

TPOINT

A Telescope Pointing Analysis System

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1 INTRODUCTION

TPOINT is a software system for analyzing telescope pointing. The version to be described in this manual runs on Unix platforms, with graphics via X windows and PostScript; other versions exist which run on MS-DOS PCs. It is a descendant of TPOINT systems that have been in use at major observatories for many years, including optical, IR, mm and radio telescopes. AAT, UKST, UKIRT, LPO, WIYN, ARC, Keck, JCMT, WHT, INT and many other major telescopes all use TPOINT routinely to maintain their pointing models and to monitor performance. The TPOINT to be described differs from these earlier TPOINTS in several key respects:

- Written entirely in ANSI C (rather than Fortran).
- Self-contained (no complicated software environment to be set up).
- Available as both a freestanding application and as a library. Use of the library is the subject of the separate *TPOINT Programmer's Manual*.

Using TPOINT you can assess the potential for accurate pointing in your telescope and measure misalignments and flexures. The information TPOINT generates can be used in telescope control systems to improve setting accuracy and to enable good coordinates to be logged at any time. In addition, misalignments can be addressed mechanically, for example through adjustments to the polar axis. Using the sophisticated pointing models that can be developed with TPOINT, the best large telescopes deliver pointing accuracy below the 2 arcsecond level and some approach 1 arcsecond, roughly the diameter of the larger satellites of Jupiter. Good amateur telescopes can easily beat 1 arcminute, placing distant planets or faint nebulae reliably in the center of even a high-power eyepiece.

1.1 Minimum Configuration

TPOINT places only modest demands on the host computer and will run on any modern Unix configuration. For example, a 486/66 PC with 16 Mb of RAM, running Linux, provides very satisfactory results even with several hundred stars in the data set being analyzed.

The system occupies less than 1 Mbyte of disk space.

1.2 Installing TPOINT on your Unix system

TPOINT and the libraries it uses are supplied in source form as separate directories on two MS-DOS 3.5-inch diskettes. The installation procedure is straightforward and, for flexibility, not excessively automated:

1. Create separate directories for the various components:

<code>tpoint</code>	TPOINT (library and freestanding application)
<code>slalib</code>	Positional-astronomy library
<code>sgs</code>	plotting library
<code>help</code>	interactive help library

2. Copy (by using `dos2unix` or some other method that handles the differing end-of-line conventions between the different operating systems) the contents of the diskettes to them:

<code>tpt_lux</code>	TPOINT
<code>sla_lux</code>	SLALIB
<code>sgs_lux</code>	SGS
<code>hlp_lux</code>	HELP

3. If necessary, edit the makefiles to suit local directory structures and compiler options. Each makefile contains instructions on what to do. In most cases the changes are all near the beginning of the file. Note that make's environment variables (for example HOME and the compiler options) can be specified on the command line, removing the need to modify the makefiles.
4. Make the libraries. If you are not using the gcc compiler, refer to the comments near the start of each makefile to see how to invoke make for your compiler. Then execute a `rehash`.
5. Make the TPOINT executable. (The same remarks apply.)
6. Depending on where you have installed the software, and what other changes you want to make, either copy the supplied `tpoint.ini` file into the directory from which you will run `tpoint` or set up a link to it, making appropriate edits.
7. Make similar links and modifications to the SGS initialization file `sgs.ini`.
8. Make sure the script `tpoint` and the executable `tpt` are in your path. (The supplied makefile puts them in `$HOME/bin`.)

1.3 System Overview

The TPOINT application is a straightforward, monolithic program which accepts commands from the keyboard. There is a simple but effective 'command procedure' capability, and a log file can be produced, recording what operations were carried out and with what result. Pointing observations are input from ordinary ASCII files (as produced by a text editor) in flexible formats. Graphics output goes to a separate X window; TPOINT can be run on a non-X system but the graphics commands will not work. A small star catalog is provided, and some sample data. There is a comprehensive hierarchical help system.

1.4 How TPOINT is Used

This is how to use TPOINT to investigate the pointing performance of your telescope:

1. Decide which place in the focal plane you want the pointing to refer to. Depending on the size of the telescope, the arrangements for viewing the field, this may be crosswires in an eyepiece, a particular pixel of a CCD, or an autoguider probe.
2. Point your telescope at a sequence of stars of known coordinates, and record the telescope readouts in a file.
3. Run TPOINT and select the INDAT command to read in the file of observations.
4. Use TPOINT's USE command to specify a likely pointing model for the telescope concerned. The extensive repertoire of TPOINT terms includes zero points, misalignments, flexures and so on as well as general-purpose harmonics and polynomials. There are standard models for equatorials and altazimuth mounts which make it very easy to get started.
5. TPOINT's FIT command automatically calculates the optimum size for each term in the model, such that the overall model is the best possible fit to the observations.
6. Using TPOINT graphics commands, the remaining pointing errors can be inspected.
7. If obvious non-random errors remain, additional terms can be added to the pointing model (and removed as necessary) and the fit repeated.

The final result shows how well the telescope can point, and what corrections need to be made to achieve this result. The coefficients which TPOINT produces (*i.e.* the numbers specifying the size of each pointing term) can be fed into the telescope's computer control system to improve the pointing. On small telescopes where there is no computer, they can be used to prepare tables of corrections for various parts of the sky. Another use of TPOINT is to identify opportunities for mechanical adjustment, for example enabling the polar axis of an equatorial mount to be set up accurately even on telescopes which cannot for some reason see the pole.

1.5 The TPOINT Philosophy

Many observatories and telescope users have their own ways of fitting models to pointing observations, and in a numerical sense TPOINT cannot be necessarily be expected to produce results that are different or better. However, TPOINT is unique among pointing-analysis programs, (a) in that the telescope model can be changed during the interactive session, and (b) in the variety of its graphical displays. These two features allow rapid exploration of the pointing possibilities of any given telescope and often leads to a better model than the one formerly used.

The general approach taken by TPOINT is that as far as possible the telescope model should describe real effects (geometrical misalignments, well understood flexures, *etc.*), and empirical functions should be used only to mop up any remaining systematic errors. There is a school of thought which advocates using empirical functions (for example polynomials or spherical harmonics) for the whole job. However, the TPOINT approach has some advantages:

- Simple geometrical misalignments – for example a miscentered instrument on a mount which is located at a Nasmyth focus but is not coincident with the elevation axis – might require very complicated empirical functions but are simple to deal with analytically.
- Direct manipulation of certain geometrical terms while the telescope is in operation can be very useful. An important application of this technique is where a star is switched from one instrument aperture to another simply by changing the collimation parameters. Another example is where the polar axis of a wide field telescope is routinely raised and lowered as a function of declination, to minimize the field rotation effects of differential refraction; the polar axis elevation parameter in the pointing model can simply be changed by the same amount and accurate pointing is maintained.
- A realistic model of a telescope frequently exposes mechanical deficiencies which can then be diagnosed and cured.
- A realistic model is likely to require fewer terms, and the number of stars observed in a pointing test can be correspondingly smaller.
- Physically-based models are less likely to misbehave when extrapolating outside the area covered by the available test data.

In any case, the models available with TPOINT allow considerable empiricism to be employed when called for. A good example of this is the AAT model, which is supplied with TPOINT as an example of what may be needed to tame a large equatorial with stringent pointing requirements. Though firmly based on well-understood geometrical misalignments and plausible tube flexure corrections, the AAT model also contains complicated harmonics describing what are believed to be flexures in the horseshoe and center section. These flexure models are encapsulated in two terms called HFX and HFD, which are always left at their nominal sizes and are not fitted when individual pointing tests are reduced. HFX and HFD were determined by empirical fits to a very large sample (well over 1000 stars) formed by superimposing the residuals from tests carried out over several years.

1.6 Running TPOINT

To run the TPOINT system from the Unix shell (typically running in an xterm window):

`tpoint logfile initfile commands messages`

The four parameters – the log file, the initialization file, the command input device and the message output device – are all optional and are normally allowed to default, respectively, to the following files:

<i>logfile</i>	<code>/dev/null</code>
<i>initfile</i>	<code>tpoint.ini</code>
<i>commands</i>	<code>stdin</code>
<i>messages</i>	<code>stdout</code>

On termination, the log file, if one has been specified, contains a full record of the session, and includes extra information (*e.g.* correlations between pointing terms) too voluminous to be displayed on the screen during the run.

Each TPOINT command line consists of one or more fields separated by spaces. The first field, of up to 6 characters, is the **command name**, and specifies the action to be performed. The subsequent fields, if any, are the **arguments**. Where the arguments are numeric, free-format decoding is performed, and numbers may be entered in a wide variety of formats. The precise way the arguments are interpreted depends on the command in question.

TPOINT deals with all forms of input – both commands and the various sorts of data file – in a standardized way which allows for comments and blank lines to be used and provides consistent handling of lowercase information. Details of these conventions are given in the section *Syntax*, later.

To abort a command, type CTRL/C. The command will terminate cleanly as soon as it can, and control will be returned to the operator ready for the next command. To exit normally from TPOINT, use the END command.

A full list of all TPOINT commands, in alphabetical order, is given later. A quick reference list can be found at the end.

Sequences of TPOINT commands can be executed from a library. A procedure library file is a sequential file of up to 80-character records, searched from the start each time. Standard TPOINT syntax applies to such libraries, which may thus contain blank lines and comments (beginning with '!') to enhance readability. In using procedures from a library, the following commands are involved:

CALL <i>x</i>	calls procedure <i>x</i> from the library
PROC <i>x</i>	specifies the start of procedure <i>x</i>
RETURN	returns from and ends a procedure

Of these commands, `CALL` alone is permissible from the keyboard; `PROC` and `RETURN` are used only in library procedures. The standard procedure library file is automatically loaded when `TPOINT` is started unless a different one is specified on the command line as described above. After loading the library, `TPOINT` automatically executes a ‘`CALL INIT`’; the `INIT` procedure supplied in the standard library does nothing, but one in a private version can contain any required preliminary operations – for instance preparations for fitting a particular model. All procedure libraries should contain an `INIT` procedure, otherwise an error message will occur during `TPOINT` setup. A private library can be loaded at any time during the `TPOINT` session by using the `INPRO` command. The `INIT` procedure is not called under these circumstances. An `INPRO` command without arguments restores the original library. By default, procedure commands are not echoed on the screen; they can be made to appear by means of the `ECHO ON` command. The volume of messages output during the running of complicated procedures can be controlled by means of the `MESLEV` command. (This command can also be used from the keyboard, though suppressing messages during normal interactive use of `TPOINT` is not recommended.)

1.7 An Example `TPOINT` Session

The best way to learn how `TPOINT` works is to reduce some real data, using one of the sample files. Proceed as follows. First start the system:

```
tpoint
```

There will be various announcements, followed by a ‘*’ prompt. Read in the sample data file, which is from the UK 1.2 meter Schmidt Telescope at Siding Spring Observatory in Australia:

```
INDAT ukst
```

(You may need to specify a full pathname for the `ukst.dat` file.) The observations will be listed on the screen. Specify the standard geometrical model for an equatorial mount, and then fit the model to the data:

```
USE IH ID NP CH ME MA
```

```
FIT
```

The values of the pointing coefficients are reported, as well as the root-mean-square (RMS) error on the sky and the population standard deviation (PSD – an estimate of what the RMS would be if the number of stars was much larger). Plot the residuals (the pointing errors which remain after the `TPOINT` model has been applied):

CALL E9

The axis labelling will be described later. In this particular case, conspicuous systematic effects are present in the dD (declination residual) versus H (hour angle) plot. The term FO (fork flexure) is a standard one for fork mounted telescopes and produces this characteristic pattern of residuals. Include the term in the model and fit again:

USE FO

FIT

Note that the RMS and population standard deviation are much improved. Plot the residuals again:

CALL E9

There are no obvious remaining systematic effects. This simple 7-term model is, in fact, the one used operationally.

This illustrates the general strategy for modeling a telescope from scratch. Begin by suitably preparing the TPOINT system and inputting the data. Then create a preliminary model consisting of the basic set of geometrical terms, and perform a fit:

INDAT *file*

USE IH ID NP CH MA ME (for an equatorial)
 or USE IA IE NPAE CA AW AN (for an altazimuth)

FIT

(Procedures for setting up the basic equatorial and altaz models are also provided in the standard library: use CALL EQUAT or CALL ALTAZ.) The fit can be repeated until the solution settles down. Make a note of the population standard deviation, which is an indication of the general quality of the telescope before any modeling of flexure *etc.* The next step is to display the residuals graphically. A useful way to start is procedure E9 or A9 in the standard library:

CALL E9
or CALL A9

9 favorite plots for an equatorial
9 favorite plots for an altazimuth

By means of the USE and FIT commands, try out extra terms to reduce any systematic errors. The simple Hooke's-law tube flexure term TF is frequently required; for fork mounted equatorials try the fork flexure term FO, and for mounts with a declination axis supported at one end only (the English cross-axis and the German mountings are examples) try the declination axis flexure term DAF. When adding new terms, pay attention to the standard deviation of the new coefficient, the effect on other terms, and whether the population standard deviation has been reduced. Remove new terms if they are reported as being indistinguishable from existing ones, or if they lead to the appearance of messages warning that the fit is ill-conditioned. With the exception of the six standard geometrical terms, it is wise to reject any terms which are not at least 2 sigma in size. For each FIT, a table of the correlations between every pair of terms is output to the log file, for inspection after the TPOINT session; values close to unity show terms which are not easily distinguished given the current data.

More advanced information on modeling strategy is given in a later section.

The current settings of various internal parameters can be displayed as follows:

SHOW

The list produced by SHOW includes the command names required to change the parameters, and is a useful guide to some of the facilities available within TPOINT.

1.8 Syntax

All TPOINT commands, procedure library records, star catalog records, model data records, and pointing data records, are subjected on input to a preliminary vetting and conditioning, as follows:

- Comments – records which are blank, or which have '!' as the first non-space character – are logged and displayed if appropriate but are otherwise ignored.
- Non-printing characters (TABs for instance) are replaced by single spaces.
- Leading blanks are eliminated as appropriate.
- Except within *string arguments*, lowercase characters are converted to uppercase.

String arguments are groups of characters delimited by pairs of either " or ' characters to show that they must stay lowercase. When a procedure library file is being input, string argument delimiters are left intact (to allow library commands to have lowercase arguments). For TPOINT commands, string argument delimiters are interpreted by the command routine itself. When star catalog files, pointing data files, and model data files are input, string argument delimiters are removed.

2 MODELING

The pointing model is a sequence of terms selected from an internal repertoire. As well as explicitly formulated terms (geometrical effects for example) there is a generic type covering a wide range of polynomials and harmonics.

Terms can be **added** to the model by means of the USE command. For example, to add the terms for polar axis misalignment:

```
USE ME MA
```

The USE command is also used to re-enable fitting after a FIX command.

Terms can be **removed** from the model by means of the LOSE command. For example, to drop the term PDH2:

```
LOSE PDH2
```

The value of the coefficient of a single term can be **specified** by means of the command:

```
coeff val
```

where *coeff* is the name of the term and *val* the value in arcseconds. Thus to set the HA index error to +20"7:

```
IH 20.7
```

You would normally only do this for 'FIXed' coefficients – ones excluded from fitting.

The current value of the coefficient of a single term can be **inquired** by entering a command consisting simply of the name of the term. For example, to display the current value of the declination index error, simply use the command:

ID

The current model is **fitted** to the observations by means of the FIT command. Individual terms can be frozen at a particular value by means of the FIX command, or reinstated in the fitting by means of the USE command.

2.1 The Pointing Terms

The pointing terms fall into five categories – equatorial, altazimuth, special (to a telescope or type of telescope), polynomial and harmonic. The model for any particular telescope may be a mixture of several of these types.

Some terms are functionally identical but have different names for historical, convenience or efficiency reasons. Most of them can be expressed using generic terms (polynomials and harmonics), though doing so will lead to slightly slower execution of the FIT and UNFIT commands. To find out what a given term means in a geometrical sense, refer to *The Pointing Terms in Detail*, later.

