SESSION G

ASTROMETRIC TECHNIQUES

MODERN DEVELOPMENTS OF THE MERIDIAN CIRCLE

(Invited Paper)

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Abstract. The successful improvements of meridian instrumentation during the past twenty years have mainly come through electronic devices and computers being applied for facilitating the data handling and for increasing the accuracy. Photographic recording of the circle and of the star has played an important role here, but has for both tasks gradually lost its attractiveness as direct photometric-electronic methods have become available. At the same time new types of the telescope system have been introduced without convincing results as yet, but this field still holds promises for the near future.

The problems of the refraction, the meridian building, the foundation of the instrument and the site selection have been treated in recent years and these efforts will be doubly repaid when the telescope and micrometers become more nearly perfect. Altogether, it need not be long before a few partly automatic instruments produce observations with a mean error of 0″.15 and a systematic error of 0″.03 at a rate of 300 observations per observing night. In addition the limiting magnitude can be $m_v = 11$ or 12, thus 2 mag. fainter than for visual observations. These goals are conservative – most of them have already sometimes been surpassed – and they should be compared to a present day good visual meridian circle giving a mean error 0″.30, a systematic error 0″.10 and 120 observations per night.

The relative roles of meridian and photographic astrometry must be defined anew in the light of the great improvements of both methods.

1. Introduction

The opinion sometimes expressed that the accuracy of meridian observations improves very slowly, can no longer be maintained. This opinion was well supported by evidence since the mean error of a single observation was about 0″.45 around 1890 and is 0″.30 for visual observations today, and since the systematic errors have hardly improved at all since then (van Herk and van Woerkom, 1961; Gliese, 1965; Gauss, 1971).

About ten years ago, however, it was obvious that the state of art of available technology would permit photographic and photoelectric micrometers to be built which would reach nearly to the limit of accuracy set by the disturbances from the atmosphere. Corresponding successful developments of three different methods were started at the Brorfelde, Bergedorf, and Bordeaux observatories which have now given about 160000 observations with an average mean error of 0″.22. It is equally obvious that further improvements of the accidental errors and even more of the systematic errors can be obtained. These improvements will – of course – not come by themselves but only if decisions are taken to support such work. It carries good promise for the future that new meridian circles employing modern techniques are being put into operation at Caracas, Sao Paolo and Washington, and one is planned for Tokyo. Regrettably, at the same time at some other places the support has been drastically reduced.

The last twenty years have brought such improvements of the circle, its reading

Gliese, Murray, and Tucker, 'New Problems in Astrometry', 243–255. *All Rights Reserved.*

and the determination of the division errors that these subjects impose no limitation on the observing accuracy or working efficiency today.

Prior to this recent period went a time when meridian astronomers started utilizing electronic computers as soon as they became available to relieve the meridian observer from the burden of routine tasks. Watts (1960) and Adams (1963) described the pioneering work at the U.S. Naval Observatory. The introduction of quartz clocks and a digital chronograph at R.G.O. Herstmonceux has been surveyed by Tucker (1963).

Thus, electronic equipment and computers have been at the center of the field, indicating that the progress will continue to be fast. On-line computers are just now starting to be employed for data-acquisition and for the control of micrometers and telescope setting. They will radically decrease the amount of routine work still involved with the operation of the recent photographic and photo-electric micrometers.

In Table I performance data of some modern meridian circles are given. The joint international enterprise of AGK3R, of wnich the contribution of the 19 cm visual Repsold instrument in Bergedorf is a part, is given as basis for a comparison. The Table gives (2) the type of micrometer, (3) the start of the observations, (4) the number of years observed, (5) the number of nights, (6) the number of observations, (7) and (8) the mean errors of one observation, (9) and (10) the arc on the sky which was tied to the FK4-stars as one unit.

