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The Carlsberg Meridian Telescope: an astrometric robotic telescope

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Abstract. An overview is given of the Carlsberg Meridian Telescope on La Palma, which is one of the oldest robotic telescopes, having started observing on La Palma in 1984. In the spring of 1997, a further stage of automation was made when we converted the telescope to remote operation. Since then, the telescope has been operated over the Internet from Britain, Denmark or Spain.

In 1997, a CCD camera, operating in a drift-scan mode, was installed. A year later the telescope underwent a major upgrade and a larger 2k×2k CCD camera was installed, with a Sloan r' filter. With the new system, the magnitude limit is $r' = 17$ and the positional accuracy is in the range $0.03''$ to $0.05''$.

The main task of the project is to map the sky in the declination range $-3°$ to $+50°$, with the aim of providing an astrometric and photometric catalogue that can accurately transfer the Hipparcos/Tycho reference frame to Schmidt plates. We will release the first data by the end of 2001. Using the photometric information, extinction data for La Palma is also provided.

Key words: astrometry – telescopes – surveys

1. Introduction

The Carlsberg Meridian Telescope (CMT) has recently started an astrometric and photometric survey that will enable the Hipparcos/Tycho reference frame to be used at fainter magnitudes. By having a system that is fully automatic, many efficiencies can be gained in operating the telescope.

One of the main uses of astrometric data is in the registration of optical data with that of radio wavelengths. It is often the case that the astrometry of radio data is much more accurate than that of the optical and that inaccuracies in the registration could change the physical interpretation of the data. Examples of where optical astrometry has been used with radio data are Catchpole, Boksenberg *et al.* 1996 and Lockley, Eyres & Wood 1997.

By using astrometric catalogues that go relatively deep, such as that from the Carlsberg, the magnitude terms that are often present in sky survey Schmidt data can be accounted for. This in turn can be used to calibrate the astrometry from CCD data since there will then be enough unsaturated stars in each of these CCD frames with good astrometry.

Many planetary (major and minor) observations have been carried out by the CMT. These have been used to refine the dynamical models of these objects and in some cases to determine the masses of some asteroids, for example, The Asteroid Mass Determination Project at the U.S. Naval Observatory (Hilton & Stone 1998). Currently, no planetary observations are being carried out due to prioritizing the completion of the survey, however, it is likely that they will be resumed in the near future.

2. History and upgrades

The telescope was built by Grubb Parsons in 1952 and originally set up in Brorfelde, Denmark, where it was run by the Copenhagen University Observatory (CUO).

The original detector was a photographic micrometer and the instrument was a manned operation. This ran from 1964 until 1976, after when a major upgrade was undertaken and a photoelectric detector was installed. At the same time the operation of the telescope was automated. This last change managed to reduce the manpower needed to observe with the telescope by a factor of about 3–4. The telescope continued in this mode of operation in Brorfelde until 1983.

In 1984, the telescope was moved to La Palma, where the observing conditions are much better. Also, the operation of the telescope changed to being jointly run by CUO, the Royal Greenwich Observatory (RGO) and Real Instituto y Observatorio de la Armada en San Fernando (ROA). For more details on the original configuration of the telescope see Helmer & Morrison 1985. Figures 1 and 2 show the CMT and its building on La Palma.

When the telescope was first moved to La Palma, it was one of the first fully automatic telescopes in the world. With

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Fig. 1. The Carlsberg Meridian Telescope (CMT).

Fig. 2. The CMT building. Below the main structure can be seen the observers flat where the observer (when present) would sleep during the observations. On clear nights, the left side of the upper building slides out over the flat so that the telescope can observe.

the original configuration, a selection of stars (about 500 a night) would be made during the day and at about sunset, the dome would open automatically and observing would begin. An observer would be present on the site (usually in the flat underneath the telescope), but would only be needed if there was an equipment failure. As more experience was gathered and the equipment made more reliable, the need for an observer to be present on-site was reduced.

In early 1997, further automation was added when the telescope was converted to a fully remote operation. A PC, running Linux, was added to the system, which could interact with the telescope control PC and be remotely interrogated over the Internet. Since then, the telescope has been operated directly from Britain, Denmark or Spain with no observer present at the telescope.

A small drawback of remote operation is if any of the equipment fails. Most problems can be solved over the network, for example, by remotely rebooting a computer, but sometimes local help is needed. Using on-site personnel from other telescope facilities, a number of mechanical and electrical problems can be investigated and solved. However, if more serious equipment failures occur, the only solution is to send out expert staff from one of the home institutions.

In June 1998, a fundamental change was made in the way that the astrometry was carried out. The detector was changed from a photoelectric scanning-slit micrometer to a charge coupled device (CCD) operating in drift-scan mode. In doing this, rather than measure the positions of the stars in an absolute manner, using the accurate pointing and timing of the telescope, the positions would be measured relative to absolute standards from the Tycho 2 catalogue (Høg *et al.* 2000) using differential measurements from the same data frame.

