Algorithms for Guide-Star Acquisition and Control of Mount and Optical Surfaces

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Abstract

Accurate algorithms for the location of guide stars in the telescope focal plane are derived and the method of autoguiding used at the WHT is described. A new approach to the problem of controlling the mount, instrument rotator, primary surface and secondary position using error signals measured using off-axis wavefront sensors is given. This is a generalization of the "virtual telescope" idea of Straede & Wallace (which considers only telescope position) to the case of higher-order wavefront errors. The method is applied to the control system for the Gemini telescopes.

1 Introduction

Accurate tracking has always been of great importance to the imaging performance of astronomical telescopes, and the use of autoguiders to remove unpredictable tracking errors has been a standard technique for many years. This paper discusses a number of topics which have become relevant recently as a result of more stringent performance requirements and the changing parameters of modern telescopes:

- Traditional telescope designs either had rather large fields, in which case an insensitive photomultiplier could be used for off-axis autoguiding, or relied on manual guiding on a bright target. The area of sky available for autoguiding in current and proposed designs is often, by contrast, quite small (typically the outer regions of a field of $5' - 10'$ diameter, the inner parts being occupied by the science instrument).
- The small size of the field requires the use of fainter guide stars and therefore of more sensitive autoguiders. Fast-readout CCD's meet this need, but considerable time is wasted in searching for guide stars unless their positions are known in advance. The Hubble Space Telescope Guide Star Catalogue (GSC) is the best currently-available source, and meets most existing requirements, but is not adequate for the even smaller fields proposed for future telescopes.
- A related constraint is the small amount of space available for relay optics and the desire to minimise the amount of obstruction of the science field by an off-axis autoguider. Both of these problems are alleviated by the use of coherent fibre bundles to feed detectors located elsewhere, but the available field sizes can be small, and the accuracy of location of the pick-off probe becomes critical for efficient operation.

- The newer wide-field, corrected foci have large (and potentially variable) field distortions, generally at their worst in the outer reaches of the field where guide stars must be found. Such distortions must be calibrated accurately in order to allow guide stars to be located quickly. Field acquisition for multi-object fibre spectrographs, a major rôle for these foci, poses very similar problems.
- Accurate acquisition of extremely faint targets onto the small entrance apertures of modern spectrographs can best be done using the autoguider to measure precise offsets. The eventual goal is to be able to acquire the target in a single step, using an off-axis guide star as a positional reference.
- In addition to orthodox autoguiding, which corrects relatively slow tracking errors, fast guiding (to remove telescope vibrations and some component of atmospheric tip-tilt by moving optical surfaces) and active optics (to measure and correct the shape or displacement of the main mirrors) will both be needed in new, high-performance telescopes.

The present paper discusses three topics arising from these considerations and applying specifically to the operation of the telescopes on La Palma or to design studies for the Gemini project. The first concerns the need for efficient selection of guide stars. The introduction of the GSC has made it much easier to find suitable stars for autoguiding ground-based telescopes, and Section 2 describes a rigorous and general set of programs (the Guide Star Search or GSS package) designed for this purpose. The second part of the paper (Section 3) outlines the techniques used for autoguiding and logging image positions on the William Herschel Telescope (WHT). The use of imaging detectors is unusual in this application, but has a number of important advantages. Thirdly, a generalisation of the autoguiding technique used on the WHT is proposed for the the Gemini telescopes, which pose the additional problem of measurement and control of optical surfaces (Section 4).

Appendix A documents the GSS in more detail and Appendix B gives a precise description of the search areas for the ING telescopes (Appendix B.1 gives a summary of notation). A technical detail concerning tangent-plane coordinates is relegated to Appendix C.

The telescopes on La Palma with which much of this paper is concerned are the 4.2-m William Herschel Telescope (WHT), the 2.5-m Isaac Newton Telescope (INT) and the 1.0-m Jacobus Kapteyn Telescope (JKT). They are known collectively as the Isaac Newton Group (ING).

Extensive reference is made to the description of the WHT Telescope Control System (TCS) in Laing (1993, hereafter *TCS*).

2 Guide Star Search Software

2.1 Background

The first step in the autoguiding process is to find guide stars which are observable with a given configuration and to position the pick-off probe(s) correctly. The specific objective of the project described in this section was to locate guide stars suitable for the La Palma Telescopes using the GSC. Software written elsewhere for similar applications proved to be difficult to adapt to our needs, either being tied to a very specific instrumental configuration or running within a hardware or software environment inconsistent with our own. Our requirements were as follows:

1. The GSS should be able to find all of the potential guide stars for a target object observed with any of the ING telescopes in a specified configuration.
2. Target position input should be possible in any coordinate system supported by the telescope control systems.

3. The search area should be defined by a very general algorithm, allowing future telescopes and instruments to be added easily without coding changes.
4. Star positions and guide probe coordinates should both be calculated.
5. The software should be written so that it can be used interactively or in batch mode at local and remote remote sites.

