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Pointing of the INT and JKT

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Summary

The results of pointing tests carried out on the INT and JKT between September 1984 and July 1985 are discussed. It is concluded that the pointing of the INT is adequate rms = 4 arcsec, provided that tests are carried out fairly frequently. The variations in some of the model coefficients (notably the elevation of the polar axis) give cause for concern, however. Some ideas for improving the pointing and tracking of the telescope are outlined.

The pointing of the JKT is currently unsatisfactory (rms = 20 arcsec, with significant hysteresis) and the results of successive tests are radically different. The pointing models for observations East and West of the pier are not mutually consistent. It is thought that most of the problems result from the primary mirror support.

Measurement and analysis

This note summarizes the results of pointing tests carried out on the INT and JKT between 1984 September and 1985 July. During a pointing test, a set of stars with accurately known positions is observed, noting the readings of the HA and DEC encoders (together with the LST) when each star is aligned with some reference mark. After removing known effects (i.e. precession, nutation and aberration if the input is in mean coordinate and refraction), the differences between the telescope's actual and expected positions are fit to a parametrized model.

In the tests reported here, 50-100 stars were observed, distributed fairly uniformly over the whole area accessible to the telescope. These were usually selected from a standard grid (PTGRID.CAT on the 8/16E's). In no case did inaccuracies in the stellar positions affect the results of the tests.

A TV camera was used as the detector in all cases and stars were centred by eye on a reference point (usually the cross-hairs of the Grinnell image display). In principle, the reference point should be the axis of the appropriate image rotator and, indeed, the software which controls aperture offsets (i.e. movements in the coordinate system of an instrument) implicitly assumes that this condition holds. The rotation axis is expected to be aligned with the optical axis of the telescope: it is one of the purposes of the pointing test to determine any misalignment. In practice, the Cassegrain rotator axis was used as a reference for the INT from 1985 April onwards. At that time, the software "centre" positions for TV and Guider probes were adjusted so that a star on the Grinnell cross-hairs did not move when the turntable was rotated. This alignment is not possible at the Prime Focus of the INT, because the TV Camera (which is in any case not part of the normal instrumentation) is not movable and the Guider probe cannot be moved onto the axis without colliding with the corrector. Pointing tests at Prime Focus will therefore have to be performed with a known offset between probe and rotator axis. The reference position for JKT observations has so far been arbitrary. The choice of reference position only affects the collimation errors in HA and DEC and makes no difference to other geometrical and flexure terms.

The name of the star, the coordinates derived directly from the encoder readings and the sidereal time for each observation were logged using the program POINT on the telescope control computer. This creates a file in a format suitable for analysis by P T Wallace's POINT software on the VAX 11/780 at Herstmonceux and, from 1985 October, the PE 3220's on La Palma, An additional file, STARS.DAT, contains the stellar positions and proper motions. The art of modelling and the least squares fit algorithm are described in detail by Wallace (1979). The model consists of a group of terms describing the geometrical errors of the telescope (encoder index errors, collimation error in HA, non-perpendicularity of HA and DEC axes and misalignment of the polar axis in azimuth and elevation), together with a set of empirical terms (polynomial and Fourier series) which describe flexure of telescope and mount.

Results from the INT

The model

After some experimentation by P.T. Wallace and the author, the 17-component model given in Table 1 has been adopted for the INT. The coefficients for the 9 pointing tests carried out so far are given in Table 2,, along with their errors (derived from the least-squares fit). The scaling is such that the errors Δh, $\Delta\delta$ and Δz in Table 1 are in arcsec if h, δ and z are in radians. The rms scatter in the data is typically 3-5 arcsec, which is acceptable.

Expected changes

Several of the coefficients in Table 2 are expected to change with time as follows:

Index errors (IH, ID). The positions of the zeroset markers for the Ferranti encoders have been altered at least twice (between tests 2-3 and 4-5). The only change in IH which is not currently understood is that between tests 7-8.

