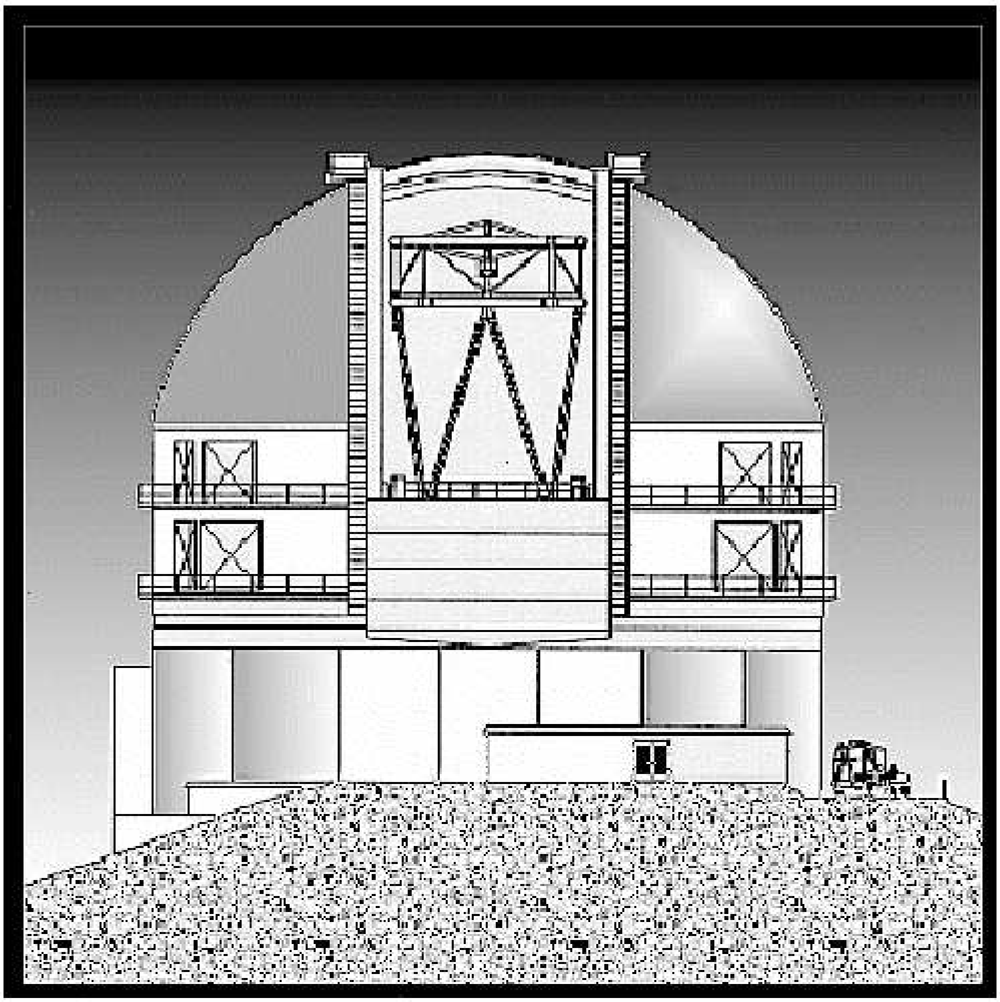
GEMINI
8-M Telescopes
Project

RPT-I-G0072

WFS CCD Controller Report



April 13, 1996

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INTRODUCTION

The following report summarizes developments since the report "CCD Controller Study: Final Report", which was issued on Aug. 18, 1995. The conclusion of that report was: "The most attractive proposition at this stage, is the San Diego State University's upgraded controller, SDSU2". Since that time, two additional proposals have been received for CCD controllers for WFS'S. The following table summarizes the requirements for a WFS CCD controller for Gemirti. In addition, the capabilities of the SDSU2, Astrocam 5 100 and Arcon controllers are listed. Pricing for two and four port controllers is included, although, all CCD based WFS's will require 4 port controllers if the EEV CCD39 chip is selected. A PCM interface option is identified, since the real time processing hardware (Heurikon Baja4700 card), has two PCM expansion interfaces. Size and weight specifications are based on assumptions that were used in the preliminary designs of GMOS and the Acquisition and Guide Unit. The availability date is the for the CCD test station from the schedule for the WFS Work Package.

