CARLSBERG MERIDIAN CATALOGUE LA PALMA

Number 12

CCD observations of positions of stars and planets March 1999 to March 2002

Version 1.0: Declination -3° to $+3^\circ$

Document Version 2

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CARLSBERG MERIDIAN CATALOGUE
LA PALMA

Number 12

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Contents

1 Introduction

This is the documentation for CMC12 (Version 1.0), an astrometric and photometric catalogue of 6.3 million stars in the red magnitude range 9 to 17.

The Carlsberg Meridian Telescope (CMT) underwent a major upgrade in March 1999. A 2k by 2k CCD camera was installed with a Sloan r' filter operating in a drift scan mode. With the new system, the magnitude limit is $r'_{\rm CMT}$ =17 and the initial positional accuracy is in the range 0.050″ to 0.100″. Further calibration improves the positional accuracy to about 0.035″.

The main task of the CMT is to map the sky in the declination range $-3°$ to $+30°$ with the aim of providing an astrometric, and photometric, catalogue that can accurately transfer the Hipparcos/Tycho reference frame to Schmidt plates.

For further information see our web page at `http://www.ast.cam.ac.uk/~dwe/SRF/camc.html`

2 This and future releases

The current release (Version 1.0) comprises all the observations made between March 1999 and March 2002 with the new CCD in the declination band -3° to +3°. It is intended to release the rest of the catalogue later.

When further observations become available covering a previous declination band, they will be included in the new release along with the old data. Similarly, if new calibrations are carried out between the data releases, they will be incorporated in the new release. Thus, later versions will completely supercede Version 1.0 *etc.*

All the data will be available from the web site: `http://www.ast.cam.ac.uk/~dwe/SRF/cmc12/`

CD-ROMs containing the data could be made if there is difficulty in obtaining the data over the internet.

3 Previous Catalogues

The previous catalogues (1 to 11) contained data taken with a photoelectric moving-slit micrometer on the telescope and covered the period May 1984 to May 1998.

Catalogues CMC1–8 were issued separately in five printed volumes (CMC1–4 1989; CMC5 1991; CMC6 1992; CMC7 1993; CMC8 1994). Catalogue CMC9 was issued on a CD-ROM in 1997. The space afforded by this CD-ROM was used to re-issue CMC1–8 and combine them with CMC9. Similarly, CMC11 was issued on CD-ROM together with CMC1–10 in 1999 (Carlsberg Consortium 1999). Although CMC10 was not published separately – being overtaken by CMC11 – its separate identity was maintained in the numbering sequence because the treatment of the observations was slightly different from CMC11.

A description of the old micrometer and telescope system is given in Helmer & Morrison 1985.

4 The Telescope System

The telescope is a Grubb Parsons refractor with an objective of 178 mm diameter and focal length 2.66 m. Originally, the detector used was a scanning-slit photoelectric micrometer, but was replaced in 1998 by a CCD camera operating in a drift scan mode. This was a major change in the method of observing, since relative astrometry with respect to a dense grid of standards within the same data frames would be used rather than absolute astrometry and offsetting the telescope with respect to the standards.

More recently (March 1999) the CCD system was upgraded to a larger detector (Kodak 2k×2k with 9μm pixels) and a filter equivalent to the Sloan Digital Sky Survey r' passband (Fukugita et al. 1996) was fitted. More information about the telescope system can be found in Evans 2001b.

The geodetic coordinates of the telescope on the WGS84 system were determined in 1993 using a GPS receiver. The astronomical and geodetic coordinates are:

$$\text{Astronomical}\begin{cases}17^\circ\,53'\,07.''8\,\mathrm{W}\\ 28^\circ\,45'\,52.''4\,\mathrm{N}\end{cases}\qquad \text{Geodetic}\begin{cases}17^\circ\,52'\,56.''70\,\mathrm{W}\\ 28^\circ\,45'\,35.''97\,\mathrm{N}\\ \text{Altitude }\ 2326\,\mathrm{m}\end{cases}$$

A summary of the telescope system is given in Table 1.

The operation of the instrument on La Palma is shared between Copenhagen University Observatory (CUO), the Institute of Astronomy (IoA), Cambridge and the Real Instituto y Observatorio de la Armada en San Fernando (ROA). The Copenhagen University Observatory is a department of The Niels Bohr Institute for Astronomy, Physics and Geophysics. The three institutions have set up a Management Committee to decide on the overall observing programme and other matters related to running the telescope.

