Application of L3 Technology to Wavefront Sensing

Simon Tulloch
Isaac Newton Group of Telescopes, Apartado 321, Santa Cruz de La Palma,
Islas Canarias, 38700, SPAIN

ABSTRACT

The new L3 Technology CCDs from E2V[1] combine sub-electron read noise with high pixel rates. This makes them ideal candidates for wavefront sensing. ING's NAOMI adaptive optics instrument is currently limited by the readout noise of its wavefront sensor CCDs. Upgrading to L3 detectors has the potential to give a large increase in performance; simulations suggest a 2 magnitude improvement to the guide star limit. At ING we have explored the behaviour of various L3 devices in applications ranging from fast photometry, fast spectroscopy through to wavefront sensing. The investigations have been done using our own cryogenic cameras containing L3 devices coupled to an SDSU controller. An integral Peltier packaged CCD60 has also been purchased specifically for the WFS upgrade. This paper describes the progress we have made to date on the L3 wavefront sensor upgrade and our future plans for its use with a Rayleigh laser beacon.

Keywords: L3 CCD WFS Adaptive Optics ING NAOMI

1. INTRODUCTION

1.1 The L3 Multiplication Process

The best conventional CCDs have a readnoise between 2 and 3e RMS. To achieve this requires slow pixel rates incompatible with wavefront sensing where hundreds of frames per second are needed. More typically the WFS noise is at least twice this figure. The new L3 technology from E2V produces an on-chip amplification of each photo-electron before it reaches the output mode of the CCD for measurement. The amplification takes place within an extension to the horizontal register (see Fig.1.) A voltage of between 20 and 45V, depending on the gain required, is applied to one of the clock phases and pixel charge packets entering this phase experience avalanche multiplication, reaching the output node amplified by a factor of up to 10,000 . At gains of over several hundred the intrinsic amplifier noise then becomes insignificant, even at very high pixel rates. Under low levels of illumination it even becomes possible to see *single* photon events.

1.2 The Ideal Wavefront Sensor

As with science detectors, a high QE is essential. Equally important is low noise and high pixel rates since WFS guide stars are faint and atmospheric turbulence rapid. These last two requirements are generally mutually exclusive and it is here that L3 technology breaks the mould by decoupling read noise from pixel rate.

1.3. Drawbacks of L3 Technology

The L3 process actually gives a low probability of avalanche multiplication and it is necessary to chain together 520 individual amplification stages to give a useful gain. The statistics of this low gain process imply a loss of SNR in high signal regimes. The consequence is that Poissonian statistics, whereby the standard deviation of the signal increases as the root of the mean signal, no longer hold. Instead the standard deviation increases as $\sqrt{2}$ times the mean of the signal. One effect of this is that the histogram of an L3 flat field image appears broader than expected, as shown in Fig 2. The effect is called 'Multiplication Noise' and it has the same impact on system throughput as a halving of QE. At the lower signal end, however, the elimination of read noise more than makes up for this loss, as shown in Fig.3. L3 chips are not entirely noise free since other low level noise sources not usually visible in a conventional CCD can become troublesome.