	Requirements	Astrocam 5100	ARCON	SDSU2
Channels	2 and 4	4 + 16	4+	16 max.
Channel Rate	200 kpx/s	5 Mpx/s max.	200 (400) kpx/s max.	312 kpx/s max.
Throughput	800 kpx/s	20 Mpx/s max.	0.4 (1.6) Mpx/s max.	2.5 Mpx/s max.
Latency[1]	2 pixel times	✔	✔	✔
Resolution	14-bits	16-bits	16-bits	16-bits
Noise	CCD limited	CCD limited	CCD limited	< 1 μv rms
Interface	VNM or PCM	PCI or SBUS (VME)	SBUS (VME)	VME or SBUS
Exposure Time[2]	0.5ms to 100s	5ms to 32000s		1 ms to 16777 s
Temperature Cntrl	TEC	TEC or LN2	LN2	TEC or LN2
Size	about 700 cu in.		8.lx5.4x7.9"	13.25x6.75x5.5"
Weight	about 13 kg		5 kg	13 kg
Power	120 VAC 50/60Hz	90-260 VAC, 45-63 Hz	110 VAC 50/60Hz 21 W	120 VAC 50/60Hz 18 W
Cost (4chan)		$25,000[3]	$29,000[4]	$20,550[5]
Cost (2chan)		$25,000[3]	$29,000[4]	$16,550[5]
Availability	2Q96	1Q97	1Q97	1Q96

1 latency measured from charge transfer to data in local memory.
2 Small exposure times can typically be achieved by using the system sequencer.
3 Based on volume purchase of 10 systems. VME interface and thermally controlled card cage would add some TBD amount.
4 $201,700/7 (cost of commercial DMA interface estimated).
5 $2000 NRE for thermally controlled card cage amortized over 8 units.

ASTROCAM 5100

Dr. Craig Mackay of Astrocam, has recently proposed an upgrade to their 4100 series of CCD controllers which will be called the 5 100. The basic unit will have 4 ports and can be upgraded in blocks of 16 ports. The proposed system will have a wide range of digitization rates, from about 50 kpx/s to 5 Mpx/s. As with the older 4100 series, the system uses a standard 16-bit parallel interface and commercial computer interface cards. Dr. Mackay proposes that a VNM interface should be relatively easy to obtain but a particular part has not yet been identified. The 5 100 system is in the early stages of development, with commercial units expected in early 1997.

ARCON

Roger Smith of CTIO has also recently proposed an upgrade to the ARCON mosaic controller which would bring the digitization rate up to about 400 kpx/s. He proposes that a commercial VUE prototyping card could be used as the basis for a VUE interface to the ARCON transputer links and a dedicated data link. He suggests that a TECooler controller could be developed in conjunction with Gemini but it was not clear from his proposal how much of the current ARCON LN2 temperature controller could be used. His proposal outlines a development schedule that would have production quantities of upgraded ARCON's available in early '97.

SDSU2

Bob Leach of the Department of Astronomy at San Diego State University, is well on his way to completing an upgrade to his SDSU controller. The new 56002 based Timing Board is basically complete, with just a few non-critical new features to be tested. A new high speed clock driver board is also completed. Components have been installed on the first PCB version of the new Dual Video Processor Board. This card was about 1/3 debugged as of Wednesday April 10, 1996. The digitization rate in the comparison table is the value quoted by Bob in his original proposal. It is based on a I **Its** reset integration and a I @s video integration. In fact, the maximum digitization rate is limited only by the conversion time of the ADC (2 @s) and the time to read the ADC output. The SDSU2 will have upgraded VUE and SBUS interfaces, although the current interfaces can be used for the Gemini WFS'S. Bob's original proposal of Aug. '95, stated that he expected to have a prototype SDSU2 controller working by lQ96. It appears as though he will be within I month of meeting that target. (Note: the "CCD Controller Study: Final Reporf' erroneously gave the availability of SDSU2's as IQ97.)

CONCLUSION

From the point of view of performance requirements, cost and availability, the SDSU2 CCD controller is currently the best choice for the Gemini WFS CCD controller.

GEMINI WFS CCD SELECTION REPORT
April 9, 1996 (Revised April 13, 1996)

Introduction

The following report provides CCD selection recommendations for the Gemini Wavefront Sensor (WFS) Work Package and outlines the basis for these recommendations.

The Gemini Project will use four types of WFS's. Two Peripheral WFS's (PWFS) are located in the Instnunent Support Structure (ISS). They are the primary source of information on atmospheric turbulence and windshake. Tip/tilt and focus errors measured by the PWFS are used to correct the incoming wavefront via the secondary mirror.

