A Mathematical Description of the Control System for the William Herschel Telescope

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Abstract

The algorithms used to convert between coordinates of an astronomical object given in a standard system and the demand position and velocity output to the telescope servo system are described in detail. Novel features of the WHT control system are emphasised, in particular the methods used to correct for errors in the different encoding systems, the control of derotation optics and the rotator and azimuth limit calculations.

1 Introduction

Precise control is critical to the pointing, tracking and imaging of modern telescopes. The control system developed for the William Herschel Telescope (WHT) has met stringent performance targets and its conceptual framework is adequate for the yet more demanding requirements of the Gemini project. The purpose of the present paper is to describe the algorithms used in the WHT control system, without much reference to details of implementation. The aims are to document the existing code and to provide a starting point for specification of a new implementation using different hardware, language and operating system.

The WHT is a 4.2-metre telescope with an altazimuth mount. It has four focal stations: Prime, Cassegrain and two Nasmyth. The Telescope Control System (TCS) is the software required to point the telescope at an astronomical object, to track and focus it accurately and to make any offsets necessary during the observation. The mechanisms to be controlled are therefore: altitude and azimuth drives, instrument rotation at each of the four focal stations, secondary mirror tilt, dome, shutters, primary mirror cover and focus. Acquisition cameras and autoguiders are not under the control of the TCS, but provide data to it.

The TCS is implemented in FORTRAN (with a minimum of Macro and C) on a Vax 4000-200 minicomputer. It is interfaced to the telescope hardware via Camac and to the autoguiders and acquisition cameras using serial lines. It may be operated either in stand-alone mode or from the system computer, to which it is interfaced using Decnet from an ADAM D-task.

Section 2 summarises the basic geometry for an altazimuth telescope and derives velocities and accelerations, which are needed in order to estimate the necessary update rates for pointing calculations.

The tangent-plane coordinate systems used later are also defined. Section 3 describes the transformation between astronomical coordinates and the mount altazimuth system and section 4 outlines the processing of encoder and transducer readings and the calculation of drive demands. The derivation of the quantities shown on the Information Display is the subject of section 5; this is mostly concerned with software limits. Section 6 outlines calibration and diagnostic procedures and section 7 suggests some directions for future development of the system.

A glossary of the symbols used is given in Appendix A. The sections of the William Herschel Telescope Users' Manual describing the TCS are attached as Appendices B – E. These give a complete specification of the system commands and display output. Their contents are: classified command summary (Appendix B), alphabetical glossary (Appendix C), interactive control using the TCS "handset" (Appendix D) and the Information Display (Appendix E).

The algorithms used for autoguiding are described elsewhere (Laing 1993; hereafter *AG*). Extensive reference is also made to the *Explanatory Supplement to the Astronomical Almanac* (Seidelmann 1992), hereafter *Explanatory Supplement*. The sign conventions for astronomical coordinates are those used in this reference:

1. Azimuth (A) is measured from north through east in the plane of the horizon and elevation (E) or altitude is measured perpendicular to the horizon ("elevation" and "altitude" are used interchangeably, following conventional usage). Zenith distance $z = \pi/2 - E$ is more often used in calculations, since it is a natural polar coordinate. Note that Wallace (1990) measures azimuth from south though east.

2. Hour angle (h) is measured westwards in the plane of the equator from the meridian and declination (δ) is measured perpendicular to the equator, positive to the north.

3. Right ascension (α) is measured from the equinox eastward in the plane of the equator.

4. Longitude is measured from the equinox eastward in the plane of the ecliptic and latitude (ϕ) is measured perpendicular to the ecliptic, positive to the north.

5. Sky position angle (PA), θ, is measured anticlockwise from north.

2 Basic Geometry

2.1 Equatorial to Altazimuth Conversion

In this section, we summarise the conversions between equatorial (h, δ, θ) and altazimuth (A, z, ϕ) coordinates and the velocity and acceleration on the sky in the latter system during sidereal tracking. ψ is the parallactic angle, *i.e.* the angle between the projections on the of the local vertical and the meridian. The conversions are contained in equation 4.5.17 of Murray (1983):

$$\begin{aligned}
\cos z &= \cos\delta\cos h\cos\phi + \sin\delta\sin\phi \\
\sin A\sin z &= -\sin h\cos\delta \\
\cos A\sin z &= \sin\delta\cos\phi - \cos\delta\cos h\sin\phi \\
\sin\psi\sin z &= \cos\phi\sin h \\
\cos\psi\sin z &= \cos\delta\sin\phi - \sin\delta\cos\phi\cos h
\end{aligned}$$

The definition of sky PA is instrument-dependent, and a spectrograph slit or one of the detector axes is generally used as a reference. The mount position angle, ρ, measures the rotation of a direction fixed in the rotator around the optical axis of the telescope anticlockwise from the vertical direction. In order to maintain a fixed relation between mount and sky position angle for different configurations, the WHT control system has an offset parameter, θ_0, which is an instrument-dependent constant. The relation between sky PA, mount PA and parallactic angle, ψ is then:

$$\rho = (\theta - \theta_0) - \psi$$

for Cassegrain and Prime foci and

$$\rho = (\theta - \theta_0) - \psi \pm E$$

for the Nasmyth foci (+ for the UES and − for the GHRIL focal stations).

2.2 Velocities and accelerations

The first derivatives of azimuth, zenith distance and parallactic angle are required in order to estimate the update rates required for pointing calculations. Primes denote differentiation with respect to hour angle. In order to get derivatives with respect to sidereal time, we need to multiply by μ or μ^2 for first and second derivatives, respectively, where μ is the sidereal tracking rate, 7.272×10^{-5} rad s^{-1}.

2.2.1 Zenith distance

$$-z' \sin z = -\cos\phi \cos\delta \sin h$$

and therefore the elevation velocity is

$$z' = \cos\delta \cos\phi \sin h / \sin z = -\sin A \cos\phi$$

A further differentiation gives

$$(z')^2 \cos z + z'' \sin z = \cos\phi \cos\delta \cos h$$

and the acceleration is

$$z'' = \cos\phi(\cos\delta \cos h - \sin^2 A \cos\phi \cos z) / \sin z$$

2.2.2 Azimuth

$$\sin z \sin A = -\sin h \cos\delta$$

$$\begin{aligned} z' \cos z \sin A + A' \cos A \sin z &= -\cos h \cos\delta \\ &= \sin z \cos A \sin\phi - \cos\phi \cos z \end{aligned}$$

and the azimuth velocity is therefore

$$A' = (\sin\phi \sin z - \cos\phi \cos z \cos A) / \sin z$$

The maximum velocity is 1 deg s^{-1}, so the radius of the "blind spot" at the zenith is 0.21°. A convenient way of writing A' is in terms of the parallactic angle, ψ, using the expression derived in the next subsection:

$$\sin\psi = -\sin A \cos\phi / \cos\delta$$

$$\cos\psi\psi' = -\cos AA'\cos\phi/\cos\delta$$
$$\psi' = -\cos\phi\cos A/\sin z$$
$$\Rightarrow A' = \cos\psi\cos\delta/\sin z$$

Consequently,

$$\begin{aligned} A'' &= \cos\delta\left(\frac{-\sin z\sin\psi\psi' - \cos\psi\cos zz'}{\sin^2 z}\right) \\ &= \frac{\cos\delta\cos\phi}{\sin^2 z}(\cos\psi\cos z\sin A - \sin\psi\cos A) \end{aligned}$$

2.2.3 Parallactic angle

$$\sin z\cos\psi = \sin\phi\cos\delta - \cos\phi\sin\delta\cos h$$

We differentiate this, and substitute for z', using the results of the previous subsection:

$$\begin{aligned} \psi' &= \frac{-\cos\phi}{\sin z\sin\psi}(\sin A\cos z\cos\psi + \sin\delta\sin h) \\ &= -\cos\phi\cos A/\sin z \end{aligned}$$

We then differentiate again and insert the expressions for A' and z' derived earlier:

$$\begin{aligned} \psi'' &= -\frac{\cos\phi}{\sin^2 z}(-\sin z\sin AA' - \cos A\cos zz') \\ &= \frac{\sin A\cos\phi}{\sin^2 z}(\cos\psi\cos\delta - \cos A\cos z\cos\phi) \end{aligned}$$

2.2.4 Recalculation of the velocity demand

The position error can be estimated by expanding the quantity concerned in a Taylor series:

$$x(h+\Delta h/2) = x(h) + x'(h)(\Delta h/2) + x''(h)(1/2)(\Delta h/2)^2 + ...$$

If the velocity demand is $x'(h)$, *i.e.* that appropriate to the middle of the period $h - \Delta h/2$ – $h + \Delta h/2$, then the error at the end of the period is given to a first approximation by:

$$x(h+\Delta h/2) - [x(h) + x'(h)(\Delta h/2)] \approx x''(h)(\delta h^2/8)$$

We wish to ensure that, within the allowed rate of the telescope ($0.2° < z < 80°$), the rate of recomputation of velocity is not the main factor affecting the timing of the servo loop (an update rate of 20 Hz is justified by the mechanics of the telescope). We use the expressions for the second derivatives of A, z and ψ calculated above. The worst cases occur near the zenith, and are approximate by $\mu^2/\sin z$ in A and z and by $\mu^2 r/\sin^2 z$ for ψ, where r is the field radius. The maximum positional error for an update rate of 20 Hz is then roughly 0.002 arcsec for A and z and 0.004 arcsec for ψ (at a field radius of 30 arcmin). These numbers are negligible compared to other sources of error in the present case.

2.3 Coordinates in the tangent plane

A common requirement is to move the telescope in such a way that an image moves by a given distance on the detector. The appropriate formulae (assuming a constant plate scale) are those for gnomonic projection onto a tangent plane (*e.g.* Murray 1983). A similar application is to offset the telescope by a given angular distance on the sky. Since the $\alpha\delta$ and Az coordinate systems are both polar, a given offset in α or A does not, of course, correspond to the same angular distance everywhere on the sky (*e.g.* it causes no movement on the axis of the coordinate system). The tangent-plane approximation is also suitable for this application and is well-behaved near the pole and zenith. The TCS uses angular units throughout, and the conversion between linear units on the detector and angular units on the sky is implicit in these equations. Three systems are used:

Equatorial Cartesian coordinates ξ and η are defined along the projected $+\alpha$ and $+\delta$ directions at the tangent point (α_0, δ_0):

$$\begin{aligned}
\tan(\alpha-\alpha_0) &= \xi\sec\delta_0/(1-\eta\tan\delta_0)\\
\alpha-\alpha_0 &\approx \xi\sec\delta_0\\
\tan\delta &= (\eta+\tan\delta_0)\cos(\alpha-\alpha_0)/(1-\eta\tan\delta_0)\\
&= (\eta+\tan\delta_0)/[(1-\eta\tan\delta_0)^2+\xi^2\sec^2\delta_0]^{1/2}\\
\delta-\delta_0 &\approx \eta
\end{aligned}$$

where the approximations are the usual ones for small displacements at positions well away from the pole.

Altazimuth An equivalent pair of coordinates σ, τ is defined in the altazimuth system, with σ along the $+A$ direction and τ along $+E$ at the tangent point (A_0, E_0) (note that the handedness is opposite to that of the equatorial system).

$$\begin{aligned}
\tan(A-A_0) &= \sigma\sec E_0/(1-\tau\tan E_0)\\
A-A_0 &\approx \sigma\sec E_0\\
\tan E &= (\tau+\tan E_0)\cos(A-A_0)/(1-\tau\tan E_0)\\
&= (\tau+\tan E_0)/[(1-\tau\tan E_0)^2+\sigma^2\sec^2 E_0]^{1/2}\\
E-E_0 &\approx \tau
\end{aligned}$$

xy Finally, x and y are defined along axes fixed with respect to a stationary instrument rotator for a virtual telescope (*i.e.* in the absence of geometrical or flexure errors and refraction). These are used to give a convenient system for offsetting the telescope interactively and the x and y axes are therefore aligned approximately with obvious directions such as detector axes or a spectrograph slit. This is, however, an approximation to the focal-plane coordinate system x_A, y_A, which is fixed with respect to the structure and therefore includes effects such as field rotation due to differential refraction and the effects of pointing errors. The xy system is rotated from the altazimuth system by the mount position angle, ρ, for a perfect telescope and from the $\xi\eta$ system by the sky position angle θ, corrected for the instrumental offset θ_0.

The conversions between these coordinate systems are simple rotations:

$$x = -\xi\cos(\theta-\theta_0)+\eta\sin(\theta-\theta_0)$$

$$\begin{aligned}
y &= +\xi\sin(\theta-\theta_0)+\eta\cos(\theta-\theta_0)\\
x &= +\sigma\cos\rho+\tau\sin\rho\\
y &= -\sigma\sin\rho+\tau\cos\rho\\
\xi &= -\sigma\cos\psi+\tau\sin\psi\\
\eta &= +\sigma\sin\psi+\tau\cos\psi
\end{aligned}$$

for Cassegrain and Prime foci, modified by an additional rotation of $\pm E$ at Nasmyth (Section 2). Complications introduced by field distortions (*e.g.* the radial error typically introduced by refracting field correctors and focal reducers) are discussed in *AG*. The TCS does not currently make any allowance for them.

3 Pointing Calculations

3.1 General

The philosophy adopted for the pointing calculations in the TCS is that of the "virtual telescope" (Straede & Wallace 1976), whose imperfections such as flexure and refraction are concealed from the user. All of the control is specified in terms of standard astronomical coordinate systems (for targets) or detector coordinates (for images) The majority of this section is concerned with the conversion between input positions and the (necessarily imperfect) measured coordinates of the mount. Mechanism control and the modelling of imperfections in the encoders are treated in the following section. Sections 3.2 – 3.11 describe aspects of the calculations in detail, whilst Section 3.12 summarises the whole sequence.

In what follows, we refer to the input coordinate system (α, δ and θ as specified by the user) and to mount coordinates (the demand values of A, E (or z) and ρ for the drives). The telescope is driven so as to make the encoder readings for these mechanisms (corrected as described in the next section) identical to these demand values.

3.2 Time

The time calculations performed by the TCS closely follow those given in Chapter 2 of the *Explanatory Supplement* and this section concerns specific details. The times used within the TCS are:

UTC Coordinated Universal Time. This is given directly by the Observatory Time Service.

TAI International Atomic Time. This is calculated from UTC, from which it differs from by a variable integer number of seconds (see below).

TDT Terrestrial Dynamical Time. This is the theoretical timescale of apparent geocentric ephemerides of solar-system bodies and is specified to be TAI + 32.184 s.

TDB Barycentric Dynamical Time is the independent variable of the equations of motion with respect to the solar system barycentre. It is determined from TDT using the expressions given by Moyer (1981).

UT1 Universal Time. This is proportional to the angle of rotation of the Earth in space, reckoned around the true position of the rotation axis. The value of UT1 $-$ UTC is normally entered directly at the start of a night's observing, but by default is calculated using the extrapolation formula given in IERS Bulletin A. The coefficients are stored in the initialization file and should be updated regularly (preferably once per week).

LMST Local Mean Sidereal Time (the hour angle of the mean equinox of date).

LAST Local Apparent Sidereal Time (the hour angle of the true equinox of date). This is determined from UT1 using the formulae of Section 2.242 of the *Explanatory Supplement*. The values for the position of the Pole required in the conversion are either entered directly or calculated using an extrapolation formula, as for UT1 − UTC.

Dates may be specified as in Julian or Besselian years, with the conventional prefixes "J" and "B", as appropriate for the FK5 and FK4 coordinate systems (see below). The standard epochs for the two systems are J2000.0 and B1950.0, respectively.

UTC is kept within 0.9 s of Universal Time (UT1) by the insertion of one-second steps (leap seconds). The procedure for inserting a leap second is as follows:

1. The date at which the leap second is to be inserted is stored (as a modified Julian Date) in the initialization file for the control system.
2. The time service is armed to put in a leap second on that date.
3. The control system then compensates for the effects of the leap second until it is next restarted. The initialization file should then have the new value of UTC - TAI included.
4. Care is needed to ensure that the ERPS coefficients used to extrapolate UT1 − UTC include the effects of the leap second.

3.3 Astronomical Coordinate Systems

3.3.1 General

The TCS accepts input in one of three equatorial coordinate systems:

1. Geocentric apparent coordinates of the current date.
2. Mean coordinates in the post-IAU1976 (FK5) system.
3. Mean coordinates in the pre-IAU1976 (FK4) system.

The procedure used to convert between systems is that described in the *Explanatory Supplement* and in Wallace (1990). The currently-available reference system is based on the FK5 star catalogue, the IAU 1976 set of constants, the IAU 1980 theory of nutation and the set of procedures outlined below. It is in good agreement with the reference frame defined by VLBI observations (although it is expected that further radio observations and data from the Hipparcos satellite will refine the system still further). A considerable number of positions are still given in the older (FK4) system, and routines are provided in the TCS to perform the conversion. The sequence of conversions is FK4 ⇒ FK5 ⇒ apparent. The procedures are unnecessarily rigorous for the application, but do not take significant CPU time: performing calculations to full accuracy makes comparison with standard test cases much more straightforward.

3.3.2 FK4 to FK5 conversion

This procedure is performed once, at the start of a new observation, and produces an FK5 J2000.0 position for the current epoch. An intermediate stage is to calculate the FK4, B1950.0 position:

1. Correct for space motion to the epoch of observation.
2. Remove E-terms of aberration.

3. Precess to B1950.0 using FK4 constants.
4. Add E-terms.

The B1950.0 position is available for display purposes (see below). The position is then transformed to J2000.0:

1. Remove E-terms.
2. Apply space motions to 1984 January 1.0.
3. Precess from B1950.0 to 1984 January 1.0 using the FK4 precession constants.
4. Apply the equinox correction FK4 to FK5 to right ascension and its proper-motion component.
5. Convert the units of proper motion (tropical to Julian centuries).
6. Precess from 1984 January 1.0 to J2000.0
7. Apply space motions to J2000.0

If no proper motions are specified for the FK4 system, then they are assumed to be zero *in the FK5 system.* The distinction is necessary because the FK4 frame rotates slightly with respect to FK5 and it makes more sense to assume that extragalactic objects have no space motions in our best approximation to an inertial frame.

3.3.3 FK5 to geocentric apparent conversion

The first stage is to correct for space motions and to derive a J2000.0 position for the epoch of observation. This is done once, on change of target:

1. Correct for space motions to the epoch of observation.
2. Precess to J2000.0.
3. Correct for parallax.

Conversion to geocentric apparent coordinates is performed continuously during tracking. The conversion matrices are updated once every 5 minutes, but are applied at 20 Hz. The steps are:

1. Correct for gravitational light deflection (negigible in practice).
2. Apply annual aberration.
3. Correct for precession and nutation.

3.4 Offsets

A number of methods are provided to allow offsetting. These are used to move the telescope so that the image of a *different* object appears at the *same* place on the detector and therefore cause the displayed right ascension and declination to change. The opposite approach (moving the image of the *same* object to a *different* place on the detector is described in section 3.7.

3.4.1 RA-Dec offsets

A group of TCS commands deals with differential offsets specified in right ascension and declination. These are applied in the input coordinate system. The first, and simplest, option allows the offset to be given directly as $\Delta\alpha$, $\Delta\delta$, in which case these are merely added to the target position (`OFFSET TIME`). Alternatively, offsets $\Delta\xi$, $\Delta\eta$ in the tangent plane (along the α and δ directions at the target position) may be given, in which case these are converted to $\Delta\alpha$, $\Delta\delta$ using the tangent-plane formulae in Section 2.3 and again added to the target position (`OFFSET ARC`). Tangent-plane offsets may be typed in, stored, listed and applied later (see `ENTER POSITION`, `SHOW POSITION` and `POSITION`); they may also be defined interactively (see below).

3.4.2 The handset

The TCS "handset" (see Appendix D) allows offsets to be introduced interactively using cursor keys. Four modes are associated with offsets: three to implement them in different coordinate systems and the fourth to set them up interactively for storage and later use. Offsets may be applied in $\xi\eta$, xy or $\sigma\tau$ systems as defined in Section 2.3. These are all tangent-plane offsets, so that a given increment causes the image to move by a given amount on the sky at any position. They are applied by rotating to the $\xi\eta$ system, converting to $\Delta\alpha$, $\Delta\delta$ using the formula given in Section 2.3 and incrementing the target position. The accumulated offsets are displayed in the coordinate system of the mode selected. The systems used by the handset are all defined with respect to the input coordinate system, in order to permit easy conversion (a frequent use of the system is to move the telescope in xy coordinates and then to switch to $\xi\eta$ in order to read off the accumulated offset on the sky). A fourth handset mode is used to set up offset positions for later use. An image is placed at some reference point and is then moved to the offset position with the handset. The motion is in the xy system, for convenience, but the offset is stored in $\xi\eta$, so as to be independent of sky position angle.

3.4.3 The blind-offset procedure

A frequent application of the TCS is to acquire faint targets onto an instrument entrance aperture (usually the slit of a spectrograph). The standard procedure is to locate a reference star whose position relative to the target is known very accurately, centre it on the instrument and then offset to the faint target. Although the RA-Dec offsets described above can be used for this purpose, a somewhat different method is neater and more flexible. The reference star is first centred on the instrument, and the accumulated handset correction is converted to tangent-plane coordinates in the mount system and applied as a temporary addition to the collimation errors in elevation and azimuth (Section 3.6.1). This is a local modification to the pointing model which is expected to be valid close to the reference star, and is used for subsequent observations of faint targets. The advantages of this procedure (the `BLIND_OFFSET` command described in Appendix C.10.) are that the target position need not be in the same coordinate system as that of the reference star and that the displayed telescope position is as accurate as possible, rather than including residual pointing corrections.