5 The Reductions

During the night, after an observation has been completed, a pipeline is started which carries out the initial reductions. The main task of these reductions is to parameterize the raw data from the CCD. The software is based on that used by the APM facility in Cambridge and produces positions (x,y), intensity and shape information for each image using a modified version of the usual intensity-weighted APM moment method (Irwin 1996). In this case an additional modified pseudo-profile weighting scheme is used, based on a smoothed (2D Hanning filter) version of the raw data.

In doing this, the data is reduced from around 2–4 GB to 6–7 MB per night. The software for reducing the data is designed to run automatically and with the minimum of user intervention.

Further calibrations are carried out off-line at Cambridge in order to account for a Charge Transfer Efficiency (CTE) problem with the CCD and positional fluctuations caused by the atmosphere (see Figures 1 and 2). The former results in a systematic error in right ascension as a function of magnitude, while the latter produces errors in both right ascension and declination as a function of right ascension (equivalent to time). More information can be found about the calibration of the CTE problem and atmospheric fluctuations in Evans, Irwin & Helmer 2002.

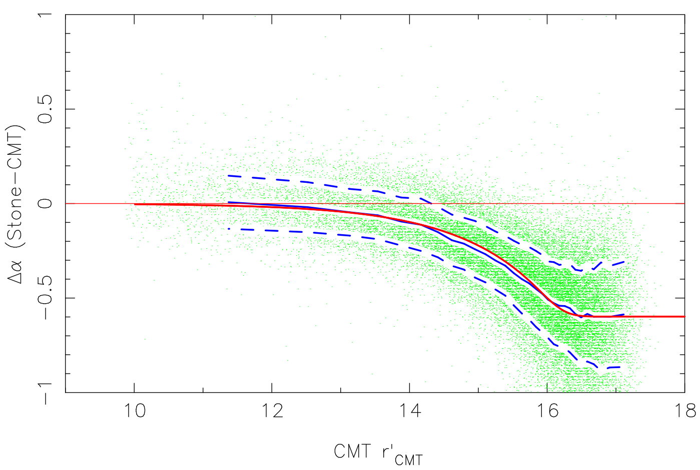
In order to carry out the calibration of the atmospheric fluctuations, overlaps are required in declination. By observing on every quarter degree of declination, an overlap of $8'$ on both the North and South sides was ensured. This means that in general, the central $7'$ will only be observed once, while the outer $8'$ will be observed twice. However, many areas were observed more than this due to constraints within the observing strategy.

The final catalogue consists of the averaged positions from the calibrated data frames. For the current version only a simple algorithm is used whereby any images within $2''$ of each other are considered as the same source. However, considering that the average image size is larger than this, it is likely that this

Table 1: A summary of the telescope and camera parameters for the current configuration.

Telescope:	Located on La Palma, Canary Islands
	178 mm objective
	2.66 m focal length
Camera:	CCD chip – Kodak (KAF-4202 Grade:C1)
	2060×2048 pixels
	Pixel size 9μm ($0.7''$)
	CUO built
	Operating temperature $-30\,^\circ$C
System:	Automatic and remotely controlled
	Drift scans (generates ~3 Gb of data per night)
	Data automatically parameterized (reduced to 6-7 Mb)
	Daily reductions take about 30 min.
	100,000–200,000 stars observed per night
	Calibrated with respect to Tycho 2
	Magnitude limit (Sloan) $r'_{\rm CMT}$ =17

Figure 1: This plot shows the general trend in RA before correction caused by the CTE problem. This is a comparison, using observations taken during dark conditions, with respect to astrometric standards. A three-parameter model has been fitted to the data. This particular example comes from the beginning few months of the survey, which had problems with the camera controller. After this was replaced, the size of the effect reduced by a factor of 6. By the end of the survey, further modifications reduced the size of the effect by a further factor of 5 to 20 mas at $r'_{\mathrm{CMT}} = 17$. This is much smaller than the random errors at this magnitude.



