A visible/infra-red Low Noise, Fast Readout Wavefront Sensor for all-sky Adaptive Optics

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ABSTRACT

Current adaptive optic systems are limited by the read noise and sensitivity of their wavefront cameras. Recent advances in substrate thinning are producing focal plane arrays with high quantum efficiencies and extended spectral response over 0.5 to 1.6 microns. Infra Red Laboratories have developed and tested a new ultra-low noise readout integrated circuit (ROIC) that has a performance of 2 electrons (r.m.s.) per pixel read. We combine these two technologies to produce a new detector capable of dramatically increasing the number of available natural guide stars across the sky (and hence increased sky coverage), even in heavily obscured regions near the Galactic plane.

Keywords: wavefront sensors, infra-red arrays, VisGaAs

1. INTRODUCTION

Low noise infra-red detectors have the potential to revolutionize the capability of current adaptive optics (AO) systems and long baseline interferometers. Current systems are severely limited in sky coverage due to the limiting magnitude attainable with current wavefront sensors, and we show that by decreasing the read noise and broadening the spectral responsivity of the detector, we can access fainter guide stars and so enable a broader range of science goals. We explain the technical details behind these new detector developments and describe the combination of new technology that will increase the detection limits attainable.

2. TOWARDS ALL-SKY ADAPTIVE OPTICS WITH NATURAL GUIDE STARS

2.1. AO Wavefront sensors

The image quality at ground-based telescopes in the visible and near infra-red is limited by rapidly changing wavefront distortions introduced as the atmosphere crosses the telescope aperture. Adaptive optics (AO) systems use a deformable optical element to counteract and minimize these atmospheric effects, and these must be measured and corrected for on the timescales of milliseconds. A wavefront sensor measures the achromatic optical path difference introduced by the atmosphere by looking at a point source as a reference - typically a nearby star or a laser beacon projected up along the axis of the telescope. These are referred to as “Natural Guide Stars” and “Laser Guide Stars” (NGS and LGS) respectively. The dynamic nature of the atmosphere requires short exposure times to “freeze” the effect of the atmospheric turbulence, and so relatively bright guide stars are needed to provide a high enough signal to noise level on the wavefront sensor. Since these arrays are read out rapidly, the dark current is not a significant contribution, and the limiting sources of noise are the photon shot noise and the read out noise from the array’s electronics.

Nearly all modern AO systems on large telescopes measure the wavefront in the visible band and use charge coupled detectors (CCDs) to sense the photons, where the read noise is typically 3 to 5 electrons per pixel read out, at a rate of typically 100 to 500 Hz. These short exposures limit the number of photons detected per read, and so guide stars of visual magnitude 14-16 or brighter are required for AO correction. The magnitude limit

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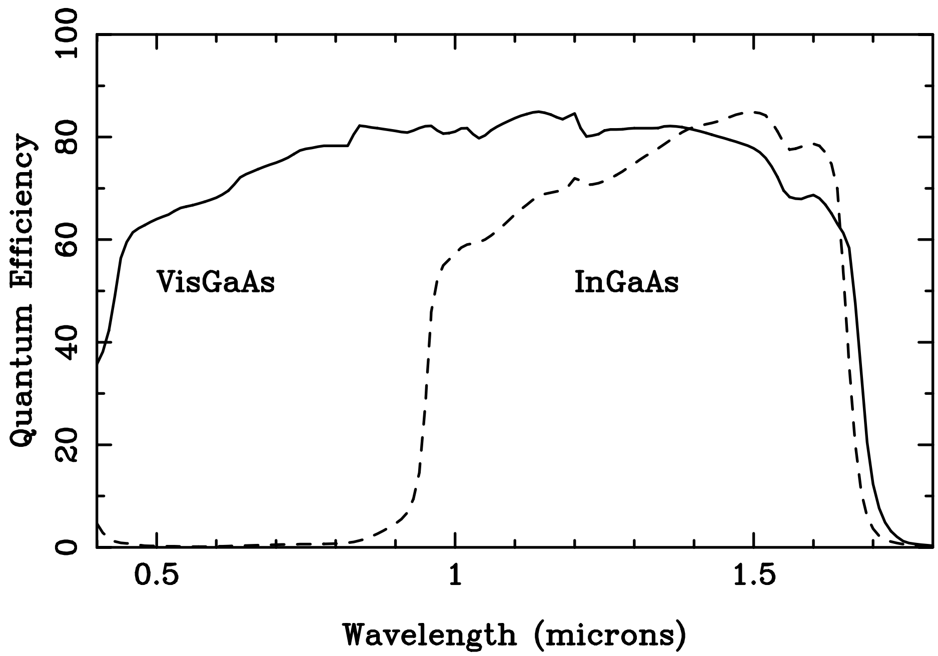