TABLE I

Performance of modern meridian circles

Meridian circle	Type of micro-meter	Observations				Mean errors		Arc	
		Start	Years	Nights	Obser-vations	$\Delta\alpha\cos\delta$	$\Delta\delta$	in α	in δ
11 m.c.'s AGK3R	visual	1956	6	–	300000	$0^{\mathrm{s}}.016$	$0''.35$	–	–
In Bergedorf	visual	1956	6	360	41611	0.016	0.42	2^{h}	60°
In Perth	MSM[a]	1967	5	580	110000	0.012	0.27	7	140
In Brorfelde	photogr.	1964	8	300	50000	0.015	0.22	2	25
In Bordeaux	tracker	1971	–	34	1500	0.007	0.20	4	80

[a] Multislit micrometer.

The photoelectric instrument in Perth has acquired observations with a statistical weight equivalent to 200000 visual observations although for technical reasons one fourth of the available clear nights were not used. During the preceding 60 years in Bergedorf 130000 observations were obtained.

The systematic errors are determined by many factors other than the micrometers and the circle: telescope, pivots, stability of foundation, and refraction inside and outside the dome. Improvements here have not yet been so obvious.

The publications on all aspects of meridian techniques found in: *Trudy Astrometricheskoi Konferenzii U.S.S.R.*, *Bulletin of Astron. Obs. Pulkovo* and *Soviet*

Astronomy (= *Astronomicheskii Zhurnal*) constitute an inexhaustible source of inspiration for the meridian astronomer, even in the cases where he can only read the summary in *Astronomischer Jahresbericht*. Since they are too numerous to mention completely in this limited space, they deserve to be quoted here as an entity prior to the following detailed discussion.

2. Micrometer

Visual micrometers of the travelling wire type are still widely used by meridian observers but cannot in the long run compete with some of the new photographic and photoelectric micrometers with respect to accuracy, limiting magnitude and ease of operation and evaluation.

Performance data for new operating or proposed micrometers are collected in Table II as they are actually obtained or expected under average seeing conditions at a 20 cm refractor and with an observing time $T = 40$ s. The mean error for R.A. is given since the accuracy of a micrometer in Decl. is mostly deteriorated by the errors of the circle reading. For the optimum micrometer defined in Section 2.3, the mean error due to image motion alone is derived from the formula (Høg, 1968)

TABLE II

Performance of meridian circle micrometers under comparable conditions

Micrometer	m.e. (in R.A.)	Limit m_v	Cathode	Autocollimation	Daytime objects
Visual	0$''$.24	10	–	yes	yes
Photogr., Brorfelde	0.22	11	–	no	no
MSM, Perth	0.18	10.5	‘S’	yes	–
MSM, proposed	0.15	11.5	‘S’	yes	yes
Tracker, Bordeaux	0.10	9	‘S’	no	no
Tracker, Klock	–	10.5	S20	yes	(yes)
Optimum photoelectric	0.13	15.2	‘S’	yes	yes

$$\sigma_T = 0''.33\,(T + 0.65)^{-0.25} \tag{1a}$$

valid for $0.2\text{ s} \leqslant T \leqslant 14000$ s and at the zenith. This is equivalent to the power spectrum

$$P(f) = 0.08\, f^{-0.5}(1 + 2f)^{-1} \square''/\text{cps} \tag{1b}$$

for the frequencies $0.00001\text{ cps} \leqslant f \leqslant 10$ cps. It must be due to a good micrometer and to an unusually small image motion in Bordeaux that this accuracy has been surpassed by Requième (1973).

The limiting magnitudes discussed below are reduced to a visual wavelength region, $\lambda > 5100$ Å, which is most important in order to minimize the difference in Decl. for different spectral types due to the atmospheric dispersion. The use of a S20 photocathode instead of a 'S' cathode would bring a gain of one magnitude provided the higher dark currents from cathode and sky can be coped with. It is worth noting that the photographic and the multislit micrometers give the faintest stars, contrary to the theoretical expectation that a tracker should utilize the light more efficiently (see Section 2.2 and Siedentopf, 1963).

Measurement of autocollimation onto a mercury mirror is important for the physical determination of the instrumental constants as needed when other than differential observations relative to an existing fundamental catalogue are wanted. Such autocollimation measurements are always possible with visual micrometers but only with the tracker of Klock (1970) and with the MSM (multislit micrometer), see Table II.