The obvious complication in using an imaging device with a meridian instrument is that the sky is constantly moving across the field of view due to the Earth's rotation. This would normally smear an image along the direction of right ascension. However, in drift-scan mode, the CCD is read out at exactly the same rate as the images are crossing the focal plane.

A disadvantage of this method is that, close to the celestial pole, the images become distorted. This is because stars do not move in straight lines across the sky and this becomes more pronounced the closer you get to the poles. Also, the ideal rate for reading out the CCD varies across the CCD (proportional to $\cos\delta$). The consequence of these effects is that there is a limited declination range where good images may be obtained with meridian drift scanning. This is in general $\pm 60°$.

The use of a CCD with the CMT has not only helped us observe fainter stars, but it also has enabled us to observe many stars at once. This one improvement has increased the number of stars we observe each night by a factor of more than 20.

3. Current system

In spring of 1999 further improvements were carried out to the system: the CCD system was upgraded to a Kodak 2k×2k chip with 9μm pixels and a Sloan Digital Sky Survey r' filter was fitted.

Increasing the chip size has a number of advantages. This includes: completing the survey faster due to a larger field of view; longer exposures, hence a deeper survey; calibration improvements due to increased frame sizes.

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

Telescope:	Located on La Palma, Canary Islands 17.8 cm objective 266 cm focal length
Camera:	CCD chip – Kodak (KAF-4202 Grade:C1) 2060×2048 pixels Pixel size 9μm (0.7$''$) CUO built Operating temperature -30°C
System:	Automatic and remotely controlled Drift scans (∼3 Gb of data per night) Data automatically parameterized (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 r' =17

The current CCD camera was built by CUO, in comparison with the previous CCD camera which was bought off-the-shelf. Although commercially produced cameras can be cheaper in terms of manpower and cost, there can be difficulties in fine-tuning and repairing such devices.

The CCD chip has a pixel size of about 9μm (0.7 arc seconds) and can be cooled to -65°C by a Peltier cooler. Currently, we are cooling the chip to -30°C since this reduces the effect of a charge transfer efficiency (CTE) problem with the chip. The higher operating temperature does not affect our magnitude limit.

The original CCD operated without any filter other than the glass of the objective, but for the new camera the r' passband from the Sloan Digital Sky Survey Photometric System (Fukugita *et al.* 1996) was chosen, since the choice of a red filter minimizes the effect of differential atmospheric refraction and also enables us to provide photometry on a well-defined system.

A summary of the telescope and camera parameters for the current configuration is given in Table 1.

These improvements with the CCD and the new filter have allowed us to observe about 4 times as many stars per night than with the old CCD system. Our current magnitude limit is $r' = 17$ and we observe between 100,000 and 200,000 stars a night. On a typical night, more than 50 square degrees are observed.

4. Automation

One of the main things that has characterized the telescope from a very early stage is its automatic operation. By doing this, many of the problems associated with manual operation have been avoided. With the current system, the running of the telescope can be carried out from anywhere in the world that has Internet access. This makes operating the telescope very flexible.

The operation of the CMT does not require much human intervention. Late in the afternoon, the observer checks on the weather conditions using data from the meteorological station and also, using a video camera trained on the roof slit area of the CMT building, checks for obstructions, such as packed snow, that might hinder the opening of the roof. If all is fine, a command is issued so that observing can proceed for that evening. No more observer intervention is required until the following morning.

At sunset, the roof of the telescope building opens, leaving a slit of about 2m in width. While the sky gets dark, the temperature within the telescope enclosure equalizes with that of the evening air, reducing the effects of dome seeing. When the Sun is 9° below the horizon, the telescope starts observing the first frame in the observing list. The system then carries on observing the predetermined frames until sunrise, when the roof closes again.

During the night, after an observation has been completed, a pipeline is started which carries out the initial reductions. These are carried out in parallel with the observing and take less time than the observations themselves. 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. In doing this, the data is reduced from around 3 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.

If the weather deteriorates during the night, the observations are suspended and the roof closed. Four sensitive rain detectors and a meteorological station enable the telescope system to assess the weather. The roof is closed if there is high humidity, high winds or it is raining. Since the closing of the roof is controlled by a computer, as a fail safe, the rain detectors are connected directly to the roof closing electronics so that even if the computers have failed, the roof will still close if it is raining. These electronics are also connected to light detectors, so the roof closes automatically when the Sun rises even if there has been a failure with the computer system.

During these interruptions, the weather is continuously monitored and, if it clears up for more than 15 minutes, the observing is restarted. Due to the meridian nature of the telescope, these interruptions cause gaps in the proposed observations which can only be filled on another night.

One of the drawbacks of remote observing is that if a major system failure occurs, the observing is stopped and the roof closed for the remainder of the night. When the telescope was manned, and such an event occurred, the on-site observer could attempt to repair the problem. Usually, this would only result in about an hour of downtime. With remote observing, half a night would be lost on average. Fortunately, this does not happen very often and is thus not a large drawback.