The implementation of the Guide-Star Search software (hereafter GSS) in 1992 led immediately to a major improvement in efficiency, since the time taken to acquire a guide star was reduced to a bare minimum. Future developments include: a version using magnetic disk storage, rather than the existing CD-ROMs, to allow easier access by multiple users; direct interfacing to the on-line control software; a Unix version (the initial implementation used VMS for compatibility with the WHT instrument computers and site network) and a method of recalibrating GSC positions locally by cross-reference to the PPM catalogue.

2.2 The Catalogue

The GSC contains roughly 1.9×10^7 objects with magnitudes in the range 7 - 16, of which more than 1.5×10^7 are classified as stars. It is based on an all-sky, single epoch, single passband Schmidt survey. Astrometry, at equinox J2000, is available at the epoch of the individual plates used in the GSC and is based on the AGK3, SAO and CPC catalogues. Systematic errors of up to 3 arcsec have been found, especially at plate edges (Taff *et al.* 1990), but an astrometric recalibration is in progress. For the present application, it may be more accurate to perform a local recalibration of the GSC reference frame by comparing the positions of bright reference stars with those given in the PPM catalogue over the minimum possible area. Small-scale errors in the GSC are typically 0.3 arcsec, and should eventually limit the accuracy of the positions.

2.3 Basic search procedure

The sequence of operations required for the guide star search software is as follows:

1. Start with a target position for the object to be observed in mean (FK5 or FK4 system) or apparent coordinates, and a sky position angle in the same system.
2. Precess the position to J2000 coordinates, as used by the GSC, not forgetting the position angle.
3. Calculate the values of right ascension and declination which just bracket the area of sky to be searched for guide stars. There are some restrictions on this process for very large fields (see below).
4. Determine the sub-fields of the GSC which include any stars in this range. There may be several such fields, especially close to the poles, and they may be distributed over two CD-ROMs. Each individual field has on average about 2000 objects, although some are much larger and a check of the maximum size is required to make sure that array sizes are not exceeded.
5. Search the fields for stars in the specified ranges of RA, Dec and magnitude.
6. Project the positions of these stars onto the tangent plane, correct for the position of the instrument in the focal plane and rotate into the guide probe coordinate system.
7. Calculate the corresponding guide probe coordinates and select the accessible stars. Descriptions of the fields are given in Appendix B.

8. Eliminate stars which are too close together to be useful.
9. If no stars are selected, output an error message and stop.
10. Sort the remaining stars in order of decreasing brightness.
11. Write out the positions, probe coordinates and magnitudes for the first n of these stars (enough to give some choice in the event of errors in the catalogue) to disk.
12. If requested, produce a plot showing the positions of the stars selected and an overlay of the guide star field.

2.4 Conventions and notation

In order to avoid getting lost in a maze of coordinate systems, we summarise our conventions at this point.

- We consider two types of guide probe: xy and $r\theta$. The former are mounted on xy stages and the latter have azimuthal and radial motions.
- We use capital letters X_P, Y_P, R_P, Θ_P for probe positions measured in encoder units, as input to their controllers.
- Their lower-case equivalents x_P, y_P, r_P, θ_P denote probe positions scaled to radians, as used internally by the TCS.
- x_A and y_A are aperture positions in the TCS focal-plane coordinate system.
- ξ and η are standard coordinates along the $+\alpha$ and $+\delta$ directions at the tangent point, respectively.
- θ is the sky position angle.

2.5 Algorithms

2.5.1 Conversion between equatorial coordinate systems

The required conversions are between mean (FK4 and FK5) or apparent coordinates of arbitrary date and mean FK5 coordinates referred to equinox J2000 and the epoch of observation (no proper motions are available for most stars in the GSC). The procedures are outlined in *TCS* and are described in detail in Seidelmann (1992).

2.5.2 Choice of an initial search area

The object here is to choose an area of sky, bounded by curves of constant right ascension and declination, which *just* includes the guide field. Stars from this area can be efficiently extracted from the GSC to provide a reasonable number for more elaborate processing. The outer boundaries of the guide fields are roughly circular or rectangular in the tangent plane. It is usually convenient to use the circle whose radius is the maximum distance of a point in the guide field from the centre of rotation, since the same search area can then be used for any position angle. For fields which are large or significantly offset from the centre of rotation, this finds too many stars, and their corners are used to define the preliminary search area.

In the former case, the ranges of RA and Dec (except for targets close to the poles) are given by:

$$\Delta\alpha = \arctan(r_{max}/\cos\delta_0)$$

$$\Delta\delta = r_{max}$$

where r_{max} is the radius of the guide field in radians. GSS stores the field radius of xy systems in encoder units and for $r\theta$ systems, R_{max} is the maximum value of the radial coordinate, which may have an offset R_0, so:

$$r_{max} = \frac{e_r}{f}(R_{max} + R_0)$$

e_r is the encoder bit size and f is the focal length, in the same units. xy systems have $R_0 = 0$, with R_{max} as the maximum field radius. The simple formula fails for the case where $\delta_0 + r_{max} > \pi/2$ or $\delta_0 - r_{max} > -\pi/2$ (*i.e.* the guide field includes one of the Poles), in which case all stars with $\delta > \delta_0 - r_{max}$ (in the North) or $\delta < \delta_0 + r_{max}$ (in the South) are selected.