The High Resolution WFS (HRWFS) is also located in the ISS. This high order (20 x 20 subapertures) WFS is used to calibrate the primary miffor figure correction. The HRWFS can also be used as an Acquisition Camera (AC). In either configuration, the HRWFS cannot be operated simultaneously with a science instrument.

On-Instnanent WFS's (OIWFS) are located on Gemini instnunents. Their primary purpose is to correct for flexure. They may also have limited use in correcting atmospheric turbulence, because they can patrol closer to the science object than the PWFS's. Infrared instruments (NIRI and NIRS) will likely have IR OIWFS's. The optical instruments (GMOS and HROS) will have visible OIWFS'S. The WFS Work Package currently makes no provision for OIWFS's for HROS.

The Gemini Adaptive Optics System (GAOS) will include a Facility WFS (FWFS). This WFS is not currently part of the WFS Work Package and its requirements have yet to be determined. Although it is likely that the FWFS would be able to use the same CCD as used in the PWFS's, the FWFS is not specifically addressed in the following comparison. If the GAOS is used with a laser guide star (LGS), the OIWFS will need to provide atmospheric tip/tilt irtfon-rtation.

Suppliers

SITE (Scientific Imaging Technologies) and EEV (English Electric Valve) are the primary contenders for WFS CCD production. Thompson, Samoff, Reticon, Texas Instnunents, Loral and Kodak also make CCD's for astronomy applications, but to date have not advertised a small-format, backside-illuminated, low-noise device.

Device Details

The detailed requirements for the various WFS devices are given in the following table. The table also includes some other data used for evaluation purposes.

Requirements are bold, other items normal.

	OIWFS	PWFS	HRWFS / AC
Format	**80X80**	**80x80**	**1024xl024**
Pixel size (lim)	**24**	**24**	**24**
Frame transfer	**Y**	**Y**	**N**
Ports	**2**	**4**	**4**
Quantum efficiency[1] @ 450nm	**30%**	**30%**	**30%**
@ 600-800nm	**70%**	**70%**	**70%**
@ 900nm	**30%**	**30%**	**30%**
Subapertures	2x2	2x2 - 8x8	20x20 / 1
Digitized p_x/subaperture	4x4	6x6	50x50 / 1024x1024[2]
Frame read time (ms)	**1**	**1 - 4**[3]	**100 - 2000**[4]
Throughput (kp_x/s)	**64**	**576**	**524**
Instantaneous digitization rate (kp_x/s/port)	**38.9**	**180**	**138**
SNR	**5 non-AO 50 AO**	**io@**	

Notes:

1) All CCDs will be thinned, anti-reflection coated and built on normal (not deep) epitaxy silicon. PWFS and OIWFS will emphasize red performance in the anti-reflection coating, wherever possible.

2) Since there is no advantage to reading out subrasters for the HRWFS mode (it takes just as long as digitizing the whole frame), we will treat HRWFS and the Acquisition Camera the same from the readout point of view.

3) PWFS frame read time is specified as a ftinction of sub-aperture geometry as follows:

Number Sub-Apertures	Frame Read Time
2x2	1 ms
4x4	1 ms
8x8	4 ms

The 4x4 mode is the most demanding in terms of pixel rates, so it is the one used for comparison.

4) In the Acquisition Camera mode, read time is specified as a function of binning factor as follows:

Binning Factor	Frame Read Time
lxl	2 s
2x2	1 s
4x4	0.25 s

8x8	0.1 s

lxl binning is the most demanding, so it is the mode used for comparison.

The devices available from the above listed suppliers which are able to meet the specifications for the OIWFS and PVVTS are CCD39 (from EEV, in both MPP and non-MPP versions) and a prototype 80x80 pixel device from SITe. For the HRWFS/AC we have evaluated CCD47 from EEV and SIA003 from SITE. The following table summarizes the characteristics of these devices.