3.5 Refraction

3.5.1 Refraction formulae

Refraction is treated separately from the other pointing corrections because it is known *a priori*. The algorithm used is derived from the expressions in Murray (1983) for refractive index n and the formulae given by Saastamoinen (1972a, b). Murray's equation 7.4.10 is used to calculate the refractive index as a function of the partial pressures of dry and wet air (in turn derived from the total pressure and relative humidity), temperature and wavelength. Murray's equation 7.6.8 gives the refraction as:

$$\begin{aligned} z_a - z &= R(z_a) = R_A \tan z_a + R_B \tan^3 z_a \\ R_A &= n - 1 - I \\ R_B &= -[I - (n-1)^2/2] \end{aligned}$$

where the apparent and true zenith distances are z_a and z, respectively and I is the integral of $\ln(n)/s$ over path length s. Saastamoinen (1972a, b) gives simple approximations to I which can be absorbed into the coefficients R_B, R_C, R_D and R_E to give a formula:

$$z_a - z = R(z_a) = R_A \tan z_a + R_B \tan^3 z_a + R_C \tan^5 z_a + R_D \tan^7 z_a + R_E \tan^9 z_a$$

This algorithm gives results within 0.1 arcsec of the numerical integration presented in the *Explanatory Supplement* for z <80°. The refraction formula as quoted is not in a suitable form for pointing calculations, since the refraction is required in terms of the true zenith distance z. We thefore expand $R(z_a)$ in a Taylor series to first order:

$$z \approx z_a + R(z) + (z_a - z)R'(z)$$

and derive the approximate formula

$$\begin{aligned} z - z_a &\approx R(z)/[1 + R'(z)] \\ &= \frac{R_A \tan z + R_B \tan^3 z + R_C \tan^5 z + R_D \tan^7 z + R_E \tan^9 z}{1 + \sec^2 z(R_A + 3R_B \tan^2 z + 5R_C \tan^4 z + 7R_D \tan^6 z + 9R_E \tan^8 z)} \end{aligned}$$

Further elaboration is not justifiable, since accurate measurements of refraction at the CAMC (Morrison, *private communication*) show unpredictable night-to-night variations of up to 0.4tan z arcsec.

3.5.2 Differential refraction

In addition to the effects of refraction on the target position, the field is rotated and distorted. The latter effect can only be corrected using additional optics (as is done at Prime focus), but the former may be taken out using the instrument rotator. This is done automatically as part of the pointing calculation described in Section 3.12, but the analytical treatments in the literature (Hinks 1898, Wallace & Tritton 1979) use obscure notation and a paraphrase is given here using the teminology of the present paper.

Consider a tangent-plane projection (σ, τ) as defined earlier. Then:

$$\sigma = \sin(A - A_0) \csc z_0 / [\cot z \cot z_0 + \cos(A - A_0)]$$

$$\tau = [\cot z - \cot z_0 \cos(A - A_0)]/[\cot z \cot z_0 + \cos(A - A_0)]$$

The effect of refraction is to decrease the value of z, leaving A unchanged. The changes in σ and τ may be calculated from:

$$\begin{aligned} \Delta\sigma &\approx (\partial\sigma/\partial z)\Delta z \\ &= [\csc z_0 \cot z_0 \csc^2 z \sin(A - A_0)]/[\cot z \cot z_0 + \cos(A - A_0)] \\ &= \cos z_0 \csc z \sigma (1 + \sigma^2 + \tau^2)^{1/2} \\ \Delta\tau &\approx (\partial\tau/\partial z)\Delta z \\ &= -[\csc^2 z \csc^2 z_0 \cos(A - A_0)]/[\cot z \cot z_0 + \cos(A - A_0)] \\ &= -(1 + \sigma^2 + \tau^2) \cot z \tan z_0 + \tau(1 + \sigma^2 + \tau^2)^{1/2} \sec z_0 \cos z \end{aligned}$$

In the linear approximation, which is entirely adequate here, we take $\Delta z \approx -R_A \tan z$ and neglect any terms that are second order in σ and τ. Then:

$$\Delta\sigma \approx -R_A\sigma$$

$$\Delta\tau \approx +R_A(\tan z_0 - \tau\sec^2 z_0)$$

We now rotate the coordinate system by the parallactic angle ψ. This leads to the relations given by Hinks (1898):

$$\Delta\sigma \approx R_A[X - (1+X^2)\sigma - XY\tau]$$

$$\Delta\tau \approx R_A[Y - XY\sigma - (1+Y^2)\tau]$$

where X and Y are the quantities defined by Hinks (but in terms of h and δ, so his formulae are messy):

$$X = \sin\psi\tan z_0$$

$$Y = \cos\psi\tan z_0$$

The first terms in the expressions for $\Delta\sigma$ and $\Delta\tau$ are just the shifts of the tangent point due to refraction, which is eliminated by moving the telescope, as discussed earlier, and the introduction of ψ makes it obvious that X and Y are components of a vertical displacement resolved along h and δ, respectively. A rotation of the field results from the fact that the projected north-south line is no longer at position angle 0. The pole is at $(0, \cot\delta_0)$ in the tangent plane, but the origin is displaced to (X, Y) by refraction, so the necessary rotator offset $\Delta\theta$ satisfies:

$$\Delta\theta \approx R_A/(\cot\delta_0 - Y) \approx R_A\sin\psi\tan z_0\tan\delta_0$$

except very close to the pole (Hinks 1898). The implications of differential refraction for off-axis autoguiding are discussed in *AG*.

3.6 The WHT pointing model

A pointing model is a set of analytical functions and look-up tables used to correct for departures from an ideal altazimuth telescope. The pointing model for the WHT uses up to 21 functions, divided into 3 groups: a geometrical model of the telescope, elevation flexure and harmonics of azimuth. Look-up tables in altitude and azimuth are implemented, but are not currently used. The residuals from a fit to a pointing test (see later) typically have an r.m.s. between 0.8 and 1.5 arcsec, depending on seeing conditions, focal station and measurement technique. An example is shown in Figure 1 and the model terms are listed in Table 1 with their names in the notation of the TPOINT analysis package (Wallace 1989), their functional forms, and typical values for the Cassegrain focus (the sign convention appears strange because the TPOINT software uses a different definition of azimuth). Note that some of the terms are now not significantly different from 0, but are retained because they have been needed in the past.

3.6.1 Geometrical and index Errors

This group has 6 terms, all with some geometrical interpretation. The angles between the instrument rotator axis (which defines the fundamental pointing direction) and the normal to the azimuth and elevation axes are known as collimation errors and the residual zero-point corrections are referred to as index errors. The index and collimation errors in elevation are not separable, and are combined in one coefficient. For this reason, and for convenience in updating the model at the start of an observing session, index errors in both coordinates are included in the pointing corrections, despite the fact that

Table 1: The Pointing Model for the WHT.

Term (TPOINT)	Description	ΔA	Δz	Value (arcsec)
IA	Azimuth index	-1	0	0.5
IE	Elevation index	0	-1	6.7
CA	Azimuth collimation	$-\csc z$	0	73.9
NPAE	Non-perpendicularity	$-\cot z$	0	-12.2
AX	NS axis tilt	$-\sin A \cot z$	$\cos A$	34.1
AY	EW axis tilt	$\cos A \cot z$	$-\sin A$	17.2
TF	Hooke's Law flexure	0	$-\sin z$	-18.0
TX		0	$-\tan z$	0.0
HZSZ4		0	$\sin 4z$	0.0
HSCA1		$\cos A$		-1.5
HSSA1		$-\sin A$		-3.3
HZCA1			$-\cos A$	3.0
HZSA1			$\sin A$	-1.6
HSCA2		$-\cos 2A$		1.5
HSSA2		$\sin 2A$		0.3
HZCA2			$\cos 2A$	-0.8
HZSA2			$-\sin 2A$	0.3
HSCA3		$\cos 3A$		0.0
HSSA3		$-\sin 3A$		2.7
HZCA3			$-\cos 3A$	-2.1
HZSA3			$\sin 3A$	0.9

Figure 1: Residuals from a pointing test at the Cassegrain focus. (a) – (f), (h): residuals in $S = A \sin z$, z, A and R (total error) plotted against A and z. Units are degrees on the x axes and arcsec on the y axes. (g) Scatter plot of residuals (U = up; L = left). (i) Histogram of errors in $X = h \cos \delta$, $D = \delta$, S, z and R.

Figure 2: The elevation component of the pointing model for the WHT Cassegrain focus, derived by fitting a model to the data, setting the $\sin z$, $\tan z$ and $\sin 4z$ terms in Δz to 0 and plotting the residuals against zenith distance.

they are logically part of the encoder model (see below). They are kept close to zero by changing the encoder model coefficients. The three simplest terms (elevation and azimuth index errors and left-right collimation) may be updated using the `CALIBRATE` procedure (see below). The remaining geometrical terms are the non-perpendicularity of azimuth and elevation axes and the tilts of the azimuth axis in the north-south and east-west directions.

It is worth noting that a clock error is equivalent to a tilt of the azimuth axis in the east-west direction, together with an azimuth index error. A 1 s clock error is equivalent to a change in axis tilt by $15\cos\phi$ arcsec and an azimuth offset of $-15\sin\phi$ arcsec. If an error is made in the time (*e.g.* because UT1−UTC is not updated frequently enough, or as a result of time service drift) when the telescope pointing is determined, then it may become absorbed in these coefficients, causing confusion later.

3.6.2 Elevation Flexure

The pointing model includes a number of terms which model the tilt and flexure of the structure. Three of these describe the effects of gravitational deflection on the telescope tube and main mirrors. The biggest effect is due to relative translation of the top and bottom ends. The pointing error is given to a surprisingly good approximation by the $\Delta z \propto \sin z$ (Hooke's Law) relation for a simple beam. The form of the deflection is plotted in Figure 2; it is modelled by an expression of the form $\Delta z = \zeta_1 \sin z + \zeta_2 \tan z + \zeta_3 \sin 4z$.

Figure 3: The elevation harmonic component of the pointing model for the WHT Cassegrain focus, derived by fitting a model to the data, setting the harmonic terms to 0 and plotting the residuals in zenith distance against Azimuth.

3.6.3 Azimuth Harmonics

The remaining terms in the pointing model are harmonics of azimuth of the form:

$$\Delta z \propto \sin nA$$

$$\Delta z \propto \cos nA$$

$$\Delta A \sin z \propto \sin nA$$

$$\Delta A \sin z \propto \cos nA$$

where n = 1, 2 or 3 ($\Delta A \sin z$ is the left-right error on the sky). These represent tilts of the entire telescope, due primarily to deviations of the azimuth track from a plane. Their effects are illustrated in Figures 3 and 4.

3.7 The focal-plane coordinate system

It is often necessary to offset the telescope in such a way that an image moves by a given vector in the focal plane, regardless of rotator position angle. The conventional usage for such an operation ("beamswitching" or "aperture offsetting") comes from two-channel photometry. The TCS defines a Cartesian coordinate system (x_A, y_A) in the focal plane for this purpose. If the position angle of the rotator in the mount coordinate system is ρ_M, then the y_A axis is aligned with the vertical direction for $\rho_M = 0$. The origin of the system is fixed by the intersection of the instrument rotator axis of the

Figure 4: The azimuth harmonic component of the pointing model for the WHT Cassegrain focus, derived by fitting a model to the data, setting the harmonic terms to 0 and plotting the residuals in $\Delta S = \Delta A \sin z$ against azimuth. The mean of the four tape encoder heads was used to measure azimuth for this test.

focal station in use with the focal plane. Positions in this system are referred to as "apertures". If a given (x_A, y_A) offset is introduced, an image coincident with the rotator centre will be moved to a position fixed in the focal plane, independent of sky position angle, θ. Consequently, any movement of the rotator causes the telescope to be offset in such a way that the field appears to rotate about (x_A, y_A). Apertures are numbered from 0 – 10, aperture 0 (the "reference position") being a special case. Aperture 0 is the default on change of source and can be set to some useful position on the instrument, such as the centre of a spectrograph slit or polarimetric dekker. It is particularly important if the instrument is significantly displaced from the axis of rotation. The remaining aperture positions are selectable by the user, as described in Appendix C under the `ENTER`, `STORE`, `APERTURE` and `BEAMSWITCH` commands.

It is possible to define an aperture interactively using a mode of the handset (see Appendix D). An image is centred on the reference position using one of the xy, $\alpha\delta$ or $\sigma\tau$ modes. The handset is then switched to the x_Ay_A system and the image is moved to the desired position in the focal plane, which is then kept for latter use. The x_Ay_A mode may be used whilst autoguiding, since the position of the guide star on the autoguider CCD is then automatically compensated for motion in the focal plane.

A rotational offset ρ_A may be introduced in an analogous way. This is conceptually a change in the conversion between virtual sky PA and actual mount PA. In the acquisition of a field onto a multislit mask or long slit, for instance, it is necessary to correct for rotational errors (*e.g.* incorrect positioning of the mask in the instrument) as well as translational ones. In addition, some instruments (*e.g.* the Utrecht Echelle Spectrograph) have a rotating slit unit which changes the relation between mount and sky PA. The `TWEAK` command (Appendix C.73) implements an $x_Ay_A\rho_A$ offset which also works whilst autoguiding. The xy coordinates for this command may be in a different system from x_Ay_A, and scale, rotation and handedness conversions are done using instrument-dependent parameters. Thus, for example, the TCS will accept the displacement and rotation output by the LEXT software used for aligning multislit fields.

3.7.1 Rotation and focus

The handset allows the sky PA and focus values to be adjusted interactively.

3.8 Tilt and translation of optical surfaces

Tilts and relative translations of the primary, secondary and tertiary mirrors cause significant pointing errors. The reproducible parts of these errors are taken out by the pointing model, but significant residuals remain. The secondary mirror tilts by small amounts within its cell as the telescope elevation changes (Figures 5 and 6). Since the tilt shows some hysteresis, it is measured using three displacement transducers and corrected as a collimation error rather than being included in the pointing model. A similar technique may be applied in the future to compensate for small tilt errors of the primary mirror measured using the support load cells. Relative translation of the primary and secondary mirrors is currently included in the pointing model, primarily in the term proportional to $\sin z$.

The pointing corrections required for primary and secondary tilts ϵ_p and ϵ_s and relative translation ζ are given by the following formulae, in the notation of Schroeder (1987). A rotation of the secondary by ϵ_s causes a displacement of the image in the focal plane of $2\epsilon_s(d + f_1\beta)$, where d is the separation of the primary and secondary mirrors, f_1 is the focal length of the primary and $f_1\beta$ is the back-focal distance. This corresponds to a pointing error of $\Delta_s = 2\epsilon_s(d + f_1\beta)/f = 2k\epsilon_s$, where f is the focal length of the two-mirror system and k is the ratio of the heights of rays at the margins of secondary and primary. For the WHT, $\Delta_s = 0.4607\epsilon_s$ if the two quantities are in the same units. A relative translation of the two mirrors by ζ perpendicular to the optical axis results in an image motion in the focal plane of $-\zeta(d + f_1\beta)/f_2$ (where f_2, the focal length of the secondary mirror, is < 0), so the pointing error is

Figure 5: The variation of secondary tilt in elevation with elevation for the William Herschel Telescope. The telescope was driven from the zenith to an elevation of 10° and back. Note the hysteresis effect.

$\Delta_t = -\zeta(d + f_1\beta)/f_2 f = -k\delta/f_2$. $\Delta_t = +15.25\zeta$ for Δ_t in arcsec and ζ in mm. Finally, the effect of tilting the primary mirror by an angle ϵ_p is an image movement in the focal plane of

$$2\epsilon_p d + 2\epsilon_p(d + f_1\beta) + 2\epsilon_p d(d + f_1\beta)/f_2 = 2\epsilon_p f$$

The corresponding pointing error is $\Delta_p = 2\epsilon_p$, as expected for a single-mirror telescope.

3.9 Derotation Optics

In order to correct field rotation for stationary instruments mounted on the Nasmyth platforms, optical derotators consisting of two Dove prisms and a flat mirror are used (Bingham 1984). These are mounted on the instrument rotators and are driven by the TCS. The derotators are aligned using the altitude axis as a reference, but small residual errors remain to be corrected by the TCS. A first-harmonic term is introduced if the components of the derotation optics are not in accurate relative alignment; a second-harmonic term corresponds to a tilt of the whole assembly with respect to the axis of rotation. For an input beam along this axis, the path of an image in the focal plane of the telescope may be

Figure 6: The variation of left-right secondary tilt with elevation for the William Herschel Telescope. The telescope was driven from the zenith to an elevation of 10° and back. Hysteresis also occurs in this direction, although much less than in elevation.

described as follows:

$$x_A = x_0 + a\cos(\rho - \rho_1) + b\cos(2\rho - \rho_2)$$

$$y_A = y_0 + a\sin(\rho - \rho_1) + b\sin(2\rho - \rho_2)$$

where ρ is the mount position angle of the instrument rotator and a, b, ρ_1 and ρ_2 are constants. This is the sum of two circular motions, with periods of 180° and 360° in mount position angle. In practice, however, the measured second-harmonic term is a mixture of two effects: the tilt of the optical assembly with respect to the rotation axis and the misalignment of the input beam with that axis. Their superposition is still a circle, and it is always possible to find a position in the field where the image is stationary (the "rotator centre") provided that the first-harmonic term is zero.

These errors are measured by imaging a star onto an autoguider or acquisition camera whose field includes the centre of rotation and logging its position periodically as the derotation optics are turned through a full revolution. An example of a measured track is shown in Figure 7. A correction is implemented as an offset in the focal-plane coordinate system: residuals are plotted in Figure 8.

3.10 Focus

The focus of the telescope depends on temperature (through expansion of the structure), on elevation and on the optical thickness of filters and other components in the beam above the focal plane. The focus value input by the user is a virtual position, whose value does not change with these quantities and which should depend only on the focal station. It is compensated for expansion using temperatures measured by a pair of platinum resistance thermometers on the upper Serrurier trusses which are connected to a Camac ADC module. A linear model is then used to correct the demand focus position. No significant variation of focus with elevation has yet been detected, although provision has been made for an appropriate model. Finally, the focus correction for above-slit filters, polarization elements and similar components are input using the `DFOCUS` command. This may be issued automatically from the system computer when the component is inserted into the beam.

3.11 Autoguiding

In order to correct for irreproducible tracking errors, two types of detector may be used to provide autoguiding signals: off-axis autoguiders and acquisition cameras (which view the spectrograph slit jaws). The methods used to autoguide the WHT are described in detail in *AG* and only a brief summary is given here.

Both types of detector measure image centroid positions, which are sent to the TCS at intervals between 0.1 and 10 s. These are converted from pixel coordinates to the TCS focal-plane system, correcting for the orientation of the guide probe if necessary, and finally rotated to mount *AE* and added to the position demand. The accumulated autoguiding corrections are stored separately as tangent-plane coordinates in the mount system, rather than being used to update the target right ascension and declination. This reflects the fact that, in normal use, the autoguider is maintaining the image of a given position at a fixed point on the instrument.

3.12 Pointing Calculations

This section outlines the sequence of calculations which perform the pointing corrections described earlier. The treatment by Wallace (1990) is followed closely. The pointing calculations can be divided into those done once (on startup, irregularly when the parameters affecting them are altered or on change of target) and those performed in three loops running at 1/300, 1 and 20 Hz. Unit vectors and matrices are used throughout for efficient and rigorous computation.

Figure 7: The track of an image on the autoguider at the UES Nasmyth focal station of the WHT during a full revolution of the derotation optics, without the corrections described in the text. The autoguider was placed at the approximate centre of rotation for this test. Note the first and second harmonic components. The best fit to the model in the text is also shown.

Figure 8: The track of an image on the autoguider at the UES Nasmyth focal station of the WHT during a full revolution of the derotation optics, with the corrections described in the text. The systematic first and second harmonic errors are negligible, but there is some random scatter due to residual tracking drift during the test, and to poor seeing.

3.12.1 Startup

When the TCS starts up, the default values of UT1−UTC and polar motion are calculated from the extrapolation formulae given in IERS Bulletin A. They may be overridden at any time thereafter.

3.12.2 Startup and on change of input parameters

A set of calculations is done at startup and thereafter only when relevant parameters are changed:

- Evaluation of the refraction coefficients R_A – R_E, which depend on pressure, temperature, humidity and wavelength.
- Correction of latitude and longitude for polar motion.
- Derivation of the rotation matrix which corrects for azimuth axis tilt.
- Calculation of the constant of diurnal aberration.

3.12.3 Source change

The operations done once, on change of target, are:

- Correction of space motions to the current epoch.
- Formation of the precession matrices needed to convert from FK4 input coordinates to FK4, B1950.0 or FK5 input coordinates to FK5, J2000.0, as appropriate.
- For a blind offset only, conversion of accumulated handset corrections to collimation corrections.

3.12.4 Slow loop: target independent calculations

A number of quantities which change slowly and which are independent of the target being observed are calculated once every 300 s. These are: TDT and TDB, Julian and Besselian epochs and the equation of the equinoxes.

3.12.5 Slow loop: target-dependent calculations

The other portion of the slow loop calculates the parameters needed to convert from mean to apparent place (precession and nutation matrices and aberration vector). These depend on the input coordinate system and the current time, but not on the target position, to which they are applied at higher frequency.

3.12.6 Medium-frequency loop

The function of the medium-frequency (1 Hz) loop is essentially to derive a pair of matrices M_{UA} and M_{AM} which perform the transformation of a unit vector pointing at the target from user coordinates (U) to apparent coordinates (A) and from apparent to mount coordinates (M), respectively. These are then applied at the full loop rate. This avoids the need to re-evaluate pointing corrections which do not change abruptly, but retains the ability to offset the telescope rapidly by changing the target position or collimation corrections. In addition, the medium-frequency loop is used to derive the displayed telescope position in a variety of coordinates systems.

M_{UA} and M_{AM}, called "osculating transformation matrices" by Wallace (1990) are determined as follows:

1. Generate three unit vectors around the target position.
2. Transform them through the relevant portion of the pointing flow.
3. Solve for the matrix that precisely transforms the input to the output vectors.

The matrix would be orthogonal for pure rotations, but some of the pointing corrections (*e.g.* refraction) cannot be modelled in this way. The matrix gives a smoothly changing transformation which should be accurate for any vector close to the target.

The computations included in M_{UA} are:

- FK4 to FK4 B1950.0, using the precession matrix calculated on source change.
- FK4 B1950.0 to FK5 J2000.0, or
- FK5 to FK5 J2000.0.
- FK5 J2000.0 to geocentric apparent.

Therefore,

$$v_A = M_{UA} v_U$$

where v_A and v_U are unit vectors in user and apparent $\alpha\delta$ coordinates.

The terms in M_{AM} are:

- Rotation from (α, δ) to $(-h, \delta)$ (by the local apparent sidereal time).
- Diurnal aberration.
- Rotation to (A, E) (by $\pi/2 - \phi$ about the elevation axis).
- Refraction.
- Correction for azimuth axis tilt.

and,

$$v_M = M_{AM} v_A$$

where v_A is a unit vector in the mount coordinate system.