For rectangular guide fields, the RA and Dec of each corner are derived from their tangent-plane coordinates (ξ, η) using the formulae:

$$\tan(\alpha - \alpha_0) = \xi \sec\delta_0 / (1 - \eta \tan\delta_0)$$

$$\tan\delta = \frac{\eta + \tan\delta_0}{[(1 - \eta\tan\delta_0)^2 + \xi^2\sec^2\delta_0]^{1/2}}$$

and the relations between ξ, η and probe coordinates given below. The widest range in each coordinate is used in the initial search. For guide fields around the poles, the selection is made on declination alone, as for circular areas.

2.5.3 Equatorial to tangent plane conversion

The first step in refining the search procedure is to derive is to derive the tangent-plane coordinates ξ and η for the guide stars. In the simplest case, the target direction coincides with the optical axis of the system and the standard coordinates are:

$$\xi = \frac{\cos\delta\sin(\alpha - \alpha_0)}{\sin\delta\sin\delta_0 + \cos\delta\cos\delta_0\cos(\alpha - \alpha_0)}$$

$$\eta = \frac{\sin\delta\cos\delta_0 - \cos\delta\sin\delta_0\cos(\alpha - \alpha_0)}{\sin\delta\sin\delta_0 + \cos\delta\cos\delta_0\cos(\alpha - \alpha_0)}$$

2.5.4 Apertures

There is a subtlety when the target direction is significantly displaced from the optical axis (our only serious case being the INT Prime Focus Camera, which is 10′ off-centre). Since the projection should be about the latter direction, we ought, in principle, to calculate its right ascension and declination and use these in the formulae given above. In fact, this effect is negligible in the present application. If the detector is at a field radius Φ radians, then the error corresponds to tilting the focal plane by Φ, so the maximum error in a guide star position is $\Gamma(1 - \cos\Phi)$, where Γ is the distance from the detector to the edge of the guide field on a line through the intersection of the optical axis with the focal plane. For the INT Camera, the error is 0.008 arcsec, which is far less than the resolution of the probe encoding (0.97 arcsec/bit). All of the other instrumental configurations have the target very close to the optical axis. Given that the effect could be important in some applications and that the necessary formulae are not in the literature, a derivation is given in Appendix C.

In the GSS software, the tangent-plane projection is made with respect to the target position, whose location in the focal plane is specified in the (x_A, y_A) coordinate system. (0, 0) in this system is the intersection of the instrument rotator axis with the focal plane and x_A and y_A are specified in angular units. For the WHT system, the tangent-plane coordinates ξ, η are modified to ξ_1, η_1, as follows:

$$\begin{aligned}\xi_1 &= \xi + x_A \cos(\theta - \theta_0) - y_A \sin(\theta - \theta_0) \\ \eta_1 &= \eta - x_A \sin(\theta - \theta_0) - y_A \cos(\theta - \theta_0)\end{aligned}$$

where x_A, y_A is the aperture position as given to the telescope control system and θ_0 is an instrument-dependent constant defining the angle between the the zero-point of position angle and the rotator (necessary because instruments can be bolted on in different orientations). Alternatively:

$$\begin{aligned}\xi_1 &= \xi + x_A \cos(\rho + \psi) - y_A \sin(\rho + \psi) \\ \eta_1 &= \eta - x_A \sin(\rho + \psi) - y_A \cos(\rho + \psi)\end{aligned}$$

where ρ is the mount position angle and ψ is the parallactic angle. The telescope control systems for the INT and JKT have a different definition of x_A and y_A (with the sign of the former reversed) and do not allow θ_0 to be varied:

$$\begin{aligned}\xi_1 &= \xi + x_A \sin\theta - y_A \cos\theta \\ \eta_1 &= \eta + x_A \cos\theta + y_A \sin\theta\end{aligned}$$

2.5.5 Radial distortion

The standard coordinates are then corrected for the effects of radial field distortion:

$$\xi_2 = \xi_1 D(r_1)$$

$$\eta_2 = \eta_1 D(r_1)$$

$$r_1 = (\xi_1^2 + \eta_1^2)^{1/2}$$

These effects should be negligible for the JKT f/15, INT f/15 and WHT f/11 Cassegrain and Nasmyth foci, but corrections are required for WHT and INT Prime and JKT f/8 (which have refracting correctors). The first of these cases has by far the tightest tolerances for location of guide stars. The distortion can in all cases be modelled accurately by:

$$D(r_1) = 1 + ar_1 + br_1^2 + cr_1^3 + dr_1^4$$

The values of the coefficients are given in Table 5 (Appendix B).

2.5.6 Differential refraction

Differential refraction between the field centre and the guide probe also affects the conversion, but is dependent on elevation (and hence on the time of observation). It is not included in the search software.

