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Alignment, pointing accuracy and field rotation of the UK 1.2-m Schmidt telescope

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Summary. An analysis of the alignment and pointing accuracy of the UK 1.2-m Schmidt telescope has resulted in a remarkably accurate determination of the parameters involved. The resulting improvement in the pointing has greatly increased the efficiency of guide star acquisition. The telescope polar axis elevation angle is adjusted for every photograph in order to minimize field rotation due to atmospheric refraction. A method of determining the optimum setting is described.

1 Introduction

The UK Schmidt telescope (UKST) on Siding Spring Mountain is a 1.2-m aperture *f*/2.5 classical Schmidt. The mirror diameter is 1.8 m, and the 356-mm square plates accommodate a 6½ × 6½ degree field. The equatorial mounting is a symmetrical fork. Automatic guiding is carried out using either of two 250-mm *f*/15 refracting telescopes whose tubes are mounted parallel to the main telescope. Each autoguider head is mounted on cross slides, by means of which guide stars up to 25 arcmin in any direction from the centre of the field being photographed may be acquired. In this paper we describe experiments concerned with the pointing accuracy of the telescope and also with the problem of field rotation.

2 Pointing

While highly accurate pointing in a telescope covering a 6½ degree field might appear to be merely a luxury it is found in practice that considerable savings in time can be achieved if guide stars – whose positions are accurately known – can be set close to the autoguider's reference point before acquisition begins. Even in a perfect telescope there will, in general, be a discrepancy between the known catalogue position of a star and the instrumental coordinates with that star on axis. The discrepancy may be reduced in either of two ways: (a) the instrumental position can be corrected before display, or (b) the catalogue position can be de-corrected before setting the telescope. Method (a) is preferable; however, the simple electromechanical dial readouts of the UKST readily permit only method (b).

The transformation from a catalogue position to instrumental coordinates can be considered in two stages, the first well understood and accurately predictable but the second less so. The first stage takes from (let us say) mean right ascension (α) and declination (δ) referred to some epoch, equator and equinox to geocentric apparent α and δ for the epoch of observation. The effects allowed for are proper motion, precession, nutation and aberration. The second stage begins with allowance for Earth rotation (adequately predictable), diurnal aberration (negligible for our purposes), atmospheric refraction (adequately predictable, especially if temperature and pressure are available) and finally instrumental defects (which in all practical cases limit the possible pointing accuracy).

We investigated the potential pointing accuracy of the UKST by making observations of stars listed in the SAO catalogue. A sequence of stars spaced about 20 degrees apart in α and δ was observed. The stars were acquired one by one using the autoguider and for each the instrumental α, δ was read from the console dials (rather coarsely graduated in units of 1 s and 0.1 arcmin but readable to perhaps 0.2 s and 3 arcsec), and the local sidereal time was noted. The ambient air temperature and pressure inside the dome were monitored. The results were analysed by means of computed programs, developed for and used successfully on the 3.9-m Anglo-Australian telescope. The discrepancies between the calculated topocentric apparent places of the stars (that is, the geocentric apparent places corrected for refraction) and the dial readings were determined and fitted to a mathematical model which contained expressions describing a variety of anticipated telescope defects. We found that apart from the purely geometrical errors that are, in general, present in any conventional telescope, the only mechanical defect that was obvious was flexure in the fork mounting.

The adopted model has only seven coefficients, all angles:

ME, MA non-parallelism between the polar axis and the Earth's axis: ME is the component in elevation and MA is the component at right angles to ME;

NP non-perpendicularity between the δ axis and the polar axis;

CH collimation error east–west: non-perpendicularity between the δ axis and the nominated optical axis (i.e. the autoguider);

FO fork flexure (using a simple model, described later);

ID δ index error (i.e. zero-point error; note that this is indistinguishable from, and therefore includes, collimation error north–south);

IH hour angle (h) index error (i.e. zero-point error; note that this is indistinguishable from clock error, which is supposed to be zero).

The forms of these errors, expressed in spherical coordinates, are given below:

Effect	Δh	$\Delta \delta$
ME	ME $\sin h \tan \delta$	ME $\cos h$
MA	$-$MA $\cos h \tan \delta$	MA $\sin h$
NP	NP $\tan \delta$	
CH	CH $\sec \delta$	
FO		FO $\cos h$
ID		ID
IH	IH	

The preliminary pointing test, which used 21 stars, gave an rms error of 5.7 arcsec ('error' means $\sqrt{(\Delta h \cos \delta)^2 + \Delta\delta^2}$). The values of the seven coefficients and their errors are given in Table 1.

