Noise Free Detectors in the Visible and Infrared: Implications for the Design of Next-generation AO Systems and Large Telescopes.

Craig D. Mackay[1], John E. Baldwin[2], Robert N. Tubbs[1.]

[1]Institute of Astronomy, Univ. of Cambridge, Madingley Road, Cambridge CB3 0HA, UK.
[2]Cavendish Astrophysics, Cavendish Lab., Madingley Road, Cambridge CB3 0HE, UK.

ABSTRACT

This paper is intended to discuss the impact of noiseless CCD detectors in three significant areas of the development of large telescopes and the instruments that go on them. These are (1) CCDs that have all the characteristics that we are used to seeing in CCDs can now be made with negligible readout noise even at higher pixel rates (> 10 MHz) and will allow rather different approaches to the design of instrument is generally, (2) the technique of achieving diffraction limited imaging in ground-based telescopes known as Lucky Astronomy in which images are taken at high speed has been demonstrated to work under a variety of different conditions and (3) some suggestions as to how these methods may be applied directly to much larger diameter telescopes in order to achieve high resolution imaging and spectroscopy without the expense of laser guide stars or multi-conjugate adaptive optics.

1. INTRODUCTION

The scientific output of the current generation of ground-based optical and near infrared telescopes has been quite remarkable. Scientists are now discussing improving the instrumentation of existing telescopes and also looking at designs of even larger telescopes. If we are to achieve the full potential of these new, extremely complex and expensive systems it is important that we look carefully at some of the assumptions that are usually made in the design of these instrument and which in some cases may be assumptions that stop us looking more broadly at how we could achieve the scientific goals of these programmes. In this paper we will look carefully at the implications of the recent development of essentially noise-free CCD imaging detectors and how this might influence our approach to achieving near-diffraction limited operation of these instrument in the visible and near infrared.

2. L3CCD CHARACTERISTICS

The recent development by E2V Ltd., Chelmsford, UK (formerly Marconi Applied Technologies, before that EEV Ltd.), of CCDs with an internal gain structure is of very great importance for astronomy. The technology of these devices has been described in detail already [1,2] and their properties will only be summarised here.

An L3CCD consists of a completely normal two-dimensional CCD (for example in full frame or frame transfer format) where the only difference is an extended output register (Fig.1). The extended section of the output register would normally be clocked with a 10 volt swing, but in this case one electrode is constructed so that when clocked with a much higher voltage (typically 40 volts) then there is a low probability (typically one or two percent) that an electron transferred into that electrode will create a second electron by avalanche multiplication. The extended multiplication register may have perhaps 600 elements

and therefore the multiplication probability of the whole register is, with one percent probability, a gain of 392 (=1.01^{600}). Following the extended register, the output amplifier is the same as is normally used with a CCD. The amplifier readout noise is a voltage noise within the output transistor. This is usually expressed as electrons (one electron is generated by the absorption of one photon in the CCD imaging area) and the conversion depends on the input node capacitance. Because of this gain factor the equivalent readout noise when expressed as electrons detected in the CCD imaging area is reduced by the gain factor. Even at high pixel rates the readout noise is still relatively low without any gain (typically ~100 electrons rms) which, with the gain factor, will be reduced to very much less than one electron rms. The gain factor may be adjusted by varying the amplitude of the high-voltage clock. This allows a trade-off to be made between the system full well capacity and readout noise, a trade-off which may be made on a frame to frame basis.

E2V Ltd. have now produced several different formats of L3CCD including the CCD 65 (576 by 288 pixels each of 20 by 30 microns and a 591 pixel multiplication register), the CCD 60 (128 by 128 pixels of 24 by 24 microns, with a 512 pixel multiplication register and available both front and back illuminated) and the CCD 87 (512 by 512 pixels each of 16 by 16 microns and a 536 element multiplication register) (Fig.1). We have used the CCD 65 extensively for astronomy and done some preliminary experiments with the CCD 60 devices. The astronomical results are described elsewhere [3,4,5]. More recently Texas Instruments have announced their own version of this technology with the TC253 device (656 by 496 pixels of 7.4 by 7.4 microns and a 400 pixel multiplication register). Samples of this device are now available.