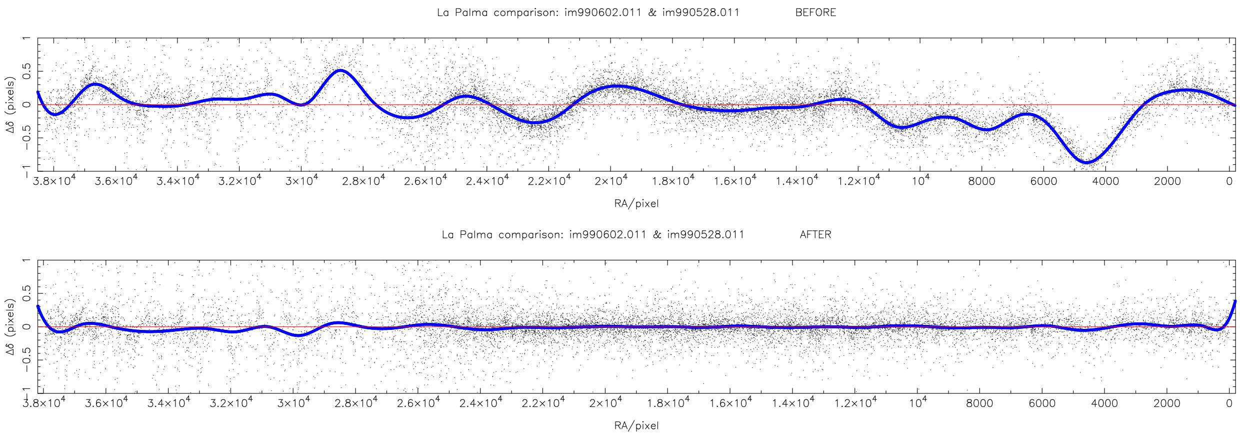


Figure 2: This shows an example of a night-to-night comparison for declination and shows the effect of the atmospheric fluctuations for a particularly poor night. The top plot is before the calibrations have been applied and the bottom one afterwards.

algorithm is sufficient. Only unflagged images are used for the average (see Section 6.9), thus consistently flagged images, *eg.* galaxies, would not appear in the main part of the catalogue. Rejected (flagged) images are available in a separate file in order to help users with diagnostics.

For more details see Evans 2001a, Evans 2001b and Evans, Irwin & Helmer 2002.

6 Properties of the Catalogue

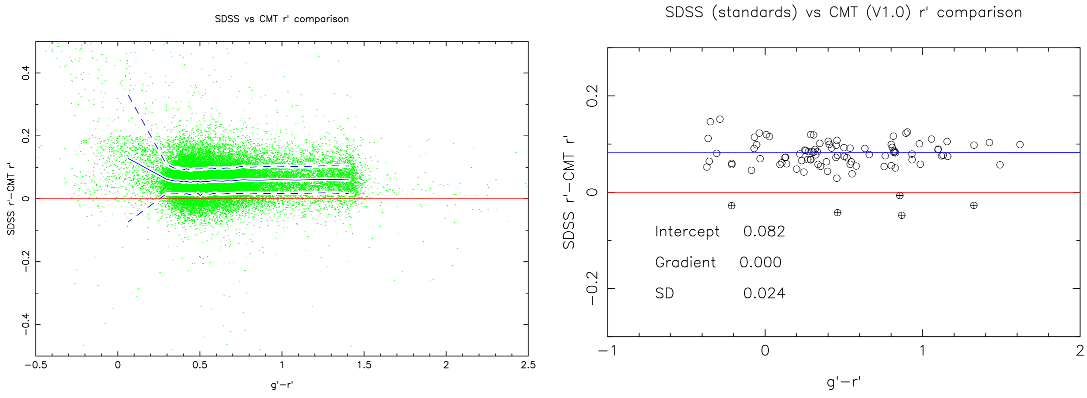
6.1 Positional system

The positional system of the catalogue is ICRS as defined by the Tycho 2 standards (Høg et al. 2000).

The main principle behind the measurements made by the CCD system is the use of relative astrometry. Although the design of the original telescope (Helmer & Morrison 1985) was with absolute astrometry in mind, better accuracy can be achieved by calibrating with respect to standards within the same data frames rather than relying on the accuracy of the telescope itself.

The astrometric standards used are those of Tycho 2 which are based on the observations collected by the star mapper of the ESA Hipparcos satellite (ESA 1997). The mean star density of this catalogue ranges from 25 to 150 stars deg^{-2} and has a magnitude limit of V$\sim$11.5.

Not all the stars in Tycho 2 are suitable for use as standards for this project. Entries have been excluded if they have no proper motion data, if they are double stars (or are suspected of being such) or have poor astrometric solutions. This excludes about 30% of the entries in Tycho 2. In doing so, we have erred on the side of caution in order to improve the robustness of the calibration.