Table 1. The seven coefficients of the UKST pointing model and their errors ($\pm 2\sigma$) in arcsec.

	Before azimuth correction	After azimuth correction
ME	$+58 \pm 5$	$+19 \pm 4$
MA	-19 ± 4	-0 ± 3
NP	-8 ± 14	-9 ± 9
CH	-46 ± 19	-57 ± 12
FO	-60 ± 11	-56 ± 10
ID	-66 ± 7	-69 ± 8
IH	$+87 \pm 17$	$+83 \pm 11$

As the 19 arcsec polar axis 'azimuth' error might be expected to produce field rotation effects, an attempt was made to correct it mechanically by rotating the mounting baseframe 22 arcsec (i.e. MA sec ϕ, $\phi = -31^\circ 16'$) in a horizontal plane, and a second sequence of pointing observations was carried out. A sample of 29 stars yielded an rms error of 4.9 arcsec, and the coefficients given in Table 1. Note that the polar axis azimuth adjustment had been reflected by a very satisfactory reduction in the MA coefficient. All other coefficients had remained essentially unchanged except that for the polar axis elevation, ME. The elevation had in fact been altered as a consequence of routine adjustments made to minimize field rotation effects at different declinations (see Section 3).

Non-perpendicularity NP is small and relatively innocuous. Fork flexure FO is not readily adjustable. The two index errors IH and ID can easily be eliminated by moving the dial zero points. The collimation error CH was adjusted by moving the guide telescope cross slide zero-point east–west; a subsequent pointing test confirmed that the adjustment had produced the desired effect.

What these tests demonstrated was that a simple model of the telescope defects might be set up that would relate a topocentric apparent place to the dial readings to an accuracy of a few arcseconds. Moreover, this level of setting accuracy is more than enough to promise a very worthwhile reduction in the time taken to acquire a guide star. The UKST has no on-line computer and so an HP-67 pocket calculator was programmed to perform the conversion all the way from 1950 mean place to dial settings. The observer merely has to enter the mean place of the star (corrected for proper motion if significant) and the approximate sidereal time; the calculator then corrects for precession, nutation, aberration, refraction, polar axis misalignment, non-perpendicularity and fork flexure, finally supplying the observer with the required dial α, δ. When the telescope is set to the requested position the star is located not only within the autoguider's acquisition aperture (diameter 2 arcmin) but normally within the guiding aperture itself (diameter 12 arcsec).

Although only the mean place and sidereal time need be entered for each new star, it is of course necessary to supply the calculator with additional information, namely the epoch of observation and the polar axis elevation setting, ME. Both of these have to be entered at the beginning of the night, but thereafter only ME need be entered, and then only if it has been changed.

Because the program neglects CH, ID and IH, it is necessary to remove them mechanically. These corrections change very little from night to night, and the only nightly calibration procedure – carried out during twilight – is to eliminate IH and ID by suitable adjustments to the dial pointers following acquisition of a reference star. Pointing test sequences are carried out every six months or so to keep a check on CH and the other coefficients so that any misalignments that appear can be corrected. Possible settling of the base of the telescope is monitored using an accurate level.

3 Field rotation

The differential effect of atmospheric refraction is to compress the scale in the direction of the vertical. Across a 6 degree field, differential refraction is very significant, for example amounting to about 11 arcsec at zenith distance 45°. Even at the zenith the compression is considerable – about 5 arcsec – and is innocuous only because it is equal in all directions. The scale compression produced by differential refraction is not in itself serious; however, during a time exposure both the amount of compression and its direction vary – the first with zenith distance and the second with parallactic angle. As a result, assuming the guider keeps the telescope accurately tracking a star near the centre of the field, the effect of differential refraction on the photograph is to introduce apparently trailed images which are progressively worse the further they are from the centre. The excellent optical performance of the UKST (images of 1 arcsec throughout the optical spectrum) means that the trailing is easily detected, and must if possible be minimized.

The compression is, of course, inherent in the telescope's view of the sky, and cannot be removed by any mechanical adjustment. However, it turns out that over most of the sky the effect has a pronounced rotation component and can be much reduced if a compensating plate rotation can be introduced. Hinks (1898) points out that such a counter-rotation can be produced by adjustments to the polar axis alignment, and we have investigated this technique and evaluated Hink's formulae.