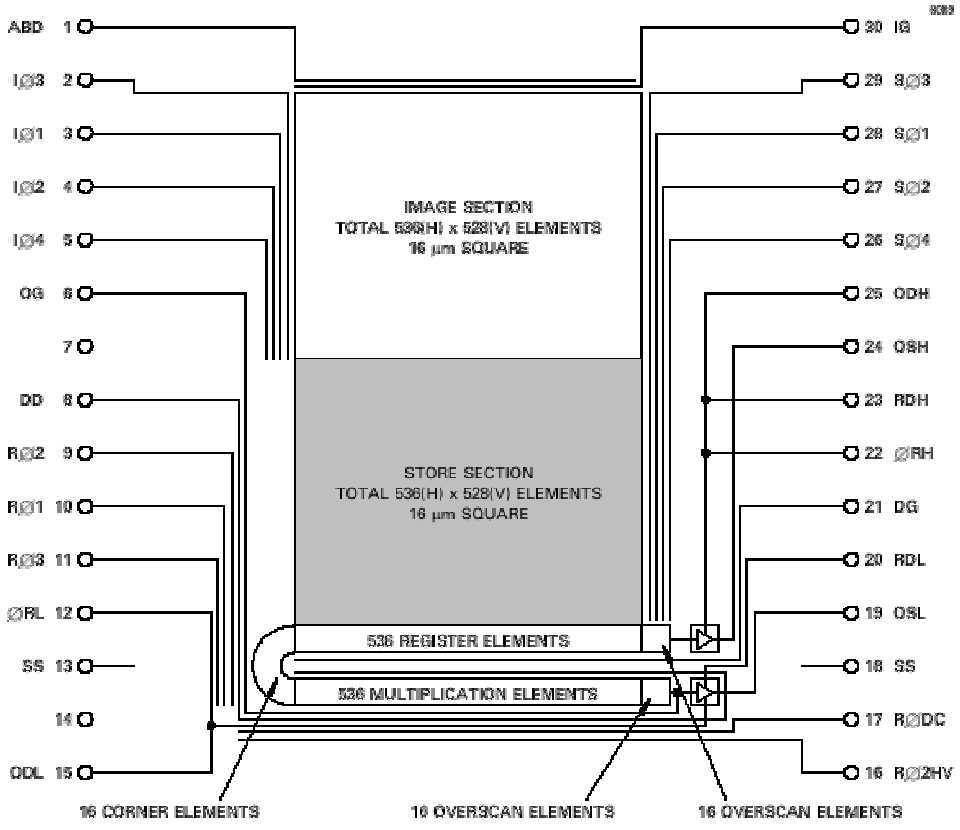

Fig. 1: The layout of a typical L3CCD from E2V Ltd. The normal output register is extended with a multiplication register clocked with a higher voltage (40 volts rather than 10 volts). This gives a low probability of an avalanche multiplication at each pixel of the extended register. After a large number of low probability gains, the overall gain can be high (hundreds or thousands) with the gain adjustment only carried out by changing the amplitude of the clock swing in the multiplication register.

The high gain and essentially zero readout noise that can be achieved with these devices allows them to be used in true photon counting mode, provided the device is cooled far enough so as to eliminate for practical purposes the dark current. The L3CCD multiplication technology is a stochastic process which adds to the photon shot-noise. The statistics of photon arrival rates mean that the uncertainty in the signal in a pixel which holds on average N photons per frame is $\sqrt{N}$. After multiplication the uncertainty in the signal is found to increase to $\sqrt{2N}$, equivalent to halving the detective quantum efficiency of the detector system. This reduction may be eliminated by using a true photon counting system where each event is recognised as a single photon, something that can be done with high accuracy given an appropriate level of gain. Basden et al[6] have further demonstrated that it is possible to achieve close to full quantum efficiency and photon counting operation even at signal levels of a few photons per pixel per frame, something that is actually quite a high signal rate in terms of photons per pixel per second, given that these devices can be operated at many tens or hundreds of frames per second.