2.5.7 Conversion to guide-probe coordinates

The $\xi\eta$ coordinates are then rotated, translated and scaled to the guide probe system (we drop the subscript 2 for clarity). For xy systems:

$$X_P = (f/e_r)[\xi\cos(\theta + \theta_{P0}) - \eta\sin(\theta + \theta_{P0})] + X_0$$

$$Y_P = \omega_p(f/e_r)[\xi\sin(\theta + \theta_{P0}) + \eta\cos(\theta + \theta_{P0})] + Y_0$$

where X_P and Y_P give the probe position. (X_0, Y_0) is the position of the centre of rotation in probe coordinates, f is the focal length in mm, e_r is the encoder resolution (mm/bit) and $\omega_P = \pm 1$ takes account of the handedness of the coordinate system. θ is the sky PA and θ_{P0} is a constant offset (both in radians). It is assumed that the probe scales are the same in both coordinates. We also use a radial coordinate:

$$R_P = [(X_P - X_0)^2 + (Y_P - Y_0)^2]^{1/2}$$

measured from the centre of rotation.

For $r\theta$ systems, we use the same equations for X_P and Y_P but add:

$$R_P = (X_P^2 + Y_P^2)^{1/2} - R_0$$

measured from the centre of *probe* rotation, and

$$\sin e_\theta \Theta_P = X_P/(X_P^2 + Y_P^2)^{1/2}$$

$$\cos e_\theta \Theta_P = Y_P/(X_P^2 + Y_P^2)^{1/2}$$

The obscure difference between the definitions of the radial coordinate arises because of confusion between vignetting (centred on the optical axis) and probe radial travel. In the one practical case, the centres are identical, so $X_0 = Y_0 = 0$ and the definitions merge. The two effects should, however, be clearly separated.

2.6 Configurations

A telescope/instrument combination is specified by a general model, referred to as a "configuration", whose parameters are stored in a an ASCII file for easy modification. A configuration is defined as follows:

Telescope The name of the telescope. A special case ("NONE") is used for making finding charts.

Instrument A name for the instrumental configuration (which may refer to focal station, detector or autoguider).

Geometry The descriptions of the search areas and the conversions between RA, Dec. and guide probe coordinates. A full description is given in Appendix B.

Magnitude A magnitude range, defining the brightest and faintest possible guide stars.

Observing aperture This is specified as an (x_A, y_A) pair, in radians, and defines the centre of the detector (see above).

Minimum separation This defines the minimum distance between a selected guide star and its nearest neighbour in the catalogue (whether or not the latter satisfies the selection criteria).

Number of stars This is the maximum number of stars to be selected during a search.

2.7 Target data

The parameters given below specify the observation:

Rotator position angle This is a sky position angle, θ, as used by the relevant telescope control system. There is an option in which guide stars are found for the complete range of position angles, to allow quick selection at a later stage, although this is not allowed for very large guide fields because of the enormous number of stars satisfying the selection criteria.

Target name and position in any of the coordinate systems supported by the WHT telescope control system. The following parameters are required:

Right ascension

Declination

Equinox Mean FK4 or FK5 systems (*e.g.* B1950, J2000) or apparent coordinates of arbitrary date. (Note that this is a change from the WHT TCS, which supports apparent coordinates of current date only. This is necessary in order to allow running of the guide star search software well before the observations take place).

The remaining parameters are optional. Parallax and radial velocity, in particular, will make very small differences to the exact selection of guide stars and to the computed guide probe positions, but are retained for consistency with the TCS and to allow direct use of WHT catalogue files.

Proper motions in RA and Dec (arcseconds per year). Defaults to zero.

Epoch (year). Defaults to equinox.

Parallax (arcsec). Defaults to zero.

Radial Velocity Defaults to zero.

Target positions can be input in a catalogue file in the format accepted by the WHT control system.

Date of observation Defaults to the current date.

3 Autoguiding

3.1 General

Having selected a suitable guide star, the next step is to measure its position and to evaluate the appropriate drive corrections. We regard an autoguider as an imaging detector with an array of rectangular pixels: the generalisation to more complicated arrays is straightforward, and the most common arrangement (a quadrant detector) can be treated as a special case. The autoguider array is positioned in the focal plane using an xy or $r\theta$ probe, as in the previous section. We require the conversion between autoguider pixel position and the telescope focal-plane coordinate system $x_A y_A$, in which corrections are applied (see *TCS*). In the remainder of this section, we describe the autoguiders and acquisition cameras used on the WHT, derive the coordinate conversions for autoguiding and closed-loop offsetting and discuss the refinements required by the possibility of relative motion between the target and an off-axis guide star.

