Starlink Project
Starlink User Note 5.18

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ASTROM

Basic astrometry program v3.7 User's Guide

Abstract

ASTROM performs "plate reductions". You supply star positions from a catalogue and the $[x, y]$ ccoordinates of the corresponding star images. ASTROM uses this information to establish the relationship between $[x, y]$ and $[\alpha, \delta]$ enabling the coordinates of "unknown stars" to be determined.

Contents

1 Introduction

ASTROM is a simple plate[1] reduction utility, designed to allow the non-specialist user to get good results with a minimum of trouble and esoteric knowledge. The user supplies a text file containing information about the exposure and the positions of reference and unknown stars; ASTROM performs the various coordinate transformation and fitting operations required, displays a synopsis report on the command terminal, and prepares a detailed report for later printing.

2 Operating Instructions

ASTROM is run by means of the following command

> `astrom` [`input=`*input*] [`report=`*report*] [`summary=`*summary*]
> [`log=`*log*] [`fits=`*fits*] [`wcsstyle=`*wcsstyle*]

All the parameters are optional, and may appear in any order. The parameters *input* and *report* default to `astrom.dat` and `astrom.lis`; the *summary* defaults to the terminal. If *log* or *fits* is not specified, no corresponding file is generated. A parameter can be defaulted either by leaving it out or by using a pair of double-quotes. The specifiers `input=` and `report=` are optional; if they are omitted, they are assigned to the first and second unqualified filenames. Thus

```
astrom astrom.input
```

would read the input file `astrom.input`, and write a report on the default `astrom.lis`.

```
astrom report=astrom.report fits=wcsout input=astrom.input
```

reads `astrom.input`, and produces its report on `astrom.report`, plus a number of FITS files with names beginning `wcsout` (see Section 4 below). The specifiers `input=-` and `report=-` cause the input to be read from, and the report to be written to, the standard input and output respectively.

A summary report normally appears on the command terminal, but can be sent to a file by giving the file's name as the `summary=` parameter. This should be monitored and any reference stars with large residuals noted. The input file can then be edited as necessary and the job rerun. Finally, the report file can be printed in the normal way. An example report file is reproduced in Appendix B. For further details on the log and FITS files, see Section 4.

3 The Input File

The input file is an ordinary text file and is terminated either by end-of-file or by a record beginning `E`. Uppercase and lowercase are both acceptable throughout the file and may be mixed

[1] For "plate" read CCD exposure *etc*.

freely; leading spaces are ignored. A comment, beginning *, can be appended to any record. Completely blank records (and any beginning with *) are ignored and can be used to improve layout and provide commentary.

Most of the records consist of (or contain) various numbers of numeric fields, separated by spaces (or commas). In many instances it is simply the number of fields present which enables ASTROM to determine which sort of record has been read. Free-format number decoding is used throughout; spaces can be freely inserted between fields, and many other freedoms are permitted (see the documentation for the SLALIB routines SLA_DFLTIN and SLA_DBJIN in SUN/67).

Each file typically specifies a single plate reduction; however, multiple *sequences* of records, each specifying a complete and separate plate reduction, can be used, each sequence being separated from the next by a record beginning /.

The overall layout of each sequence is as follows:

Group	*Records*	*Mandatory?*
results equinox	1	no
telescope type	1	no
plate data	1	yes
observation data	1-3	no
reference stars	2-3 per star	at least 2 stars
unknown stars	1-2 per star	no

Several sorts of record involve celestial positions. Although ASTROM can be made to work internally in *observed* coordinates (*i.e.* as affected by refraction *etc.*), all input data and reports are in terms of various sorts of *mean* $[\alpha, \delta]$. In any particular instance, the mean coordinate system is specified by quoting an *equinox*. An *epoch* is also required, for the calculation of proper motion; in the case of catalogue stars this is frequently the same as the equinox.

Both the old pre IAU 1976 (loosely FK4) system and the new post IAU 1976 (loosely FK5) system are supported, and data in the two systems can be mixed freely. ASTROM follows the established convention of using the equinox to distinguish between the two systems. If the equinox is prefixed by B (which stands for *Besselian*) then the position is an old FK4 one; if a prefix of J is used (standing for *Julian*), the position is a new FK5 one. If no prefix is used, pre 1984.0 equinoxes indicate the old FK4 system, and equinoxes of 1984.0 or later indicate the new FK5 system. The B or J prefix may also be used with epochs although the distinction is unlikely to be significant. The two most common equinoxes are B1950 and J2000. All FK4 positions include E-terms of aberration, consistent with published catalogues.

When using the old system (*e.g.* B1950) to specify the position of an object whose proper motion is presumed to be negligible, it is necessary to specify an epoch (as well as the equinox). This is because the old system is not an inertial frame; failure to recognize galactic rotation at the time the system was first established means that the FK4 frame is rotating, and that even extragalactic objects have fictitious proper motions which need to be taken into account in precise work. ASTROM accepts an optional format of reference star data for such cases, where the proper motions are omitted and an epoch is mandatory.

For most ASTROM applications, star positions in the frame of the Hipparcos catalogue can be assumed to be equivalent to FK5 J2000. However, it is unwise to mix Hipparcos and pre-Hipparcos positions. If only Hipparcos-compatible stars are used, and if for ASTROM purposes they are regarded as FK5 J2000, the results of the ASTROM fit will be in the Hipparcos frame to a high degree of accuracy.

Appendix A contains a detailed specification of the syntax of the ASTROM input file, together with a comprehensive example. As an introduction, we will look at a simple but typical example of such a file:

```
B1950                                    * Results in FK4
SCHM                                     * Schmidt geometry
19 04 00.0  -65 00 00  B1950.0  1974.5   * Plate centre, and epoch
18 56 39.426  -63 25 13.23  -0.0002  -0.036  B1950.0  * Ref 1
44.791   85.643
19 11 53.909  -63 17 57.57   0.0058  -0.044  1950.0   * Ref 2
-46.266   92.337
19 01 13.606  -63 49 14.84   0.0020  -0.026  1950.0   * Ref 3
17.246   64.945
19 08 29.088  -63 57 42.79   0.0016   0.018  1950.0   * Ref 4
-25.314   57.456
19 02 10.088  -63 29 16.73   0.0012  -0.019  1950.0   * Ref 5
11.890   82.766
-5.103    58.868                     *  Candidate
19 09 46.2  -63 51 27  J2000.0       *  Radio pos
END
```

Taking each record (or group of records) in turn:

```
B1950                                       * Results in FK4
```

This is the **results equinox** record. It specifies the mean equator and equinox for the coordinate system of the report. If this record is omitted, the results will be in J2000.

```
SCHM                                        * Schmidt geometry
```

This is the **telescope type** record, which describes the projection geometry. The telescope type is given by the first four characters of the record; there are currently six options. `SCHM`, as used here, is for Schmidt telescopes. `ASTR` selects the tangent plane or *gnomonic* projection, produced by conventional astrographic telescopes (and by pinhole cameras). Then there are three special AAT options: `AAT2` and `AAT3` for the Prime Focus doublet and triplet correctors, and `AAT8` for the $f/8$ Ritchey-Chrétien focus (using the vacuum plateholder). The option `JKT8` models the field distortion of the JKT ($f/8$ Harmer-Wynne focus). Finally, the option `GENE` specifies generalized pincushion/barrel distortion, the magnitude of which is given by a single numeric parameter q following the telescope type string; further details are given in Section 5.

```
19 04 00.0  -65 00 00  B1950.0  1974.5    * Plate centre, and epoch
```

This is the mandatory **plate data** record, specifying the point on the sky corresponding to the pole of the projection geometry (which is usually, but not necessarily[2], at the geometrical centre of the plate) and the date on which the exposure occurred. The $[\alpha,\delta]$ is expressed as h m s ° ′ ″. The hours, minutes, degrees and arcminutes fields must all be integers. The sign of the δ precedes the degrees. The $[\alpha,\delta]$ must be followed by an equinox. The epoch specifies when the picture was taken, needed for the proper motion calculation. The epoch can be omitted if more precise information is to be supplied later via the optional observation data records.

```
18 56 39.426  -63 25 13.23  -0.0002  -0.036  B1950.0  * Ref 1
44.791   85.643
```