	CCD39	SITE 80x80	CCD47	SIA003
Format	80x80 split frame transfer	80x80 split frame transfer	1024x1024 frame transfer	1024x1024 full frame
Pixel size **(**μm**)**	24	18	13	24
Output structure	two-stage source follower	single LDD source follower	two-stage source follower	single LDD source follower
Number of output ports	4	4		4 non-TEC, 2 TEC
Thinned	thinned, backside illuminated	thinned, backside illuminated	thinned, backside illuminated	thinned, backside illuminated
MPP	available	yes		yes
Minimum clock periods	1 μ**s** parallel, 300 ns serial	1 μ**s** parallel, 300 ns serial		200 μ**s** parallel, 1.8 μ**s** serial
Node responsivity (μV/e^-)	13	1.8	13	1.8
Availability	soon (non-TEC, non-MPP) 6m ARO (TEC, non-MPP) 8 m ARO(MPP)	IQ97	?	12 wks ARO
Price ($ US)	$7k std pkg $9k TEC vkg	$10k std pkg or TEC pkg	?	$16.2k TEC pkg

Performance

The basic performance figure used for comparison is the Signal to Noise Ratio (SNR) per subaperture, for probable guide star magnitudes given the patrol area of each WFS. The OIWFS is required to have 90% sky coverage, while the PWFS must have 99% coverage. All calculations are based on monochromatic light (R Band) and for the OIWFS we have assumed the entire GMOS guide field of 26.3 square arc minutes is available.

The OIWFS performance is broken down into two parts, corresponding to its operation with and without Adaptive Optics (AO). The difference is basically the reduced throughput and increased resolution requirement. We have assumed that the OIWFS will receive a 10% beam split from the AO system. Note that the actual performance will be somewhat better since 90% to 95% of the light longward of 1μm will be available to the OIWFS.

Three noise components are included: read noise, sky background noise and dark current noise. The read noise component includes both the CCD output circuit noise and noise contributions of the controller. For the controller we assumed a 0.7 ADU conversion noise and a 1μv input-referred amplifier noise. The output circuit noise figures for the devices were calculated using a mathematical model from EEV which relates integration time to read noise:

$$\sigma = k\sqrt{\frac{1 + f / f_0}{R_n}}$$

where k is a constant scale factor, f = 1/(2*T*) where *T* is the period of each integration, f_o is the 1/*f* corner frequency and R_n is the responsivity of the output node. The following parameters were used:

	CCD39	SITe 80x80	SIA003
f_o	150kHz	20kHz	20kHz
R_n (μV/e^-)	13	1.8	1.8
k	5	1.5	3

The SITE 80^2 and S1003A predictions use scale factors based on fits to experimental data (2e^- at 50kHz and 4e^- at 50kHz, respectively)

The sky background noise was calculated using the R-band figure for sky background (20th magnitude per arcsec^2) . Although the incoming light is split into several subapertures, we have assumed that the overlap of the images from each lenslet is such that all sections of the CCD receive background light equivalent to that of the entire WFS field-of-view.

The dark current noise is calculated based on nominal dark current figures provided by the manufacturers. The dark current has been evaluated for several different temperatures to determine whether cooling apparatus is necessary to meet the requirements. From temperature data recorded on Cerro Pachon, we have assumed a worst case ambient temperature of 15^{o}C. The cooled operating temperature of -50^{o}C is based on figures quoted by SITE for their theffno-electric coolers (60-70 degrees below the heat sink temperature) and a heat sink temperature of 10^{o}C. For the non-MPP CCD39 device we have taken into account the dark current suppression due to clocking speed, based on EEV's data.

The following table summarizes the parameters used in the noise calculations.

Parameters	**OIWFS**	**OIWFS with AO**	**PWFS**	**ACQ**	**HRWFS**
Pixel scale (arcsec/p_x)	0.075	0.075	0.15	0.1	0.1
Sky background (e^-/ p_x /s)	14.06	1.41	56.25	25.0	25.0
Minimum integration time (s)	0.005		0.005	2	
Maximum integration time (s)	600	600	1		600
iguide star magnitude (R mag)	16.5	16.5	14		

We found that the SNR requirements in the long integration cases, with the sole exception of the OIWFS in AO mode, were easily met by all the devices, so three driving cases emerged: short integration for PWFS and OIWFS without AO and long integration for OIWFS with AO. Fast readout of the OIWFS in AO mode would be necessary for monitoring a natural guide star for tip/tilt, while performing higher order corrections using a laser guide-star. In this case, most of the visible spectrum can be directed to the OIWFS, the same conditions that are used in the short integration non-AO case. The following tables summarize the results for the idenfified cases (results for other cases appear in the appendix).