(a) SDSS Early Release Data

(b) SDSS Standards

Figure 3: The residuals between SDSS data and CMT as a function of colour. Only entries with $r' < 15$ were used for plot (a). The offset is due to a combination of the difference between the Vega and AB_ν magnitude scales and a possible zero point determination error in the CMT data.

6.2 Magnitude system

The photometric data used as the standards are the B_T and V_T values from the Tycho 2 catalogue (Høg et al. 2000). Although there are photometric catalogues with higher accuracies at the faint end, Tycho 2 is uniquely homogeneous and dense.

The intensities determined from the images are first converted into magnitudes ($m = -2.5 \log_{10} i$) and are then corrected in order to take into account the difference between isophotal and total magnitudes (Irwin & Hall 1983). Following this, the calibration then simply consists of determining the zero point of the magnitude scale for each frame.

Since the CMT only observes in one passband, photometry from the telescope cannot be placed on a standard photometric system without additional colour information. However, using the colour data in the Tycho 2 catalogue, it is possible to calibrate onto the instrumental magnitude system. By using an *a priori* colour term, the V_T of the Tycho 2 standards can be converted into the natural system of the CCD and filter combination. This is close to the Sloan r' passband, but will be on the Vega scale rather than the spectrophotometric AB_ν magnitude system (Fukugita et al. 1996) and thus we have labeled it $r'_{\rm CMT}$. Figure 3 shows the comparisons carried out with respect to two sources of Sloan data as a function of colour. No detectable colour terms were found. Although not strictly calibrated onto the Sloan r' passband, adding +0.08 to the $r'_{\rm CMT}$ values will give photometry that is close to the Sloan r' passband on the AB_ν system.

When the photometric solution is carried out, a quality statistic is also generated which can indicate whether the photometric data should be accepted or not. It is possible for the astrometry to be accepted, while the photometry is not and hence there can be entries with no photometric data in the catalogue ($n_p = 0$). In such cases, an approximate value for the magnitude is given. The reason for not reobserving such data is that the main purpose of the catalogue is astrometry.

Fainter than about $r'_{\rm CMT} = 15$ a non-linearity in the photometry starts, which is probably caused by a combination of the isophotal correction used and the detection threshold. This amounts to a few tenths of a magnitude for the faintest stars. Using a comparison with respect to data taken from the Early Data Release of the Sloan Digital Sky Survey (SDSS), a correction was derived and applied to the data. The photometric accuracies are listed in Section 6.10.

6.3 Completeness

CMC12 is **not** complete. The intention is to provide enough data to be able to calibrate Schmidt plates over the range where a magnitude term will cause problems, thus completeness is not a requirement. It has been determined using comparisons with respect to the Sloan Digital Sky Survey that CMC12 has an overall completeness of 95–98%. The density of stars in the catalogue ranges from 600 to 10,000 stars

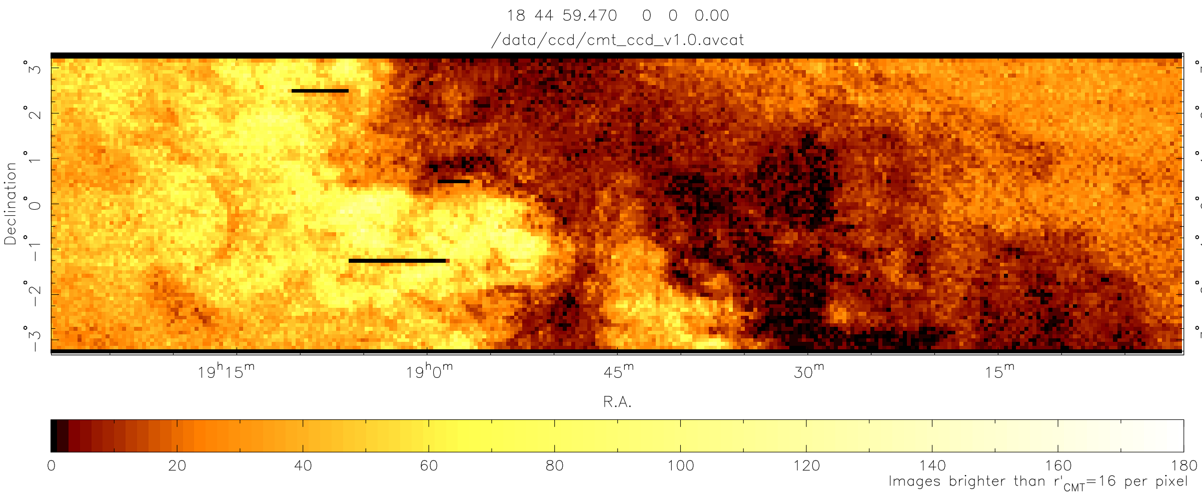


Figure 4: This shows the density variations crossing the Galactic plane. The 3 black stripes are three of the 12 holes in the catalogue mentioned in the text.

per square degree.