In addition to transforming the three probe vectors in order to derive M_{UA} and M_{AM}, the medium-frequency loop does the same for the precise target position. The results of intermediate stages in the computation are used to generate the displayed telescope position in various coordinate systems.

3.12.7 Fast loop

The fast (20 Hz) loop performs the following operations:

1. Get UTC and calculate UT1 and local apparent sidereal time.
2. Work out the UTC interval since the start of the track.
3. Apply handset xy, $\alpha\delta$ or $\sigma\tau$ increments accumulated since the last cycle to the running total.
4. Add offsets, handset corrections and non-sidereal tracking corrections to the target position. and generate a unit vector v_U in the user coordinate system.
5. Correct the autoguider reference position for $x_A y_A$ or rotational offsets since the last cycle.

6. For the current and next cycles:
    (a) Apply M_{UA} and M_{AM} to generate a unit vector in the mount coordinate system, v_M.
    (b) Work out the collimation corrections which are specified in the focal-plane (x_A, y_A) system and rotate them to mount (A, E). These are aperture offsets, autoguiding errors and the corrections for misalignment of the derotation optics.
    (c) Add the collimation corrections which are specified in (A, E), that is the azimuth collimation error, non-perpendicularity of azimuth and elevation axes, harmonic terms and blind offset model. The collimation errors are applied by calculating the azimuth and elevation corrections ΔA, ΔE from the tangent-plane offsets σ, τ using the formulae given earlier and rotating the unit vector by these amounts.
    (d) Correct for elevation flexure.
    (e) Calculate demand A and E from the unit vector and apply index errors.

7. The demand positions for the next and current cycles are differenced to derive a velocity prediction.

8. The demand mount position angle is derived by constructing a vector in the user coordinate system which is orthogonal to the target vector and parallel to the projected north-south direction. This is transformed into mount coordinates by multiplying by the matrices M_{UA} and M_{AM} and the angle between it and a vector along the direction of the local vertical in the focal plane is generated.

9. A correction is then made for collimation errors, which are not included in the matrices.

10. The calculation is also done for the current and next cycles, in order to derive a velocity.

Rotator index errors are included in the encoder model.

3.12.8 Sequence of operations on change of source

The use of cascaded loops requires some care on change of source, in order to avoid using matrices derived for one object in calculations for another, especially as only the fast loop is uninterruptible. The order of operations is as follows:

1. One-off calculations are done by the user interface command routine.

2. The slow loop is then triggered immediately. Since it can be interrupted, its results are not made accessible to the rest of the TCS until the calculations are complete (meanwhile, the results of the last cycle are used).

3. The medium-frequency loop is then triggered in a similar way. When it has completed, it instructs the relevant mechanisms to move by modifying their command fields (see below).

4. Finally, the next cycle of the fast loop detects that a source change has happened, and performs a number of special operations:
    (a) Set the new target position.
    (b) Clear positional, aperture and rotator offsets and handset corrections.
    (c) Store the UTC at the start of the track in order to apply non-sidereal tracking corrections.
    (d) Stop autoguiding.
    (e) Recalculate the sky position angle if the rotator is being driven so as to minimise the slew time or to set the spectrograph slit vertical at the start of an observation.
    (f) Decide which way to move the azimuth and rotator if there is more than 360° of travel and the demand position is ambiguous (the closest position is always selected).

4 Drives and Encoders

4.1 Mechanism control

4.1.1 General

Each mechanism is described within the TCS by a record containing the following fields:

Demand position The desired position for the mechanism in the mount coordinate system, either updated continuously during a sidereal track or set to a constant value if a mechanism is to be moved to a given position and stopped.

Actual position The position of the mechanism in the mount coordinate system (corrected for any errors peculiar to the encoding system). This should be equal to the demand position if the telescope is tracking or stopped in position.

Command field The field set by the user-interface command routines in order to instruct the mechanism to move, stop or zeroset.

Status field The field which records whether the mechanism is: moving or stopped, following or not following, in position or not and zeroset or not.

Servo constants A general servo algorithm is used for the main mechanisms. This allows for:

1. A velocity demand proportional to the square root of the position error at large distances from the target.
2. A PID controller for small errors. The velocity demand for a sidereal track is the sum of that predicted by the pointing loop and the output of the PID algorithm.

Limits Software limits on position (positive and negative), velocity and acceleration can be set, although some (*e.g.* the rotation limits for the Nasmyth turntables) are not often used. If the demand position is outside a software limit, then the mechanism is stopped and an alarm is triggered; excessive velocities and accelerations are clipped.

Stopping radius This is the tolerance within which a mechanism will be set by a command to move to position and stop.

In-position radius The in-position radius defines the tolerance within which observing is possible for a moving mechanism. If the position error is less than this value, then the mechanism is said to be "tracking".

"Following" means that the position of the mechanism is being updated continuously. For altitude, azimuth, field and dome rotation this is done during a sidereal track; the focus is adjusted in response to changes in temperature.

The TCS performs mechanism control in three logical stages:

1. The user-interface routines (one for each of the commands listed in Appendix C) either initiate the continous updating of demand positions required if the mechanisms concerned are following or set a constant value if not. They then modify the appropriate command and status fields.

2. The pointing calculation is executed in four loops (once/source change, 1/300, 1 and 20 Hz) as described in Section 3 if a sidereal track is in progress. All this does is to update the demand position.

3. A second set of routines running at 20 Hz reads and decodes the time and encoders, looks at the command and status fields for each mechanism, and at the demand and actual positions, calculates velocity demands, checks for software limits and outputs appropriate commands to the drives.

4.1.2 Rotator modes

A number of different ways of controlling the field rotation have proved to be useful in practice:

1. The sky position angle is specified explicitly, as discussed earlier.
2. On change of target, the demand sky position angle is recalculated to cause the minimum rotation from the present position. Thereafter, sidereal tracking continues as in the first option.
3. The mount position angle is specified. The main applications are: to keep a spectrograph slit vertical so that differential refraction does not cause significant light loss and optical testing, where the test equipment should not rotate with respect to the mirrors. Off-axis autoguiding is not currently possible in this mode, although modifications to allow it over a limited range of rotation are described in *AG*.
4. The sky position angle is reset on change of target to place the slit vertical, but thereafter to track at sidereal rate. This allows autoguiding whilst minimising the effects of refraction.

At the Nasmyth foci, three modes are possible:

1. The instrument is stationary and derotation optics are used to maintain the field orientation. The field then rotates by twice the change in mount position angle.
2. The instrument is stationary and the derotation optics are not fitted (the situation where they are fitted, but stopped, is not identical, since there is a constant rotational offset).
3. The instrument is mounted directly on the rotator, as at the other focal stations, and is rotated to track the sky.
4. The instrument is mounted directly, but is rotated to track the Nasmyth flat ($\rho = \pm E$ to a first approximation). This maintains the orientation of the instrument with respect to the telescope optics and is appropriate for optical testing and some interferometric applications.

The TCS treats a Nasmyth focus with and without derotation optics as two separate focal stations, although the same physical drive and encoders are used for both. Different scaling factors are used for position and rate and the pointing models are independent. A stationary instrument without derotation optics is currently treated as a special case of a rotating instrument with a constant mount position angle but this is unsatisfactory in principle (*e.g.* flexure of the rotator is relevant only if the instrument is attached to it).

4.1.3 Wrap problems

Azimuth and Cassegrain field rotation have more than 360° of travel and parts of their ranges are ambiguous. On change of target, the TCS selects the nearest option by default, regardless of the time remaining before a limit is hit (Section 5.2). It is therefore occasionally necessary to rotate by a full turn in order to avoid tracking into a limit or to reset the mechanism if a limit has been hit during observing. This is done using the `UNWRAP` command (Appendix C), which has four modes of operation, depending on the initial state of the mechanism:

1. If the mechanism is tracking normally, and is in its ambiguous range, then the demand position is changed by 360°.
2. If a software limit is encountered during tracking, then the demand position is reset and the mechanism is commanded to move. Offsets and other accumulated corrections are preserved; otherwise the effect is the same as slewing to the target again.
3. If the mechanism is stopped in an ambiguous part of its travel, then it is rotated by 360° and stopped again.
4. If the mechanism is in the process of being driven to a fixed position, then this position is altered by 360° (if possible) and the move continues.

4.2 Encoders

4.2.1 General

Multiple encoding systems are used on the azimuth, elevation and rotator axes. The purpose of the encoder models used by the TCS is to produce estimates of the position of each axis which are independent of the details of the encoding hardware, so that values from different encoders can be combined or compared. Four types of encoder are used:

Absolute These are optical absolute encoders of relatively coarse resolution used primarily to set initial zero-points and thereafter as a check. They are gear-driven and are used on all axes.

Gear The primary encoders used in normal operation are gear-driven optical incremental systems. They are zeroset against the absolute encoders when the TCS starts up.

Tape The azimuth axis is equipped with an inductive tape encoder with four reading heads (Amos *et al.* 1992). This has higher performance than the gear encoder and is likely to become the primary system for azimuth once its stability and robustness have been verified.

Roller The altitude and azimuth axes are also fitted with friction-driven encoders. These have proved to be unsatisfactory and are not currently used.

The raw values read from the encoders are processed through a model which has the following components (not all of which are used for every encoder):

1. Scale and zero-point.
2. A look-up table, which is derived from smoothed tracking data.
3. Sinusoidal and triangular functions of arbitrary period and phase.
4. A correction derived from displacement measurements (see below).

The zero-points of the incremental encoders may be determined in a number of different ways: by comparison with the absolute encoders; by driving the telescope past a reference position where a proximity detector produces a hardware signal to clear the counter or by driving the telescope to one of its hardware park position, which are defined by independent microswitches.

Figure 9: The azimuth drive and encoder gear train (from Amos *et al.* 1992).

4.2.2 Azimuth gear encoder

Fourier analysis of tracking and encoder difference data can be used to identify periodic components and this has been done in detail for the azimuth axis as part of the test programme for the tape encoder (Amos *et al.* 1992). Several obvious spatial frequencies result from the layout of the drive chain and encoder gearing (Figure 9): these are listed in Tables 2 and 3, respectively. The most sensitive way of detecting short-period errors is to difference the gear and tape encoders whilst the telescope is moving very slowly and then to take a Fourier Transform (Figure 10).

The largest systematic error affects the gear-driven encoder on the azimuth axis. The radial hydrostatic support of the telescope is insufficiently stiff to prevent sideways movement. There are two main effects. Firstly, the opposing anti-backlash torques of the two azimuth drive motors cause the telescope to displace sideways by about 50 μm along the perpendicular to the line joining them. Rotation in azimuth then leads to a first-harmonic error. Secondly, there is a sideways movement with the tooth period of the main drive gear (0.4018°). The encoder sees a component of the translation as an apparent azimuth error of amplitude $2-3$ arcsec (Figure 11). In order to remove these effects, a pair of displacement transducers is used to measure the translation along the appropriate direction. These are mounted on a fixed part of the structure, and impinge on a nominally cylindrical, precision-ground surface on the telescope. Their readings are scaled, averaged (to remove the effects of elliptical distortion of the surface on which they bear) and subtracted from the encoder readings. Figure 12 shows the scaled displacement corresponding to the tracking data in Figure 11. The correction removes approximately 97% of the 0.4018° error, but is still not entirely satisfactory, since additional errors are

Figure 10: A FFT of the difference between one of the tape encoder heads and the gear encoder in azimuth over a period when the telescope was being driven at a very slow, constant rate. Significant periods associated with both encoding systems are marked. The units of spatial frequency are degrees^{-1}.

Table 2: Characteristic spatial frequencies for the azimuth drive and gear chain.

Component	Calculation	Period (deg)	Detected?
Spur tooth / bull gear	360/896	0.4018	Yes
Spur gear rotation	38 × 0.4018	15.276	No
First stage gear tooth	15.276 / 142	0.1076	No
First stage gear rotation	38 × 0.1076	4.088	No
Second stage gear tooth	4.088 /147	0.0278	Yes
Motor shaft rotation	26 × 0.0278	0.7228	No
First motor cogging frequency	0.7228/(190/2)	7.608×10^{-3}	Yes
First tacho ripple frequency	0.7228/(139/2)	0.0104	?

Table 3: Characteristic spatial frequencies for the azimuth gear encoder chain.

Component	Calculation	Period (deg)	Detected?
Pinion tooth	360/896	0.4018	Yes
Pinion rotation	22 × 0.4018	8.8392	?
Intermediate gear tooth	8.8392/170	0.0520	Yes
Intermediate gear rotation	21 × 0.0520	1.092	Yes

Figure 11: The azimuth component of image motion measured with an on-axis acquisition camera. The gear encoder was used without corrections, in order to show the 0.4° error due to horizontal translation.

introduced because the ground surface is not a perfect cylinder.

Figure 13 shows the residual error in azimuth after subtracting the 0.4° component. The major remaining systematic error is a symmetrical sawtooth with the period (1.09°) of rotation of the second gear in the encoder gearbox and an amplitude of 0.88 arcsec. It is modelled using a triangular function derived from tracking data. An example of a tracking test with all encoder corrections turned on is shown in Figure 14. Note that the error measured on the sky is multiplied by $\cos E$ (≈ 0.62 for this test).

Figure 15, shows an FFT of open-loop tracking errors using the gear encoder. The trace is dominated by three components: the translation error at 0.4018° and the rotation (1.09°) and tooth (0.052°) periods of the second encoder gear. The first two of these are the residuals of the corrections described earlier, and represent roughly 3% and 11% of the original uncorrected error, respectively.

4.2.3 The azimuth tape encoder

The tape encoder deals with the problem of translation by averaging the readings from heads placed 180° apart, which see equal and opposite effects. The residuals for a single tape head show a first-harmonic component of amplitude 3 arcsec due to the wander of the axis of rotation mentioned earlier and the 0.4018° translational error, but neither of these effects is significant in the mean.

The tape is manufactured with a pitch of 2 mm, and errors at the first (0.038°) and second (0.019°)

Figure 12: The correction to the azimuth gear encoder reading derived from displacement transducer readings for the data in the previous figure.

Figure 13: The azimuth component of image motion measured with an on-axis acquisition camera after subtracting the 0.4° translational error from the gear encoder reading. The 1.09° sawtooth corresponding to the rotation period of the second gear in the encoder gearbox is clear in this diagram.

Figure 14: The azimuth component of image motion measured with an on-axis acquisition camera for a track between elevations of 49° and 56°. The gear encoder was used to measure azimuth position, after correction for 0.4° and 1.09° errors. Note that the error measured on the sky is $\cos E \approx 0.62$ of that displayed here.

Figure 15: FFT of open-loop tracking errors in azimuth, measured using an on-axis TV camera for the gear encoder. The units of spatial frequency are degrees^{-1}. The three prominent periods are: the residual from the second encoder gear rotation period (0.9 deg^{-1} or 1.09°), the residual translational error at the main drive tooth period (2.5 deg^{-1} or 0.4018°) and the tooth period of the second encoder gear (19.2 deg^{-1} or 0.052°).

harmonics of this period are expected. The r.m.s. pitch errors for a single head are <0.025 arcsec (first harmonic) and 0.036 arcsec (second harmonic) on average, with significant differences between individual heads. When all four heads are averaged, however, these errors are undetectable (<0.01 arcsec and <0.025 arcsec r.m.s., for first and second harmonics, respectively). Large-scale errors are expected from the manufacturing process (these were calibrated before the tape was fitted), from uneven fitting of the tape to the telescope and from the tape join. With no calibration, the maximum discontinuity on the WHT would be averaged to 0.3 arcsec and scale non-linearities are no worse than one part in 20000. The use of empirical look-up tables (implemented in the TCS but not yet calibrated) should lead to further improvements. Models for individual heads should also be introduced in order to allow arbitrary combinations to be used in case of failure.

The superior tracking performance of the azimuth tape encoder is illustrated in Figures 16 and 17 (compare Figures 14 and 15, noting the changes of scale). The tape encoder is free of obvious periodic components (even tape pitch errors) and this test gives a good illustration of current performance limits under optimum conditions. The r.m.s. error is 0.11 arcsec, superimposed on a mean drift of 0.12 arcsec in 36 minutes. During this period, the servo position error was 0.049 arcsec r.m.s. In addition, some contribution to image motion (very roughly 0.05 arcsec r.m.s.) comes from the atmosphere, so a best estimate of the contribution from systematic encoding errors is 0.09 arcsec r.m.s. The tape encoder is also superior on large scales: the r.m.s. residuals in $A \cos E$ from a pointing model fit are typically 0.8 arcsec and 0.6 arcsec, respectively, for the gear and mean tape encoders.

The tape encoder is clearly superior and will become the primary encoding system in azimuth once its stablity and reliability have been fully tested. As a results of the study described in Amos *et al.* (1992) and summarised here, encoders of this type have been selected for the Gemini telescopes.

4.2.4 Elevation encoding

The elevation axis has not been subjected to as detailed an analysis as the azimuth axis, partly because only one encoder is fitted, but also because its systematic errors are much smaller. Part of the reason for this is that translational errors act against gravity, and are therefore much less likely to move the

Figure 16: The azimuth component of image motion measured with an on-axis acquisition camera. The mean of the four tape encoder reading heads was used to derive the azimuth position. The duration of the track was 36 minutes and the initial elevation was 45°, so the error measured on the sky is $\cos E \approx 0.7$ of that displayed here.

Figure 17: FFT of open-loop tracking errors in azimuth, measured using an on-axis TV camera for the mean of the four tape encoder heads. The units of spatial frequency are degrees^{-1}. Note the change of scale from the equivalent plot for the gear encoder.

Figure 18: The elevation component of image motion for a tracking test between elevations of 49° and 56°.

telescope. The encoder gearbox is also significantly better than the azimuth equivalent. Figure 18 shows the elevation component of the tracking test in Figure 14.

5 Display Calculations

5.1 The Information Display

5.1.1 General

The Information Display is a set of text pages updated at 1 Hz which describes the current state of the telescope. Its layout is described in detail in Appendix E and the present section is concerned only with non-trivial calculations, particularly those involving limits (section 5.2). The other areas worth noting are the calculation of telescope α and δ and air mass.

The telescope right ascension and declination are only displayed when the position errors are small. The reason for this is that they are derived (in the medium frequency pointing loop) from the *demand* positions, after making a small correction for the servo error, in order to avoid a full reverse transformation. Since the errors are in (slightly) different coordinate systems, this approximation breaks down far from the tracking condition. For similar reasons, there are restrictions on the coordinate system in which the telescope position may be displayed, as described in Appendix C.18. The pointing transformations are carried out in the order: mean FK4, mean FK5, geocentric apparent, topocentric h, δ, as described earlier. The position may be displayed in any system downstream of the input system, but not in one requiring a reverse conversion.

The formula used for air mass relative to zenith is equation 7.5.34 of Murray (1983) rather than the commonly-used $\sec z$.

5.2 Limit Calculations

The efficient planning of a sequence of observations depends on the ability to calculate the period of time a target can be observed, starting from a given telescope position. This is complicated in the case of an altazimuth mount by the fact that the azimuth and rotator drives have finite ranges of travel. The following calculations have not been published elsewhere, and are therefore given in detail.

5.2.1 Elevation Limits

It is clear that an object is always above the horizon limit if $\delta > \pi - \phi - z$ and always below it if $\delta < \phi - z$. These declinations are $+71.24^\circ$ and -51.24°, respectively for the WHT. An object with declinations between these values rises above the elevation limit at an hour angle $-h$, where:

$$\cos z = \cos\delta\cos h\cos\phi + \sin\delta\sin\phi$$

or

$$h = \arccos\left(\frac{\cos z - \sin\delta\sin\phi}{\cos\delta\cos\phi}\right)$$

and sets at hour angle $+h$.

5.2.2 Azimuth

Azimuth is given in terms of hour angle and declination by the expressions in Section 2. Therefore:

$$a = \tan A = \frac{-\sin h\cos\delta}{\sin\delta\cos\phi - \cos\delta\cos h\sin\phi}$$

Squaring this equation gives a quadratic in $c = \cos h$:

$$Bc^2 + Cc + D = 0$$

where

$$\begin{aligned} B &= \cos^2\delta(1 + a^2\sin^2\phi) \\ C &= -2a^2\sin\delta\cos\delta\sin\phi\cos\phi \\ D &= a^2\cos^2\phi\sin^2\delta - \cos^2\delta \end{aligned}$$

The discriminant of this equation is:

$$C^2 - 4BD = 4\cos^2\delta[a^2(\cos^2\delta - \cos^2\phi) + \cos^2\delta]$$

An object *never* encounters an azimuth limit if

$$\cos\delta < |\sin A\cos\phi|$$

or

$$\delta > \arccos(|\sin A\cos\phi|)$$

for a telescope in the Northern hemisphere. The WHT's positive azimuth limit is set at A = 355°, which corresponds to a declination of $\delta = 85.62°$. For declinations less than this value, the quadratic has the solutions:

$$h = \pm \arccos \left\{ \frac{a^2 \sin\delta \sin\phi \cos\phi \pm [a^2(\cos^2\delta - \cos^2\phi) + \cos^2\delta]^{1/2})}{\cos\delta(1 + a^2\sin^2\phi)} \right\}$$

The first ± in the solution results from the fact that we have used an equation for $\cos h$ and cannot distinguish between positive and negative hour angles. The ambiguity can be sorted out by inspection or more formally by noting that, since $\sin A = -\cos\delta \sin h / \sin z$ with $-\pi/2 \le \delta \le \pi/2$ and $0 \le z \le \pi/2$, $\sin A$ and $\sin h$ must have opposite signs. The second ± occurs because an object may pass through the same azimuth twice. The telescope will, however, be moving in opposite directions in azimuth in the two cases and a limit forbids motion only in one of these.