Noise figures	**CCD39 non-MPP**	**CCD39 MPP**	**SITE 80x80**
PWFS (4x4 subapertures, 5ms integration, 99% probable guide star)			
Read noise (e^-/p_x)	2.26	2.26	4.06
Sky background noise (e^-/p_x)	0.53	0.53	0.53
Temperature = -50°C			
Dark current noise (e^-/p_x)	0.08	0.08	0.04
Total noise (e^-/p_x)	2.32	2.32	4.09
SNR	**11.88**	**11.90**	**8.60**
Temperature = 15°C			
Dark current noise (e^-/p_x)	6.89	2.67	1.42
Total noise (e^-/p_x)	7.27	3.54	4.33
SNR	**5.41**	**9.48**	**8.26**
OIWFS without AO (4x4 binning, 20ms integration, 90% probable guide star)			
Read noise (e^-/p_x)	1.62	1.62	2.09
Sky background noise (e^-/p_x)	2.12	2.12	2.12
Temperature = -50°C			
Dark current noise (e^-/p_x)	0.62	0.62	0.33
Total noise (e^-/p_x)	2.74	2.74	3.00
SNR	**17.6**	**17.6**	**17.2**
Temperature = 15°C			
Read noise (e^-/p_x)	3.25*	1.62	2.09
Dark current noise (e^-/p_x)	54.8*	21.4	11.32
Total noise (e^-/p_x)	55.0	21.5	11.7

Noise figures	**CCD39 non-MPP**	**CCD39 MPP**	**SITE 80x80**
SNR	**1.82**	**4.55**	**7.89**
OIWFS with AO			
(4x4 binning, 600s integration, 90% probable guide star)			
Read noise (e^-/p_x)	1.62	1.62	2.09
Sky background noise (e^-/p_x)	116	116	116
Temperature = -50°C			
Dark current noise (e^-/p_x)	477	107	56.6
Total noise (e^-/p_x)	491	158	129
SNR	**>100**	**>100**	**>100**
Temperature = 15°C			
Read noise (e^-/p_x)	563*	563*	726*
Dark current noise (e^-/p_x)	9570*	3700	1960
Total noise (e^-/p_x)	9590	3740	2090
SNR	**31.4**	**80.3**	**143**

***** these figures were calculated using co-added 5ms frames

For the HRWFS/AC, there is no sky coverage requirement, so the signal to noise ratio can be made arbitrarily large by using a very bright guide star. In the following table we simply show the noise figures for the device to demonstrate that its performance is reasonable.

Noise figures	**S1003A, TEC**	**S1003A**
HRWFS		
(600s integration)		
Read noise (e^-/p_x)	13.1	7.56
Sky background noise (e^-/p_x)	122	122
Temperature = -50°C		
Dark current noise (e^-/p_x)	18.9	
Total noise (e^-/p_x)	**125**	
Temperature = 15°C		
Dark current noise (e^-/p_x)		654
Total noise (e^-/p_x)		**665**
Acquisition Camera (2s integration)		
Read noise (e^-/p_x)	13.1	7.56
Sky background noise (e^-/p_x)	7.07	7.07
Temperature = -50°C		
Dark current noise (e^-/p_x)	1.09	
Total noise (e^-/p_x)	**15.0**	
Temperature = 15°C		
Dark current noise (e^-/p_x)		37.7
Total noise (e^-/p_x)		**39.1**

Discussion

English Electric Valve
EEV, in collaboration with RGO, has designed and fabricated a high speed and small fornnat CCD, which they intend to make available as a commercial product, identified as the CCD-39.

This device is currently undergoing testing and uses standard processes and designs from other EEV parts. It is not seen as a technological risk. In particular, it is expected to have the same extremely good noise performance that other recent parts have had. Test results from RGO are expected within weeks, but poor results from this part should not be viewed as failure.

UnforUmately, this initial design produces a part which is not able to run in Multiple Pinned Phase (MPP) operation: a technique which results in a factor of 20 - 100 reduction in dark current. Very small and lowrisk design changes will produce an MPP part, but there will be a schedule impact in doing so.

EEV will not, at this time, quote on selling the CCD-39. They are evaluating a venture proposal, and suggest that if the proposal is successful then the prices will probably be $7K for the CCD-39 without a TECooler, and $9K with a TECooler. The non-MPP parts should be available easily within our schedule, but the MPP parts would be available 6-8 months after contract awarded.

Advantages.
- lower read noise.
- advanced product development state.
- suited for use as a FWFS because of the better speed/noise product.

Risks and problems:
- new TECooler design.
- higher dark current.
- not physically compatible with any HRWFS chip (will need another PCB design).
- price has been very elusive. (EEV continue to express a desire to make the price be about $10K, but keep proposing larger numbers).