Figure 1. Measured quantum efficiency of Visible/GaAs compared to InGaAs. The peak quantum efficiency of the Visible/GaAs detector is 85%.

can be increased by either slowing down the wavefront sensor readout rate and/or decreasing the read noise in the detector.

The degree of AO correction falls off as a function of distance from the guide star, and this is characterized by the **isoplanatic angle**, which varies as a function of wavelength and the local sites atmospheric conditions. For infra-red wavelengths, this isoplanatic patch diameter is typically 40 to 80 arcseconds at H band ($1.65\mu m$). The Keck AO system has measured an isoplanatic angle of 48 arcseconds radius on one particular night,[1] whilst the VLT have reported closer to 30 arcseconds on one of their typical nights. With our MMT NGS AO system, we have measured an isoplanatic angle of 25 arcseconds on a night of poor seeing. One therefore needs an NGS sky density of approximately one NGS per square arcminute to cover the whole sky.

One example of a current state of the art NIR wavefront sensing is the VLT NAOS AO system, a Rockwell IR array with a Shack-Hartmann wavefront sensor. The system uses a 7 by 7 subaperture division to reach 9 to 12th magnitude in J and H, limited by the read noise of about $10e^{-}$on the detector and the throughput of the system.

2.2. Estimate of Magnitude Limit for Visible-Infrared Wavefront Sensors

To predict the limiting magnitude of guide stars using various detectors we have gone through the following calculations. We have estimated the quantum efficiency for a visible-infrared (VisIR) InGaAs using measurements from Indigo Systems (see Figure 1 for the VisIR quantum efficiency curve). We have approximated the total throughput of the system by using the atmospheric transmission model ATRAN[2] and additional factors which take into account reflection losses from wavefront sensor optics. The resulting throughput for the calculation is shown in Figure 2.

We carry out the calculation for a speed of 100 Hz (10 ms) integration time. For the calculation we assume the wavefront sensor will have 1 m subapertures. Under moderate seeing conditions and wind speed (0.8 arcsec and $v = 10m/s$) this is expected to yield an H band Strehl of 10% or a K band Strehl of 28%. This is consistent with actual observations using the MMT AO system.

To understand the photon rate from a star we must both know its magnitude and its color. For this calculation we assume the guide stars are blackbodies with spectra corresponding to their effective temperature. The photon

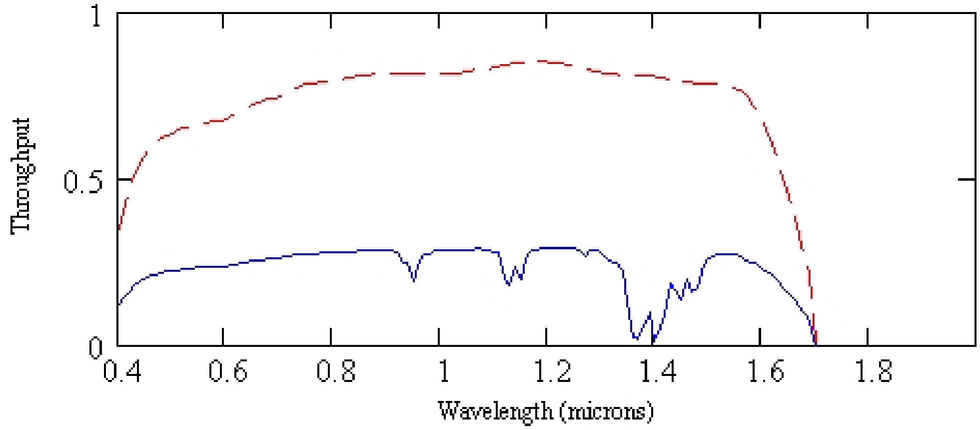

Figure 2. The quantum efficiency (dashed line) and total throughput (solid line) for the limiting magnitude calculation of a VisIR wavefront sensor system.