The following terms are most useful when modeling an **equatorial** telescope:

IH	index error in HA
ID	index error in Dec
NP	nonperpendicularity of HA and Dec axes
CH	nonperpendicularity of Dec and pointing axes
ME	polar axis elevation error
MA	polar axis error east-west
FO	fork flexure
DAF	flexure of cantilevered Dec axis
HCES	HA centering error (sin component)
HCEC	HA centering error (cos component)
DCES	Dec centering error (sin component)
DCEC	Dec centering error (cos component)
DNP	dynamic nonperpendicularity
X2HC	$\cos(2h)$ term EW
AUX1H	HA change supplied through auxiliary reading 1
AUX1X	EW change supplied through auxiliary reading 1
AUX1D	Dec change supplied through auxiliary reading 1
AUX2H	HA change supplied through auxiliary reading 2
AUX2X	EW change supplied through auxiliary reading 2
AUX2D	Dec change supplied through auxiliary reading 2

The following terms apply to **altazimuth** telescopes; some also describe effects in zenith distance which apply equally well to equatorial telescopes:

IE	index error in elevation
IA	index error in azimuth
CA	nonperpendicularity of elevation and pointing axes
AN	NS misalignment of azimuth axis
AW	EW misalignment of azimuth axis
NPAE	nonperpendicularity of azimuth and elevation axes
NRX	Horizontal displacement of Nasmyth rotator
NRV	Vertical displacement of Nasmyth rotator
TF	tube flexure – $\sin \zeta$ law
TX	tube flexure – $\tan \zeta$ law
ACES	Az centering error (sin component)
ACEC	Az centering error (cos component)
ECES	El centering error (sin component)
ECEC	El centering error (cos component)
AUX1A	Az change supplied through auxiliary reading 1
AUX1S	LR change supplied through auxiliary reading 1
AUX1E	El change supplied through auxiliary reading 1
AUX2A	Az change supplied through auxiliary reading 2
AUX2S	LR change supplied through auxiliary reading 2
AUX2E	El change supplied through auxiliary reading 2

The following terms are **special** to the AAT (and are included as examples of what is likely to be involved in improving the pointing model for any large telescope as experience builds up):

ZH	AAT HA Z-gear effect in HA
ZE	AAT HA Z-gear effect in polar axis elevation
HF	AAT main east-west horseshoe flexure
HGES	36^m gear error in HA – sin
HGEC	36^m gear error in HA – cos
DGES	9° gear error in Dec – sin
DGEC	9° gear error in Dec – cos
TFP	AAT tube flexure – non-Hooke's-law term
HFX	AAT residual horseshoe east-west
HFD	AAT residual horseshoe north-south
CD4A	AAT coudé 4 collimation error A component
CD4B	AAT coudé 4 collimation error B component
CD5A	AAT coudé 5 collimation error A component
CD5B	AAT coudé 5 collimation error B component

There are two types of **Generic** term, where the name of the coefficient spells out the required polynomial or harmonic formula.

Polynomial terms have names of the form:

$Prc [i [c [i]]]$

One example would be a term PXH2D1, which would model an effect which produced an east-west shift on the sky (X) proportional to $h^2\delta$ (H2D1).

The initial 'P' identifies this term as a polynomial.

The r field describes the result, and is one of the following:

H	result is in hour angle
X	result is east-west on the sky
D	result is in declination
U	result tilts polar axis up/down
L	result tilts polar axis left/right
P	result changes HA/Dec nonperpendicularity
A	result is in azimuth
S	result is left-right on the sky
Z	result is in zenith distance
N	result tilts azimuth axis north/south
W	result tilts azimuth axis east/west
V	result changes Az/El nonperpendicularity

The two ci fields indicate the independent variables and their powers. Each i is in the range 0–9; each c can be any of:

H	hour angle
D	declination
A	azimuth
Z	zenith distance
Q	parallactic angle

Trailing ci or i fields, if omitted, default to unity. For example, a change in HA proportional to HA (*i.e.* a scale change, such as might be necessary with a roller-driven encoder) can be produced by using the term PHH.

Harmonic terms have names of the forms:

$$\text{H r f c [i] [f c [i]]}$$
 or

$$\text{H r f c i i}$$

One example might be a term HXSH2, which would model an effect which produced an east-west shift on the sky (X) proportional to sine (S) of $2h$ (H2).

The initial 'H' identifies this term as a harmonic.

The r and c fields describe the result and an independent variable respectively, and are as for polynomials, above.

Each fci , fci and fci field indicates a function of an integer multiple of an independent variable c . The f field is either S for sine or C for cosine. Each i is in the range 0–9, allowing frequencies from zero to 999 cycles per revolution in the case of simple one-coordinate harmonics, and 0 to 9 cycles per revolution in the case of compound two-coordinate harmonics. An omitted i defaults to unity, as does an omitted trailing fci .

2.2 Order of Terms

To match different styles of telescope control system, the model can either start with raw telescope positions and predict the corresponding *observed*¹) position, or alternatively can start with “observed” star positions and predict the required raw telescope position. The selection is made with the ADJUST command. The sign convention for the coefficients is the same for both options, so that the two options should deliver coefficients that are substantially the same. When the ADJUST command is used to change the option, the order of the terms in the model is reversed so that more or less the same coefficient values will be produced if a FIT is carried out (following a RESET to cancel the previous set of corrections).

Normally, each term in the model is *chained* to the previous one, the input position for each term being the output position from the previous term. Sometimes this may not be appropriate, and a set of terms can instead share one input position and their adjustments be added in as a group; in this case the terms are said to be *parallel*. The commands CHAIN and PARAL select which option applies to a given term, the first in a parallel group being marked ‘chained’ and the rest marked ‘parallel’ to indicate they share the former’s starting point.

In typical cases the coefficients will not be much altered by changing the order of terms, or switching terms between chained and parallel. Significant changes are likely only if some coefficients are large, or if high order polynomials or harmonics are employed. It is

¹*i.e.* corrected for everything up to and including diurnal aberration and refraction. In this context, the word “observed” has a specific technical meaning, namely the true line-of-sight direction, and should not be read as if it means telescope readouts logged during a pointing test, or anything else that has been “observed”!

nevertheless reassuring if the model being fitted matches the way the pointing corrections are implemented in the telescope control system itself, in direction, order, formulation, and chaining.

2.3 Sizes of Coefficients

The mathematical expressions used by TPOINT are rather simple and designed to give results of adequate accuracy when not too close to the pole of the mounting and *when the pointing errors of the telescope are small*. Flexures and misalignments of up to a few arcminutes are unlikely to give problems; they will not interact significantly with one another, and will be calculated by TPOINT to sufficient accuracy. However, terms with larger coefficients may not be so well-behaved, especially near a pole.

A particular source of problems in practice is collimation error, the non-perpendicularity of the chosen pointing axis with respect to the declination or elevation axis of the mounting. If the measuring device – eyepiece, autoguider probe, CCD, TV camera *etc.* – is offset too far, there may be unmodeled pointing errors due to such effects as optical distortion. The best plan is to ensure that the measuring device is offset no more than a few minutes of arc. If this is impossible it is advisable to pre-process pointing observations to remove the bulk of the offset before the TPOINT run. This might involve rigorous calculation of the tangent-plane projection and optical distortions.

2.4 Saving Models

Commands are provided for writing the current model to a file, and for replacing the current model with one read from such a file:

OUTMOD <i>file</i>	write model to a file
INMOD <i>file</i>	read model from a file

where *file* is the name of the file containing the model. As well as providing long-term storage for models, the file may also be read by programs external to the TPOINT system. In addition to the model information required by INMOD, the file contains the current caption and the basic statistics which relate the model to the current data list. The INMOD command ignores these latter items.

The file consists of variable length formatted character records in ‘list’ format (*i.e.* the records do not contain printer vertical format characters). The order of records within the file is:

caption record
 method, statistics and refraction record
 term records (one per term in the model)
 end record

Here is an example file:

```
AAT_f/15_1979/06/11
T_49_1.1206_52.015_-0.0624
_IH_+175.2234
_ZH_+3.5100
_ID_+20.7048
_&=HF_X_+1.0000
_&=HF_D_+1.0000
_&_HF_-22.4514
_&_X2HC_-3.0225
_&_NP_+2.9841
_&_CH_-19.1780
_ZE_+0.7000
_&_ME_+57.9758
_&_MA_+3.2308
_TF_+8.0261
_&_TFP_-2.1594
END
```

The **caption** record can be up to 80 characters long.

The **method, statistics and refraction** record can be read with a FORTRAN FORMAT specification of (A1, I5, F9.4, F9.3, F9.4) or a C `scanf` format string of "%c %5d %9lf %9lf %9lf". The five fields are:

method: T or S
 number of active observations
 sky RMS (arcsec)
 refraction constant A (arcsec)
 refraction constant B (arcsec)

A method of 'T' means that the model corrects the telescope readings, whereas 'S' means that the model is applied to star positions to predict the required telescope setting.

Each **term** record can be read with a FORTRAN FORMAT specification of (2A1, A8, F10.4, F12.5) or a C `scanf` format string of "%c %c" "%8" "%1" "%12lf". The fields are:

chained/parallel flag
 fixed/floating flag
 term name
 coefficient value
 coefficient sigma

The chained/parallel flag is either a space (for ‘chained’ terms - ones which are computed from the position as affected by all previous terms) or an ampersand (for ‘parallel’ terms - members of a group all computed from the same starting position). The fixed/floating flag is either a space (for coefficients that are to be fitted) or an equals sign (for coefficients of fixed value). The term name and the coefficient value and sigma have their normal meanings.

The **end** record consists of the string ‘END’. Reading programs should also interpret end-of-file as equivalent to an end record.

Note: population standard deviation can be obtained as follows. Count the number of floating coefficients (ones not marked ‘=’) and call it n . With sky RMS ρ and number of active observations o , PSD $\sigma = \sqrt{\rho^2 o / (o - n)}$.

3 GRAPHICS

The TPOINT graphics commands are as follows:

CAPT	enable/disable plotting of caption
FRAME	enable/disable plotting of graph frame
G	plot residuals in one coordinate against another
GAM	look for changing polar/azimuth axis misalignment
GC	special functions: clear screen, write hardcopy file
GDIST	plot error distributions
GHYST	look for hysteresis
GMAP	plot error vectors on Cartesian Cylindrical projection
GSCAT	plot residuals as a scatter diagram
GSMAP	plot error vectors on orthographic projection
MARKH	specify marker size
PENS	specify pens for lines and text
PLTZ	specify plotting zone

The PLTON command opens a plotting window which can optionally be named. The various graph plotting commands are then available – G, GAM, GDIST, GHYST, GMAP, GSCAT and GSMAP. PLTZ will be useful for displaying several small graphs at once

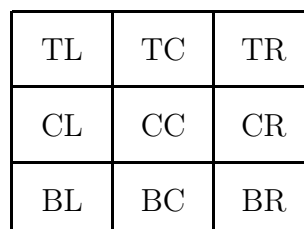
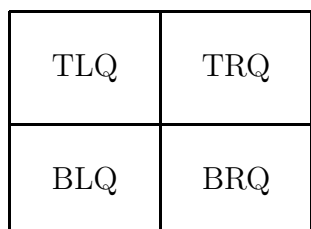
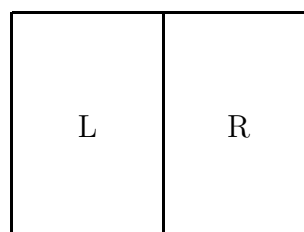
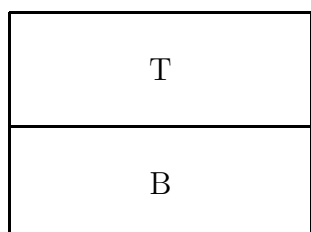
instead of one full-size graph. GC can be used to clear the whole screen beforehand. The PLTOFF command closes the current plotting window and reverts to the earlier one, if any. (There is, as a rule, no need to use PLTON and PLTOFF; a graphics window is, if necessary, opened automatically if there is any plotting to be done, and closed again when TPOINT is terminated.)

The remaining commands – CAPT, FRAME, MARKH, PENS – are used either for reducing plotting time, or for achieving special effects for demonstration and publication purposes. They can be ignored by novice users.

All of TPOINT's plotting goes to the screen. Multiple plotting zones are supported, allowing several plots to be displayed at once. The current plotting zone is specified by the PLTZ command:

PLTZ	use full display surface
or PLTZ name	use named region
or PLTZ x1 x2 y1 y2	use numerically specified region

The predefined zone names specify regular subdivisions of the display surface:



If numeric parameters are supplied they describe directly the region of the display surface which is to contain the plotting zone. The numbers are the two X extremes and the two Y extremes respectively, in units where the corresponding dimension of the display surface is unity. All four numbers are required. Irrespective of the shape of the zone and how it

was specified, plotting will actually occur in a zone of the standard aspect ratio centered within this area.

Hardcopy, in the form of a color PostScript file, can be generated by entering the command:

```
GC P file
```

The filename defaults to `tpoint.ps` in the standard TPOINT distribution. Some experimentation with pen and background colors (see the section on initialization files, later) may be necessary to get the best results, especially on black-and-white printers.

3.1 Using the G... Commands

The commands in TPOINT which plot graphs all have names beginning with G. The most important one for deciding what terms to add to the model is called simply **G**, and plots one component of the residuals against one coordinate. It has the following syntax:

```
G ydata xdata [scale]
```

The argument *ydata* specifies which component of the residuals is to be plotted:

H	in HA
X	EW on the sky
D	in Dec
P	corresponding to HA/Dec nonperpendicularity
A	in azimuth
S	horizontally on the sky
Z	in zenith distance
V	corresponding to Az/El nonperpendicularity
R	total residual

The argument *xdata* specifies what coordinate to plot against:

H	hour angle
D	declination
A	azimuth
Z	zenith distance
Q	parallactic angle
N	observation order

The optional argument *scale* indicates the vertical plotting scale: it is the absolute value of the largest residual to be plotted. In default, a scale is chosen automatically to suit the data.

The general strategy is to plot different components of the residuals against the various coordinates. Terms can then be added to the model (USE followed by FIT) to target any systematic effects that are seen. Some plots are more likely than others to have a mechanical interpretation, and attention should be confined to these, at least to start with. For example, an apparent relationship between polar axis elevation and azimuth, on the evidence of a G U A plot, should be treated with great scepticism (especially on an altazimuth mount), whereas systematic residuals on G N A and G W A plots (for an altazimuth) or on G U H and G L H plots (for an equatorial) are much more credible.

Because files of pointing observations are normally written in time order, G *ydata* N plots are useful for exposing shifts or drifts that have happened during the pointing run. Other x-axis meanings can be contrived by appropriately sorting the observation file prior to input.

The other plots have a variety of presentational and diagnostic roles. **GSCAT** plots residuals as a scatter diagram, like a shooting target; as well as being a good way of presenting the overall pointing performance, it exposes errant observations and abnormal distributions. **GSMAP** displays the residuals as error vectors on an orthographic projection (a distant view of the celestial sphere looking down on the zenith from above). The vectors (lines projecting from the square symbols which mark the stars) are the great-circle continuations of the pointing residuals. **GMAP** plots error vectors on a Cartesian Cylindrical projection, either HA/Dec or Az/El. **GDIST** plots histograms showing various sorts of error distribution, and is useful for testing whether the residuals are reasonably normal. **GAM** looks for changing polar/azimuth axis misalignment. Each residual is interpreted as being due to a misalignment of the specified “roll” axis – either polar or azimuth as specified. A histogram is plotted to show if the residuals do, in fact, favor one particular direction. The mean direction is calculated and reported, and then the component of each residual in the direction of this misalignment is plotted. **GHYST** looks for hysteresis, by drawing the error vector at a position which indicates the direction from which the telescope has come, assuming that the original data file contains all the observations and in the correct order, and that any hysteresis is related to the direction of the large scale movements in cylindrical coordinates (either HA/Dec or Az/El). A numerical estimate of the hysteresis is made, by summing the residuals oriented relative to the telescope movements.