Scientific Imaging Technologies
SITE is the same group which was Tektronix CCDs and has been under new management for the last few years.

They are embarking on a new product development to create a standard product line of small and high frame rate wavefront sensor CCDS. The product is being developed jointly by SITE and Jim Janesick, recently of JPL, using the same standard fabrication processes employed by that group for the last eight years.

This line consists of 4 small CCDS, the least ambitious of which is that being proposed for the WFS work: an 80x80, 18 micron pixel four output device. The device conceptual design is complete, and mask design is underway with completion expected this month. SITE has a product development plan which targets commercial availability of these parts by the end of '96. The output amplifiers being used on this part are the same as those used on their 2K*4K CCD, and our WFS noise models are based on independent measurements of the noise on that device.

SITE proposes delivering engineering parts during the summer for evaluation, with a prototype thinned part which meets all specs except noise by 01 September. The noise on that part may be $5e^-$ (@50kPix/s) which is felt to be acceptable proof that one should be able to select for appropriately quiet parts. Final parts will become available through the remainder of the year, meeting a noise spec of $2e^-$ (@50kPix/s), as modeled.

SITE quotes a cost $10K each whether or not a TECooler is desired. If we wish to have a cooler, it will be of the same mechanical package as their standard TK512 and SIA003 (1024^2) coolers, so that there is no new development risk and less WFS design work.

Advantages:

- lower dark current.
- good record for meeting advertised schedules for product development (The 2K*4K was advertised a year ago as being available by about the end of '95, and it was).
- we have a quotation.
- stable TECooler process.

Risks and problems:

- small pixel size. (18 microns).
- greater read noise. (This impacts the PWFS high speed mode, and reduces the flexibility to run at rates faster than spec.)
- limited charge transfer rates. (It remains to be seen if this part will meet our clocking speed requirement.)
- earlier in the design cycle (more unknowns and schedule risk).

Appendix

Noise figures	**CCD39 non-WP**	**CCD39 MPP**	**SITe 80x80**
PWFS (2x2 subapertures, 5ms integration, 99% probable guide star)			
Read noise (e^-/p_x)	1.64	1.64	2.15
Sky background noise (e^-/p_x)	0.53	0.53	0.53
Temperature = -50°C			
Dark current noise (e^-/p_x)	0.08	0.08	0.04
Total noise (e^-/p_x)	1.73	1.73	2.22
SNR	**30.1**	**30.1**	**29.2**
Temperature = 0°C			
Dark current noise (e^-/p_x)	2.45	1.36	0.72
Total noise (e^-/p_x)	2.94	2.19	2.33
SNR	**27.6**	**29.3**	**29.0**
Temperature = 10°C			
Dark current noise (e^-/p_x)	4.96	2.15	1.14
Total noise (e^-/p_x)	5.25	2.75	2.49
SNR	**22.4**	**28.1**	**28.7**
Temperature = 15°C			
Dark current noise (e^-/p_x)	6.89	2.67	1.42
Total noise (e^-/p_x)	7.10	3.18	2.63
SNR	**18.9**	**27.2**	**28.4**
PWFS (2x2 subapertures, 1s integration, 99% probable guide star)			
Sky background noise (e^-/p_x)	7.50	7.50	7.50
Temperature = -50°C			
Read noise (e^-/p_x)	1.64	1.64	2.15
Dark current noise (e^-/p_x)	4.87	1.09	0.58
Total noise (e^-/p_x)	9.09	7.75	7.82
SNR	**>100**	**>100**	**>100**
Temperature = 0°C			
Read noise (e^-/p_x)	23.2*	1.64	2.15
Dark current noise (e^-/p_x)	34.6*	19.2	10.2
Total noise (e^-/p_x)	42.3	20.7	12.8
SNR	**>100**	**>100**	**>100**
Temperature = 10°C			
Read noise (e^-/p_x)	23.2*	1.64	2.15
Dark current noise (e^-/p_x)	70.2*	30.4	16.1
Total noise (e^-/p_x)	74.3	31.3	17.9
SNR	**>100**	**>100**	**>100**
Temperature = 15°C			
Read noise (e^-/p_x)	23.2*	1.64	2.15
Dark current noise (e^-/p_x)	97.4*	37.7	20.0
Total noise (e^-/p_x)	100	38.5	21.5
SNR	**>100**	**>100**	**>100**