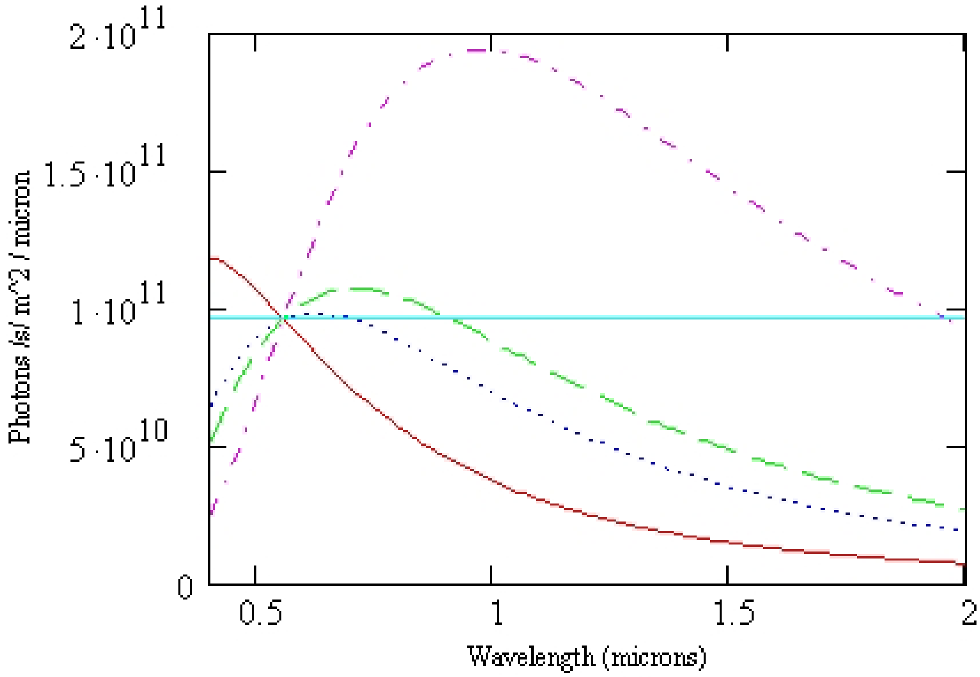

Figure 3. Photon blackbody flux curves for 0th magnitude A0 (solid), F0, G0, K0, and M0 (dot dashed) stars.

flux curves shown are normalized to the photon rate of $9.6 \times 10^{10} photons/s/m^{2}$[3] for a 0th magnitude A star. Figure 3 shows the photon rate from stars ranging from A0-M0.

Typical field stars have a color corresponding to a $T = 4100K$ blackbody, very close to a K4 spectral type, consistent with being the most numerous spectral type in the Galaxy.[3] Using this as the reference spectrum for estimating the limiting magnitude of a Vis/IR detector and assuming the wavefront sensor is a Shack Hartmann design with quad cells for subapertures, the signal-to-noise (SNR) can be written as[4]:

$$SNR = \frac{n}{\sqrt{n + 4R^2}}$$

where n is the number of photons per subaperture and R is the read noise (in electrons) for the detector. The design for the Vis/IR system will be a pyramid wavefront sensor[5] to take advantage of the additional sensitivity that a pyramid approach provides for faint guide stars[6] but the above equation still provides a conservative indication of the limiting magnitude.

Using the above parameters and assuming a limiting SNR of 3 for the subapertures we can calculate that the limiting magnitude for the Vis/IR sensor is approximately V=18.0 for a readout noise of $5e^-$. If we are able to achieve a readout noise of $2e^-$ the magnitude is V=18.7. Since the planned detector will have nondestructive read capability, we may be able to use multiple reads to reduce the noise to less than $1e^-$. For this optimum case we can expect a guide star sensitivity of V=19.2. We still expect approximately 20 photons per subaperture per integration time for this magnitude.

We have not considered OH sky background photons in the SNR calculation. The typical brightness of the OH background suggests the number of photons should be similar to the number of stellar photons for a $V \sim 18$, K4 star. Although this may slightly reduce the sensitivity of the WFS we still expect significant improvements over existing approaches.