This is the first of several record pairs describing the **reference stars**. At least two such pairs are needed in order to run ASTROM, and three if both sorts of linear fit are to be done. At least 10 stars are required if fitting of the radial distortion and/or plate centre is to be attempted. A typical number for an ordinary linear fit would be about a dozen stars; a thorough job covering a large area of a plate and with automatic determination of the radial distortion and plate centre selected would require perhaps 50. The current limit is 2000. The first record contains $[\alpha,\delta]$, proper motions in seconds per year and arcseconds per year respectively (*n.b.* not centuries as in some catalogues), and equinox, followed optionally by epoch and/or parallax. If the epoch is omitted (as in the above example), it is assumed to be the same as the equinox. Parallax, which is in arcseconds, defaults to zero. For reference stars whose positions are given in the old FK4 system, and whose proper motions are presumed to be zero in an inertial sense, an alternative format is available, with the proper motions omitted and the epoch mandatory:

```
18 56 39.422  -63 25 14.00  B1950.0  1971.3           * Ref 1
```

(Because the FK4 system is not inertial, using the format described earlier and simply putting zero for the proper motions would **not** give the same effect.) The first 10 characters of any comment are picked up and appear on the reports as 'name'. The second record of the reference star pair is the measured $[x,y]$. For the 4-coefficient model to work properly, x and y must be in the same units. The reports will look best if the units are millimetres or thereabouts and the offsets from zero are reasonably small. Orientation and handedness are immaterial; x=east and y=north is the recommended convention as it matches the run of α and δ.

[2]JKT $f/8$ plates, for example, are mounted eccentrically. The plate data record must specify the celestial coordinates of the optical axis, preferably to within a millimetre or so. Section 8 gives details of how the plate centre (and the radial distortion) can be determined automatically.

```
-5.103    58.868                        *  Candidate
19 09 46.2  -63 51 27  J2000.0          *  Radio pos
```

These two records both specify *unknown stars*. The first is $[x, y]$, from which $[\alpha, \delta]$ will be determined. The second is $[\alpha, \delta]$ and equinox, from which $[x, y]$ will be determined. It is not necessary to include any unknown star records at all, if the intention is simply to determine a plate scale or to check a set of plate measurements.

The above example gives a position for the first unknown star of `19 05 01.794 -63 56 16.70`. The equinox was specified in the results equinox record, and the epoch in the plate data record. One way to express this information in a publication might be as follows:

19 05 01.79 -63 56 16.7 B1950 epoch 1974.5

The example does not include the optional **observation data** and **colour** records, which enable ASTROM to reconstruct the precise appearance of the field rather than allowing various predictable rotations and distortions to be absorbed into the fit. Also omitted from the example are requests to include the radial distortion and plate centre in the fit. Details of these refinements are given in Sections 7 and 8.

4 Output

The report file (named by the `report=` parameter, and defaulting to `astrom.lis`) is a human-readable report of ASTROM's actions and its results. The summary file, which normally appears on the terminal, contains observations and warnings about ASTROM's progress, and should be monitored. Neither of these files, however, is intended to be easily machine-parseable, and so if ASTROM is used within a larger system, the other output files will be useful. The log file is a report on ASTROM's actions and results which is easy to parse, and easy to extract information from. The WCS files contain ASTROM's results in the form of a FITS header, containing FITS WCS keywords. Both these files are described in the subsections below.

4.1 Log output

The log file is a report on ASTROM's actions and results which is easy to parse, and thus easy for another program, acting as a harness for ASTROM, to find out about ASTROM's progress.

The log file consists of a number of statements describing the fits ASTROM has performed, and its success. The statements describing each fit are bracketed in a pair of statements '`FIT` $\langle n \rangle$' and '`ENDFIT`', for some fit number $\langle n \rangle$. The statements thus bracketed are in table 1.

The `INFO`, `WARNING` and `ERROR` statements share a common set of codes, and are described in Appendix D.

The `RESIDUAL` message reports the size of the residuals for the given source number in the input file. The residuals are reported in the x and y directions, plus $\delta r = \sqrt{\delta x^2 + \delta y^2}$.

The `STATUS` message is `OK` if the fit succeeded, and `BAD` otherwise.

The `RESULT` statements give feedback about the results of the fit. Much of the information is also in the FITS WCS headers, if they are generated. The keywords are listed in table 2.

Result	`RESULT` *keyword value*
Status	`STATUS` [`OK`|`BAD`]
Residuals	`RESIDUAL` *source-number dx dy dr*
Information	`INFO` *code details...*
Warnings	`WARNING` *code comment*
Errors	`ERROR` *code comment*

Table 1: Log file statements

keyword	**meaning**
`nstars`	number of ref stars
`xrms`	RMS errors in fitted x, arcsec
`yrms`	...in y
`rrms`	...in r
`plate`	(mean) plate scale, arcsec
`prms`	`rrms` in pixels
`nterms`	number of terms in fit
`rarad`	projection pole RA, radians
`decrad`	projection pole Dec, radians
`rasex`	projection pole RA, sexagesimal
`decsex`	projection pole Dec, sexagesimal
`wcs`	name of FITS WCS header file

Table 2: Information returned in log-file `RESULT` statement

4.2 FITS WCS output

If requested (by the presence of the `fits=` specifier on the command line), ASTROM will write out the plate solution in a series of FITS files, containing headers conforming (largely) to the FITS WCS standards (known as 'Paper I' and 'Paper II') [1, 2]. ASTROM will generally attempt more than one fit. The file names will start with the string given in the `fits=` parameter.

There is more than one way to encode the required WCS information, and which way is used depends on the value of the parameter `wcsstyle=` on the command line. The allowed values of this are `qtan` and `xtan`, and these are discussed now.

There is a standard for specifying world coordinate systems in FITS files [2], and ASTROM conforms to this. At present (May 2003) there is only an early *draft* standard for representing distortions, *Representation of distortions in FITS world coordinate systems*, Calabretta et al. (also known as 'Paper IV'), available at Mark Calabretta's web pages [3]. Part of ASTROM's function is to determine and report such distortions, but since there is not yet any standardised way to do this, we have something of a problem.

This program does not attempt to produce output using the distortion model described in Paper IV; that seems premature. Instead, it describes distortions using the model described as 'distorted gnomonic' (`TAN`) in the late *draft* versions of Paper II. If you specify `wcsstyle=xtan` (not recommended), then ASTROM emits FITS headers which fully conform to these drafts; if you specify `wcsstyle=qtan`, the FITS headers are essentially the same, but with the draft paper's `PVj_m` headers replaced by non-standard `QVj_m`. In this latter case, the headers are conformant with the final Paper II, but the distortion information is available to software which knows how to use it. You are strongly advised *not* to produce new FITS files using option `wcsstyle=xtan`, unless you are obliged to by old versions of software.

The 'distorted gnomonic' `TAN` projection is not documented here (deliberately), and the drafts describing it are no longer readily available on the web. However, should you need to, you would probably be able to find a copy through Mark Calabretta's WCS web pages [3].

This is an interim solution. It's anyone's guess how long it will take for the FITS community to agree on a final version of Paper IV. Once that is finalised, however, it's quite possible that ASTROM's support for the above header styles will be removed.

5 Method

For each input sequence, up to three astrometric solutions are reported. The first is a four coefficient linear model (zero points, scale and orientation), requiring at least two reference stars. The second, computed in addition to the 4-coefficient model if there are at least three reference stars, is a six coefficient linear model (zero points, scales in x and y, orientation and nonperpendicularity). The third solution, which is performed on request and providing at least 10 reference stars have been supplied, has 7-9 coefficients and includes in the model the radial distortion coefficient and/or the plate centre, along with the six linear terms.

The 4-coefficient model is useful (1) for rough and ready astrometry, *e.g.* from a print using a ruler or graph paper, and (2) for identifying an erroneous reference star, the higher order fits tending to disguise the error. On most occasions, the 6-coefficient solution will be the most useful.

Internally, the modelling is done in idealized "plate coordinates", and the various $[\alpha, \delta]$ and $[x, y]$ data input to or output from ASTROM are converted to and from this internal standard as required. The conversion from $[\alpha, \delta]$ to plate coordinates consists of the following steps:

(1) Appropriate operations to transform the supplied $[\alpha, \delta]$ into either observed coordinates (if the optional observation data have been provided) or mean coordinates at the plate epoch (if not).