Daytime observations of the Sun, the inner planets and stars are required for absolute observations of the zero-points of the celestial coordinate system. Again, besides visual micrometers, only Klock's tracker (at a later stage of development) and the MSM will be capable of doing this.

2.1. PHOTOGRAPHIC MICROMETERS

Photographic micrometers have long been used at photographic zenith tubes and the same principle of moving the plate along with the star has been transferred to the meridian circle in Brorfelde by Laustsen (1967). This micrometer is convenient to operate for a single observer, it gives a mean error of $0''.22$ in both coordinates. No measurement of autocollimation or daytime objects is possible. The measurement of the photographic plates constitutes a bottle neck, although a digitized manual measuring machine is used. A number of plates have been measured with the automatic measuring machine GALAXY but without an encouraging success although GALAXY performed perfectly well. The task of identifying the measured images with the images on the plate caused problems (Fogh Olsen, private communication).

Although vertical circles are outside the scope of this paper we mention the photographic micrometer of the Pulkovo vertical circle described by Zverev *et al.* (1966), and at the present symposium by Bagildinskij. By observation of star trails a mean error of $0''.25$ for one absolute observation of Decl. is obtained.

2.2. PHOTOELECTRIC MICROMETERS

Photoelectric micrometers have a long history in meridian instrumentation, starting with Strömgren's proposal in 1933 of a slit micrometer. But the early ideas had to await the advent of the photomultiplier, digital electronic equipment and of the digital computer before they could bear efficiently in practice. Pavlov (1956) has used a slit micrometer with a reflecting grid for regular transit observations and has obtained over 80000 observations of R. A. (Pavlov *et al.*, 1971).

A photoelectric multislit micrometer for simultaneous observation of R.A. and Decl. described by Høg (1970, 1972a) has been used in Perth since 1967. The faintest stars in the SRS catalogue were of $m_v = 10.5$ and no fainter stars could have been set by the observer in the average night although they could have been measured.

Measurements of autocollimation onto the nadir mirror were obtained every 3 or 4 hours. Daytime objects were not observed, mainly due to lack of time.

An improved multislit micrometer has been proposed (Høg, 1972b). The new grid is not fixed as in the previous micrometer but must be mounted on a stage with a very accurate motion in the direction of R.A. This motion will give three advantages:

(1) Stars very near to the pole (polarissimae) can be observed in the same time as other stars when a scanning motion of the grid is used.

(2) An automatic star acquisition (after a coarse setting in declination) is provided so that one of the two observers required with the old micrometer is no longer needed.

(3) The autocollimation measurement is simplified. Thus, the draw-backs of the old micrometer will be removed. Observation of all daytime objects including Venus will be possible.

The use of a photoelectric star sensor or star tracker is the most direct way to replace the human eye in the impersonal Repsold micrometer. An account of the many different types of star sensors has been given by Kühne (1971) and only a few names shall be mentioned here: Rotating knife-edge, quadrant sensors with and without chopper, tridrant sensor, frequency method, counting method.

The tracker for the Automatic Transit Circle at Washington (Klock, 1970) has promising universal capabilities as stated above.

Requième (1973) presents results from a rotating knife-edge micrometer at the 19 cm meridan circle at Bordeaux. A limiting magnitude of at least 10^m is expected when the sky background is reduced but only using a large wavelength region down to about $\lambda 4100$.

The tridrant star sensor with chopper developed by Kühne (1971) has a limiting magnitude $8\overset{m}{.}0$ with a 15 cm refractor, a S20 cathode and without color filter.

A limitation of the color regions for the sensor of Requième and Kühne to $\lambda > 5100$ Å will bring a loss of at least one magnitude.

The somewhat disappointing sensitivity of star trackers may in principle be improved by increasing the time constant of the detecting system (about 1 s in Requième's tracker), by using sensor systems with more than one photo-detector (quadrant sensor) and by improved photometric evaluation with an on-line digital computer. A (remote) design goal of an optimum micrometer is presented below.