The TCS uses radians internally, and it is convenient to scale the probe positions given earlier. We define:

$$x_P = \frac{e_r}{f}(X_P - X_0)$$

$$\begin{aligned} y_P &= \omega_P \frac{e_r}{f}(Y_P - Y_0) \\ r_P &= (x_P^2 + y_P^2)^{1/2} \end{aligned}$$

For $r\theta$ probes,

$$\theta_P = e_\theta \Theta_P + \theta_0 + \theta_{P0}$$

and for xy probes,

$$\theta_P = \theta_0 + \theta_{P0}$$

These give the position of the probe with respect to the origin of the focal-plane coordinate system and the angle between the coordinate systems. The TCS stores ω_P, e_r/f, e_θ (rad / encoder unit), $\theta_0 + \theta_{P0}$, $e_r X_0$, $e_r Y_0$ and $e_r R_0$ (rad) as scaling constants.

3.2 Autoguiders and Acquisition Cameras

This section describes the use of CCD autoguiders and TV cameras for autoguiding of the WHT. The system is somewhat unusual in using imaging detectors and allowing operation of more than one of them at once: two-dimensional arrays have proved to have a number of advantages over devices such as quadrant detectors for autoguiding and diagnostic applications. We refer to on-axis, fixed detectors as "acquisition cameras" and movable (generally off-axis) ones as "autoguiders", although their operation is to a large extent independent of physical implementation. The devices used on the WHT are intensified Westinghouse TV cameras capable of on-target integration with further summation and recursive filtering in software and Peltier-cooled CCD devices used with windowed readout in frame transfer mode. The TV cameras can reach substantially fainter limiting magnitudes than the CCD's, because of their low noise and dark current, but have significant geometrical errors, including departures from rectilinearity and time variations. They are also vulnerable to over-illumination. For autoguiding and measurement applications, the CCD devices are usually superior, but TV cameras are preferred for faint-object acquisition. On the WHT, the Cassegrain and GHRIL acquisition cameras are TV's, and all of the off-axis autoguiders (Cassegrain, Prime and UES), together with the UES slit-viewer, are CCD's.

Both devices are capable of on-line image measurement at rates of up to 10 Hz and their interfaces to the telescope control system are identical. They are connected via RS232 serial lines in order to avoid network delays. There are two channels, generally connected to the microprocessors associated with acquisition camera and autoguider respectively, although other devices can be attached instead. Information is sent to the TCS as a series of packets, one per centroiding operation, each containing the coordinates of the image centroid (x_G, y_G) in detector pixels, the integration time (used by the TCS to test for timeouts) and codes for low signal level or image lost. The information needed to convert from detector coordinates to the focal-plane system used by the TCS is therefore stored only on the latter system.

The TCS is informed of the position of the guide probe by the system computer or directly by the user. For normal autoguiding applications, the position of an xy probe is irrelevant, since the orientation of the detector does not change with respect to the instrument, and only the θ coordinate of an $r\theta$ probe is required. It is possible to view the field by moving it to the autoguider, however, and the full position of the probe is needed by the TCS for this purpose.

The TCS can then perform any of the following actions:

1. Log one or both sets of coordinates for subsequent analysis. Simultaneous logging of on- and off-axis data allows tracking and rotational errors to be separated.

2. Autoguide on one of the channels. The image position is maintained by converting the offsets between the measured centroid and the guiding reference position to altazimuth coordinates and applying them as a correction to the demand position. The guiding position is, by default, that of the first packet received after the loop is closed, but can be set to any value.

3. Offset the telescope or instrument rotator using the autoguider as a precise measuring device. The technique here is to calculate the change in the image position on the detector introduced by a given (x_A, y_A) or rotational offset and then simultaneously to perform the offset and modify the guiding reference position. Given that the stability of the CCD autoguider for small offsets is extremely good and that the pixel scale is known to high accuracy, this provides a very precise method of aligning a target field on the instrument. Positional offsets are used for single objects; the additional complication of rotation is needed for long-slit and multi-slit spectroscopy.

3.3 Application of autoguider corrections

The corrections generated by the autoguider are applied in the focal-plane coordinate system (x_A, y_A), whose transformation to altitude and azimuth is described in *TCS*. The conversion from autoguider pixel coordinates (x_G, y_G) to the focal-plane system is:

$$\Delta x_A = -\omega_G g_X \Delta x_G \cos(\theta_G + \theta_P) - g_Y \Delta y_G \sin(\theta_G + \theta_P)$$

$$\Delta y_A = +\omega_G g_X \Delta x_G \sin(\theta_G + \theta_P) - g_Y \Delta y_G \cos(\theta_G + \theta_P)$$

Here, θ_G is the rotational offset of the autoguider with respect to the probe, g_X and g_Y are the pixel scales in x_G and y_G and ω_G $(= \pm 1)$ defines the handedness of the autoguider coordinate system. θ_P is a constant for xy probes, of course.