(2) Conventional gnomonic projection, using the given plate centre $[\alpha, \delta]$, to obtain tangential coordinates $[\xi, \eta]$.

(3) A small adjustment to allow for departures from tangent-plane geometry.

The distortion model in step 3 is the usual "cubic" one, where the vector from the plate centre to the star image is lengthened by an amount proportional to the cube of the length of this vector. The adjustment is carried out by multiplying each of ξ and η by the factor $(1 + q(\xi^2 + \eta^2))$, the coefficient q depending on the telescope type specified. The values for each telescope type are given in the following table:

telescope type	*description*	q
`ASTR`	astrograph	zero
`SCHM`	Schmidt	$-1/3$
`AAT2`	AAT PF doublet	+147.1
`AAT3`	AAT PF triplet	+178.6
`AAT8`	AAT $f/8$	+21.2
`JKT8`	JKT $f/8$	+14.7
`GENE`	general	specified

Notes:

- Positive q values correspond to pincushion distortion, negative to barrel distortion.
- In the case of telescope type `GENE` (generalized pincushion/barrel distortion), q is specified directly as a numeric parameter, and therefore can be used for any telescope or camera which is adequately described by the distortion model.
- The difference between the Schmidt and tangent-plane projections is conventionally assumed to be that between r and $\tan r$; ASTROM's $q = -1/3$ is equivalent to making the approximation $\tan r \simeq r + r^3/3$.
- The coefficient q can, optionally, be determined automatically.

For the 4- and 6-coefficient linear models, the fitting process consists of finding a set of coefficients which transform the measured reference star $[x, y]$ data into plate coordinates which approximate those calculated from the $[\alpha, \delta]$ data. For the 7-9 coefficient solutions, revised estimates of the plate centre $[\alpha, \delta]$ and/or radial distortion coefficient q are made as well.

The models relate the following three types of coordinate:

- The *estimated* coordinates $[x_e, y_e]$, derived from the reference star $[\alpha, \delta]$ by gnomonic projection and the application of radial distortion, using the current estimates of the plate centre and radial distortion coefficient.
- The *measured* coordinates $[x_m, y_m]$, as supplied.
- The *predicted* coordinates $[x_p, y_p]$, derived by the application of the current linear model to the measured coordinates.

Two varieties of **4-coefficient linear model** are tried, one the mirror-image of the other. The *standard* model is:

$$\begin{aligned} x_e &\simeq a_1 + a_2 x_m + a_3 y_m \\ y_e &\simeq b_1 - a_3 x_m + a_2 y_m \end{aligned}$$

The *laterally inverted* model is:

$$\begin{aligned} x_e &\simeq a_1 + a_2 x_m + a_3 y_m \\ y_e &\simeq b_1 + a_3 x_m - a_2 y_m \end{aligned}$$

The one delivering the smallest RMS error is selected. If only two reference stars have been supplied, the standard model is used.

The **6-coefficient linear model** is as follows:

$$\begin{aligned} x_e &\simeq a_1 + a_2 x_m + a_3 y_m \\ y_e &\simeq b_1 + b_2 x_m + b_3 y_m \end{aligned}$$

Instead of the coefficients a_n, b_n being found directly, the fits are, in fact, implemented in terms of corrections $\Delta a_n, \Delta b_n$ to assumed approximate values of a_n, b_n. For example, the 6-coefficient model is fitted as:

$$\begin{aligned} x_e - x_p &\simeq \Delta a_1 + \Delta a_2 x_m + \Delta a_3 y_m \\ y_e - y_p &\simeq \Delta b_1 + \Delta b_2 x_m + \Delta b_3 y_m \end{aligned}$$

When determining the **plate centre**, the following extra non-linear terms are added to the basic 6-coefficient linear model:

$$\begin{aligned} x_e - x_p &\simeq \cdots + p_1(x_p^2 + q(3x_p^2 + y_p^2)) + p_2(x_p y_p + q(2x_p y_p)) \\ y_e - y_p &\simeq \cdots + p_1(x_p y_p + q(2x_p y_p)) + p_2(y_p^2 + q(x_p^2 + 3y_p^2)) \end{aligned}$$

The coefficients p_1 and p_2 estimate the offset between the pole of projection and the current $[x_p, y_p]$ origin. This offset is used to improve the plate centre $[\alpha, \delta]$ (and to correct the zero point $[a_1, b_1]$) prior to recomputing $[x_p, y_p]$ for each reference star.

When determining the **radial distortion coefficient**, the following extra terms are added:

$$
\begin{aligned}
x_e - x_p &\simeq \cdots - \Delta q(x_p^2 + y_p^2)x_p \\
y_e - y_p &\simeq \cdots - \Delta q(x_p^2 + y_p^2)y_p
\end{aligned}
$$

The Δq obtained from the fit is added to the current q to provide a better estimate.

The above expressions are similar to those derived by Murray in sections 8.3.1*ff* of *Vectorial Astrometry* (Adam Hilger, 1983). The main difference is that in ASTROM the centres of the gnomonic projection and cubic distortion are assumed to be coincident.

All three types of solution are found by the iterative application of a least-squares algorithm based on *singular value decomposition* of the *design matrix*. (See sections 2.9 and 14.3 of *Numerical Recipes*, Press *et al.*, Cambridge University Press, 1986.) This algorithm gives identical results to the traditional *normal equations* approach, but copes better with the ill-conditioned character of the 7-9 coefficient model. The fit minimizes $\Sigma((x_e - x_p)^2 + (y_e - y_p)^2)$. Each reference star thus produces two rows of design matrix – one for x and one for y. Internally, the measured coordinates $[x_m, y_m]$ are scaled to unit RMS to reduce the risk of numerical problems during the fitting process.

In the case of the 4- and 6-coefficient linear models, a single iteration is, in principle, all that is needed, whatever the starting values for the coefficients. However, a second iteration is performed in order to minimize rounding errors.

The 7-9 coefficient models are highly nonlinear, with adjustments of plate centre and – especially – radial distortion producing large changes in the scales and zero points which depend on the distribution of reference stars. To ensure convergence, given reasonable starting values for the plate centre and radial distortion coefficient, the following strategy is used:

- ASTROM insists that at least 10 reference stars be available if a non-linear fit is to be attempted.
- A fixed and ample number of iterations is used – currently 20.
- Iterations which fit the plate centre and/or the distortion alternate with ones containing the six linear terms alone. The final iteration is the linear model.
- Where fitting of both the plate centre and the distortion has been requested, for the first few iterations only one or other of these is included in the fit, in alternation. Once reliable estimates of each have been obtained the full model is fitted at once.

6 Limitations

ASTROM aims to deliver results better than 1 arcsec from typical Schmidt plate measurements, and better than 0.1 arcsec from carefully measured JKT and AAT plates *etc*. Astrometric specialists will, nonetheless, be aware of a number of shortcomings, including the following:

- The fit is limited to a 6-coefficient linear model plus cubic distortion and plate tilt. Colour effects – arising for example from chromatic aberrations in the camera optics – are not allowed for, no magnitude or image shape terms are included in the model, and the refraction cannot be adjusted automatically.
- The zonal distortions of the reference catalogues are neglected.
- There is no provision for the simultaneous fitting of more than one plate. This prevents an extended area being modelled via overlapping plates, and the determination of proper motion and parallax from plates taken at different epochs.
- Only rudimentary error information is produced.

Despite these limitations, which stem mainly from the need for simplicity of use, the accuracy of the result tends in practice to be dominated by the quality of the input data rather than by ASTROM itself.

7 Reduction in Observed Place

Normally, the ASTROM reduction is carried out (internally) using *mean* places for the epoch of the plate – positions corrected for precession, but not for nutation, aberration, deflection, and refraction, the effects of which are simply absorbed into the fit. This approach keeps the input file simple, and delivers perfectly adequate results for most practical purposes. However, there are some occasions on which a more precise reduction may be worthwhile.

Although the nutation, aberration and deflection are always relatively innocuous – the nutation produces a small and harmless rotation, the aberration varies very slowly across the sky, and the deflection is tiny except close to the Sun – the effects of atmospheric refraction can be quite important. As far as ASTROM is concerned, the refraction has two aspects:

- *Differential refraction* causes the picture to be distorted. The distortion is in the form of a non-linear scale reduction in the vertical direction, the reduction being larger near the bottom; this cannot be fully corrected by ASTROM's linear model.
- *Atmospheric dispersion*, important for detectors of wide spectral coverage, causes the images of stars of different colour to appear shifted vertically from their nominal positions.