2.3. LIMITING MAGNITUDE

For comparison with real micrometers we introduce the concept of the optimum photoelectric micrometer which must be able to integrate in a perfectly linear way the two-dimensional intensity distribution of the star image during the observing time. A subsequent evaluation shall give the mean position of the image. A photographic plate moved along with the star is an approximation to this optimum concept but has the disadvantages of a non-linear integration and a relatively low quantum efficiency. For the optimum micrometer we suppose the same quantum efficiency as available 'S' photocathodes, (5% at $\lambda 5500$), although S20 cathodes would bring a gain of at least one magnitude for the visual region.

The limiting magnitudes which can be obtained with different micrometers under comparable conditions are given in Table II. For the trackers a loss of one magnitude has been supposed when only the visual wavelength region is used as for all the other micrometers. The values for the proposed MSM and for the optimum micrometer have been obtained using the realistic image profiles $i'_{\text{star}}(x)$ shown in Figure 1a measured with a very narrow slit (Høg, 1971b). The counting rate for $m_v = 11.5$ has been supposed to be $i_{\text{star}} = 100 \text{ c s}^{-1}$ as is obtained with a 'S' cathode. For a slit of width $s_w = 4$ (see Figure 1b) the signal $i_s(x, s_w)$ is shown in Figure 1c. Using the median method to derive the transit time for both the MSM and the optimum micrometer similar deductions as used earlier (Høg, 1970) give the shot noise at a single slit to

$$\sigma_{\text{shot}} = v(2bi_d + s_t i_{\text{star}})^{0.5}/(2i_{\text{slit}}) \tag{2}$$

and the shot noise for the optimum micrometer to

$$\sigma_{\text{shot}} = (Ti_d + Ti_{\text{star}})^{0.5}/(2i'_{\text{star}}T), \tag{3}$$

where $v[''/\text{s}]$ is the speed of the star, $b = 6''\!.6/(v \cos 45°)$, $s_t = s_w/(v \cos 45°)$ and T the total observing time. The dark current i_d from sky and photocathode is nearly negligible for a dark sky of 130 $\square''$ area and a 1 mm cathode.

It is evident from Table II that all photoelectric micrometers are very far from an optimum utilization of the photons even though a low quantum efficiency has been supposed for the optimum micrometer.

3. Declination Circle

The classical declination circle consists of equidistant narrow lines every few minutes of arc which are measured by four or six equidistant microscopes. The microscopes must be moved to other positions on the periphery for determination of division errors. Other types of circles exist but an analysis shows that for different reasons none of them are complete alternatives for a meridian circle. E.g. the Inductosyn used by Klock *et al.* (1970) has the handicap that its division errors can only be determined by means of another classical circle on the same axis.

Four problems of the classical declination circle may be distinguished:

(1) The quality of the circle, be it of metal or of glass.
(2) The illumination of the circle to provide lines of high contrast.
(3) The recording and measuring, be it photographic or photoelectric.
(4) The division corrections.

3.1. CIRCLE ILLUMINATION

Some modern meridian instruments have a circle consisting of a massive glass ring which carry photochemically produced division lines. Lines on glass must be illuminated *from behind* in order to create a high contrast which is essential for repeatable readings. Einicke *et al.* (1971, p. 13) obtained in this way and with photoelectric

