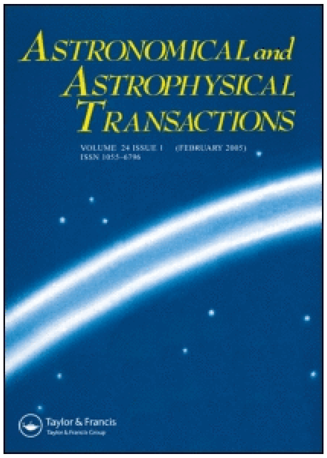

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 July 1997
To cite this Article: Pinigin, G. I., Zhigang, Li and Zi, Zhu (1997) 'A new role of CCD meridian circles in modern astrometry', Astronomical & Astrophysical Transactions, 13:1, 83 - 91
To link to this article: DOI: 10.1080/10556799708208117
URL: http://dx.doi.org/10.1080/10556799708208117

Astronomical and Astrophysical Transactions, 1997,
Vol. 13, pp. 83-91
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A NEW ROLE OF CCD MERIDIAN CIRCLES IN MODERN ASTROMETRY

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(Received December 27, 1995)

The ground-based modern meridian circles are discussed from the perspectives of the tremendous achievements in astrometry. A method of CCD star position determination by short strips is proposed. An observing programme of 12–14 stars around the extragalactic radiosources for the connection of the optical/radio reference frame using the Mykolayiv Axial meridian circle (AMC) and Danish–Chinese meridian telescope (DCMT) is described.

KEY WORDS Astrometry, reference frames, meridian circles

1 INTRODUCTION

The success of the space mission HIPPARCOS in 1989–1993 gave rise to the creation of two perfect catalogues: (a) the Hipparcos Catalogue (HC) has a homogeneous and fairly dense stellar network of 2.7 stars per square degree (120 thousands stars) with the brightness up to 11 mag and an expected internal accuracy in the range of 1–1.5 mas (Perryman, 1995); (b) the Tycho Catalogue (TC) has a density of 25 stars per square degree (one million stars) with the brightness up to 12 mag and an expected position accuracy about 30 mas (Hog, 1995a). Moreover, impressive results from space projects after the Hipparcos epoch. For example, with new satellite ROEMER+ a precision of 10 microarcseconds for positions, parallaxes and annual proper motion will be achieved for one million stars up to 10 mag during a 2.5 year mission (Hog, 1995b). In this connection the future of ground-based meridian astrometry is called into question. On the other hand, elaboration of new meridian circle (MC) design, applications of CCD detectors and computer control in the recent times are very promising. Taking this into account we try to show how modern MCs can be implemented in existing and future astrometric programmes.

At present the best reference frame (ERF) is based on the positions of compact extragalactic radio sources with the negligible proper motion (IAU IB, 1995). Using

VLBI the positions of 606 radio sources (RS) from pole to pole with an accuracy of 0.2–1.0 mas were determined (Implementation of the IERS CRF, 1995). Almost all of them have optical counterparts in the magnitude range of 17–21^m. For using the ERF it should have a global network of more bright objects with a high density over the sky and comparable accuracy with the RS positions. From 1997 onwards the HC will be the reference frame for optical astrometry. However, to link the HC to the ERF with magnitude range about 10^m is not easy. There are several ways for it and some of them could be realised with the automatic MC (Gubanov *et al.*, 1990; Argue, 1991; Kovalevsky, 1995).

First, a multi-step approach is used which provides intermediate systems of reference stars around the RSs (12–14^m, 16–18^m) in selected areas. It was proposed to use wide field astrographs in order to guarantee a sufficient number of intermediate reference stars for the determination of precise positions of faint RSs. The primary reference stars from the final HC should be used. Finally, the large optical telescopes with a small field should be employed. However, this method for the multi-step link has not an efficient accuracy when it is added up.

Another way for linking an optical reference frame to the ERF is to observe radio stars with optical telescopes and the VLBI technique. There are about two hundreds radio stars involved in the Hipparcos Catalogue. The current ground-based programs including more than 300 radio stars are carried out on the Bordeaux meridian circle and Carlsberg Automatic Meridian Circle (CAMC), (Morrison, 1994).

The direct optical observations of RS and Hipparcos stars are the main interest for the link. It is realized by the HST (Lattanzi, 1993). The positions of 48 quasars with magnitudes up to 17.5^m were determined on the eight-inch Flagstaff Astrometric Scanning Transit Telescope (FASTT), (Stone 1994; Stone and Dahn, 1995).

All of the data obtained by different ways are used to link the HC to the ERF and observations with automatic MCs provide a valuable contribution to the research of this problem.