Both these effects can be eliminated if the optional time, observatory, meteorological and colour records are included in the input file. The advantages of bothering to do this are as follows:

- A more accurate result. The improvement is likely to be modest in most instances, but may be significant for low elevations and wide fields.
- More nearly equal scales will be reported in x and y, and will be constant all over the sky. Apart from providing additional reassurance that the fit is good, accurate knowledge of the scales is clearly vital if the optical parameters of the telescope are being measured for later use in predictions for guide stars or fibre feeds *etc*.

- The effects of colour may be important and can at least be quantified.

The optional records all begin with an explicit identifier, of which only the first character (T, O, M or C) is significant. They must immediately follow the plate data record, but can be in any order. Here is an example:

```
Time 1984 01 20  16 00

Obs 149 04.0  -31 16.6  1164

Met 288 899

Col 600
```

If the time, observatory and meteorological records are all omitted, any colour records subsequently encountered will be ignored. In the absence of full information, ASTROM makes plausible guesses to make good the deficiencies. If insufficient information for the observed place predictions is available, warnings are issued and the astrometry is done using mean place. If any of the three observation data records appears twice, the new information supplants the old, and no error is reported.

The TIME record specifies the time for mid-exposure; this can be given as a UT date and time (as five numbers, year, month, day, hour, minutes), or a local sidereal time (hour and minutes) or a Julian epoch (a single float). If the time record specifies a UT, and an epoch is specified on the plate data record, the latter is ignored. If the ST option is used, the epoch on the plate data record must be specified (and should be accurate to a day or two if the annual aberration and solar deflection are to be correctly computed). In the absence of a UT, it is reasonable to guess that the exposure occurred near upper culmination, which simply requires the ST to be set equal to the plate centre α. For example, to perform an observed place reduction on a plate of a field at $\alpha = 19^h 13^m$, the following TIME record might be used:

```
Time 19 13   * Estimated LST
```

The OBSERVATORY record can either specify one of the observatory identifiers recognized by the SLALIB routine SLA_OBS (see SUN/67):

```
Obs AAT
```

or the observatory position can be given explicitly as in the example given earlier. If the TIME record specifies sidereal time, the observatory longitude may optionally be omitted. The height (metres above sea level) is of limited importance unless the meteorological record is absent, in which case the height is used to estimate the pressure.

The METEOROLOGICAL record specifies the temperature and pressure at the telescope, in °K and mB respectively. The temperature defaults to 278°K; the default pressure is computed from the observatory height.

COLOUR records can appear anywhere after the time, observatory and meteorological records, except between a pair of reference star records. Here is an example:

```
Colour 550
```

The effective wavelength specified by such a record applies to all stars from that point onwards. Should two colour records follow consecutively, the second supplants the first, and no error is reported. Prior to the first colour record, a default of 500nm is assumed. Appendix C contains rough estimates of the effective wavelength for sources of different colour temperature and detectors of different passband. For the photographic case, the following table (compiled with the help of D. Malin) suggests effective wavelengths for some common combinations of emulsion, filter and star colour; the *blue* and *red* columns refer to very blue and very red (thermal) sources respectively (the effects may, of course, be more extreme for emission-line objects and other non-blackbody sources). For a star of spectral type G0, the effective wavelength will lie about halfway between the *blue* and *red* figures.

<table>
<tr><th>band</th><th>emulsion</th><th>filter</th><th>blue</th><th>red</th></tr>
<tr><td>U</td><td>O
J</td><td>UG 1</td><td>365</td><td>365</td></tr>
<tr><td rowspan="2">B</td><td>IIa O</td><td>GG 385
GG 395</td><td>410</td><td>420</td></tr>
<tr><td>IIa J</td><td>GG 385
GG 395</td><td>410</td><td>480</td></tr>
<tr><td>V</td><td>IIa D</td><td>GG 495</td><td>550</td><td>600</td></tr>
<tr><td rowspan="2">R</td><td rowspan="2">IIIa F
103a E
098-04</td><td>RG 610
RG 630</td><td>675</td><td>675</td></tr>
<tr><td>GG 495</td><td>600</td><td>675</td></tr>
<tr><td>I</td><td>IV-N</td><td>GG 695</td><td>800</td><td>800</td></tr>
</table>

It must again be pointed out that there may be other important colour effects, apart from atmospheric dispersion, notably where refracting optics have been used. There is no attempt in ASTROM to model such phenomena.

8 Fitting Plate Centre and Radial Distortion

Given a sufficient number of reference stars, measured to high accuracy and evenly distributed over the whole plate, it is possible to supplement the normal 4- and 6-coefficient linear solutions with one in which the plate centre and/or the radial distortion are determined automatically.

The option of fitting the plate centre (*i.e.* the $[\alpha, \delta]$ of the centre of projection, which *a priori* may well not be known to adequate accuracy) is selected simply by beginning the plate centre record with the tilde character '~' (meaning "approximately"):

```
~ 12 53 00.0  -42 00 00  B1950.0  1974.5  * Approx plate centre
```

Even though the plate centre is to be adjusted, it is advisable to start off with the best available estimate. The difference between this and the actual centre of the projection pattern is what textbooks refer to as *tilt*. Determination of the tilt is most secure where the radial distortion is pronounced. Schmidt astrometry is relatively insensitive to tilt, and attempting to fit the plate centre may be unwise unless the reference stars are numerous and well-distributed.

A further option (intended for investigating the properties of previously unmodelled telescopes rather than for routine use), is to fit the radial distortion coefficient. This is selected by prefixing the telescope type record with the tilde character '~':

```
~ AAT3                * Guess
```

Tilt and distortion may be fitted simultaneously. Neither adjustment will be attempted unless at least 10 reference stars are supplied. If the fit proves to be unacceptably ill-conditioned, or if the adjustments are unrealistically large, the fit is rejected.

Though no check is made, it is clearly unwise to request that the tilt and distortion be included in the model if the reduction is not taking place in *observed* coordinates (see the previous section).

9 Parallax

As described in Section 3, reference star celestial positions may be expressed in either of two formats. The most usual format includes proper motions and has an optional epoch which defaults to that of the equinox. The other common format, used for reference stars whose proper motions are assumed to be zero in an inertial frame, has no proper motions and must have an epoch as well as an equinox.

The first format (*i.e.* with proper motions) has the supplementary option of allowing the annual parallax to be specified, following or instead of the epoch. Here are two fictitious reference star $[\alpha, \delta]$ records each of which includes parallax:

```
14 39 36.087  -60 50 07.14  -0.49486 +0.6960  J2000.0  0.752 * Ref 1
09 16 19.03 -10 52 23.2 -0.0401 -0.006 B1950.0 1978.9 0.032 * Ref 2
```

In the case where the parallax is supplied without an epoch, which of the two is meant is deduced from the size of the number given.

In the case where an epoch is supplied as well as well as a parallax, it is assumed that the parallax has yet to be applied. In other words, the option to have the parallax removed from a reference star at the given catalogue epoch and then put back in for the epoch of the plate is **not** provided. The parallax is only taken into account (except for second-order effects on the proper motion) when a reduction in observed place has been requested (by supplying observatory, time and refraction information – see Section 7). Note that no provision is made to specify the radial velocity of a reference star. This would only matter in cases where the plate epoch was very distant from the reference star epoch and where both radial velocity and parallax were large.

No provision exists in ASTROM for specifying the parallax (or proper motion) of the unknown stars.

References

[1] E. W. Greisen and M. R. Calabretta. Representations of world coordinates in FITS. *Astronomy and Astrophysics*, 395(3):1061–1076, December 2002. 'Paper I', also available at [3]. 4.2

[2] M. R. Calabretta and E. W. Greisen. Representations of celestial coordinates in FITS. *Astronomy and Astrophysics*, 395(3):1077–1122, December 2002. 'Paper II', also available at [3]. 4.2

[3] M. R. Calabretta et al. FITS WCS pages. Web page [cited May 2003]. `http://www.atnf.csiro.au/people/mcalabre/WCS/`. 4.2, 1, 2

A The Input File

This appendix gives a more formal and complete specification of the input file than is given in the main text, and concludes with a more comprehensive example.