As a check on the above calculation, we have also carried out the same procedure for our existing CCD-based wavefront sensor on the MMT AO system. The system has been used to carry out AO correction using guide stars as faint as approximately V=14.5. The CCD has a read noise of $7e^-$, subapertures of 0.5m and a slowest speed of 110 Hz. The calculation described above predicts a limiting magnitude of V=14.8 assuming an $T = 4100K$ guide star. For these parameters we expect 75 photons per subaperture, and we have confirmed this in examining frames from our current wavefront sensor.

Typically a pyramid sensor will allow for an extra magnitude of sensitivity. Unlike a Shack-Hartmann sensor, the pyramid wavefront sensor increases its signal to noise as the AO loop is closed and the image fidelity increases - both of these points are discussed in Section 3.3.

2.3. Expected Sky Coverage with a Vis/IR Wavefront Sensor

To understand the expected density and color of guide stars we use the 2MASS reference fields.[7] The number of stars down to a given magnitude per square degree are shown in Figure 4 for a field at the North Galactic Pole and one in the galactic plane at $l = 55, b = +0.9$. The three sets of points show the results for J, H, and K band detections, with a roll-off at 15th magnitude due to the incompleteness limit of the 2MASS surveys. Looking at the North Galactic Pole in the direction of least extinction, the average $J - K$ color of a field star is approximately 0.9. This corresponds to the spectral type of a K4 star with an effective temperature of approximately $T = 4100K$.

Near the galactic plane, the number density of stars is considerably higher. Stars near the plane of the galaxy have their spectral energy distributions significantly modified by the presence of interstellar dust. This absorption is strongly wavelength dependent, significantly so in the visible bands where most NGS wavefront sensors work. This trend can be seen clearly in the difference in number counts between the J, H, K bands in the right hand plot of Figure 4. The average $J - K$ color of stars in this field is ~ 1.5. The extra color is due to interstellar reddening by dust in the plane of the Galaxy, and this corresponds to a $V - K$ extinction of 3.4 magnitudes, meaning that for a star with $K = 15$, a typical field star would have a V magnitude of 21.45 - unreachable by any visible WFS sensor. Our VisIR detector can integrate light from V band through to H band,

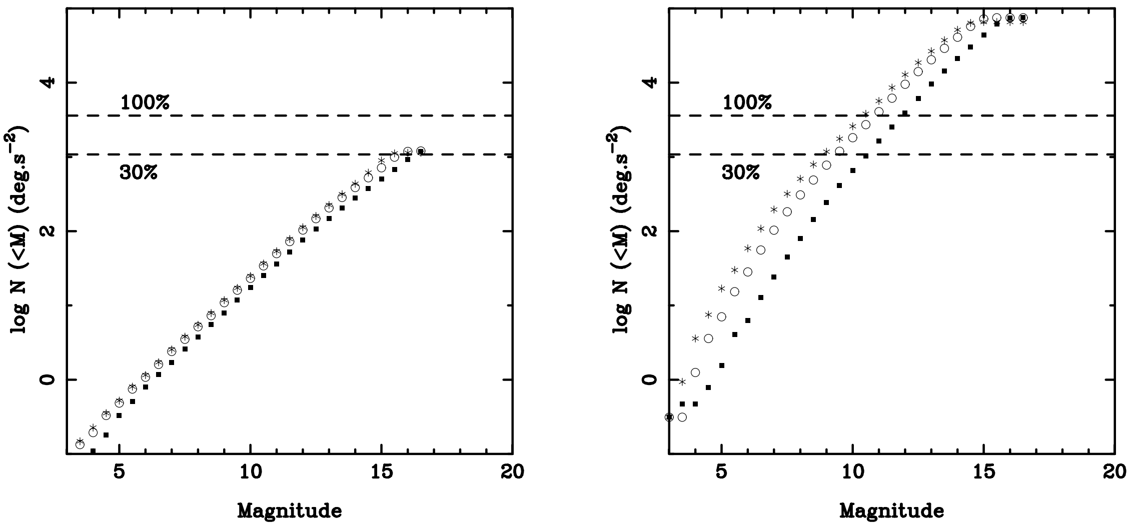

Figure 4. J, H and K band star counts from the 2MASS Point Source Catalog. The left plot shows the North Galactic Pole, the right plot is from a field in the Galactic plane. The two dashed lines represent the fraction of NGS AO sky coverage assuming an isoplanatic patch diameter of 1 arcminute. The roll-off in the star counts at 15th magnitude represents the detection limit of the survey. J are filled squares, H are circles, and K the stars.