Other programs for ground-based astrometry in which the modern MCs could take part are: (a) reobservation of the HC and TC for the determination of their proper motion. Up to 2000 star positions in the HC will be wrong by 2 to 20 mas, and in the TC by 30 to 40 mas (Hog, 1995b); (b) extension of the HC and TC to faint magnitude 17^m with a direct link to the RSs and (c) producing input catalogues for the following space projects.

2 EXISTING AND EXPECTED CAPABILITIES OF MODERN GROUND-BASED MERIDIAN CIRCLES

In the course of the development, especially in the last decade, the ground-based MCs have been improved with more high efficiency and accuracy. Now modern MCs are fully automatic: preparing input data, operating routines for telescope control, numerous observations of celestial bodies, data sampling and processing. Several

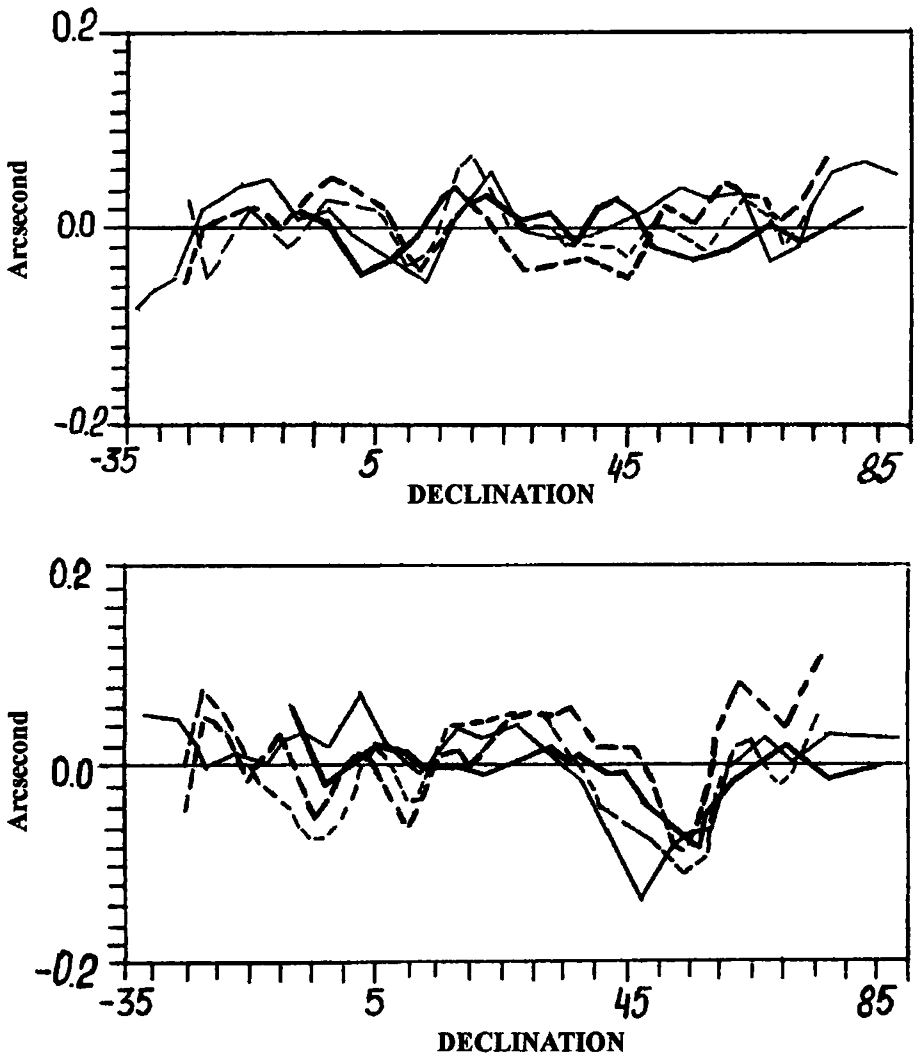

Figure 1 The comparison of the mean systematic differences $\Delta\alpha_\delta$ (upper panel) and $\Delta\delta_\delta$ (lower panel) in the sence of (Cat-FK5 found in four catalogues made with the modern MCs: Bordeaux MC (1984–1987) - - -, CAMC (1984–1987) — — —, Pulkovo HMC (1988–1990) —, Tokyo PMC (1986–1988) —.

important catalogues have been compiled from observations on automatic MCs (Morrison, 1994).