In the case of the WHT, the positive and negative limits are at A = 355° and A = −175°, respectively. The azimuth velocity is given by:

$$A' = \sin\phi - \frac{\cos\phi \cos z \cos A}{\sin z}$$

The azimuth of an object at A = −175° therefore always *increases* with time and the negative limit is irrelevant for normal tracking. The positive limit can only be encountered when tracking a Northern object below the Pole and this corresponds to the solution:

$$h = +\arccos \left\{ \frac{a^2 \sin\delta \sin\phi \cos\phi - [a^2(\cos^2\delta - \cos^2\phi) + \cos^2\delta]^{1/2}}{\cos\delta(1 + a^2\sin^2\phi)} \right\}$$

Objects below a certain declination will encounter the horizon limit first. We equate the expressions for $\cos h$ derived for the elevation and azimuth limits. The resulting equation reduces to a quadratic in $s = \sin\delta$:

$$Es^2 + Fs + G = 0$$

where

$$\begin{aligned} E &= 1 + a^2 \\ F &= -2\cos z \sin\phi(1 + a^2) \\ G &= \cos^2 z(1 + a^2\sin^2\phi) - \cos^2\phi \end{aligned}$$

For the WHT, A = 355°, z = 80° and $\phi = 28.76°$. This gives the solution $\delta = 70.66°$. Hence the azimuth limit is only relevant for declinations between 70.66° and 85.62° when tracking below the Pole.

5.2.3 The zenith blind spot

The condition for the tracking speed in azimuth to exceed V is $\mu|dA/dh| > V$, where μ is the tracking rate in hour angle (15 arcsec s^{-1}). We define $v = \pm V/\mu$ (= ±240 for the WHT, the sign being negative to the North of the zenith and positive to the South) and solve the equation $dA/dh = v$ for $\cos h$ to give the hour angle at which an object enters the blind spot.

$$\begin{aligned} v &= dA/dh \\ &= \cos\psi \cos\delta / \sin z \\ &= \frac{\cos\delta(\cos\delta \sin\phi - \sin\delta \cos\phi \cos h}{1 - (\cos\delta \cos h \cos\phi + \sin\delta \sin\phi)^2} \end{aligned}$$

This can be rewritten in the form:

$$Hc^2 + Ic + J = 0$$

where (as before) $c = \cos h$ and

$$\begin{aligned} H &= +v\cos^2\delta\cos^2\phi \\ I &= \cos\delta\sin\delta\cos\phi\,(2v\sin\phi - 1) \\ J &= \cos^2\delta\sin\phi - v + v\sin^2\delta\sin^2\phi \end{aligned}$$

The relevant solutions are:

$$\cos h = \frac{\sin\delta(1 - 2|v|\sin\phi) \pm (\sin^2\delta - 4|v|\sin\phi + 4v^2)^{1/2}}{\pm 2|v|\cos\delta\cos\phi}$$

where the + and − signs refer to objects passing South and North of the zenith, respectively.

Solution of this equation confirms that a simple approximation is sufficient to give the range of declinations which is affected by the zenith blind spot. Close to transit:

$$dA/dh \approx \cos\phi/\sin(\delta - \phi)$$

so the condition $|dA/dh| > |v|$ gives $|\delta - \phi| < \cos\phi/v$. For the WHT, this corresponds to $\delta = \phi \pm 0.21°$ or $28.55° < \delta < 28.97°$. In the worst case, the azimuth velocity first exceeds 1 deg s^{-1} at an hour angle of –31 s, so for all practical purposes it can be thought of as entering the blind spot exactly at transit. The telescope will then rotate as rapidly as possible in order to acquire the object at the other side of the blind spot. This takes roughly 3 minutes at full speed.

5.2.4 Rotation limits

We start from the expressions relating sky and mount position angles and parallactic angle given in Section 2. The variation of parallactic angle with hour angle for various declinations is shown in Figure 19. The parallactic angle is undefined at the zenith ($\delta = \phi$, $h = 0$) and the nadir ($\delta = -\phi$, $h = \pi$). In the special cases $\psi = 0$ and $\psi = \pi$, the hour angle is given by:

$\psi = 0 \Rightarrow h = 0$ for $\delta < \phi$ and $h = \pi$ for $\delta > -\phi$.

$\psi = \pi \Rightarrow h = 0$ for $\delta > \phi$ and $h = \pi$ for $\delta < -\phi$.

Curves of $\psi(h)$ (Figure 19) pass through the following points:

$h = \pi$, $\psi = \pi$ and $h = 0$, $\psi = 0$ for $\delta < -\phi$.

$h = \pi$, $\psi = 0$ and $h = 0$, $\psi = 0$ for $-\phi < \delta < \phi$.

$h = 0$, $\psi = 0$ and $h = \pi$, $\psi = 0$ for $\delta > \phi$.

During a sidereal track, a given parallactic angle may occur once, twice or not at all. The condition for 0 or 2 solutions is that the function $\psi(h)$ has extrema. Its derivative at a maximum or minimum is:

$$\psi'(h) = -\cos\phi\cos A/\sin z = 0$$

giving the solutions $\cos A = 0$ or A = $\pm\pi/2$. The expression for $\cos A$ given in Section 2 can be used to reduce this to:

$$\cos h = \tan\delta/\tan\phi$$

Figure 19: The variation of parallactic angle with hour angle for the latitude of the La Palma Observatory. Curves are plotted for declinations of $-45°$, $-30°$, $-15°$, $0°$, $15°$, $30°$, $45°$, $60°$, $75°$ and $90°$. The curves are only plotted for observable elevations ($> 10°$). Declination increases upwards in the top-right quadrant and downwards in the bottom-left quadrant.

which only has solutions if $-\phi \leq \delta \leq \phi$. The maximum occurs for $h > 0$ (A = $\pi/2$), so

$$\sin\psi = -\cos\phi\sin A/\cos\delta = \cos\phi/\cos\delta$$

and the minimum at $h < 0$ (A = $\pi/2$), so

$$\sin\psi = -\cos\phi/\cos\delta$$

Hence:

- There are *no* solutions if $-\phi \leq \delta \leq \phi$ and $\mid \psi \mid < \pi/2$, $\sin\psi > \cos\phi/\cos\delta$ or $\sin\psi < -\cos\phi/\cos\delta$.
- There are *two* solutions if $-\phi \leq \delta \leq \phi$ and $-\cos\phi/\cos\delta < \sin\psi < \cos\phi/\cos\delta$.
- There is *one* solution if $\delta > \phi$ or $\delta < -\phi$.

In order to determine the hour angle corresponding to a given parallactic angle and declination, we start from the relations for $\sin\psi$ and $\cos\psi$ given earlier. These give:

$$p = \tan\psi = \frac{\cos\phi\sin h}{(\cos\delta\sin\phi - \sin\delta\cos\phi\cos h)}$$

This relation can again be squared and rearranged to give a quadratic in c = $\cos h$:

$$Kc^2 + Lc + M = 0$$

with

$$K = (1 + p^2\sin^2\delta)\cos^2\phi$$
$$L = -2p^2\sin\delta\cos\delta\sin\phi\cos\phi$$
$$M = p^2\cos^2\delta\sin^2\phi - \cos^2\phi$$

There are no solutions if $L^2 - 4KM < 0$, which reduces to:

$$\sin^2\psi > \frac{\cos^2\phi}{\cos^2\delta}$$

as before. Otherwise, the possible solutions are:

$$h = \pm\arccos\left\{\frac{p^2\sin\delta\cos\delta\sin\phi \pm [p^2(\cos^2\phi - \cos^2\delta) + \cos^2\phi]^{1/2}}{\cos\phi(1 + p^2\sin^2\delta)}\right\}$$

As with azimuth, the use of an equation for $\cos h$ with terms in $\tan^2\psi$ introduces ambiguities (ψ and $\pm\psi + n\pi$ give the same value of p for any integer n). The sign of the arccos function is determined by noting that $h < 0$ if $\psi < 0$ and $h > 0$ if $\psi > 0$. We therefore take $+$arccos for $\psi > 0$ and $-$arccos for $\psi < 0$. This leaves the positive and negative roots of the quadratic. For $\delta > \phi$, it is obvious from Figure 19 that there is only one solution for a given parallactic angle. In fact, for $0 \leq \psi \leq \pi$ the roots correspond to parallactic angles ψ and $\pi - \psi$. Similarly for $\delta < -\phi$, $-\pi \leq \psi \leq 0$ and the roots correspond to ψ and $-\psi - \pi$. The situation for $-\phi \leq \delta \leq \phi$ is different: either there are no roots (see above) or both roots correspond to the *same* parallactic angle.

If $\psi = \pm\pi/2$, $p^2 \to \infty$ and the roots merge. In this case,

$$h = \pm\arccos(\pm\tan\phi/\tan\delta)$$

with the special cases $h = \pm\pi/2$ at the Poles.

Finally, we consider the sense of rotation.

$$\psi'(h) = -\frac{\cos\phi\cos A}{\sin z} = -\frac{\cos\phi\sin\phi\cos\delta}{\sin^2 z}\left[\frac{\tan\delta}{\tan\phi} - \cos h\right]$$

It is clear from this equation that $\psi'(h)$ is always < 0 for $\delta > +\phi$ and > 0 for $\delta < -\phi$. For intermediate declinations, the quadratic has two valid solutions. The condition that its discriminant is zero is $\cos h = \tan\delta/\tan\phi$. Thus the positive root has $\cos h > \tan\delta/\tan\phi$, so $\psi' > 0$. Conversely, the negative branch has $\cos h < \tan\delta/\tan\phi$ and $\psi' < 0$.

The limit conditions are as follows (note that the mount PA and parallactic angle increase in opposite senses):

$\delta > \phi$ $\psi' < 0$ for all hour angles, so the rotator can only track into the positive mount PA limit. Since the rotation is monotonic, the limit will eventually be reached from any starting position provided that the telescope is not stopped by the azimuth or horizon limit, each complete rotation taking 24 hours. It is possible for the telescope to track continuously if $\delta >85.62°$, in which case the length of the observation is restricted only by the positive mount PA limit (admittedly a somewhat academic example). The positive root of the quadratic applies if $\mid \psi \mid > \pi/2$, otherwise the negative root.

$-\phi < \delta < \phi$ There are no solutions if $\mid \sin\psi \mid > \cos\phi/\cos\delta$ or $\mid \psi \mid > \pi/2$, in which case no limits can be hit; otherwise both roots give valid solutions and either limit can be encountered provided that the initial value of the mount PA is sufficiently close. The condition is:

$$(\theta - \theta_0) - \arcsin(\cos\phi/\cos\delta) < \rho < (\theta - \theta_0) + \arcsin(\cos\phi/\cos\delta)$$

where ρ is the current mount position angle and $(\theta - \theta_0)$ is ranged by adding or subtracting multiples of 2π so that $(\theta - \theta_0) - \rho_\pm$ is in the range $[-\pi, \pi]$. The positive root corresponds to the negative mount position angle limit, and conversely.

$\delta < -\phi$ The positive root is allowed, so $\psi' > 0$ and the rotator can track into the negative mount PA limit. As for $\delta > \phi$, the rotation is monotonic, so the turntable will eventually hit the limit provided that the object does not set first. For a telescope in the Northern hemisphere, such as the WHT, objects with $\delta < \phi$ are not circumpolar, so it is impossible for the turntable to rotate by more than a full turn whilst the object remains above the horizon. The negative root of the quadratic applies if $\mid \psi \mid > \pi/2$, otherwise the positive root.

5.2.5 Summary and practical limitations

The effects of the elevation and azimuth limits and of the zenith blind spot are summarised for the WHT in Table 4. Only the elevation limit need be considered in most cases, the possibility of encountering the azimuth limit being restricted to a few northerly objects observed below the Pole.

It should be noted that the azimuth and elevation limits are defined in the *mount* coordinate system and that further transformations are required in order to convert to astronomically-useful (h, δ). Since the index errors for the WHT are included to a good approximation in the encoder model, the difference between mount and topocentric apparent systems is not significant at the level of accuracy required ($\approx$ 1 minute of time). If higher precision is required, then the full pointing model must be included in the calculation. The theoretical radius of the zenith blind spot has been used, and it is likely that tracking will become progressively less accurate as this is approached. For practical purposes, a larger radius might be appropriate. The rotator limits are summarised in Table 5(the same caveats apply as for azimuth and elevation limits).

Table 4: Summary of effective limits for the WHT.

Declination	Effective limit
$\delta < -51.24°$	Never above elevation limit
$-51.24° < \delta < 28.55°$	Rises and sets at elevation limit
$28.55° < \delta < 28.97°$	Rises and sets at elevation limit; passes through blind spot
$28.97° < \delta < 70.66°$	Rises and sets at elevation limit
$70.66° < \delta < 71.24°$	Rises at elevation limit; sets at positive azimuth limit (+ wrap) or elevation limit (− wrap)
$71.24° < \delta < 85.62°$	Always above elevation limit; Sets at positive azimuth limit (+ wrap only)
$85.62° < \delta$	No limits

Table 5: Summary of turntable limits for the WHT ($\psi = \theta - \theta_0 - \rho$, where θ is the sky position angle, θ_0 is an instrument-dependent offset and ρ is the mount position angle of the limit).

Declination	Effective limit
$\delta < -28.76°$	Can hit negative mount PA limit
$-28.76° < \delta < 28.76°$	No limits if $\mid \sin\psi \mid > \cos\delta/0.877$ or $\mid \psi \mid > \pi/2$; otherwise can hit either mount PA limit
$28.76° < \delta$	Can hit positive mount PA limit

6 Diagnostic Procedures

6.1 Pointing tests

In order to measure the terms in the pointing model, a grid of stars with accurately known positions covering all of the accessible parts of the sky is used. The stars are slewed to in sequence and centred on a given point in the focal plane (usually the rotator centre). The values of α and δ in the encoder system are then logged, together with the sidereal time. 100 – 150 measurements are taken, concentrating on the zenith where a number of the terms become easier to distiniguish. The data are analysed using the TPOINT package (Wallace 1989), which uses a least-squares fit to the functional forms give in Table 1 in order to estimate the coefficients. Tests are performed 3 or 4 times a year at each focal station, and after any major mechanical change.

6.2 The CALIBRATE procedure

The CALIBRATE procedure is a short pointing test performed at the start of a night's observing in order to measure the three coefficients which are most likely to change (the azimuth and elevation index errors and the horizontal collimation) and to provide an estimate of the telescope's pointing performance. Seven stars are selected from the standard grid, on the northern or southern meridian (whichever is closer) and with a range of elevations. The telescope is slewed to each star in turn and the operator is invited to centre it on the reference position. The data are logged and automatically analysed as in a standard pointing test, but with all except the three coefficients set to the default values for the current focal station. The values of the coefficients and the r.m.s. fitting error are displayed and the raw data are stored for later analysis. The operator may then accept the new coefficients or revert to the previous or default values. Sky r.m.s. errors significantly in excess of 1 arcsec generally indicate either a breakdown or a slow change in the pointing model.

6.3 Tracking, rotation and encoder performance

The TCS is capable of logging image centroids from an acquisition camera or autoguider and a variety of data concerned with tracking performance at rates up to 20 Hz. These may then be plotted, analysed further (*e.g.* to generate look-up tables or to fit simple functions) or exported using the TCS PLOT utility. Several examples of the use of this technique were given in Section 4.2; it is also used to measure the misalignment of the derotation optics. In order to test the rotator performance at the Cassegrain and Prime foci, an acquisition camera is used to autoguide on a star at the centre of rotation (eliminating tracking errors) whilst an off-axis autoguider simultaneously logs the centroid of an image at the edge of the field.

6.4 Other diagnostic software

Two other utilities are used primarily for hardware testing. GSEXAM sets and reads the global variables used by the TCS for interprocess communication and allows easy access to raw encoder and transducer data. CAMAC_TEST is a test program for the hardware interface which is independent of the TCS.

7 Summary and Future Development

The present paper has summarised the calculations performed by the WHT telescope control system in a manner independent of implementation. The TCS has proved to be accurate and reliable in practical use, and its algorithms are well-tested. Enhancements are planned in two main areas: measurement and control of main mirror position and more sophisticated autoguiding.

Shack-Hartmann testing of the telescope optics has shown that the secondary mirror tilts and translates in such a way as to introduce significant coma away from the zenith (where the alignment is optimised). The coma is a reproducible function of elevation and can, in fact, be predicted from the pointing model and direct measurements of secondary tilt. The tilt of the secondary mirror can be controlled by the TCS, although the drive was not designed for continuous use and may have to be rebuilt. Calculations show that tilt of the secondary alone can remove coma at the field centre without introducing excessive astigmatism at large field radii and this would lead to significant gains in image quality. A second, somewhat easier, possibility is to measure residual tilt on the primary mirror (which is significant at the 0.1 arcsec level and tends to vary slowly with time) and to correct its effects on pointing using the mount.

The aim of improvements to the autoguiding algorithms (see *AG* for more detail) is to allow accurate blind acquisition given an off-axis guide star with an accurately-known displacement from the target. The requirements are:

1. A very accurate calibration of the focal-plane geometry (autoguider probe movement, detector orientation, scale and rotation).
2. An algorithm which predicts the coordinates of the off-axis guide star on the autoguider given its position on the sky and the location of the guide probe. This would be updated continuously in order to allow for time-variable effects such as differential refraction between guide star and target, probe flexure and (for solar-system objects) non-sidereal motion.

The control system for the Gemini telescopes differs from that for the WHT in one major respect: the optical surfaces are under full computer control, some at high speed. The WHT system as described here is entirely adequate to control the mount, field rotation and auxiliary mechanisms of the Gemini telescopes, but requires additional routines to deal with the primary and secondary mirror supports and their associated wavefront sensors. In addition, the hardware and software environment proposed by the Gemini project differs in almost all respects from that used at the WHT. Nevertheless, the work described in this paper goes a considerable way towards solving the problems posed by the new project.

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A Notation

ϕ Latitude of the telescope ($\phi = 28°45' 38.1''$)

h Hour angle

α Right ascension

δ Declination

E Elevation

z Zenith distance ($z = \pi/2 - E$)

A Azimuth

ψ parallactic angle

θ Sky position angle

θ_0 Instrument-dependent position angle offset

ρ mount position angle

μ Sidereal tracking rate in hour angle

ξ, η Cartesian coordinates in the tangent plane, parallel to $+\alpha$ and $+\delta$, respectively

σ, τ Cartesian coordinates in the tangent plane, parallel to $+A$ and $+E$, respectively

x, y Cartesian coordinates in the tangent plane along mount position angle 0° and 90°, respectively in the input coordinate system

x_A, y_A Cartesian coordinate system fixed in the focal plane

f_1, f_2, f Focal lengths of the primary and secondary mirrors, and of the Cassegrain combination, respectively

ϵ_p, ϵ_s Tilts of the primary and secondary mirrors with respect to the axis of the instrument rotator(s)

ζ Relative transverse displacement of primary and secondary mirrors

β Back focal distance / f_1

k Ratio of heights of rays at the margins of the secondary and primary mirrors

d Separation of primary and secondary mirrors

Δ_p, Δ_s, Δ_t Pointing errors due to primary tilt, secondary tilt and decentre, respectively

$R_A - R_E$ Refraction coefficients

M_{UA} Matrix to transform a unit vector from user to apparent coordinate system

M_{AM} Matrix to transform a unit vector from apparent to mount coordinate system

B TCS user interface commands: a classified list

This section contains a summary of the commands available at the user interface of the telescope control system, classified into functional groups. Details of individual commands are given in the alphabetical list of Section C.

B.1 General TCS commands

`EXIT`	Select engineering mode and close down the control system.
`HANDSET`	Select handset mode.
`HELP`	Get help on a command.
`RECALL`	Recall a previous command.
`TRANSFER`	Transfer control to or from a remote terminal.

B.2 Source data entry

`DEC`	Enter declination of edit source.
`DIFF_RATES`	Enter non-sidereal tracking rates for the edit source.
`EPOCH`	Enter epoch of position for edit source.
`EQUINOX`	Enter equinox for edit source.
`PARALLAX`	Enter parallax of edit source.
`PM`	Synonym for `PROPER_MOTION` (*q.v.*).
`PROPER_MOTION`	Enter proper motions of edit source.
`RA`	Enter right ascension of edit source.
`RADIAL_VEL`	Enter radial velocity of edit source.
`RV`	Synonym for `RADIAL_VEL` (*q.v.*).
`SOURCE`	Enter name, right ascension, declination and equinox for edit source.

B.3 Catalogue handling

`ADD`	Add the contents of the edit source data block to the catalogue as a named entry.
`CATALOGUE`	Replace the current user catalogue with a new binary catalogue.
`CAT_EDIT`	Edit a text-file catalogue from the user interface.
`DUMP`	Save the current user catalogue as a binary file.
`ERASE`	Clear the user catalogue.
`FIND`	Get a named catalogue entry and put it in the edit source block.
`INCLUDE`	Append a text catalogue to the current user catalogue.
`MARK`	Store the current telescope position as a named catalogue entry.
`OUTPUT`	Output the current catalogue to an ASCII file, terminal or line printer.
`REMOVE`	Delete a catalogue entry.

B.4 Source change

• `BLIND_OFFSET`	New source (from catalogue) with local corrections to the pointing model.
• `GOCAT`	New source (from catalogue; specified by name only).
• `GOTO`	New source (direct input of name, right ascension, declination and equinox).
• `NEXT`	New source (using data in edit source block).

B.5 Positional and Aperture offsets

• `APERTURE`	Execute a preset (numbered) aperture offset.
• `BEAMSWITCH`	Execute an aperture offset with direct input of x and y.
• `ENTER`	Input data for numbered aperture or positional offsets.
• `OFFSET`	Execute a positional offset with direct input of $\Delta\alpha$, $\Delta\delta$ or ξ, η.
• `POSITION`	Execute a preset (numbered) positional (ξ, η) offset.
• `STORE`	Store aperture or positional offsets set up using the handset.
• `TWEAK`	Apply a given (x_A, y_A, ρ_A) aperture offset.

B.6 Autoguiding

• `AGSELECT`	Identify the autoguider currently in use.
• `AGVIEW`	Aperture offset to move image to autoguider field.
• `AUTOGUIDE`	Lock or unlock the autoguider loop.
• `PROBE`	Input (r, θ) coordinates of guide probe.
• `TVCAMERA`	Identify the TV camera currently in use.
• `TVGUIDE`	Lock or unlock the TV guiding loop.
• `XYPROBE`	Input (x, y) coordinates of guide probe.

B.7 Calibration procedures

• `CALIBRATE`	Determine encoder zero-points and collimation errors.

B.8 Mechanism control

• `ALTITUDE`	Move the telescope to a given altitude and stop it.
• `AZIMUTH`	Move the telescope to a given azimuth and stop it.
• `DOME`	Move the dome to a given azimuth and stop it.
• `ELEVATION`	Synonym for `ALTITUDE` (*q.v.*).
• `DFOCUS`	Change the focus by a specified amount.
• `FOCUS`	Move the focus to a specified position.
• `ROTATOR`	Move the rotator to a given sky PA (tracking) or mount PA (stopped).
• `STOP`	Stop a mechanism or combination of mechanisms.
• `UNWRAP`	Move azimuth or rotator by 360°.

