TELESCOPE POINTING ERRORS AND CORRECTIONS

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With the widespread use of digital readout devices for telescope position it has become possible to investigate and calibrate for some very small mechanical errors in your telescope system. Of course it has always been possible to do what is described here but it can now be done in a fraction of the time and with more accuracy. Good mechanical setting circles are capable of being read to about 0.1 degrees with a vernier gauge but digital setting circles now provide this accuracy without any special procedure. The latest amateur computerised telescopes provide much higher angular resolution of the order of 10's of arcseconds.

Any errors in pointing usually result from:

1) Polar axis mis-alignment.
2) Zero offset on declination circle.
3) Non perpendicularity between RA and DEC axis.
4) Optical collimation errors.
5) Tube flexure.
6) Bearing errors.

If manual slow motions or a drive system is attached then there can also be:

7) Gearing errors.
8) Drive train torsion errors
9) Backlash.

Measuring and Compensating for errors

10) Measuring the errors
11) Autoguiders
12) T-Point Modelling

The result of having a mix of these is a) photographic trailing of objects and b) loss of accuracy when trying to find the next object. We shall discuss all of these and describe the impact they make so that if you measure your telescope system you may decide that something should and could be done to improve pointing performance.

The situation is complicated by the fact that many of these effects are interactive and so a gross error in one of them could give measurable effects in the other ones. The correct procedure is to go through all of them, correct for the worst as much as possible then re-measure the whole set. Repeating the procedure several times should give errors which are "stable". It is not as bad as it sounds as the tests described are designed to be selective in that the effect of the other errors are minimised as much as possible for the error being measured. However, polar axis mis-alignment can mask other pointing errors and so this must be carried out first.

I shall discuss the errors for equatorially mounted telescopes. Similar expressions can be worked out for Alt-Azimuth mounted telescopes. Throughout this article **H** represents hour angle and for computation this will be in degrees (and fractions thereof) and δ represent declination.

This article assumes you know where you want to point your telescope. An object with a catalogued position (the *mean place* at an epoch) must have several corrections applied to get the *apparent place* and it must be this one that the telescope is pointing to. These will include corrections for precession, nutation, aberration and refraction amongst others. All of these are small (less than 20 arc seconds) except for refraction which is zero at the zenith increasing non-linearly to over 0.5 degrees at the horizon and precession which increases with time. For a good discussion of the astronomical corrections see ref 2 chapter 6 and ref 4.

1 POLAR AXIS MIS-ALIGNMENT

The effect of polar axis misalignment is to cause a drift in declination and some field rotation. It masks errors from other sources making it very difficult to disentangle them. For accurate work it is essential to align the polar axis as well as you can, checking the adjustments after setting up. The alignment error (rotation axis compared with Earth's rotation axis) is resolved into two components - an error in azimuth and an error in altitude. An easy method for assessing the accuracy of the alignment is to carry out drift examination when the telescope is pointing in various parts of the sky. It helps to have cross hairs on a high power eyepiece as drift can be detected quicker. The cross hairs should be aligned with one axis in the RA movement direction. This can be a fairly slow procedure depending on how accurate you want the setting. You do not need to have the RA driven.

- Azimuth error.

  This causes the declination drift to be most pronounced on the meridian. If the azimuth error is to the East then the star will drift south both sides of the meridian and the corrective action is to move the pole azimuth to the West by rotating the mounting anticlockwise (northern hemisphere observers). At HA exactly 6 hours, the azimuth error has NO EFFECT in DEC but introduces RA tracking errors.

- Altitude error

  There is no drift in DEC on the meridian but declination drift is most pronounced with a star in the east or west (at an Hour Angle of 6 hours). The effect is symmetrical about the meridian. If a star in the east drifts north then the rotation axis is too high.

Drift table for Northern Hemisphere observers:

star in	**drift dir**	**polar axis error**	**corrective action**
east	north	too high	lower pole
west	south	too high	lower pole
east	south	too low	raise pole
west	north	too low	raise pole
south	south	too far east	rotate anticlockwise
south	north	too far west	rotate clockwise

Methods of polar axis alignment with and without setting circles are given in ref 1 chapter on "setting an equatorial head".