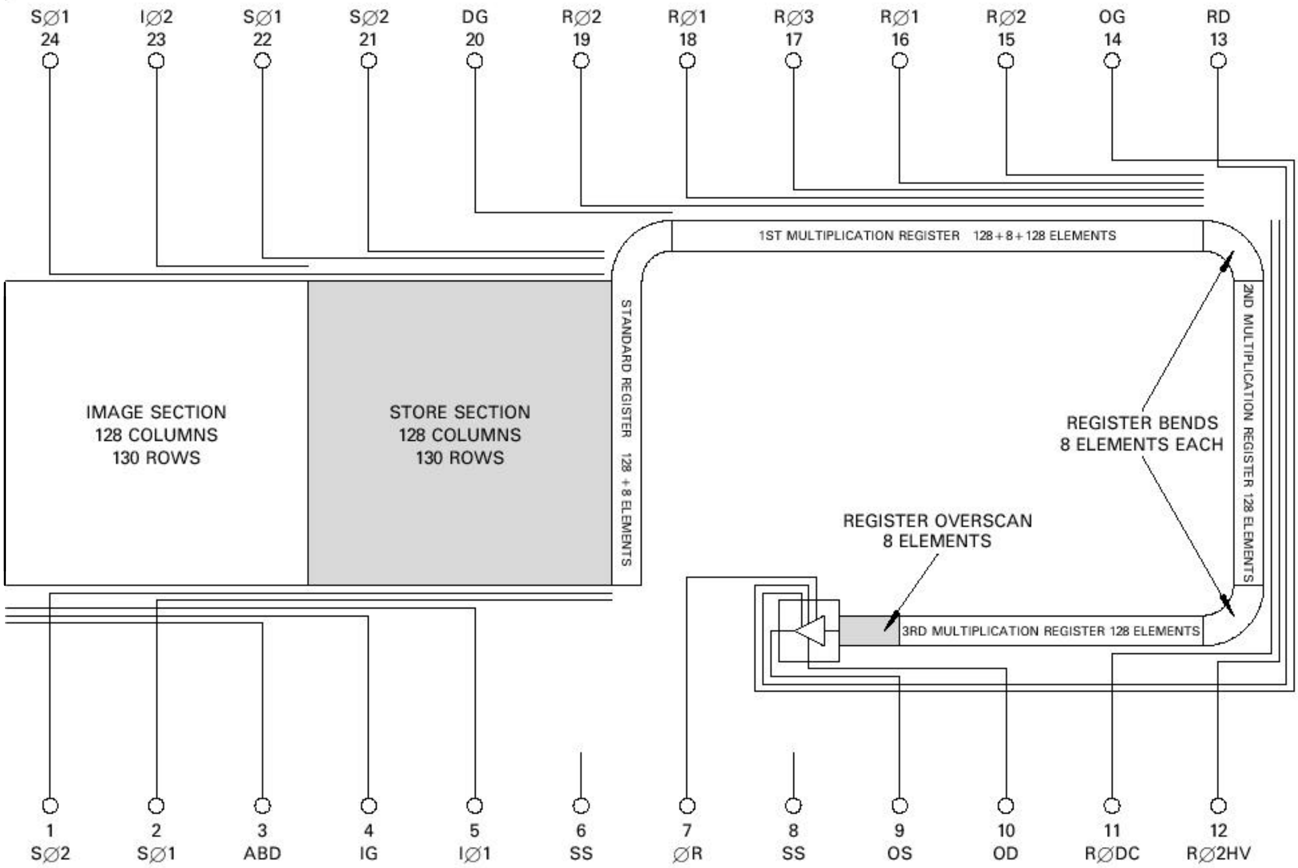


Fig. 1. The CCD60 showing the geometry and position of the multiplication register (E2V Technologies).

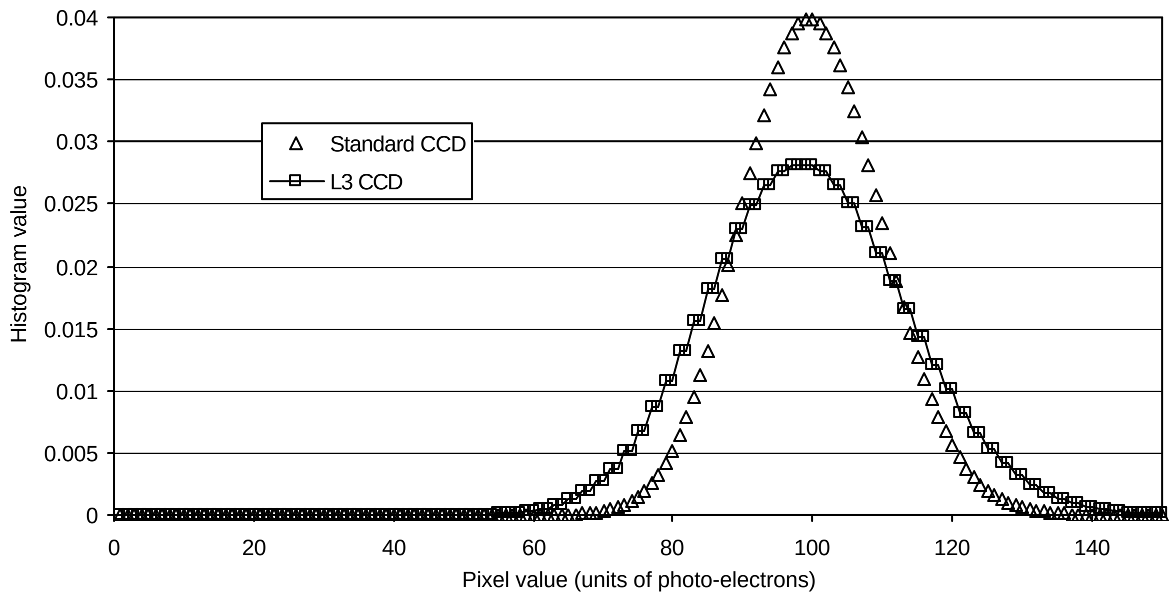


Fig.2. Histogram values for a flat field of mean illumination 100 photo-electrons, showing the effect of multiplication noise.