3.4 Closed-loop offsetting

3.4.1 Offsetting without moving the guide probe

The use of an imaging detector for autoguiding makes it straightforward to offset the telescope with the guiding loop locked, since the guide probe does not have to be moved. This method is very precise, but is restricted to offsets small compared with the guiding readout window unless autoguiding is suspended during the offset and resumed once it is complete. At the WHT Cassegrain focus, the readout window is a small fraction of the illuminated area on the CCD, so it is possible to suspend autoguiding, move the window to an appropriate position and then resume. This is not worthwhile at the Prime and UES Nasmyth foci, since the guiding fields (coupled by coherent fibre bundles) are much smaller and fill the readout windows. If the offset takes the image of the guide star outside the available field, then the probe must be moved, as described later. Any offset in the focal-plane coordinate system (using the `APERTURE` or `BEAMSWITCH` commands or the APOFF mode of the handset) automatically updates x_G and y_G. The TCS command `TWEAK` can change the rotational offset ρ_A as well as x_A and y_A. This is used to align a field with the instrument in position and rotation. A displacement results in the following corrections to the guiding position (as in the previous subsection, but with a change of sign):

$$\Delta x_G = \frac{\omega_G}{g_x}[\Delta x_A \cos(\theta_P + \theta_G) - \Delta y_A \sin(\theta_P + \theta_G)]$$

$$\Delta y_G = \frac{1}{g_y}[\Delta x_A \sin(\theta_P + \theta_G) + \Delta y_A \cos(\theta_P + \theta_G)]$$

(notation as above). The position of the centre of rotation in autoguider pixel coordinates is:

$$x_{GC} = (x_{G0} - x_G) - r_P \sin\theta_G / g_x$$

$$y_{GC} = (y_{G0} - y_G) - r_P \cos\theta_G / g_y$$

where (x_{G0}, y_{G0}) is the detector position corresponding to that of the probe. The offset on the chip due to a rotation $\Delta\rho_A$ is then:

$$\Delta x_G = (\cos\Delta\rho_A - 1)x_{GC} + \sin\Delta\rho_A y_{GC}$$

$$\Delta y_g = \sin\Delta\rho_A x_{GC} + (\cos\Delta\rho_A - 1)y_{GC}$$

Note that the TCS currently makes the assumption that the centre of rotation coincides precisely with the centre of probe coordinates for $r\theta$ system. This is insufficiently general (although it currently works in practice) and will be changed shortly.

3.4.2 Offsetting by moving the probe

If the offset is large enough that the guide star moves completely out of the field of the detector, then it is necessary to adjust the position of the guide probe. We combine the equations for the change in ξ and η due to an offset in the focal-plane coordinate system (Section 2.5.4) with the relation between ξ and η and probe coordinates in Section 2.5.7 to give the probe movement:

$$\Delta X_P = \frac{f}{e_r}[\Delta x_A \cos(\theta_0 + \theta_{P0}) + \Delta y_A \sin(\theta_0 + \theta_{P0})]$$

$$\Delta Y_P = \frac{\omega_P f}{e_r}[\Delta x_A \sin(\theta_0 + \theta_{P0}) - \Delta y_A \cos(\theta_0 + \theta_{P0})]$$

In the case of an $r\theta$ probe, the changes in R_P and Θ_P are derived using the relations in Section 2.5.7.

3.5 Viewing a target field with the autoguider

It is occasionally useful, especially in the absence of an acquisition camera, to view a target field on the autoguider. The offset required to do this in the focal-plane system is:

$$\begin{aligned} x_A &= -r_P \sin\theta_P \\ y_A &= -r_P \cos\theta_P \end{aligned}$$

3.6 Blind Acquisition

Given suitable accuracy and repeatability of guide probe movement, it should be possible to acquire a target using an off-axis guide star as a precise positional reference. To do this to an accuracy of <0.25 arcsec, as required for typical slit spectrographs, requires excellent relative astrometry, an accurately-calibrated guide probe and fairly sophisticated software. The following is an outline of a suitable procedure, which is currently under development:

1. Slew to the target position. The target should be within a few arcsec of the desired position in the focal plane, but will not be precisely centred.

2. Place the guide probe at the position of a suitable guide star, whose position relative to the target is known with a precision significantly better than the size of the instrument aperture.

3. Compute the expected autoguider pixel coordinates:

   (a) Start with the position of the guide star in equatorial coordinates.

(b) Process this through the entire telescope pointing loop (as described in *TCS*), omitting corrections which apply only to the target such as increments added to its position, movements in focal-plane coordinates and non-sidereal tracking rates. The refraction correction should use the effective wavelength of the guide star rather than that of the target. The result is a demand position in the mount (altazimuth) coordinate system.

(c) Difference this from the demand position of the target, and project into the tangent plane.

(d) Rotate into focal-plane plane coordinates (x_A, y_A).

(e) Use the formulae given earlier to predict the autoguider coordinates (x_G, y_G), given the actual probe position. It may be necessary to apply an empirical model of probe flexure at this point.

4. Servo the telescope to maintain the guide star at (x_G, y_G), as in normal autoguiding. The target should then be centred precisely on the instrument.

This procedure has the advantage that the required autoguider coordinates (x_G, y_G) are updated continuously as the displacement between the target and guide star changes. Differential refraction, probe flexure and (for solar-system objects) non-sidereal motions are automatically compensated, so the tracking accuracy is also improved.

