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A&G Services to Telescope and Instrumentation

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Vía Láctea, s/n (Instituto de Astrofísica de Canarias)

38200 La Laguna (Tenerife) - SPAIN - Phone 34-922-315031 - Fax 34-922-315032

URL: http://www.gtc.iac.es E-Mail: gtc@iac.es

Approval control

Prepared by	Nicholas Devaney Optics group	**Signed in the original copy**
Revised by	Javier Castro Optics Manager Marisa L. García Instrumentation Manager Peter Hammersley Science group	**Signed in the original copy** **Signed in the original copy** **Signed in the original copy**
Approved by	José M. Rodriguez Espinosa Project scientist Pedro Alvarez Project Director	**Signed in the original copy** **Signed in the original copy**
Authorized by	Pedro Alvarez Project Director **Date:**	**Signed in the original copy** **15-07-98**

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Reference documents

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1	GTC System Specification	ESP/STMA/0017-L	1.C
2	Atmospheric Seeing and its effect on the alignment of segmented and multiple mirror telescopes	REF/KECK/0323-L	
3	Study of a pre-focus AO system for the GTC	NTE/OPTI/0014-R	1.A
4	General Scientific Requirements for the GTC	ESP/CCIA/0008-L	1.A

List of acronyms and abbreviations

A&G	Acquisition and Guiding
AO	Adaptive Optics
FOV	Field of View
GTC	Gran Telescopio Canarias
SNR	Signal to Noise Ratio
TBM	Telescope Behaviour Model

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1. SUMMARY

This document describes the services which will be provided by the GTC A&G system. It is the result of preliminary studies and is not a requirements document.

2. INTRODUCTION

The aim of this document is to specify the services which will be provided by the GTC A&G system.The basic aim of the A&G system is, as the name implies, to allow acquisition of astronomical targets and to enable the GTC to track with the required precision. As well as these services, it is contemplated that the A&G will contain wavefront sensing capabilities in order to allow optimization of the optical quality of the telescope. These may be divided into telescope behavior model calibration services, and services for closed-loop active optics. It may also include services useful for the scientific instruments. It is not the purpose of this document to specify how these services will be implemented. When reference is made to a specific item, e.g. an ‘acquisition camera’ , it should be understood that this may or may not coincide with the hardware used for wavefront sensing or guiding. While it is not a requirements document, the use of shall/should is consistent with requirements already stated in the ‘GTC System Specification’ (ref 1).

3. DEFINITIONS

3.1 Fiducial Position

This refers to the nominal position of the science aperture on the Acquisition camera.

3.2 Guide probe

The term Guide probe refers to a device which can be positioned within the field to extract the beam from a guide star and allow the guide star to be focused on a detector.

4. ACQUISITION

The acquisition system shall allow sources to be positioned accurately inside the science aperture. Acquisition will require either (i) that the target be visible on the acquisition camera or (ii) that the offset of the target from a reference star which is visible on the Acquisition camera is known. In the first case, the target is simply placed at a fiducial position on the acquisition camera (corresponding to the known position of the instrument aperture), and guiding commences using a suitable guide star. If the target is invisible to the acquisition camera, then the reference star will be placed at the fiducial position and the required offset applied. If the target is invisible to the acquisition camera and the offset is known with poor accuracy, then the acquisition will necessarily involve the scientific instrument. Fig. 1 summarizes a possible procedure.

4.1 Camera position

It should be possible to position the acquisition camera anywhere within the focal plane. This may not be necessary if the positional accuracy w.r.t. the science aperture is as required (4.2). The object or reference would then be acquired on the acquisition camera and the offset applied.

4.2 Positional accuracy

It shall be possible to position the camera to an accuracy of 0.015 arcsecs relative to the science aperture.

4.3 Camera FOV

In principle the camera FOV need not be much larger than the pointing accuracy of the telescope combined with the seeing-limited image size. However, in order to allow acquisition of objects with positions or proper motions which are not well known, the camera should have a field of view of at least 1 arcminute (diameter). The image quality at the edge of the field will be limited by the field curvature, although this may be partially compensated by tilting the detector.