Many of the plotting commands have arguments, for specifying scales and selecting HA/Dec and Az/El options *etc.* Full details are given in the section *Commands*, later.

4 POINTING DATA

At present, only one command is provided within TPOINT for reading a set of pointing observations: INDAT. Several different formats are supported; all are converted into a standard internal form, called the **data list**. The command is:

INDAT *file*

where *file* is the name of the file of pointing observations.

The new observations may either replace or be appended to any previous ones. This is controlled by a flag armed by the APPEND command. The flag is reset once the new data have been appended. In the append case the caption is reset and the one supplied in the data file is ignored. The new latitude replaces the previous one; it would, however, be very unusual to combine the data from several telescopes.

The MASK and UNMASK commands allow specified subsets of the observations to be suppressed temporarily. They are useful for verifying the independence of the solution in these different subsets. The most common application is where observations from only a specified region of the sky are included. Another use of MASK and UNMASK is to suppress observations whose total residual, on the sky, is greater than some specified amount; however, this is a dubious practice unless there are *a priori* reasons for suspecting the data are invalid – telescope malfunction or star misidentification for example. MASK and UNMASK can also remove and re-instate individual observations or sequences of observations. Genuinely erroneous observations (for example misidentified stars) should be removed outside TPOINT simply by using a text editor.

Note that observations with particularly large residuals can be identified by using the SLIST command with the optional argument, the threshold radial error in arcseconds.

4.1 Reference Frames

In the internal form produced by the INDAT command, each observation consists of the raw mechanical HA/Dec of the telescope and what is called in TPOINT the “observed” HA/Dec of the star (*i.e.* as affected by both diurnal aberration and refraction).

The raw telescope HA/Dec normally means either the mechanical HA/Dec directly read from dials or encoders, or, in the case of non-equatorial mounts, the HA/Dec obtained by

applying the appropriate canonical transformation to the actual readings. Az/El data, for example, are transformed by the standard text-book Az/El to HA/Dec rotation, using the longitude and geodetic latitude of the observatory as affected by polar motion. For telescope control systems which can only conveniently log mean places, an option is provided to convert this back to “observed” HA/Dec, assuming that all the telescope pointing corrections proper have been disabled but that refraction and diurnal aberration (as well as precession/nutation and annual aberration) have been included.

In order to avoid having to log anything which changes rapidly, the equatorial coordinates accepted by INDAT are in the form of RA/Dec rather than HA/Dec. The telescope HA is deduced simply by subtracting the given RA from the given sidereal time. This applies to all but one of the data formats, where star and telescope azimuths and elevations are supplied directly and must all correspond to one moment in time.

The star “observed” HA/Dec positions are obtained by allowing as necessary for proper motion, precession, nutation, annual aberration, and light deflection to obtain geocentric apparent place, followed by corrections for diurnal aberration and atmospheric refraction. It is also possible to supply the star data as “observed” RA/Dec by (i) including an optional record which disables the diurnal aberration corrections and (ii) omitting the temperature, pressure, *etc.* to disable the refraction corrections. This would be done in cases where the telescope control system which generated the pointing data has already applied these corrections (either correctly, or at least in a way which will be consistent with any subsequent implementation of the pointing model obtained from TPOINT).

The modeling procedures available elsewhere in this package have the job of expressing the relationship between these two sets of coordinates. It is thus the responsibility of the telescope control system itself to perform accurate mean to apparent place transformations, and to allow for Earth polar motion, diurnal aberration, refraction, *etc.*, before applying the pointing model as determined by using this package. Further information on the mean-to-observed place transformation can be found in the section *The Pointing Terms in Detail*, later.

4.2 INDAT Data Formats

The INDAT input file consists of free-format records up to 120 characters in length, as follows:

- CAPTION record
- OPTION records (optional)
- RUN PARAMETERS record
- OBSERVATION records
- 'END' or end-of-file

Blank lines and comments (which begin with a '!' character) can be included anywhere.

CAPTION record:

First 80 characters used, trailing blanks eliminated

OPTION records (optional):

' : NODA'	disables correction for diurnal aberration
' : ALLSKY'	disables horizon/zenith/pole checks
' : <i>equinox</i> '	required if telescope positions are mean places

The correction for diurnal aberration (maximum 0"3) should be disabled if the telescope control system itself omits it. The ALLSKY option is useful in cases where, for one reason or another, the observations are scattered all over the celestial sphere. Where the telescope positions are mean places, only one *equinox* (probably 'B1950' or 'J2000') may be specified, and applies to the whole file.

RUN PARAMETERS record:

latitude (°, ', ")
 UTC date (y,m,d)
 temperature (°C)
 pressure (mB)
 height above sea level (metre, default determined from pressure)
 relative humidity (range 0–1, default 0.5)
 observing wavelength (micrometre, default 0.55)
 tropospheric lapse rate (°K/metre, default 0.0065)

The latitude is mandatory. If the UTC date is omitted, the star and telescope data must not be mean places. If the refraction data (temperature and so on) are omitted, no corrections for refraction are made. Optical refraction is computed for wavelengths below 100 micrometres, and radio refraction for wavelengths longer than this figure. In the radio case, it is important to specify the humidity accurately.

OBSERVATION records – there are four different ways of expressing each observation, as follows:

Observation record format 1:

star geocentric apparent RA/Dec (h,m,s,°, ', ")
 telescope raw RA/Dec (h,m,s,°, ', ")
 local apparent sidereal time (h,m)
 [up to 2 auxiliary readings]

Observation record format 2:

star mean RA/Dec (h,m,s,°,′,″, μ_α, μ_δ , equinox)
 telescope raw RA/Dec (h,m,s,°,′,″)
 local apparent sidereal time (h,m)
 [up to 2 auxiliary readings]

Observation record format 3:

'*'
 identifier from star catalog
 telescope raw RA/Dec (h,m,s,°,′,″)
 local apparent sidereal time (h,m)
 [up to 2 auxiliary readings]

Observation record format 4:

star “observed” Az/El (°,°)
 telescope raw Az/El (°,°)
 [up to 2 auxiliary readings]

Note that format 4 requires exact times to be extracted from the telescope control system, whereas formats 1-3 use instead the telescope RA/Dec, which is unlikely to vary rapidly during tracking of a star and is therefore easier to get right. Moreover, precisely consistent Az/El and time information may simply be unavailable if special provision has not been made in the control software. However, in the case of formats 1-3, if sidereal time of high precision is available, this information can, and should, be supplied, by appending decimals to the sidereal time minutes.

Following the normal convention, the azimuths in format 4 are reckoned from north through east (though internally within the TPOINT software they go from south through east).

Two approaches are available for reading ‘foreign’ data formats. The first is to implement a local TPOINT command which accepts the foreign format and converts it directly into the internal form. The second approach, which does not involve modifications to TPOINT, is to write a freestanding program which translates the foreign format into one of the INDAT formats. Such translation programs are apt to be laborious to write, and frequently involve applying positional astronomy adjustments that will all be undone again when INDAT reads the file. Nevertheless, this approach is probably the best in most cases.

4.3 Star Catalogs

Several small star catalogs are supplied with the TPOINT system, as follows:

<code>stars20f.dat</code>	102 FK5 stars, 20° spacing, 5 ^m and fainter.
<code>stars20b.dat</code>	102 FK5 stars, 20° spacing, 5 ^m and brighter.
<code>stars15.dat</code>	183 FK5 stars, 15° spacing.
<code>stars10.dat</code>	411 FK5 stars, 10° spacing.
<code>starssch.dat</code>	UK Schmidt calibrators
<code>stars.dat</code>	default

`stars.dat` is loaded automatically when the system is initialized. TPOINT is delivered with `stars.dat` containing a concatenation of `stars20b.dat` and `starssch.dat`.

The catalogs are needed for cases where, in a file of pointing observations, the stars' catalog numbers are given rather than their full $[\alpha, \delta]$, proper motions *etc.* However, they are also valuable for actually carrying out pointing tests; using the chosen catalog and observing every star visible on the night concerned, a set of observations will be obtained where the samples are evenly spread over the sky, and where the plots of the results display minimal “bunching.” Regarding the latter effect, it is a common mistake to select stars on a straightforward $[\alpha, \delta]$ grid; because the stars all lie on meridians or small circles, they are bunched together on the plots, making it harder to see trends.

A private star catalog can be substituted, either at startup time via the command line or during a TPOINT session via the INST command. The original catalog can be restored at any time by means of an INST command with no arguments.

A star catalog is a sequential file of up to 80-character records. Here is an example record:

```
073716 00 00 51.781 +20 23 22.02 +0.0051 -0.146 1950.0
```

The first six characters of each record are an alphanumeric star identifier. The remainder of the record is the mean RA/Dec (hours, minutes, seconds, degrees, arcminutes, arcseconds), RA/Dec proper motions (seconds and arcseconds per year) and equinox (optionally preceded by 'B' or 'J' to distinguish between the FK4 and FK5 systems). Free-format input decoding is used. The file is terminated by 'END' or end-of-file. See the INCLUDE file STARS for the current maximum allowed number of records.

The standard TPOINT syntax rules apply to such catalog files, which may thus contain blank lines and comments (beginning with '!') to enhance readability. The INST command merely reads the records; actual decoding of the information in the catalog is deferred until a star is to be looked up, and errors will not come to light until then.

4.4 Coordinate Ranges

Most equatorial mountings can be configured so that the mechanical declination range extends “beyond the pole”. For example a horseshoe mounting normally allows access to regions of sky underneath the pole, and asymmetrical mounts such as cross-axis or German equatorials have to be inverted in declination in order to cross the meridian.

TPOINT accepts data containing a mixture of observations, and fits models where the various pointing terms change appropriately as the telescope switches into the other configuration. To obtain this behaviour, telescope $[\alpha, \delta]$ coordinates in the INDAT data file must be “mechanical” rather than “logical”. This means that in one of the two configurations, declinations beyond the pole should appear, paired with hour angles that are 12 hours from the logical value. Such observations are flagged ‘b’ on the SLIST listing; the $[h, \delta]$ coordinates reported appear in the conventional ranges.

Implementation of a pointing model should include provision for detecting the “beyond the pole” case; in general, the mechanical coordinates should be used in the formulas, and then the sign of the NS and EW corrections $\Delta\delta$ and $\Delta h \cos \delta$ should be reversed.

Note that the above features apply only to equatorial mountings. TPOINT does not include support for altazimuth mountings that have an elevation range that extends “beyond the zenith”; elevations must lie in the range 0–90°.

4.5 Saving and Combining Processed Data

When the modeling possibilities of any one set of pointing data have been exhausted it will be necessary to combine the results of several runs if further systematic effects are to emerge from the noise. In general, the different runs cannot simply be concatenated (which is done with the APPEND command) because some of the terms will have changed – the collimation corrections in particular. The UNFIT command allows this difficulty to be overcome.

UNFIT applies a pointing model in reverse, taking the current adjusted positions and predicting the observations that produce those adjusted positions when the model is applied. Thus a canonical model can be applied to a set of pointing residuals to yield new ‘observations’ which can be combined for further analysis. Two modes of operation are provided:

	UNFIT	to apply the current model
or	UNFIT N	to apply a null model (coeffs all zero)

If the star to telescope modeling option has been chosen (via the ADJUST command), the star positions are set and the telescope positions left alone. If the telescope to star option has been chosen, the reverse is true.

To understand UNFIT, think first of what the FIT command does. Assume that the modeling option ‘telescope to star’ has been chosen (the default). Under these circumstances, the FIT command takes the raw telescope positions and computes what coefficient values in the current model will give the smallest residuals, then applies the model to the ‘raw telescope’ positions to give the ‘adjusted telescope’ positions. The differences between these ‘adjusted telescope’ positions and the ‘star observed’ positions are the pointing residuals. UNFIT leaves these pointing residuals at their current values, but applies the pointing model in reverse to generate fictitious ‘observations’ (in this case raw telescope positions) which are consistent with both the current model and the current residuals.

If the current residuals and coefficient values are both simply the result of fitting, UNFIT will not have any significant effect. However, if one or more of the coefficients is set to a different value, UNFIT will produce a changed set of observations which, if fitted with the same model, will reproduce the changed coefficient values. This is how different pointing runs can be combined. First, you fit each run to the full model in the normal way, to determine the residuals; then you set all the coefficients, one by one, to whatever standard values are thought suitable; then you invoke the UNFIT command, to make the residuals and the model match; and finally you write out the amended data by using the OUTDAT command:

OUTDAT *file*

where *file* is the name of the file to be written. Two or more amended runs can then be combined (by using APPEND followed by INDAT), and will match as long as the other coefficients were consistent from run to run. If the combined file is fitted with the normal model, the arbitrary coefficients will have approximately the values that were chosen for them, and the other coefficients will be intermediate between the the values produced by each of the two runs separately.

Very often, a null model (all coefficients zero) is required, and here the UNFIT N command is useful. UNFIT N has essentially the same effect as setting all the coefficients to zero by hand and then executing an UNFIT command, except that it leaves the original coefficient values intact. UNFIT N is useful for recording pure residuals and eliminating the need for fitting with the original model when new terms are being investigated.

Before using OUTDAT you should set an appropriate caption with SETCAP.

4.6 Sample Data

Four examples of authentic pointing data are provided: from the UK Schmidt Telescope (1.2 metre aperture, fork equatorial); from the Anglo-Australian Telescope (3.9 metre, horseshoe equatorial) in the f/15 Cassegrain configuration; from the Palomar 5 metre telescope (horseshoe equatorial) in the f/17 IR configuration; and from the central reference

telescope of the Multiple Mirror Telescope (4.5 metre equivalent aperture, altazimuth). The UKST file refers to the star catalog `starssch.dat` (the same stars are included in the default `stars.dat` file; the other three files use explicit star positions and are therefore self-contained. The filenames are as follows:

UK Schmidt	<code>ukst.dat</code>
AAT	<code>aat15.dat</code>
Palomar	<code>hale.dat</code>
MMT	<code>mnt.dat</code>

(When using the `INDAT` command it is not necessary to specify the `.dat` filename extension. If the filename doesn't end in `.xxx` you can append a forward slash to stop the `.dat` being added.)

The recommended analysis procedure, which was described in the earlier section *An Example TPOINT Session*, begins as follows:

```

INDAT file

CALL EQUAT                      (equatorial)
or CALL ALTAZ                   (altazimuth)

FIT

CALL E6                          (equatorial)
or CALL A6                       (altazimuth)

```

It is then usual to start trying obvious extra terms via the `USE` command – tube flexure `TF`, fork flexure `FO`, *etc.*, as appropriate. Example models (which in the case of the `UKST` and `AAT` are the ones actually in service) are supplied as procedures, yielding the results shown in the following table:

datafile	procedure	σ''	terms
UKST	UKST	6.17	7
AAT15	AAT	1.26	10 fitted + 4 fixed
HALE	HALE	2.39	10
MMT	MMT	0.73	11

To reproduce, for example, the `AAT` result, you would simply type:

```
INDAT aat15
CALL AAT
```

(It will usually be necessary to give the full path for the `aat15.dat` file, something like `/usr/etc/tpoint/aat15`.) To display this AAT result as a scatter diagram, type:

```
GSCAT
```

(In this case, the circle in the middle of the diagram is roughly the size of a dime seen from a distance of one mile.)

It is important to understand that the RMS pointing figures which TPOINT produces are *a posteriori* and may not be realized in practice. They do not take into account long term stability, the effectiveness of any pre-observing calibration procedures, the correctness of the implementation of the model within the telescope control software, or the ability of the user interface to give the astronomer access to the available pointing performance.

4.7 Simulated Pointing Tests

When developing the pointing-model part of a telescope control system, refer to *The Pointing Terms in Detail*, later, for information on the mathematical form of TPOINT's various pointing terms. The operational implementation of the terms may well involve techniques which differ in some way from TPOINT's – perhaps by being more elaborate and general. Any substantial inconsistencies between TPOINT and the telescope software will manifest themselves as pointing errors, and telescope users will not experience the levels of performance which the TPOINT results appear to offer.

