Optical reference frame defined by Carlsberg Meridian Catalogue La Palma Number 4

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ABSTRACT. The contribution of the Carlsberg Meridian Catalogue La Palma Number 4 to the determination of the optical reference frame is discussed. This catalogue of almost 51000 stars provides one of the most accurate optical reference frames at the present epoch, having a density of 1 star per square degree, and an average accuracy of $0\overset{''}{.}12$ in position and $0\overset{''}{.}003$ per year in proper motion for stars with V<9. The catalogue also contains positions of reference stars with V>11 in the fields of benchmark extragalactic radio sources which can be used in linking the optical reference frame defined by the FK5 to the extragalactic frame.

1. Carlsberg Automatic Meridian Circle

The Carlsberg Automatic Meridian Circle (CAMC) is operated jointly by Copenhagen University Observatory, the Royal Greenwich Observatory and the Real Instituto y Observatorio de la Armada en San Fernando at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias situated on the island of La Palma. The astronomical coordinates are:
17° $53'$ $07\overset{''}{.}8$ West, 28° $45'$ $52\overset{''}{.}4$ North,   2326m altitude.
The telescope has an aperture of 18cm. It has been in operation continuously since May 1984, except for short periods due to technical problems and maintenance.

The same moving-slit micrometer has been used throughout the period of observation of this catalogue, and the photoelectric circle-reading system has also remained unchanged. All the processes, from setting the telescope to the scanning of the star during meridian passage and the reading of the circle, were carried out completely automatically under the control of two minicomputers. A general description of the system is given by Helmer & Morrison (1985).

The major changes to the instrumental system during the observation of the catalogue were as follows. An air circulation system was installed in the tube of the

telescope in August 1985 in order to remove the internal refraction caused by the thermal stratification of the air (Høg & Fabricius 1988). An azimuth mark 130m to the south was observed from January 1986 onwards, and another 50m to the north from December 1986. These were automatically observed hourly together with the line of collimation, the horizontal flexure, and the level and zenith point of the circle which were obtained by observing the reflected image in a nadir pool of mercury.

2. Observational programme

The observing list consisted of the following programmes (limited to declinations above -45°, apart from the FK5 which was limited to -55°):

TABLE 1. Carlsberg Meridian Catalogue No.4: observational programmes

Reference frame programmes	Total size	No. stars CMC No.4
FK5	1500	
International Reference Stars	32524	21328
General Catalogue	24297	8957
Reference stars in radio fields	11397	6829
PZT stars	1957	797
Reference stars in selected Schmidt fields	1014	822
Geodetic stars (Dec +7 to +10)	374	356
Radio stars	313	203
Hipparcos non-astrometric (Dec 0 to −25)	3708	1687
Hipparcos poor SAO positions	1352	1043
Gliese catalogue of nearby stars	1114	412
Proper motion programmes		
F-type stars within 100pc	10550	9209
G-type d&g and K-type g within 300pc	9243	5665
Nearby O-B associations	5629	2548
Sample of A5-G0 stars in NGP	3098	399

Solar system	No. obs. CMC No.4
Mars	137
Callisto	92
Saturn	131
Titan	70
Uranus	284
Neptune	294
Minor planets (62)	6940

3. Real-time selection

The selection of celestial and calibration objects was performed in real-time according to a pre-assigned priority. About 7% of the time was spent on calibration objects, 73% on programme stars, 18% on FK5 stars and 2% on planets. The scanning time was a function of the magnitudes of the objects: stars brighter than 9.5 took 16s, those between 9.5 and 11.0 took 32s, and those fainter than 11.0 took 64s. FK5 stars at zenith distances greater than 60° were observed for 32s, and those greater than 75° for 64s, irrespective of their magnitude. In order to improve the efficiency of the observing, stars were observed up to 40s from the meridian after November 1985.

The same observing slits ($33'' \times 4''$)were used for all objects except for Mars and Saturn which were observed in a pair of large slits ($83'' \times 4''$). Very long slits ($2' \times 4''$) were used in a special search mode to locate stars with very poor input positions. Observations of these stars were, however, carried out in the normal slits after resetting the telescope.

