Pixel size considerations for the Acquisition camera

RGO NAOMI technical note 5

note-5.rtf

wht-naomi-95

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Version 1.4
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1. Introduction

Following the descoping procedure, the acquisition camera has changed from a large format EEV 42 2000^2 CCD detector to a small autoguider head. This was decided at the 21 May project meeting. This note provides the background to the current design and suggests a pixel scale and therefore design factors for the relay optics. The Autoguider heads are normally 384x288 frame transfer but can be operated in a 384x576 non frame transfer mode, if a shutter is available.

2. References

1. "A comparison of digital Centering algorithms"
Ronald C Stone,
Astronomical Journal Vol. 97 No 4, April 1989

2. “Design fundamentals for photon counting systems”
James Dick, Charles Jenkins and Jacek Ziabicki.
PASP 101,684-689 July 1989

3. “Seeing on the WHT”
Mike Breare, Neil O Mahoney, ING
PPARC Spectrum No 10, June 1996 pp 6-9

4. “Adaptive optics for astronomy: theoretical performance and limitations”
R.W. Wilson and C.R. Jenkins
MNRAS 268, 39-61 (1996)

3. Chronology

Here are extracts from the discussions to date.

3.1 Input from Richard Myers: 7/6/96

Bruce: pixel scales - have checked obs/acq/alig scenarios and discussed with Ron. As Charles says, the blind acquisition requirements (into 0.1 arcsec slits!) mean we can indeed live without very high accuracy on the TV. We just need to be able to tell one guide star from another which we could do with 0.5 arcsec or if really desperate 1.0 arcsec pixels. If we did want to get into centroiding these we would get pixel/10 accuracy anyway?

Awaiting response from SAB on whether another AG ccd camera controller may be available.

3.2 Input from Ron Humphreys 12/6/96

Thanks for the recent e-mail. I also quickly read your note-5.txt.

As a result of discussions with Andy and Richard this morning we arrived at 0.45 arcsecond/pixel. I should point out that Andy was only marginally happy with this. He would like to have made it smaller (<0.45 sec) but he was concerned that we would need an x-y stage to cover the full field. As it is we still need a one-dimensional stage to do this.

Andy has suggested that we make provisions for two filters; one would transmit > 0.55 um and the other > 0.45 um.

Cheers,

Ron.

4. Pixel scale considerations

Clearly the discussion reported above does not at first sight require high accuracy on the pixel scale in the detector. If the functionality is simply to find the approximate position of the guide star, and to use the XY stage axis as the high-accuracy calibrated offset mechanism, then 0.1 pixels at 0.45 arcsecs per pixel should allow 0.045 arcsec resolution of the guide star in the field.

4.1 An acquisition error budget

4.1.1 Acquisition procedures

The acquisition process is based on the most demanding case, that of acquiring a star onto a 0.1 arcsecond spectrograph slit where the object is only visible in the IR. The procedure can be based on one of two assumptions

1. That the acquisition camera is in a fixed position in the field and thus the pixels of the detector can be taken as the fiducial point for the acquisition process. Calibration of the system will arrange for the acquisition camera to be aligned with the IR spectrograph slit (or imaging detector axis).
2. That the Wavefront sensor & tip tilt sensor XY pick-off carriages are manufactured and calibrated to such a level of performance that the XY position in the field of the pick-off is the definition of position in the field.

The second case calls for very high precision slides which are likely to be technically feasibly, although prohibitively expensive, whereas the first case calls for a stationary on-axis acquisition camera. if feasible, this should be the clearly preferred option. If the acquisition camera cannot view the whole field, then putting it onto a X or XY stage will mean that either this stage or the WFS/TTS stages have to be made to the precision required by the acquisition scenario as the absolute field position reference in the system.

If we take the case of the stationary acquisition camera and assume it can see the whole field, then the acquisition scenario is as shown in Figure 1 below. The slit S is possibly about 1/5 of a pixel wide on the detector. The object cannot be seen by the acquisition camera. The aim is to get the object O centred on the slit S. Since this is an AO observation, we need a reasonably bright visible guide star G in the field. We know from astrometric measurements the distance from the guide star to the science object, i.e. the vector OG.