L3CCD technology may be added to most normal CCD geometries. It may well be that the geometry that you would prefer for your ideal detector system is not already in production but it is clear that the costs of modifying an existing design to add L3CCD performance may well be acceptable, particularly when all the benefits of existing CCD technology (very high quantum efficiency, exceptionally low charge transfer inefficiency etc.) may be had in addition to the virtues of L3CCD operation.

3. LUCKY IMAGING

The application of L3CCD imaging technology has made practical a new approach to obtaining diffraction limited images from a ground based telescope. If we imagine looking at a bright star with a telescope of diameter ~7 r_0 (where r_0 is the Fried parameter) then on average we expect to get an image of a star with a diameter appropriate to r_0. However the statistics of the atmospheric turbulence show that in a few percent of images taken at high speed (faster than the Fried time, t_0) we expect that the phase fluctuations across our telescope will become small enough to give us a diffraction limited image with the star image diameter the diffraction limited size from the whole diameter of the telescope rather than set by r_0. By selecting these images, shifting and co-adding them we will accumulate a diffraction limited image with good signal-to-noise. Once we have established the point spread function of the telescope we can use that information to deconvolve the next few tens of a percent of the images which will principally suffer from de-focus and astigmatism. In this way it is possible to make an acceptable fraction of the images usable and therefore achieve a good overall telescope efficiency. These methods have already been demonstrated to give high resolution imaging in the I band [4,5] and a more recent observing run on the Nordic Optical Telescope (NOT) has improved further the quality of results obtained (Fig.2).