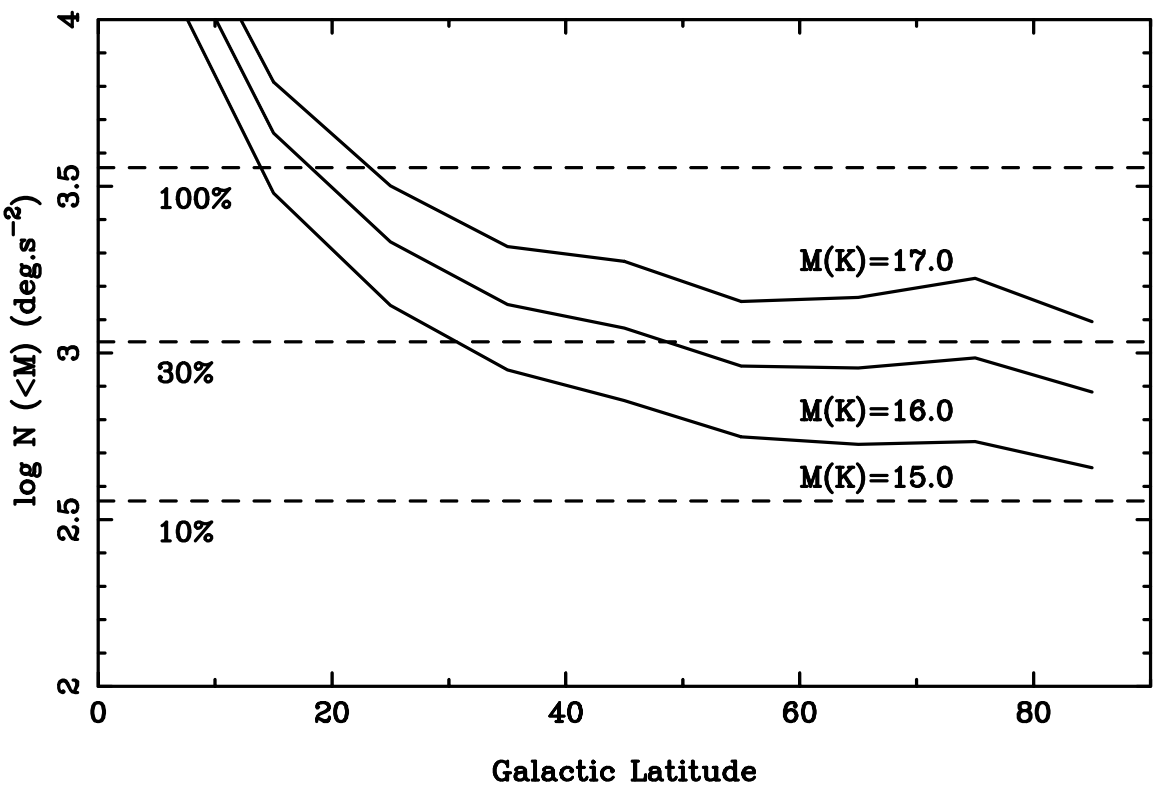

Figure 5. The number of stars brighter than a given K-band magnitude as a function of Galactic latitude. The K band star counts are extrapolated from the 2MASS Point Source Catalog. The dashed lines indicate the fraction of NGS sky coverage assuming complete coverage with one NGS per square arcminute.

meaning that even for heavily extincted regions in the plane of the Galaxy, we can find a suitable natural guide star in the near infra-red.

For reasonable adaptive optics correction the guide star must be within the isoplanatic patch of the object of interest. The size of the isoplanatic patch is set by the average height of the turbulence above the telescope. This can vary depending on observing conditions, but we can expect to get reasonable correction for guide stars within 30 arcseconds of the science object for K band observations. Roughly, we would like to have a guide star density greater than 3600 stars / square degree in order to ensure a guide star within the isoplanatic patch of a randomly placed science object. The lines for 100%,30% and 10% sky coverage at 1 star per square arcminute are shown on Figure 5.