In order to check that the model as implemented in the telescope system is consistent with TPOINT, a “dummy” pointing test is recommended. This is like a real pointing test except that the telescope is left where it is after each blind setting rather than being guided onto the star. When the dummy pointing test is reduced with TPOINT, a perfect fit should be reported, and the coefficients should exactly match the values used by the control software. Without a test of this sort, errors of scaling and (especially) sign may go unnoticed.

Note that the dummy pointing test just described is a check on the software alone, with the telescope itself playing no part. Consequently, it is usually best to arrange that the control software can operate in a “simulation” mode, capable of generating a dummy pointing test offline. It is **strongly** recommended that dummy pointing tests be carried out from time to time, to verify that any revisions of the telescope software and TPOINT have not led to incompatibilities.

When TPOINT is used to process data from dummy pointing tests, it should be borne in mind that only if the model is implemented in *exactly* the same way as it is in TPOINT will the residuals be identically zero. For example, if spherical trigonometry formulae are used to apply corrections for which TPOINT uses a vector formulation, this may have detectable effects, especially if the affected terms have large coefficients and particularly for stars near the pole and/or zenith. Another possible cause for slightly imperfect fits is where all the terms in the model are ‘parallel’ rather than ‘chained’; although TPOINT computes all the corrections from the same starting-point, it accumulates them sequentially, and the telescope-control code should follow suit. Grouping the terms sensibly and then chaining the groups will, in general, give better results, especially if any of the coefficients (for example encoder zero-points) are large.

5 ADVANCED MODELING

TPOINT allows a straightforward model for a telescope to be generated easily and without requiring great cunning or insight, but also provides the tools more experienced and determined users will need when conducting more exhaustive analyses.

As already described, the general strategy for modeling a telescope from scratch is to input a data file with INDAT, to set up a basic geometrical model using CALL EQUAT or CALL ALTAZ, and to fit using the FIT command, repeating as necessary until the coefficients settle down. With the aid of the G... commands, plots of residuals can then be made and inspected for signs of systematic error. Plausible flexure terms can be tried (USE TF *etc.*), and any others that the particular telescope design suggests.

When adding new terms, pay attention to the standard deviation of the new coefficient, the effect on other terms, and whether the population standard deviation has gone down; a new term will almost always reduce the RMS but population σ is a better indication of whether the improvement is real. If an attempt is made to use two terms which are more or less indistinguishable (for example CH and PXH0, which are identical), the condition will be reported; if this happens, get rid of one of them via the LOSE command. In such ill-conditioned cases, the singular value decomposition (SVD) methods used by FIT will normally return a meaningful model, with the “true” value of a duplicated term being shared out between the two (or more) coefficients involved. Two common cases are (i) if two inseparable terms are present from the start, they each receive an equal share of the value, and (ii) where a new term is added to an already fitted model, and that term is inadequately distinguished from something already present, then the new term will be left close to zero. This behavior can be controlled by means of the FITTOL command, which allows the SVD ill-conditioned criterion to be set. A command FITTOL 0 will switch off the detection of ill-conditioning, whereupon FIT will return a conventional least squares fit, and any highly correlated terms will head off towards cancelling infinities. A FITTOL argument of between 10^{-3} and 10^{-2} will give a useful degree of control over ill-conditioning; the value is set to 10^{-2} initially. With FITTOL arguments much bigger

than 10^{-2} , there is increasing danger that respectable terms will be excluded from full fitting. However, whenever FIT decides to take action over ill-conditioning, it reports that this has occurred.

Do not try to extract more information from a given sample of data than the size of the sample justifies. A preliminary assessment of a telescope's capabilities can be made using perhaps 20-30 stars. Routine fitting of a typical operational telescope model, consisting of six geometrical terms, two or three flexures, and perhaps a few scale adjustments, centering corrections, *etc.*, calls for 50-100 stars, well-distributed over the whole observable sky. A campaign to expose high-frequency flexures and bumps should not be embarked upon without a sample of 500-1500 stars, obtained by combining multiple tests by means of the UNFIT and APPEND facilities. Even with this large number of stars, fitting a full set of polynomials or harmonics up to the required degree in one go is impractical, and new terms must be tried out in groups of no more than about 20.

When first analysing a new telescope, it is not uncommon to see obvious systematic residuals on the simple graphs of error in one coordinate plotted against that or another one – plotting error in zenith distance versus against zenith distance (G Z Z) for example. However, once these straightforward effects have been treated, systematic errors can still hide in what looks like noise. Some of these can be exposed by using more specialized plots – zenith distance errors against parallactic angle (G Z Q), errors in HA/Dec non-perpendicularity plotted against HA (G P H), and so on. However, certain effects which depend simultaneously on two coordinates may prove more stubborn; given a data set of adequate size, the solution is to use the MASK and UNMASK commands to select bands in one coordinate, allowing the residuals for that one band to be plotted.

At various stages, the GHYST command should be tried, to assess whether the current pointing accuracy seems to be limited by hysteresis.

When pursuing low-level flexures and irregularities, difficult questions arise. To what extent is the model physically meaningful? Has adding empirical terms affected the supposedly well-understood underlying model? Is it worth trying to keep a grip on physical reality, or wouldn't it be just as good to fit a massive set of polynomials or harmonics?

An approach that seems to preserve the considerable advantages of having a model firmly based on mechanical reality, yet which allows all the power of empirical modeling to be unleashed, is to construct a model which includes both physical and empirical terms, but at no stage to leave both sets free to float at once during fitting. The following procedure is one way to do this:

1. Fit many pointing tests with the best available model; reject any obviously bad runs; UNFIT the rest onto a model with a fixed set of typical coefficient values; OUTDAT to a file; use APPEND to concatenate all these files; INDAT the result.
2. FIX everything except maybe one or two zero points.
3. USE a selection of empirical terms.

4. FIT; reject any disruptive or poorly-determined terms and FIT again. Repeat until only well-determined terms (say 2σ or better) remain.
5. Plot the residuals to see what extra terms might help.
6. Repeat from step 3 until further improvements seem unlikely.
7. FIX everything, un-fix the original model from step 1 by means of USE, and FIT.
8. Repeat from step 2 until neither the physical model nor the empirical terms are changing significantly.
9. Repeat from step 1 inserting into to the standard model the newly determined empirical terms **FIXed at the values just determined**. Depending on how the terms will be coded operationally, decide whether to flag them CHAINED or PARALLEL.
10. Once everything has stabilized, code the empirical model into scripts in your own procedure library, remembering to FIX the terms in question.

Such advanced modeling will require repeated fitting of large datasets. This will take time and be prone to mistakes. A good way to proceed is to pre-program the key steps using a private procedure library. Such a library can be edited during the TPOINT run by means of the SPAWN command, and then re-input with the INPRO command. A private library is also an option when running in batch mode; instead of specifying TPOINT commands in the batch control file, the latter can simply start TPOINT, read the procedure library with INPRO, and execute the required library routine by means of an appropriate CALL.

6 HISTORY AND ACKNOWLEDGMENTS

TPOINT grew out of the work John Straede and the present author carried out at the AAT between 1974 and 1980 using Interdata 70 computers. Most of the early least-squares software was written by John Straede, culminating in the very successful IBORL2 program. The present author then developed a new program based on the IBORL2 fitting algorithm, but with improved interactive model building capabilities, extra graphics options, *etc.*; this program was the direct ancestor of the present TPOINT Fortran implementations. In the early 1980s the program was ported from the Interdata to the VAX and then refined and expanded, exploiting the Starlink SGS/GKS graphics facilities and the present author's SLALIB positional-astronomy library as they became available. VAX-TPOINT underwent a major refurbishment in 1986/87 to prepare it for release through Starlink. During the period 1990-92 a version which could be run on multiple Starlink-supported Unix platforms was developed. In parallel, a proprietary PC/MS-DOS version was developed, using Microsoft FORTRAN, followed by a completely new implementation using ANSI C. The latter provides an almost identical interface to the user as that for

earlier TPOINTS, but has an entirely different software architecture, designed to allow the system's component parts to be embedded within telescope control applications.

Those who have given advice and encouragement during TPOINT's history include: Peter Gillingham, Joe Wampler, Don Morton, Steve Lee, Robert Laing, Ken Elliott, Hilton Lewis, Bob Kibrick, Fang Yanling, Russ Owen, Stephen Bisque and Krister Wirestrand.

7 THE COMMANDS IN DETAIL

This section contains a description of every TPOINT command, in alphabetical order. A quick reference list is given at the end of the document.

coeff Set/Inquire Coefficient Value *coeff*

FUNCTION :

The value of any of the coefficients in the current model may be set or inquired by using its name as the command.

COMMAND :

coeff value

where *coeff* is the name of the coefficient, and *value* is the value.

NOTES :

If no argument is supplied, the coefficient is unaltered – merely logged.

In most cases *value* is in arcseconds; a few terms have dimensionless coefficients.

ADJUST Select Model Direction **ADJUST**

FUNCTION :

ADJUST allows one of two methods of applying the pointing model to be selected – whether the telescope positions are to be adjusted to fit the star positions or *vice versa*.

COMMAND :

ADJUST T	to adjust the telescope positions
or ADJUST S	to adjust the star positions

NOTES :

If no argument is supplied, the method is unaltered – merely logged.

If the ADJUST command results in the direction being changed, the order of the terms in the pointing model is reversed to match.

A given set of data will not produce precisely the same coefficients if the model is reversed. The differences will be small unless one or more of the coefficients is

very large – hundreds of arcseconds or more. Under these circumstances there is in any case a danger that TPOINT's simple formulation of the pointing terms does not match exactly the way the model is implemented in the control software of the telescope concerned. Large collimation corrections, in particular, may require more rigorous geometry than TPOINT can conveniently offer, and detailed knowledge of field distortions.

The results of any previous FIT are not changed when ADJUST is used and, if a fresh FIT is to be carried out, the RESET command should be used first in order to eliminate the previous corrections.

APPEND Prepare to Append Data APPEND

FUNCTION :

APPEND prepares to concatenate the next set of pointing observations with the ones already input.

COMMAND :

APPEND ON	next set of observations will be appended
or APPEND OFF	cancel previous APPEND request

NOTES :

The argument defaults to ON.

The new data will be appended when the next INDAT command is executed.

At the time an APPEND request is made, a set of pointing observations must already be present in the data list.

CALL Call a Library Procedure CALL

FUNCTION :

CALL calls a TPOINT library procedure.

COMMAND :

CALL *procedure*

where *procedure* is the name of the procedure to be called (1–10 characters).

ECHO Enable/Disable Command Echoing **ECHO**

FUNCTION :

ECHO enables or disables the echoing of commands to the screen during execution of library procedures.

COMMAND :

	ECHO ON	enable command echoing
or	ECHO OFF	disable command echoing

NOTES :

The argument defaults to ON. However, echoing is disabled when TPOINT is started.

Echoing is useful for debugging, but can clutter the screen at other times.

END Terminate the Session **END**

FUNCTION :

END terminates TPOINT.

NOTE :

Additionally, QUIT, QU and CTRL/Z are all interpreted as END commands.

FIT Fit Model to Data **FIT**

FUNCTION :

FIT computes the coefficient values for the current pointing model which fit the observations best, and updates either the adjusted telescope coordinates or the adjusted star coordinates depending on which of these two options is in force (see the ADJUST command).

COMMAND :

	FIT	to perform a normal fit
or	FIT N	to apply the current model without fitting

NOTES :

If two terms in the model are too highly correlated to be reliably distinguished, this is reported by FIT so that one of them can be eliminated from the model. The FITTOL command provides control over the treatment of such ill-conditioned cases, allowing the acceptance criterion used by the “singular value decomposition” fitting method used in FIT to be specified. If this criterion is set to zero, by means of a FITTOL 0 command, the fit is simply a conventional least-squares approximation, and any highly correlated terms will be awarded meaningless, large and mutually cancelling values, accompanied as a rule by a poor overall RMS result. With a FITTOL parameter of (for example) 0.01, such correlated terms are kept under control and the model is sound.

If all the coefficients have been FIXed, the result of the FIT command is simply to recompute the residuals, and in this case FIT and FIT N are equivalent.

FITTOL	Set ill-conditioning tolerance	FIT
---------------	--------------------------------	------------

FUNCTION :

FITTOL specifies and reports the acceptance criterion for the singular value decomposition algorithm used in the FIT command.

COMMAND :

FITTOL *v*

where *v* is the tolerance used by the FIT command to decide whether action is to be taken to keep a poorly determined solution under control.

NOTES :

A tolerance value *v* between zero and 0.01 is recommended. The initial value is 0.01.

If no argument is supplied, the current tolerance is reported but not changed.

FIX	Fix the Specified Terms	FIX
------------	-------------------------	------------

FUNCTION :

FIX excludes one or more terms from the fit but not from the model.

COMMAND :

FIX *coeff1 coeff2 etc.*

where the arguments are the names of the coefficients to be frozen at their current values.

NOTES :

If no arguments are supplied, the whole model is fixed.

If any argument is unrecognized, the entire command is rejected.

FRAME Enable/Disable Frames **FRAME**

FUNCTION :

FRAME enables or disables the plotting of graph frames. A frame is a rectangular box drawn just inside the edge of the plotting zone.

COMMAND :

	FRAME ON	enable plotting of frames
or	FRAME OFF	disable plotting of frames

NOTE :

If no argument is supplied, the default is frames enabled.

G Plot Residuals **G**

FUNCTION :

G plots the pointing residuals as the component in one coordinate against that or another coordinate.

COMMAND :

G *ydata xdata scale*

where *ydata* is one of the following:

H	pointing error in HA
X	pointing error EW on the sky
D	pointing error in Dec
P	pointing error corresponding to HA/Dec nonperpendicularity
A	pointing error in azimuth
S	pointing error horizontally on the sky
Z	pointing error in zenith distance
V	pointing error corresponding to Az/El nonperpendicularity
R	total pointing error

and *xdata* is one of the following:

H	hour angle
D	declination
A	azimuth
Z	zenith distance
Q	parallactic angle
N	observation order

The optional argument *scale* indicates the vertical plotting scale: it is the absolute value of the largest residual to be plotted. In default, a scale is chosen automatically to suit the data.

NOTE :

The residuals are in the sense telescope minus “observed”.

GAM Look For Axis Misalignment **GAM**

FUNCTION :

GAM plots the pointing residuals interpreted as a misalignment of either the polar or the azimuth axis. Two superimposed graphs are plotted, showing respectively (i) the orientation and (ii) the amount of misalignment of the polar or azimuth axis that would produce each of the residuals. Graph (i) consists of the orientations calculated for each observation plotted in histogram form. Graph (ii) shows the component of pointing residual for each observation in the direction of the mean orientation. The x-axis of the two graphs is the hour angle or azimuth.

COMMAND :

GAM *type scale*

The *type* is E or Q for equatorial and A or Z for Az/El. The equatorial plots have hour angle as their x-axis and look for misalignment of a polar axis. The Az/El plots have azimuth as their x-axis and look for misalignment of an azimuth axis. The Q and Z options suppress an informational message which is normally sent to the screen. This argument defaults to E.

The *scale* indicates the plotting scale for the amount-of-misalignment plot, and is the absolute value of the largest residual to be plotted. In default, a scale is chosen automatically to suit the data.

NOTE :

When constructing the histogram and computing the mean orientation, each individual orientation is weighted by the size of the supposed axis misalignment.

GC Graphics Device Control **GC**

FUNCTION :

GC provides special control functions for the graphics device. Two functions are supported by the present implementation of TPOINT:

GC [C] clears the display surface
 GC P [*file*] writes a file for printing

NOTES :

For the 'P' option, the filename defaults to that specified in the initialization file `tpoint.ini`.

GDIST Plot Error Distributions **GDIST**

FUNCTION :

GDIST plots distributions of the pointing residuals.