INPUT FILE

SEQUENCE
/
SEQUENCE
/
⋮
SEQUENCE
`END`
Blank records are ignored. Any record may end in a comment, which begins with an asterisk. Where records contain numbers these are free-format, decoded by the SLA_DBJIN and SLA_DFLTIN routines in SLALIB (see SUN/67), separated by spaces or a single comma. Lowercase and uppercase can be freely mixed. Any number of sequences is permitted.

SEQUENCE

RESULTS EQUINOX RECORD, optional
TELESCOPE TYPE RECORD, optional
PLATE DATA RECORD
OBSERVATION DATA, 0-3 records
REFERENCE STARS, 2-3 per star for 2-2000 stars
UNKNOWN STARS, 1-2 per star for any number of stars

OBSERVATION DATA

TIME RECORD
OBSERVATORY RECORD
METEOROLOGICAL RECORD
(Any order; any selection; repeats harmless.)

REFERENCE STAR

COLOUR RECORD (optional; repeats harmless)
REFERENCE STAR RA,DEC RECORD
REFERENCE STAR X,Y RECORD
A colour record applies to all subsequent stars, both reference and unknown.

UNKNOWN STAR

COLOUR RECORD (optional; repeats harmless)
and/or:
UNKNOWN STAR X,Y RECORD
or:
UNKNOWN STAR RA,DEC RECORD

RESULTS EQUINOX RECORD

EQUINOX
In the absence of this record, J2000.0 is used.

TELESCOPE TYPE RECORD

[APPROX] PROJECTION
In the absence of this record, `SCHM` is assumed.

PLATE DATA RECORD

[APPROX] RA DEC EQUINOX [EPOCH]
The position specified is that of the plate centre. The epoch is optional only if the information is supplied later in a time record (see next item).

TIME RECORD

Either:
`T...` UT
or:
`T...` ST
The first of these forms allows the epoch to be omitted from the plate data record.

OBSERVATORY RECORD

Either:
`O...` STATION
or:
`O...` [LONGITUDE] LATITUDE [HEIGHT]
The longitude may be omitted only if the sidereal time has been or will be specified via a time record. The height defaults to an estimate based on the air pressure.

METEOROLOGICAL RECORD

`M...` TEMPERATURE [PRESSURE]
The temperature defaults to 278°K. The pressure defaults to an estimate based on the height.

COLOUR RECORD

`C...` WAVELENGTH
A wavelength, once specified, applies to all stars from then on. The starting default is 500 nm.

REFERENCE STAR RA,DEC RECORD

Either:
RA DEC PMR PMD EQUINOX [EPOCH] [PARALLAX] [NAME]
or:
RA DEC EQUINOX EPOCH [NAME]
The second format implies inertially zero proper motion.

REFERENCE STAR X,Y RECORD

X Y

UNKNOWN STAR X,Y RECORD

X Y [NAME]

UNKNOWN STAR RA,DEC RECORD

RA DEC EQUINOX [NAME]

EQUINOX

The epoch of the equator and equinox of a mean $[\alpha, \delta]$ coordinate system. A Besselian epoch implies the pre IAU 1976 system (as used in the FK4 catalogue) and a Julian epoch implies the post IAU 1976 system (as used in the FK5 catalogue).

APPROX

~ (tilde)
At the start of the telescope type and plate data records, this specifies that the radial distortion and plate centre, respectively, are to be fitted.

PROJECTION

`ASTR...` = astrograph
or
`SCHM...` = Schmidt (default)
or
`AAT2...` = AAT prime focus doublet
or
`AAT3...` = AAT prime focus triplet
or
`AAT8...` = AAT $f/8$ with vacuum plateholder
or
`JKT8...` = JKT $f/8$ Harmer-Wynne
or
`GENE...` DISTORTION = generalized pincushion/barrel distortion

DISTORTION

A number, the parameter q in the pincushion/barrel distortion expression $\boldsymbol{r'} = (1 + q \mid \boldsymbol{r} \mid^2)\boldsymbol{r}$, where $\boldsymbol{r'}$ is the radial vector to the star image from the intersection of the optical axis and the plate, and $\boldsymbol{r}$ is the same vector but assuming tangent-plane geometry. The vectors are in units of one focal length.

EPOCH

A Besselian or Julian epoch: a single number resembling years AD, optionally preceded by `B` (for *Besselian*) or `J` (for *Julian*). In the absence of a prefix, epochs before 1984.0 are assumed to be in the Besselian timescale, and epochs from 1984.0 onwards are assumed to be in the Julian timescale.

RA DEC

A mean $[\alpha, \delta]$ expressed as six numbers: hours, minutes, seconds, degrees, arcminutes, arcseconds. The seconds and arcseconds can be given to any reasonable precision; the others must be integers. All the numbers except the degrees must be positive; southern δ is indicated by minus degrees (even if zero).

UT

The UT epoch of observation expressed as six numbers: years AD, month, day, hours, minutes. All but the minutes must be integers. The year, month and day must form a valid date in the Gregorian calendar.

ST

The local (apparent) sidereal time of observation expressed as two numbers: hours, minutes. The hours must be an integer.

STATION

A character string specifying one of the observatories supported by the SLA_OBS routine in SLALIB (see SUN/67).

LONGITUDE

The east longitude, expressed as two numbers: degrees (which must be an integer) and arcminutes. West longitudes may be indicated either by minus degrees (even if zero) or by east longitude $> 180^{\circ}$.

LATITUDE

The (geodetic) latitude, expressed as two numbers: degrees (which must be an integer) and arcminutes. South latitude is indicated by minus degrees (even if zero).

HEIGHT

A single number, the height above sea level in metres.

TEMPERATURE

A single number, the ambient temperature in $^{\circ}$K.

PRESSURE

A single number, the pressure in mB.

WAVELENGTH

A single number, the effective wavelength in nm.

PMR PMD

Two numbers, the proper motions in seconds and arcseconds per year respectively.

PARALLAX

A single number, the annual parallax in arcseconds.

NAME

The name field, which is always optional, is simply the first 10 characters of the comment, excluding the $*$ and any leading spaces.

X Y

Two numbers, the Cartesian coordinates on the plate; the units of x and y should preferably be the same and in the μm to m range (*e.g.* mm), and the zero points should not be too far from the region of measurement.

The example input file which appears on the next page includes two sequences. The first is for a typical run using measurements from a Schmidt plate, while the second is for precise reduction, in observed place, of AAT $f/8$ measurements, including automatic determination of the radial distortion and plate centre. For brevity, neither sequence includes as many reference stars as would normally be advisable.

```
B1950                                    * Results in FK4
SCHM                                     * Schmidt geometry
19 04 00.0  -65 00 00  B1950.0  1974.5    * Plate centre, and epoch
18 56 39.426  -63 25 13.23  -0.0002  -0.036  B1950.0  * Ref 1
44.791   85.643

19 11 53.909  -63 17 57.57   0.0058  -0.044  1950.0   * Ref 2
-46.266   92.337

19 01 13.606  -63 49 14.84   0.0020  -0.026  1950.0   * Ref 3
17.246   64.945

19 08 29.088  -63 57 42.79   0.0016   0.018  1950.0   * Ref 4
-25.314   57.456

19 02 10.088  -63 29 16.73   0.0012  -0.019  1950.0   * Ref 5
11.890   82.766

-5.103    58.868                     *  Candidate
19 09 46.2  -63 51 27  J2000.0       *  Radio pos

/                                    *  End of first sequence

* AAT plate 2266 (f/8 RC)  NGC 3114
~ AAT8    * To be fitted
~ 10 01 00.0 -59 53 01 B1950   * To be fitted
Time 1984 01 20  16 00
Obs AAT
Met 288 899
Colour 450    *  Default colour for reference stars
10 01 21.203 -59 52 14.05 B1950 J1984.1
9.0353 18.4211 *130
10 00 16.401 -59 52 52.16 B1950 J1984.1
1.7304 17.9282 *70
10 00 18.516 -59 53 10.20 B1950 J1984.1
1.9669 17.6566 *73
10 00 19.620 -59 49 01.62 B1950 J1984.1
2.1223 21.3760 *74
10 00 20.525 -59 52 01.09 B1950 J1984.1
2.2025 18.6888 *75
10 00 21.416 -59 51 30.27 B1950 J1984.1
2.3067 19.1501 *76
10 00 22.896 -59 53 49.60 B1950 J1984.1
2.4544 17.0626 *80
10 01 26.159 -59 50 38.50 B1950 J1984.1
9.6143 19.8435 *134
10 01 28.328 -59 51 16.86 B1950 J1984.1
9.8509 19.2653 *138
10 01 54.446 -59 54 39.28 B1950 J1984.1
```

B Example Report

Here is an example of the report produced by ASTROM. It is the result of a run using the specimen input file presented in Section 3. The first part of the report lists the raw data. The second part gives the results of the 4-coefficient solution. The third part (next page) gives the results of the 6-coefficient solution. The fourth part gives the predictions for the unknown stars.