Noise figures	**CCD39 non-WP**	**CCD39 MPP**	**SITe 80x80**
PWFS			
(4x4 subapertures, 5ms integration, 99% probable guide star)			
Read noise (e^-/p_x)	2.26	2.26	4.06
Sky background noise (e^-/p_x)	0.53	0.53	0.53
Temperature = -50°C			
Dark current noise (e^-/p_x)	0.08	0.08	0.04
Total noise (e^-/p_x)	2.32	2.32	4.09
SNR	**11.9**	**11.9**	**8.60**
Temperature = 0°C			
Dark current noise (e^-/p_x)	2.45	1.36	0.72
Total noise (e^-/p_x)	3.37	2.69	4.15
SNR	**9.75**	**11.1**	**8.51**
Temperature = 10°C			
Dark current noise (e^-/p_x)	4.96	2.15	1.14
Total noise (e^-/p_x)	5.48	316	4.25
SNR	**6.87**	**10.2**	**8.4**
Temperature = 15°C			
Dark current noise (e^-/p_x)	6.89	2.67	1.42
Total noise (e^-/p_x)	7.27	3.54	4.33
SNR	**5.40**	**9.48**	**8.26**
PWFS			
(4x4 subapertures, 1s integration, 99% probable guide star)			
Sky background noise (e^-/p_x)	7.50	7.50	7.50
Temperature = -50°C			
Read noise (e^-/p_x)	2.26	2.26	4.06
Dark current noise (e^-/p_x)	4.87	1.09	0.58
Total noise (e^-/p_x)	9.22	7.91	8.55
SNR	**>100**	**>100**	**>100**
Temperature = 0°C			
Read noise (e^-/p_x)	32.0*	2.26	4.06
Dark current noise (e^-/p_x)	34.6*	19.2	10.2
Total noise (e^-/p_x)	47.7	20.8	13.3
SNR	**>100**	**>100**	**>100**
Temperature = 10°C			
Read noise (e^-/p_x)	32.0*	2.26	4.06
Dark current noise (e^-/p_x)	70.2*	30.4	16.1
Total noise (e^-/p_x)	77.5	31.4	18.2
SNR	**97.1**	**>100**	**>100**
Temperature = 15°C			
Read noise (e^-/p_x)	32.0*	2.26	4.06
Dark current noise (e^-/p_x)	97.4*	37.7	20.0
Total noise (e^-/p_x)	102.8	38.5	21.8
SNR	**76.4**	**>100**	**>100**

Noise figures	CCD39 non-WP	CCD39 MPP	SITe 80x80
PWFS			
(8x8 subapertures, 5ms integration, 99% probable guide star)			
Read noise (e^-/p_x)	2.14	2.14	3.72
Sky background noise (e^-/p_x)	0.53	0.53	0.53
Temperature = -50°C			
Dark current noise (e^-/p_x)	0.08	0.08	0.04
Total noise (e^-/p_x)	2.21	2.21	3.76
SNR	**4.07**	**4.07**	**2.63**
Temperature = 0°C			
Dark current noise (e^-/p_x)	2.45	1.36	0.72
Total noise (e^-/p_x)	3.29	2.59	3.83
SNR	**2.95**	**3.60**	**2.59**
Temperature = 10°C			
Dark current noise (e^-/p_x)	4.96	2.15	1.14
Total noise (e^-/p_x)	5.43	3.08	3.93
SNR	**1.87**	**3.13**	**2.53**
Temperature = 15°C			
Dark current noise (e^-/p_x)	6.89	2.67	1.42
Total noise (e^-/p_x)	7.23	3.46	4.02
SNR	**1.42**	**2.83**	**2.48**
PWFS			
(8x8 subapertures, 1s integration, 99% probable guide star)			
Sky background noise (e^-/p_x)	7.50	7.50	7.50
Temperature = -50°C			
Read noise (e^-/p_x)	2.14	2.14	3.72
Dark current noise (e^-/p_x)	4.87	1.09	0.58
Total noise (e^-/p_x)	9.20	7.87	8.39
SNR	**>100**	**>100**	**>100**
Temperature = 0°C			
Read noise (e^-/p_x)	30.3*	2.14	3.72
Dark current noise (e^-/p_x)	34.6*	19.2	10.2
Total noise (e^-/p_x)	46.6	20.7	13.2
SNR	**41.7**	**75.0**	**91.6**
Temperature = 10°C			
Read noise (e^-/p_x)	30.3*	2.14	3.72
Dark current noise (e^-/p_x)	70.2*	30.4	16.1
Total noise (e^-/p_x)	76.8	31.4	18.2
SNR	**26.5**	**57.4**	**80.4**
Temperature = 15°C			
Read noise (e^-/p_x)	30.3*	2.14	3.72
Dark current noise (e^-/p_x)	97.4*	37.7	20.0
Total noise (e^-/p_x)	102	38.5	21.7
SNR	**20.1**	**48.9**	**73.1**