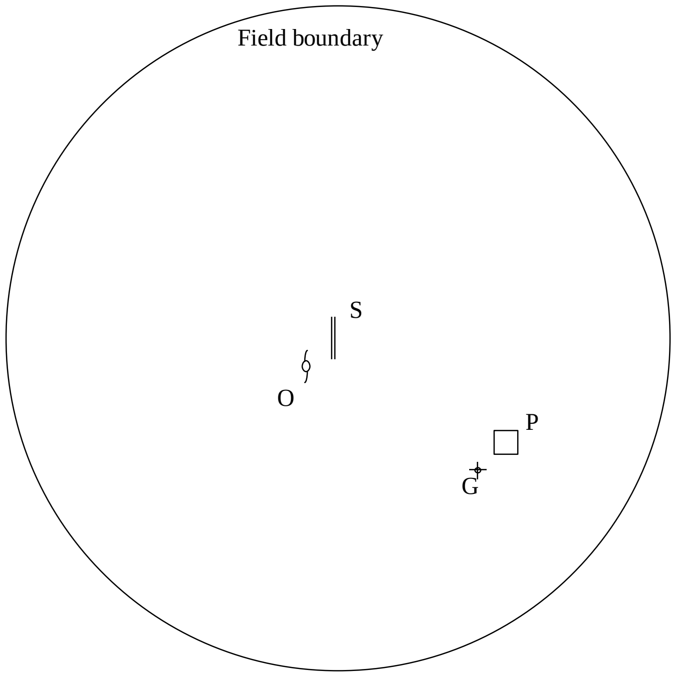

Figure 1 Acquiring an object onto a slit

All we know is that the guide star G appears in the field of view somewhere near to where we expect. The rms pointing error of the WHT is 1.5 arcsecs at Nasmyth (observers guide 1994) and the short term tracking accuracy is 0.3 arcsecs over 3 minutes. If we assume that the acquisition takes place within 20 seconds, then we can assume that the tracking drift will be within about 0.1 arcsecs. This poses the following acquisition scenario which assumes the functionality of being able to image the guide star on both WFS TTS and acquisition cameras, i.e. that the TTS and WFS probes can be partially transmitting.

1. Point telescope at science object and image guide star on acquisition camera
2. measure centroid of star, calculate the offset to desired field position for the guide star
3. move probe to this position
4. offset telescope to put science object roughly on slit.
5. close TT loop on target field position
6. re-measure star with acq cam once TT loop stable
7. adjust probe to centre object on slit, possibly repeat steps 2-6 until
8. fix TTS probe position
9. move WFS probe to same position
10. start wfs & use tilt info to adjust wfs probe to be in same place
11. as TTS probe
12. close DM loop
13. start science exposure

If the WFS/TTS probe cannot be partially transmitting then the telescope will have drifted off whilst the probes are moved. The absolute offset between the probe centre and the slit will thus be the reference by which the object is aligned with the slit, and the probe slide is thus the field position reference. The function of the acquisition camera is thus only to get the guide star within the WFS field of view. An addition of a simple mechanism to chose the field stop size for the WFS/TTS would then allow the WFS/TTS to see a field big enough to cover the WHT pointing error plus astrometric errors and thus dispense with the need for an acquisition camera entirely.

4.1.2 Error analysis

The sources of error in the above acquisition procedure are as follows:

?? WHT pointing Error - 1.5 Arcsecs rms at Nasmyth.
This is negligible in comparison to the size of the acquisition camera field.

?? WHT tracking drift.
This is within 0.1 arcsec rms for a 20 second period, based upon a measured 0.3 arcsec over 3 minutes. In the time it takes to acquire and close the tip tilt loop, the drift is comparable with the slit size. Therefore the position must be re-registered with the slit by measuring the image position after the TT loop has been closed. This removes the tracking drift error from the error budget.

?? IR spectrograph slit alignment position error w.r.t. the optical axis.

?? Acquisition camera alignment to optical axis

?? Non common mode differential refraction errors between the acquisition, WFS, TTS and IT paths in the AO system

?? Acquisition errors

?? Acquisition camera field distortion pattern residual error (after curve fitting)

?? TT loop static offsets when closed. (ignore these if a second position measurement is done after the loop is closed).