Unfortunately with most computerised scopes it is impossible to find out how far out the polar axis is because the error is removed during calibration. If a one point calibration can be done then it is easy to correct. Select a known star near the celestial equator and meridian and do the calibration on this star. Then command the telescope to move to a star within 20 degrees of the pole and near the meridian. Centre the star using the Dec electronic hand control and the azimuth mechanical adjustment of the equatorial head. Repeat this using a star in the east near the celestial equator and driving the telescope up to a star with nearly the same RA near the pole. Adjust the mechanical altitude of the equatorial head and the RA electronic hand control to centre the star. Repeat! to improve the accuracy.

Any small errors left will only show by drift test with a high power eyepiece fitted with crosshairs. One must also make sure that there are no severe optical alignment problems (visible usually as coma). An optical alignment check would be a good idea.

In some telescopes it is virtually impossible to adjust mechanically to remove any residual errors because there are no fine adjustments to the position of the equatorial head. Fixed scopes on a pier may have to accept some residual error unless a mechanical arrangement can be engineered to provide a fine control on these adjustments. Computerised tracking corrections, autoguiding or using TPOINT (ref 4) are the only way to go for these mounts.

The tracking equations for **H** and δ give errors

$$\Delta\mathbf{H} = \tan\delta\ (\mathbf{M_{ns}} \sin\mathbf{H} - \mathbf{M_{ew}} \cos\mathbf{H})$$

$$\Delta\delta = \mathbf{M_{ns}} \cos\mathbf{H} + \mathbf{M_{ew}} \sin\mathbf{H}$$

These are then worked back to the polar axis:

The elevation error $\mathbf{M_{EL}} = \mathbf{M_{ns}}$

The azimuth error $\mathbf{M_{AZ}} = \mathbf{M_{ew}}$ / cos latitude

The constants can be deduced from a two point calibration with widely separated objects in declination and hour angle, as is done in the AWR Intelligent Drive System.

2 ZERO OFFSET ON DECLINATION CIRCLE

This is not a problem for computerised readouts. However, related to this error is one of the scale factor of each step as fed back from the encoders. The exact number of steps for a full rotation must be known. With a stepper motor and worm gear wheel reductions this can be calculated precisely. The intelligent handset (or computer) should be capable of being calibrated with this information.

3 OPTICAL COLLIMATION ERROR

A small mis-alignment between the optical and mechanical axis introduces a small error in the telescope pointing accuracy. This angle has two components, an east-west error **Cew** (of constant size) and a north-south error **Cns**. The declination will describe a circle parallel to the meridian. The correction equations are as follows:

$$\Delta\mathbf{H} = \mathbf{Cew} \sec\delta$$

$$\Delta\delta = \mathbf{Cns}$$

Note $\sec\delta$ is 1 when the declination is zero and so $\Delta\mathbf{H} = \mathbf{Cew}$. Near the pole $\sec\delta$ goes to a very large value, although $\Delta\mathbf{H}$ will still be a small angle when converted to degrees.

Cns and **Cew** can be measured by selecting a star on the meridian and celestial equator, reversing the telescope under computer control (RA by 180 degrees and Dec by twice the north polar distance) to centre the star again. The difference in Dec readout will be twice the angle **Cns**. The difference in RA readout (when converted to degrees) will be twice the angle **Cew**. For this to be performed the telescope must be driveable over the pole so it is not suitable for some mounting types.

4 NON-PERPENDICULARITY BETWEEN RA AND DEC AXIS

A small angle **p** being the difference between 90 and the actual angle between the mechanical RA and DEC axes introduces a small correction to the Hour angle and Declination. The effect is such that when you have selected a star on the celestial equator and meridian and you move the telescope through declination only, the telescope will sweep out a circle which misses the pole by angle **p**. The small corrections are given by the following equations:

$A = \mathbf{p} \sin\delta$ where A is the angle in RA in degrees
$\Delta\delta = \mathbf{p}\ A$
$\Delta H = A \sec\delta$

Note: there is no error if the declination of the star is zero and the maximum error (of **p**) when the declination is 90 degrees.