During observing, an area was deemed observed if the magnitude limit (defined by the 95th percentile) was fainter than $r'_{\rm CMT} = 16$. However, the median magnitude limit was $r'_{\rm CMT} = 16.8$. Thus, observations will be generally available in all areas down to $r'_{\rm CMT} = 16$, but often down to $r'_{\rm CMT} = 17$.

There are a number of small holes in the catalogue caused by lack of observations. There are 12 areas which require further observations and these will be filled in subsequent versions of CMC12. Three of these can be seen in Figure 4.

There are also holes surrounding bright stars where the image has saturated and the charge has leaked into the surrounding area. This causes spurious images to be detected and these have to be masked out. Similarly, diffraction spikes will also cause spurious images to be detected. This can affect the area surrounding stars down to $r'_{\rm CMT} = 8$. Since these areas are magnitude and observing-condition dependent, no simple shape can be defined to "drill" out the spurious objects from the catalogue. How this is achieved is described in Section 6.9.

6.4 Double stars

It was occasionally the case that when double stars were observed on more than one occasion, the observing conditions were sufficiently different that the pair were resolved on one night and not the other. If this happens, the standard deviation of the astrometry will be large (0.5–1.0″).

6.5 Galaxies

Although there are not many galaxies with $r'_{\rm CMT} \lesssim 17$ (~ 40 deg^{-2}), any that would have been observed by the survey would probably have been flagged as Diffuse or Elliptical (see Section 6.9) and thus been rejected. It is possible that these images can be found in the rejected data files.

6.6 Planets

Minor planets have not been removed from the catalogue and would have $n_t = 1$. Most have been identified, but work in comparing the residuals with respect to the latest ephemerides is ongoing.

6.7 Proper motions

Note that **no** proper motions are included in this catalogue.

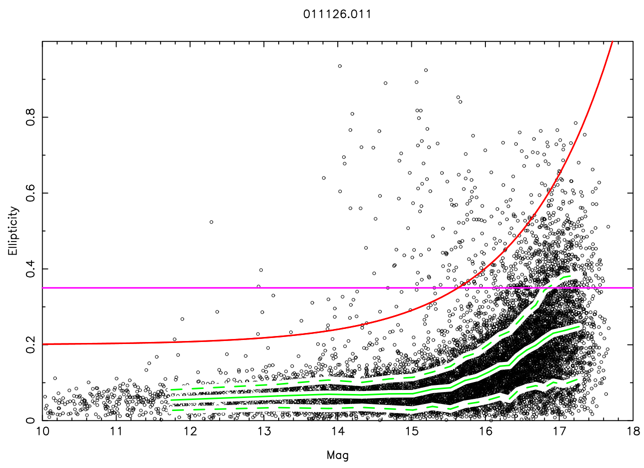


Figure 5: This plot shows the magnitude-dependent ellipticity limits (red line) used in the survey. Also shown is the old constant limit (magenta line) which caused many faint stars to be flagged needlessly. The green lines show the median and width (equivalent to a Gaussian sigma) of the ellipticity distribution.

6.8 Refraction correction

A small systematic effect exists in declination as a function of colour. This is caused by the wavelength dependence of atmospheric refraction. Using a spectral atlas it is possible to calculate the correction appropriate for the passband defined by the r' filter and the response of the KAF-4202 CCD chip.

Although the analysis calculates an absolute constant of refraction, it is only a relative term that is required as a correction since the calibration with respect to the Tycho 2 has already accounted for the average refraction term. In the equation below, the offset used is the average colour of the Tycho 2 stars used in the calibrations. This was found to be $(\mathrm{B}-\mathrm{V})_\mathrm{J} = 0.60$ (equivalent to $(\mathrm{B}-\mathrm{V})_\mathrm{T} = 0.71$, see Equation 1.3.20 of Volume 1 of ESA 1997). This colour corresponds to that of a G0 star.