?? Flexure /temperature effects in AO system

From all of these sources of error, it is reasonable to argue that for a 0.1 arcsecond slit, we should aim for all of the errors to total to 0.05 arcsec rms. For 6 sources of error, we could assign 0.05/root(6) = 0.02 arcsec to each of them. Thus we choose an acquisition error budget of 0.02 arcsecs.

4.1.3 The acquisition error budget

For blind acquisition from a nearby star, this acquisition error budget of 0.02 arcsec may have at least the following sources of error:

1. Astrometric errors in the estimate of the stellar offset between the guide star and the science object. These arise from the matching of IR positions in the field with visible positions in order to find a common reference from which to measure the two objects.
2. Differential refraction correction. This is the residual error after correction for the field positions of the stars due to atmospheric refraction.
3. Centroiding errors in the acquisition camera
4. Errors due to optical PSF distortions, e.g. telescope coma off axis.

These four errors could be given equal weights, in which case each error could be given as 0.01 arcsec rms error.

The centroid error itself is made up of two components, the error due to the pixellation of the detector and that due to readout noise in the detector.

4.2 Performance of centroid algorithms.

To explore this further, I have done a simple mathematical calculation of the centroid error, assuming a perfect intra-pixel response function. This should be good enough for the region where we have of the order of 1 pixel per FWHM. The resulting error function is shown below in Figure 2 . It does not assume pixel smoothing, which improves the performance. If pixel smoothing is taken into account, the result can be shown to have a simple mathematical form (ref. 2) of

$$\text{error}(w,x) := \frac{\sin(2\cdot ?\cdot x)}{?}\cdot\exp\left(-2\cdot ?^2\cdot w^2\right)$$

The peak error occurs when x = 0.5. This is also shown in Figure 2. Note that the profile FWHM =2.35w.

From Figure 2, we can see that to get a centroid error of 0.01 arcsec, we need 1 pixel per FWHM. If we assume that the pixels were significantly non linear, then the solid curve could be taken , which gives a required resolution of greater then 1.3 pixels per fwhm. Any real system will be somewhere between the two limits so taking the more pessimistic would be reasonable.