It should be noted that the report file contains Fortran printer codes.

```
1* * * * * * * * * * * * *
 *  A S T R O M E T R Y  *
 * * * * * * * * * * * * *



 Equinox for mean coordinates of results:  B1950.0

 Projection geometry:  Schmidt

 Plate centre:  19 04 00.0   -65 00 00     Equinox B1950.0     Epoch B1974.500


 Reference stars:

               n              RA            Dec          pmR     pmD    Equinox   Epoch

               1         18 56 39.426  -63 25 13.23  -0.0002 -0.036  B1950.0  B1950.000
               2         19 11 53.909  -63 17 57.57  +0.0058 -0.044  B1950.0  B1950.000
               3         19 01 13.606  -63 49 14.84  +0.0020 -0.026  B1950.0  B1950.000
               4         19 08 29.088  -63 57 42.79  +0.0016 +0.018  B1950.0  B1950.000
               5         19 02 10.088  -63 29 16.73  +0.0012 -0.019  B1950.0  B1950.000
```

```
1Plate solution: 4-coefficient
 -----------------------------

     X,Y = expected plate coordinates (radians)

     X =  +0.2328072E-03                          Y =  -0.7392285E-03
          -0.3274547E-03 * Xmeas                       -0.5543943E-06 * Xmeas
          -0.5543943E-06 * Ymeas                       +0.3274547E-03 * Ymeas


 Xmeas =  +0.7071360                          Ymeas =   +2.258696
           -3053.849     * X                            -5.170293     * X
           -5.170293     * Y                            +3053.849     * Y


      Plate scale (in measuring units):          67.5425 arcsec
                           Orientation:          +0.097  deg and laterally inverted


 Reference stars:
                            Mean RA,Dec         Equinox B1950.0      Epoch B1974.500
               n                    catalogue                     calculated

               1            18 56 39.421  -63 25 14.11    18 56 39.468  -63 25 14.27
               2            19 11 54.051  -63 17 58.65    19 11 54.082  -63 17 58.00
               3            19 01 13.655  -63 49 15.48    19 01 13.580  -63 49 15.88
               4            19 08 29.127  -63 57 42.35    19 08 29.016  -63 57 42.72
               5            19 02 10.117  -63 29 17.20    19 02 10.220  -63 29 16.92

                                                                                    RMS :
```

```
1Plate solution: 6-coefficient
 -----------------------------

     X,Y = expected plate coordinates (radians)

     X =  +0.2457761E-03                          Y =  -0.7296778E-03
          -0.3274742E-03 * Xmeas                       -0.5253092E-06 * Xmeas
          -0.7235166E-06 * Ymeas                       +0.3273299E-03 * Ymeas


 Xmeas =  +0.7455928                          Ymeas =   +2.230379
           -3053.665     * X                             -4.900618     * X
           -6.749697     * Y                             +3055.011     * Y


     Plate scales (in measuring units):      X    67.5465 arcsec
                                             Y    67.5168 arcsec
                                          mean    67.5316 arcsec
                   Nonperpendicularity:           +0.035  deg
                           Orientation:           +0.109  deg and laterally inverted


 Reference stars:
                             Mean RA,Dec         Equinox B1950.0      Epoch B1974.500
               n                     catalogue                    calculated

               1             18 56 39.421  -63 25 14.11    18 56 39.395  -63 25 14.22
               2             19 11 54.051  -63 17 58.65    19 11 54.031  -63 17 58.70
               3             19 01 13.655  -63 49 15.48    19 01 13.633  -63 49 15.48
               4             19 08 29.127  -63 57 42.35    19 08 29.132  -63 57 42.37
               5             19 02 10.117  -63 29 17.20    19 02 10.181  -63 29 17.01

                                                                                     RMS :




1Unknown stars:    B1950.0 mean places for epoch B1974.500

             :              4-coefficient model                 :                6-coeffici
             :   Xmeas    Ymeas          RA              Dec     :   Xmeas    Ymeas
             :                                                   :
             :   -5.103   +58.868 -> 19 05 01.697  -63 56 17.13 :   -5.103  +58.868 -> 19 0
             :   -5.120   +58.862 <- 19 05 01.874  -63 56 17.54 :   -5.111  +58.856 <- 19 0
```

The residuals `dX` and `dY` are, loosely, in *standard coordinates*; except at the poles, positive `dX` means that the measured position of the image lies to the east of the expected position, and positive `dY` means that the measured position lies to the north of the expected position.

If a 7-9 coefficient fit is requested, and providing there are at least ten reference stars, an extra section of report precedes the unknowns. If the fit is successful, the two solutions used to process the unknown stars are the 6 and 7-9 coefficient ones, and the 4-coefficient model is not used.

C Effective Wavelengths

Most ASTROM reductions work in mean $[\alpha, \delta]$ of date, absorbing various small rotations and distortions of the field into the fit. This normally delivers results of adequate accuracy. However, for slightly improved accuracy, especially at low elevations and with wide fields, ASTROM can optionally be supplied with additional information (an accurate date and time, observatory location, *etc.*) to enable reduction in *observed* place. The further possibility is then available of correcting for atmospheric dispersion, by supplying effective colours for the reference and unknown stars; this can sometimes be important.

The following tables estimate the effective wavelength for different spectral types and detector/filter passbands. The figures given are the median wavelength of the appropriate blackbody spectrum within the specified band, and are thus only a very rough guide. Some detectors peak strongly; some filters leak outside their nominal passband; both may roll off gradually at the edges of the passband; some stellar spectra have pronounced absorption or emission features.

The tables cover blue cutoffs from 320 nm and red cutoffs up to 800 nm, in steps of 20 nm and with a minimum passband of 100 nm, for 13 colour temperatures. B−V and U−V colours and the nearest main-sequence spectral types are also given, as listed in Table 99 of *Astrophysical Quantities*.

For any given exposure, only one line in the tables will be needed, corresponding to the spectral response of the detector plus filter used. The appropriate effective wavelength for any star in the exposure can then be found by looking in the appropriate column.

