of the detector (2.0 electrons rms).

In order to evaluate whether a further improvement in read noise was attainable, the next stage of the experiment was to rewire the cryostat to disconnect two of the genuine output amplifiers from the readout electronics and connect the dummy outputs instead. As this involved a complete rewire of the cryostat, the opportunity was taken to weave into a twisted pair the matching dummy and real amplifier signal leads so as to expose them to as similar an electromagnetic environment as possible. The resulting configuration was as per Figure 4.

As with the pseudo-dummy setup, both the real and dummy outputs were read out and saved as separate extensions within the image FITS file to allow evaluation of individual and subtracted images. The performance of this setup is shown in Figure 5. It is similar to the pseudo-dummy setup at fast readout speeds, however at slow speeds the performance appears significantly better ($\sim$ 2.2 electrons rms). This is approaching the limit of the detector specification and seems to indicate that the expected $\sqrt{2}$ performance degradation is not being encountered in this configuration.

We note that due to the tight coupling between the dummy and image output wiring in this setup, a small amount of crosstalk is present in the dummy image. This was characterized as linear and at a level of 0.5% of the true image value. It therefore has no significant effect on the final image when subtracted off other than an effective gain reduction of 0.5%.

5. CONCLUSIONS

We have demonstrated that by reading out either a pseudo-dummy (using a real output amplifier but not clocking charge to it) or a true-dummy amplifier as an image simultaneously with the science image allows subtraction in software that removes pickup and other sources of common mode noise. An advantage of the pseudo-dummy technique is that it should be widely and easily applicable to any CCD with more than one readout amplifier assuming software modification of the readout waveforms and digitization scheme is possible. This can be accomplished without any wiring changes assuming the existing amplifiers are wired up. A disadvantage of this approach is that by effectively switching from dual to single (or quad to dual etc.) readout, the total array readout time will be increased by a factor of 2.

Our experiments also indicated that the use of a true dummy amplifier seems to provide better performance at the lowest noise levels, although there is the possibility that this reduction is also due to the altered (twisted pair) wiring introduced in that experiment. This is the final configuration we have selected for IO:O, and will also be used in the WEAVE[4] spectrograph detector system being built for the William Herschel Telescope.

In both configurations a significant advantage is that the technique does not force selection of a differential readout mode on the observer at the time of data acquisition. A simple data pipeline can evaluate the read noise in both the raw science image, and that with the dummy image subtracted, and choose the best (lowest-noise) image for further reduction. In addition this method removes the need for additional preamplifier circuitry to provide an output source current to the detector when using the electronic differential input of the AstroCam controllers.

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