Collimation errors (CH, ID again). Changes in the collimation are expected whenever: the top end is switched; optics are realigned,; components are moved in the relevant A&G assembly or the reference marker is altered. Consequently, no attention will be paid to the stability of ID and CH until conditions are stable between successive tests.

Polar axis alignment (ME, MA). Deliberate changes were made to the polar axis elevation between tests 1-2 (elevation) and 2-3 (both). The values measured using a theodolite are consistent with those derived from the least-squares fit.

Tube flexure (TF) is expected to change with the mass on the top end. In particular, the value should be larger for the Prime-focus top end with its cable wrap (test 8), as observed,

More generally, test 1 used only 1 pair of Ferranti encoders whereas the remainder all used 3 pairs. No obvious effects were seen. The other major change - the removal and replacement of the mirror cell and adjustment of the primary support - occurred between tests 4 and 5. Observed effects were again slight.

Analysis of changes.

Changes with time have been monitored quantitatively for all terms except IR, ID and CH. For the reasons noted above, ME and MA are considered for tests 3-9 and TF for the Cassegrain focus only.

The results of calculating weighted mean coefficients and testing for constancy using the χ^2 statistic are given in Table 3. Variations in D2HS, D2HC, D4HC, PDO1 and PD40 (i.e. the declination flexure terms) are not particularly significant (> 10% level). There is one discrepant value of NP (test 9) and variations in tube flexure (TF) are significant at the 7% level, with no obvious systematic effects. The serious discrepancies occur in the HA flexure terms (PH10, PH30, PX20, PX30 - although PX50 shows no major variations) and the polar axis position.

The most worrying case is that of the polar axis elevation error, ME, which is the only term to show a steady drift (Figure 1). In order to minimize field rotation (Wallace and Tritton 1979), ME should be set at ≈ -60 arcsec. The recent large variations (tests 7-8-9) may result from settling after excavation of the new garage. Whatever the cause, it is essential to monitor the value of ME and to check for movement of the pier.

The changes in the HA flexure terms may result from: modifications to the servo preamplifier; consequent retuning of the software position loop; alterations in the anti-backlash current; changes in the hydraulics (e.g. oil viscosity) or balance problems. A detailed analysis in collaboration with the technical group on La Palma is needed.

Questions and suggestion

The movement of the polar axis is worryingly quick. Is this due to settling? Can it be halted?

What causes the random variations in HA flexure terms? Can mechanical and electronic conditions be kept sufficiently stable to stop them changing?

An additional source of error when the Baldwin encoders are used (generally the case at least in RA) is the periodic error introduced by the slow-motion gearing. Its most important manifestation is as a wobble with a period of 1 minute during tracking. It should be possible to eliminate this effect by logging the open-loop autoguider errors during tracking (using the once/revolution marker pulse as a reference), fitting a suitable function and subtracting this from the Baldwin encoder readings. Data were taken for this purpose on 1985 September 13 and analysis is in progress. Calibration in DEC is more difficult as continuous tracking is not possible.

It is clear from logging the individual Ferranti encoder readings that their large-scale errors may be as big as ~ 10 arcsec (e.g. at a tape join). At present, the mean value for the 3 reading heads is used. A more intelligent approach would be to determine corrections to individual encoders by logging their values during a pointing test and solving simultaneously for overall telescope errors and encoder inaccuracies. It would be worth logging the difference between the encoders so as to identify bad pieces of tape.

Is it worth evaluating both index and collimation errors at the beginning of a night's observing? Which is more important?

Results for the JKT

The model

The 13-component model in use at present is given in Table 4. The results of tests made with the Telescope East of the pier are given in Table 5 and a comparison of tests made on the same night both East and West of the pier is in Table 6. Note that test E4 (Table 5) was done during normal observing, so the sky coverage is poor and the weighting eccentric.