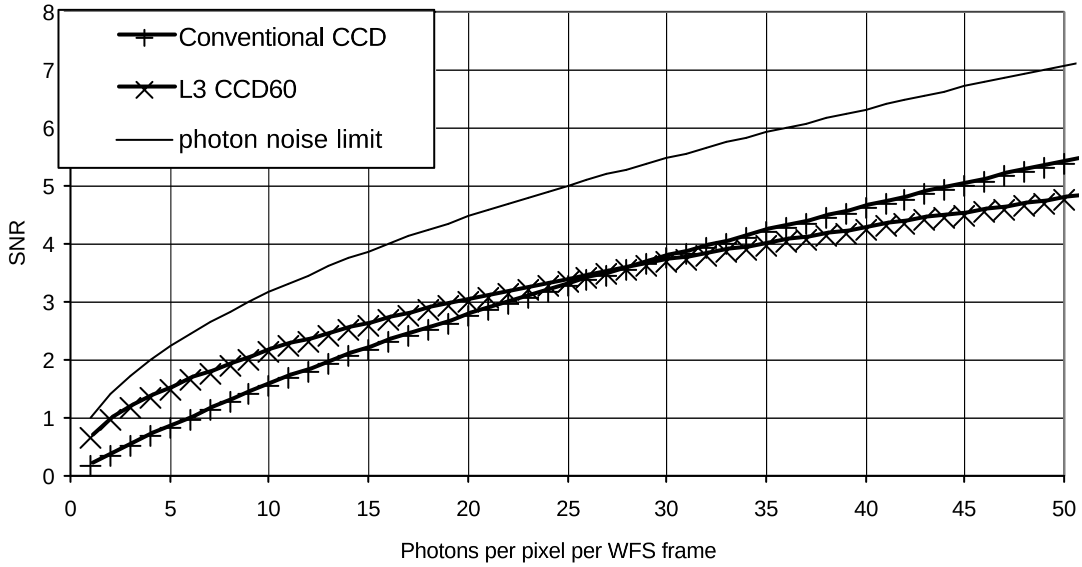
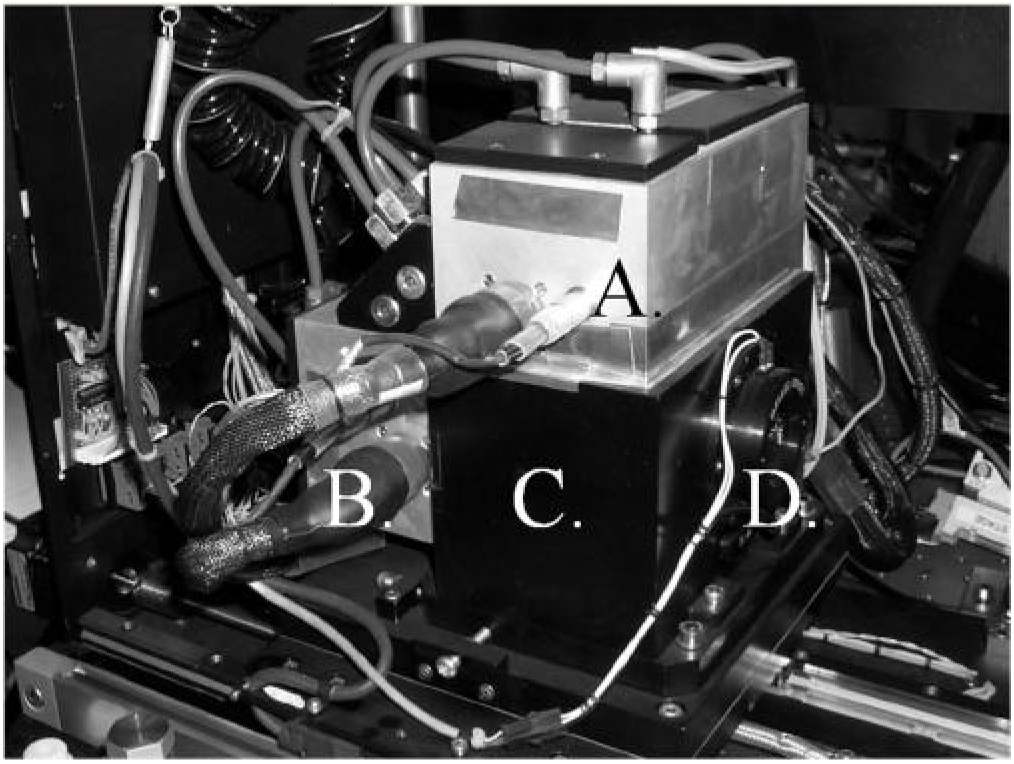


Fig.3 SNR Improvements at low signal levels with L3 sensors. Conventional CCD assumed to have 5e noise.

One of these noise sources is Clock Induced Charge (CIC) whereby a rising clock edge can actually produce spurious electrons in the detector that appear as true photo-electrons. The clock edges must be carefully set up to minimise these effects. It has also been noticed that L3 chips suffer from a lower horizontal charge transfer efficiency than we have come to expect of science grade detectors. Fig. 12. shows the appearance of CIC in a cut through a CCD60 image.