The correction that should be applied to the data, ΔR, can be calculated from

$$\Delta R = -13.5[(\mathrm{B}-\mathrm{V})_\mathrm{J} - 0.60] \text{ (mas)} \tag{1}$$

which can then be applied to the declination using the following formula:

$$\delta_{\mathrm{new}} = \delta + \Delta R \tan(\delta - 28^\circ\,45'\,52''\!.4)/3.6\times10^6 \text{ (degrees)}. \tag{2}$$

Since colours are generally not available for the stars in the survey, this correction has not been applied, however for the majority of stars in the survey ($0.0 \lesssim (\mathrm{B}-\mathrm{V})_\mathrm{J} \lesssim 1.5$), ΔR varies by about ±10 mas and consequently the correction to declination will be less than 10 mas for all the survey *cf.* the astrometric accuracy at the bright end of 36 mas.

6.9 The flagging system

Before the images from the different frames are combined to produce averaged astrometry and photometry, various flags can be set depending on the properties of the image or its location. These are:

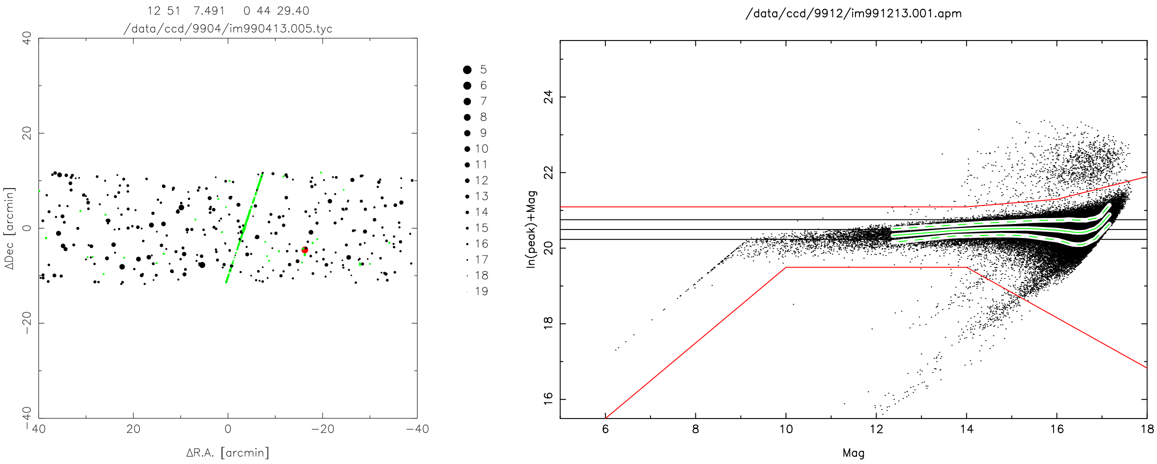
Saturated Peak height exceeds 60,000 counts.

Elliptical Image has an ellipticity that is larger than a magnitude-dependent limit (see Figure 5). The ellipticity (defined as $1-\frac{b}{a}$) of an image can be calculated from its second-order moments. This flag manages to eliminate most spurious objects such as satellite trails (see Figure 6(a)).

Sharp Image is sharper than the average image (probable noise image).

Diffuse Image is more diffuse than the average image (possible galaxy). Figure 6(b) shows the boundaries for the Sharp and Diffuse definitions.

Close to a Bright Star If an area of a frame contains an overdensity of flagged images it is likely that this is close to a bright star and that most images in this area are spurious. All images within these areas are thus flagged. This also manages to flag spurious images within satellite trails that have been missed by the Elliptical flag. Figure 7 shows the effect of the brightest star within the bounds of the catalogue. Note that in the before diagram, a large number of the spurious images



(a) Satellite trail

(b) Definition of Sharp and Diffuse

Figure 6: Plot (a) shows a satellite trail identified by the flagging of elliptical images (green). Plot (b) illustrates the definition of the Sharp and Diffuse flags. (ln(peak height) + magnitude) is plotted against magnitude and the stellar locus identified. The red lines bound the acceptable images. The upper section images are then flagged as sharp and the lower section ones flagged as diffuse.

surrounding the star have not been flagged by the other methods. However, it should be noted that in high density regions (globular clusters or the Galactic plane) large numbers of images merge and tend to be flagged as elliptical. Because of this high concentration of flagged images, the bright star mask will flag such areas and create small holes. Considering that these holes are small and that completeness is not the primary goal of the catalogue, this feature is acceptable.

Any image that is flagged is not considered for the catalogue average. If all images of a source are flagged then it will not appear in the main catalogue, but will appear in the rejected images files.