NOTE :

The histograms labelled X, D, S and Z are the components east-west, north-south, left-right and up-down; the histogram labelled R is for the total pointing errors.

GHYST Hysteresis Plot **GHYST**

FUNCTION :

GHYST attempts to expose hysteresis by assuming that the direction (and perhaps distance) from the current observation to the previous observation determine the direction (and perhaps size) of the effect. The format is a polar plot, with north at the top if the equatorial option has been selected, or up at the top if the altazimuth option has been selected. Each observation (except the first) is plotted as a square marker, from the center of which comes a line indicating the pointing residual. The position of the marker shows in what direction the telescope had to move in order to travel from the previous star, and how far (on a logarithmic scale).

COMMAND :

GHYST *type scale*

The *type* is E or Q for equatorial and A or Z for Az/El. The equatorial plot has north at the top, whereas the Az/El plot has up at the top. The Q and Z options suppress an informational message which is normally sent to the screen. This argument defaults to E.

The *scale* is the residual in arcsec to give a vector of nominal maximum length. This defaults to the largest actual residual providing it is reasonable.

NOTES :

A numerical estimate of the hysteresis is made and reported. It is obtained by rotating each pointing residual by the orientation of the preceding telescope movement, accumulating vectorially, and finally dividing by the number of active observations.

Note that various important but dubious assumptions are being made:

- The order of observations in the data list is the same as in reality.
- The telescope travelled directly from one star to the next, along a straight line in Cartesian Cylindrical coordinates.
- Any hysteresis comes from the large scale movements between observations and is unaffected by small scale adjustments during acquisition.

Residuals are in the sense telescope minus “observed”.

For equatorial mounts, there may be hysteresis in both HA/Dec and Az/El, and it is worth trying both. Altazimuth mounts are not likely to display any HA/Dec effects, and the (default) E option is not appropriate for this case.

Because most observing sequences tend to favor particular telescope movement directions the graph produced by GHYST is cluttered, with many points bunched together. The appearance may be improved by using the MARKH command to reduce the size of the markers.

GMAP Cartesian Cylindrical Plot GMAP

FUNCTION :

GMAP draws a map of the pointing residuals as error vectors on a Cartesian Cylindrical projection.

COMMAND :

GMAP *type scale*

The *type* is E for equatorial and A for Az/El. This argument defaults to E.

The *scale* is the residual in arcsec to give a vector of nominal maximum length. This defaults to the largest actual residual providing it is reasonable.

HELP Enter HELP Session **HELP**

FUNCTION :

HELP enters a HELP session.

COMMAND :

HELP *topic*

where *topic* is the HELP topic to be displayed.

NOTES :

If no *topic* is specified, the top level HELP topics are displayed.

The TPOINT online HELP library resembles a VAX/VMS HELP library, and may be explored in the same straightforward way. To end the HELP session, either keep pressing ENTER until the * prompt reappears or type CTRL/Z followed by ENTER.

INDAT Read File of Observations **INDAT**

FUNCTION :

INDAT reads a file of telescope pointing observations and converts it into the internal form required for analysis.

COMMAND :

INDAT *file*

where *file* is the name of the file of pointing observations.

NOTES :

The internal form generated by INDAT is called the *data list*.

Several input formats are supported. Details are given in the section *Pointing Data*, earlier.

INMOD	Read Model from File	INMOD
--------------	----------------------	--------------

FUNCTION :

INMOD reads a pointing model from a file.

COMMAND :

INMOD *file*

where *file* is the name of the file containing the model.

NOTES :

Model files can be written by the OUTMOD command.

Any existing model is superseded by the one input.

In addition to the model itself, the file contains a caption, a number of observations, and an RMS; these latter items are not used by INMOD.

INPRO	Input a Procedure Library	INPRO
--------------	---------------------------	--------------

FUNCTION :

INPRO inputs a procedure library, replacing any previous one.

COMMAND :

INPRO *file*

where *file* is the name of the procedure file to be input.

NOTES :

If a filename is not specified, the procedure library which was input at the start of the TPOINT session is re-read.

This command is not permitted within procedures.

A useful sample procedure library is supplied with the TPOINT system and is loaded automatically when the system is initialized. The command INPRO with no arguments will reload it.

The initialization procedure INIT, called when TPOINT is first started, is **not** called when INPRO is used.

MARKH Specify Marker Height **MARKH**

FUNCTION :

The MARKH command specifies the marker height for plotting.

COMMAND :

MARKH *h*

where *h* is the marker height in plotting units.

NOTES :

The default is 0.2.

The markers controlled in this way are the square and asterisk symbols used by the G... commands.

The normal use of MARKH is to reduce the marker size where the number of observations is large and the default size gives a cluttered result.

MASK Flag Selected Observations Inactive **MASK**

FUNCTION :

MASK flags selected pointing observations inactive. The selection is made by area of sky, total residual, or sequence number.

COMMAND :

MASK *quantity condition value*
or MASK *n1 n2*

where the arguments are as follows:

<i>quantity</i>	H (HA), D (Dec), A (Az), Z (ZD), R (radial error) or N (observation number)
<i>condition</i>	L (less than) or G (greater than)
<i>value</i>	cutoff value (hours for H, degrees for D, A or Z, arcseconds for R, number for N)
or	
<i>n1</i>	first observation number
<i>n2</i>	last observation number (defaults to <i>n1</i>)

NOTES :

If the arguments are omitted, all observations are MASKed.

The inverse command is UNMASK.

Azimuths lie within the range 0 to 360°, reckoned from north through east.

Observation numbers:

- start at 1 and refer to all observations, whether or not currently active;
- can be given in either order;
- can be less than 1 or greater than the current number of observations without ill effect.

EXAMPLES :

MASK H L 60	makes inactive all observations where hour angle is less than 60° (4 ^h)
MASK Z G 20	makes inactive all observations where zenith distance is greater than 20° (elevation less than 70°)
MASK N G 20	makes inactive all but the first 20 observations
MASK 3	makes inactive the 3rd observation
MASK 1 25	makes inactive the first 25 observations
MASK	makes all the observations inactive

MESLEV Specify Message Level **MESLEV**

FUNCTION :

MESLEV allows the volume of messages going to the screen and to the log file to be restricted to a nominated “severity level”.

COMMAND :

MESLEV *mess rept*

where *rept* and *mess* are the limiting message severity levels for the report and message devices respectively, each an integer in the range 0 to 5.

NOTES :

Different *rept* and *mess* values have the following effects:

mess/rept

- 0 don't suppress any messages
- 1 suppress presentational messages
- 2 ... and informational messages
- 3 ... and warning messages
- 4 ... and application error messages
- 5 suppress all messages including system errors

If the second argument is omitted, the existing setting for the report device remains in force. If both arguments are omitted, both values are set to zero.

This command is most useful for reducing the volume of messages during the execution of library procedures; during interactive use it is best to enable all messages.

OUTDAT Write file for INDAT **OUTDAT**

FUNCTION :

OUTDAT outputs the current pointing data as a file that can be read in by INDAT.

COMMAND :

OUTDAT *file*

where *file* is the name of the file to be written.

NOTES :

Only active observations (those not rendered inactive via the MASK command) are output.

The file which is written does not contain "observed" star right ascensions. Zero sidereal time and dummy right ascensions equal to minus the hour angle are used instead.

OUTMOD Write model to a file **OUTMOD**

FUNCTION :

OUTMOD outputs the current model to a file.

COMMAND :

OUTMOD *file*

where *file* is the name of the file to be written.

NOTES :

The file can be read by means of the INMOD command.

As well as writing the model information itself, OUTMOD stores the caption, number of stars, and RMS for the current set of observations.

PARAL Apply Terms in Parallel **PARAL**

FUNCTION : PARAL is used to indicate which terms are to be evaluated in parallel to the immediately preceding term in the model. This allows several consecutive terms to use the same position as their starting point, rather than each successively adjusting the position before it is used by the next term.

COMMAND :

PARAL *coeff1 coeff2 etc.*

where the arguments are the names of the terms to share starting points with their predecessors.

NOTES :

If no arguments are supplied, all the terms in the model use the same starting point – the initial, unadjusted position.

If any argument is unrecognized, the entire command is rejected.

The starting position for a term named in this command will be the adjusted position produced by the last term which is ‘chained’ rather than ‘parallel’. Thus the first term in a group of terms sharing a common starting point will, in fact, be ‘chained’.

The converse command is CHAIN.

PENS Specify Pens **PENS**

FUNCTION :

PENS specifies and reports the pens used for plotting on the current workstation.

COMMAND :

PENS *f c a l p o*

where the arguments are the SGS pen numbers for:

f	frame
c	caption
a	axes
l	labels
p	points which are valid
o	points which are off-scale

NOTES :

Arguments default to the existing value. If any argument is invalid none of the pens are changed.

The actual colors and line styles are dependent on the implementation of the GKS graphics package being used. Note that although colored pens may be used to produce both colored lines and text, pens giving dotted or broad lines may not produce analogous effects on text.

PERFCT	Create Ideal Observations	PERFCT
---------------	---------------------------	---------------

FUNCTION :

PERFCT creates a list of artificial error-free pointing observations.

COMMAND :

PERFCT ϕ

where ϕ is the telescope latitude to which the artificial observations will correspond, given as degrees, arcminutes, arcseconds.

NOTE :

The arcminutes and/or arcseconds may be omitted. If the entire argument is omitted the latitude found in any existing data list is used. If the data list is empty, latitude zero is used.

PLTOFF	Close Plotting Window	PLTOFF
---------------	-----------------------	---------------

FUNCTION :

PLTOFF closes the current plotting window and reverts to the previous one, if any.

COMMAND :

PLTOF

PLTON Open Plotting Window **PLTON**

FUNCTION :

PLTON opens a new plotting window.

COMMAND :

or PLTON *label*

where *label* appears as the name of the window.

NOTE :

If no plotting window is open when a graphing command is used there is an automatic PLTON.

PLTZ Select a Plotting Zone **PLTZ**

FUNCTION :

PLTZ selects a plotting zone.

COMMAND :

PLTZ use full display surface
 or PLTZ *name* use named region
 or PLTZ *x1 x2 y1 y2* use numerically specified region

where *name* is the zone name (see below) and *x1 x2 y1 y2* specify the zone extent directly.

NOTES :

The zone *name* refers to a range of regular subdivisions of the display surface. For 3×3 partitioning, the names are TL, TC, TR, CL, CC, CR, BL, BC, BR (T=top, C=center, B=bottom, L=left, R=right). For 2×2 the names are TLQ, TRQ, BLQ, BRQ. For 2×1 the names are T, B, L, R.

If numeric parameters are supplied (all four are required) they specify the X range and Y range in a coordinate system where the display surface is a unit square with its origin at the bottom left-hand corner.

REPLEN Specify Report Length **REPLEN**

FUNCTION :

REPLEN selects the report length option.

COMMAND :

REPLEN *option*

where *option* is either S for short or L for long.

NOTES :

The default option is L.

REPLEN affects the volume of output from commands such as INDAT and SLIST.

RESET Zero the Coefficients **RESET**

FUNCTION :

RESET sets all pointing coefficients to zero and removes all pointing corrections from the data list.

RETURN Return from a Procedure **RETURN**

FUNCTION :

RETURN returns from a library procedure.

NOTE :

A RETURN command issued from the command device results in an error message.

SETCAP	Set the Caption	SETCAP
---------------	-----------------	---------------

FUNCTION :

SETCAP sets the caption string.

COMMAND :

SETCAP *string*

where *string* is the required caption, and consists of either the whole of the command line following the command name but with leading and trailing blanks eliminated or, if the first non-space character following the command name is a ' or " delimiter, the string between that delimiter and the next appearance of the same one (unless the end of the command is reached first).

NOTES :

If no argument is supplied the caption is set to a single space.

If the caption contains lowercase characters, enclose it in single or double quotes.

SHOW	Display Parameters	SHOW
-------------	--------------------	-------------

FUNCTION :

SHOW displays and logs the current values of various TPOINT internal parameters.

NOTE :

The output from SHOW is a useful guide to some of the features of TPOINT, and includes the names of the commands used for changing the parameters listed.

SLIST	List the Observations	SLIST
--------------	-----------------------	--------------

FUNCTION :

SLIST lists the pointing observations and the current residuals.

SLIST *r*

where *r* is the report threshold – the minimum radial error below which an observation is not listed (in arcseconds, default zero).

NOTES :

The SLIST output includes the residuals in various directions rather than simply in radius.

If just the RMS residuals are needed the command 'REPLEN S' may be used to suppress reporting the individual observations.

The usual value for r is the default zero, so that all stars are listed (always depending on the report-length option, controlled by the REPLEN command).

MASKed stars are regarded as having zero radial error, so that they never appear in the listing for non-zero r .

The azimuths are reckoned from north through east.

SPAWN	Execute a Shell Command	SPAWN
--------------	-------------------------	--------------

FUNCTION :

SPAWN executes one or more C-shell commands.

COMMAND :

SPAWN *string*

where *string* is the required shell command, and consists of either the whole of the TPOINT command line following the 'SPAWN' name but with leading and trailing blanks eliminated or, if the first non-space character following the command name is a ' or " delimiter, the string between that delimiter and the next appearance of the same one (unless the end of the command is reached first).

NOTE :

If no argument is supplied a new shell is spawned, allowing a sequence of commands then to be entered. To return to TPOINT, issue an **exit** command.

UNFIT	Apply Model in Reverse	UNFIT
--------------	------------------------	--------------

FUNCTION :

UNFIT applies a pointing model in reverse, taking the current adjusted positions and predicting the observations that produce those adjusted positions when the model is applied.

COMMAND :

	UNFIT	to apply the current model
or	UNFIT N	to apply a null model (coeffs all zero)

NOTES :

If the star to telescope modeling option has been chosen, (via the ADJUST command) the star positions are set and the telescope positions left alone. If the telescope to star option has been chosen, the reverse is true.

A common use for the UNFIT command is where a canonical model is applied to a set of pointing residuals to yield ‘observations’ which can be combined for further analysis.

For further details, see the section *Combining and Saving Processed Data*, earlier.

UNMASK Flag Selected Observations Active **UNMASK**

FUNCTION :

UNMASK flags selected pointing observations active. The selection is made by area of sky, total residual, or sequence number.

COMMAND :

	UNMASK	<i>quantity condition value</i>
or	UNMASK	<i>n1 n2</i>

where the arguments are as follows:

<i>quantity</i>	H (HA), D (Dec), A (Az), Z (ZD), R (radial error) or N (observation number)
<i>condition</i>	L (less than) or G (greater than)
<i>value</i>	cutoff value (hours for H, degrees for D, A or Z, arcseconds for R, number for N)
or	
<i>n1</i>	first observation number
<i>n2</i>	last observation number (defaults to <i>n1</i>)

NOTES :

If the arguments are omitted, all observations are UNMASKed.

The inverse command is MASK.

Azimuths lie within the range 0 to 360°, reckoned from north through east.

VT Clear the text screen **VT**

FUNCTION :

VT declares the text screen VT100-compatible, selects the scrolling region and clears the screen.

COMMAND :

VT *top bottom* (declares ANSI and specifies scroll)
or VT N (declares non-ANSI)

NOTES :

The scrolling region extends from line *top* to line *bottom* inclusive. On a VT100-compatible screen, the top line is line 1, and the bottom line is line 24. The specified region must be at least two lines in extent.

The default values are 24 for *bottom* and 1 for *top*. Thus if only the first argument is given the scrolling region extends down to the bottom of the screen, and if no arguments are given the whole screen is used.

The screen is cleared each time this command is used, unless the “N” option is specified. The VT command without arguments is thus a useful way of decluttering the screen on terminals which have independent but superimposed graphics and alpha planes.

The effect of using this command to declare that the terminal is ANSI cannot be predicted on non-ANSI terminals.

8 THE POINTING TERMS IN DETAIL

This section contains a description and a formula for every TPOINT pointing term; the list is in alphabetical order.