1.4. Isaac Newton Group AO System Design

The ING natural guide star adaptive optics instrument is called NAOMI and at its heart is a 76 element segmented deformable mirror (DM). Each segment is free to move in tip, tilt and piston and is driven by piezo-electric actuators that have integrated strain-gauge feedback sensors. The optical train also includes a tip-tilt mirror for compensating low order overall wavefront tilts. The wavefront sensor unit, shown in Fig.4. contains a Shack-Hartmann (SH) lenslet array projecting a 10 x 10 SH spot array onto two separate CCD39 detectors. These two detectors each receive half of the SH light by way of an amplitude splitting beam splitter, although it is possible to slide this out of the optical path so that all light falls onto one chip only. This latter option has been used exclusively with the result that the other head has been made redundant. The original justification for two heads was that it allowed higher frame rates, with one detector measuring X centroids and the other Y centroids, however, the higher speed modes have never been required. Pixel data is first transmitted via fibre to a VME receiver card and from there via an RS422 link to an array of C40 DSP processors that do the centroiding and wavefront reconstruction. This data path is described in more depth by Goodsell[2].



A: Redundant CCD39 WFS Head (To be replaced by L3 CCD60) B. Active CCD39 WFS Head
C: Beam splitter housing D. Input port/shutter

Fig. 4. The current NAOMI WFS Unit

2. L3 TEST CAMERA DESIGN

2.1 Test Cryostats

On paper and in computer simulations the L3 chips looked very attractive so an L3 CCD60 detector was purchased and mounted in an LN_2 cryostat (Fig.5.) for imaging tests. At the time of purchase no Peltier packaged device was available, although these are now on the market. The camera was coupled to a modified SDSU II controller which contained an extra circuit board specially designed to generate the high voltage multiplication clock not normally available in these controllers. The camera cryostat used a standard mechanical interface and it was possible to make some on-sky observations[3] of a pulsar to augment the lab-based tests. No on-sky wavefront sensing has yet been done with the L3 detector.

2.2 Camera Controller

A standard SDSUII can supply all but one of the bias and clock signals that the L3 devices require. The multiplication clock needs to have a swing of approximately 40V to get a useful L3 gain and this is above what the SDSU can supply. Fortunately E2V also sell a high voltage clock module that is small enough to fit in a spare slot within the SDSU controller and requires only a 16V rail that can be found on the controller backplane. Clock and gain control signals to this board were made from the unmodified SDSU clock and video boards. The operation was therefore flexible and fully configurable from software. All the test data was obtained using this board but we have since developed our own multiplication clock driver using DC-DC converters and high speed MOSFET transistors to do the same job.