We can also derive stellar density from the 2MASS Source Point Catalog. Looking at the North Galactic Pole (the worst case scenario for field guide stars) we find that at a magnitude of $K = 15$ ($V = 18.05$ assuming a K4 star) there are 500 stars per square degree. Log N is increasing at approximately 0.33 per magnitude, and so if we reach a limiting magnitude of V=19.2 (corresponding to a VisIR detector read noise of $1e^{-}$) using the VisIR sensor on average we will be able to lock on one in 3 fields at high latitude, and for the half of the sky containing the Galactic plane we expect to be able to find a guide star wherever we wish to look.

3. THE COMPONENTS OF A LOW NOISE, RAPID READOUT VISIR WAVEFRONT SENSOR

A VisIR wavefront sensor consists of three distinct technologies to improve the limiting magnitude. An ultra-low noise readout multiplexer will lessen the number of photons needed to measure the wavefront. A detector with broad spectral coverage both shortward and longward of 1 micron wavelength will make maximum use of the available photons. Finally, a pyramid based wavefront sensor will detect wavefront aberrations with improved sensitivity compared to the more common Shack-Hartmann approach.

3.1. Low Noise Readout-Integrated Circuit

Infrared Laboratories, Inc. (IRL) has developed a proprietary readout integrated circuit (ROIC) which is a promising alternative for NIR wavefront sensing. The detector has been developed by the company's founder, Frank Low, to work with IRL's IR Emission Microscopes (IREM) for use in semiconductor testing. The capabilities of the ROIC have been demonstrated by mating it to a photosensitive layer of Indium-Gallium-Arsenide for efficient detection in the $1 - 1.54\mu m$ region at $78K$. The detector has 320x256 pixels with $30\mu m$ pitch, although a subsection of the array can be read out at faster frame rates. The array is currently read at 0.5 Megapixels/second, and a plot showing the low readout noise of 2 electrons per pixel is shown in Figure 6.

The ROIC can be used as the basis for a wavefront sensing detector. As discussed in the next section, we plan to work with IRL to develop a custom ROIC designed to work with the thinned InGaAs array at improved speeds to form the basis for our new low noise detector. We expect the design will have the same pixel size and geometry as the currently existing design.

3.2. Characteristics of InGaAs on a Thinned Substrate

Sensors Unlimited has a history of successfully bonding VisIR arrays to different types of ROIC chips. The array itself is made of Indium Gallium Arsenide, an alloy of gallium arsenide and indium arsenide that is collectively referred to as InGaAs. To form a photodiode array, the InGaAs is sandwiched between two layers of indium phosphide (InP), and in most arrays, the InP has two very different thicknesses. The sandwich consists of a 100 micron thick InP substrate, the light sensitive InGaAs layer, and a cap of InP that is typically only one micron thick. In 2-D arrays, electrical connections to each photodiode are made through indium "bumps" that reach from the ROIC and contact on the InP cap side, and so the incoming light has to pass through the 100 micron thick InP substrate to reach the InGaAs layer - these are referred to as "backside illuminated" arrays.

InGaAs is light sensitive from 400nm through to 1.7 microns, but it is the presence of the thick InP substrate that blocks visible light from 400 to 900nm. A new technique of mechanically thinning and etching the InP substrate layer now allows the shorter wavelength light through to the InGaAs, and when this is mated to the custom ROIC, we refer to this as the VisIR detector. The effect of the thinning substrate process can be seen in Figure 1.