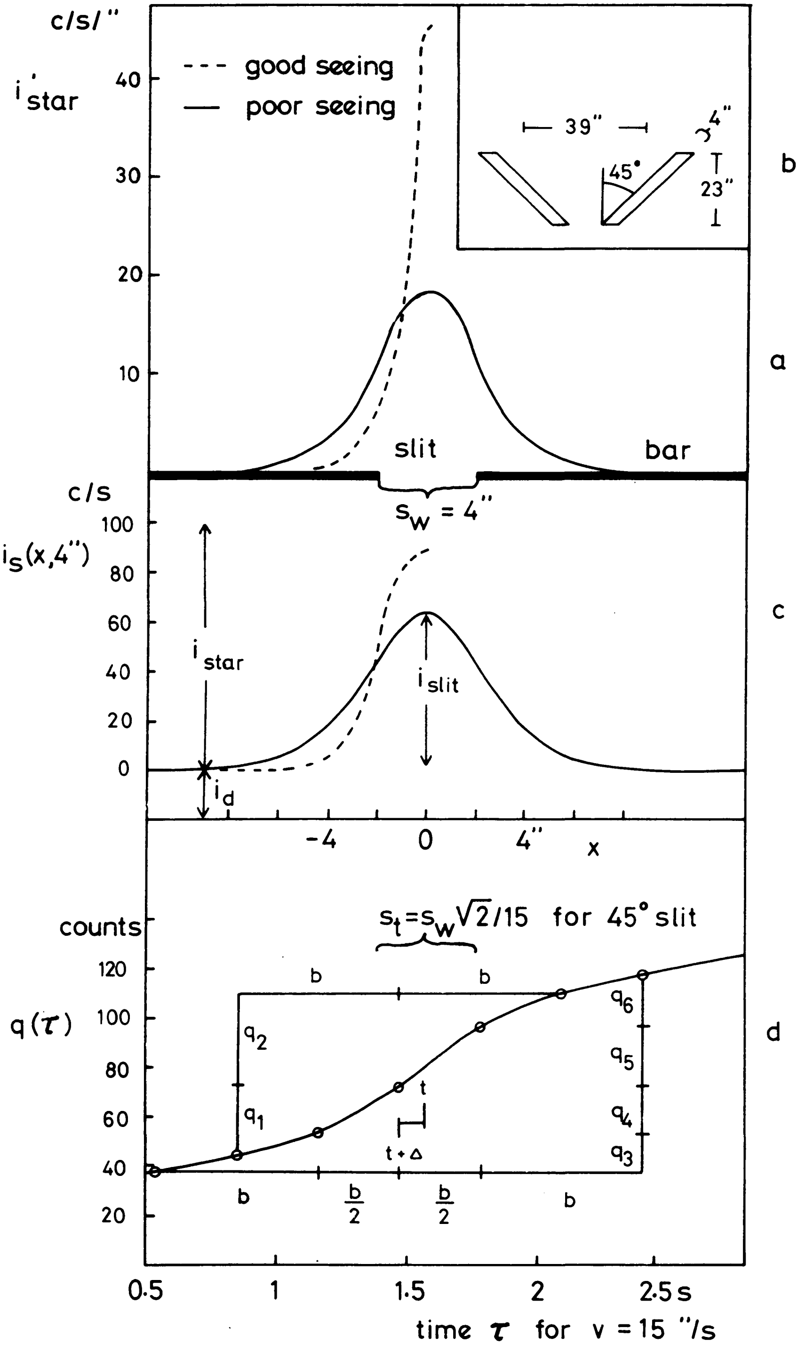

Fig. 1. (a) Realistic smoothed profiles of focal images ($m_v = 11.5$), (b) slits of proposed multislit micrometer, (c) realistic smoothed photometric curves from this micrometer, (d) integrated photometric curve (for poor seeing), cf. Høg (1970, p. 94).

scanning micrometers the best accuracy ever seen: 0.″03 as the mean error for reading at six microscopes (including the errors of the division corrections).

Older meridian instruments have steel circles where the lines are engraved in a layer of gold and filled with a dark material. Such lines do not have a high contrast, and the mean error of a reading on four microscopes even with scanning micrometers was only 0.″15 (Høg, 1972a). Since it is difficult to replace the metal circle on an old instrument with a glass circle, it is important to note the existence of two new methods: (1) to divide metal circles with very sharp lines of high contrast as offered by Société Genevoise d'Instruments de Physique, and (2) to mount a very thin glass circle directly on the old circle as offered by Teledyne Gurley, New York.