4. Differential reduction to FK5

The real-time reduction to micrometer coordinates of the photon counts was carried out as described in Helmer *et al.*(1984) and Helmer & Morrison (1985). A differential reduction for each night was carried out the following day by the observer using interactive computer programs. When available and reliable, the hourly values of the instrumental calibrations were subtracted from the FK5 residuals before the least-squares adjustment was made for the whole night, which comprised about 9 FK5 stars per hour down to a zenith distance of 84° . Stars above declination $+67^\circ$ were observed at either upper or lower culmination. Effectively, on most nights the least-squares adjustment amounted to a single rotation for the whole night in right ascension and declination to bring the instrumental system into agreement with the average position of the FK5 stars. The resulting positions in the catalogue are therefore not subject to possible zonal systematic errors in the FK5 frame.

The atmospheric extinction and instrumental absorption was determined nightly by least-squares adjustment to about 50 photoelectric standards spread through the night.

The least-squares adjustment in position and magnitude was then applied to the programme stars and solar system objects. The positions and magnitudes were compiled daily into a catalogue, and stars with the requisite number of observations (normally 6) were automatically deleted from the observing list.

5. Formation of the catalogue

The scanning slit micrometer was replaced by a new one in March 1988; so it was decided to combine all the observations made in the period May 1984 to February 1988 into one catalogue, superseding the three annual catalogues published for

1984, 1985 and 1986. In total, observations carried out in 8872 hours of operation on 955 nights were compiled into this catalogue. This represents 68% efficiency in observing.

Before forming the unweighted means of the positions of programme stars, about 6% were rejected because their stellar images were badly defined, being either too faint or not properly centered in the slits. A further 1% were rejected because they had large residuals. One night was completely rejected in declination due to problems with the circle-reading system. In magnitude, 111 nights of observations were rejected because their photometric quality was too poor.

6. Accuracy of the catalogue

The internal standard deviation (mean error) of a *single* observation was calculated from the scatter of the observations about their means. These were averaged in 5° ranges of declination and the resultant values for stars with V<10 are plotted in Figure 1(a). The average error curves in right ascension, declination and magnitude are:

$$\sigma_\alpha = 0\overset{''}{.}187\sec^{0.6}z \qquad \sigma_\delta = 0\overset{''}{.}181\sec^{0.9}z \qquad \sigma_m = 0^m.055\sec z,$$

where z is the zenith distance. The mean error as a function of magnitude, reduced to the zenith, is plotted in Figure 1(b). It follows from this Figure that the average curves in right ascension and declination are only valid for stars with V<11, and the average curve in magnitude for stars with V<9.

The standard error of a catalogue position (formed from the mean of n single observations) has been investigated using stars observed on both clamps, assuming that the standard error follows the relation;

$$\epsilon_n = \sqrt{a^2 + \sigma^2/n},$$

where a is the asymptotic mean error and σ is the standard deviation. Evaluating this for $a=0\overset{''}{.}068$ in right ascension and $a=0\overset{''}{.}076$ in declination we derive the values in Table 2.

TABLE 2. Standard error of a catalogue position

n	z=0° δ= +29°		z=30° δ= -1°, +59°		z=60° δ= -31°, +89°		z=73.8° δ= -45°	
	ϵ_α	ϵ_δ	ϵ_α	ϵ_δ	ϵ_α	ϵ_δ	ϵ_α	ϵ_δ
3	".13	".13	".14	".14	".18	".21	".24	".34
4	".12	".12	".12	".13	".16	".19	".21	".30
5	".11	".11	".11	".12	".14	".17	".19	".27
6	".10	".11	".11	".11	".13	".16	".18	".25
7	".10	".10	".10	".11	".13	".15	".17	".23