Band	3000	3800	4500	5400	6000	6700	7600	9000	11100	15400	23000	38000	70000	T_c (°K)
320-420	392	386	382	377	375	373	371	368	365	362	360	359	358	
320-440	408	400	395	389	386	383	380	377	373	369	366	364	363	
320-460	424	415	408	401	397	394	390	385	381	375	372	369	367	
320-480	440	430	422	413	408	404	399	393	387	381	377	373	371	
320-500	456	444	435	424	419	413	407	401	394	387	381	377	375	
320-520	472	458	448	436	429	423	416	408	400	391	385	381	378	
320-540	488	472	460	447	439	432	424	415	406	396	389	384	381	
320-560	503	486	473	457	449	441	432	421	411	400	392	387	384	
320-580	519	500	485	468	458	449	439	428	416	404	395	389	386	
320-600	534	513	497	478	468	457	446	434	421	408	398	392	388	
320-620	549	527	508	488	476	465	453	439	426	411	401	394	390	
320-640	563	540	520	498	485	473	459	444	430	414	403	396	391	
320-660	578	552	531	507	493	480	466	449	434	417	405	397	393	
320-680	592	565	542	516	501	487	472	454	437	419	407	399	394	
320-700	607	577	552	525	509	493	477	459	441	422	409	400	395	
320-720	620	589	563	533	516	500	482	463	444	424	410	402	396	
320-740	634	601	573	541	523	506	488	467	447	426	412	403	397	
320-760	648	612	582	549	530	512	492	470	450	428	413	404	398	
320-780	661	623	592	557	537	517	497	474	452	430	414	405	399	
320-800	674	634	601	564	543	522	501	799	799	799	799	799	799	
340-440	410	404	400	396	394	392	390	387	385	382	380	379	378	
340-460	426	418	413	407	405	402	399	396	393	389	387	385	383	
340-480	441	432	426	419	415	412	408	404	400	396	392	390	388	
340-500	457	446	438	430	426	421	417	412	407	401	397	394	393	
340-520	473	460	451	441	436	431	426	419	413	407	402	398	396	
340-540	488	474	464	452	446	440	434	427	420	412	406	402	400	
340-560	504	488	476	463	456	449	442	433	425	416	410	405	403	
340-580	519	502	488	473	465	457	449	440	431	421	413	408	406	
340-600	534	515	500	483	474	465	456	446	436	425	417	411	408	
340-620	549	528	511	493	483	473	463	452	440	428	419	414	410	
340-640	564	541	523	503	492	481	470	457	445	432	422	416	412	
340-660	578	554	534	512	500	488	476	462	449	435	425	418	414	
340-680	593	566	545	521	508	495	482	467	453	438	427	420	416	
340-700	607	578	555	530	516	502	488	472	456	440	429	421	417	
340-720	621	590	565	538	523	508	493	476	460	443	431	423	418	
340-740	634	602	575	546	530	515	498	480	463	445	433	424	420	
340-760	648	613	585	554	537	520	503	484	466	447	434	426	421	
340-780	661	624	595	562	544	526	508	488	469	449	436	427	422	
340-800	674	635	603	569	550	531	512	799	799	799	799	799	799	
360-460	428	422	418	415	413	411	409	407	405	402	401	399	399	
360-480	443	436	431	426	423	421	418	415	412	409	407	405	404	
360-500	459	450	443	437	434	430	427	423	420	416	413	410	409	
360-520	474	463	456	448	444	440	436	431	427	422	418	415	414	
360-540	490	477	468	459	454	449	444	438	433	427	423	419	418	
360-560	505	491	480	469	463	458	452	445	439	432	427	423	421	
360-580	520	504	492	479	473	466	460	452	445	437	431	427	424	
360-600	535	517	504	489	482	475	467	458	450	441	435	430	427	
360-620	550	530	515	499	491	482	474	464	455	445	438	433	430	
360-640	564	543	526	509	499	490	481	470	460	449	441	436	432	
360-660	579	555	537	518	508	497	487	476	464	452	444	438	434	
360-680	593	568	548	527	516	505	493	481	469	456	446	440	436	
360-700	607	580	558	536	523	511	499	486	472	459	449	442	438	
360-720	621	592	569	544	531	518	505	490	476	461	451	444	440	
360-740	635	603	579	552	538	524	510	494	480	464	453	446	441	
360-760	648	615	588	560	545	530	515	499	483	466	455	447	443	
360-780	662	626	598	568	551	536	520	502	486	468	456	448	444	
360-800	674	636	607	575	558	541	524	799	799	799	799	799	799	
380-480	446	441	437	434	432	430	428	427	425	423	421	420	419	
380-500	461	454	449	444	442	440	437	435	432	429	427	426	425	
380-520	476	467	461	455	452	449	446	443	440	436	433	431	430	
380-540	491	481	473	466	462	458	455	450	446	442	438	436	435	
380-560	506	494	485	476	472	467	463	458	453	447	443	440	439	
380-580	521	507	497	486	481	476	471	465	459	452	448	444	443	
380-600	536	520	508	496	490	484	478	471	465	457	452	448	446	
380-620	551	533	520	506	499	492	485	477	470	462	456	452	449	

Band	3000	3800	4500	5400	6000	6700	7600	9000	11100	15400	23000	38000	70000
400-720	623	597	578	558	548	539	529	519	508	497	490	484	481
400-740	637	608	588	567	556	545	535	523	512	501	492	486	483
400-760	650	620	597	575	563	551	540	528	516	504	495	489	485
400-780	663	631	607	582	569	557	545	532	520	506	497	490	487
400-800	676	641	615	589	576	563	550	799	799	799	799	799	799
420-520	483	478	475	472	470	469	468	466	464	463	461	461	460
420-540	497	490	486	482	480	478	476	474	472	470	468	467	466
420-560	511	503	498	492	490	487	485	482	479	476	474	472	471
420-580	526	516	509	502	499	496	493	490	486	482	480	478	476
420-600	540	528	520	512	508	505	501	497	493	488	485	482	481
420-620	555	541	531	522	517	513	508	503	499	493	489	487	485
420-640	569	553	542	531	526	521	516	510	504	498	494	491	489
420-660	583	565	553	541	534	529	523	516	510	503	498	494	492
420-680	597	577	563	550	543	536	529	522	515	507	502	498	495
420-700	611	589	573	558	550	543	536	528	520	511	505	501	498
420-720	624	601	584	567	558	550	542	533	524	515	508	504	501
420-740	638	612	593	575	565	557	548	538	528	518	511	506	503
420-760	651	623	603	583	573	563	553	543	532	522	514	509	505
420-780	664	634	612	591	579	569	559	547	536	525	516	511	507
420-800	677	644	621	598	586	575	563	799	799	799	799	799	799
440-540	502	497	494	491	490	489	487	486	484	483	482	481	480
440-560	515	509	505	501	499	498	496	494	492	490	488	487	486
440-580	529	521	516	511	509	507	504	502	499	497	494	493	492
440-600	543	534	527	521	518	515	512	509	506	503	500	498	497
440-620	557	546	538	531	527	524	520	516	513	508	505	503	502
440-640	571	558	549	540	536	532	528	523	519	514	510	508	506
440-660	585	570	559	549	544	540	535	530	524	519	515	512	510
440-680	599	582	570	558	553	547	542	536	530	524	519	516	514
440-700	613	593	580	567	561	554	548	542	535	528	523	519	517
440-720	626	605	590	576	568	561	555	547	540	532	526	522	520
440-740	640	616	600	584	576	568	561	552	544	536	530	525	523
440-760	653	627	609	592	583	575	566	557	549	539	533	528	525
440-780	666	638	619	600	590	581	572	562	553	543	535	530	527
440-800	678	648	627	607	596	587	577	799	799	799	799	799	799
460-560	520	516	513	511	509	508	507	506	504	503	502	501	501
460-580	534	528	524	521	519	517	516	514	512	510	509	508	507
460-600	547	540	535	530	528	526	524	522	519	517	515	513	513
460-620	561	552	546	540	537	535	532	529	526	523	521	519	518
460-640	575	564	556	549	546	543	540	536	533	529	526	524	523
460-660	588	575	567	559	555	551	547	543	539	534	531	529	527
460-680	602	587	577	568	563	559	554	549	545	539	536	533	531
460-700	616	599	587	576	571	566	561	555	550	544	540	537	535
460-720	629	610	597	585	579	573	567	561	555	549	544	540	538
460-740	642	621	607	593	586	580	574	567	560	553	547	544	541
460-760	655	632	616	601	594	587	580	572	565	557	551	547	544
460-780	668	643	626	609	601	593	585	577	569	560	554	550	547
460-800	681	653	634	616	607	599	591	799	799	799	799	799	799
480-580	539	535	533	530	529	528	527	526	524	523	522	521	521
480-600	552	547	543	540	538	537	535	534	532	530	529	528	527
480-620	566	558	554	550	547	546	544	541	539	537	535	534	533
480-640	579	570	564	559	556	554	552	549	546	543	541	540	539
480-660	592	582	575	568	565	562	559	556	553	549	547	545	544
480-680	606	593	585	577	574	570	567	563	559	555	552	549	548
480-700	619	604	595	586	582	578	574	569	565	560	556	554	552
480-720	632	616	605	595	590	585	580	575	570	565	561	558	556
480-740	645	627	615	603	597	592	587	581	575	569	565	562	560
480-760	658	638	624	611	605	599	593	587	580	574	569	565	563
480-780	671	648	633	619	612	605	599	592	585	578	572	568	566
480-800	683	658	642	626	619	612	604	799	799	799	799	799	799
500-600	558	554	552	550	549	548	547	546	544	543	542	542	541
500-620	571	566	562	559	558	557	555	554	552	550	549	548	548
500-640	584	577	573	569	567	565	563	561	559	557	556	554	554
500-660	597	588	583	578	576	573	571	569	566	564	562	560	559
500-680	610	600	593	587	584	582	579	576	573	570	567	565	564
500-700	623	611	603	596	593	589	586	583	579	575	572	570	569