The technique is not widely used since most telescopes are not equipped with provision for easy and frequent re-adjustment of the polar axis. However, because of the Schmidt's wide field, arrangements for adjusting the elevation of the polar axis were provided as part of the original design. In fact, the problem of field rotation is so important that a motorized system has now been installed further to facilitate the adjustment, which has now become a routine operation carried out for each photograph. The determination of the optimum setting as a function of declination has been approached as follows.

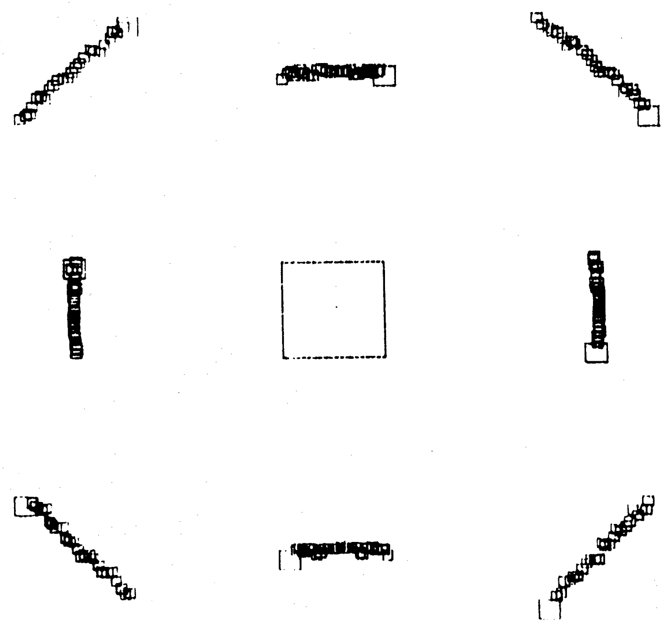
A series of test photographs was taken to measure the effect by recording the positions of images at the start, middle and end of a 1-hr exposure about the meridian. Such photographs are rather difficult to obtain, since they require a large amount of telescope time in good seeing at a range of polar axis settings and declinations. A comprehensive programme of tests would be laborious and time consuming. A computer program was therefore written to simulate the star trails and display them on a graphics CRT.

The program, which was developed and run on the computers of the Anglo-Australian Observatory, simulates (for the latitude and elevation of the UKST) an exposure centred on the meridian. For each simulation, the operator is asked for the following parameters:

(1) declination,
(2) polar axis elevation ME (above unrefracted pole),
(3) a plotting scale factor,
(4) star spacing,
(5) exposure time.

All input is in free-format and has convenient default conventions, enabling many combinations of parameters to be tried in a short time. The simulated starfield consists of eight stars lying at the corners and in the middles of the sides of a square. The star spacing parameter permits the field size to be varied at will, but was set to 3 degrees when simulating the UKST. The exposure time was standardized at 60 min.

For each set of parameters, the program produces a plot on a graphics display screen showing the positions of the eight stars at 25 times during the exposure. Figs 1–3 are photographs of such plots. The patterns are similar to those derived by Bowen (1967) and Argue (private communication). The pattern for each star is so positioned on the screen that at the midpoint of the exposure the eight 'images' fall on the corners and on the middles of the sides of a square, imaging the test pattern itself. The plotting scale, which the operator can vary, is indicated by a 1 arcsec reference square in the middle of the plot. Varying the scale simply varies the trail lengths for optimum visibility and does not affect the overall positioning of the pattern for each star.



Figures 1–3. The combined effects of differential refraction and polar axis elevation setting are shown in these reproductions of the graphical output of the computer simulation described in the text. The trails – whose scale is indicated by the 1 arcsec square in the middle of each plot – are computed for eight stars outlining a 6° × 6° field. Each simulation is of a 1-hr exposure centred on the meridian, for the latitude and elevation of the UK Schmidt telescope. North is at the top, and east to the left. The slight irregularities in the trails are due to the limited computing precision employed.

Figure 1. The simulation of an exposure at $\delta = -31°$, with the telescope passing through the zenith. The polar axis has been set to the refracted pole (ME = 84 arcsec) resulting in trails of 1.4 arcsec.