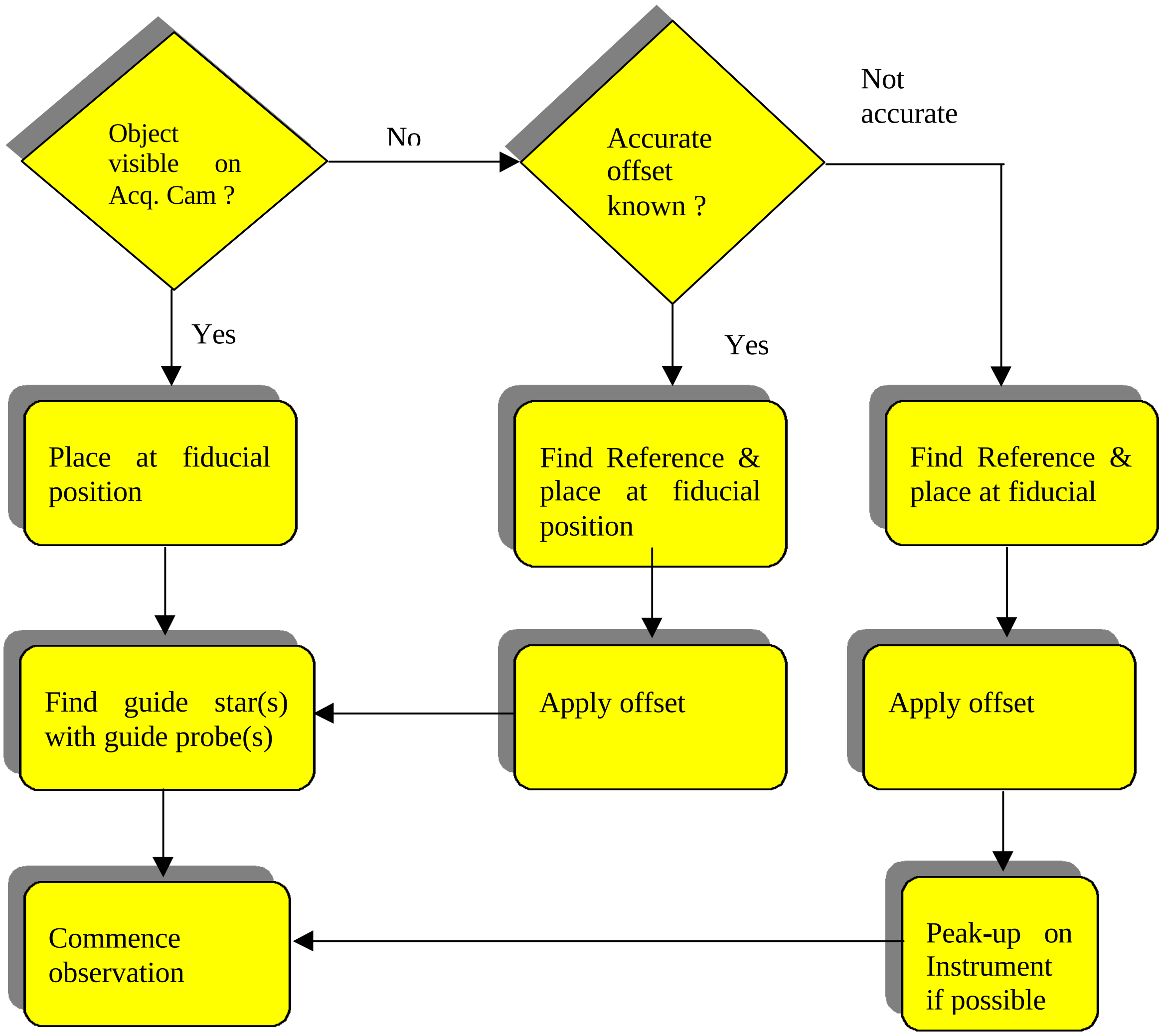

Fig.1 Possible Modes of Acquisition

4.4 Pixel scale

The pixel scale should be 0.1 arcsecs per pixel at most. This would allow centroiding of up to 0.01 arcsecs, depending on the signal to noise. It would over-sample the best expected seeing and reduce the problem of saturation. This pixel scale will require the insertion of a focal reducer; the direct image scale would be 0.03 arcsecs on a 24 μm pixel.

4.5 Readout Speed

It should be possible to read out the camera at up to at least 1 Hz in order to reduce the time spent acquiring objects. The maximum integration time possible should be at least 60 seconds.

4.6 Sensitivity

The throughput to the acquisition camera detector and the detector's quantum efficiency and read noise should allow centroiding to 0.01 arcsecs on a star of V magnitude 23 in 60 seconds assuming a sky background of 21.1 magnitudes per square arcsecond in the V band (see Appendix I)

4.7 Filters

It should be possible to insert neutral and standard (B,V,R,I) filters before the acquisition camera, as this will help to identify sources.