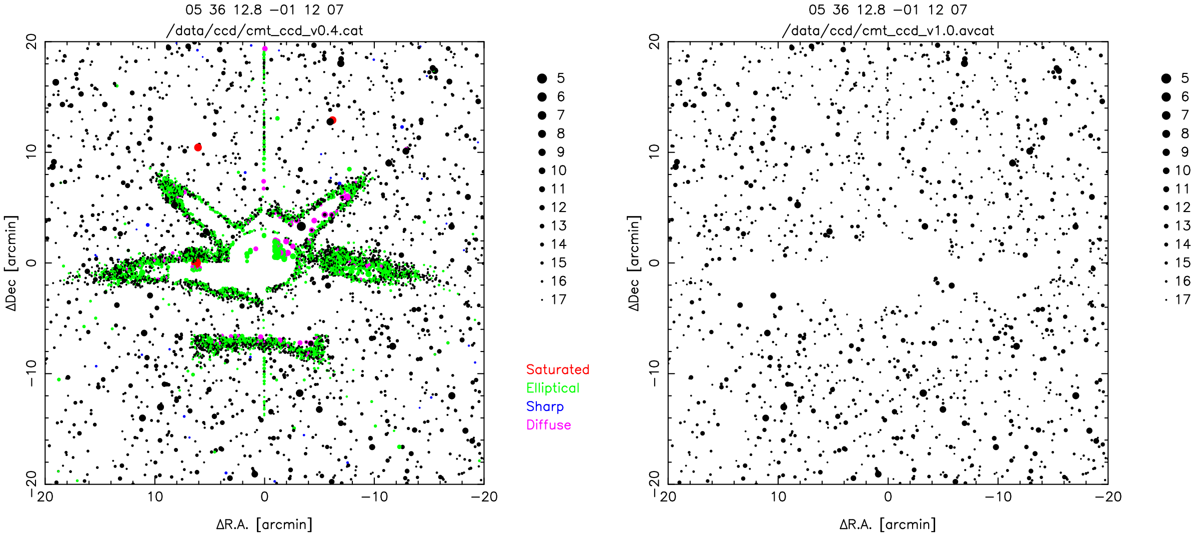
6.10 Summary of accuracies

Using the data from repeat observations and the overlap regions, the internal errors can be measured. These are given in Table 2. Since correlations between the data and uncorrected systematic errors exist, the internal errors underestimate the true, external, errors of the data. Thus, further information is required.

Comparison with Tycho 2 yields information limited to the brighter end ($r' < 12$) of the CMT catalogue. However, using comparisons with 2 or more deep astrometric catalogues, it is possible to measure the external errors directly.

Using this additional data, it can be shown that the astrometric accuracy of the CMT catalogues, before allowing for the atmospheric fluctuations, is 50–80 milli arc seconds (mas) at the bright end. After further calibrations are carried out, the accuracy improves to 25–45 mas. Further details are given in Table 2 and Figure 8. The reason for the range of accuracies is due to the varying density of Tycho 2 standards across the sky. The more standards that are available, the better the calibration.

For bright stars ($r' < 13$), the accuracy of the astrometry is about 35 mas for both RA and declination, but as you go fainter, the RA accuracy becomes gradually worse than that for declination. The likely explanation for this is that this is caused by inaccuracies in the CTE calibration which only affects RA.



(a) Before (b) After

Figure 7: This figure shows the area around Epsilon Orionis (Alnilam) a 1.7 magnitude star, before and after the bright star mask has been applied.

Table 2: The median internal and external errors for the CMT. The units for the RA and declination are milli arc seconds and those for the magnitudes are millimagnitudes.

Internal				External			
r'_{CMT}	RA	Dec	Mag	r'_{CMT}	RA	Dec	Mag
<13	21	21	16	<13	36	37	25
14	31	26	30	14	45	40	35
15	55	42	58	15	68	55	70
16	112	91	124	16	113	90	170

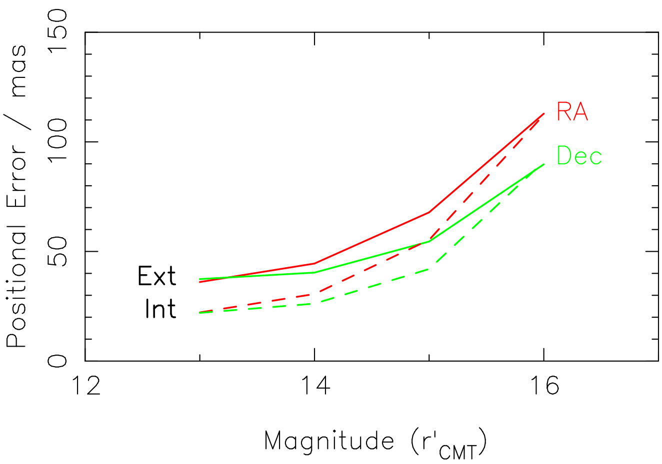


Figure 8: The internal and external positional errors as a function of magnitude. The solid line gives the median external errors and the dashed line shows the equivalent internal errors. RA is shown in red and declination in green.