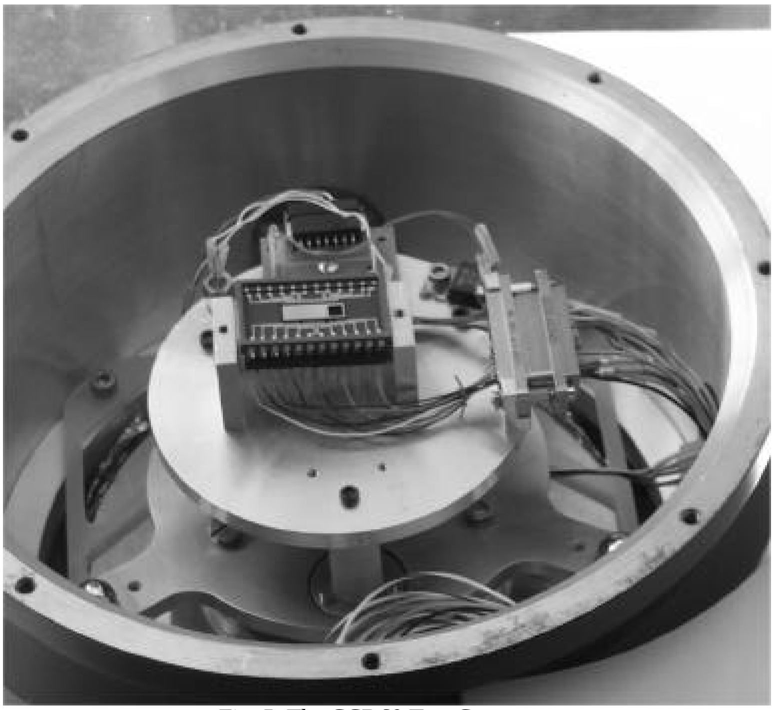


Fig. 5 The CCD60 Test Camera

3. L3 TEST CAMERA PERFORMANCE

3.1 Readout Speed

The NAOMI SH sensor contains a 10 x 10 micro lens array, of which only the central 8 x 8 are actually used for centroiding and DM control. The micro lenses are mounted in a wheel for rapid interchange with other lower order arrays. The spacing of the SH spots on the CCD is 8 pixels. A window of 4 x 4 pixels is defined around each of these spots so the total pixel count is 1024 per frame, if we consider only the active pixels. NAOMI has other wavefront sensor modes, some with binning that reduce each spot measurement to a simple quad cell read as well as accommodating the lower order micro lenses. The 1024 pixel per frame mode is the most common and was chosen as the most representative for the laboratory tests. These involved imaging a perforated screen onto the L3 sensor with a simple doublet lens. The screen contained a 10 x 10 array of pinholes that were illuminated from behind. The resultant CCD image was a good simulation of a real micro lens array. The screen image was used to confirm that the windowing algorithm implemented in the SDSU controller was working correctly. The image data was acquired using the CCDTool Data Acquisition System (DAS) that comes bundled with the controllers. The NAOMI WFS DAS was not used but as the bottleneck on pixel rate is the SDSU controller, rather than the DAS, any speed measurements made with CCDTool will still be valid. Exact timing of the frame rates was done using an oscilloscope connected to the CCD clock lines. Each frame actually contained a short ‘movie strip’ of 10 separate exposures (Fig. 6) acquired contiguously. This not only made the ‘scope measurements easier but also allowed the image quality in continuous TV style readout to be more accurately assessed. The frame rate when reading all 10 x 10 SH spots was 211Hz, increasing to 320Hz when only the central 8x8 were read out.

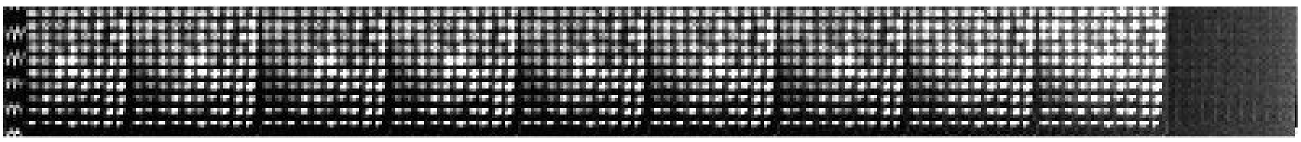


Fig 6. Short movie strip of 10 windowed CCD60 SH images. Frame rate 211Hz.

3.2 Readout Noise

The CIC was at a very low level and it was necessary to sum together 300 bias frames to obtain a good measurement. Each frame was first bias subtracted (the bias level was automatically measured for each frame by histogramming the pixels and identifying the histogram maximum) before being added to the sum. CIC in the CCD60 test camera amounted to a tiny 0.2e per pixel per readout. The intrinsic amplifier noise was in all cases completely negligible.

3.3 L3 Gain Stability

The gain is very volatile. It rises considerably with only a small change in multiplication clock voltage. There is also a strong temperature dependence; the gain rising as the CCD is cooled. Fig. 7. shows some data obtained with the CCD60 test camera at two different temperatures across a range of gains.

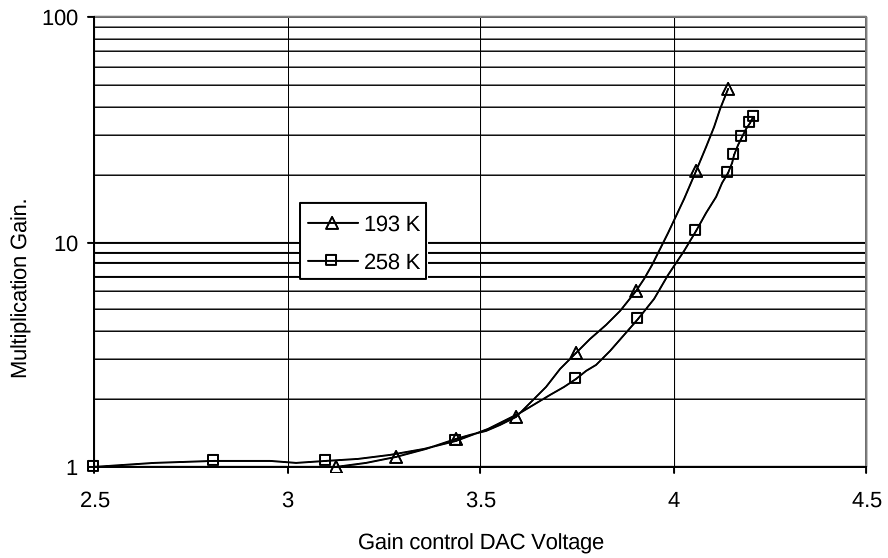


Fig.7. Temperature dependence of L3 gain.