The formulas are an essential resource for anyone wishing to write telescope control software incorporating TPOINT corrections. However, note that for clarity they are given in the simplest form possible, usually as spherical trigonometry expressions, and it may not be enough simply to code them into BASIC, FORTRAN, C *etc.* as they stand: it is up to the programmer to attend to such details as numerical precision, wrap-around and the avoidance of computational problems in awkward cases such as close to zenith, pole and horizon.

In addition, the programmer is responsible for providing the transformation from catalog mean place into the “observed” place which is the starting-point for TPOINT corrections. Starting from J2000 mean $[\alpha, \delta]$, the sequence of operations involved in this transformation is shown diagrammatically in Figure 1. Algorithms for the standard transformations (precession *etc.*) can be found in standard text books.

The pointing terms obey the following nomenclature and sign conventions:

- **hour angle:** h is positive west of the meridian.
- **declination:** δ is positive north of the equator.
- **parallactic angle:** q is positive west of the meridian.
- **azimuth:** A is zero for due south, and 90° for due east.²
- **zenith distance:** the zenith is at $\zeta = 0^\circ$.
- **elevation:** $E = 90^\circ - \zeta$.
- **hour angle and east-west corrections:** Δh and $\Delta X (= \Delta h \cos \delta)$ are positive when the corrected telescope position is west of the uncorrected position.
- **declination corrections:** $\Delta \delta$ is positive when the corrected telescope position is north of the uncorrected position.
- **azimuth and left-right corrections:** ΔA and $\Delta S (= \Delta A \cos E)$ are positive when the corrected telescope position is to the left of the uncorrected position as seen by someone standing at the telescope looking at the sky.
- **elevation corrections:** ΔE is positive when the corrected telescope position is above the uncorrected position.

²Be careful! The more usual sign convention for azimuth is north through east, but for TPOINT a right-handed system was preferred.

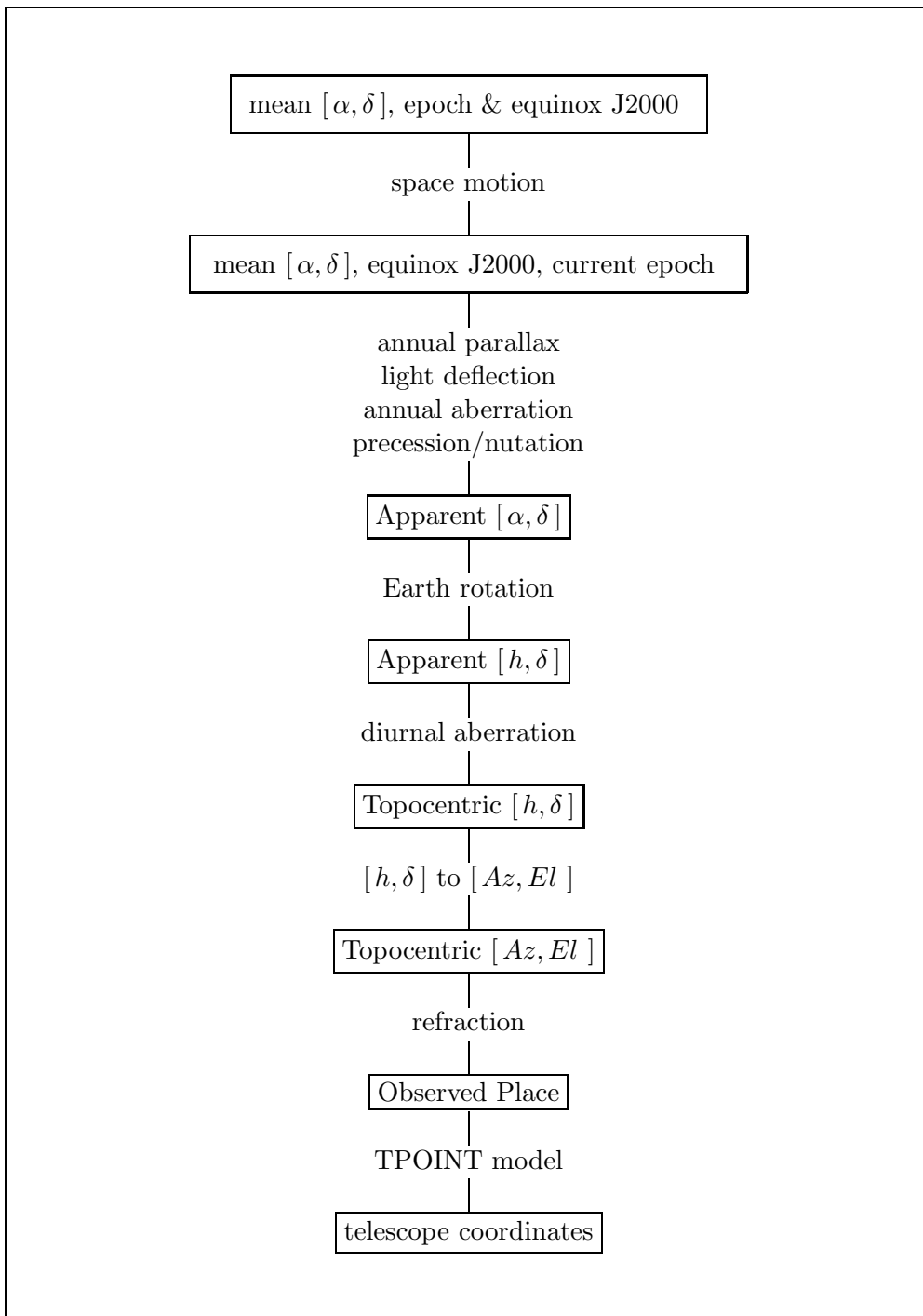


Figure 1: The TPOINT corrections are just part of the sequence of transformations and corrections needed to bridge the gap between (i) where the catalog says a star is and (ii) where the telescope needs to be pointed to see it. It is up to whoever is writing the telescope software to provide the basic transformation from catalog coordinates to “observed place”. (In the diagram, parallax, light deflection and diurnal aberration are included for completeness but are negligible for most practical purposes related to TPOINT.)

H	hour angle
D	declination
A	azimuth
Z	zenith distance
Q	parallactic angle

expressed in radians. Trailing *ci* or *i* fields, if omitted, default to unity. For example, a change in hour angle proportional to hour angle (*i.e.* a scale change, such as might be necessary with a roller-driven encoder) can be produced by using the term PHH.

The same independent variable can be specified twice, allowing powers up to 18 to be used.

FORMULA :

The general scheme is as described above. To take a specific example, PSA1E2 is a polynomial (P) which models an effect which produces a leftwards shift on the sky (S) proportional to $A \cdot E^2$ (A1E2):

$$\Delta S = + \text{PSA1E2 } A E^2$$

A and E are in radians.

NOTES :

Polynomials are very powerful and general, but when $i > 1$ are apt to behave badly outside the area covered by pointing observations. They can be useful for attacking specific irregularities and flexures which gentler, trigonometry-based, terms are too smooth to attack. When using polynomials in this way, it is wise to FIX the “theoretical” model, except for zero-point terms (IH, ID, CH, IA, IE, CA), allowing the polynomial access only to the residual errors.

Note that polynomials are sensitive to “wrap”: azimuth 10° and azimuth 370° are **not** the same thing to a polynomial (unlike a trigonometrical term).

harmonic

HARMONIC

harmonic

DESCRIPTION :

Terms with names that start with the letter ‘H’ are harmonics, which apply adjustments to a *result* coordinate which are proportional to the sine or cosine of one *input* coordinate with the sine or cosine of another. As a rule, such terms are used empirically, but in many cases there may be a simple mechanical interpretation. Indeed, most of the non-empirical terms can be “spelt out” as harmonics.

SYNTAX :

Harmonic terms have names of the forms:

$H r f c [i] [f c [i]]$
 or $H r f c i i$

The initial 'H' identifies this term as a harmonic.

The r field describes the result, and is one of the following:

H	result is in hour angle
X	result is east-west on the sky
D	result is in declination
U	result tilts polar axis up/down
L	result tilts polar axis left/right
P	result changes HA/Dec nonperpendicularity
A	result is in azimuth
S	result is left-right on the sky
Z	result is in zenith distance
N	result tilts azimuth axis north/south
W	result tilts azimuth axis east/west
V	result changes Az/El nonperpendicularity

Each fci , fci and fci field indicates a function of an integer multiple of an independent variable c , one of:

H	hour angle
D	declination
A	azimuth
Z	zenith distance
Q	parallactic angle

The f field is either S for sine or C for cosine. Each i is in the range 0–9, allowing frequencies from zero to 999 cycles per revolution in the case of simple one-coordinate harmonics, and 0 to 9 cycles per revolution in the case of compound two-coordinate harmonics. An omitted i defaults to unity, as does an omitted trailing fci .

FORMULA :

The general scheme is as described above. To take a specific example, the term HXCH2SD would model an effect which produced an east-west shift on the sky (X) proportional to cosine (C) of $2h$ (H2) times sine (S) of δ (D):

$$\Delta X = + HXCH2SD \cos 2h \sin \delta$$

NOTES :

Harmonics, like polynomials, are a very powerful way of treating pointing errors empirically, but are less likely to diverge outside the area covered by pointing observations. It is usually advisable to FIX the “theoretical” model, except for zero-point

terms (IH, ID, CH, IA, IE, CA), before using a set of harmonic terms to tackle the residual errors.

As noted earlier, it is possible to build most of the theoretical terms by using harmonics (though there is a small speed advantage in using the “named” term). For example, to model fork flexure in an equatorial mount the terms FO and HDCH are identical. However, where a single mechanical error affects both coordinates (for example polar axis elevation error), using two separate harmonics would not be the same as the single theoretical term because the two coefficients would not be constrained to be identical.

ACEC Azimuth Centering Error, Cosine Component **ACEC**

DESCRIPTION :

The cosine component of the once-per-revolution cyclic errors produced by a mis-centered azimuth setting-circle.

FORMULA :

$$\Delta A = + \text{ACEC} \cos A$$

(Take care with sign conventions: inside TPOINT, azimuth increases anticlockwise.)

NOTES :

The sine component is the term ACES.

ACES Azimuth Centering Error, Sine Component **ACES**

DESCRIPTION :

The sine component of the once-per-revolution cyclic errors produced by a mis-centered azimuth setting-circle.

FORMULA :

$$\Delta A = + \text{ACES} \sin A$$

(Take care with sign conventions: inside TPOINT, azimuth increases anticlockwise.)

NOTES :

The cosine component is the term ACEC.

AN Azimuth Axis Misalignment North-South **AN**

DESCRIPTION :

In an altazimuth mount, misalignment of the azimuth axis north-south: rotation about a horizontal east-west axis equal to coefficient AN.

FORMULA :

$$\Delta A = + AN \sin A \tan E$$

$$\Delta E = + AN \cos A$$

(Take care with sign conventions: inside TPOINT, azimuth increases anticlockwise.)

NOTES :

AN is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, IE, CA, NPAE and AW.

If AN is positive, the pole of the mounting is north of the zenith.

The other (*i.e.* east-west) component of the azimuth axis misalignment is the term AW.

AUX1A Azimuth Adjustment from Aux. 1 **AUX1A**

DESCRIPTION :

Change in azimuth equal to coefficient AUX1A multiplied by first auxiliary reading.

FORMULA :

$$\Delta A = + AUX1A \cdot aux_1$$

AUX1D Dec. Adjustment from Aux. 1 **AUX1D**

DESCRIPTION :

Change in declination equal to coefficient AUX1D multiplied by first auxiliary reading.

FORMULA :

$$\Delta \delta = + AUX1D \cdot aux_1$$

AUX1E	Vertical Adjustment from Aux. 1	AUX1E
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DESCRIPTION :

Vertical change equal to coefficient AUX1E multiplied by first auxiliary reading.

FORMULA :

$$\Delta E = + \text{AUX1E} \cdot \text{aux}_1$$

AUX1H	H.A. Adjustment from Aux. 1	AUX1H
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DESCRIPTION :

Change in hour angle equal to coefficient AUX1H multiplied by first auxiliary reading.

FORMULA :

$$\Delta h = + \text{AUX1H} \cdot \text{aux}_1$$

AUX1S	Horizontal Adjustment from Aux. 1	AUX1S
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DESCRIPTION :

Change left-right on the sky equal to coefficient AUX1S multiplied by first auxiliary reading.

FORMULA :

$$\Delta A = + \text{AUX1S} \cdot \text{aux}_1 \cdot \sec E$$

AUX1X	E-W Adjustment from Aux. 1	AUX1X
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DESCRIPTION :

Change east-west on the sky equal to coefficient AUX1X multiplied by first auxiliary reading.

FORMULA :

$$\Delta h = + \text{AUX1X} \cdot \text{aux}_1 \cdot \sec \delta$$

AUX2A	Azimuth Adjustment from Aux. 2	AUX2A
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DESCRIPTION :

Change in azimuth equal to coefficient AUX2A multiplied by second auxiliary reading.

FORMULA :

$$\Delta A = + \text{AUX2A} \cdot \text{aux}_2$$

AUX2D	Dec. Adjustment from Aux. 2	AUX2D
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DESCRIPTION :

Change in declination equal to coefficient AUX2D multiplied by second auxiliary reading.

FORMULA :

$$\Delta \delta = + \text{AUX2D} \cdot \text{aux}_2$$

AUX2E	Vertical Adjustment from Aux. 2	AUX2E
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DESCRIPTION :

Vertical change equal to coefficient AUX2E multiplied by second auxiliary reading.

FORMULA :

$$\Delta E = + \text{AUX2E} \cdot \text{aux}_2$$

AUX2H	H.A. Adjustment from Aux. 2	AUX2H
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DESCRIPTION :

Change in hour angle equal to coefficient AUX2H multiplied by second auxiliary reading.

FORMULA :

$$\Delta h = + \text{AUX2H} \cdot \text{aux}_2$$

AUX2S	Horizontal Adjustment from Aux. 2	AUX2S
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DESCRIPTION :

Change left-right on the sky equal to coefficient AUX2S multiplied by second auxiliary reading.

FORMULA :

$$\Delta A = + \text{AUX2S} \cdot \text{aux}_2 \cdot \sec E$$

AUX2X	E-W Adjustment from Aux. 2	AUX2X
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DESCRIPTION :

Change east-west on the sky equal to coefficient AUX2X multiplied by second auxiliary reading.

FORMULA :

$$\Delta h = + \text{AUX2X} \cdot \text{aux}_2 \cdot \sec \delta$$

AW	Azimuth Axis Misalignment East-West	AW
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DESCRIPTION :

In an altazimuth mount, misalignment of the azimuth axis east-west: rotation about a horizontal north-south axis equal to coefficient AW.

FORMULA :

$$\Delta A = - \text{AW} \cos A \tan E$$

$$\Delta E = + \text{AW} \sin A$$

(Take care with sign conventions: inside TPOINT, azimuth increases anticlockwise.)

NOTES :

AW is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, IE, CA, NPAE and AN.

If AW is positive, the pole of the mounting is west of the zenith.

The other (*i.e.* north-south) component of the azimuth axis misalignment is the term AN.

CA	Left-Right Collimation Error	CA
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DESCRIPTION :

In an altazimuth mount, the collimation error is the non-perpendicularity between the nominated pointing direction and the elevation axis. It produces an left-right shift on the sky that is constant for all elevations.

FORMULA :

$$\Delta A = + \text{CA} \sec E$$

(Take care with sign conventions: inside TPOINT, azimuth increases anticlockwise.)

NOTES :

CA is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, IE, NPAE, AN and AW.

A non-zero CA on its own means there is an area around the zenith inside which the telescope cannot point (irrespective of velocity and acceleration limits close to the zenith).

Collimation error has many causes – misalignment of the optics, an inaccurately centered eyepiece graticule and so on.

CD4A	AAT Coudé 4 Collimation A Component	CD4A
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DESCRIPTION :

AAT coudé 4 collimation error, A-component: a change in hour angle equal to coefficient CD4A, and a change in declination equal to the same coefficient multiplied by $\sin \delta$.