Typical rms errors are ≈ 20 arcsec (the value of 12 arcsec for test E4 cannot be taken seriously. It is clear, however,, that there is significant hysteresis, as measurements are not repeatable, especially on returning to a star after a long slew. Part of this effect may be caused by the acquisition mirror shifting.

Expected changes

Index errors (IH, ID)
The HA index error was expected to change by +5096 arcsec between tests El-E2, since a hard-coded correction of that magnitude was removed from the control software. The Declination zeroset marker was moved at the same time (from the Pole to close to the zenith) , so the large change is understandable.

Analysis of changes

CH and NP
In order to look at the variation of these terms, test E4 was fit using the coefficients derived from test E3, allowing only IH, ID, CH and NP to float (Table 7): this should avoid any problems with poor sky coverage. Both terms have changed drastically between tests E3 - E4; the value of the collimation error is in any case extremely large for a supposedly aligned optical assembly (c.f. Table 2).

PD01 and PH10
There was an enormous change in both terms between tests El and E2. PD01 thereafter stayed fairly constant, but PH10 increased again between tests E3 and E4. The effect of an incorrect value of PH10 is a constant drift in HA; in the present case this would correspond to 0.0154 arcsec/sec if the value from test El was used when that for E2 was
appropriate. This problem was one of the causes of the tracking drift observed on the JKT between 1985 February and May. The relation between this effect and the other contributing factor - encoder miscounting - is
obscure. As the encoders only miscounted when the telescope was close to tracking speed, the error occurred in HA only and was cumulative. Consequently, its apparent correlation with HA depended on the order of measurements during a pointing test and it may or may not have had a significant effect on test El.

It is unknown why PD01 and PH10 are so variable, but it is suspicious that the biggest change coincided with work on the drive amplifiers. At that time, anti-backlash torque was re-introduced, and this is the most obvious physical change to the system. Further investigation (e.g. by varying the anti-backlash current in a controlled way between pointing tests) is essential.

Remaining flexure terms (PD20, PH30, PX20, PX22, PX50)
Test E4 gave extremely uncertain values for these terms and was ignored. Changes in PX20 and PX22 are not significant; PH20 and PD20 altered slightly and PX50 varied significantly between tests El and E2 (Table 8).

Polar axis (MA, ME)
No significant changes were observed. The elevation error (–132 arcsec) needs to be reduced to ~ –60 arcsec to minimize field rotation for long-exposure photography.

Comparison of results with telescope E and W of the pier

Table 7 summaries the results of 2 tests, carried out sequentially with no readjustment of the encoders between them. The coefficients behave qualitatively as expected, but there are large quantitative discrepancies. The last column of Table 7 shows whether the coefficient is expected to change sign on opposite sides of the pier.

The following coefficients are consistent ($<2\sigma$ different) from W to E: MA, ME, PD01, PH10, PH30, PX20, PX22, PD20 and PX50. There are serious discrepancies for the index errors, IH and ID, the HA collimation error, CH, and the axis non-perpendicularity, NP.

Questions and suggestions

All bets are off until the primary mirror support is fixed: this certainly contributes to the hysteresis and may be the dominant "flexure" effect. When the new support system is installed, the following questions need to be answered:

Is the collimation error in HA still large? If so, are the optics aligned correctly? Is the TV camera on-axis? Is the axis of the Cassegrain turntable aligned with the optical axis?

Are the two dominant "flexure" modes ($\Delta h \propto h$, $\Delta\delta \propto \delta$) still present? Do they depend on drive characteristics (especially anti-backlash torque?) Do they vary?

Why does the HA/DEC non-perpendicularity change with time?

Why do IH, ID, NP and CH not transform correctly when changing from E to W of the pier?

The polar-axis elevation should be changed to ~ –60 arcsec.

Conclusions and actions

The pointing of the INT is adequate, although some of the model coefficients are not stable. Further progress is possible by correcting for encoder errors.

Very little can be done to improve the pointing of the JKT until the primary support system is fixed. There are several severe errors which, if they persist, require intensive investigation.