B.9 Mechanism configuration

`ENCODER`	Set the combination of encoders used for pointing.
`ENGINEERING`	Select engineering mode.
`RATE`	Set the encoder used by the hardware position loop.
`SENSOR`	En/disable corrections from displacement transducers.
`TRACK`	Turn focus, dome, rotator or telescope tracking on or off.
`WRAP`	Override the azimuth wrap determined from the zone switch in case of failure.
`ZEROSET`	Determine incremental encoder zero-points.

B.10 Change of focal station and instrument

Note that "Select" in this context means "set up software and drive the correct rotator": the Nasmyth flat is not moved.

`CASSEGRAIN`	Select Cassegrain focus.
`GHRIL`	Select GHRIL (alias cable-wrap side) Nasmyth focus.
`INSTRUMENT`	Tell the TCS which instrument is in use.
`PRIME`	Select prime focus.
`UES`	Select UES (alias drive-side) Nasmyth focus.

B.11 Display functions

`DISPLAY`	Change the coordinate system of the displayed telescope position.
`MOON`	Give the current right ascension and declination of the Moon.
`PAGE`	Switch to another information display page.
`SHOW`	List the edit source block.
`VERSION`	Display TCS account and version.

B.12 Logging of test data

`LOG`	Log tracking errors and associated data.
`POINT`	Write encoder coordinates to a data file.
`SNAPSHOT`	Record the current information display page.

B.13 Meteorological and Earth-rotation data

`HUMIDITY`	Input relative humidity used in refraction calculation.
`POLE`	Input values of polar motion.
`PRESSURE`	Input barometric pressure used in refraction calculation.
`TEMPERATURE`	Input temperature used in refraction calculation.
`UT1UTC`	Input UT1 − UTC.
`WAVELENGTH`	Input wavelength used in refraction calculation.

C TCS user interface commands: an alphabetical glossary

The following section gives a brief summary of the operation of each command together with examples and defaults.

Notation:

- Examples of commands entered at the terminal are in typewriter font: `DEC 12 34 56.78`;
- Angle brackets denote parameter values or keywords: `<angle>`;
- Square brackets denote optional parameter values or keywords: `[x,y]`; all other parameters and keywords are obligatory;
- Keywords (parameters which must take one of a number of preset values) are indicated by bold type: **CASSEGRAIN**.

In most cases, TCS commands can be issued either at the local user interface terminal or at the VaxStation running ICL. Users who wish to coordinate control of telescope and instruments are encouraged to take advantage of the latter mode of operation. Every effort has been made to make the command syntax identical on the two machines, but differences between the DCL and ICL command languages may cause some confusion. In general, if a command is issued correctly with all of its parameters, then the two systems will behave similarly. Both command languages are set up for minimum matching of command strings and neither is sensitive to case. The main differences are:

1. ICL will always acknowledge completion of a command. Response will be almost instantaneous except for commands which move the telescope mechanisms. These complete when the mechanisms concerned are in position.
2. Prompting for unspecified input has differences of detail.
3. Error messages differ, usually in the sense that the TCS gives a terser and more accurate description of the problem.
4. ICL does not allow a command to be issued if a previous attempt at the same action is still in progress. The TCS allows the first command to be overridden by the second. This can sometimes lead to problems from ICL (*e.g.* if the wrong object is selected).
5. A few commands (primarily those which produce screen output) are not available from ICL. These are noted explicitly below.

C.1 ACKNOWLEDGE

Turn off the engineering mode and/or software limit alarms.

Format: `ACKNOWLEGDE <alarm_type>`
Defaults: `ACKNOWLEDGE ALL`
Parameters: None.
Keywords:

LIMIT	turn off an alarm caused by an altitude, azimuth or rotator software limit;
ENGINEERING	turn off an alarm caused by an unexpected switch into engineering mode;
ALL	turn off any alarm.

Example: `ACKNOWLEDGE`

Comments: An alarm (continuous bleeping) is triggered if the telescope or rotator encounters a software limit whilst tracking or when requested to slew to an object below the horizon or if a switch from computer to engineering mode occurs unexpectedly (i.e. not as a result of an `ENGINEERING` or `EXIT` command).

C.2 ADD

Write the current contents of the edit source data area as a new entry in the user catalogue.

Format: `ADD`
Defaults: None.
Parameters: None.
Keywords: None.

C.3 AGSELECT

Select which autoguider to use.

Format: `AGSELECT <autoguider_name>`
Defaults: None. The Cassegrain autoguider is selected on startup.
Parameters: None.
Keywords: Valid autoguider names are:

CASSEGRAIN	the Cassegrain off-axis autoguider;
UESSLIT	the UES autoguider used to view the spectrograph slit and to guide on the object being observed;
UESCOARSE	the UES autoguider used with the coarse fibre bundle;
UESFINE	the UES autoguider used with the fine fibre bundle;
PRIME	the prime-focus off-axis autoguider;
AF2_FIXED	the fixed probe of the Autofib2 fibre positioner;
AF2_MOVING	the moving probe of the Autofib2 fibre positioner.

Examples: `AGSELECT CASS`
Comments: The TCS needs to be told which autoguider is currently in use in order to perform the conversion between guide star pixel position and drive corrections.

C.4 AGVIEW

Perform an aperture offset to move an image onto the autoguider CCD.

Format: `AGVIEW`
Defaults: None.
Parameters: None.
Keywords: None.
Comments: This command allows a field to be viewed using the autoguider. An offset is applied to move the image from the nominal aperture (usually the rotator centre) to the centre of the autoguider field. It is essential to tell the TCS which autoguider is in use and to define its position in the focal plane (use the `AGSELECT`, `PROBE` and `XYPROBE` commands as necessary).

C.5 ALTITUDE

Move to the specified altitude and stop.

Format: `ALTITUDE <angle>`
Defaults: None.

Parameters: The angle in degrees.
Keywords: None.
Examples: `ALTITUDE 85.72`
Comments: To park the telescope at the zenith without moving it in azimuth, type `ALTITUDE 90`. This is much faster than the hardware ZENITH PARK function and is all that is required in most circumstances. Tracking in azimuth and for the rotator are also disabled by this command.

C.6 APERTURE

Offset the telescope so that an object moves by a vector fixed in the focal plane.
Format: `APERTURE <aperture_number>`
Defaults: None. The reference position (aperture 0) is selected on startup. This is usually also the rotator centre, (0,0).
Parameters: The aperture number is in the range 0–10. The corresponding (x_A, y_A) displacement must have been set up previously in the initialisation file, or by using the `ENTER` or `STORE` commands. `APERTURE 0` is the reference position (see below).
Keywords: None.
Examples: `APERTURE 2`
Comments: As described in Section 3.7, an (x_A, y_A) shift in the focal plane is divided into two parts: the reference position, which is unaltered on source change and an aperture offset which is reset to zero on source change. The `APERTURE` command provides a means of switching between the reference position and previously-defined aperture offsets.

C.7 AUTOGUIDE

Lock or unlock the CCD autoguider loop.
Format: `AUTOGUIDE <state> [x y]`
Defaults: None.
Parameters: The optional parameters x and y are the desired pixel coordinates for the guide star and are used with the **ON** keyword. If they are not specified, the system will adopt the current position of the guide star.
Keywords: Valid autoguider states are:

ON	specifying that the telescope should be guided in response to guiding errors from the CCD autoguider.
OFF	specifying that autoguiding should be switched off, *i.e.* that any guiding errors from the CCD autoguider should be ignored.
SUSPEND	Put the TCS in a state where pixel coordinates are read from the autoguider and the current reference position is maintained, but guiding errors are not applied.
RESUME	Restart guiding if the loop has been suspended.

Examples:
```
AUTOGUIDE ON
AUTOGUIDE ON 122.5 63.2
```
Comments: The autoguider sends xy pixel coordinates of a guide star to the telescope control computer. The TCS then adjusts the telescope drives to keep the star at a given location on the autoguider CCD. If the intention is to maintain the current positioning of a field (*e.g.* if acquisition onto a spectrograph slit has been verified), then the command `AUTOGUIDE ON` should be used. This takes the first position received from the autoguider after the

command is issued, and keeps the guide star there. On the other hand, if the autoguider coordinates are already known, then the appropriate command is `AUTOGUIDE ON x y`. There are two cases where this is likely to be useful. The first is when an observation is to be repeated and the field is to be positioned at the same place on the detector. The guide probe and pixel positions should be repeated. The second case is guiding on the target object using the UES slit viewer. The x and y should be the pixel coordinates of the centre of the slit. Note that, for technical reasons connected with use of the command from ICL, the command `AUTOGUIDE ON -1 -1` means the same as `AUTOGUIDE ON`. The TCS must be told the autoguider in use (see `AGSELECT`) and, at Cassegrain, the orientation of the guide probe (see `PROBE`), otherwise the telescope corrections will be in the wrong direction. The function key F17 on the TCS keyboard is equivalent to the `AUTOGUIDE OFF` command. The function key F18 on the TCS keyboard is equivalent to the `AUTOGUIDE ON` command.

C.8 AZIMUTH

Move to the specified azimuth and stop.
Format: `AZIMUTH <angle>`
Defaults: None.
Parameters: The angle in degrees.
Keywords: None.
Examples: `AZIMUTH 275.34`
Comments: Tracking in altitude and for the rotator are also disabled by this command.

C.9 BEAMSWITCH

Offset the telescope so that an image moves by a vector fixed in the focal plane.
Format: `BEAMSWITCH <offset_x> <offset_y>`
Defaults: None. On source change (*e.g.* `GOTO`), offsets are reset to to the nominal values (this can also be done with the `BEAMSWITCH 0 0` or `APERTURE 0` commands: see `APERTURE`).
Parameters: The aperture (x_A, y_A) positions in arcseconds.
Keywords: None.
Examples: `BEAMSWITCH 20.2 -100`

C.10 BLIND_OFFSET

Offset between a reference object which is centred on the acquisition TV and a faint target object.
Format: `BLIND_OFFSET <source_name>`
Defaults: None.
Parameters: The name of the faint target object.
Keywords: None.
Examples: `BLIND 0512+22E`
Comments: This is the standard method for locating very faint objects, which are difficult or impossible to see on the acquisition TV. Accurate positions for a brightish star and the faint target object must be entered in the catalogue. Slew to the bright star using `GOCAT` and centre it on the reference position with the handset keys. Then type `BLIND <source_name>` for the faint object. This offsets the telescope so that the faint object is accurately aligned with the reference position. It can then be moved around the detector using the `BEAMSWITCH` or `APERTURE` commands. `BLIND_OFFSET` performs a local correction to the

pointing model, assuming that the position of the reference object is accurate. Subsequent executions of `BLIND_OFFSET` all use this correction, so several faint objects can be observed using the same reference star. The `NEXT`, `GOTO` and `GOCAT` commands revert to the default global pointing solution.

C.11 CALIBRATE

Update pointing coefficients at the start of an observing session.

Format: `CALIBRATE <solution>`

Defaults: `CALIBRATE NEW`

Parameters: None.

Keywords: Valid calibrate solutions are:

LAST	recalls the last pointing solution. This may be useful if the running of the control program has been interrupted, but does not ensure very accurate pointing because the encoder zero-points may have changed.
DEFAULT	reverts to the default pointing solution in the initialisation file. This is a suitable course of action if the `CALIBRATE` command fails (*e.g.* gives very large rms errors).
NEW	packages a sequence of commands to do a short pointing calibration.

Examples:

```
CALIBRATE
CALIBRATE LAST
```

Comments: The `CALIBRATE NEW` command initiates an automatic sequence which does a restricted pointing measurement on 7 stars from the pointing grid in order to update the values for the encoder zero-points in azimuth and elevation and the collimation error in azimuth. Stars are selected to be close to the meridian and either North or South of the zenith, depending on the initial azimuth. A range of elevations must be covered. The telescope is driven to the first star and the handset mode is selected. When the telescope is tracking, the star should be moved on to the reference position using the handset keys. Once you are satisfied, press the HANDSET key. This logs the position and drives to the next star. Repeat these operations until all 7 positions have been logged. You will then be asked whether all of the stars were centred correctly. If you do not answer `Y` to this question, then the procedure will be aborted. The derived and previous values will be displayed, together with their r.m.s. errors, and you will be asked whether the solution is reasonable. The errors should be in the range 0.5–1.0 arcsec for IE, 1.0–2.0 arcsec for CA and 1.0–3.0 arcsec for IA. If the errors are much larger than these values, then the solution should be rejected. Unless there has been a major change of configuration, the coefficients should not alter by more than a few arcseconds from night to night. Gross differences may indicate a problem. CTRL–Z may be used to abort the procedure at any time, but all of the measurements will be lost. Note that, although this command is available on the system computer (from ICL), you will *not* be asked whether all stars have been centred correctly or whether the solution is acceptable.

C.12 CASSEGRAIN

Select the Cassegrain focal station.

Format: `CASSEGRAIN`

Defaults: None.
Parameters: None.
Keywords: None.
Comments: Applies Cassegrain pointing model, enables Cassegrain rotator and disables all other rotators. Note that the Nasmyth flat *cannot* be stowed under computer control, so the button on the engineering desk must be used for this purpose.

C.13 CATALOGUE

Delete the current TCS user interface catalogue and copy the named binary file as the new user catalogue.
Format: `CATALOGUE <catalogue_name>`
Defaults: Node: `LPVB`,
Directory: `USER_CAT`,
Extension: `.SAV`.
Parameters: The name of the input catalogue in the format:
`[[[<node>::]<device>:]<directory>]<file>[.<extension>]`.
Keywords: None.
Examples: `CATALOGUE USER_CAT:CAT.SAV`, or
`CATALOGUE CAT`

Comments: The binary file is copied into memory as the current user catalogue. Existing entries are lost. Although the command can be used to copy a file from the data reduction computer (see below), it is expected that the normal mode of use will be to copy a text file into the user catalogue with `INCLUDE` (*q.v.*), to dump a binary copy to the default catalogue area on the telescope computer with `DUMP <filename>` and then to `CATALOGUE` this copy on subsequent nights. Binary copies need only be made of very large catalogues (> 100 objects). Note that the command `ERASE` can be used to erase the entire user catalogue.

C.14 CAT_EDIT

Edit a text-file catalogue from the TCS user-interface terminal.
Format: `CAT_EDIT <catalogue_name>`
Defaults: Node: `LPVB`,
Directory: `USER_CAT`,
Extension: `.CAT`.
Parameters: The name of the input catalogue in the format:
`[[[<node>::]<device>:]<directory>]<file>[.<extension>]`.
Keywords: None.
Examples: `CAT_EDIT CATACLYSMICS`
Comments: The editor is basic EVE and is documented in the VAX/VMS Guide to Text Processing, Chapter 3. Note that this command is not currently available on the system computer (from ICL).

C.15 DEC

Enter a declination in the edit source data area.
Format: `DEC <dec_degrees> <dec_minutes> <dec_seconds>`
Defaults: Value of declination: None,
Sign of declination: '+'.

Parameters: The declination in degrees, minutes and seconds or arc. The value is rejected if any of the components lie outside the following ranges:

`dec_degrees`	0–89 inclusive
`dec_minutes`	0–59 inclusive
`dec_seconds`	0.0–59.99... inclusive

Keywords: None.
Examples: `DEC -12 34 56.78`

C.16 DFOCUS

Offset the focus to compensate for additional optical elements.
Format: `DFOCUS <focus_offset>`
Defaults: None.
Parameters: Focus offset, in mm.
Keywords: None.
Examples: `DFOCUS 0.3`
Comments: This command is intended to be used when the telescope focus has to be changed to compensate for the additional optical thickness of a filter. The virtual focus reading is unchanged, and the focus offset in use is displayed in the DF field on the bottom line of the Information Display.

C.17 DIFF_RATES

Enter differential tracking rate in right ascension and declination.
Format: `DIFF_RATES <diff_rate_in_ra> <diff_rate_in_dec>`
Defaults: None. Unspecified differential rates are assumed to be zero.
Parameters: Right ascension and declination differential tracking rates in seconds/second and arcseconds/second, respectively.
Keywords: None.
Examples: `DIFF_RATES 0.01 -0.3`
Comments: The differential (non-sidereal) tracking rates are added to the edit source data block. They must be actioned using the `NEXT` command. Note that differential rates are not included in a catalogue entry.

C.18 DISPLAY

Change the coordinate system of the information display.
Format: `DISPLAY <coordinate_system>`
Defaults: None. The default coordinate system on startup is **INPUT**.
Parameters: None.
Keywords: The allowed coordinate systems are:

INPUT	α and δ in the system used to input the source position;
APPARENT	α and δ in geocentric apparent coordinates;
J2000	α and δ in J2000 mean coordinates;
B1950	α and δ in B1950 mean coordinates;
HA_DEC	Topocentric hour angle and declination.

Examples: `DISPLAY J2000`
Comments: The systems are described in more detail in Section E. For technical reasons, there are restrictions on the permitted combinations of input and display coordinates, as follows:

INPUT	always allowed;
APPARENT	always allowed;
J2000	not allowed for input in apparent coordinates;
B1950	not allowed for input in apparent or FK5 (J) coordinates;
HA_DEC	always allowed.

C.19 DOME

Move the dome to the specified azimuth and stop.

Format: `DOME <angle>`
Defaults: None.
Parameters: The angle in degrees.
Keywords: None.
Examples: `DOME 275.34`

C.20 DUMP

Save a binary version of the current user catalogue in the named file.

Format: `DUMP [[[<node>::"<username password>"] <device>:]<directory>] <file>[.<extension>]`
Defaults: Node: `LPVB` (telescope computer),
Device/directory: `USER_CAT`,
Extension `.SAV`.
Parameters: The name of the output file.
Keywords: None.
Examples: `DUMP LASTNIGHT` to save a file in the default catalogue area with the filename LASTNIGHT.SAV.
`DUMP LPVE::"GUEST01 GDHUDG"DISK$USER1:[GUEST01.CATS]LASTNIGHT` to copy a file to the VAX 4000 data reduction computer (LPVE). The file will be in the [.CATS] subdirectory of the GUEST01 account on the USER1 disk and will be called LASTNIGHT.SAV.
Comments: The extension .SAV is mandatory. If another extension is specified, it will be removed and .SAV substituted.

C.21 ELEVATION

Synonym for `ALTITUDE` (*q.v.*)

C.22 ENCODER

Set the combination of incremental encoders used for pointing in azimuth.

Format: `ENCODER <encoder_name>`
Defaults: None. The gear encoder is selected on startup.
Parameters: None.
Keywords: Valid encoder names are:

GEAR	gear encoder;
ROLL	friction-driven roller encoder;
TAPEn	individual inductive tape encoder reading heads (n = 1, 2, 3 or 4);

TAPEn_m	means of opposing tape reading heads (the allowed combinations are **TAPE1_3** and **TAPE2_4**);
TAPE_MEAN	mean of all four tape reading heads.

Examples: `ENCODER GEAR`

Comments: There are three independent incremental encoding systems on the WHT azimuth axis, any of which may be used for pointing and tracking. These are: a gear encoder, coupled to the telescope via the main drive gear; an inductive tape encoder with four reading heads and a friction-driven roller encoder. The roller encoder is not recommended, as it slips. The gear (default) and the mean of the four tape heads are the best for normal use: the remaining tape combinations are used for test purposes.

C.23 ENGINEERING

Put the telescope into engineering mode.

Format: `ENGINEERING`

Defaults: None.

Parameters: None.

Keywords: None.

Comments: This command should be used: as part of the normal shutdown procedure at the end of the night, to return to engineering mode at any time, or in an emergency to remove power from the drives and put on the brakes. It is equivalent to turning the COMP/ENG key on the engineering desk to the ENG position. To return to computer mode, turn the key to the COMP position and press the COMP/ENG button next to it on the desk.

C.24 ENTER

Set up aperture and positional offsets for repeated use.

Format:

```
ENTER APERTURE <aperture_number> <x_offset> <y_offset>
ENTER ARC_POSITION <position_number> <ra_offset> <dec_offset>
ENTER TIME_POSITION <position_number> <ra_offset> <dec_offset>
```

Defaults: None.

Parameters: `<aperture_number>` is an integer in the range 0–10, 0 being the reference position (the default on source change).

`<position_number>` is an integer in the range 1–10. Position 0 is a zero offset and may not be redefined.

`<x_offset>`, `<y_offset>` and `<dec_offset>` are in arcseconds.

`<ra_offset>` is in seconds of time if the **TIME_POSITION** keyword is specified, or arcseconds if the **ARC_POSITION** keyword is specified.

Keywords: Valid offset modes are: **APERTURE**, **ARC_POSITION**, **TIME_POSITION**.

Examples:

```
ENTER APERTURE 3 1.5 20.3
ENTER ARC_POSITION 3 -3.0 12.0
ENTER TIME_POSITION 1 -0.33 -11
```

Comments: `ENTER APERTURE` sets up an aperture offset which can be applied using the `APERTURE` command. `ENTER ARC_POSITION` and `ENTER TIME_POSITION` set up a positional offset which can be added to the telescope demand position using the `POSITION` command.

C.25 EPOCH

Enter a value for the epoch of the position into the edit source data block.

Format: `EPOCH <date>`

Defaults: None.
Parameters: The epoch in years.
Keywords: None.
Examples: `EPOCH 1967.35`
Comments: The epoch is used in conjunction with the proper motions to compute the position of date.

C.26 EQUINOX

Enter a value for the equinox of the position into the edit source data block.
Format: `EQUINOX <equinox>`
Defaults: None.
Parameters: A code for the coordinate system, followed (for mean coordinates) by the equinox, in years. The allowed systems are:

APPARENT	Geocentric apparent coordinates;
J<year>	Mean coordinates (FK5 system);
B<year>	Mean coordinates (FK4 system).

Keywords: None.
Examples:

```
EQUINOX B1950
EQUINOX J1992.5
EQUINOX APP
```

Comments: The year must be in the range 1800.0 to 2100.0.

C.27 ERASE

Erase all entries from the current user catalogue.
Format: `ERASE`
Defaults: None.
Parameters: None.
Keywords: None.