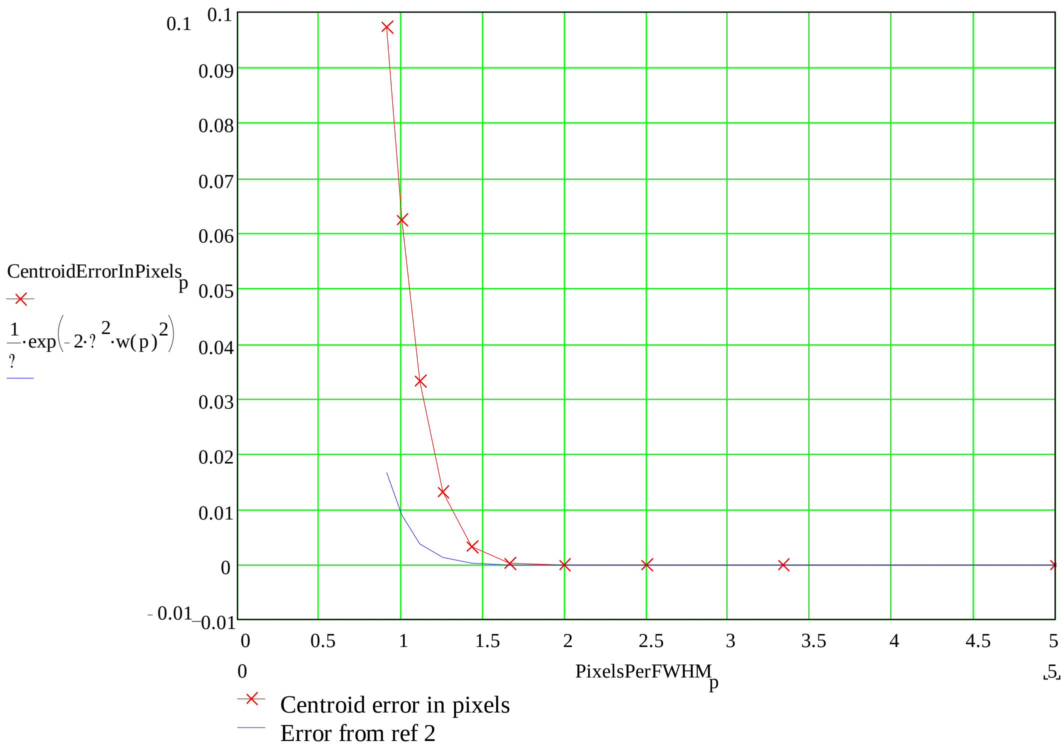

Figure 2 Centroid error for simple moment vs. pixel size

4.3 What seeing disc to assume

Results from the half arcsecond programme have just been published in ref. 3, which give median seeing discs of 0.95 arcseconds at cassegrain and 0.69 arcsecs as measured by the WHT DIMM. Clearly the dome will always have some effect thus the DIMM figure can be taken as a sensible lower limit on the image size as seen by this acquisition camera.

Theoretical estimates for AO system performance (Figure 7 in ref. 4) allow us to estimate the FWHM of a tilt corrected image in the visible for this sized image, giving a reduction from 22 ? / d to 18 ? / d which gives a tilt corrected image size of 0.56 arcseconds. This will be an estimate of a lower limit on the size of the image which the acquisition camera has to sample.

5. <u>Choice of field pixel scale</u>

From the above discussion we have a minimum FWHM of 0.54 arcsec and a suggested minimum pixel scale of 1.3 pixels per FWHM which suggests a pixel scale finer than 0.43 arcseconds per pixel.

The CCD is 384x576 (non frame transfer), which would give the following field sizes.

Table 1 field sizes for example pixel scales.

arcsec/pixel	pixel/arcsec	field (arcsec)	arcmin
0.47	2.13	180x270 arcsecs	3'00" x 4'54"
0.43	2.32	165x248 arcsec	2'45" x 4'48"

The X dimension of the CCD does not quite fill the whole field but the remainder is insignificant as Figure 3 shows.

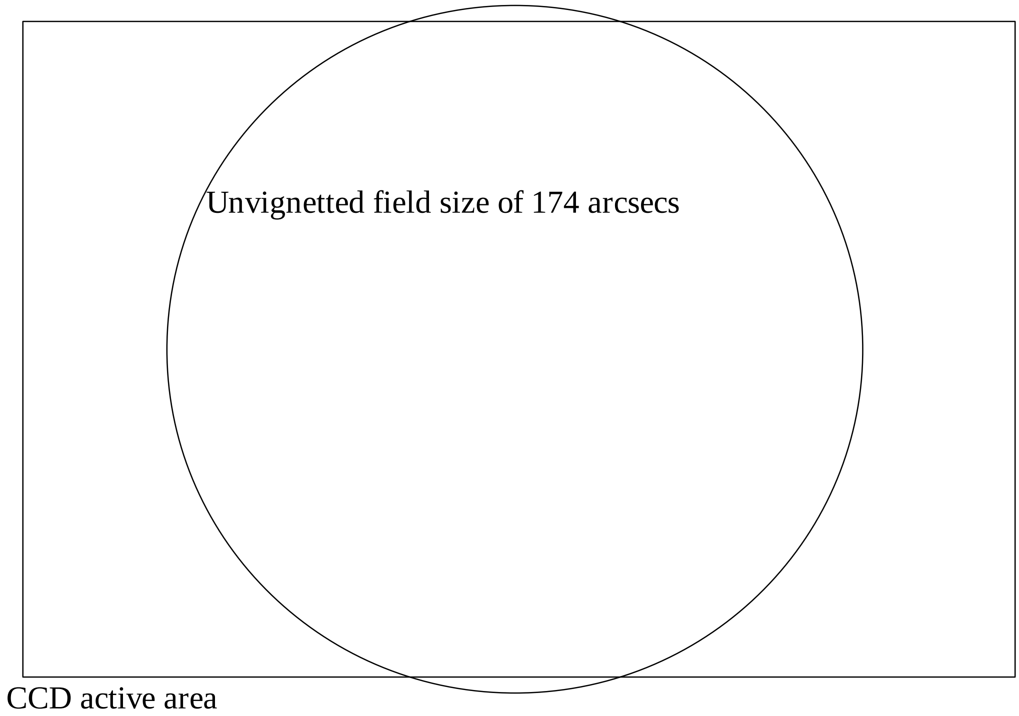

Figure 3 Acquisition camera field of view

6. Performance of the existing Autoguider system

The suggested route is to use the existing WHT ghril autoguider system and add a new camera head in the AO system. This provides, at no extra hardware cost than the camera head, the facility to view the field and perform accurate centroiding. This uses an algorithm which combines Gaussian cross-correlation with a first order moment calculation to provide better than 0.1 pixel accuracy calculation of the image centroid, even for poorly illuminated stars. Performance works down to about 10 sigma. This has guided successfully on 18.5 mag stars with a 4 second integration time at Cassegrain.