The astrometric requirements are quite stringent: a relative accuracy of <0.25 arcsec (preferably <0.1 arcsec) is required. Absolute positions of guide stars are difficult to measure to this precision, and the present version of the GSC is wholly inadequate for the purpose. A forthcoming astrometric recalibration could well solve the problem; it may also be possible to correct its positions locally by reference to the PPM or Hipparcos catalogues. The Carlsberg Automatic Meridian Circle can reach faint enough magnitudes to measure guide stars for a majority of fields, and is starting to do this for faint AGN. This is particularly useful for objects whose absolute positions are known from radio observations, but which are very faint optically. The most useful general method, however, is likely to be relative astrometry from Schmidt plates (measured on automatic machines such as APM or Super-Cosmos) or large-area CCD frames.

Initial calibrations suggest that this procedure is capable of a positional accuracy of <1 arcsec without any modelling of probe flexure, so it is clearly worth further effort.

4 Autoguiding and Active Optics for the Gemini Telescopes

4.1 Background

The control of the Gemini 8-m telescopes is significantly more complicated than that of the WHT because of the need to maintain the figure of the primary mirror and to control the decentre, tilt and focus of the secondary. The requirements for wavefront sensing have been discussed in some detail (*e.g.* Jenkins *et al.* 1993). This section deals with a particular aspect of the problem, namely the portion of the telescope control loop which calculates the error signal in closed-loop operation and applies corrections to the appropriate mechanisms. This is one of the areas in which the Gemini telescope will break new ground, and it is important to establish a clear conceptual model for its operation.

The criterion for successful operation of the telescope control system is that an object whose position is specified in one of the standard astronomical coordinate systems is imaged perfectly onto a specified position and with a specified orientation on a science instrument. This is equivalent to saying that the Zernike terms representing the deviation from a perfect wavefront arriving from the target are zero and that the the image of a second object displaced by an infinitesimal amount from the target in a specified position angle on the sky is imaged on the detector at a position displaced from the target image in a given direction. The mechanisms available to the controller are the main telescope drives (altitude, azimuth and rotation), the xyz translation and tilts of the secondary mirror, and the degrees of freedom available to the primary support system via its pneumatic actuators. The measuring devices fall into two categories:

1. encoders associated with the various drive mechanisms and
2. wavefront sensors (hereafter WFS).

4.2 Wavefront sensors

The WFS's and their probes need not be controlled by the TCS, although (as for ordinary autoguiding) there are some applications in which direct probe control would be an advantage. The sensors are expected to have a reasonable field of view. They can operate continuously, providing a series of measurements to the telescope controller (conceptually, Zernike mode amplitudes, although in the case of a simple autoguider this is equivalent to sending the pixel coordinates of an image, as in the WHT system). The sensor controllers have no role in deciding the corrections to be applied to the telescope mount or optics, but act entirely as measuring devices. Small offsets can be accommodated without mechanical movements of the probe carrying the sensor (Section 3.4.1). Larger offsets will require the probe to be moved (Section 3.4.2), but the calculation of the required displacement need not be done to very high accuracy: all that is required is that the precise position of the probe is supplied to the telescope controller. There may be applications which require frequent probe movements, for example if the WFS field is small, the rotator is stopped to keep a spectrograph slit precisely vertical or a rapidly-moving solar-system object is being observed. It might then be more straightforward to allow the TCS to control the probe directly.

In closed-loop operation, the telescope controller has available (at various update rates) information from one or more wavefront sensors. It then has to decide what corrections should be made to the demand positions for the telescope and optics mechanisms determined using the open-loop model. Its criterion of success is that the amplitudes of the Zernike coefficients supplied by the sensors take specified (not necessarily zero) values. For the higher-order Zernike modes (everything except wavefront tilt, focus and coma, making 5 coefficients in all), only one set of mechanisms is relevant, namely the primary mirror support. This is a natural extension of the position-based approach pioneered by Strade & Wallace (1976) on the AAT and used in many subsequent systems, including the WHT TCS.

It is likely that the following WFS's will be available, to be used in combination as appropriate:

1. A calibration sensor to be used in detailed evaluation of the behaviour of the optical system as a function of elevation and periodically thereafter. This will be used only at the field centre and is required to be positioned at a reproducible position there and retracted when not in use. It could be implemented as a many-element Shack-Hartmann array, as in the NTT and WHT devices. There is no requirement for fast readout (in any case, averaging over seeing fluctuations for at least 20 s is required).

2. An autoguider, mounted on a movable, precisely encoded probe and capable of accessing all of the available field. This should be capable of measuring focus as well as wavefront tilt (alias position) and must read out at the rate required to control secondary tip-tilt. It may be regarded as a two-aperture Hartmann mask, although it is probably more sensible to implement it as a curvature sensor.

3. A low-order WFS to be used for periodic (slow) checks on the primary figure and for monitoring of field rotation. Again, this needs to access the whole field. It could be physical identical to the autoguiding device.

4. The Adaptive Optics WFS, which needs to work rapidly, but at low order and close to the field centre. Given these requirements, the most sensible arrangement (at least in the infrared) will be to pick off using a dichroic close to the instrument.