Noise figures	**CCD39 non-WP**	**CCD39 MPP**	**SITe 80x80**
OIWFS without AO			
(4x4 binning, 20ms integration, 90% probable guide star)			
Sky background noise (e^-/p_x)	2.12	2.12	2.12
Temperature = -50°C			
Read noise (e^-/p_x)	1.62	1.62	2.09
Dark current noise (e^-/p_x)	0.62	0.62	0.33
Total noise (e^-/p_x)	2.74	2.74	3.00
SNR	**17.6**	**17.6**	**17.2**
Temperature = 0°C			
Read noise (e^-/p_x)	3.25*	1.62	2.09
Dark current noise (e^-/p_x)	19.6*	10.9	5.96
Total noise (e^-/p_x)	20.0	11.2	6.49
SNR	**4.89**	**8.19**	**12.3**
Temperature = 10°C			
Read noise (e^-/p_x)	3.25*	1.62	2.09
Dark current noise (e^-/p_x)	39.7*	17.2	9.11
Total noise (e^-/p_x)	39.9	17.4	9.58
SNR	**2.50**	**5.55**	**9.29**
Temperature = 15°C			
Read noise (e^-/p_x)	3.25*	1.62	2.09
Dark current noise (e^-/p_x)	54.8*	21.4	11.3
Total noise (e^-/p_x)	55.0	21.5	11.7
SNR	**1.82**	**4.55**	**7.89**
OIWFS without AO			
(4x4 binning, 600s integration, 90% probable guide star)			
Sky background noise (e^-/p_x)	367	367	367
Temperature = -50°C			
Read noise (e^-/p_x)	1.62	1.62	2.09
Dark current noise (e^-/p_x)	477	107	56.6
Total noise (e^-/p_x)	602	383	372
SNR	**>100**	**>100**	**>100**
Temperature = 0°C			
Read noise (e^-/p_x)	563*	563*	726*
Dark current noise (e^-/p_x)	3390*	1880	998
Total noise (e^-/p_x)	3450	2000	1290
SNR	**>100**	**>100**	**>100**
Temperature = 10°C			
Read noise (e^-/p_x)	563*	563*	726*
Dark current noise (e^-/p_x)	6870*	2970	1580
Total noise (e^-/p_x)	6910	3050	1770
SNR	**>100**	**>100**	**>100**
Temperature = 15°C			
Read noise (e^-/p_x)	563*	563*	726*
Dark current noise (e^-/p_x)	9540*	3700	1960

Noise figures	CCD39 non-WP	CCD39 MPP	SITe 80x80
Total noise (e^-/p_x)	9570	3760	2120
SNR	**>100**	**>100**	**>100**
OIWFS with AO (4x4 binning, 600s integration, 90% probable guide star)			
Sky background noise (e^-/p_x)	116	116	116
Temperature = -50°C			
Read noise (e^-/p_x)	1.62	1.62	2.09
Dark current noise (e^-/p_x)	477	107	56.6
Total noise (e^-/p_x)	491	158	129
SNR	**>100**	**>100**	**>100**
Temperature = 0°C			
Read noise (e^-/p_x)	563*	563*	726*
Dark current noise (e^-/p_x)	3410*	1880	998
Total noise (e^-/p_x)	3460	1970	1240
SNR	**86.9**	**>100**	**>100**
Temperature = 10°C			
Read noise (e^-/p_x)	563*	563*	726*
Dark current noise (e^-/p_x)	6900*	2970	1580
Total noise (e^-/p_x)	6920	3030	1740
SNR	**43.5**	**99.1**	**>100**
Temperature = 15°C			
Read noise (e^-/p_x)	563*	563*	726*
Dark current noise (e^-/p_x)	9570*	3700	1960
Total noise (e^-/p_x)	9590	3740	2090
SNR	**31.4**	**80.3**	**>100**

*these figures were calculated using co-added 5ms frames.