In practice temperature dependant gain changes are unlikely to be a problem since the WFS and its electronics sit in a temperature controlled environment required primarily for the stability of the optics. The graph above shows the control DAC voltage along the x-axis rather than the actual multiplication clock voltage. A DAC voltage of 3.7V corresponded to a 40V multiplication clock amplitude. The L3 gain can also be greatly affected by the relative timing of the multiplication clock and the H1 clock. Multiplication occurs when H1 makes a high to low transition. The multiplication clock must be stable at its high level before this transition occurs; even small mis-timing between these two clocks can have a large impact on gain. E2V also report that the L3 gain may be subject to ageing.

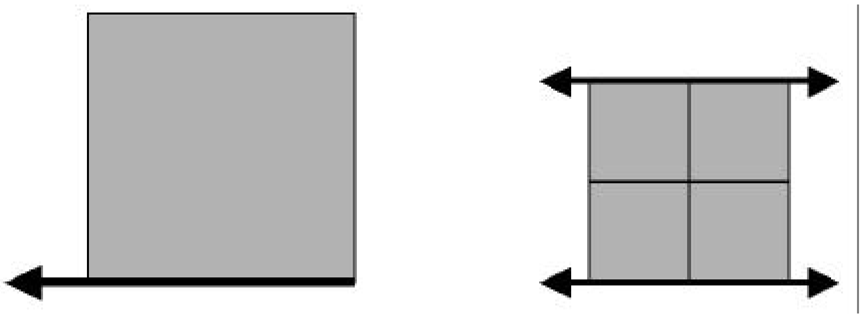
4. L3 UPGRADE PLAN

4.1 Upgrade of current NGS sensor

The short term plan at ING is to make use of the space occupied by the redundant CCD39 WFS head and mount in its place a recently available Peltier packaged L3 CCD60. The existing 50:50 beam splitter will then be replaced with a fully reflecting mirror. The mirror will be mounted on a slide. When in its ‘out’ position the SH light will pass through as normal, directly onto the standard CCD39. For L3 tests it will be slid to the ‘in’ position. The CCD60 package envelope is smaller than the CCD39 so we are manufacturing a mechanical copy of the original head (Fig.8) with only small modifications. The set-up is ideal in that we can quickly switch between systems for a balanced evaluation of the L3 merits.

Fig.8. The CCD39 WFS head built by the ATC

The CCD39 is a 4 quadrant device with 4 output amplifiers, whereas the CCD60 has only a single amplifier (Fig.9). This causes problems with the format of the pixel data since the C40 adaptive optics processor expects interleaved pixel data from 4 quadrants.

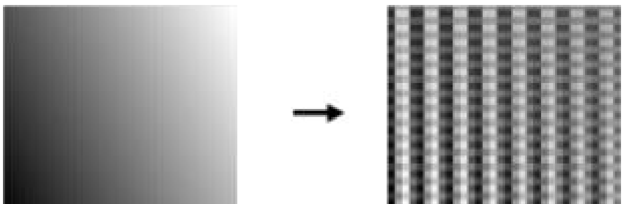


CCD60
128 x 128 x 24µm pixels

CCD39
80 x 80 x 24µm pixels

Fig.9. Readout amplifier formats of the WFS CCDs

If the L3 WFS behaves as expected then a rewrite of the C40 DSP code will be justified but in the first instance it was decided to reformat the CCD60 pixel data within the SDSUII controller so that it appears to the C40 to be coming from the original CCD39 detector. The SDSU can reformat a 1Kpix image in this way in 140µs if the algorithm is executed in internal processor RAM. The reordered data then needs to be transmitted over the fibre optic and this took approximately 1.2ms. With some optimisation it is expected that the total overhead for 'quadrantising' of data will drop below 1ms. The frame rate in the 8x8 SH spot mode (4x4 pixel window defined around each spot) will then drop to 250Hz. More efficient architectures can easily be proposed but the chosen one offers a fast track test of the suitability of L3 technology. Fig.10. shows input test data and the output of the quadrantising algorithm. When the quadrantised image was transmitted to a DAS set up to expect quadrant data (in this case CCDTool), the image was indeed correctly displayed.