5. GUIDING

The guiding system will allow the image of the target to be maintained at the required position within the science instrument aperture. The guiding may be carried out either on-axis or off-axis. The guiding may be either slow or rapid. Rapid guiding will be fast enough to allow correction of windshake and atmospheric tip-tilt by the secondary mirror. Typically, rapid guiding will require a sampling frequency in the range 100-200 Hz. Slow guiding refers to correction of perturbations using a bandwidth smaller than the eigenfrequencies of the telescope. The correction is usually carried out using the azimuth and elevation drives of the telescope. The typical slow guiding frequency is of order 1Hz.

5.1 On-axis guiding

It is envisaged that off-axis acquisition and guiding will be sufficiently accurate to allow most types of observation foreseen with the GTC. In some cases, on-axis guiding may be required e.g. fast guiding to compensate atmospheric image motion. Some spectrographic instruments may decide to implement slit-viewing. Since the implementation of on-axis guiding severely affects the operation of instruments, this will need to be studied on an instrument-by-instrument basis and as such is not considered here. In general, the telescope will provide the detector and processing to carry out the acquisition and guiding, and it will be up to the instrument (in collaboration with the project office) to decide on the opto-mechanical design.

5.2 Off-axis guiding

Off-axis guiding will be the responsibility of the GTC A&G system. It may be divided into slow guiding and fast guiding.

5.2.1 Slow Guiding

5.2.1.1 Camera position

It should be possible to position the guide camera anywhere within the focal plane. Calculations (Appendix I) indicate that it will be possible to find a suitably bright guidestar within an area of ~33 $arcmin^2$. The focal area corresponding to 33 $arcmin^2$ is 0.08 m^2. If the search region is annular with an outer radius (R2) of 10 arcmin, then the inner radius (R1) would be 9.4 arcmin in the case of a complete annulus or 8.9 arcmin in the case of using a half-annulus (Fig.2). Alternatively, the search region could be confined to a segment of a circle with the required area (angle ~ 38 deg.). It is also possible that the field used for guiding would be further off-axis, although in the case of the Nasmyth foci it will be necessary to study the effect of the strong vignetting of the tertiary mirror (this will change the shape of the pupil and could lead to errors in guiding).

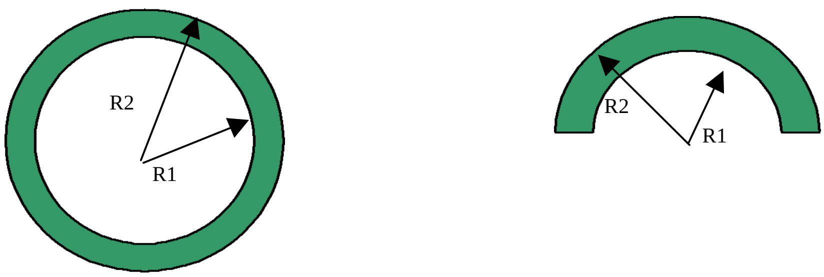

Fig.2

5.2.1.2 Positional accuracy

It shall be possible to position the camera to an accuracy of 0.015 arcsecs relative to the science aperture.

5.2.1.3 Time to position

It shall be possible to position the camera in less than 10 seconds.

5.2.1.4 Positional stability

The camera should maintain its position w.r.t. the science aperture to *better than* 0.01 arcsecs over one hour and should degrade at not more than 0.01 arcsec per hour (TBC).

5.2.1.5 Camera FOV

In principle, the FOV could be as small as a few arcsecs but it should be possible to have a field of view of 20 arcseconds diameter in order to allow guiding on both ends of the chop cycle while chopping up to 15 arcsecs (see 5.2.1.8)

5.2.1.6 Pixel scale

The guiding accuracy shall be 0.01 arcsecs rms (bidimensional). The pixel scale should be 0.1 arcsecs per pixel or less in order to allow centroiding to this level.

5.2.1.7 Readout Speed

It should be possible to read out the camera at up to 10 Hz allowing correction of guiding errors up to 1 Hz (f_{0dB}).

5.2.1.8 Optimisation

It should be possible to optimise the sampling rate as a function of guide star magnitude, sky magnitude, seeing and windshake.