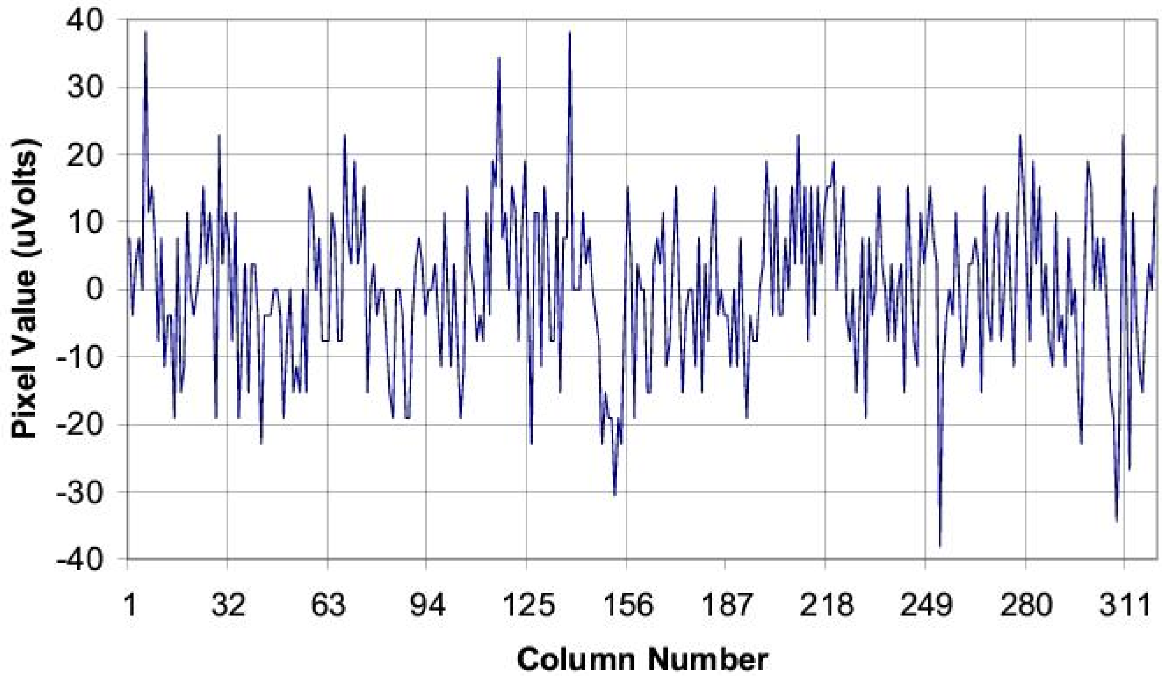

Figure 6. Cut through an IRL detector after subtracting two successive reads from the device, separated by 215ms. The r.m.s. variation is $11.6\mu V$ and the capacitance of the device is approximately 0.04pF, which corresponds to a noise level of 3 electrons, or approximately $2e^{-}$r.m.s. per detector read.

3.3. The Pyramid Wavefront Sensor

Pyramid wavefront sensors operate by dividing the starlight into four beams through the creation of an image of the star at the tip of a four-sided pyramid. An image of the pupil for each beam is then formed. The intensity distribution of the four pupil images allows the measurement of wavefront variations in a way very similar to wavefront reconstruction using a Shack-Hartmann (SH) sensor.

The advantage of a pyramid sensor over that of a more conventional Shack-Hartmann is the gain achieved in sensing low order modes[5] . This can be most easily seen by comparing the signals derived for tip-tilt errors in the Shack Hartmann and the pyramid designs.

For a Shack Hartmann design the tip measurement is an average of the centroid (or slope if each subapertures is a quad cell) for all the subapertures. Thus, if there are 120 subapertures, each with a SNR of 3 for the centroid estimate, the resulting tip value is known[8] to an uncertainty, dx, of

$$dx = \frac{FWHM}{SNR} = \frac{FWHM}{3 * \sqrt{120}}$$

where $FWHM$ is the width of the subaperture image. Each subaperture image has a width of λ/d where λ is the wavelength being observed and d the size of one subaperture as projected on the telescope primary mirror.

For the pyramid sensor, the tip signal can be thought of as a single slope measurement of a quad cell the size of the telescope. For this measurement we can expect to achieve a similar total SNR for the tip value, but the image width is limited only by diffraction from the full pupil rather than the subaperture. Thus we expect an increase in SNR of roughly (D/d), where D is the diameter of the telescope. Depending on the number of subapertures in the SH and the level of correction this will result in a 1-3 magnitude gain over comparable SH systems. Calculations of the expected limits suggests this is the case even for sensors in the visible where the Strehl may be quite low.[6]

The fabrication of a pyramid sensor is currently being carried out for the facility adaptive optics system for the Large Binocular Telescope. The novel portion of the LBT design is the pyramid itself. These have been developed and tested by a group lead by Simone Esposito at Arcetri Observatory. The system has been successfully demonstrated in the lab[9] and on the sky.[10] The LBT AO system is currently being tested with delivery to the telescope planned for 2006. We will base the VisIR pyramid design on the mature LBT concept after it has been successfully demonstrated on the sky.