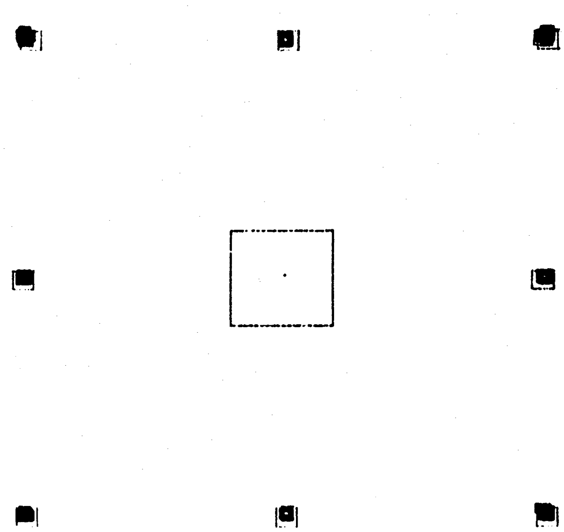


Figure 2. As for Fig. 1 except that ME has been set to + 23 arcsec in accordance with formula (1). The trails have been reduced to less than 0.1 arcsec.

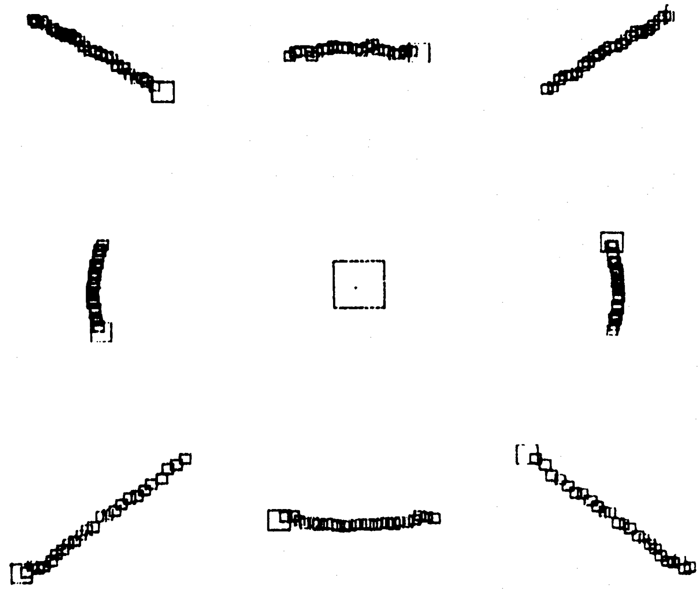


Figure 3. The simulation of an exposure at $\delta = +30°$ (culminating at a zenith distance of 61°) and for ME $= -20$ arcsec. Trails of up to 4 arcsec, in disparate directions, occur. In this case differential refraction cannot be well compensated simply by introducing a field rotation.

The simulation assumes atmospheric refraction and polar axis elevation error only. No other pointing effects are allowed for, and in the case of the UKST are not thought to affect the problem significantly. For each point in the exposure, and for each star, the geocentric apparent h, δ is expressed as a unit vector in Cartesian coordinates, then transformed to alt-az (by rotating through $90° + \phi$), corrected for refraction (using an $A \tan z + B \tan^3 z$ law) and finally rotated into instrumental h, δ (by rotating through $90° + \phi - \text{ME}$). This position is then projected on to the tangent plane, yielding an x, y which is appropriately scaled and zeroed for plotting.

(We should point out that the refraction law as normally stated transforms a refracted position into an unrefracted position, whereas we wish to carry out the inverse transformation. To do this we simply use an empirically adjusted value for the B coefficient, which gives very accurate results over the whole of the UKST's sky. The values used in the simulation, corresponding to temperature 10°C and pressure 670 mm Hg, were (in arcsec) $A = 51.26, B = -0.076$. The values for STP are 60.36 and -0.090.)

At a chosen value of δ, a range of polar elevations was tried out to locate the value which gave the minimum overall trail length. No numerical criterion was applied nor were different distributions of stars available; judgment was entirely by eye and the simulation was restricted to the eight star square. The optimum ME value for each δ was tabulated for a range of declinations. The result was compared with a series of actual test photographs in order to (a) confirm the validity of the simulation and (b) obtain the zero-point of the mechanical polar axis elevation scale. The agreement between simulation and experiment was excellent (see Fig. 4). The optimum ME value determined from the simulation as a function of δ is now used for the routine setting of the UKST polar axis on all exposures.