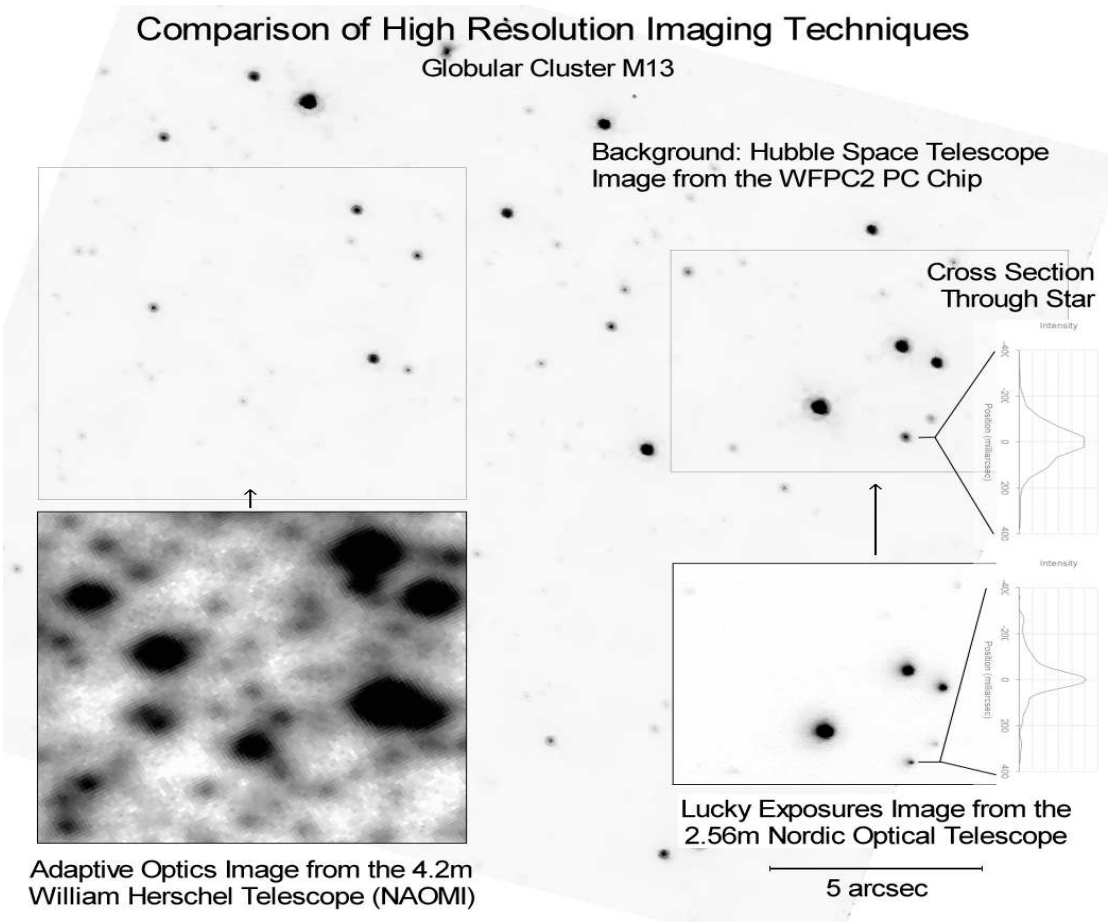

Fig. 2: Results from Lucky Imaging. The background is an image of the Globular Cluster M13, from the Hubble Space Telescope WFPC2 taken at 870nm. The full width at half maximum (FWHM) is about 0.12-0.15 arcsec. Below that on the left is part of the field imaged with one of the few AO systems working in the visible, NAOMI at 660nm, and images with a FWHM of ~0.4 arcsec. Below on the right is a Lucky exposure on the NOT at 810nm showing images with a FWHM of about 0.1 arcsec, better than the HST images because the Lucky images are better sampled.

Lucky Imaging requires a reference star within the isoplanatic patch that is bright enough to measure its Strehl ratio and therefore establish the quality of each frame being recorded. The method is extremely attractive because it can be used with natural guide stars since the star has to be bright enough within an aperture that is ~$7r_0$ rather than within an aperture of ~$2r_0$ which is typical in conventional Shack Hartmann AO sensors. This means that the reference star for Lucky Imaging will be approximately 3 magnitudes fainter than is needed for natural guide star AO work. This gives a relatively low probability of *not* finding a reference star near to any random science object whereas with a conventional AO system there is only a low probability of finding a suitable reference star. In addition the size of the isoplanatic patch is much larger with Lucky Imaging because it is related to the angle subtended by the diameter of the collecting area (~7 r_0 for Lucky but only ~2 r_0 for AO) at the characteristic height of the turbulent layer. This further increases the probability of finding an adequately bright reference star within the field of view of the system.

The results obtained so far have been very encouraging. We have obtained diffraction limited 810 nm images of faint objects using nearby reference stars brighter than I = 16 on a 2.56 m telescope[8]. The full width half maximum of the isoplanatic patch that the technique gave was found to be 50 arc seconds, giving an approximately 20 percent sky coverage for a suitable reference stars. The CCD which was used for this work was a front illuminated (non-thinned) device. With a back illuminated (thinned) device we should be able to work with stars that are approximately one magnitude fainter, substantially increasing the sky coverage percentage. We also predict that the isoplanatic patch we measure is reduced because the telescope we use is itself not diffraction limited, in common with most telescopes of this size.

The imaging system that we are using is very far from ideal. At present we need to record every frame onto tape for subsequent processing. This is somewhat eased because our camera is not able to run at very high pixel rates. An ideal camera system would achieve the full potential of the CCD read-out (in the region of 15 MHz for the CCD 65) and would also examine each frame as it is taken, in real time, to establish the Strehl ratio of the reference star (or indeed from a combination of several reference stars within the isoplanatic patch). It would then assign to each frame a quality parameter. Using the already accumulated best few percent of the images to establish the point spread function of the instrument and the telescope the system we would then carry out a real time deconvolution of the frames which are deemed to be of adequate quality for the purpose. These frames would then be stored for later addition into the total over the field of view. We are in the process of developing such a camera system which is described elsewhere at another session of this SPIE meeting[6]. Although this method makes considerable demands on real time image processing hardware there is little doubt that this is well within the capacity of presently available digital signal processor (DSP) chips.