5.2.1.9 Chopping

It should be possible to guide while chopping. The chopping will not affect the guiding if the chopping is faster than the readout speed of the guide camera. If the chopping is slow, then readout of the guide camera should be synchronised with the chopping. Guiding while chopping on sources of large angular extent (e.g. galaxies) would be facilitated by the use of two guide probes separated by the chop throw. When observing point sources, the throw of the chopper will be about 15 arcsecs and the guide camera should have a FOV large enough to guide on both ends of the chop cycle.

5.2.2 Fast guiding

Fast tracking for correction of atmospheric image motion should be sensed using an object within the isokinetic patch of the scientific target. The ideal system for rapid guiding will therefore be on-axis, and hence part of the instrument requiring it. However, since (i) the isokinetic patch is large in the thermal infrared (wavelengths longer than ~3.5 μm) and (ii) rapid guiding is effective over large fields when windshake is important, the A&G system shall provide for off-axis rapid guiding.

5.2.2.1 Camera position

If the fast guiding is used to correct windshake rather than atmospheric image motion, then the reference star can be acquired anywhere within the focal plane. Using the same analysis and detector parameters as for slow guiding, it is found that it should be possible to find a suitably bright guidestar within an area of 83 arcmin^2. The corresponding annular region would have inner and outer radii of 8.6 and 10 arcmins respectively, while a half-anular region would have inner and outer radii of 6.9 and 10 arcmin respectively. For guiding further off-axis at the Nasmyth focus the effect of vignetting by the tertiary mirror will have to be studied.

If the rapid guiding is used to correct seeing-induced image motion then on-axis guiding is the most appropriate approach. However, since the isokinetic patch increases with wavelength, it may be possible to use the off-axis guider in the thermal IR. For example, the isokinetic patch at 4.8 μm will be of order 2 arcmin, and of order 4 acrmin at 10 μm. In these cases, the guide probe will have to be able to extend into the inner part of the focal plane (where it will vignette).

5.2.2.2 Positional accuacy

It shall be possible to position the camera to an accuracy of 0.015 arcsecs relative to the science aperture.

5.2.2.3 Time to position

It shall be possible to position the camera in less than 10 seconds.

5.2.2.4 Positional stability

The camera should maintain its position w.r.t. the science aperture to better than 0.01 arcsecs per hour of observation. This will allow sub-diffraction limited accuracy for observations with tip-tilt correction at 4.8 μm. If used in this manner, the probe will have to be able to reach the inner arcminute of the focal plane.

5.2.2.5 Camera FOV

The camera should have a field of view of at least 3 arcseconds in order to avoid clipping the image which is being used for guiding.

5.2.2.6 Pixel scale

The pixel scale should be 0.1 arcseconds per pixel. With centroiding, it should be possible to reach an accuracy of about $1/10^{th}$ of a pixel, or 0.01 arcsecs.

5.2.2.7 Readout Speed

It should be possible to read out the camera at up to 200 Hz. This is set mainly by the requirement to allow correction of windshake; in principle the bandwidth required for correction of atmospheric image motion is much less. The characteristic frequency for atmospheric image motion is given by v/D, where v is the turbulent windspeed, typically 10 ms^{-1}, and D is the telescope diameter.

5.2.2.8 Optimisation

It should be possible to optimise the sampling rate as a function of guide star magnitude, sky magnitude, seeing and windshake.

5.2.2.9 Chopping

It should be possible to carry out tip-tilt correction and chopping (up to ~1 Hz (TBD)) simultaneously.

6. CALIBRATION OF THE TELESCOPE BEHAVIOUR MODEL

Open-loop active optics will use the telescope's active degrees of freedom in real-time to correct the predictable errors due to gravitational and thermal effects. It will rely on a telescope behavior model (TBM) to do so. This model will need to be calibrated by measuring the real optical configuration of the telescope. The instruments necessary for calibration of the TBM will be integrated into the A&G system. The calibration procedure should avoid modifying the optical configuration of the telescope, and *ideally* should be carried out in parallel with scientific observations. However, it may be necessary that some of the calibration be carried out using observing time. At most, 2% of useful observing time may be assigned to calibration procedures. The calibration system shall be capable of measuring all local (i.e. segment) and global Low Spatial Frequency (LSF)[1] errors. These errors may be divided into the following terms:

1. Primary mirror-secondary mirror tilt, collimation and focus
2. Segment tilts
3. Segment phases
4. Segment figure

These terms will be measured using wavefront sensors; in principle Shack-Hartmann wavefront sensors will be employed for all measurements with the possible exception of segment phases.