FORMULA :

$$\Delta h = + \text{CD4A}$$

$$\Delta \delta = + \text{CD4A} \sin \delta$$

NOTES :

There are many variants of the coudé optical configuration, and the above AAT term may not be applicable to other telescopes.

CD4B AAT Coudé 4 Collimation B Component **CD4B**

DESCRIPTION :

AAT coudé 4 collimation error, B-component: a change east-west on the sky equal to coefficient CD4B multiplied by $-\sin \delta$, and a change in δ equal to the same coefficient multiplied by $\cos \delta$.

FORMULA :

$$\Delta h = - \text{CD4B} \tan \delta$$

$$\Delta \delta = + \text{CD4B} \cos \delta$$

NOTES :

There are many variants of the coudé optical configuration, and the above AAT term may not be applicable to other telescopes.

CD5A AAT Coudé 5 Collimation A Component **CD5A**

DESCRIPTION :

AAT coudé 5 collimation error, A-component: a change east-west on the sky equal to coefficient CD5A multiplied by $-\sin(h + \delta)$, and a change in δ equal to the same coefficient multiplied by $\cos(h + \delta)$.

FORMULA :

$$\Delta h = - \text{CD5A} \sin(h + \delta) \sec \delta$$

$$\Delta \delta = + \text{CD5A} \cos(h + \delta)$$

NOTES :

There are many variants of the coudé optical configuration, and the above AAT term is unlikely to be applicable to other telescopes.

CD5B AAT Coudé 5 Collimation B Component **CD5B**

DESCRIPTION :

AAT coudé 5 collimation error, B-component: a change east-west on the sky equal to coefficient CD5B multiplied by $\cos(h + \delta)$, and a change in δ equal to the same coefficient multiplied by $\sin(h + \delta)$.

FORMULA :

$$\Delta h = - \text{CD5B} \cos(h + \delta) \sec \delta$$

$$\Delta \delta = + \text{CD5B} \sin(h + \delta)$$

NOTES :

There are many variants of the coudé optical configuration, and the above AAT term is unlikely to be applicable to other telescopes.

CH East-West Collimation Error **CH**

DESCRIPTION :

In an equatorial mount, the collimation error is the non-perpendicularity between the nominated pointing direction and the declination axis. It produces an east-west shift on the sky that is constant for all declinations.

FORMULA :

$$\Delta h = + \text{CH} \sec \delta$$

NOTES :

CH is one of the six purely geometrical terms that affect all equatorial mounts, the others being IH, ID, NP, ME and MA.

A non-zero CH on its own means there is an area around the pole inside which the telescope cannot point.

Collimation error has many causes – misalignment of the optics, an inaccurately centered eyepiece graticule and so on.

DAF	Declination Axis Flexure	DAF
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DESCRIPTION :

Downward sag of cantilevered declination axis (*e.g.* English cross-axis and German equatorial mountings), proportional to the sine of the zenith distance of the declination axis.

FORMULA :

$$\Delta h = - \text{DAF} (\cos \phi \cos h + \sin \phi \tan \delta)$$

NOTES :

The sign convention corresponds to a declination axis which emerges from the polar axis towards the west when the telescope points at the meridian.

DCEC	Dec Centering Error, Cosine Component	DCEC
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DESCRIPTION :

The cosine component of the once-per-revolution cyclic errors produced by a mis-centered declination setting-circle.

FORMULA :

$$\Delta \delta = + \text{DCEC} \cos \delta$$

NOTES :

The sine component is the term DCES.

DCES	Dec Centering Error, Sine Component	DCES
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DESCRIPTION :

The sine component of the once-per-revolution cyclic errors produced by a mis-centered declination setting-circle.

FORMULA :

$$\Delta \delta = + \text{DCES} \sin \delta$$

NOTES :

The cosine component is the term DCEC.

DGEC	AAT 9° Dec Gear Error, Cosine Term	DGEC
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DESCRIPTION :

The AAT declination encoder pinion is geared 40:1 with respect to the declination, corresponding to 9°. The term DGEC is the cosine component of a cyclic error of this frequency.

FORMULA :

$$\Delta\delta = + \text{DGEC} \cos 40\delta$$

NOTES :

The corresponding sine term is DGES.

The AAT's 9° gear errors are at the upper end of the frequency range which is amenable to analysis through pointing tests, unless extremely dense sets of stars are used.

DGES	AAT 9° Dec Gear Error, Sine Term	DGES
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DESCRIPTION :

The AAT declination encoder pinion is geared 40:1 with respect to the declination, corresponding to 9°. The term DGES is the sine component of a cyclic error of this frequency.

FORMULA :

$$\Delta\delta = + \text{DGES} \sin 40\delta$$

NOTES :

The corresponding cosine term is DGEC.

The AAT's 9° gear errors are at the upper end of the frequency range which is amenable to analysis through pointing tests, unless extremely dense sets of stars are used.

DNP Dynamic Nonperpendicularity **DNP**

DESCRIPTION :

For an equatorial mount, a change in the h/δ nonperpendicularity proportional to $\sin h$.

FORMULA :

$$\Delta h = + \text{DNP} \sin h \tan \delta$$

NOTES :

The static form is the term NP.

ECEC Elevation Centering Error, Cosine Component **ECEC**

DESCRIPTION :

The cosine component of the once-per-revolution cyclic errors produced by a mis-centered elevation setting-circle.

FORMULA :

$$\Delta E = + \text{ECEC} \cos E$$

NOTES :

The sine component is the term ECES.

ECES Elevation Centering Error, Sine Component **ECES**

DESCRIPTION :

The sine component of the once-per-revolution cyclic errors produced by a mis-centered elevation setting-circle.

FORMULA :

$$\Delta E = + \text{ECES} \sin E$$

NOTES :

The cosine component is the term ECEC.

FO	Fork Flexure	FO
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DESCRIPTION :

Flexure in an equatorial fork mounting: change in declination proportional to $\cos h$.

FORMULA :

$$\Delta\delta = + \text{FO} \cos h$$

NOTES :

This model of fork flexure is based in the idea that the flexure is at a maximum on the meridian, that it affects only declination, and that at $h = 6^{\text{h}}$ the flexural displacement leaves the pointing direction unaffected. These assumptions are usually borne out well in practice.

HCEC	HA Centering Error, Cosine Component	HCEC
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DESCRIPTION :

The cosine component of the once-per-revolution cyclic errors produced by a mis-centered hour angle setting-circle.

FORMULA :

$$\Delta h = + \text{HCEC} \cos h$$

NOTES :

The sine component is the term HCES.

HCES	HA Centering Error, Sine Component	HCES
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DESCRIPTION :

The sine component of the once-per-revolution cyclic errors produced by a mis-centered hour angle setting-circle.

FORMULA :

$$\Delta h = + \text{HCES} \sin h$$

NOTES :

The cosine component is the term HCEC.

HF	AAT Horseshoe Flexure	HF
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DESCRIPTION :

HF is an effect peculiar to the AAT. Flexure in the horseshoe and yoke part of the mounting produces sizeable east-west image shifts proportional to the sine of hour angle.

FORMULA :

$$\Delta h = + \text{HF} \sec \delta$$

NOTES :

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope.

The HF effect was observed in early AAT pointing tests and had been predicted by structural analysis carried out prior to construction. It reaches about 20" in size.

HFD	AAT Horseshoe Flexure, North-South	HFD
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DESCRIPTION :

This term is one component of a complicated flexure model for the AAT's horseshoe and yoke. It produces a north-south adjustment equal to the coefficient HFD multiplied by a canonical expression in hour angle and declination.

FORMULA :

$$\begin{aligned} \Delta \delta = & -2.529 \sin 2h + 3.964 \sin 3h + 3.008 \cos 3h - 2.428 \sin 4h \\ & -0.921 \cos 5h - 0.233 \cos 12h + 0.163 \sin 6\delta \\ & -0.147 \cos 11\delta - 0.244 \cos 15h \sin \delta \\ & +(-4.330 \cos h - 2.958 \cos 2h - 1.805 \sin h) \cos \delta \\ & +1.666 \cos h \cos 2\delta \end{aligned}$$

NOTES :

The coefficient HFD is nominally unity (with the above coefficients in arcseconds).

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope. This particular term, along with the east-west component HFX, was obtained by fitting empirical harmonics to the residuals left after a conventional model had been devised. Its largest effects occur at extreme hour angles.

HFX	AAT Horseshoe Flexure, East-West	HFX
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DESCRIPTION :

This term is one component of a complicated flexure model for the AAT's horseshoe and yoke. It produces an east-west adjustment equal to the coefficient HFX multiplied by a canonical expression in hour angle and declination.

FORMULA :

$$\begin{aligned} \Delta h = & (0.219 \sin 5h + 0.368 \cos 6h + 0.195 \sin 15h + (1.279 \sin 2h \\ & - 1.718 \sin 4h + 1.202 \cos 5h) \sin \delta - 1.928 \sin 3h \cos \delta \\ & + (3.662 \sin h + 0.381 \cos 3h) \sin 2\delta - 1.156 \sin 3h \cos 2\delta \\ & + (-0.633 \sin 2h + 0.723 \sin h) \sin 5\delta) \sec \delta \end{aligned}$$

NOTES :

The coefficient HFX is nominally unity (with the above coefficients in arcseconds). This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope. This particular term, along with the north-south component HFD, was obtained by fitting empirical harmonics to the residuals left after a conventional model had been devised. Its largest effects occur at extreme hour angles.

HGEC	AAT 36 ^m HA Gear Error, Cosine Term	HGEC
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DESCRIPTION :

The AAT hour angle encoder pinion is geared 40:1 with respect to the polar axis, corresponding to 36^m. The term HGEC is the cosine component of a cyclic error of this frequency.

FORMULA :

$$\Delta h = + \text{HGEC} \cos 40h$$

NOTES :

The corresponding sine term is HGES.

The AAT's 36^m gear errors are at the upper end of the frequency range which is amenable to analysis through pointing tests (as opposed to tracking tests), unless extremely dense sets of stars are used.

HGES	AAT 36 ^m HA Gear Error, Sine Term	HGES
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DESCRIPTION :

The AAT hour angle encoder pinion is geared 40:1 with respect to the polar axis, corresponding to 36^m. The HGES is the sine component of a cyclic error of this frequency.

FORMULA :

$$\Delta h = + \text{HGES} \sin 40h$$

NOTES :

The AAT's 36^m gear errors are at the upper end of the frequency range which is amenable to analysis through pointing tests (as opposed to tracking tests), unless extremely dense sets of stars are used.

The corresponding cosine term is HGEC.

IA	Index Error in Azimuth	IA
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DESCRIPTION :

Azimuth index error in an altazimuth mount: the zero-point error in A .

FORMULA :

$$\Delta A = + \text{IA}$$

(Take care with sign conventions: inside TPOINT, azimuth increases anticlockwise.)

NOTES :

On many altazimuth telescopes, IA is arbitrarily set at the start of each night by pointing at a calibration star, and on telescopes without absolute encoders or readouts there is no choice; under these circumstances the IA value returned by TPOINT has no lasting significance. However, note that it is not the same thing as a horizontal error on the sky, such as might be caused by a badly adjusted primary mirror; the latter, addressed by the CA term, would produce the same image displacement at all elevations, whereas IA has a lessening effect as the pole is approached.

IA is one of the six purely geometrical terms that affect all equatorial mounts, the others being IE, CA, NPAA, AN and AW.

ID	Index Error in Declination	ID
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DESCRIPTION :

Declination index error in an equatorial mount: the zero-point error in δ .

FORMULA :

$$\Delta\delta = + \text{ID}$$

NOTES :

ID produces a fixed offset of the image north-south. On many telescopes it is arbitrarily set at the start of each night by pointing at a calibration star, and on telescopes without absolute encoders or readouts there is no choice; under these circumstances the ID value returned by TPOINT has no lasting significance. It is indistinguishable from various other north-south shifts, such as those caused by a badly adjusted primary mirror.

ID is one of the six purely geometrical terms that affect all equatorial mounts, the others being IH, CH, NP, ME and MA.

IE	Index Error in Elevation	IE
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DESCRIPTION :

Elevation index error in an altazimuth mount: the zero-point error in E .

FORMULA :

$$\Delta E = + \text{IE}$$

NOTES :

IE produces a fixed vertical offset of the image. On many altazimuth telescopes it is arbitrarily set at the start of each night by pointing at a calibration star, and on telescopes without absolute encoders or readouts there is no choice; under these circumstances the IE value returned by TPOINT has no lasting significance. It is indistinguishable from various other vertical shifts, such as those caused by a badly adjusted primary mirror.

IE is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, CA, NPAE, AN and AW.

IH	Index Error in Hour Angle	IH
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DESCRIPTION :

Hour angle index error in an equatorial mount: the zero-point error in h .

FORMULA :

$$\Delta h = + \text{IH}$$

NOTES :

IH has the same effect on pointing as an error in the clock or using an inaccurate value for site longitude. On many telescopes it is arbitrarily set at the start of each night by pointing at a calibration star, and on telescopes without absolute encoders or readouts there is no choice; under these circumstances the IH value returned by TPOINT has no lasting significance. However, note that it is not the same thing as an east-west error on the sky, such as might be caused by a badly adjusted primary mirror; the latter, addressed by the CH term, would produce the same image displacement at all declinations, whereas IH has a lessening effect as the pole is approached.

IH is one of the six purely geometrical terms that affect all equatorial mounts, the others being ID, CH, NP, ME and MA.

MA	Polar Axis Misalignment in Azimuth	MA
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DESCRIPTION :

Misalignment of the polar axis of an equatorial mount to the left or right of the true pole: a rotation about an axis through ($h = \delta = 0$) equal to coefficient MA.

FORMULA :

$$\Delta h = - \text{MA} \cos h \tan \delta$$

$$\Delta \delta = + \text{MA} \sin h$$

NOTES :

In the northern hemisphere, positive MA means that the pole of the mounting is to the right of due north.

In the southern hemisphere, positive MA means that the pole of the mounting is to the right of due south.

To avoid unwanted field rotation effects it is best to eliminate MA mechanically by an appropriate azimuth adjustment. To eliminate MA arcseconds of polar axis azimuth error, rotate the mounting MA sec ϕ arcseconds anticlockwise as seen from above.

The other (*i.e.* up-down) component of the polar axis misalignment is the term ME.

ME Polar Axis Misalignment in Elevation **ME**

DESCRIPTION :

Vertical misalignment of the polar axis of an equatorial mount: a rotation about an east-west axis equal to coefficient ME.

FORMULA :

$$\Delta h = + \text{ME} \sin h \tan \delta$$

$$\Delta \delta = + \text{ME} \cos h$$

NOTES :

In the northern hemisphere, positive ME means that the pole of the mounting is below the true (unrefracted) pole. A mounting aligned the refracted pole (for most telescopes probably the simplest and best thing to aim for in order to avoid unwanted field rotation effects) will have negative ME.

In the southern hemisphere, positive ME means that the pole of the mounting is above the true (unrefracted) pole, and a mounting aligned the refracted pole will have positive ME.

The other (*i.e.* left-right) component of the polar axis misalignment is the term MA.

NP HA/Dec Non-perpendicularity **NP**

DESCRIPTION :

In an equatorial mount, if the polar axis and declination axis are not exactly at right angles, east-west shifts of the image occur that are proportional to $\sin \delta$.

FORMULA :

$$\Delta h = + \text{NP} \tan \delta$$

NOTES :

NP is one of the six purely geometrical terms that affect all equatorial mounts, the others being IH, ID, CH, ME and MA.

The image displacement produced by NP is zero on the celestial equator and reaches a maximum at the pole.

Most telescope sites lie well away from the equator of the Earth and hence the correction for NP tends to be the same sign most of the time. Furthermore, because there is more sky at lower declinations than near the pole there are likely to be fewer pointing observations in a given declination-band near the pole than in a similar band nearer the equator. These two effects conspire so that the NP effect tends to be poorly sampled when pointing tests are made, and hence the NP coefficient is apt to be poorly determined. In some cases, it can be better to omit NP from the model and rely on other terms mopping up any NP-like effects that are preset.