Positional astronomy is always troubled by instrumental errors. Now the high internal accuracy of measurements of the MC parameters is about 0.1 μ that is about $0\overset{''}{.}008$ by $F = 2500$ mm. However, the systematic differences (Cat-FK5) with accuracy about $0\overset{''}{.}02$–$0\overset{''}{.}03$ obtained on the best MCs of standard design show large disagreements up to $0\overset{''}{.}1$ (Figure 1), (Yoshizawa and Suzuki, 1989; Morrison

Table 1. Errors of meridian circles with different design

Type of meridian circle	*Deformation errors*		
	Horizontal flexure		*Collimation*
	value	*variation/1° C*	*variation/1° C*
Standard design: PMC, CAMC and Bordeaux MC	1.″–1.″5	0.″05–1.″0	0.″1–0.″25
Horizontal design in meridian:			
Pulkovo HMC	0.″01–0.″02	–	0.″004–0.″005
MAHIS	0.″01*	–	0.″02
Horizontal design in prime vertical:			
Mykolayiv AMC	0.″037	–	0.″026
DCMT in CSAO	0.″01*	–	0.″20

Note. *Calculated accuracy.

et al., 1990; Yoshizawa *et al.*, 1992). At the same time the average accuracy of the FK5 is 0.″04. The annual disagreements of the same differences for the PMC over three years observation show similar values of 0.″05–0.″01 (Yoshizawa *et al.*, 1992). In spite of good agreement of the systematic trends of (Cat-FK5) caused by systematic errors of FK5, we can see also a real instability and unfitting of the systematic differences for the MCs of standard design. For an explanation of this let us consider instrumental parameters such as flexure and collimation. Surely, these parameters influence the determination of the declination (flexure) and right ascension (collimation). The Table 1 shows horizontal flexure and collimation and their variations with temperature (Gumerov *et al.*, 1986; Yoshizawa, 1986; Morrison *et al.*, 1990; Kirian *et al.*, 1993; Li Zhigang, 1993; Pinigin *et al.*, 1994). It can see that values of these parameters for the standard MCs are much larger then for the MC of horizontal design (HMC). Particularly, we note that the variation of flexure and collimation with temperature is very small for the HMC. It is very important for the stability of the instrumental system. As a result, the systematic differences (Cat-FK5) of the Pulkovo HMC shows high stability and an accuracy of about 0.″02–0.″03 (Figure 1). Moreover, it is from a smaller amount of observations than standard MCs (Kirian and Pinigin, 1993). Obviously, the systematic differences (Cat-FK5) of standard MCs include some residual instrumental errors such as flexure and collimation.

We expect promising results can be obtained from the new type of horizontal MC in the prime vertical which has advantages over the HMC in the meridian. It provides direct real-time monitoring of star positions relative to the reference collimator direction and permits one to exclude shifts of the tube extremities and a more stable instrumental orientation to be obtained.

A very important stage of astrometry began at the time that the CCD detector was introduced. It provides an opportunity to determine also star positions, parallaxes and proper motions with high accuracy and efficiency of radio stars, extragalactic objects and bodies in the solar system. Due to high quantum efficiency, a large dynamical range (about 8 mag) and less readout noise the CCD observations have a measured accuracy of stellar image with a few percent pixel and the photometric accuracy reaches 0.05 mag. There are some reports about experiments with the CCD micrometer which has no moving parts on the USNO, Tokyo and Bordeaux MCs (Requeme *et al.*, 1993, 1995; Stone and Dahn, 1995; Yoshizawa, 1995). With the CCD micrometer on the FASTT the observed limiting magnitude reached was 17.5 mag. Several thousands stars can be observed per hour on the CCD MCs and their new programs provide up to millions of star observations per year.

The influence of refraction is another important problem for the ground-based CCD astrometry when measurements of large angles on the sky are carried out. Differential observation with an efficient number of reference stars on a CCD strip can reduce the influence on refraction variations, such as diurnal and annual variations. Anomalous refraction such as room refraction is reduced successfully by the help of meteorological data collection. The refraction fluctuation caused by atmosphere turbulence with high frequency has a dominant influence. This type of refraction can be reduced via measurements in the duration of one to two minutes by $0\farcs04$ for stars up to 14^m according to Stone and Dahn (1995), by $0\farcs03$–$0\farcs06$ for stars in the range of 9–16^m according to Requieme *et al.* (1995). Stone and Dahn (1995) report that the CCD MC with $30' \times 30'$ field of view and an exposure time of 100 seconds could theoretically measure star positions differentially to the Tycho catalogue with an accuracy of 22 mas. A more promising estimate was done by Pan *et al.* (1995) that for wide angle observations at visible wavelengths with the help of two-colour techniques an atmospheric limit about 10 mas can be achieved.