6.1 Primary-secondary collimation & focus

This refers to measurement of secondary mirror decenter, tilt and defocus. These may be derived from Shack-Hartmann measurements with a small number of subapertures on the whole telescope pupil (~3x3). Integration times should be long enough (≥300 seconds) to reduce errors due to atmospheric turbulence.

6.2 Segment tilt

Segment tilt could be measured employing a single subaperture per segment. It shall be possible to measure segment tilt with an accuracy of better than 0.01 arcsecs. The subaperture images should be integrated over a time long enough to reduce the errros due to atmospheric turbulence to this level. A study by Chanan (Ref.2) shows that the required integration time depends on the size of the outer scale of turbulence. While data on the outer scale in La Palma is lacking, it appears that integrations of 300 secs or shorter (if the outer scale is small) should be sufficient to reach an accuracy of 0.01 arcsecs. It should be noted that global focus and coma errors due to misalignment of the primary and secondary mirrors will appear as correlated segment tilt errors in the device measuring segment tilts. It will therefore be possible to measure these errors using the segment tilt measuring device. The integration time of 300 seconds will reduce the effect of atmospheric turbulence on the measurements more than the case of segment tilts (i.e. a shorter integration time could be used).

6.3 Segment phasing

A system will be provided to allow nocturnal/twilight phasing of the primary mirror segments. Possible systems include copies of the two systems currently employed at the Keck telescope; the Keck phasing camera system and the ‘phase discontinuity sensor’, which is a modified curvature sensor. A separate system (not considered here) will be provided for phasing the segments in daylight.

6.3.1 Accuracy

The rms error in the segment phasing shall be no more than 35 nm measured at the mirror surface.

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[1] LSF errors are those errors whose period is not small in comparison to the aperture.

6.3.2 Range

The phasing should be possible when the initial phasing error is 10 μm rms (TBC) measured at the mirror .

6.4 Segment Figure

It will be possible to measure at least segment focus and astigmatism. This will require at least 3x3 subapertures per segment. The number of subapertures per segment should be maximized in order to improve the accuracy of the measurements. The currently allocated wavefront errors are 12.0 nm for focus and 12 nm for each mode of astigmatism.

7. CLOSED LOOP ACTIVE OPTICS

Closed-loop active optics refers to wavefront measurement *and* correction while scientific observations are being carried out. The measurements necessary for closed-loop active optics shall be provided by the A&G system. Telescope focus may be tracked by on-instrument sensors (if the instrument deems it necessary to do so) or by the A&G sensor. In closed loop, it would ideally be possible to measure all the local and global Low Spatial Frequency wavefront errors.

7.1 Primary-secondary collimation & focus

It should be possible to measure secondary mirror decenter, tilt and defocus in parallel with scientific observations. The speed and accuracy requirements are the same as those presented for calibration (6.1).

7.2 Segment tilt

A system will be provided which will at least measure segment tilt in parallel with scientific observations. The requirements are the same as for calibration (6.2).

7.3 Segment phasing

The phasing of the primary mirror will be controlled by the capacitive position sensors once they have been calibrated by an optical phasing system. Ideally (i.e. the goal) it should be possible to check the segment phasing (with an rms accuracy of 35 nm) optically in parallel with scientific observations.

7.4 Segment figure

The goal is to measure segment defocus and astigmatism in parallel with scientific observations. Same requirements as 6.4

8. SERVICES TO INSTRUMENTS

It is possible that the A&G will provide some services to Instruments. Since it is foreseen that the A&G should be basically the same at all foci, these services should be those which may be required by several instruments. Such services could include the following;

8.1 Wavelength Calibration lamps

The A&G system may be required to provide wavelength calibration sources which could be used by spectrographic instruments.

8.2 Flat-fielding

The A&G system may be required to provide a system allowing flat-field calibration for the instruments. This system would typically contain continuum sources covering the wavelength range of observations, of sufficient brightness to allow flat-fielding with adequate signal to noise in a short time. These would provide uniform illumination (or simulate the telescope illumination) of the focal plane.

8.3 On-axis guiding

As mentioned in 5.1, on-axis acquisition and guiding (e.g. slit-viewing or atmospheric image motion correction) will be the responsibility of the instruments requiring it. However, the detector will be provided by the telescope, and the data processing will be carried out in an identical fashion to the case of off-axis guiding. Use of the space in front of the focal plane for on-axis guiding should be negotiated between the instrument teams and the Project Office.