Each of these devices can be regarded as producing periodic measurements of two or more Zernike coefficients. They differ in the number of modes and in their update rates, but are otherwise conceptually identical.

4.3 Open and closed-loop operation

The operational modes of the controller include the following:

4.3.1 Open-loop operation

In this mode, no information from any of the WFS's is used. Demand positions are calculated for each of the mechanisms based on the input position and a set of predetermined models incorporating the imperfections of the telescope. These include:

1. tilt and translation of the optical surfaces to correct for gravitational deflections;
2. adjustment of the primary figure;
3. a pointing model for the mount and rotator (note that this differs slightly from the WHT implementation in that it contains no terms which may be ascribed to relative displacement of optical surfaces, but does include any effect which may be described as a pure wavefront tilt or mount rotation).

The demand positions for the mount, rotator and optics are expected to be close to the correct values under all circumstances. Information provided by the WFS's should generate small corrections.

4.3.2 Autoguiding

The simplest closed-loop mode is one in which only residual wavefront tilts (or pointing errors) and defocus are corrected. This is a simple generalisation of the procedure described in Section 3.6. The telescope is initially driven to the target position and the probe carrying a WFS is moved to the anticipated position of a suitable guide star (calculated by GSS or an equivalent program). The TCS then evaluates the anticipated output of the detector, taking into account such effects as differential refraction (in colour and elevation) between the target and guide star and flexure of the probe. For example, if the WFS is a two-aperture Hartmann sensor, the controller predicts the positions of the two images. It then derives a difference between the demand and measured positions which is converted to errors in altitude, azimuth and focus. The first two need then to be apportioned between the main drives and the secondary mirror control. The most obvious way of doing this is to filter the error so that the slowly-varying component is fed to the mount and the remaining (low-amplitude, one hopes) signal is used to control the secondary. It would be straightforward to implement a general recursive filter in the time domain, whose characteristics could be optimised later.

4.3.3 Control of rotation

It is not yet clear whether closed-loop control of rotation will be necessary, but experience with the WHT suggests that slowly-varying errors at a level exceeding the extremely stringent Gemini error budget will occur. Correction can be handled by a simple extension of the autoguiding algorithm described in the previous section, but using two detectors.

4.3.4 Control of primary figure

It is expected that the primary figure will only have to be adjusted at intervals of >100s or so, which is ample to average over seeing fluctuations. Again, the approach is to predict the values of the Zernike coefficients required for an off-axis guide star to ensure that the on-axis image is perfect. This does not necessarily mean that the off-axis terms are zero, of course, and a Ritchey-Chrétien system has a noticeable radial dependence of astigmatism. Most of the terms can only be corrected using the primary support system, but there are a few problems of arbitration, associated with the lowest-order coefficients (tilt, focus and coma). The first is the use of translation and tilt to eliminate coma. Errors due to decentre and tilt cannot be distinguished by a single measurement of coma. This leads to problems, because although coma can be eliminated at the field centre by adjusting either translation or tilt, the images elsewhere in the field will not be correct (and, in fact, will show significant non-radial variation of astigmatism). In practice, the calibration star will be off-axis, so the prediction of the wavefront correction at the science instrument may be wrong. The tolerances are clearly much looser for a Ritchey-Chrétien system than for a classical Cassegrain, but some independent way of measuring translation is still highly desirable. For the moment, we assume that the translation has been calibrated accurately and that small residual corrections can be handled by tilting the secondary. This points to the second problem, which is that moving the secondary to correct coma automatically introduces an additional wavefront tilt. It makes sense to take account of this by moving the mount at the same time to compensate. Positional (tilt) information will normally continue to arrive from the autoguider during this operation, and the goal is that it should see no positional error as the secondary is moved. This requires that the secondary be translated slowly. Finally, the slow WFS should give a better estimate of focus than the autoguider (especially if any spherical aberration is present) and its estimate should probably be preferred unless it is far from the field centre.

4.3.5 Adaptive Optics

If a full adaptive optics system is in operation then, by definition, the low-order modes are determined at high bandwidth. The telescope and its optics need to be adjusted to keep the adaptive mirror comfortable. Smoothing of the output coefficients of the adaptive optics WFS gives estimates of the relevant Zernike coefficients, which can be corrected exactly as described earlier.

5 Summary

This paper has discussed three aspects of the acquisition and guiding problem for modern telescopes:

- The selection of suitable guide stars and the prediction of their positions in the focal plane. This has been solved in a fairly general way by the GSS package, whose algorithms were described in detail. The main limitation of its primary input catalogue, the GSC, is inadequate absolute astrometry but, as the available guide-star fields become smaller, deeper catalogues will be needed.

- Autoguiding techniques using imaging detectors. These have been applied successfully to the WHT, and an extension to cope with blind acquisition and relative motion of the target and guide star is in progress.

- Extension of these methods to the control of optical surfaces. The autoguiding methods described here can be applied straightforwardly to the control of primary and secondary mirrors, as needed wrfor the new generation of high-performance telescopes.

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