A non-zero NP on its own means there is an area around the pole inside which the telescope cannot point.

NPAE	Az/El Non-perpendicularity	NPAE
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DESCRIPTION :

In an altazimuth mount, if the azimuth axis and elevation axis are not exactly at right angles, horizontal shifts of the image occur that are proportional to $\sin E$.

FORMULA :

$$\Delta A = + \text{NPAE} \tan E$$

NOTES :

NPAE is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, IE, CA, AN and AW.

The image displacement produced by NPAE is zero on the horizon and reaches a maximum at the zenith.

Just as E is always positive, the correction for NPAE never changes sign. Furthermore, because there is more sky at lower elevations than near the zenith there are likely to be fewer pointing observations in a given elevation-band near the zenith than in a similar band nearer the horizon. These two effects conspire so that the NPAE effect tends to be very poorly sampled when pointing tests are made, and hence the NPAE coefficient is apt to be poorly determined. In some cases, it can be better to omit NPAE from the model and rely on other terms mopping up any NPAE-like effects that are preset.

A non-zero NPAE on its own means there is an area around the zenith inside which the telescope cannot point (irrespective of velocity and acceleration limits close to the zenith).

NRX Nasmyth Rotator Displacement, Horizontal **NRX**

DESCRIPTION :

In a Nasmyth altazimuth mount, a horizontal displacement between the elevation axis of the mount and the rotation axis of the Nasmyth instrument-rotator produces an image shift on the sky with a horizontal component proportional to cosine elevation and a vertical component proportional to minus sine elevation.

FORMULA :

$$\Delta A = + \text{NRX}$$

$$\Delta E = - \text{NRX} \sin E$$

(Take care with sign conventions: inside TPOINT, azimuth increases anticlockwise.)

NOTES :

The same corrections apply even if there is no Nasmyth rotator, except that the displacement is between the elevation axis and the nominated pointing-origin in the Nasmyth focal-plane.

NRX is positive when the elevation axis emerges from the Nasmyth focal plane to the right of the rotator axis.

NRV Nasmyth Rotator Displacement, Vertical **NRV**

DESCRIPTION :

In a Nasmyth altazimuth mount, a vertical displacement between the elevation axis of the mount and the rotation axis of the Nasmyth instrument-rotator produces an image shift on the sky with a horizontal component proportional to sine elevation and a vertical component proportional to cosine elevation.

FORMULA :

$$\Delta A = + \text{NRV} \tan E$$

$$\Delta E = + \text{NRV} \cos E$$

(Take care with sign conventions: inside TPOINT, azimuth increases anticlockwise.)

NOTES :

The same corrections apply even if there is no Nasmyth rotator, except that the displacement is between the elevation axis and the nominated pointing-origin in the Nasmyth focal-plane.

NRV is positive when the elevation axis emerges from the Nasmyth focal plane above the rotator axis.

The NRV correction has an identical form to the two terms NPVE and TF acting in combination. This unfortunately prevents simultaneous fitting of pointing observations to a model containing all three terms. The recommended procedure for Nasmyth telescopes is to determine a canonical value of TF from observations at a non-Nasmyth focus (prime, Cassegrain, Newtonian *etc.*) and then to fit Nasmyth pointing observations to a model which includes TF fixed at this value.

TF	Tube Flexure (sine)	TF
-----------	---------------------	-----------

DESCRIPTION :

Classical tube flexure: change in zenith distance proportional to $\sin \zeta$.

FORMULA :

$$\Delta E = - \text{TF} \cos E$$

In equatorial spherical coordinates:

$$\Delta h = + \text{TF} \cos \phi \sin h \sec \delta$$

$$\Delta \delta = + \text{TF} (\cos \phi \cos h \sin \delta - \sin \phi \cos \delta)$$

NOTES :

This is the classic tube flexure model, which assumes that the telescope obeys Hooke's Law. In practice there is often a rapid increase in the vertical displacement towards the horizon, and it is sometimes found that a tangent law is a better approximation than a sine law: see the TX term.

TFP	AAT Tube Flexure Supplementary Term	TFP
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DESCRIPTION :

The AAT displays a more rapid increase in vertical deflection at large zenith distances than predicted by a pure Hooke's Law tube flexure model (the term TF). The special TFP term adds a ζ^4 component, the effect of which is felt only at the lowest elevations.

FORMULA :

$$\Delta E = - \text{TFP } \zeta^4$$

NOTES :

This special AAT term illustrates the observed tendency of telescopes not to be well-modeled by the expected TF term. In the case of the AAT, the size of the supplementary TFP term is noticeably dependent on which of the AAT's interchangeable top-ends is in use, whereas the main TF term is broadly independent of top-end.

TX	Tube Flexure (tangent)	TX
-----------	------------------------	-----------

DESCRIPTION :

Empirical tube flexure: change in zenith distance proportional to $\tan \zeta$.

FORMULA :

$$\Delta E = - \text{TX } \cot E$$

In equatorial spherical coordinates:

$$\Delta h = + \text{TX } \cos \phi \sin h / ((\sin \delta \sin \phi + \cos \delta \cos h \cos \phi) \cos \delta)$$

$$\Delta \delta = + \text{TX } (\cos \phi \cos h \sin \delta - \sin \phi \cos \delta) / ((\sin \delta \sin \phi + \cos \delta \cos h \cos \phi) \cos \delta)$$

NOTES :

The classical tube flexure model, TF, which assumes that the telescope obeys Hooke's Law, is a sine rather than tangent law. In practice there is often a rapid increase in the vertical displacement towards the horizon, and it is sometimes found that the present term, TX, is a better approximation than TF.

Note that TX will compensate for any scaling error in the refraction corrections.

X2HC	Cos (2H) Term East-West	X2HC
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DESCRIPTION :

Change east-west on the sky proportional to $\cos 2h$.

FORMULA :

$$\Delta h = + \text{X2HC} \cos 2h \sec \delta$$

NOTES :

The same as the generic harmonic HXCH2 but marginally faster, this term is part of the AAT model.

ZE	AAT HA Z-gear Effect on Polar Axis Elevation	ZE
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DESCRIPTION :

ZE is an effect peculiar to the AAT: see the notes below. It takes the form of a change in polar axis elevation proportional to the first auxiliary reading.

FORMULA :

$$\Delta h = + \text{ZE} \cdot \text{aux}_1 \cdot \sin h \tan \delta$$

$$\Delta \delta = + \text{ZE} \cdot \text{aux}_1 \cdot \cos h$$

NOTES :

The AAT final drive consists of a large spur gear (the “Z-gear”) at the northern end of the mounting yoke, driven by a gearbox at its lowest point. Varying upward pressure from the drive gearbox causes an unwanted rise-and-fall of the entire northern end of the mounting. This is corrected by directly measuring the rise-and-fall of the Z-gear, using an electronic displacement pickup, and injecting the readings into the pointing model. During pointing tests, the measurements are logged and find their way into the TPOINT input file as an “auxiliary reading” (the last field in the sample data file `aat15.dat`).

The principal effect of the rise-and-fall is on the hour angle encoder readouts, affecting tracking directly: see the term ZH.

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope. This particular term demonstrates TPOINT’s “auxiliary readings” capability; a similar approach can be used on any telescope the pointing of which is influenced by mechanical shifts or run-outs that are hard to predict but which can be measured in real-time.

ZH AAT HA Z-gear Effect on Hour Angle **ZH**

DESCRIPTION :

ZH is an effect peculiar to the AAT: see the notes below. It takes the form of a change in hour angle proportional to the first auxiliary reading.

FORMULA :

$$\Delta h = + \text{ZH} \cdot \text{aux}_1$$

NOTES :

The AAT final drive consists of a large spur gear (the “Z-gear”) at the northern end of the mounting yoke, driven by a gearbox at its lowest point. A separate gearbox, mounted to one side, drives the encoder system. Varying upward pressure from the drive gearbox causes an unwanted rise-and-fall of the entire northern end of the mounting, which affects the encoder readings and hence the tracking. This is corrected by directly measuring the rise-and-fall of the Z-gear, using an electronic displacement pickup, and injecting the readings into the pointing model. During pointing tests, the measurements are logged and find their way into the TPOINT input file as an “auxiliary reading” (the last field in the sample data file `aat15.dat`).

The rise-and-fall also affects the polar axis elevation directly: see the term ZE.

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope. This particular term demonstrates TPOINT’s “auxiliary readings” capability; a similar approach can be used on any telescope the pointing of which is influenced by mechanical shifts or run-outs that are hard to predict but which can be measured in real-time.

9 THE INITIALIZATION FILES

TPOINT can be configured at run-time by specifying the appropriate initialization file. The easiest option is to create a link to the standard initialization file in the directory from which TPOINT will be run, for example:

```
ln -s /usr/etc/tpoint/tpoint.ini tpoint.ini
```

An alternative is to make a copy of the file, which can then be edited appropriately. A third possibility is to specify the initialization file when TPOINT is started, through the command line.

9.1 The TPOINT Initialization File

Here is an example `tpoint.ini` file. It contains explicit filenames; however, in the `tpoint.ini` supplied with the release, the pathnames contain the symbol `HOME`, and the actual pathname is substituted when the file is installed by `make`.

```
!
! - - - - -
!   t p o i n t . i n i
!   - - - - -
!
! Initialization file for Unix version of TPOINT.
!

procedure_library      /usr/etc/tpoint/procs.dat
star_catalog           /usr/etc/tpoint/stars.dat
help_prefix            /usr/etc/tpoint/
help_name              tpoint
help_suffix            .shl
graphics_device_name  tpoint
graphics_hardcopy      tpoint.ps
SGS_initialization    /usr/etc/sgs/sgs.ini
pen_frame              18
pen_caption            5
pen_axes               17
pen_labels             12
pen_points             13
pen_offpoints          2
font_caption           1
```

```

font_labels          1
text_precision       2

end

```

The commands, which can be presented in any order, have the following meanings:

- The first two items specify the files containing the default star catalog and procedure library.
- The three “help” items specify the full name of the top-level help library and enable the subsidiary libraries to be found.
- The graphics device name is the default argument for the PLTON command.
- The graphics hardcopy name is the default name for the file produced when the GC command’s “P” function is invoked.
- The next item points to the separate initialization file for the SGS graphics system. An example is given below.
- The next six items specify the default pen colors. The colors corresponding to the different pen numbers are specified in the SGS initialization file.
- The font numbers specify the default fonts for captions and labels.
- The text precision specifies the default text precision for all plotting.

(*n.b.* The TPOINT implementations covered at present by this document do not support multiple fonts or text precisions.)

9.2 The SGS Initialization File

Here is an example `sgs.ini` file:

```

!
!  - - - - -
!  s g s . i n i
!  - - - - -
!
!  SGS initialization file
!

hardcopy_file    sgs.ps

```

```

shell          /usr/local/bin/wish
width         510

background    black
pen1          white          ! pen 1 = white
pen2          #F00           ! pen 2 = red
pen3          #0F0           ! pen 3 = blue
pen4          #00F           ! pen 4 = green
pen5          #FF0           ! pen 5 = yellow
pen6          #F0F           ! pen 6 = magenta
pen7          #0FF           ! pen 7 = cyan
pen8          #000           ! pen 8 = black
pen9          #777           ! pen 9 = dark grey
pen10         #CCC           ! pen 10 = light grey
pen11         #FFF           ! pen 11 = white
pen12         #F99           ! pen 12 = light red
pen13         #9F9           ! pen 13 = light green
pen14         #99F           ! pen 14 = light blue
pen15         #FF9           ! pen 15 = light yellow
pen16         #F9F           ! pen 16 = light magenta
pen17         #9FF           ! pen 17 = light cyan
pen18         #D83           ! pen 18 = brown

commands:

end

```

The `hardcopy_file` item is the default name for the file produced by when the SGS `hardcopy` option is invoked. In fact TPOINT always overrides this name with its own default (`tpoint.ps` in the example `tpoint.ini` file shown earlier), and so the entry here is simply for completeness. The `shell` item refers to the windowing shell which supports Tcl and Tk commands. The `width` item allows the width of the graphics window to be specified, in pixels. It will be rounded down to the nearest multiple of three, to allow an exact 3:4 aspect ratio. The value above, 510, is suitable for a laptop PC; a rather larger number may be more suitable on a full-size workstation. The background color (choose one defined in the local X configuration and formatted in Tk style) is specified through the `background` item. The pen colors are defined through items `pen1-18`, in any of the Tk formats; the format used in the above example specifies colors as three hexadecimal digits which represent the red, green and blue intensities respectively. Finally, between the `commands:` line and the `end` line, it is possible to put Tcl/Tk commands for transmission to the windowing shell just after it has been created, to achieve special effects.

10 COMMAND SUMMARY

COMMAND	FUNCTION	DEFAULT
<i>coeff value</i>	set and report coefficient value	report only
ADJUST T or S	select model direction	report only
APPEND ON or OFF	next observations will [not] be appended	will be appended
CALL <i>proc</i>	call library procedure <i>proc</i>	–
CAPT ON or OFF	enable/disable plotting of captions	captions enabled
CHAIN <i>c1 c2 etc.</i>	selected terms are applied sequentially	whole model chained
CLIST	list current coefficients	–
ECHO ON or OFF	enable/disable procedure command echo	echo on
END	exit	–
FIT N	fit [or apply model without fitting]	fit
FITTOL <i>t</i>	specify and report ill-conditioning tolerance	report only
FIX <i>c1 c2 etc.</i>	exclude selected terms from fit	fix all terms
FRAME ON or OFF	enable/disable plotting of frames	frames enabled
G <i>y x s</i>	plot residuals	autoscale
GAM <i>t s</i>	look for axis misalignment	equatorial, autoscale
GC <i>f s</i>	graphics device control	clear screen
GDIST	plot distributions of residuals	–
GHYST <i>t s</i>	look for hysteresis	equatorial, autoscale
GMAP <i>t s</i>	Cartesian Cylindrical plot	equatorial, autoscale
GSCAT <i>t r</i>	scatter plot	equatorial, autoscale
GSMAP <i>s</i>	orthographic map	autoscale
HELP <i>topic</i>	enter HELP session	enter at top level
INDAT <i>file</i>	read file of observations	–
INMOD <i>file</i>	read model from a file	–
INPRO <i>file</i>	read library file	original library
INST <i>file</i>	read star catalog	original catalog
LOSE <i>c1 c2 etc.</i>	remove selected terms from model	discard all terms
MARKH <i>h</i>	set marker height	0.2
MASK <i>q c v</i> or <i>n1 n2</i>	flag selected observations inactive	mask all observations
MESLEV <i>m r</i>	limit messages to given severity levels	all messages
OUTDAT <i>file</i>	write file of observations	–
OUTMOD <i>file</i>	write model to a file	–
PARAL <i>c1 c2 etc.</i>	terms <i>c1 c2 etc.</i> are applied in parallel	whole model parallel
PENS <i>f c a l p o</i>	specify and report pens	report only
PERFCT ° ' "	create ideal observations	ϕ from data list
PLTOF	close plotting window	–
PLTON <i>label</i>	open new plotting window	–
PLTZ <i>z</i>	select plotting zone	use whole display surface
PROC <i>x</i>	start of library procedure <i>x</i>	–
REPLEN S or L	specify report length option	full length reports
RESET	zero coefficients and cancel corrections	–
RETURN	return from a procedure	–
SETCAP <i>string</i>	specify caption	caption blank
SHOW	display system parameters	–
SLIST R	list the observations	list all
SPAWN <i>string</i>	execute shell command	spawn new shell
UNFIT N	apply pointing model in reverse	current model applied
UNMASK <i>q c v</i> or <i>n1 n2</i>	flag selected observations active	unmask all observations
USE <i>c1 c2 etc.</i>	include selected terms in model	unfix all terms
VT <i>top bottom</i>	clear the text screen	–
CTRL/C	abort current command	–