So far we have only used a single CCD in the focal plane of a telescope. However there is no reason why the focal plane should not be populated with an array of devices all working independently. Each device would have its own moment of excellent seeing and would need to accumulate its own set of images rated in the above way in terms of quality. With simple mosaicing methods as have been used already with the CIRSI infrared camera system[7] it would be possible to cover fairly large areas of sky and achieve close to diffraction limited imaging in a reasonable amount of observing time. For example our simulations predict on the basis of the results we have already achieved that selecting 10 percent of images from a 1 hour total exposure we would achieve limiting (5 sigma) I band detection of approximately 25.0 magnitudes. By using an array of detectors we will be able to cover a substantial area of sky (fractions of a degrees square) in the equivalent of a single night of observations. With a 2.5 m telescope this would give a wide field imaging coverage with a resolution of approximately 0.1 arc seconds, something that we have no prospect of achieving by any other method than possibly re-engineering the Hubble Space Telescope. In addition we have the option of combining images after the event and therefore deciding whether we want the very best resolution at the expense of limiting sensitivity or whether we want to maximise sensitivity at the expense of resolution. The trade-off can be done later depending on the priorities of the observer. The technique of Lucky Imaging is extremely simple, particularly when compared with traditional AO systems. It uses no moving parts and a budgetary hardware cost of such a system is probably in the region of $20,000.

4. LARGE TELESCOPE LUCKY IMAGING

The results obtained above have been very exciting but can they be extended and applied to telescopes significantly larger than the 2.5 m instruments used for the above work? Firstly if we use an aperture that is significantly larger than the ~7 r_0 used in the above experiments then the probability of finding individual frames that are diffraction limited rapidly becomes vanishingly small. In I band, 7 r_0 corresponds to approximately 2.5 m but in K band (2.2 microns wavelength) then 7 r_0 corresponds to an aperture of 8.3 m (r_0 is proportional to $\lambda^{1.2}$). It is clear that the technique would work well with telescopes in the 7.5-10 m class at K band provided there were detectors available at this wavelength. Recent developments at

Rockwell (Thousand Oaks, California) have been directed towards developing fast read-out MCT detectors (1-5 micron response) with sub-electron readout noise. There is therefore a real prospect that the Lucky Imaging technique could be used in the near future on large telescopes in the near infrared.

However it would also be very interesting if we were are able to use these Lucky imaging techniques at much shorter wavelengths on 6-10m class and larger telescopes so as to give us significantly better resolution and can be achieved from the Hubble Space Telescope. The statistics of atmospheric turbulence show us that we could use any shape of aperture (and here we are thinking of groups of separate apertures) which together add up to the equivalent area of a 2.5 m telescope, and expect the same probability of obtaining individual frames with diffraction limited images were it not for the importance of the significant levels of turbulent power on large scales. The turbulent power is dominated by simple tip tilt, with focus and astigmatism being next in importance. We can conceive of an instrumental setup where a low order AO system is used to remove the largest scales of turbulence across a large diameter telescope so as to make the incoming wavefront phase-flat on scales larger than ~2.0 m. By reconfiguring the pupil plane of the telescope so that separate images are formed from groups of apertures each of which have an area of approximately that of a 2.5 m telescope we should achieve much the same probability of recording high quality images. Each of these separate images would have to be directed to separate detector systems. Each would have its own characteristic point spread function and each would accumulate as with the conventional Lucky imaging methodology its own set of images representing the different quality grades. These images would then be combined to give images which had the point spread function of the whole telescope. By careful choice of the positions of each of the apertures that make up an individual group it should be practical to achieve close to the diffraction limited imaging capability of the whole telescope. This method is very similar to that of aperture synthesis used by radio astronomers for many years.