C.28 EXIT

Initiate an orderly shutdown of the telescope control system.
Format: `EXIT`
Defaults: None.
Parameters: None.
Keywords: None.
Comments: This command puts the telescope into engineering mode before shutting down the control system. Note that this command is not currently available on the system computer (from ICL).

C.29 FIND

Retrieve data for the named source from the user or system catalogues and place them in the edit source data block.
Format: `FIND <source_name>`
Defaults: None.

Parameters:	The name of the the source to be retrieved. It can be a string of up to 20 characters; extra characters are lost. To include spaces the whole string should be enclosed within double quotes.
Keywords:	None.

Examples:	`FIND HD123456`
	`FIND NGC_4151`
	`FIND "Supernova in LMC"`

Comments:	The user catalogue is searched first, followed by the system catalogue.

C.30 FOCUS

Drive the focus to a specified setting and stop it.

Format:	`FOCUS <setting>`
Defaults:	None.
Parameters:	The focus in mm (34.5 – 129.0 mm).
Keywords:	None.
Examples:	`FOCUS 50.5`

C.31 GHRIL

Select the GHRIL (Nasmyth cable-wrap side) focal station.

Format:	`GHRIL <rotator_mode>`
Defaults:	None.
Parameters:	None.
Keywords:	The valid rotator modes are:

DEROTATOR	is for use when the derotation optics are mounted. It drives the rotator so as to give a stationary image.
ROTATOR	assumes that the instrument is mounted directly on the turntable.
NOROTATOR	is for use when the derotation optics are not mounted and the instrument is stationary on the optical table.

Examples:	`GHRIL DEROTATOR`
Comments:	Applies GHRIL pointing model, enables GHRIL rotator and disables all other rotators. Does not move the Nasmyth flat, which is not under computer control.

C.32 GOCAT

Retrieve the entry for the named source from the user catalogue and then send the telescope to track that source.

Format:	`GOCAT <source_name>`
Defaults:	None.
Parameters:	The name of the target object.
Keywords:	None.
Comments:	The user catalogue is searched first, followed by the system catalogue.

C.33 GOTO

Move the telescope to a new source and track it.

Format:	`GOTO <source_name> <right_ascension> <declination> <equinox>`
Defaults:	None.

Parameters: `<source_name>` The name of the new source. It must be a string of up to 20 characters; extra characters are lost. To include spaces the whole string should be enclosed within double quotes.

`<right_ascension>` Specifies the right ascension of the new source in three fields separated by spaces. Format: `<ra_hours> <ra_minutes> <ra_seconds>`. The right ascension is rejected if any of the components lie outside the following ranges:

`<ra_hours>`	0–23 inclusive
`<ra_minutes>`	0–59 inclusive
`<ra_seconds>`	0.0–59.99... inclusive

`<declination>` Specifies the declination of the new source in three fields separated by spaces. The <dec_degrees> field may be signed. If not signed, the default is '+'. Format: `<dec_degrees> <dec_minutes> <dec_seconds>`. The declination is rejected if the any of the components lie outside the following ranges:

`<dec_degrees>`	0–89 inclusive
`<dec_minutes>`	0–59 inclusive
`<dec_seconds>`	0.0–59.99... inclusive

`<equinox>` Specifies the equinox of the source coordinates. A valid equinox must have two components: a leading letter indicating the system of the coordinates; and a number indicating the epoch of the mean equator and equinox of that system. Format: `<letter-year>`, *e.g.* `B1950`, `J2000` or `APPARENT` (for which no number is required). Note that only `B`, `J` or `A` are acceptable as leading letters. The year must lie in the range 1800.0 to 2100.0.

Keywords: None.

Examples: `GOTO HD123456 12 34 56.78 76 54 32.10 J2000`

C.34 HANDSET

Place the TCS user interface in handset mode.

Format: `HANDSET`

Defaults: None.

Parameters: None.

Keywords: None.

Comments: In handset mode, the keypad may be used to guide the telescope, set up offsets or apertures, change the focus or move the rotator. See Section D for a more detailed description. This command is bound to the DO key on a standard VT220 keyboard. To exit from the handset mode press the DO key and control will return to the `USER>` prompt.

C.35 HELP

Provide information about the commands available from the TCS user interface.

Format: `HELP [topic [subtopic]...]`

Defaults: Lists all available commands.

Parameters: The command you wish to receive help on.

Keywords: None.

Examples: `HELP GOTO EQUINOX`

Comments: Invoking the `HELP` command initiates an interactive dialogue with the user interface HELP library, a normal VMS HELP library. In response to a Topic? or subtopic prompt you may:

- Type the name of the command/topic for which you need help;
- Type a question mark (`?`) to redisplay recently requested text;
- Press the RETURN key one or more times to exit from HELP;
- Press CTRL–Z once to exit from HELP;
- Abbreviate any topic name, but note that ambiguous abbreviations result in *all* matches being displayed.

Note that this command is not currently available on the system computer (from ICL).

C.36 HUMIDITY

Enter the value of the relative humidity used in the calculation of refraction.
Format: `HUMIDITY <relative_humidity>`
Defaults: None. The value assumed on startup is 0.5.
Parameters: The fractional humidity in the range 0–1.
Keywords: None.
Examples: `HUMID 0.5`

C.37 INCLUDE

Read in a text format source catalogue.
Format: `INCLUDE <catalogue_name>`
Defaults: Node: `LPVB`,
Directory: `USER_CAT`,
Extension: `.CAT`.
Parameters: The name of the input catalogue in the format:
`[[[<node>::]<device>:]<directory>]<file>[.<extension>]`.
Keywords: None.
Examples: `IN USER_CAT:SPECPHOT.CAT` or `IN SPECPHOT` to input a file called SPECPHOT.CAT in the default directory, or
`IN LPVE::DISK$USER1:[GUEST02.CAT]TARGETS` to input a file called TARGETS.CAT in the [.CAT] subdirectory of the GUEST02 account on the VAX 4000 data reduction computer (LPVE).

C.38 INSTRUMENT

Tell the TCS which instrument is in use.
Format: `INSTRUMENT <instrument_name>`
Defaults: None. The parameters for ISIS are set on startup.
Parameters: None.
Keywords: Valid instrument names are:

ISIS	ISIS and FOS spectrographs.
TAURUS	Taurus imaging Fabry-Perot interferometer.
MES	Manchester Echelle Spectrograph.
DURPOL	Durham imaging polarimeter.
AUXCCD	Cassegrain auxiliary port CCD camera.

UES	Utrecht Echelle spectrograph.
LDSS	Low-dispersion survey spectrograph.
PFCCD	Prime focus imaging CCD camera.
AUTOFIB	Prime-focus automatic fibre positioner.
OWN	Spare for users' own instrument.

Examples: `INSTRUMENT ISIS`

Comments: This command sets the origin of position angle used for a specific instrument and the scale and orientation for the `TWEAK` command (*q.v.*). Position angle on the sky is normally defined to be along the slit in a spectrograph and aligned with one of the detector axes for an imaging instrument. The scale and orientation parameters are currently set to match the standard TCS xy coordinate system except for the **LDSS** keyword, where they correspond to the system used by the LEXT software package.

C.39 LOG

Log tracking errors and associated data from TV, autoguider and telescope encoders.

Format: `LOG <system> <state> [<period>]`

Defaults: The period parameter defaults to 20 cycles (1 second).

Parameters: The period, in integer cycles of the synchronous loop (0.05 s). The allowed range is 1 – 20000. This parameter is only used with the **ENCODER** and **AZIMUTH** keywords.

Keywords: `<system>` – valid keywords are:

TV	pixel coordinates produced by the acquisition TV system's GUIDE or I-GUIDE functions;
AUTOGUIDER	pixel coordinates produced by one of the CCD autoguiders,
ENCODERS	encoder readings, servo errors and drive demands for the altitude, azimuth and current rotator drives,
AZIMUTH	all possible encoders on the azimuth axis to allow comparison between independent systems.

`<state>` – valid keywords are: **ON** or **OFF**.

Examples:

```
LOG TV ON
LOG ENC ON 5
LOG AZIMUTH ON
```

Comments: If logging is turned on when it is already enabled for the keyword in question, the log file is closed and a new one is opened. Any of the logging functions may be run simultaneously. Beware of running out of disk space if very rapid encoder logging is used.

C.40 MARK

Store the current position of the telescope as a named catalogue entry.

Format: `MARK <source_name>`

Defaults: None.

Parameters: The name of the source.

Keywords: None.

Examples : `MARK SUPERNOVA`

Comments: This command stores the current position to allow return to an object at a later date. The position is stored in the current input coordinate system.

C.41 MOON

Display the geocentric and topocentric apparent right ascension and declination of the Moon.

Format: `MOON`
Defaults: None.
Parameters: None.
Keywords: None.
Comments: This command is not currently available on the system computer (from ICL).

C.42 NEXT

Send the telescope to track the source whose data are in the edit source block.

Format: `NEXT`
Defaults: None.
Parameters: None.
Keywords: None.
Comments: The user catalogue is searched first, followed by the system catalogue.

C.43 OFFSET

Offset the telescope by a given amount in right ascension and declination.

Format: `OFFSET <offset_system> <offset_ra> <offset_dec>`
Defaults: None.
Parameters: If the **ARC** keyword is specified (see below), the offsets in right ascension and declination must be in arcseconds. If the **TIME** keyword is specified (see below), the offset in right ascension must be entered in seconds of time and offset in declination must be entered in arcseconds.
Keywords: The valid offset systems are:

ARC	offsets the telescope by given amounts parallel to right ascension and declination in the tangent plane. Positive offsets imply that the right ascension and declination of the telescope both increase. The magnitude of the offset is independent of position.
TIME	offsets the telescope by given amounts in right ascension and declination. The magnitude of the offset depends on declination. $\Delta\alpha$ and $\Delta\delta$ are assumed to be in the input coordinate system.

Examples:

```
OFFSET ARC 12.6 -18.8
OFFSET TIME 0.32 -13.4
```

C.44 OUTPUT

Write out the current user catalogue in text format to the printer, TCS user interface or to a disk file.

Format: `OUTPUT <output_device>`, or
`OUTPUT[[<node>"<username password>"]`
`::<device>:]<directory>]`
`<file>[.<extension>]`
Defaults: There is no default output device. The defaults for the catalogue name are:
Node: `LPVB` (telescope computer),

Directory/device: `USER_CAT` (*alias* `U1:[WHT.TCS.USER.CAT]`),
Extension: `.CAT`.

Parameters: The full path for the output file (if the **FILE** keyword is specified – see below).

Keywords: Valid output devices are: **PRINTER**, **TERMINAL**, **FILE**.

Examples:

```
OUTPUT PRINTER
OUTPUT TERMINAL
OUTPUT FILE LPVE"GUEST01 GDHUDG"::DISK$USER1:[GUEST01.CATS]LASTNIGHT
```

Comments: The catalogue may be saved in the default catalogue area on the telescope computer, whence it may be recovered on a subsequent night. It will, however, be deleted when you leave the site. Files which are to be backed up should be transferred to your account on the VAX 4000 (LPVE). The syntax for this is somewhat cumbersome: the username and password must be specified, otherwise the file will be owned by DECNET and will therefore be unreadable by the user. The password is needed in order to avoid overwriting of other users' files. The .CAT extension is mandatory. If any other extension is specified, then it will be removed and .CAT substituted. To print the catalogue on the line printer in the WHT, type `OUTPUT PRINTER` and to list it at the user interface terminal, type `OUTPUT TERMINAL`.

C.45 PAGE

Display the next page in the cycle of information and status displays.

Format: `PAGE <display_screen>`

Defaults: `PAGE NEXT` – the next display screen in the cycle. The information display appears on startup.

Parameters: None.

Keywords: The various displays in the cycle are, in order:

NEXT	Display the next page in the cycle;
INFO	Top-level information display (appears on startup);
ENCODERS	Encoder readings;
LIMITS	Limit indicators;
ALARMS	Alarm indicators;
DOME	Dome status and manual overrides.

Examples:

```
PAGE ENC
PAGE
```

Comments: See Section E for more details.

C.46 PARALLAX

Enter a parallax into the edit source data area.

Format: `PARALLAX <parallax_arcsecs>`

Defaults: None. Unspecified parallaxes are assumed to be zero.

Parameters: The parallax in arcseconds.

Keywords: None.

Examples: `PARALLAX 0.023`

Comments: The parallax is rejected if it lies outside the range 0.0 to 10.0 arcseconds.

C.47 PM

Synonym for `PROPER_MOTION` (*q.v.*).

C.48 POINT

Log, in TPOINT format, the present position of the telescope as read on the encoders.

Format: `POINT <file_status>`

Defaults: `POINT OLD`

Parameters: None.

Keywords: The log file may be either an old file (specified by the **OLD** keyword) or a new file (specified by the **NEW** keyword).

Examples: `POINT`
`POINT NEW`

Comments: The data are logged to a pointing data file in a format suitable for input to the TPOINT analysis package. `POINT NEW` always creates a new pointing file. `POINT` or `POINT OLD` uses the latest file created that night or creates a new one if none has been created that night. The function key $\boxed{\text{F20}}$ is equivalent to the `POINT` command.

C.49 POLE

Input values of polar motion.

Format: `POLE <x_position> <y_position>`

Defaults: None. See comments below.

Parameters: The polar motion xy corrections in arcseconds.

Keywords: None.

Examples: `POLE 0.10 -2.10`

Comments: This command overrides the initial values for polar motion, which are derived from an interpolation formula supplied by the Earth Rotation Prediction Service. It makes a very small difference to the pointing of the telescope and is too esoteric for normal use.

C.50 POSITION

Move the telescope by a previously-stored (ξ, η) offset.

Format: `POSITION <position_number>`

Defaults: None. `POSITION 0` (zero offset) is automatically selected on startup or change of source.

Parameters: The position number is an integer in the range 0-10. The offset values for a given position number must have been set up using the `ENTER` or `STORE` commands. `POSITION 0` corresponds to a zero offset and returns the telescope to the reference position.

Keywords: None.

Examples: `POSITION 2`

C.51 PRESSURE

Enter the value of the barometric pressure used in the calculation of refraction.

Format: `PRESSURE <pressure>`

Defaults: None. The pressure assumed on startup is 779 millibar.

Parameters: The barometric pressure in millibars.

Keywords: None.

Examples: `PRESSURE 779.5`

Comments: The refraction correction is proportional to the pressure. An error of 5 millibar is just about noticeable (it corresponds to a pointing deviation of 1 arcsecond at a zenith distance of 75°).

C.52 PRIME

Select the prime focal station.

Format: `PRIME`

Defaults: None.

Parameters: None.

Keywords: None.

Comments: Applies prime focus pointing model, enables prime focus rotator and disables all other rotators.

C.53 PROBE

Enter current position of the Cassegrain autoguider probe in (r, θ) coordinates.

Format: `PROBE <radius> <theta>`

Defaults: None.

Parameters: The autoradial position in microns and the autotheta position in millidegrees.

Keywords: None.

Examples: `PROBE 10000 10000`

Comments: These values can be read directly from the ICL mimic display. If the θ coordinate is incorrect, then spurious guiding corrections will be applied. Both coordinates are needed for the `AGVIEW` command to work.

C.54 PROPER_MOTION

Enter proper motions into the edit source data area.

Format: `PROPER_MOTION <pm_in_ra> <pm_in_dec>`

Defaults: Unspecified proper motions are assumed to be 0.

Parameters: The proper motion in right ascension and declination in units of seconds/year and arcseconds/year, respectively.

Keywords: None.

Examples: `PROPER_MOTION -1.54 0.675`

Comments: The synonym `PM` can also be used.

C.55 RA

Enter a right ascension in the edit source data area.

Format: `RA <ra_hours> <ra_minutes> <ra_seconds>`

Defaults: None.

Parameters: The right ascension in hours, minutes and seconds of time. The right ascension is rejected if the any of the components lie outside the following ranges:

`ra_hours`	0–23 inclusive
`ra_minutes`	0–59 inclusive
`ra_seconds`	0.0–59.99... inclusive

Keywords: None.

Examples: `RA 12 34 56.789`

C.56 RADIAL_VEL

Enter a radial velocity in the edit source data area.

Format: `RADIAL_VEL <radial_velocity>`

Defaults: Unspecified radial velocities are assumed to be 0.

Parameters: The radial velocity in km/sec. A positive velocity implies a receding source.
Keywords: None.
Examples: `RADIAL_VEL -98`
Comments: The synonym `RV` can also be used.

C.57 RATE

Set the encoder used in the Azimuth hardware position loop.
Format: `RATE <encoder>`
Defaults: None.
Parameters: None.
Keywords:

GEAR	The Azimuth gear encoder.
TAPE	The Azimuth tape encoder.

Examples: `RATE TAPE`
Comments: This command is used to change the source of pulses received by the Marconi servo electronics and used in the hardware part of the position loop. Compare `ENCODER`, which changes the encoder combination used by the software part of the loop. The command forces a switch to engineering mode. Note that changes to the switch settings on the rate generator board are also needed.

C.58 RECALL

Recall a previous command.
Format: `RECALL <command_name>`
Defaults: Last command.
Parameters: A string containing the first part of the command you wish to recall.
Keywords: None.
Examples: `RECALL GOCAT`
Comments: `RECALL` is used to recover the last occurrence of a typed command within a 50-line buffer, just as in DCL. Note that this command is not available on the system computer (from ICL).

C.59 REMOVE

Remove the entry for the named source from the user catalogue.
Format: `REMOVE <source_name>`
Defaults: None.
Parameters: The name of the source to be deleted. The name may be a string of up to 20 characters; extra characters are lost. To include spaces, the whole string should be enclosed within double quotes.
Keywords: None.
Examples:

```
REMOVE NGC_4151
REMOVE "Supernova in LMC"
```

C.60 ROTATOR

Move the rotator to the specified mount or sky position angle or change its mode of operation.
Format: `ROTATOR <rotator_mode> <position_angle>`
Defaults: None.

Parameters: `<position_angle>` – the position angle in degrees. This parameter is only required when using the **SKY** and **MOUNT** keywords (see below). Sky position angle must be in the range 0° – 360° (the nearest corresponding mount position angle is selected). The Cassegrain rotator has mount position angle limits of −250° – +250°; the Nasmyth turntables currently have no limits enabled, since they are capable of continuous rotation.

Keywords: `<rotator_mode>` – the following keywords represent the valid rotator modes:

SKY	This keyword gives a position angle on the sky (measured anticlockwise from North which is 0° and defined by a natural axis in the instrument such as a spectrograph slit). If rotator tracking is enabled (as is the case on startup), then the rotator will follow this position angle as the telescope moves.
MOUNT	This keyword specifies that the parameter gives a mount position angle, *i.e.* measured with respect to a fiducial mark fixed to the mirror cell. `ROTATOR MOUNT`stops the turntable at the requested position angle (it makes no sense to track a mount position angle).
FLOAT	This option is designed to minimise unnecessary rotation in the case where the precise value of the sky position angle is unimportant. On source change, the rotator is set to a sky position angle corresponding to its current mount value. Thereafter, it rotates as for the **SKY** keyword.
VERTICAL	This keyword sets the reference axis in the instrument to the vertical direction and stops the rotator tracking. It is intended to minimise loss of light due to differential refraction during spectroscopic observing. Note that autoguiding is not possible, since off-axis images move in the focal plane.
VFLOAT	This keyword sets the slit to the vertical direction on source change and then tracks at a constant sky position angle. It is therefore equivalent to typing: `ROT SKY <parallactic_angle>`. This is generally more useful than the **VERTICAL** option, since autoguiding is possible.

Examples:

```
ROTATOR SKY 275.34
ROTATOR MOUNT 28.0
ROTATOR FLOAT
```

C.61 RV

Synonym for `RADIAL_VELOCITY` (*q.v.*).

C.62 SENSOR

Enable or disable tracking corrections derived from displacement transducers.

Format: `SENSOR <sensor_type> <state>`

Defaults: None.

Parameters: None.

Keywords: `<sensor_type>` This selects the sensors whose tracking corrections are to be en/disabled.

SECONDARY	The three displacement transducers which are used to measure the tilt of the secondary mirror.
HORIZONTAL	The two transducers which measure the horizontal movement of the telescope. These are used to provide tracking corrections in Azimuth for the gear incremental encoder, but are not relevant if the tape encoder is used (see `ENCODER`, *q.v.*).

`<state>`

ON	enables corrections.
OFF	disables corrections.

Examples: `SENSOR HORIZ ON`

C.63 SHOW

Display data on the topic indicated by the keyword.

Format: `SHOW <show_topic>`

Defaults: None.

Parameters: None.

Keywords: `<show_topic>` – The following keywords are valid show topics:

APERTURES	Displays the x_A and y_A coordinates of apertures 0 – 10 and the currently-selected aperture. See `APERTURE`, `BEAMSWITCH`, `ENTER` and `STORE`.
ASTROMETRY	Displays the user-modifiable astrometric parameters: wavelength, pressure, temperature, relative humidity (all used to calculate refraction); UT1-UTC, and polar motion. TAI-UTC is also shown. See `WAVELENGTH`, `PRESSURE`, `TEMPERATURE`, `HUMIDITY`, `UT1UTC` and `POLE`.
AUTOGUIDER	gives the autoguider currently selected by the TCS (see `AGSELECT`), the associated probe position (see `PROBE` and `XYPROBE`), the guiding pixel coordinates and the state of the guiding loop (unlocked, locked or suspended: see `AUTOGUIDE`).
CALIBRATE	displays the values of elevation index error, azimuth index error and azimuth collimation, together with their rms errors and the sky sigma for the last `CALIBRATE` at the current focal station. The corresponding parameters for the default pointing model are also given.
CATALOGUES	gives a directory of user catalogues.
EDIT	displays the parameters of the edit source, which will be selected by the `NEXT` command.
ENCODERS	lists the encoders and transducers currently being used by the TCS to control the telescope. See `ENCODER`, `RATE` and `SENSOR` for information on how to change the configuration.
FOCAL_STATION	gives the current hardware and software selection of focal station. This option is intended to allow the user to check that the combination of optical configuration, TCS selection of focal-station, autoguider and instrument

	is self-consistent. See `PRIME`, `CASSEGRAIN`, `GHRIL`, `UES`, `INSTRUMENT` and `AGSELECT`.
LIMITS	lists the software position limits in altitude, azimuth, rotation (all focal stations) and focus.
LOGGING	shows the current status of data logging (see `LOG`).
MECHANISMS	displays the status of all of the main mechanisms. Altitude, azimuth and rotator are said to be "following" during a sidereal track. For the dome, "following" means that it is tracking the telescope and for the focus, that it is being adjusted to compensate for temperature changes (see `TRACK`). The software and hardware limit status for the mechanism is shown next (including the cable wrap for the Cassegrain rotator). The mechanism is "moving" if it is being driven under computer control, otherwise "stopped". The next field reads "in position" if the mechanism is either tracking or stopped within a defined position error, depending on its requested state. The final field shows whether the mechanism can be driven under computer control (if not, the status shown is "Manual override" or "Engineering mode".
POSITIONS	Lists the RA-Dec offsets (1 – 10) currently defined and any offset in use. See `OFFSET`, `POSITION`, `ENTER` and `STORE`.
TV	gives the TV camera currently selected by the TCS (see `TVCAMERA`), the guiding pixel coordinates and the state of the guiding loop (unlocked or locked: see `TVGUIDE`).