Actions

(INT) : Investigate polar axis movement
Calibrate worm error
Investigate Ferranti encoder errors
Test effect of altering anti-backlash torque

(JKT): After new mirror support is installed:
Test for hysteresis and reproducible pointing
Repeat pointing tests on both sides of the pier and proceed according to the results

References

Wallace, P.T. (1979) AAO Preprint (unpublished)

Wallace, P.T. & Tritton, K.P. (1979) MNRAS 189, 115

The pointing model for the INT

Table 1a Geometrical terms

IH	Index error in hour angle	$\Delta h = IH$
ID	Index error in Declination[1]	$\Delta\delta = ID$
CH	Collimation error in HA	$\Delta h = CH/\cos\delta$
NP	HA/Dec axis non-perpendicularity	$\Delta h = NP \tan\delta$
ME	Polar axis elevation error[2]	$\Delta h = ME \sin h \tan\delta$
		$\Delta\delta = ME \cos h$
MA	Polar axis azimuth error	$\Delta h = -MA \cos h \tan\delta$
		$\Delta\delta = MA \sin h$

[1] Collimation and index errors have the same form in Declination.

[2] Note that a negative value of ME corresponds to a polar axis above the true pole.

Tabel 1b Flexure terms

	TF	Hooke's law tube flexure	$\Delta z = TF \sin z$
Fourier terms	D2HS		$\Delta\delta = D2HS \sin 2h$
	D2HC		$\Delta\delta = D2HC \cos 2h$
	D4HC		$\Delta\delta = D4HC \cos 4h$
Polynomial terms	PD01		$\Delta\delta = PD01\ \delta$
	PD40		$\Delta\delta = PD40\ h^4$
	PH10		$\Delta h = PH10\ h$
	PH30		$\Delta h = PH30\ h^3$
	PX20		$\Delta h = PX20\ h^2 /\cos\delta$
	PX30		$\Delta h = PX30\ h^3 /\cos\delta$
	PX50		$\Delta h = PX50\ h^5 /\cos\delta$

h, δ and z are hour angle, Declination and zenith distance; Δh, $\Delta\delta$ and Δz are the errors on these quantities.

Table 2 Summary of coefficients (INT)