The new metal circle divisions are engraved on a specular reflecting layer of nickel on a plane steel base, but they are not filled with dark material. This specular reflecting surface gives a higher contrast to the lines than the old gold circles which had a partly diffuse and a partly specular reflection. The illumination system must be carefully designed to avoid vignetting, which easily arises when illuminating a specular reflecting surface, and which would cause serious systematic errors.

3.2. Circle reading

Both for reasons of economy and accuracy the direct photoelectric scanning of the circle with a slit is preferable to the widely applied photographing and subsequent measurement in the laboratory. Scanning is now used at the observatories of Brorfelde, Perth and Washington either with output of all photometric values on punched tape or, more recently, onto a small on-line computer, thus avoiding the kilometers of tape formerly needed.

3.3. Division corrections

The determination of division errors of every single diameter is required nowadays. Formerly, with visual reading and laborious methods of reduction this could take about 10 man-years. With the general symmetric method (Lévy, 1955; Høg, 1960b) and scanning micrometers it was done in one man-year for two circles with 3′ divisions (Fischer-Treuenfeld, 1968) and in a man-month (Einicke *et al.*, 1971) for one circle with 5′ divisions. This year it has been done in Brorfelde with an on-line computer in one man-week! (Fogh Olsen, private communication.) Many irregular errors in observations of declinations and also systematic errors >0.″1 over large arcs (Einicke *et al.*, 1971, p. 23) may be explained by incomplete knowledge of the division errors which were often determined only for the half-degree lines.

4. Telescope System

If we look back a decade to van Herk's and van Woerkom's account (1961) of the problems in meridian astronomy it is noteworthy that good solutions have been developed for the problems of the micrometer and of the circle and its reading. But we should still look carefully at their discussion of the telescope and the local meteorological effects.

The photoelectric micrometer seems to stabilize the telescope itself as the expected consequence of the much smaller thermal influence of the observer on the telescope. This is concluded from the small clamp differences in R.A. of the Perth observations (Høg and Nikoloff, 1973) which show that internal agreement within $0\overset{\prime\prime}{.}02$ can be obtained provided the pivots are good enough.

I do therefore think that classical and even old meridian circles can perform excellent work if the micrometers, the circle, the pivots and the dome are brought up to a modern standard, including an exact determination of pivot and circle errors. The development of a new telescope system is not the most urgent task – but surely the most difficult.

One of the strongest reasons to develop a new telescope system is the desire to eliminate the flexure of the rotable telescope tube, a problem which has been discussed by many authors (Atkinson, 1955). Also the small uncontrolled shifts of the lens elements need a new solution (Orlow, 1953; Naumov, 1966). The predictions in this paper of the future accuracy of meridian circles are based on the use of conventional instruments and do not include the possibly very great improvements from new telescope systems.

Three new types of meridian circles are depicted in Figure 2 together with the conventional and shall be discussed here.

Development of the horizontal meridian circle (*c*) which carries the names of R. d'E. Atkinson and of L. A. Sukharev has been pursued at the observatories of Greenwich, Ottawa, Oporto and Pulkovo, but has now been abandoned for different reasons at the three first places. The most recent results from testing the instrument in Pulkovo with which only R.A. can be measured are given by Pinigin (1972 and private communication) who states that the mean error of one photoelectric autocollimation reading is about $0\overset{\prime\prime}{.}01$ and of one determination of Bessel's n is $\pm 0\overset{s}{.}010$. 3000 visual observations of stars have been obtained with a mean error $0\overset{s}{.}011 \sec \delta$ and they are essentially free from systematic errors. The instrument has only very small variations with time and temperature.

A cassegrain type automatic mirror transit circle, ATC, is being tested at the U.S. Naval Observatory by Klock (1970, 1973).

A horizontal glass meridian circle, GMC, has been proposed by Høg (1971a).

A direct comparison of these three instruments is impossible since they are in completely different stages of development but some basic problems seem worthwhile to point out.