The longer sensing wavelength compared to the CCD-based LBT pyramid sensor will allow us to take full advantage of the gain of a pyramid system. Even for the faintest guide stars, the significant Strehl at H band will improve performance over that of a SH sensor.

4. OTHER APPLICATIONS FOR A VISIR SENSOR

4.1. Speckle Imaging

In contrast to providing rapid optical compensation of the atmosphere, speckle imaging relies on rapid imaging to freeze image motion and diffraction limited imaging achieved by post processing of the images using variations such as bispectrum speckle image reconstruction.[11,12] By reducing the read out noise, fainter targets can be imaged and a larger range of targets becomes accessible.

4.2. Interferometric Imaging and Fringe Tracking

Interferometers combine signals from two or more separate telescopes to provide the angular resolution of a telescope whose aperture encompasses all the individual telescopes. Interferometers measure the visibility of fringes generated from the interference of light from separate telescopes, and as the angular resolution is proportional to the wavelength being observed, there is a strong science driver to work at shorter and shorter wavelengths. Systems such as the Cambridge Optical Aperture Synthesis Telescope (COAST)[13] have pioneered near infra-red interferometry with single element detectors and avalanche photodiodes, and interferometer systems at the VLT now use fast readout arrays to record the fringe patterns that calibrate that path differences between separate telescopes. In the near future, imaging interferometers such as the Large Binocular Telescope Interferometer[14] promise direct interferometric imaging of astronomical objects, and these too require arrays for fringe tracking. The science enabled covers astrophysical objects such as stellar dust shells, binaries, protoplanetary disks, recurrent novae ejecta and various active galactic nuclei phenomena.

4.3. Laser tip-tilt sensors

Laser guide stars for AO systems cannot sample tip-tilt motion of the science field, as the laser path passes twice through the atmosphere. The tip tilt component sampled by the laser as is passes upwards through the atmosphere is removed as the return beam from the laser passes back down to the telescope. A natural guide star must be used to measure the tip-tilt component of the atmosphere. Tip-tilt measurements require only four sensors to detect guide star motion, and so the laser guide star systems can use guide stars typically 3-4 magnitudes fainter than their higher order NGS AO systems. These tip tilt stars can be up to an arcminute away from the science target (resulting in a decrease in image quality), and the Keck LGS AO system is limited to $V < 18.5$ stars.[1] By using our new detector design, fainter tip tilt stars can be used much closer to the science field, resulting in an increase in Strehl ratio and image quality.

4.4. Precision Adaptive Optics

Adaptive optics techniques which seek to maximize the Strehl and minimize the scattered light are being planned for several of the 8 m class telescopes in order to carry out faint companion detection. An important component of such a system is a wavefront sensor which operates at the same wavelength as the observation. The low-noise characteristics of the proposed detector will be ideal for these approaches which seek to maximize the signal to noise of the wavefront measurement.

5. CURRENT PROGRESS AND FUTURE PLANS

As of May 2006, we are operating a ULN MUX in the laboratory to characterise the variation of readout noise with array readout speed. In this way we will determine the number of channels required on an appropriate controller. Current estimates suggest we will be using a 16 channel controller for the VisIR detector, which tests will confirm. We plan to explore trade-offs between reset-read-integrate-read schemes and multiple non-destructive reads in order to optimize the detector for wavefront sensing. Modifications of the ROIC design will determine a suitable readout configuration.

The pyramid optical design requires achromatic performance from 0.5 to 1.8 microns, which we expect to be the most stringent requirement in the fabrication process. A simple lens reimages the four pupils onto the VisIR detector, and these four images are read out into the wavefront computer on the MMT AO system. Pyramid wavefront sensors are being built for the Large Binocular Telescope AO systems, and we will work with the Italian group who produces these optics and test their optics as part of our integration and design.

On-sky tests at the 61-inch Kuiper telescope in Tucson will confirm on-sky performance and measure the sensitivity and quantum efficiency of the new VisIR array. Once all these tests are successfully completed, we will begin an integration program with the MMT NGS AO system. The final step is the permanent installation of the pyramid wavefront sensor into the MMT AO system.

The integrated pyramid wavefront sensor will provide all-sky AO correction with natural guide stars near the Galactic plane, and up to 35% sky coverage at the Galactic poles. The VisIR sensor alone will increase the range of science accessible at the MMT telescope. We anticipate that the detector will find a range of uses in astronomical applications.

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