Coefficient	840928 CASS	841017 CASS	841115 CASS	850129 CASS	850417 CASS	850422 PRIME	850506 CASS	850702 PRIME	850730 CASS
IH	-312.9	-304.9	-274.8	-281.5	-270.3	-275.9	-274.6	-294.2	-298.4
±	3.1	3.3	2.7	l.7	2.2	2.5	3.1	3.1	2.9
ID	-561.2	597.3	-643.3	-645.9	-661.1	-515.0	-646.0	-701.7	-640.8
±	5.7	6.7	4.9	2.6	4.5	4.4	4.8	4.6	6.5
CH	-57.5	-62.1	-l.4	+21.2	+18.3	+3.l	-7.5	-29.9	+24.9
±	3.0	3.3	2.6	1.7	2.3	2.5	3.0	3.0	3.0
NP	-7.4	-9.0	-6.0	-10.9	-9.8	-7.7	-7.5	-6.6	-21.l
±	2.7	4.4	2.4	l.3	2.4	2.3	2.4	2.5	3.2
D2HS	+10.3	+14.4	+15.9	+11.4	+12.8	+11.0	+l3.7	+14.2	+14.9
±	1.8	2.8	1.4	0.7	l.5	1.4	1.4	l.5	2.2
D2HC	+20.5	+16.8	+17.4	+18.4	+17.3	+17.6	+18.5	+18.0	+40.4
±	3.4	5.7	3.0	1.2	3.6	2.8	2.4	2.9	6.9
D4HC	-7.5	-5.9	-6.1	-4.7	-5.4	-4.9	-6.0	-5.2	-12.7
±	l.6	2.2	1.3	0.7	l.5	l.5	l.3	1.5	2.7
PD01	-44.8	-44.4	-49.7	-43.0	-48.5	-49.4	-50.4	-41.2	-45.2
±	5.5	5.8	4.5	2.3	3.7	3.8	4.5	4.2	4.4
PD40	-2.8	-3.8	-2.3	-3.8	-2.3	-2.7	-2.1	-3.1	+8.3
±	1.9	4.4	-1.7	0.6	2.4	l.5	l.2	l.6	5.1
PH10	-90.2	-104.9	-93.8	-93.9	-97.1	-112.5	-112.2	-103.7	-96.3
±	6.8	6.6	5.3	3.1	4.5	4.9	5.7	5.2	5.7
PH30	+18.4	+23.5	+18.9	+17.0	+17.8	+26.9	+27.6	+24.9	+6.6
±	6.4	6.7	3.8	1.6	3.6	3.1	3.7	3.3	5.7
PX30	+25.4	+16.2	+1.7	+11.1	+5.7	+5.2	+7.4	+3.5	+25.1
±	7.1	8.2	5.3	2.1	5.l	4.3	4.3	4.5	6.6
PX20	+2.6	+3.2	+2.8	+5.5	+4.7	+4.3	+3.7	+6.4	+9.4
±	1.1	1.9	0.9	0.4	1.0	0.9	0.9	0.9	l.3
PX50	-9.3	-8.1	-1.1	-4.1	-2.9	-4.1	-4.4	-3.2	-7.1
±	2.4	3.7	2.0	0.7	2.3	l.7	l.4	l.7	3.5
ME	-162.9	-401.0	-33.3	-40.9	-45.2	-49.3	-49.9	-62.0	-73.4
±	3.7	4.0	3.3	1.8	3.0	3.1	3.3	3.1	3.3
MA	+l7.4	+14.5	-27.1	-24.0	-23.0	-20.6	-26.6	-26.5	-30.3
±	2.0	4.0	l.7	0.6	l.8	l.6	l.6	l.7	2.9
TF	-42.5	-32.9	-30.2	-37.4	-24.4	-39.2	-21.5	-50.6	-31.3
±	6.6	6.9	5.6	3.1	4.7	4.9	5.7	5.3	5.5
RMS	3.4	3.l	3.5	2.7	3.1	4.7	4.5	4.2	3.9
No. of stars	49	53	71	97	74	95	82	82	84

Table 3 Changes of coefficients between tests (INT)

$\chi 2$ is evaluated for the hypothesis that the coefficient remained constant.

Coefficient	Weighted mean value	$\chi 2$	Degrees of freedom	% significance
NP (all data)	-10.05	20.3	8	1
NP (tests 1-8)	-8.78	5.8	7	Insignificant
D2HS	+12.56	14.7	8	10
D2HC	+18.58	10.9	8	20
D4HC	-5.58	10.5	8	20
PD01	-45.75	5.1	8	Insignificant
PD40	-3.13	7.5	8	Insignificant
PH10	-99.52	20.2	8	1
PH30	+l9.92	21.2	8	<0.5
PX30	+9.64	17.6	8	2.5
PX20	+4.96	31.5	8	<0.5
PX50	-4.18	9.2	8	Insignificant
MA (tests 3-9)	-24.44	16.8	6	1
TF (Cass only)	-32.26	11.7	6	7

IH, ID and CH are expected to change; ME is so obviously variable as not to be worth analysing.