Six specific problems exist for the Atkinson type instrument most of which have already been pointed out by Atkinson: (1) refraction and seeing disturbances in the long horizontal light paths, (2) a tilt-free connection within $0\overset{\prime\prime}{.}01$ between the mirror and the axis and the circle, (3) two telescopes are needed to cover all declinations, (4) these horizontal telescopes tend to obstruct the line of sight to any possible azimuth marks, (5) different parts of the mirror are used at different declinations and (6) the circle must be read with twice as high an accuracy.

The supporting system for the mirror tested by Atkinson (1961) was shown to

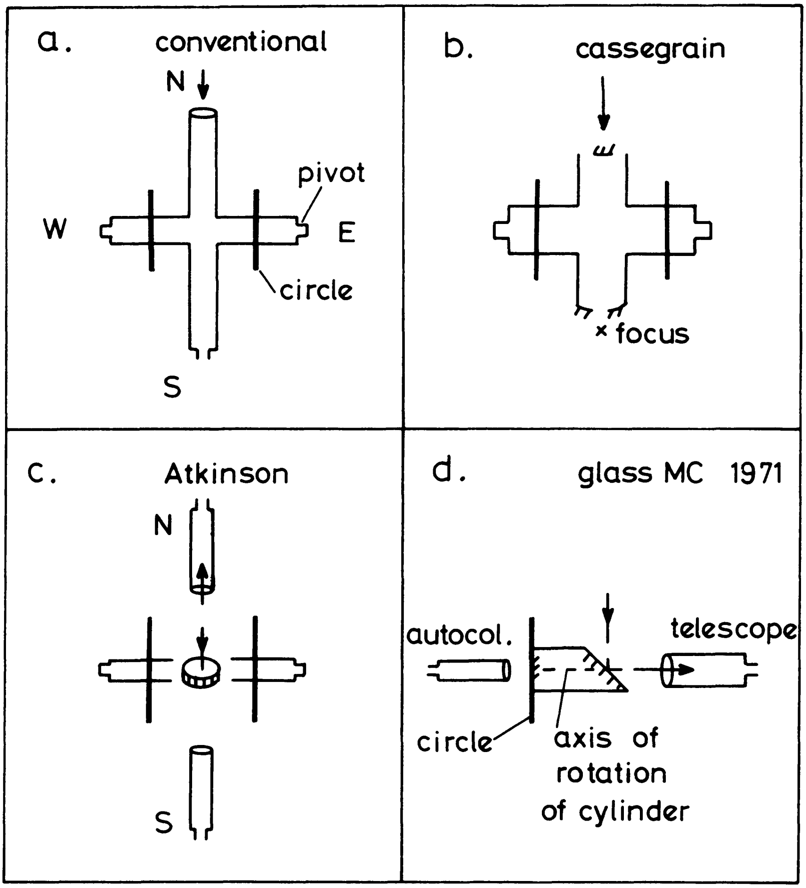

Fig. 2. Four types of meridian circles all pointed at north and viewed from the zenith: (a) rotable refracting telescope, (b) rotable cassegrain telescope, (c) rotable mirror and two fixed horizontal telescopes, (d) rotable zero-expansion glass cylinder.

solve the second problem in R.A. while no direct check of the tilt in Decl. at different zenith distances is possible. In the Pulkovo mirror transit the mirror and the axis is one piece of steel, thus solving radically problem No. 2.

A specific problem of the new ATC in Washington seems to be that the optical-mechanical system is very complicated. This is certainly a danger for the economy and possibly a danger for the accuracy and the reliability. Its automatic operation under computer control is an important step forward and will help to acquire a wealth of astrometric information.

Four specific problems of a GMC in the new version, Figure 3, have been pointed out (Høg, 1972c) and concern the support and bearing for the glass cylinder, the horizontal refraction and the quick measurement of autocollimation. The principal advantages of a GMC are: (1) very small flexure, (2) relative simplicity, (3) it requires a much smaller building than a conventional meridian circle (Høg, 1973).

5. Foundation, Building, Site

The performance of a meridian circle depends on its surroundings, the more so as the instrument becomes more perfect. Since this concern will find expression in several other lectures of this symposium we can be brief here.