Input test frame
Output of SDSU 'quadrantising' algorithm

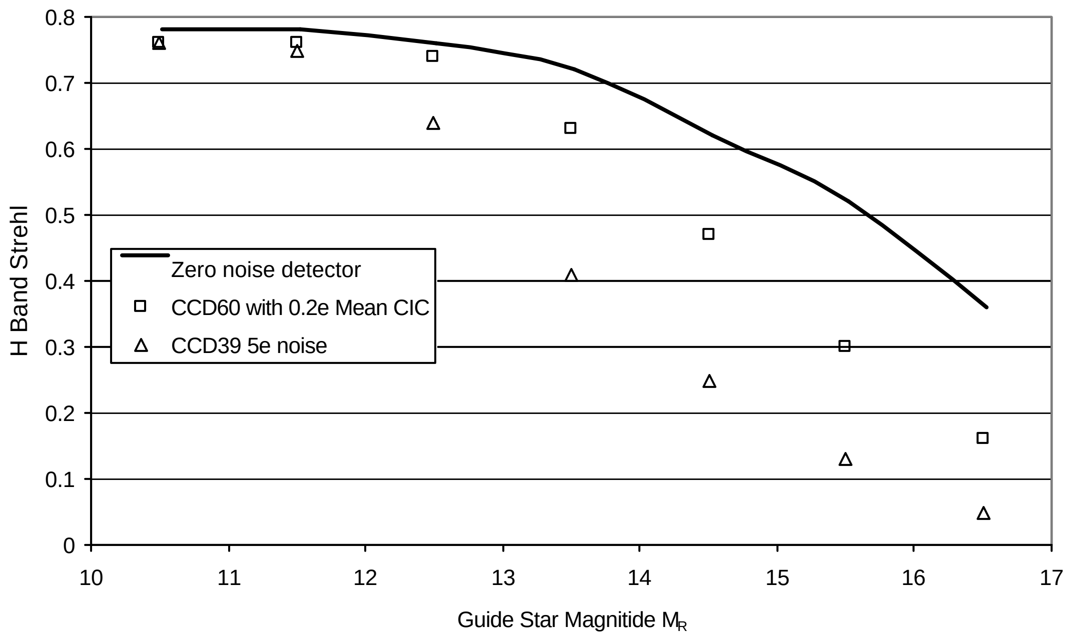
Fig.10. Pixel data is reformatted inside the SDSU to emulate a 4 quadrant readout

4.2 Use with ING Rayleigh Laser Beacon

ING has recently been awarded a grant for the development and commissioning of a Rayleigh Laser upgrade for NAOMI. This is named the Ground Layer Adaptive Optics System (GLAS)[4]. GLAS aims to use a 30W pulsed laser and a fast electro-optic shutter to define a Rayleigh Laser beacon 20 km above the William Herschel Telescope. This should increase the sky coverage from a few percent to almost 100%. As with all laser beacon systems a natural guide star (NGS) is also required to remove the atmospheric tip-tilt terms to which the Rayleigh laser is insensitive. The GLAS upgrade therefore requires two WFS systems, one SH sensor for the laser beacon and one tip tilt sensor for the NGS. Given that the laser may be launched in any direction on the sky, the NGS sensor will need to observe much fainter stars in order to have a high probability of finding one in any randomly selected search area. This will be partly offset by the fact that the NGS is observed with the full telescope aperture rather than through one of 64 sub-apertures as is the case with the SH, but there is still a case for using an L3 NGS sensor. The plan is to continue using the upgraded CCD60 WFS head to observe the NGS. Since it will be imaging just a small window placed around the star, as opposed to the full matrix of SH spots, very rapid readout should be possible. The laser beacon SH spot array will then need to be measured using a second WFS head in a separate branch of the optical train. This could be the original CCD39 head, made redundant by the CCD60 upgrade, or it could be a second Peltier cooled CCD60; we have yet to decide.