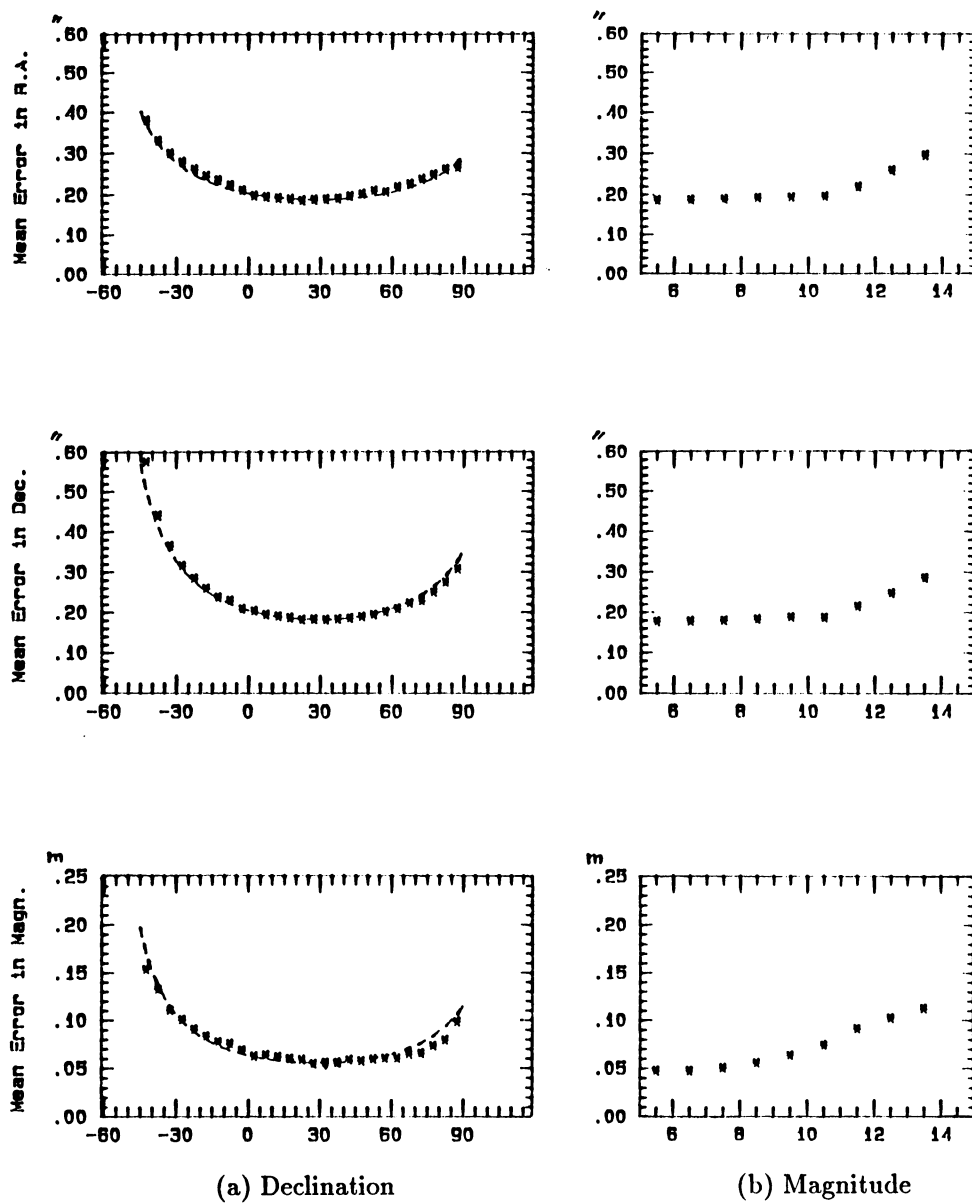(a) Declination   (b) Magnitude

Figure 1. Mean error of a *single* observation as a function of
(a) declination, and (b) magnitude.

7. Proper motions

Proper motions were derived for almost 42000 of the stars by combining the position from this catalogue with positions from earlier epochs, using mainly the large photographic surveys of Yale, AGK2, AGK3 and Cape. Systematic corrections were applied to bring them on to the FK5. The distribution of the standard errors of the proper motions is shown in Figure 2. About 80% are better than $0\overset{''}{.}004$ per year.
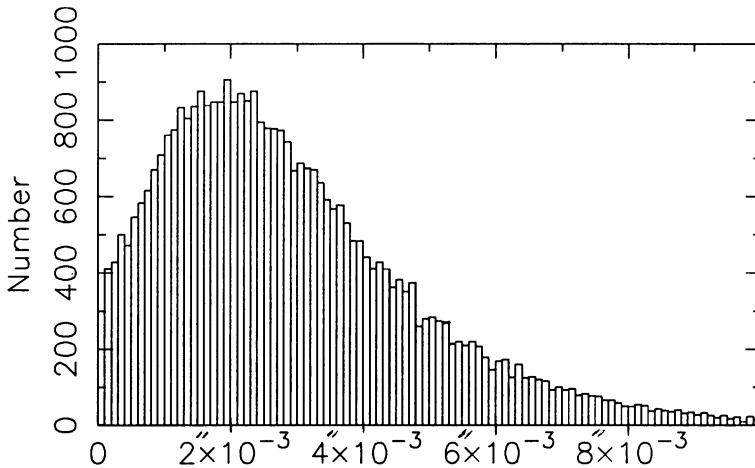

Figure 2. Distribution of standard errors of proper motions.