A discussion has recently been given elsewhere (Høg, 1973) about refraction anomalies and of the foundation and its possible improvements.

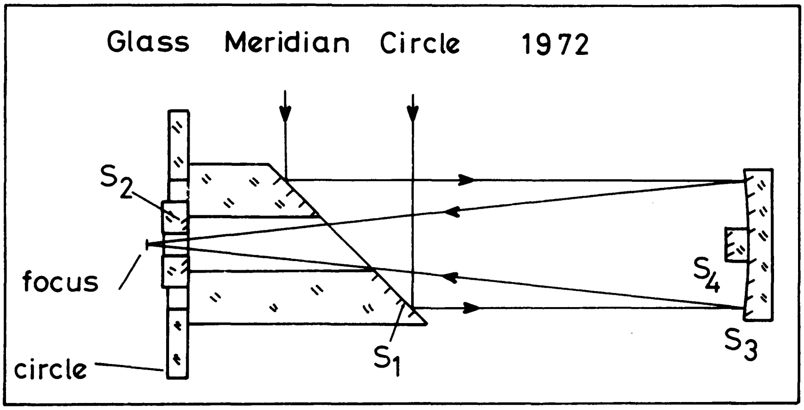

Fig. 3. The Glass Meridian Circle in the new version where the fixed telescope and the autocollimator have been combined in the mirror S_3. The mirror S_4 is cemented to S_3 and since its center of curvature coincides with the focus of S_3, it can serve to control the tilt of S_3.

The building protects the instrument when it is not used, but should, ideally, be completely removed during observing in order not to create local heating of the instrument and atmosphere. This ideal can be most nearly reached if the instrument is so constructed that no protection against the wind is required and only a small building is needed. The ideal has been approached with success for the transit instrument by Pavlov (1963, 1972), while the bulky structure of the conventional type of meridian circle and the Atkinson type prevents much progress in this respect. Promising is the pavilion for the Glass Meridian Circle as shown by Høg (1972c, 1973).

The selection of a site especially for an astrometric observatory has been undertaken for the first time in France as described by Laclare (1969) and Kovalevsky (1972). The very slow parts of atmospheric image motion extending over minutes and hours of time are of primary relevance to astrometric observations whereas they hardly influence other astronomical observations. Therefore, observations with the Danjon astrolabe were used to measure the stability of the images. The best stability was found at stations where air masses of marine origin dominate.

6. Conclusion

With the implementation of available meridian techniques absolute positions of faint stars of $m_v = 11$ and 12 can soon be obtained with an accuracy of 0.″05 from observations with a single *conventional* meridian circle. Such observations of reference stars for long-focus astrometric measurement of optical positions of radio sources would bring a corresponding improvement of the accuracy of ±0.″15 obtained by Murray *et al.* (1971). The accuracy of absolute radio positions is about ±0.″5 (Fricke, 1972) and is gradually improving towards the limit now reached in optical meridian astrometry where the atmosphere becomes the most important disturbance, which will therefore contribute similarly to the errors of optical and of radio positions.

This common limitation and the peculiar characteristics of the power spectrum of image motion (Høg, 1968) are mostly forgotten when a positional accuracy of 0.″001 is predicted for radio astrometry. It is a challenge to meridian astrometry to maintain its lead concerning the accuracy of absolute positions, but in any case the two techniques must complement each other as far as they are concerned with different celestial objects.

The future will see fewer meridian circles acquire an increasing number of more accurate positions at a lower cost thanks to the automation. At the same time photographic observations will be available with improved astrographs (de Vegt, 1973) of the 2 m focal length class measured with automatic machines and reduced with the overlap-technique. It is important to discuss anew the most efficient combinations of the improved meridian and astrograph techniques for the many different astronomical purposes.

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DISCUSSION

Klock: I would just like to mention my concurrence with Dr Høg on many of the ideas in his paper and particularly note his foresight in the close race being given to us by the radio astrometrist, as evidenced by the papers presented here yesterday.