So, the best and most promising modern MC would appear to be the HMC in prime vertical with reflective optic, computer control and CCD about $30' \times 30'$. In this case it is possible to diminish refraction influence by the use of multi-colour procedure, producing direct real-time monitoring of instrumental parameters and high observation efficiency. It seems, the level accuracy of 20 mas will be available with the ground-based HMC before 2000.

At present, two HMCs in the prime vertical are of great interest as nearly as promising MCs. The AMC of the Mykolayiv Astronomical Observatory (MAO) has an original scheme including a horizontal telescope with a zero-expansion glass prism in front of the objective (D = 180 mm, F = 2480 mm) and a fixed aligned vacuum collimator (D = 180 mm, F = 12 360 mm) in the prime vertical. Investigation of the AMC shown: the horizontal flexure is negligible, about $0\farcs037$; collimation is stable and can be described by the formula $c = c' + at$, where t is temperature, $a = 0\farcs026$ and c' = const. The variation of the inclination of the collimator is of the order of $0\farcs09$ per 1° C (Pinigin *et al.*, 1994).

The DCMT (D = 240 mm, F = 2667 mm) of the Shaanxi Astronomical Observatory (CSAO) is another type of HMC in the prime vertical (Li Zhigang, 1993).

The design of this reflective horizontal MC is very promising. It would have a small, stable flexure with an expected value not more than $0\overset{''}{.}01$. The weakness of the setting with the whole tube motion for the standard MC is avoided on the compact DCMT. So, the aperture is larger than by any standard MC. The design of the DCMT allows direct real-time monitoring of the instrumental parameters and automatic operation during star observation. So, it would have small errors of instrumental system and a more stable residual collimation. According to trial observations, the variation of collimation is about $0\overset{''}{.}20$ per 1° C and for inclination – $0\overset{''}{.}22$ per 1° C.

3 OBSERVING METHOD AND PROGRAM

There are different methods for measuring the position of celestial bodies with a CCD micrometer. The essential drift scan mode provides observations with long narrow strips when the telescope and CCD are kept stationary and the stellar images cross the CCD with the diurnal rate (Requieme *et al.*, 1993; 1995; Stone and Dahn, 1995). It lasts about two hours or more for differential observations. Determined stellar positions relative to reference stars from available reference catalogue are measured. However, the variations of instrumental parameters and atmosphere refraction deform long strips in the direction of rigth ascension and declination. It will cause a loss of accuracy. For reducing errors caused by the shifts of instrumental parts a laser metrology system has been used (Stone and Dahn, 1995). However, with a more stable HMC we can propose a new observing model.

Basis on the stability of the HMC and the possibility of direct real-time monitoring of the instrumental parameters it can use uniform short strips with their regular distribution over the sky. Each strip has to be accompanied by at least two real-time measurements to determine the instrumental parameters and exclude the strip deformation. Determined stars should be observed by the differential method. The strip length depends on the instrumental stability and distribution of the determined stars. Including reference stars into the strip will lead to an improvement of the control of strip stability.

The further reduction in the right ascension is given by the expression:

$$(O - C)_a = (\Delta u + m) + (\Delta u + m)'\Delta t + (n + n'\Delta t)\tan\delta,$$

where $(\Delta u + m)$, $(\Delta u + m)'$ and n, n' are the Besselian constants and their rates of change with time Δt. The Δu is the clock correction. The parameters such as relative azimuth and collimation can be monitored on the prime vertical HMC by optical devices in the duration of star observations and applied.

The declination is given by following expression:

$$(O - C)_\delta = (\Delta\phi + \Delta M_0) + (\Delta\phi + \Delta M_0)'\Delta t + (\Delta r + \Delta r'\Delta t)\tan Z,$$

where $(\Delta\phi + \Delta M_0)$ and $(\Delta\phi + \Delta M_0)'$ are the corrections to the adopted latitude and zero-point of the divided circle and its rate of change. Δr and $\Delta r'$ are the refraction correction and its rate of change; Z is the zenith distance resulting from circle readings with diameter corrections applied. Four parameters $(\Delta u + m)$, $(\Delta u + m)'$, n and n' in the right ascension and other four $(\Delta\phi+\Delta M_0)$, $(\Delta\phi+\Delta M_0)'$, Δr and $\Delta r'$ in declination are determined as unknowns for each night in a least square solution with the required distribution reference stars over the sky. In case of a stable and small HMC instrumental system it can use the limited amount of unknowns for improvement of the accuracy of the solution. Later these parameters are used for calculation of the coordinate of the determined star.