8. Reference frame defined by this catalogue

Figure 3 shows the distribution on the sky of the stars in this catalogue. Of the 51000 stars, about 34000 have V< 9 and these are evenly spread over the sky. About 21000 of these stars are IRS, the other 13000 coming from the first two proper motion programmes in Table 1. The square clumpy regions are selected Schmidt fields, whilst the irregular clumpy areas are reference stars in the fields of extragalactic radio sources. The trail of stars running down below the equator near 22^h are the reference stars along the orbit of comet Halley which were observed in connection with the Giotto mission.

8.1 An IRS-type reference frame

The 34000 stars brighter than 9th magnitude should constitute a useful reference frame for photographic astrometry. The density is slightly greater than 1 star per square degree, which is comparable to the IRS; but, of course, it lacks the homogenity of spectral types, as there is a concentration towards F, G and K-types originating from the first two proper motion programmes of Table 1. Also, the streakiness in Figure 3 shows that there are a few areas, particularly around 7^h and 8^h, where the density is less than 1 star per square degree.

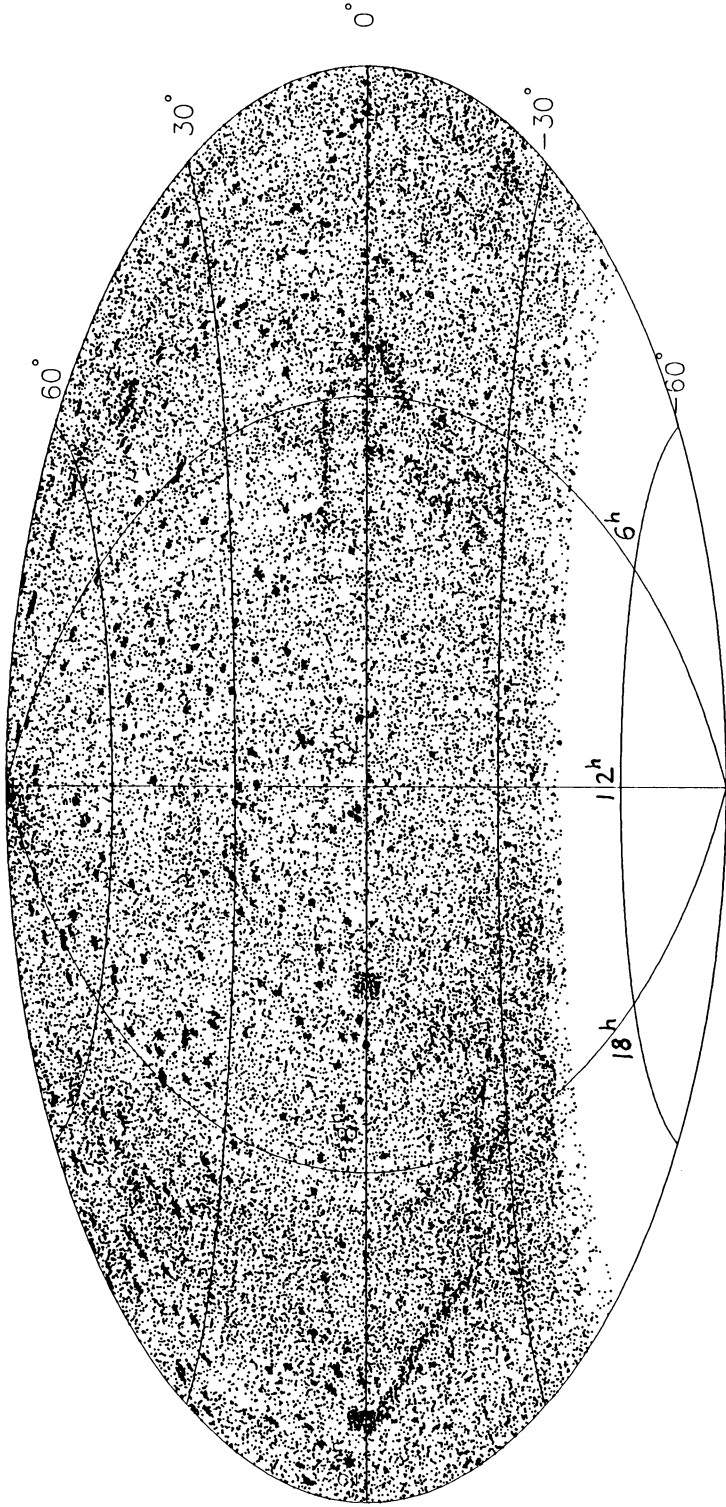Carlsberg Meridian Catalogue No.4

Figure 3. Equal-area plot in right ascension and declination of Carlsberg Meridian Catalogue No.4.