Such an approach should be practical although more work is needed to demonstrate it fully. However what it does offer potentially is a method which would allow diffraction limited imaging on large diameter telescopes to be obtained without laser guide stars or with multi-conjugate adaptive optic systems both of which are are technically very challenging as well as being extremely expensive. With a large telescope using the Lucky method outlined above, the low order adaptive optic system will be able to work with natural guide stars because the characteristic scale over which the corrections are to be made is large and therefore the natural guide star needed for such a system can be quite faint (I~17 magnitude) giving a high probability of a suitable object being found in the field. In addition the isoplanatic patch of this method will be large, further increasing the probability that a reference star can be found.

The description above is clearly oriented very much towards direct imaging, whereas it is spectroscopy that is arguably of greater scientific importance on large telescopes. It is particularly spectroscopy that would benefit if high-resolution images could feed spectrographs. The method outlined above will not help if it is designed to feed a conventional slit spectrograph. However if one imagines a spectrograph that is fed with an Integral Field Unit (IFU) such as the one used in CIRPASS[8], and using a spectroscopic detector that uses L3CCD technology then the seeing fluctuations will cause the bright image core to jump from element to element, and the light from one element will sometimes be smeared over two of three adjacent elements. However in the same way as we select images for Lucky direct imaging we can select the best spectroscopic images and the use that information to deconvolve what is happening on the other fibres. In this way it should be possible to operate a fibre fed spectrograph in the way that it can benefit from the technique described above.

5. CONCLUSIONS

The development of essentially noiseless detectors in the visible, and the prospect of very low noise detectors in the near infrared, will undoubtedly revolutionise the design of large telescopes and the instrument that are used with them. They have a capacity for simplifying greatly the method used to achieve diffraction limited imaging at telescopes and in conjunction with L3CCD technology gives the promise of relatively simple approaches to imaging and spectroscopy close to the diffraction limit of these telescopes which would be available to scientists much more quickly than is likely to be the case for systems involving laser guide stars and multi-conjugate adaptive optics.

ACKNOWLEDGEMENTS

We are most grateful for the help and advice received from many at E2V Ltd. (formerly Marconi) in connection with the operation of the L3CCDs. We are also grateful to the Director of the Nordic Optical Telescope (NOT) on La Palma for making available telescope time for these tests.

REFERENCES

1. Mackay, C D, et al., (2001), "Sub-Electron Read Noise at MHz Pixel Rates", SPIE vol. 4306A, San Jose, January 2001,p289-298.
2. P. Jerram, P. Pool, R. Bell, D. Burt, S. Bowring, S. Spencer, M. Hazlewood, I. Moody, N. Catlett, P. Heyes, "the LLLCCD: Low Light Imaging without the need for an intensifier, SPIE vol. 4306, 2001.
3. Baldwin, J.E, Tubbs, R.N., Mackay, C.D., et al, (2001), Diffraction-limited 800nm imaging with the 2.56m Nordic Optical Telescope, Ast & Astrophys, vol. 368, L1-4.
4. Tubbs, R. N, Mackay, C. D., et al., (2002), "Diffraction Limited CCD Imaging with faint reference stars", Ast & Astrophys, vol. 387, L21-24.
5. Tubbs. R.N., Mackay. C.D., Baldwin, J. E., (2002), “Diffraction-limited I band imaging with faint reference stars”, SPIE 4839, Hawaii, August 2002.
6. Basden, A. G, Mackay, C.D., et al., (2002), “Low Read-Out Noise CCDs in Optical Interferometry”, SPIE 4838, Hawaii, August 2002.
7. Mackay, C.D., et al., (2000), CIRSI: the Cambridge infrared survey instrument for wide-field astronomy, Proc SPIE vol. 4008, 1317-1324.
8. Ian Parry, Craig Mackay, Richard McMahon, Alfonso Aragon-Salamanca, Andrew Dean, A. N. Ramaprakash, Jim Pritchard, Dave King, Rachel Johnson, Richard Ellis, Steve Medlen, Chris Sabbey, (2000), "CIRPASS - A NIR integral field and multi-object spectrograph", Proc SPIE vol. 4008, 1193-1202.