The performance of this system is dominated by the readout characteristics of the CCD chip. Analogue signal processing offsets in the CCD camera limit the performance in windowed guiding mode. In full field readout mode, the star finding performance is robust.

The centroid accuracy of the existing system has been shown to be better than 0.1 pixels, and when measured, was in fact limited by the inaccuracies in the measurement equipment rather than the imaging/centroiding system. This accuracy is to be expected when there is a signal to noise ratio > 10.0. This corresponds to a photon count of > 280 for a CCD with 10 e- rms noise in the image.

The sub-pixel position is generated by generating the dot product of
a) the cross-correlation of the signal with a suitably scaled gaussian, and
b) the stellar profile
then linearly interpolating between the two peak pixel bins. At pixel scales of less than 2 pixels per FWHM, the linear assumption breaks down so this is not to be recommended.

The Forth Autoguider system provides centroids to 0.1 pixels. The replacement vxWorks system will output to 0.01 pixels and will use the same centroid algorithm by default. This system should be available on the WHT in time for the AO system commissioning.

7. Which Autoguider implementation to use.

There are two possible systems, the current Forth based system and the replacement vxWorks system.

The Forth system has a serial line interface via the UtilNet to an ADAM D-task and displays its images via a dedicated monitor. It has been in service for several years, and the most recent versions are robust and in use every night. The output has a resolution of 0.1 pixels. The CCD controller which goes with this system would have to have slight modifications to the firmware to enable non-frame transfer readout.

The vxWorks system is controlled via a DRAMA server program and can provide information about star centroids and the images via the DRAMA system to a networked X display. This image and centroid information can easily be incorporated into the rest of the AO observing system. This system is still under development although it will be installed in the INT and be in service long before the AO system project is due to be integrated. The output has a resolution of 0.01 pixels. Finer resolution could easily be provided. This system is planned to be fitted to the WHT. It should be available will before the AO system commissioning. given that the AO system only requires the TV and FIELD functions, which will be operational on the INT in 1996, this system could be incorporated for AO only use with little overhead. The CCD controller firmware supports both frame transfer and non frame transfer readout modes.

Integrating the Forth autoguider is simply a matter of providing an DRAMA ADITS server task which forwards messages to the AUTO D-task and monitors the AUTO noticeboard for status information. The image display would be done via the dedicated Autoguider monitor screen and this image information would not be available for the rest of the AO or observing system.

Integrating the vxWorks system is simpler, though involves more work. It is controlled via a DRAMA server thus will integrate directly into the AO architecture. This will be much cleaner than the ADAM D-task interface for the Forth system. The work involved would be to replicate the DRAMA control interface for the INT (or WHT DRAMA autoguider) system. The components of the INT system should be available as either working code to display images or templates. Much of the INT source code may be available to be re-used directly.

Both systems use the same CCD heads and camera controller hardware. The CCD camera firmware is slightly different in the vxWorks system but will be available at LPO in time for the AO commissioning as a proven system.

It is clear that the preferred long term solution is to go straight to the VxWorks/DRAMA based system. Only if the hardware is not available should the ADAM/Forth system be used.

8. Functionality required

1. provide display of single image of full field area
2. provide repeated display of full field image.
3. search for stars in defined area of field, report centroids of stars found.

9. Conclusions

1. The Autoguider system will provide a low cost alternative to a large format science grade CCD as the acquisition camera for the NAOMI system. It can provide all the required functionality and the accuracy of centroiding should be sufficient to acquire onto a 0.1 arcsec slit and still image virtually the full 2.9 arcmin field.
2. It will provide an easily integratable system with a DRAMA control surface.
3. Blind acquisition onto a 0”1 slit is only possibly if the WFS/TTS pick off can be partially transmitting to allow imaging of the guide stars with the pick off in the field.