8.2 Link to the extragalactic frame via quasars

As can be seen from Table 1, the programme of observation of reference stars in the fields of extragalactic radio sources, mainly with V>11, is slightly more than half way towards completion. Many fields do not yet have enough observed stars to reduce photographic plates satisfactorily. However, some fields that were given higher priority have been nearly completed, and work is proceeding in taking and measuring plates of these fields.

8.3 Link to the extragalactic frame via radio stars

Observations of radio stars have been carried out, and these have been combined with observations from the Bordeaux meridian circle in a comparative study with VLBI and VLA radio positions. This work is reported elsewhere in these conference proceedings (Morrison *et al.*).

8.4 Reliability of the reference frame defined by this catalogue

Comparisons have been carried out with the FK5 in order to check how closely the frame defined by this catalogue matches that of the FK5. Similar work was also carried out at Bordeaux, and a cross-comparison of the CAMC and Bordeaux frames (Morrison *et al.*1987) showed very good agreement over the the declination range of the comparison which extended from $-20°$ to $+80°$. The systematic differences, $\Delta\alpha_\delta cos\delta$ and $\Delta\delta_\delta$, are reproduced here in Figure 4. The reference frames defined by CAMC and Bordeaux exhibit mutual agreement at the level of $0\overset{''}{.}03$, and indicate warps in the FK5 frame reaching $0\overset{''}{.}1$ in places at the epoch of the comparisons, 1986. Below $-30°$, the CAMC frame is not so well tied down, particularly in declination. However, above $+80°$ more investigations have been carried out in right ascension by combining observations at upper and lower culmination.

Figure 5 shows the differences $\Delta\alpha_\delta cos\delta$ for CAMC-FK5 in the declination range $+68°$ to $+90°$. There is clear evidence of a systematic difference of $0\overset{''}{.}1$ around $+80°$ to $+85°$. Since the CAMC observations at both culminations, and thus at varying zenith distance, are in agreement, this suggests that most of the distortion lies in the FK5.

9. Future programmes

A new scanning slit micrometer was fitted to the telescope in March 1988, and came into full use in May 1988. This micrometer has improved sensitivity and accuracy, as reported in these proceedings by Fabricius *et al.* It is possible to reach V=14.5 on a routine basis.