Comments: This command is not currently available on the system computer (from ICL).

C.64 SNAPSHOT

Dump a copy of the information display screen to a file or physical device.

Format:	`SNAPSHOT <filename>`
Defaults:	Directory: LOG_DIR on the telescope computer, Extension: .LOG.
Parameters:	The name of the file or physical device.
Keywords:	None.

Examples:	`SNAPSHOT ARCHIVE`
	`SNAPSHOT LP:`
	`SNAP NGC1234.DAT`

Comments:	This command may be used to record information relevant to an observation or to provide evidence of problems. Most users will find it easiest to print the screen directly using `SNAPSHOT LP:`. In case of a problem with the telescope, please record all of the information display screens on disk (*e.g.* using `SNAPSHOT ERROR`).

C.65 SOURCE

Enter new source data into the edit source data area.

Format:	`SOURCE <source_name> <right_ascension> <declination> <equinox>`
Defaults:	Name, right ascension, declination, equinox: None. All other source values: User defaults.

Parameters: `<source_name>` The name of the new source. It must be a string of up to 20 characters; extra characters are lost. To include spaces the whole string should be enclosed within double quotes.

`<right_ascension>` Specifies the right ascension of the new source in three fields separated by spaces. Format: `<ra_hours> <ra_minutes> <ra_seconds>`. The right ascension is rejected if any of the components lie outside the following ranges:

`<ra_hours>`	0–23 inclusive
`<ra_minutes>`	0–59 inclusive
`<ra_seconds>`	0.0–59.99... inclusive

`<declination>` Specifies the declination of the new source in three fields separated by spaces. The `<dec_degrees>` field may be signed. If not signed, the default is '+'. Format: `<dec_degrees> <dec_minutes> <dec_seconds>`. The declination is rejected if the any of the components lie outside the following ranges:

`<dec_degrees>`	0–89 inclusive
`<dec_minutes>`	0–59 inclusive
`<dec_seconds>`	0.0–59.99... inclusive

`<equinox>` Specifies the equinox of the source coordinates. A valid equinox must have two components: a leading letter indicating the system of the coordinates; and a number indicating the epoch of the mean equator and equinox of that system. Format: `<letter-year>`, *e.g.* `B1950`, `J2000` or `APPARENT` (for which no number is required). Note that only `B`, `J` or `A` are acceptable as leading letters. The year must lie in the range 1800.0 to 2100.0.

Keywords: None.

Examples: `SOURCE HD123456 12 34 56.789 11 22 33.44 B1900`

Comments: `SOURCE` copies the user default values for all source values into the edit source entry and then takes the command line or prompted input for source name, right ascension, declination and equinox.

C.66 STOP

Stop the named mechanism by ramping the velocity to zero.

Format: `STOP <mechanism>`

Defaults: `STOP ALL`

Parameters: None.

Keywords: Valid mechanism names are: **ALL**, **ALTITUDE**, **AZIMUTH**, **DOME**, **FOCUS**, **ROTATOR**, **TELESCOPE_DOME**.

Examples:

```
STOP TEL
STOP
```

Comments: The `STOP ALL` or `STOP` commands stop all mechanisms. The `STOP TEL` command stops the altitude, azimuth, rotator and dome.

C.67 STORE

Store aperture and positional offsets.

Format: `STORE <offset_type> <offset_number>`

Defaults: None.

Parameters: `<offset_number>` is the aperture number if the **APERTURE** keyword is specified (see below). It must be an integer in the range 0–10. `APERTURE 0` is the reference position and is not reset on source change (see Section 3.7).
`<offset_number>` is the position number if the **POSITION** keyword is specified (see below). It must be an integer in the range 1–10 (position 0 corresponds to a zero offset and cannot be overwritten).

Keywords: Valid offset types are:

POSITION	sets up a positional offset which can be added to the telescope reference position using the `POSITION` command.
APERTURE	sets up a beamswitch position which can be applied to the telescope using the `APERTURE` command.

Examples: `STORE APERTURE 3`

Comments: The command may be used to store positional or aperture offsets which have been found using the APOFF or OFFSET handset modes or input using the `BEAMSWITCH` or `OFFSET` commands. They may then be recalled for future use with the `APERTURE` or `POSITION` commands. When `STORE` is executed, the aperture or offset stored becomes the current one and the Information Display is updated.

C.68 TEMPERATURE

Enter the value of the outside air temperature used in the calculation of refraction.

Format: `TEMPERATURE <temperature>`

Defaults: None. A temperature of 5° C is assumed on startup.

Parameters: The outside air temperature in degrees Centigrade.

Keywords: None.

Examples: `TEMPERATURE 7.5`

Comments: An error of 10°C gives a pointing error of 1.7 arcseconds at an elevation of 45°.

C.69 TRACK

Turn the focus, dome, rotator or telescope tracking on or off.

Format: `TRACK <track_system> <track_state>`

Defaults: None.

Parameters: None.

Keywords: The `<track_system>` keyword selects the mechanism which is to have its tracking state changed. The allowed mechanisms are: **DOME**, **FOCUS**, **ROTATOR**, **TELESCOPE**. The `<track_state>` keyword sets the tracking either **ON** or **OFF**.

Examples: `TRACK FOCUS OFF`

Comments: The effect of the `TRACK ROTATOR ON` command is to cause the instrument rotator to start tracking at its current sky position angle. It is therefore useful if there is no constraint on the detector position angle, as it causes the rotator to slew by the minimum amount (this is equivalent to the `ROTATOR FLOAT` command).

C.70 TRANSFER

Control the operational state of remote terminals.

Format: `TRANSFER <remote_state>`

Defaults: None.

Parameters: None.

Keywords: The `<remote_state>` keyword may take the following values:

COMMAND	This keyword allows command input from a remote terminal. This would usually be in the GHRIL room or on the engineering desk, but could be configured elsewhere if required using the switch-box located on top of the telescope computer. It also copies the control-room user-interface display to the remote terminal if this has not already been done with the `TRANSFER DISPLAY` command.
DISPLAY	This keyword enables the remote terminal so that a copy of the control room display appears on it. It also disallows command input and returns control to the default terminal in the control room.
OFF	This keyword disables the remote terminal entirely, returns command input to the control room terminal and clears the remote display.

Examples: `TRANSFER COMMAND`

C.71 TVCAMERA

Identify the TV camera currently in use for autoguiding using the GUIDE or I-GUIDE options.

Format: `TVCAMERA <camera_name> [<camera_mode>]`

Defaults: None.

Parameters: None.

Keywords: The `<camera_name>` keyword specifies the TV camera currently in use for autoguiding. The options available are:

SLIT	Cassegrain camera viewing the ISIS slit;
FIELD	Cassegrain camera with the field-viewing mirror;
ON_AXIS	direct camera (test mode only);
OFF_AXIS	off-axis camera (test mode only).

The `<camera_mode>` keyword specifies the field of view of the camera; either **DIRECT** or **REDUCE**. The `<camera_mode>` keyword is only required if the **SLIT** or **FIELD** cameras are selected.

Examples:

```
TVCAMERA SLIT REDUCE
TVCAMERA ON_AXIS
```

Comments: This command is used to tell the TCS to use scale and orientation parameters for a particular TV camera. These are needed when using the `TVGUIDE` command to autoguide or when logging test data. The **DIRECT** keyword represents a TV scale of approximately 5 mm/arcsec. The **REDUCE** keyword represents a TV scale of approximately 12 mm/arcsec.

C.72 TVGUIDE

Turn TV guiding off, or turn it on with an optional xy position.

Format: `TVGUIDE <state> [x y]`

Defaults: None.

Parameters: The optional parameters x and y are the desired pixel coordinates for the guide star. If they are not specified, then the system will adopt the current position of the guide star.

Keywords: Valid states are:

ON	specifying that the telescope should be guided in response to guiding errors from the TV system in GUIDE or I-GUIDE mode.
OFF	specifying that TV guiding should be switched off, *i.e.* that any guiding errors from the TV system should be ignored.

Examples: `TVGUIDE ON`
`TVGUIDE ON 122.5 63.2`

Comments: When the TV system's GUIDE or I-GUIDE function are selected, xy pixel coordinates of a guide star are sent to the telescope control computer. The TCS then adjusts the telescope drives to keep the star at a given location on the TV camera. If the intention is to maintain the current positioning of a field (*e.g.* if acquisition onto a spectrograph slit has been verified), then the command `TVGUIDE ON` should be used. This takes the first position received from the TV system after the command is issued, and keeps the guide star there. On the other hand, if the TV coordinates are already known, then the appropriate command is `TVGUIDE ON x y`. This is likely to be useful when an observation is to be repeated and the field is to be positioned at the same place on the detector. Note that, for technical reasons connected with use of the command from ICL, the command `TVGUIDE ON -1 -1` means the same as `TVGUIDE ON`. The TCS must be told the camera in use (see `TVCAMERA`), otherwise the telescope corrections will be in the wrong direction.

C.73 TWEAK

Apply a given (x_A, y_A, ρ_A) aperture offset to align a field on an instrument.

Format: `TWEAK <x_offset> <y_offset> <rotation>`

Defaults: `<rotation>` defaults to 0.

Parameters: `<x_offset> <y_offset>` are displacements in x_A and y_A, in arcsec.
`<rotation>` is the rotation of the field in degrees.

Keywords: None.

Examples: `TWEAK 0.5 -0.6 0.1`

Comments: This command is used to position a field precisely on an instrument. It can be used whether or not the telescope is being autoguided. Its main application is with LDSS, where the objective is to centre a large number of target objects on the slit mask, but it may also be useful for long-slit spectroscopy, especially when two objects are to be placed on the slit simultaneously. It is not advisable to use displacements of more than 1 arcsec or rotations of more than $0.1°$ when autoguiding, since the guide star may be lost. Larger offsets can be split into successive smaller ones, or autoguiding may be suspended whilst the CCD window is moved. For LDSS, the sign convention corresponds to that used by the LEXT software package (the `INSTRUMENT LDSS` command must be used to inform the TCS). For other instruments, the TCS focal plane (aperture) coordinate system is used, with position angle measured anticlockwise.

C.74 UES

Select the UES (Nasmyth drive-side) focal station.

Format: `UES <rotator_mode>`

Defaults: None.

Parameters: None.

Keywords: The valid rotator modes are:

DEROTATOR	is for use when the derotation optics are mounted. It drives the rotator so as to give a stationary image.
ROTATOR	that an instrument is mounted directly on the turntable and is unlikely to be used with UES in place.
NOROTATOR	for use when the derotation optics are not mounted and the instrument is stationary (as is the case for UES).

Examples: `UES DEROTATOR`
Comments: Applies UES pointing model, enables UES rotator and disables all other rotators. Does not move the Nasmyth flat, which is not under computer control.

C.75 UNWRAP

Rotate either the Azimuth axis or the current rotator by 360° from its current position, if this is possible.
Format: `UNWRAP <mechanism>`
Defaults: None.
Parameters: None.
Keywords:

AZIMUTH	The azimuth axis.
ROTATOR	The currently- selected rotator.

Example: `UNWRAP ROTATOR`
Comments: The azimuth axis, and those rotators which have limits enabled (Cassegrain and Prime foci) have more than 360° of travel and part of their ranges are ambiguous. The `UNWRAP` command is used to rotate these mechanisms by 360° in order to avoid tracking into a limit or to reset the mechanism if a limit has been hit during observing. There are four possible modes of operation, depending on the initial state. Firstly, if the mechanism is tracking normally, and is in its ambiguous range, then it is rotated by 360° and tracking is resumed. This is useful if there is insufficient time to complete an observation before a limit is hit. Secondly, an azimuth or rotator software limit may be encountered whilst the telescope is tracking. `UNWRAP` then moves the mechanism to the correct position, as on change of source, and tracking is resumed (this is always possible provided that the target is still above the horizon limit). Thirdly, if the mechanism in question is stopped in an ambiguous part of its travel, then `UNWRAP` will drive it to a position 360° away and stop it. Finally, if the mechanism is in the process of moving to a fixed position (as a result of an `AZIMUTH` or `ROTATOR MOUNT` command, for example), then the demand position is altered by 360° if possible. In all cases, an error message is generated if the mechanism is on the unambiguous part of its range. `UNWRAP ROTATOR` is not useful for the Nasmyth rotators, which do not have limits enabled, and is not allowed if they are in use.

C.76 UT1UTC

Enter the value of the correction to Universal Time (UT1–UTC) used in the control system.
Format: `UT1UTC <correction>`
Defaults: None. This command overrides the startup value of $UT1 - UTC$, which is determined from an interpolation formula supplied by the Earth Rotation Prediction Service.
Parameters: The correction in seconds.
Keywords: None.
Examples: `UT1UTC -0.0222`

Comments:	The IERS bulletin is pinned up on a noticeboard in the WHT control room. The correction UT1–UTC for each night is listed in a table which starts on page 3 of the bulletin.

C.77 VERSION

Display TCS account (TCS_DEV, TCS_LOGIN, TCS_OLD) and version (*e.g.* v0-4-1) currently in use.

Format:	`VERSION`
Defaults:	None.
Parameters:	None.
Keywords:	None.
Comments:	This command is not currently available on the system computer (from ICL).

C.78 WAVELENGTH

Enter the value of the effective wavelength of light used in the calculation of the refraction correction.

Format:	`WAVELENGTH <wavelength>`
Defaults:	None. The startup value is 0.4 μm.
Parameters:	The wavelength in microns.
Keywords:	None.
Examples:	`WAVELENGTH 0.55`

C.79 WRAP

Override the azimuth wrap value (*i.e.* the multiple of 360° which must be added to the raw encoder reading to give the correct azimuth).

Format:	`WRAP <wrap_value>`
Defaults:	None.
Parameters:	The wrap value in units of multiples of one revolution. The allowed values are '0' and '−1'.
Keywords:	None.
Examples:	`WRAP -1`
Comments:	The absolute encoder in azimuth has a travel of exactly 360°, after which it repeats. The telescope has a total travel of 530° in azimuth, and the ambiguity must therefore be resolved on startup by reading the position of a zone switch. The `WRAP` command should only be necessary when the zone switch fails, in which case the azimuth reading will be incorrect by 360° and the telescope will sometimes slew into a hardware limit. In this case, `WRAP` may be used to enter the correct value.

C.80 XYPROBE

Enter the x and y coordinates of an autoguider probe (appropriate for the Prime, UES Nasmyth and Autofib2 autoguiders).

Format:	`XYPROBE x y`
Defaults:	None.
Parameters:	The x and y coordinates of the guide probe, in units used by the system computer (μm for all cases at present).
Keywords:	None.
Examples:	`XYPROBE 20000 20000`
Comments:	This command allows the TCS to calculate the position of the guide probe in focal-plane (x_A, y_A) coordinates. This is needed, for example, by the `AGVIEW` command, but is *not*

used directly for autoguiding, since the detector maintains a constant orientation with in the focal plane if it is mounted on an x-y stage.

C.81 ZEROSET

Set the zero-points of incremental encoders by a variety of methods.

Format: `ZEROSET <mechanism> <method> [<position>]`

Defaults: None.

Parameters: The `[<position>]` parameter is required only if the **TO** `<method>` keyword is specified (see below). The position should be entered in the format: `<degrees>` `<minutes>` `<seconds>`.

Keywords: `<mechanism>` – The following mechanisms may be zeroset:

ALTITUDE	
AZIMUTH	
ROTATOR	(the currently-selected rotator)

`<method>` – Several different methods are provided to set the zero-points of the incremental encoders, in order to reduce the dependence on individual bits of electronics. These are:

TARGET	This method is, in principle, capable of the highest accuracy. A mechanical target is used to provide a fixed reference point. Currently, this method may be used on the altitude and azimuth axes only. Their targets are located at an altitude 88° 39′ and azimuth −02° 27′, respectively. The mechanism is driven slowly through the standard position in engineering mode and the encoder is reset when the target is detected electronically, in which case the user terminal will bleep and output a suitable message. Altitude and azimuth target zerosets may be active simultaneously.
CANCEL	This is used to cancel a target zeroset request if, for some reason, it fails.
ABSOLUTE	The incremental encoders are forced to read the same as the absolute encoders for the same mechanism. This is done automatically on startup, to provide an initial estimate. It is prone to failure because the bulbs in the absolute encoders are not especially reliable, although this situation will be improved once the new LED encoders are operational.
TO	Allows the current position of the mechanism to be input. This would normally be derived from the engineering-desk synchros (in altitude and azimuth) or from the scale on the Cassegrain rotator and is corrected for known zero-point errors. This method provides a starting point for the `TARGET` procedure and a backup in case of failure of both the absolute encoder and the target electronics.
ZENITH	This is used to set the zero-points in altitude and/or azimuth assuming that the telescope is at its hardware zenith park position. This is a useful backup option when

	there is a problem with one of the absolute encoders, since the telescope can be moved to a reproducible position independently of the encoders.
AP1	As for **ZENITH** but using the hardware Access Park 1 position.
AP2	As for **AP1** but using the hardware Access Park 2 position.

Examples:

```
ZEROSET ALTITUDE ABSOLUTE
ZERO AZIMUTH TARGET
ZERO AZ ZENITH
ZERO ROT TO 60 00 00
```

Figure 20: An example of the handset display. This example applies to change of the reference position in x, y coordinates and is the default on startup.

D The TCS Handset

D.1 General

The handset provides an interactive way of incrementing the position of the telescope in various coordinate systems, setting apertures and offsets and altering the focus and rotator position angle. The handset is selected by pressing the HANDSET key or typing `HANDSET` at the user interface. Pre-defined and user-selectable increments may be used and the arrow keys are used to input the steps. These auto-repeat when held down, so a continuous motion may be generated by selecting a small increment and holding down the appropriate key. The left INC and right INC keys select the next smaller and next larger increments, respectively. OWN requests the input of an increment value. Enter the value, in the appropriate units, and then hit the RETURN key. Just hit RETURN to escape from increment selection if you press OWN by accident. The handset display (a variant of that shown in Figure 20) is drawn at the top of the user-interface screen. It shows the available increment values, the accumulated increments and the modes. Currently-selected values are in reverse video. Only the keys labelled in Figure 21 remain active. The HANDSET key is used to return to the `USER>` prompt. The default on first selecting the handset is the X_Y mode with an increment of 1.0 arcseconds. Thereafter, the accumulated increments in each mode and the currently-selected mode and increment value are remembered on exit to `USER>` level and restored when the handset is next used. They are reset on source change (using the `GOTO`, `GOCAT`, `NEXT` or `BLIND_OFFSET` commands).

D.2 Handset modes

There are seven handset modes, each of which can be selected using the labelled function key on the user interface keyboard. The seven functions divide naturally into three groups:

- ALT_AZ, RA_DEC and X_Y increment the demand position in the input coordinate system and differ only in the directions of the increments. The increments displayed are therefore the accumulated values from all three modes in the coordinate system of the current mode. The tracking position on the information display also changes.
- OFFSET and APOFF are used in conjunction with the `STORE` command to set up positional and aperture offsets interactively. The tracking coordinates do not change.
- FOCUS and ROTATOR move individual mechanisms.

Figure 21: The portion of the VT220 or VaxStation user-interface keyboard used in handset mode. Only those keys with labelled functions are active.

We describe each handset mode in more detail below:

D.2.1 ALT_AZ mode

Changes the demand position in altitude and azimuth (units are arcseconds). The image is moved horizontally or vertically on the sky. Increments are defined in the tangent plane, so their magnitudes do not depend on elevation. This mode is used to establish the vertical direction (*e.g.* when worrying about differential refraction) or to ascertain whether a failure in telescope tracking or pointing is predominantly in azimuth or elevation.

D.2.2 RA_DEC mode

Changes the demand position in right ascension and declination (units are arcseconds). The image is moved in the east-west or north-south direction. Increments are defined in the tangent plane, so their magnitudes do not depend on declination. Image movement on the TV and detector will depend on the chosen sky position angle. At a sky position angle of 0°, the movements in X_Y and RA_DEC are identical. RA_DEC mode is most useful for wandering around finding charts and establishing orientations on the instrument. It can also be used for offsetting from a reference source although this can be done more flexibly with other methods such as the `BLIND_OFFSET` command.

D.2.3 X_Y mode

Changes the demand position in directions fixed in the focal plane (units are arcseconds). This is the most commonly used of all the modes. It moves the telescope in a sensible way corresponding to the customary sense of x, y coordinates on the acquisition TV screen (independent of rotator orientation and with equal steps in x and y) and is the normal method for final alignment of an object on to an instrument aperture such as a spectrograph slit, unless the guiding loop is already locked (see APOFF, below). It cannot, however, be assumed that the same xy increments can be used for more than one observation of the same field. The reason is that the handset is being used to compensate both for pointing errors (which tend to be functions of azimuth and elevation and therefore rotate with respect to the focal plane when the *mount* position angle changes) and for errors in the position of the object (which are fixed on the sky and therefore rotate when the *sky* position angle changes).

D.2.4 OFFSET mode

This is used in conjunction with the `STORE POSITION` command to set up positional offsets which may be recalled with the `POSITION` command. To define an offset, move an object to the start position using one of X_Y, RA_DEC or ALT_AZ. Then switch to OFFSET mode, move the object to the end position, exit from the handset and store the offset with `STORE POSITION <position_number>`, where `<position_number>` is in the range 1–10. `POSITION <position_number>` recalls the offset, which is defined in the tangent plane.