Table 4 The pointing model for the JKT

a) Geometrical Terms. As for the INT: see Table l(a)

b) Flexure terms (all polynomial)

PD20 $\Delta\delta = PD20\ h^2$
PD01 $\Delta\delta = PD01\ \delta$
PH10 $\Delta h = PH10\ h$
PH30 $\Delta h = PH30\ h^3$
PX20 $\Delta h = PX20\ h^2 / \cos\delta$
PX22 $\Delta h = PX20\ h^2\delta^2 / \cos\delta$
PX50 $\Delta h = PX50\ h^5 / \cos\delta$

Table 5 Summary of coefficients for the JKT east of the pier (all f/15 focus)

Coefficient	E1	E2	E3	E4
	841126	858506	850510	850530
IH	-257.5	+4861.8	+4894.2	+2598.8
	22.1	19.4	13.7	24.5
ID	-31.1	-2875.3	-2873.0	-2117.8
	15.5	11.0	8.6	18.5
CH	-453.9	-463.6	-504.4	-735.6
	19.4	17.0	12.6	29.4
MA	-12.2	-9.5	-11.9	+5.1
	5.4	4.4	3.9	9.1
ME	129.0	-122.9	-133.4	-153.3
	14.8	10.5	8.1	18.0
NP	-213.3	-197.0	-l91.2	-74.6
	13.5	9.6	8.5	21.5
PD01	+5.7	+303.6	+303.9	+282.9
	5.3	4.2	3.8	5.5
PD20	-9.9	-28.4	-30.3	-7.0
	9.0	7.4	5.1	10.8
PH10	+58.0	+270.1	+301.5	+401.3
	17.2	12.2	10.1	36.0
PH30	-35.7	+33.7	-5.2	+261.8
	28.6	21.5	12.2	102.3
PX20	+97.5	+109.3	+118.2	-271.7
	10.3	9.3	6.5	104.1
PX22	-56.3	-71.0	-70.8	+125.1
	12.0	11.0	6.3	62.8
PX50	+6.5	-28.4	-30.3	-23.4
	12.0	7.4	5.1	24.8
RMS	17.5	20.1	20.8	12.0
No. of stars	32	72	100	80

Table 6 Comparison of results with telescope east and west of the pier

Both tests were caried out on 1985 May 10, using a single zeroset (E of the pier). The last column shows whether the coefficient is expected to change sign (–) or not (+) going from E to W of the pier.

Coefficient	East (test E3)		West (test W1)		Expected transform
IH	+4894.2	± 13.7	+6374.6	± l9.6	+
ID	-2873.0	± 8.6	2013.1	± 9.5	–
CH	-504.4	± 12.6	+605.6	± 17.9	–
MA	-11.9	± 3.9	-15.5	± 4.1	+
ME	-133.4	± 8.1	-112.2	± 8.9	+
NP	-191.2	± 8.5	+147.4	± 9.2	–
PD01	+303.9	± 3.8	+299.2	± 4.2	+
PH10	+301.5	± 10.1	+318.2	± 12.8	+
PH30	-5.2	± 12.2	-49.3	± 23.7	+
PX20	+118.2	± 6.5	-139.2	± 9.3	–
PX22	-70.8	± 6.3	+47 .6	± 11.0	–
PD20	-30.3	± 5.1	-23.8	± 6.5	+
PX50	+17.9	± 3.3	+29.0	± 9.6	+
RMS error (arcsec)	20.8		17.7		
No. of stars	100		68		

Table 7 Analysis of test E4 on the JKT with coefficients from test E3, allowing only IH, ID, CH, NP to vary

IH	+ 2562.2	± 47.7
ID	- 2128.7	± 3.8
CH	- 741.5	± 62.5
NP	- 78.3	± 47.3
rms	= 34.3 arcsec	

Table 8a Significance of changes in JKT coefficients, tests E1-E3

Coefficient	Weighted mean	χ^2 (2 degrees of freedom)
PD20	-26.2	4.0
PH30	-0.6	4.2
PX20	+111.5	3.0
PX22	+68.3	l.2
PX50	-25.7	8.1

Table 8b Significance of changes in JKT coefficients, tests E1-E4

Coefficient	Weighted mean	χ^2 (2 degrees of freedom)
MA	-10.0	3.2
ME	-131.7	2.2

Figure 1 INT polar axis error (date: 1984 - 1985)