The proposed method has the following pecularities: it is possible to determine all shifts of the instrument and CCD for different strips by producing at least two real-time measurements of instrumental parameters or by observing two or more reference stars in a strip. The shifts in a short strip between the reference and determined stars should be negligible. Also, there is a very small difference in the influence of refraction between these stars. By using a reference catalogue with high density such as the TC it can make the strip quite short. So, the method of short strips should have all the advantages of small field differential astrometry.

Let us consider the implementation of the short strip method with the available Mykolayiv AMC and CSAO DCMT for linking the HC with the ERF. The aim is to determine the positions of the intermediate reference stars of 12–14^m around RS and so to exclude one step from the multi-step approach and to obtain higher accuracy than with wide field astrographs.

At present two programs for intermediate reference stars of 12–14^m are available: the CAMC for faint reference stars including about 12 thousand stars in areas $50' \times 50'$ around 200 RSs is nearly finished in the Canaries (Morrison *et al.*, 1990; Morrison, 1994); a star list on the base of the CONFOR Programme (CONnection of Frame in Optical and Radio region) including 5764 reference stars from the Guide Star Catalogue (GSC) in areas $40' \times 40'$ around 232 RSs is under observation with a wide field astrograph in the Kiev university observatory (Tel'nyuk–Adamchuk *et al.*, 1991; Pasichnik *et al.*, 1992).

Intermediate reference stars from the GSC around of 200 defining RSs (Implementation of the IERS CRF, 1995) were selected for the HMC link programme (MLP). The preference was given for stars belonging to the CAMC and CONFOR lists. About 50 GSC stars per one square degree area around RS were selected. For the AMC ($\phi = +47°$) the MLP contains about 10 thousand secondary reference stars in the declination range from $+90°$ to $-20°$. This programme was started in 1995 with the AMC in Mykolayiv (Pinigin *et al.*, 1995). The available CCD had 256×288 pixels, 32×24 μ and the field was $9' \times 13'$ by $83''$ mm^{-1}. By these conditions it was possible to observe a field around the RS by some narrow strips with size $9'$ in declination and 7 minutes in the right ascention. During one strip it can observe seven GSC stars, three TC stars and additionally make two measurements on a strip periphery. Due to large distances between RSs the HC stars can be observed only by direct setting of the AMC. In the AMC MLP three thousand HC stars were included. So, each hour contains four strips with RSs, 10 strips without one and encludes 28 GSC stars, 10 HC stars and 42 TC stars. During one year (about 1000 clear night hours in Mykolayiv) about 28 000 observations of GSC stars, 10 000 observations of HC stars and 42 000 observations of TC stars can be made. Three years will be enough to reach an accidental accuracy of 30 mas for the determined GSC stars differentially to the HC. However, more efficient results can be obtained with the large CCD size of a $30' \times 30'$ field. In this case earch short seven minutes strip will contain 25 GSC stars, 2–3 HC stars and additionally 12 TC stars. During one hour about 8 strips with 200 GSC stars, 20 HC stars and 100 TC stars can be observed. Naturally, observations of each strip should be followed by real-time measurements.

For the DCMT with a large CCD and nearly the same MLP during one year (about 1200 hours in CSAO with a latitude of $+34°$) about 240 thousands observations of GSC stars, 24 thousands observations of HC stars and 120 thousands observations of additional TC stars could be obtained. One year will be enough for reaching an accidental accuracy of 20 mas, or two years with the same accuracy for a twice as large MLP with 400 RSs.

4 CONCLUSION

The promising meridian circle such as the HMC provides precise stellar positions with negligible errors on the level of 20 mas. The possibilities of MC with computer control and CCD are enlarged to faint magnitudes up to 17^m and an efficiency of millions of star observations per year. It permits us to use the ground-based promising MC in current and near future astrometric programs as: (a) a precise meridian telescope for wide-field astrometry by extension of the optical reference frame to faint stars, by producing an input catalogue for the following space projects, by reobservations of existing catalogues for the determination of proper motions; (b) a CCD telescope for small-field differential astrometry by the linking of optical/radio reference frames, by high quality position determination of solar system bodies and selected objects in the fields of galactic astronomy and stellar astrophysics.

The proposed programme for making available the Mykolayiv AMC and DCMT meridian link would permit us to create an intermediate reference frame of $12–14^m$ stars in a short observation period with high accuracy by a short strip method.

Acknowledgements

The authors would like to thank R. W. Argule, L. V. Morrison and V. V. Tel'nyuk–Adamchuk for providing of the CAMC and the CONFOR star lists.

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