8.4 Others

Other services may be requested by individual instruments e.g. a system to extract a beam for an instrument observing in parallel with the on-axis instrument.

9. ADAPTIVE OPTICS

AO should be integrated with the A&G system. Since it is recommended that the AO be provided as a telescope service, it is foreseen that a unit the wavefront correction unit will be installed at or near the A&G system. The A&G design should therefore include the possibility of providing a service to extract the telescope beam and re-insert the corrected beam. A pre-design of such a system was presented in a previous document (Ref. 3)

When AO is in operation, the AO wavefront sensor will provide the information necessary for closed loop active optics.

10. SEEING MEASUREMENT

If the wavefront sensor can be read out fast enough (≥ 500 Hz), then it would be possible to provide measurements of seeing parameters. The differential image motion between subapertures can be used to estimate r_0, the Fried parameter, as well as the outer scale. Temporal correlation of the data may be used to determine the temporal coherence of the seeing. This information may be used by the queue scheduler in order to decide what type of observations to perform as a function of seeing conditions.

11. EXECUTIVE SUMMARY

The following is an executive summary of the services which will be provided by the A&G system:

1. It will provide an Acquisition service allowing scientific objects to be acquired and placed on the science aperture with an rms accuracy of 0.015 arcsecs.

2. It will provide an off-axis guiding service which will maintain the scientific object on the science aperture with an rms accuracy of 0.01 arcsecs. over one hour. It will be possible to perform guiding at a speed fast enough to correct windshake and atmospheric image motion.

3. It will provide a service to calibrate the telescope behavior model. This will be capable of measuring primary mirror segment piston, tilt, focus and astigmatism as a minimum, as well as allowing determination of secondary mirror mis-alignment.

4. A wavefront sensing service will be provided for closed-loop active optics. This will measure at least segment tilt in parallel with scientific observations.

5. Services for instruments will be provided which may include a facility for wavelength calibration and flat-fielding, and other services requested by individual instruments.

6. When adaptive optics is provided by the GTC, the A&G may be responsible for extraction of the telescope beam to the wavefront correction unit and re-insertion of the corrected beam.

7. The A&G system will provide data allowing estimation of the seeing parameters (spatial and temporal coherence, and outer scale).

APENDIX I CALCULATION OF LIMITING MAGNITUDES & SKY COVERAGE

The error in centroiding an image is given by

$$s = \frac{s_w}{SNR}$$

Where SNR is the signal to noise in the measurement, and σ_w is a measure of the image width. If the image width is determined by seeing then we use

$$s_w = 0.71 \frac{l}{r_0}$$

Where λ is the wavelength at which the measurement is made, and r_0 is the Fried parameter at that wavelength. The SNR is given by

$$SNR = \frac{f_* t}{\sqrt{f_* t + n_{pix}(f_{sky} t + s_e)}}$$

Where f_* is the flux from the star (photo-electrons per second), t is the exposure time, f_{sky} is the flux from the sky (photo-electrons per second per pixel), n_{pix} is the number if pixels and σe is the read noise (photo-electrons per pixel). The values used in calculating the centroiding errors for slow guiding are presented in Table 1.

D (m)	10.0
R_0 (m)	0.2416 at 0.55 μm (0.4 arcsec seeing)
λ (μm)	0.55
Radiometric zeropoint (photons/sec/cm^2)	9.72e5
Throughput*Quantum Efficiency	0.5*0.8
M_{sky} (mags/$arcsec^2$)	19.35 (at zenith when moon is full)
w_{pix} (arcsec)	0.1
n_{pix}	100
σ_e (electrons)	10

Table 1.

Using the above expressions, the guide star brightness required to give a certain centroiding error can be found. In the case of slow guiding, this is found to be V=18th mag while it is V=15th mag for fast guiding. Using data on star counts as a function of magnitude, the probability of finding a guide star of at least this brightness in a certain area of sky can be found. If Σ is the number of stars per square degree at the north galactic pole bright enough to use as guide stars, then the area of sky, θ^2, large enough to have a 99% probability of finding at least one suitable guide star is found by solving

$$0.99 = 1 - \exp(-q^2 \Sigma)$$

For V=18th mag. stars, the density is ~500 stars per square degree at the north galactic pole (Ref.4), and the corresponding area is ~33 $arcmin^2$. For V=15th mag. Stars, the density is ~200 per square degree and the area required is ~83 $arcmin^2$.