If a failure does occur, this will be spotted by the duty observer during the morning checks, who will then contact the site services staff from the ING on La Palma to attempt to diagnose the problem and repair it. If no simple procedure for repairing the system is found, someone from the home institutions has to travel to La Palma to carry out the repair.

With the early CCD system, one of the common causes for loss of observing was the hanging of the telescope control computer. The solution to this problem was simply to reboot the computer. Circuitry was then installed that could trigger a reboot from the Linux computer. Whenever this problem now occurs, a script automatically initiates a reboot and only a minimal amount of observing is lost.

Early during the day, the operator logs on to see how the previous night's observations have progressed. One of the primary duties is to check that the roof has closed properly and that there are no telescope nor computer emergencies that need dealing with. Various log files are checked and statistics accumulated from them, so that an idea about night quality can be determined. Also, initial calibrations are carried out with respect to Tycho 2 which provides further quality control information. The data is then archived so that all the data relevant to that particular night can easily be retrieved by any of the home institutions. Finally, an observing list is prepared for the following night using the data-quality information generated by the calibrations.

Further calibrations are carried out off-line at Cambridge in order to account for the CTE problem and astrometric fluctuations caused by the atmosphere. 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 atmospheric fluctuations in Evans 2001.

5. Current survey

The main task that is currently being done by the telescope is to map the Northern sky using the upgraded CCD detector. The intention is to provide accurate positions of stars, allowing a reliable link to be made between the bright stars measured by Hipparcos and the fainter stars seen on photographic plates (as measured by the APM and similar measuring machines).

The current area of the survey is between $-3°$ and $+30°$ in declination. Extensions of the survey to $+50°$ in the North and $-15°$ in the South are planned with some of the observations having already been taken. It is expected that the observations for the primary survey area, up to $+30°$, will be mainly completed by January 2002. A subset of the catalogue will be released at the end of 2001. Following this, there will be further phased releases of the data.

In addition to the astrometry, from the photometry, the nightly extinction for La Palma is also derived. Using an instrumental zero-point, derived from the long-term performance of the CCD, and a correction for $\sec z$, the extinction in r' can be calculated. This assumes a value of 0.09 for the r' extinction for a dust-free night.

The extinction data can be obtained from the CMT web pages.[1]

6. Accuracy

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 unaccounted for systematic errors cause these measurements to underestimate the true, external, errors of the data, further information is required.

Table 2. The 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'	RA	Dec	Mag	r'	RA	Dec	Mag
<13	24	25	19	<13	43	41	20
14	32	30	32	14	49	45	35
15	59	48	65	15	74	58	70
16	117	95	127	16	115	94	165

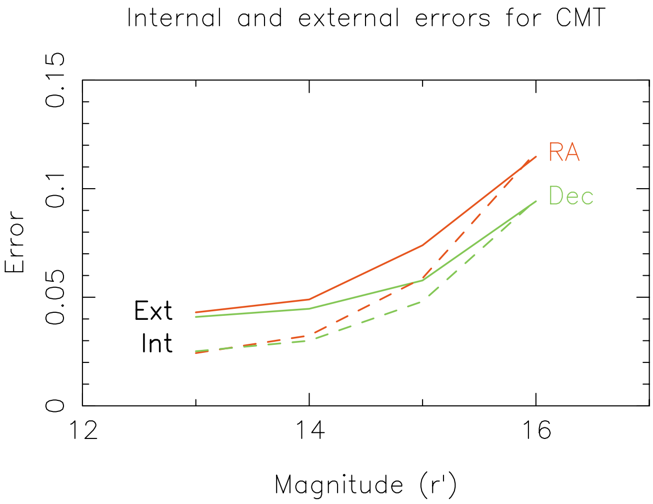

Fig. 3. The internal and external errors as a function of magnitude. The solid line gives the median external errors and the dashed line shows the equivalent internal errors. RA is shown in red and declination in green.

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 30–50 mas. Further details are given in Table 2. 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. Figure 3 shows these results in graphical form.

For bright stars ($r' < 13$), the accuracy of the astrometry is 40 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.

7. Other automated astrometric telescopes

A number of automated astrometric telescopes are currently operating. These include: the sister telescope of the

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[1] http://www.ast.cam.ac.uk/~dwe/SRF/camc.html

CMT – the CMASF Transit Circle at El Leoncito, Argentina; the Bordeaux Automatic Transit Circle at Bordeaux, France (Viateau *et al.* 1999); the FASTT Transit Circle at Flagstaff, USA (Stone *et al.* 1996); the UCAC Astrograph originally at CTIO, Chile and currently at Flagstaff, USA (Zacharias *et al.* 2000).

8. Conclusions

The automatic operation of the CMT has enabled many efficiencies to be made over the years in the running of the telescope. Conversion to remote operation was a further step in this process.

Also, by using a CCD in drift-scan mode, a new lease of life has been breathed into the telescope. However, this will only be useful over the next ten years or so. At that point, data from astrometric satellites such as DIVA and FAME will become generally available and will supersede the accuracy of ground-based astrometry.

The web site of the telescope is at:
http://www.ast.cam.ac.uk/∼dwe/SRF/camc.html

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