This angle **p** can be measured by selecting a star near the pole on the meridian. Note the co-ordinate reading when the star is centred. Then reverse the telescope under computer control (RA by 180 degrees and Dec by 180 degrees) to centre the star again. Note the new co-ordinate position. The differences ($\Delta\delta$, ΔH) can be put into the equations above to determine **p**. Halve this angle as the error introduced by this technique is twice the angle we are after. However the angle **Cew** from collimation error is also present and so must be subtracted.

Skew in the apparent coordinate frame can also be resolved by a three point calibration, all the stars lying in the same hemisphere. Maximum sensitivity would be given by a cal1 at HA 6hr Dec 0 degrees; cal2 HA 0hr Dec 0 degrees and cal3 HA 0 hr Dec 90 degrees. A compromise is required to reduce refraction effects and to get to actual stars.

5 TUBE FLEXURE

This introduces a non-linear term to the optical collimation error angles, usually dependant on the zenith distance but can depend on the construction of the tube. A non-symmetrical tube will have a varying constant of flexure depending on Hour Angle. The errors introduced can be tabulated according to zenith angle and appropriate corrections then carried out. The procedure for finding this error is to work out the error in declination of stars of known position, calculating the zenith distance for each one. Stars at constant hour angle should be used.

6 BEARING ERRORS

It is possible for shafts to have small "bumps" which cause the telescope to suddenly point in a different direction. This can also occur if there is some sideways give in the bearings on a shaft and a shift in the weight distribution can then cause a small pointing error. It should be possible to minimise these errors by inspection and tightening up bearings, cleaning surfaces etc. Worn bearings with flats should also be replaced. This is a common problem with the EQ6 mount.

7 GEARING ERRORS

Normally known as a periodic error when an oscillatory component is introduced by mechanically imperfect gears. Each pair of gears is going to have an oscillation amplitude and period. The period is fixed by the rotation time for one revolution and the amplitude depends on how well accurately the gear was machined and mounted on the shaft. The shaft must be driven and to get rid of it one must compensate for the error by speeding up and slowing down the motor. This can be done manually by pressing the handset controls but is much better done automatically with an intelligent drive controller.

The usual form of periodic error is from a worm wheel period with a sine wave error due to non-centred axis. The amplitude can be 10s of arc minutes. This can be measured by taking a prime focus image of a star on the meridian near the celestial equator as outlined in section 10.

Non-periodic errors are also possible. A friction drive can suffer from a 'flat' or 'bump' on one or more wheels then the gear ratio changes while it is contact and so will produce a sudden change in drive rate which does not recover. Non-periodic errors can also happen in geared systems with poor bushing on axes (sideways float), dirt in the teeth etc, so strip down and clean the gears and bearings, replacing any worn parts and re-assemble and grease with a good carbon loaded grease.

An autoguider such as that provided with some CCD cameras is capable of guiding on objects, compensating for this error automatically. It is possible for some electronic hand controllers to be programmed to compensate for periodic error. The corrections would be 'read' from your keypresses over the rotation time of the worm (4 minutes for 360:1 worm) then stored and automatically repeated. An INDEX PULSE occuring once per rotation and generated by a sensor gives a good zero point to start the playback trace of the handset buttons, but it can be done without the index pulse.

8 DRIVE TRAIN TORSION EFFECTS

When there is a large amount of torque to be applied to turn the telescope then long shafts can twist slightly. The effect of this is to make the telescope not point to where it is commanded. If there is position feedback on the final drive element then this error is irrelevant. An out of balance telescope can change the torque required depending on the position pointed to and this can result in unpredictable torsion errors if the drive train is susceptible.

Fork mounts also suffer from this due to twists in the fork. The declination motor is fitted to one of these arms and in order to turn a heavy telescope it must exert an equal and opposite force on the fork arm

9 BACKLASH

Backlash in the drive train manifests itself when the direction of rotation is reversed. This shows up by the telescope not moving even though the adjust button is being pressed. During guiding in RA the small corrections applied should not be a problem as the small speed changes should be 30% or less of sidereal rate superimposed on the 15 arcseconds per second to counteract the Earth's rotation. This means the motor is always moving in the same direction. The motor will be rotating slightly slower or faster, but not backwards. Backlash in Declination is a problem as it is likely there will be constant direction changes. When guiding for a photograph there should be no need for Dec changes unless the polar axis is not aligned properly.