The completion of the IRS (to $\delta = -45°$) and the reference stars in the fields of extragalactic radio sources are two of the main priorities of the present programme.
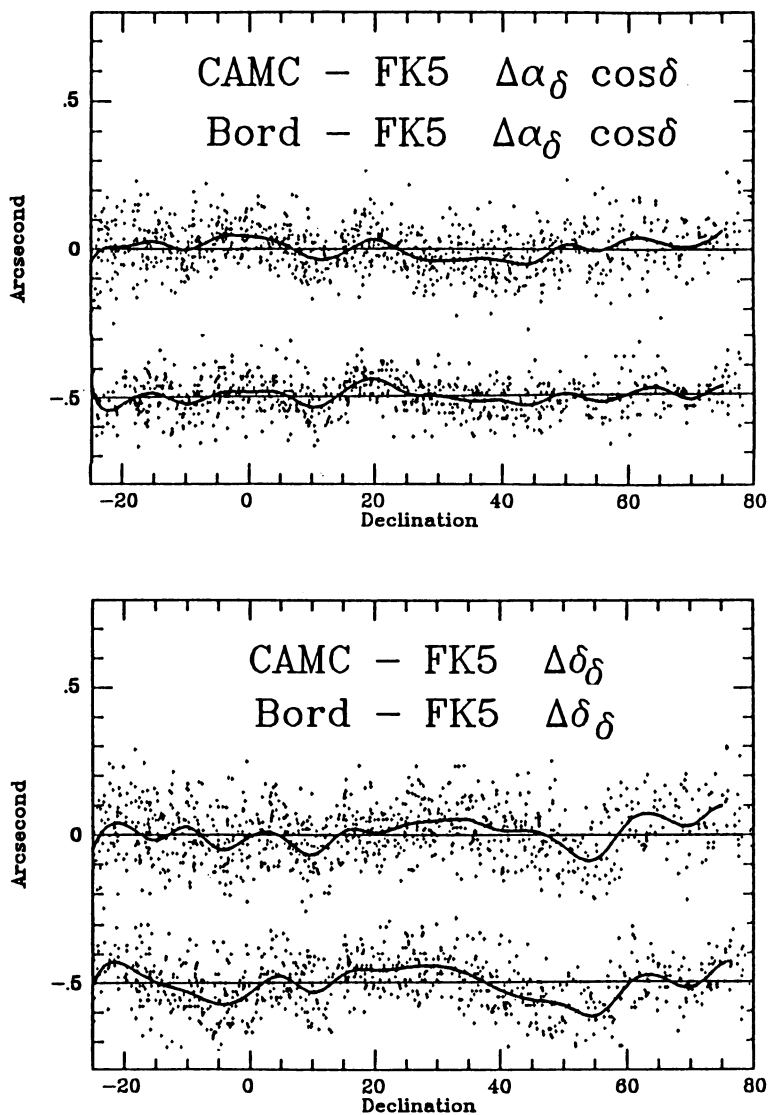
Figure 4. Systematic differences in right ascension and declination as a function of declination between CAMC and Bordeaux and FK5. The Bordeaux differences have been displaced by 0".5 in order to make the comparison clearer.
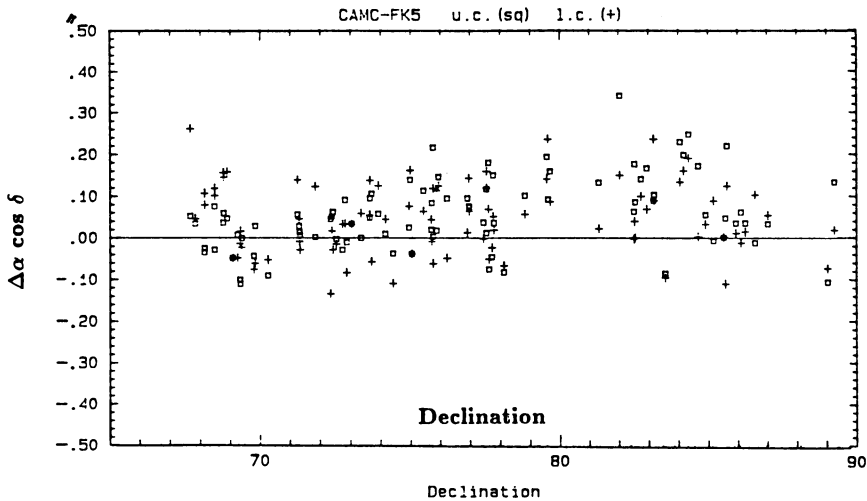
Figure 5. Differences in right ascension as a function of declination between CAMC and FK5 for stars observed at upper and lower culmination.

A new programme which has been started is the faint reference extension to the IRS. Stars have been selected with magnitude V=11-12 at a density of 1 star per square degree from the Astrographic Catalogue. So far, about 21000 stars have been included in the observing programme between declinations -17° to $+90^{\circ}$. Work is proceeding in selecting stars south of -17°.

10. References

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Discussion

MIYAMOTO: Concerning the proper motion accuracy to be attained by Carlsberg Meridian Catalogues, could you tell me what kind of data for the first epoch observations will be used?

MORRISON: I have used mainly the large photographic catalogues: Yale, AGK2 and AGK3.

PULYAEV: How many polarissimae stars do you observe every night?

MORRISON: We observe 3 polar stars per hour, so it's approximately 30 per night.

HUGHES: What criterion or criteria do you use for rejecting observations? The genesis of my question is that 7% seems to be a high rejection rate and one might assume that some of the rejects are actually within a reasonable distribution.

MORRISON: The rejection figure of 7% largely comprises unsuccessful observations, such as those that were not properly scanned because of poor input positions. About 1% are rejected from criteria based on the size of the residual.

NEMIRO: Are there plans to use the Carlsberg instrument for determination of absolute positions? If not, it's a pity.

MORRISON: We do carry out observations which can eventually be used in an absolute discussion of the observations. For example, we observe three polarissimae each hour which can be used to define the absolute azimuth.