7 Files contained in this directory or on this CD-ROM

`00ReadMe`	A contents listing of the directory
`cmc12_documentation.pdf`	A PDF version of this documentation
`cmc12_documentation.ps`	A Postscript version of this documentation
`cmt_ccd_v1.0.fits`	Version 1.0 of CMC12 (FITS binary table)
`cmt_ccd_v1.0.txt.gz`	Version 1.0 of CMC12 (Gzip'd ASCII)
`cmt_ccd_v1.0_rej.fits`	Entries rejected from CMC12 (FITS binary table)
`cmt_ccd_v1.0_rej.txt.gz`	Entries rejected from CMC12 (Gzip'd ASCII)

8 Data Formats

The catalogue is provided in two formats. FITS binary tables and gzip'd ASCII files. The exact format of the FITS binary tables is contained within their headers and further information can be found about them in NASA 1999. For information about CFITSIO, a FITS file subroutine library, see `http://heasarc.gsfc.nasa.gov/fitsio/`.

The first record of the ASCII file contains header information and the five entries are in free format and separated by blanks:

1. Version number of the catalogue
2. "AVCAT3" – version of the file format
3. Total number of records including the header
4. Minimum declination (radians)
5. Maximum declination (radians)

The data is sorted in right ascension and the lines are each terminated by `\n`. Including the terminator, each record contains 81 bytes.

Catalogue entries:

Bytes	Format	Explanations
1–15	a15	Identifier (IAU standard)
16–18	i3	Right Ascension (Hours) (ICRS)
19–21	i3	Right Ascension (Minutes)
22–29	f8.4	Right Ascension (Seconds)
30–30	1x	
31–31	a1	Sign of declination (minus only)
32–33	i2.2	Declination (Degrees) (ICRS)
34–36	i3	Declination (Arc minutes)
37–43	f7.3	Declination (Arc seconds)
44–50	f7.3	Magnitude (r'_{CMT}, Vega scale)
51–51	a1	Photometric flag (: if non-photometric, blank otherwise)
52–53	i2	Total number of observations (n_t) - includes bad observations
54–55	i2	Number of astrometric observations (n_a)
56–57	i2	Number of photometric observations (n_p)
58–63	f6.3	Standard deviation of RA (arc seconds) (0.0 if $n_a \leq 1$)
64–69	f6.3	Standard deviation of declination (arc seconds) (0.0 if $n_a \leq 1$)
70–75	f6.3	Standard deviation of magnitude (magnitudes) (0.0 if $n_p \leq 1$)
76–80	i5	Mean epoch of the astrometry (days since 26/3/1999 *ie.* observations taken on the evening of 26 March 1999, first light, are epoch 0)

If $n_a = 0$ then position is not astrometric
If $n_p = 0$ then magnitude is not photometric
Although the standard deviation measures are not a direct measure of the accuracy of the measurements (due to larger systematic effects) they can be indicative of problems with a particular measurement and are thus a good diagnostic.

9 Acknowledgements

The IoA personnel are part of the Cambridge Astronomical Survey Unit which is funded by the Particle Physics & Astronomy Research Council of the United Kingdom.

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The Danish participation in the project has been funded by the Copenhagen University Observatory.

During the period March 1999 to March 2002 the following people observed remotely with the telescope: Leif Helmer, Miguel Vallejo, Jose Muiños, Fernando Belizón, Dafydd Evans, Bob Argyle, Ole Einicke, Mike Irwin and Floor van Leeuwen.

Most of the software development was carried out by Dafydd Evans, Leif Helmer, Mike Irwin and Claus Fabricius.

Technical development was carried out by Leif Helmer, Torben Knudsen, Niels Michaelsen and Jens Klougart.

We would also like to take this opportunity to acknowledge the enormous contribution that Leslie Morrison made to the success of the CMT and his foresight in helping to initiate the changeover to CCD drift scanning.

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