Backlash is caused by slack in the mesh of the worm in the main drive wheel; float in the end bearing of the slow motion shaft or slack in other gears (or gearbox) attached to a motor (typically 2 degrees on the final output shaft of a gearbox). Slack in either axis can be measured. Set the adjust speed to 2x which should provide 15 arcsec per sec adjustment in all directions. Select a star near the celestial equator and measure as follows:

> DEC: Go north until the star moves, then go south back to the selected star. Then press the north button and measure the time until the star starts moving.
>
> RA: Move the telescope backwards under handset control . Stop the drive, select normal Sidereal rate then start it when a star passes and measure the time until the star starts moving.

Typical backlash times are up to 4 seconds if the main worm wheel has 144 teeth, just over 1 second if there are 360 teeth. It will pay to reduce this error as much as possible. Most worm wheel sets provide some means of adjusting the mesh of the worm, hence part of the backlash can be removed. End float on the worm wheel axis may also be reduced by fitting shim washers. Backlash up to 10 seconds can be seen in lower priced budget mountings.

Calibration with intelligent controllers can make this reduce to a negligible time. They keep track of when the motor reverses and compensate by moving the right number of steps at a fast speed (and hence a short time) to take up the backlash. The danger is that the telescope can suddenly shoot away if there is overcompensation.

10 MEASURING PERIODIC ERRORS

Prime focus photography is very useful in quantifying any small drive irregularities. The technique basically is to introduce a steady DEC drift by rotating the mount in azimuth and then exposing for about 20 minutes while pointing to a bright star near the meridian. If the whole trail then fits on the photograph then it can be measured.

At the Meridian an azimuth error creates DEC drift of 0.25 arcminute per minute of exposure per degree of azimuth error. So to get a 20 arcminute trail over 10 minutes exposure time, the polar axis has to be rotated 8 degrees from the true position.

The length of the exposure should be about two revolutions of your worm. Measure the amplitude of any wiggles in the trail from the photograph when blown up in a projector. You also need to know the image scale so it is best to photograph a double star of known separation, or photograph the Moon through the same camera / eyepiece arrangement.

Prime focus does not have to be used. Any normal method of photographing an area of sky about 0.5 degrees across can be used such as the afocal method where a low power eyepiece in the telescope is used, and the camera lens focused to infinity. You do need to rigidly attach the camera to the telescope and the camera shutter must be capable of being held open for the time exposure.

11 AUTOGUIDERS

CCD Camera autoguiders or webcams plus a computer are very good at determining sub-pixel movements in the image and can produce compensation signals to remotely press the telescope movement buttons, and so bring the image back. When properly set up with the correct guide rate, aggressiveness and other factors these can do a marvellous job of keeping stars round. There is no need to worry about periodic error or polar alignment problems.

However backlash in DEC is still a problem and must be sorted. A way of overcoming this is to offset the polar axis so there is a continual drift in DEC (you need an azimuth and an elevation offset) in one direction. Thus the motor is biased and will only be required to speed up or slow down, not alter direction.

If the polar alignment is not correct, there will also be field rotation in long exposure photographs.

Another benefit of an autoguider is that the correction file is accessible making possible FFT Analysis of all the harmonic errors. AWR have done this with an Alter D6 mount and measure the main periodic error component and other periods which can be traced back to particular mechanical objects in the drive train. For further information see ref 5.

12 T-POINT MODELLING

This software package allows computing of all the constants described here and goes on to adjust position requirements produced by planetarium programmes to counteract all the small effects and so land the telescope on the exact object required. It does this by building up a matrix of errors over 20 or so stars spread all over the sky. It works best with intelligent drive systems that produce a coordinate readout to high precision. For further information and a more detailed discussion see ref 4.

REFERENCES

1. Amateur Astronomer's Handbook by J.B.SIDGWICK (Pelham Books). A good chapter on setting an equatorial head.

2. Microcomputer control of telescopes by TRUEBLOOD & GENET (Willmann-Bell). Chapter 7 describing the telescope errors.

3. Many hints and tips on the ATM web site maintained by Mel Bartels (search on the internet).

4. TPOINT Programme - discussion of errors and computer modelling. See http://www.tpsoft.demon.co.uk/pointing.htm

5. AWR Technology periodic error analysis www.awrtech.co.uk/ih/fft_anal.htm