T_c (°K)

Band	3000	3800	4500	5400	6000	6700	7600	9000	11100	15400	23000	38000	70000	T_c (°K)
540-740	659	647	641	634	631	628	626	622	619	616	614	612	611	
540-760	671	658	650	643	639	636	633	629	625	622	619	617	615	
540-780	683	669	659	651	647	643	639	635	631	627	623	621	620	
540-800	695	678	668	658	654	650	645	799	799	799	799	799	799	
560-660	616	613	611	609	608	607	606	605	605	604	603	602	602	
560-680	628	623	621	618	617	616	615	614	612	611	610	609	609	
560-700	640	634	630	627	626	624	623	621	620	618	617	616	615	
560-720	652	645	640	636	634	632	631	629	627	625	623	622	621	
560-740	664	655	650	645	643	640	638	636	633	631	629	627	626	
560-760	677	666	659	654	651	648	645	642	640	637	634	633	632	
560-780	689	676	669	662	658	655	652	649	646	642	639	638	636	
560-800	700	686	677	670	666	662	659	799	799	799	799	799	799	
580-680	635	632	630	629	628	627	626	625	625	624	623	623	622	
580-700	647	643	640	638	637	636	635	634	632	631	630	630	629	
580-720	659	653	650	647	645	644	643	641	640	638	637	636	636	
580-740	671	664	660	656	654	652	651	649	647	645	643	642	642	
580-760	683	674	669	664	662	660	658	656	654	651	649	648	647	
580-780	695	685	678	673	670	668	665	663	660	657	655	653	652	
580-800	706	694	687	681	678	675	672	799	799	799	799	799	799	
600-700	655	652	650	648	648	647	646	645	645	644	643	643	643	
600-720	666	662	660	658	657	656	655	654	653	651	651	650	649	
600-740	678	673	669	667	665	664	663	661	660	658	657	657	656	
600-760	690	683	679	675	674	672	670	669	667	665	664	663	662	
600-780	701	693	688	684	682	680	678	676	674	672	670	669	668	
600-800	712	703	697	692	689	687	685	799	799	799	799	799	799	
620-720	674	671	670	668	668	667	666	666	665	664	663	663	663	
620-740	685	682	679	677	676	675	675	674	673	672	671	670	670	
620-760	697	692	689	686	685	684	683	681	680	679	678	677	676	
620-780	708	702	698	695	693	692	690	689	687	685	684	683	683	
620-800	719	712	707	703	701	699	698	799	799	799	799	799	799	
640-740	694	691	689	688	687	687	686	686	685	684	684	683	683	
640-760	705	701	699	697	696	695	695	694	693	692	691	690	690	
640-780	716	711	708	706	705	704	703	701	700	699	698	697	697	
640-800	727	721	717	714	713	711	710	799	799	799	799	799	799	
660-760	713	711	709	708	707	707	706	706	705	704	704	703	703	
660-780	724	721	719	717	716	715	715	714	713	712	711	711	710	
660-800	735	730	728	725	724	723	722	799	799	799	799	799	799	
680-780	733	730	729	728	727	727	726	726	725	724	724	724	723	
680-800	743	740	738	736	736	735	734	799	799	799	799	799	799	
700-800	752	750	748	747	747	746	746	799	799	799	799	799	799	
nm	M5	M0	K5	K0	G5	G0	F5	F0	A5	A0	B5	B0	O5	
	+1.61	+1.39	+1.11	+0.84	+0.70	+0.57	+0.45	+0.30	+0.16	0.00	−0.17	−0.31	−0.45	B−V
	+1.19	+1.24	+1.06	+0.46	+0.20	+0.04	−0.01	+0.02	+0.09	0.00	−0.56	−1.07	−1.20	U−B

D Error and Warning Messages

Except where otherwise stated, the following messages appear on both the command device (typically the terminal) and the report device (typically the file to be printed). The 'Log:' information shows the severity and message number which appear in the log file (if one was specified; see Section 4.1).

`Can't open file` *nn*

The above message may appear when ASTROM is started and usually means either that the specified data file doesn't exist, or that file protection problems prevent the report file from being written.

```
Please run ASTROM from the correct script!
ASTROM improperly invoked!
GETARG error!
```

These are examples of other messages which appear when ASTROM is started and which depend on the particular type of computer being used. They indicate either software errors or some other gross error. Attempting to run the ASTROM executable image directly rather than through the correct command procedure is one possible cause.

`^^^^^^  POSSIBLE DATA ERROR?  ^^^^^^`
(Log: error 1)

This message is output to the command device only. It means that at least one of the fields in the plate centre $[\alpha, \delta]$ was suspect – unexpectedly negative, fractional when it should have been integer, or outside the conventional range.

`Observation data were incomplete and will be ignored`
(Log: error 14)

Many of the observation data may be omitted and have sensible defaults, but certain combinations of omission make it impossible for ASTROM to carry out a reduction in observed place. When this happens, the above message is output and a mean place reduction is carried out.

`For the given observation data, the plate centre ZD is` *xxx.x* `degrees!`
`Reduction will be in MEAN place.`
(Log: warning 2)

This indicates that the zenith distance of the field centre, if the observation data are to be believed, is greater than 90°. The most likely causes are an incorrectly specified time or observatory site.

`sla_DS2TP status` *n*
(Log: error 9)

The above message indicates something badly wrong with the reference star or plate centre positions.

```
Impossible sla_SVD error!
```
(Log: error 9)

If this message appears please ask your Starlink Site Manager to contact the Starlink User Support group.

`sla_SVD warning` *n*
(Log: warning 3)

Certain very rare combinations of (perfectly valid) data can provoke the above message. If it appears, please check the rest of the output to see if it looks reasonable. If you prefer, you can almost certainly make the condition disappear by changing one of the data values *very* slightly. If the results look suspect, or if changing the data fails to eliminate the problem, please ask your Starlink Site Manager to contact the Starlink User Support group.

```
Fit was ill-conditioned!
```
(Log: warning 4)

This warns that the input data failed to define all the fitted parameters adequately. The cure is to use more reference stars or not to fit the plate centre and/or the distortion.

```
Radial distortion coefficient cannot reliably be determined!
```
(Log: warning 6)

This message, which appears only on the report device, warns that the data were of insufficient quality to allow the distortion to be determined. This can happen, for example, if the distortion is very small or if there aren't enough reference stars.

```
Plate centre cannot reliably be determined!
```
(Log: warning 8)

The above message, which appears only on the report device, warns that the data were of insufficient quality to allow the plate centre to be determined. This can happen, for example, if the radial distortion is very small or if there aren't enough reference stars.

```
*************** INVALID DATA ****************
```
(Log: error 12)

This indicates that there is something fatally wrong with the most recent input record.

```
------ PREMATURE END OF DATA ------
```
(Log: error 16)

This indicates that the input file has ended, or that an end-of-sequence record or an end-of-file record has been read at a time when more input records are needed before a plate solution can be attempted.

```
****** PLATE EPOCH WAS NOT SPECIFIED ******
```
(Log: error 17)

This happens if no plate epoch is available. This information must be supplied, either as part of the plate data record or in a time record.

`****** TOO MANY REFERENCE STARS; MAX` *n* `******`
(Log: error 18)

ASTROM internal workspace limits have been reached; reduce the number of reference stars. If you have a legitimate requirement for a larger number of reference stars than is currently allowed, please ask your Starlink Site Manager to contact the Starlink User Support Group.

`------ FIT` *n* `ABORTED ------`

This message always follows one of those described earlier, which will indicate the source of the problem.

```
----- UNKNOWNS BUT NO SOLUTION ------
```
(Log: error 19)

An unknown star record has been encountered before the records defining a plate solution have been input. Check the order of records in the input file.

`FITS Filename` <*filename*> `too long.  FITS writing abandoned`
(Log: error 10)

The requested FITS header file name is too long (the maximum is around 100 characters).

```
FITS filename blank!?  FITS writing abandoned
```
(Log: error 11)

The requested FITS headef file name appears to be blank.

```
Unrecognised FITS WCS style, xxx.  FITS writing abandoned
```
(Log: error 15)

The header style requested is not one of the supported ones. No FITS file will be written.

```
FITS error detected:  ...
```
(Log: error 13)

The FITS system reported some error (reproduced in the message). FITS writing will be abandoned.