D.2.5 APOFF mode

This mode changes the aperture offset interactively. It is intended to be used to shift an object to an instrument aperture away from the reference position. The aperture coordinates may be recorded for future use with the command `STORE APERTURE`. The image moves in x and y on the TV and/or detector. To set up a new aperture, move an object to the reference position using X_Y, RA_DEC or ALT_AZ mode, switch to APOFF, move it to the new aperture (spectrograph slit or whatever), exit from the handset and type `STORE APERTURE <aperture_number>`, where `<aperture_number>` is in the range 0–10. `STORE APERTURE 0` redefines the reference position.

The APOFF mode may be used even when the autoguider loop is locked. This is useful for making small corrections (*e.g.* to optimise a target position on the spectrograph slit). The telescope offset and the reference pixel coordinates on the autoguider are changed simultaneously in such a way that the guiding errors remain zero. The image appears to move in the same way as in the X_Y mode. Small increments (<1 arcsec) should be used, in order to avoid losing the guide star.

D.2.6 FOCUS mode

Changes the telescope focus (units are millimetres). Always allow time for the focus to settle after an increment, as the drive is a bit sticky. It should eventually stop within 0.01 millimetres of the requested position.

D.2.7 ROTATOR mode

This increments the *sky* position angle of the rotator (units are degrees). It therefore only works when the rotator is tracking.

D.3 Sign conventions

The first five of the handset modes cause an image to move in the focal plane. The sense of motion for the keys has been set so that the *image* moves in the obvious way. The displayed cumulative totals for each mode refer to the motion of the *telescope*. This, coupled with the variety of different 'hand' conventions of astronomical coordinate systems, requires the sign conventions summarised below:

- **ALT_AZ** mode.
    - ⇐ Image moves left on the sky; −azimuth displayed;
    - ⇒ Image moves right on the sky; +azimuth displayed;
    - ⇑ Image moves up on the sky; −altitude displayed;
    - ⇓ Image moves down on the sky; +altitude displayed.

- **RA_DEC** mode.
  - ⇐ Image moves east; −right ascension displayed;
  - ⇒ Image moves west; +right ascension displayed;
  - ⇑ Image moves north; +declination displayed;
  - ⇓ Image moves south; −declination displayed.
- **X_Y** mode. The sign convention has been used to be consistent with that used for apertures (set up with the `BEAMSWITCH` and `ENTER APERTURE` commands).
  - ⇐ Image moves left on TV; $-x$ displayed;
  - ⇒ Image moves right on TV; $+x$ displayed;
  - ⇑ Image moves up on TV; $-y$ displayed;
  - ⇓ Image moves down on TV; $+y$ displayed.
- **OFFSET** mode. As for **X_Y**.
- **APOFF** mode. As for **X_Y**.
- **FOCUS** mode.
  - ⇐ −Focus;
  - ⇒ +Focus.
- **ROTATOR** mode.
  - ⇐ −Sky position angle;
  - ⇒ +Sky position angle.

If the image appears to move in a direction opposite to that expected, check that the TV scan switches are in their correct positions for the optical configuration in use.

D.4 Use of the handset from the system computer

In order to allow easy control of telescope and intruments by a single user, the handset will be made available as a window on the user-interface VaxStation. At present, this can only be done from a programmer's account on the TCS, but the response of the system to the handset keys is sufficiently rapid that it will certainly be worthwhile to make this function available from the standard system.

Figure 22: The telescope information display. This is the first of the display screens and is the default on startup.

E The TCS Display

E.1 General

The display has five screens, arranged as follows:

- Source and telescope information (appears on startup);
- Encoder and transducer readings;
- Limit, computer mode and emergency stop indicators;
- Alarm indicators;
- Manual overrides, dome and mirror cover status, access park interlocks and focal station information.

The first screen is intended for normal operation, the rest for fault-finding. The user-interface command `PAGE` (*q.v.*) is used to cycle through them. The following sub-sections describe the contents of the pages in more detail.

E.2 Source and telescope information

The layout of this, the default screen, is shown in Figure 22. Its contents are as follows:

- Time.
  - ◦ Date
  - ◦ UT—Universal time (UTC) from the time service.
  - ◦ ST—Local apparent sidereal time.

  - MJD—Modified Julian date (*i.e.* Julian date − 2400000.5), in days.

- Input data for the current source.
  - Name.
  - Right ascension.
  - Declination.
  - Equinox—Mean pre-IAU76 (B), post-IAU76 (J) or apparent.
  - Differential tracking rates (blank if not specified).
  - Proper motions and epoch (blank if not specified).
  - Parallax and radial velocity (blank if not specified).

- Apertures and offsets.
  - Positional offset currently enabled (blank if zero). If the `POSITION` command was used, then the offset number (1 – 10) is given in the first field (this is left blank if the `OFFSET` command was used instead). The second two fields give the offset components in the RA and Dec directions, in arcsec.
  - Aperture offset currently enabled (blank if zero). If the `APERTURE` commmand was used, then the first field gives the aperture number (1 – 10); if `BEAMSWITCH` was used instead, then the field is left blank. The next two fields give the x_A and y_A components of the offset, in arcsec.
  - Reference position (alias aperture 0) offset from the rotator centre in x_A and y_A (arcsec).

- Telescope state. The possible messages are:
  - ENG MODE: (the system is in engineering mode.
  - STOPPED: the telescope drives are stopped.
  - MOVING: the telescope is in motion, but has not yet reached its required position.
  - TRACKING: the telescope is within 1 arcsecond of its demanded position during a sidereal track.
  - TV GUIDE: autoguiding on signals provided by the TV system.
  - A/GUIDE: autoguiding on signals provided by the CCD autoguider.
  - S/W LIM (flashing): the demanded position is inaccessible. This will occur when the telescope tracks into a software limit or, on source change, when the new object is below the horizon.

  These messages exclude the instrument rotator which is treated separately below.

- Telescope position.
  - Right ascension or hour angle and declination (displayed only when the telescope is tracking). This is in the coordinate system set by the `DISPLAY` command and indicated by the equinox field (see below).
  - Equinox (usual conventions).
  - Topocentric azimuth (A) and elevation (E).
  - Position errors in azimuth and elevation. Note that the pointing error in azimuth *on the sky* is ΔAcosE, so a relatively large ΔA may be tolerated at high elevation.

  Note that the coordinate system may be changed using the `DISPLAY` command. The available `DISPLAY` options are:

  - `INPUT` (default)—the coordinate system used to input the source data. Any space motions have been removed, so the position refers to the *current* epoch. If proper motions, parallax or radial velocity are specified, then the position will differ from the input position even in the absence of offsets.
  - `B1950`—available for pre-IAU76 mean input coordinates only. Current epoch.
  - `J2000`—available for any mean input coordinates. Current epoch.
  - `APPARENT`—geocentric apparent coordinates of the current date. Always available.
  - `HA_TOPO`—topocentric hour angle and declination. Always available.

- TV / autoguider coordinates
  - If the telescope is being autoguided using a TV camera or CCD autoguider, then the pixel coordinates of the requested position of the guide star are displayed.
- Limit information
  - Elevation limit information (this refers to the *software* limit of 10°). If the object is circumpolar, the message displayed is "No El limit". If it is currently visible above the limit, but will eventually set, the message "Sets in", together with the sidereal time remaining is shown. If the object has set, the message is "Rises in", followed by the sidereal time interval until it becomes visible again. Finally, for objects which are too far South ever to be seen by the WHT, the message is "Never rises".'
  - Other telescope limits. There are two of these, which cannot both occur for the same object. The first is the zenith blind spot, which affects objects with Declinations between 28.55° and 28.97°. If the object will track into the blind spot, the message "Blind spot in", followed by the sidereal time remaining, is displayed. The second is the positive azimuth software limit of 355°. This is rarely encountered, since it affects only objects with Declinations between 70.66° and 85.62° tracked below the Pole. The message is "Az limit in", again followed by the sidereal time interval. The field is left blank if neither limit is relevant.
  - Rotator limits. This applies to the Cassegrain and Prime rotators only (the Nasmyth rotators are allowed to go round continuously). The Cassegrain software mount position angle limits are ±250°; those for Prime are −85° and 273°. Which (if any) rotator limit can be hit is a complicated function of hour angle, Declination and starting position angle. The messages are "+Rotator limit in", "−Rotator limit in" and "No rotator limit", followed by the sidereal time interval in the first two cases. See Section 5.2 for a fuller discussion of limit problems.

- Turntable information.

  - The message STOPPED, MOVING, TRACKING or S/W LIM is displayed, with the same meanings as for the telescope, except that the software limit can only be encountered during tracking, never on source change and the meaning of TRACKING is that the rotator is within 30 arcsec of its demand position (equivalent to 0.1 arcsec in position at the maximum field radius).
  - The focal station currently selected. This means that the software has been configured for that focal station and that the appropriate turntable will be driven. It does *not* refer to the position of the Nasmyth flat. The options are CASSEGRAIN (default), GHRIL and UES, the latter two also indicating DEROTATOR when the turntable is to be driven at a rate appropriate for the derotation optics rather than a directly-mounted instrument.
  - Demand sky position angle (as input using `ROTATOR SKY` and modified subsequently using the handset. Blank if the rotator is not tracking (*e.g.* for a `ROTATOR MOUNT` command).
  - Mount position angle.

Figure 23: The encoder display screen.

  - Mount error, *i.e.* the error in mount position angle (only displayed when the rotator is tracking). Note that an error of 1 arcsecond corresponds to a displacement on the sky of 0.003 arcseconds at a typical maximum field radius of 10 arcminutes.
  - Parallactic angle.

- Miscellaneous.
  - Focus position (mm). This is a virtual focus position which should not depend on temperature, elevation or the presence of filters in the beam. It should, in theory, remain constant for a given focal station.
  - The focus offset, TC (mm) applied to compensate for expansion of the structure.
  - The focus offset, DF (mm) used to correct for additional optical elements (*e.g.* filters) in the beam.
  - Dome azimuth. The label flashes if the dome is out of position. This will occur during a slew and, briefly, during tracking. If the flashing is continuous and the dome is mot moving to the correct azimuth, then there is likely to be a fault in the dome drive (most likely the TEM-L system).
  - Air mass (relative to the zenith).
  - Alarm warning. This indicates that one of the other screens shows an alarm condition.

E.3 Encoder display

The second page displays the encoder readings for altitude, azimuth and all of the instrument rotators, together with relevant displacement transducer values. In addition, the positions of the dome, shutter, windshield, primary mirror cover are shown. The layout is shown in Figure 23. In case of pointing difficulties, it is particularly useful to compare the absolute and (tape or gear) incremental encoders on the same axis. The values displayed are as follows:

- Azimuth (units are degrees:minutes:seconds). The encoder combination used for tracking can be changed using the `ENCODER` and `RATE` commands.
    - Absolute (AZ ABS).
    - Incremental gear (AZ GEAR).
    - Incremental roller (AZ ROLL)—not currently in use.
    - Incremental inductive tape encoder. There are 4 reading heads (AZ TAPE1 – AZ TAPE4).
- Elevation (units are degrees:minutes:seconds).
    - Absolute (EL ABS).
    - Incremental gear (EL GEAR).
    - Incremental roller (EL ROLL)—not currently in use.
- Cassegrain rotator (units are degrees:minutes:seconds).
    - Absolute (CA ABS).
    - Incremental gear (CA INC).
- Prime focus rotator (units are degrees:minutes:seconds).
    - Absolute (PF ABS).
    - Incremental gear (PF INC).
- Nasmyth (UES/Drive side—units are degrees:minutes:seconds). There are two displays, which apply to instruments mounted directly on the rotator `UES ROTATOR` and to stationary instruments looking through the derotation optics `UES DEROTATOR`, respectively. The latter will almost always be the case for UES. The same physical encoders are read in each case, but the scales and zeropoints are different and the `ZEROSET` command only applies to the option currently selected.
    - Absolute (UES ROT ABS); instrument on turntable.
    - Incremental gear (UES ROT INC); instrument on turntable.
    - Absolute (UES DEROT ABS); derotation optics.
    - Incremental gear (UES DEROT INC); derotation optics.
- Nasmyth (GHRIL/cable-wrap side—units are degrees:minutes:seconds) See the notes for the UES rotator immediately above.
    - Absolute (GHRIL ROT ABS); instrument on turntable.
    - Incremental gear (GHRIL ROT INC); instrument on turntable.
    - Absolute (GHRIL DEROT ABS); derotation optics.
    - Incremental gear (GHRIL DEROT INC); derotation optics.
- Secondary mirror position transducers. These are used to measure the tilt of the secondary mirror in its cell. Tracking corrections are applied to compensate for the resulting image motion. The raw readings are displayed as integers in the range ±2047 (±100 μm). The readings are expected to fluctuate by ±5 or so during normal tracking. Wild excursions or unchanging readings indicate problems and should be reported.
    - SECONDARY 1: transducer channel 7 (bottom); expected range ±1200 units (±60 μm); reading -1200 units -60 μm at zenith.

Figure 24: The limits screen.

  - SECONDARY 2: transducer channel 8 (GHRIL side); expected range ±800 units (±40 μm); reading 0 at zenith.
  - SECONDARY 3: transducer channel 9 (UES side); parameters as for SECONDARY 2.
- Horizontal displacement transducers. These are used to correct the azimuth gear encoders for the effects of sideways movements of the telescope. They do not affect the tracking if the tape encoder is used. The raw readings are displayed as integers in the range ±2047. Fluctuations should be around ±5 units when the telescope is stopped. The expected range *in computer mode* is about ±1600 units (±120 μm). The range is limited by the Camac ADC: values close to ±2047 indicate saturation and should be reported. Note that the transducers are normally saturated in engineering mode.
  - HORIZONTAL 1: transducer channel 5.
  - HORIZONTAL 2: transducer channel 6.
- Shutter—not yet functional.
- Lower windshield—not yet functional.
- Dome (units are degrees:minutes).
- Mirror cover position in arbitrary units from 0 (closed) to 100 (fully open).

E.4 Limit page

This page displays the state of the hardware limits and pre-limits for the altitude, azimuth, rotator and focus drives, together with emergency stop, power and engineering/computer mode indicators. The layout is shown in Figure 24.

- Emergency stop. This shows the state of the red emergency stop buttons (ACTUATED or RELEASED). None of the drives will function unless *all* the buttons are out, in which case the display shows RELEASED.
- Telescope power. Should be ON.
- Computer reset button. This is the button on the engineering desk which is pressed to switch from engineering to computer mode. It is ENABLED (lamp on) when switch-over is allowed; DISABLED if not.
- Mode selected. COMPUTER or ENGINEER (duplicated on the top-level display).
- Azimuth limits. These are *hardware* limits and should not be encountered in normal (computer-controlled) operation. The pre-limits are hit first, and cause the system to revert to engineering mode. The telescope can only be driven out of a main limit by hand. The display should show CLEAR for all limits and pre-limits in normal operation and SET (with the message in reverse video) if the limit has been hit. The nominal hardware limit positions are:
    - ◦ LIMIT+ 362°;
    - ◦ PRE-LIMIT+ 360°;
    - ◦ PRE-LIMIT− −180°;
    - ◦ LIMIT− −182°.
- Altitude limits. As for azimuth, except that the final limit refers to the Access Park 3 position, which can only be reached under engineering-mode control from the balcony. The nominal positions are:
    - ◦ LIMIT+ 97°;
    - ◦ PRE-LIMIT+ 95°;
    - ◦ PRE-LIMIT− 6°.5;
    - ◦ LIMIT− 6°.0;
    - ◦ FINAL LIMIT− 0°.75.
- Prime focus turntable limits. There are no pre-limits and no cable wrap limits. If a hardware limit is hit, then the system switches to engineering mode.
    - ◦ LIMIT+ 274°;
    - ◦ LIMIT− −86°.
- Cassegrain turntable limits. There are no pre-limits. If a limit is hit, the drive is turned off and the system switches to engineering mode. The turntable must be driven out of the limit using the + and − buttons on its base. The Cassegrain cable-wrap is driven independently (using a simple hardware servo) and therefore has its own limits (activated if it is more than 1°.75 out of phase with the turntable. If it hits one, then the *turntable* must be driven under engineering control until the cable-wrap limit is cleared.
    - ◦ LIMIT+ 253°;
    - ◦ LIMIT− −254°.
- Nasmyth turntable limits. Not currently implemented—the Nasmyth turntables are allowed to rotate continuously, as they normally carry derotation optics, if anything. The GHRIL-side limits may be used in the future for instruments attached directly to the rotator. *Warning:* the status bits may indicate that both limits are SET if they are disconnected. This should be ignored.

Figure 25: The alarms screen.

- Focus limits. Hitting a limit stops the focus drive, but does not cause a switch to engineering mode.
    - LIMIT+ 129.5 mm;
    - LIMIT− 34.0 mm.

E.5 Alarms page

This page contains alarm indicators for serious faults, principally in the hydraulic support system, mirror support and power supply. All except the control room temperature and dome emergency stop alarms have counterparts on the alarm panel of the engineering desk (red light + audible alarm). The layout is shown in Figure 25.

- Hydraulic and lubrication system.
    - Oil pad alarm. Indicates high or low pressure at one of the hydraulic support pads. Check the engineering desk to ascertain which pad(s) are involved. Warning only—does not cause switch to engineering mode. Normal state CLEAR, alarm state SET.
    - Gearbox oil alarm. Indicates incorrect oil pressure in the gear-boxes. Warning only. Normal state CLEAR, alarm state SET.
    - Oil pump alarm. Normal state CLEAR, alarm state SET.
    - Altitude and azimuth oil filter alarms. Normal state CLEAR, alarm state SET.
    - Oil temperature. Should read NORMAL, alarm state HIGH.
    - Oil pressure. Should read NORMAL, alarm state HIGH.
- Power.

    - Mains alarm. Normal state CLEAR, alarm state SET.
    - Power amplifier. Normal state WORKING, alarm state FAULTY.

- Primary mirror support.
    - Nitrogen pressure. Normal state NORMAL, alarm state LOW. A failure here generally means that the nitrogen supply has run out.
    - Load cell alarm. Indicates that the forces on the radial or axial load cells which control the position of the mirror are excessive. Normal state CLEAR.
    - Mirror height. Normal state NORMAL.

- Weather alarms (none connected: ignore).
    - Wind speed. Normal state CLEAR.
    - Ice. Normal state CLEAR.
    - Rain. Normal state CLEAR.
    - Dust. Normal state CLEAR.

- Control room temperature alarm. This is used to detect a failure of the air-conditioning system and to turn off the power supply to the computers if the control room overheats. Normal state CLEAR; alarm state SET.
- Nasmyth gate alarm. This is triggered if one of the Nasmyth access gates on the balcony is open, but there is no Nasmyth platform next to it. It causes a switch to engineering mode. Normal state NOT OPEN.
- Dome emergency stop. Normal state CLEAR.

E.6 Dome status and manual overrides page

This page contains the engineering override indicators for individual mechanisms and the status bits concerning dome and shutters. The layout is shown in Figure 26.

- Engineering overrides. These cause computer control for individual mechanisms to be disabled and are controlled by latching buttons on the engineering desk. Overrides are on when the buttons are latched down. The yellow lamps will be lit when the mechanisms concerned are under engineering control, either because the system as a whole is in engineering mode or as a result of overrides. The display shows ENGINEER when the mechanism is overridden; COMPUTER otherwise. Mechanisms which may be overridden and their states in normal (computer-controlled) operation are:
    - Dome (normally COMPUTER);
    - Focus (normally COMPUTER; note that the focus drive does not work under override);
    - Shutters (normally ENGINEER);
    - Mirror cover (normally ENGINEER).

- Control locations. These show the state of the remote/local/off keyswitches on the gallery control panel. REMOTE means that the mechanism can be driven from the control room; LOCAL that it must be driven from the balcony panels.
    - Dome (normally REMOTE);
    - Shutter (normally LOCAL);
    - Windshield (normally LOCAL).

Figure 26: Dome status and manual overrides screen.

- Power. Normally ON; alarm state OFF.
  - Dome;
  - Shutter;
  - Windshield.
- Overtravel alarms. Normally CLEAR; alarm state SET.
  - Shutter;
  - Windshield.
- Torque trip alarms. Shut down the drive until reset on the gallery control panel. Normally CLEAR; alarm state TRIPPED.
  - Shutter;
  - Windshield.
- Windshield parked indicator: PARKED or NOT PARKED.
- Shutter and windshield OPEN/CLOSED.
- Platform pin. If IN, this disables dome rotation. Normally OUT.
- Dome interlock. Normally DISABLED; alarm state ENABLED.
- Focal station in use (displays SELECTED).
  - Cassegrain (secondary mirror on; Nasmyth flat stowed).
  - Prime (prime focus unit on).
  - GHRIL Nasmyth focus (secondary mirror on; Nasmyth flat in GHRIL position).

  - UES Nasmyth focus (secondary mirror on; Nasmyth flat in UES position).
  - Folded Cassegrain (secondary mirror on; Nasmyth flat in folded Cassegrain position; not yet in use).

- Primary mirror cover.

  - CLOSED/NOT CLOSED. Reads CLOSED when the cover is *fully* shut; NOT CLOSED otherwise.
  - OPEN/NOT OPEN. Reads OPEN when the cover is *fully* open; NOT OPEN otherwise.

- Nasmyth flat. STOWED is the appropriate position for Cassegrain and prime foci; NOT STOWED for Nasmyth and folded Cassegrain. The flat should always be STOWED when not in use.
- Secondary mirror cover. Always OFF, since the cover is only used when the mirror is not on the telescope.
- Azimuth zone. This gives the position of the switch that is read on startup to resolve the ambiguity in the azimuth absolute encoder. RED $\Rightarrow -180^\circ <$ azimuth $< +120^\circ$ and YELLOW $\Rightarrow +120^\circ <$ azimuth $< +360^\circ$, approximately.
- Access/zenith park ties. These are inserted to stop the telescope moving when it is out of balance (*e.g.* when the mirror cell has been removed or during an end change) and force engineering mode. Normal state OUT; alarm state IN.
- Revolving floor latch. This stops the telescope moving in azimuth when it is at the correct position for the mirror to be removed (*i.e.* with the fixed and moving parts of the mirror trolley rails lined up). Normal state CLEAR; alarm state SET.
- AP 3 access barrier. This stops the telescope being driven in azimuth when the barrier is removed to give access to the top-end ring. Normal state STOWED; alarm state DEPLOYED.