The form of the empirically determined function ME(δ) is well represented by the expression:

$$\text{ME} = \pm \arcsin \left\{ (n-1) \frac{\cos \phi \sin \delta}{\cos (\phi - \delta)} \right\} \quad (1)$$

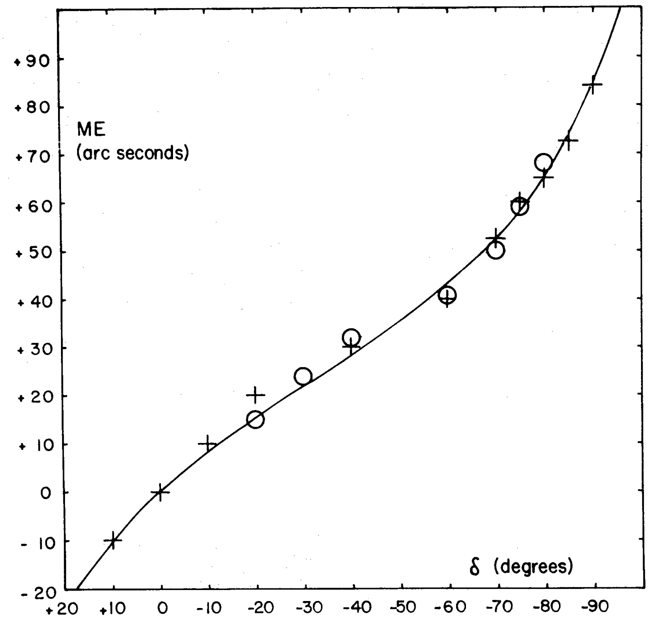


Figure 4. ME is plotted as a function of δ. Crosses represent values obtained from the computer simulation. Circles represent mean values of the results obtained from test photographs; these have been shifted vertically onto the curve by a constant which corresponds to the zero-point of the polar axis elevation scale. The solid curve is plotted from formula (1), assuming a latitude of $-31° 16'$ and a refractive index of 1.00025.

(where the plus sign is taken for a telescope in the northern hemisphere and the minus in the southern). ϕ is the latitude of the observatory and n the refractive index of the air near the telescope. A derivation of this formula is given in the Appendix. Ideally the value of n used should be appropriate to the waveband of observation and the temperature and pressure at the time of observation. For most declinations, only extreme variations of these conditions warrant any correction from a mean value; however, these effects need to be allowed for near the celestial pole.

For exposures not centred on the meridian, a polar axis adjustment in azimuth could further improve the rotation correction. In the extremely unusual case of an exposure centred on hour angle 6^h, a pure azimuth adjustment would be required. Also, continuous adjustments in both elevation and azimuth could in principle eliminate any rotation, as of course could a computer-controlled plate rotator. However, such complications are not worthwhile since the non-rotation component of the distortion (a shear) is not eliminable and in all practical cases is the dominant effect once most of the rotation has been removed by offsetting the polar axis in elevation. For exposures centred on the meridian and of normal duration the combination of a non-rotating plateholder and a polar axis adjustable only in elevation is quite adequate.

Acknowledgment

Computer-generated star trails resembling our Figs 1–3 had been derived by Mr A. N. Argue, Cambridge University Observatories, as part of a design study for the Anglo-Australian Telescope in 1968. Argue had also derived values for the elevation of the polar axis required to counteract the field rotation effects of atmospheric refraction, and our values from Fig. 4 have been found to agree within a few arcseconds.

References

Bowen, I. S., 1967. *Q. Jl R. astr. Soc.*, **8**, 9.
Hinks, A. R., 1898. *Mon. Not. R. astr. Soc.*, **58**, 428.

Appendix: derivation of formula (1)

Hinks gives two formulae, one for the rotation of the field due to the displacement of the polar axis, and one for the rotation of the field due to atmospheric refraction. These are, respectively, in radians per hour:

$$\frac{\sin e \cos (h - H)}{\sin p} \quad (\text{for } \sin p \neq 0)$$

and

$$\frac{n-1}{\tan P}\left\{(\sin P - Y \cos P) \sec^2 h - \cos P \tan h \frac{dY}{dh}\right\}.$$

In these formulae it is assumed that the instrumental pole is elevated an angle e above the true pole in the direction of hour angle H. The quantities p and P are respectively the instrumental polar distance and the true polar distance of the field (in practice $p = P = 90° - \delta$ or $90° + \delta$, according to the hemisphere of the telescope, very closely). Y is defined as follows:

$$Y = \frac{\cot \delta - \cot \phi \cos h}{1 + \cot \delta \cot \phi \cos h}.$$

We simplify these general equations by taking $p = P = 90° - \delta$, $H = 0$ (no offset in azimuth) and $h = 0$ (telescope on the meridian). In this case e is our quantitiy ME. Equating the two rates of rotation gives formula (1) after some simplification.