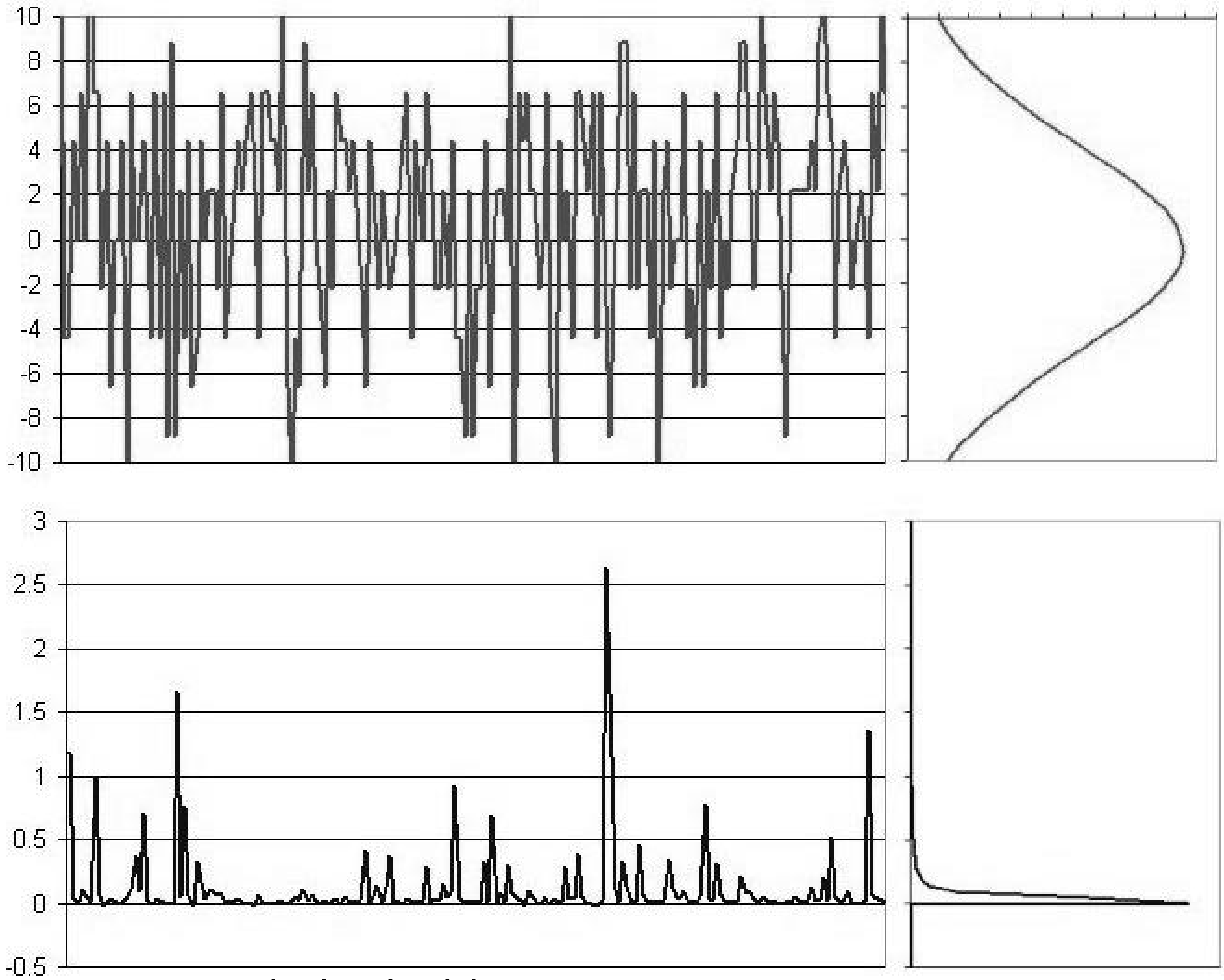
5. MODELLING OF ON-SKY L3 PERFORMANCE

Richard Wilson of the University of Durham has developed a model of the NAOMI AO system on the WHT. It incorporates the noise and QE characteristics of the CCD39 WFS but has been modified slightly to predict the likely performance of an L3 NGS SH sensor. To account for the multiplication noise, the QE of the L3 chip was taken to be half its actual value. Accounting for the CIC was rather less straightforward due to the 'spiky' nature of this noise source. The mean level of the CIC was 0.2e per readout, however, it would be wrong to incorporate this into the model as representing 0.2e RMS of read noise since it is clearly non-Gaussian and also non-symmetric (see Fig.12). To be more accurate, the model instead used pixel noise values extracted at random from a real bias image file.



Model assumes typical La Palma turbulence conditions [5]
Exposure time optimised for each guide star magnitude.
Zero non-common path errors with AO system assumed.

Fig. 11. Expected gains from using an L3 CCD WFS on the William Herschel Telescope.



Plots along 1 line of a bias image | Noise Histograms

Fig. 12. Comparison of noise traces in a conventional CCD (top) and L3CCD (bottom). Vertical scale is in electrons.

The model predicts considerable gains from using L3 technology. It should be noted that the level of CIC is expected to drop once the CCD60 has been further optimised, for example an L3 CCD operated by the University of Cambridge IoA has a CIC level of only 0.004e per pixel per readout. The model (Fig.11) shows a 1.5 magnitude gain but the final result is likely to be closer to 2. The model optimises the integration time for each guide star magnitude. This varies from 5ms at M_v11.5 to 20ms for M_v16.5 : well within the range of the SDSUII. The assumption that the non-common path errors within NAOMI are zero is rather optimistic but this in no way reduces the relative gains to be made by the switch to an L3 sensor.

CONCLUSIONS

The lab based imaging tests and computer models show that the L3 CCDs can give a significant improvement in guide star limit of approximately 2 magnitudes. This has the short term potential of increasing the sky coverage of our current NGS WFS by as much as a factor of 4 and in the longer term of improving the performance of the planned GLAS Rayleigh beacon AO system. The CIC noise source in the WFS detector must be minimised by careful shaping of the clock waveforms if the full potential of L3 is to be realised. Although the integrated contribution of CIC in the test camera was only 0.2e per pixel per frame, it had a disproportionate impact on the WFS centroiding algorithm due to its impulsive nature. The readout speed of the CCD60+SDSUII system (approximately 250Hz) is adequate for proving the worth of L3 technology but may benefit from the use of a newer controller such as the SDSUIII.

ACKNOWLEDGEMENTS

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