THE SYSTEM OF THE PPM CATALOGUE

SIEGFRIED ROESER
Astronomisches Rechen-Institut
Mönchhofstr. 12 – 14
D-6900 Heidelberg
Federal Republic of Germany

ABSTRACT. The coordinate system of the Catalogue of Positions and Proper Motions (PPM) was constructed as an extension of the FK5 sytem to higher star densities and fainter magnitudes. Zonal deviations from the FK5 were minimised on scales of 7 × 7 square degrees via AGK3R and CMC catalogues. Compared with these catalogues, no magnitude equation was found for stars brighter than $m(\text{pg}) = 10.5$.

1. Introduction

PPM (Roeser and Bastian, 1989) is a new catalogue of reference stars on the northern celestial hemisphere. It contains the positions and proper motions of 181731 stars for equinox and epoch J2000.0 on the system of FK5.

The Fifth Fundamental Catalogue (FK5) (Fricke *et al.*, 1988) is the presently adopted official coordinate system of the IAU. This system is defined by the positions and proper motions of the 1535 basic fundamental stars evenly distributed over the sky. The FK5 defines the system, but how shall an astronomer refer his observations to FK5? The spatial stellar density of FK5 is so low (1 star per 27 square degrees) that only instruments able to perform large-scale astrometry like meridian circles or astrolabes can make direct use of FK5. So, the FK5 stars serve as the knots in a network which spans over the whole sky, but secondary knots have to be introduced in order to make the net denser. This densification of the net can be achieved with a single instrument provided that this instrument measures large angles free of all kinds of systematic errors. The HIPPARCOS satellite, according to its design and measuring principle, would have been the ideal instrument if it had worked as intended. Under the present circumstances, however, HIPPARCOS will not be able to supply positions *and* proper motions with the required systematic accuracy. Of course, PPM cannot be a substitute to the desired HIPPARCOS system, it should only be considered as a practical tool to refer observations to the system of FK5.

This paper describes the measures, U. Bastian and myself have taken to construct the system of PPM from catalogues which were produced by conventional earthbound observing techniques.

J. H. Lieske and V. K. Abalakin (eds.), Inertial Coordinate System on the Sky, 469–478.

2. The Problem

The problem of the construction of the PPM system is twofold. First, the FK5-system has to be extended to higher star density and fainter magnitudes. Second, all the observational catalogues which are used for PPM must be rigourously reduced to this system. We will concentrate on the first topic now and cover the second part at the end of the paper. For the northern hemisphere — only this is covered by PPM at present — a "natural" extension of FK5 is AGK3R (Scott, 1968), and for even higher star densities AGK3 (Heckmann *et al.*, 1975), if properly transformed to FK5. Table 1 shows a comparison of the spatial stellar densities between these three catalogues. Loosely speaking, it can be interpreted that one FK5 star determines the system for about 225 AGK3 stars. The mean photographic magnitude in FK5 is 5.5 mag, it increases to 8.8 mag in AGK3R and to 9.7 mag in AGK3/PPM.

Table 1. Spatial stellar density and mean photographic magnitudes in the catalogues FK5, AGK3R and AGK3/PPM.

Catalogue	*Stars/sq. deg.*	*mean magnitude (phot.)*
FK5	0.04	5.5
AGK3R	1	8.8
AGK3/PPM	9	9.7

In conclusion from Table 1 we are faced with the problem of extending a coordinate system defined for a few bright stars to much fainter stars without making a systematic error usually called magnitude equation. In a similar way we must verify that the final system has no colour equation, *i.e.* red stars must not be rotated with respect to blue stars.

So, the construction of the system of positions and proper motions of PPM was carried out in a "natural" way. Starting from FK4/5 we went via AGK3R and CMC to AGK3/PPM applying all the necessary corrections found from catalogue comparisons.

3. Catalogue Comparisons

In this section we describe the methods used for the comparisons of catalogues and the reduction of individual catalogues to our system. Systematic differences between catalogues were investigated depending on the position on the sky, on magnitude and on spectral type. Position-dependent systematic differences are determined in the following way: In right ascension and declination they are given by a spatial moving average filter whose grid-points are the stars common to both catalogues. The spatial frequency of this filter is chosen such that about 30 to 40 neighbouring stars contribute to each star's systematic correction.

For comparison in magnitude and spectral type simple step functions are determined on magnitude intervals of 1 mag and 1 spectral class. In our case, where the primary catalogue to compare with is AGK3, a finer subdivision would overinterpret the effects, because of the uncertainties in AGK3 magnitudes and spectral types. Usually global magnitude and colour corrections are applied, but dependence of the colour equation on declination, for instance, was always investigated.

4. The Construction of the System

For practical reasons we started with FK4 as reference system. Systematic comparisons of some of the source catalogues with FK4 were already available. AGK3R has been compared with FK4 by Schwan (1985 and private communication) with his method of representing spatial systematic differences and magnitude equations by series developments. Schwan found that AGK3R is on the system of FK4. As AGK3R is the reference star catalogue for AGK3, we can say that reducing rigourously AGK3 onto AGK3R means AGK3 is on the system of FK4 for the mean epoch of 1958. In the same paper, Schwan (1985) also compared AGK3 with AGK3R and found no significant deviation of AGK3 from AGK3R at the observational epoch of AGK3. To study the proper motion system of AGK3, Schwan compared it with NIRS (Corbin, 1976) and detected small deviations. We added these corrections to AGK3 proper motions, and in all comparisons below the term AGK3 should always be understood as AGK3 including Schwan's corrections. In the construction of the PPM system we repeated this comparison using the methods described above with the intention to analyse the difference between AGK3 and AGK3R on spatial scales smaller than those investigated by Schwan. The results of this comparison are shown in Figure 1. From bottom to top in this figure, the systematic differences between AGK3R and AGK3 as functions of magnitude, spectral type, right ascension and declination are plotted. Plots on the left hold for differences in r.a. times cos δ, those on the right for differences in declination. No magnitude equation and no spatial systematic differences between AGK3 and AGK3R were found even on scales of 7×7 square degrees, a scale which was much smaller than that used by Schwan in his comparisons. This figure documents that the authors of AGK3 successfully reduced their measurements onto the system of AGK3R with one exception.

This exception shows up in the comparison between AGK3 and AGK3R declinations as a function of spectral type. A small systematic slope from blue stars towards red stars is noted, a so-called colour equation. The effect seems to be very small, but Figure 1 is a global curve, *i.e.*, all 20 500 stars on the northern hemisphere common to AGK3 and AGK3R enter this comparison. To further investigate this effect we repeated this plot for different declination zones. This is shown in Figure 2 and gives the hint to the solution. The effect is stronger at lower declinations, and reverses its sign near the pole. So, one must suspect that this colour equation is caused by differential colour refraction. This effect has not been considered in the construction of AGK3, at least it is not mentioned in the AGK3 introduction (Heckmann *et al.*, 1975; see also de Vegt, 1988). To correct AGK3 for this effect, all AGK3 declinations were corrected by $\Delta\delta$ given by

$$\Delta\delta = A + B \tan(\phi - \delta),$$

where ϕ is the geographic latitude of Hamburg, and the coefficients A and B are determined from the actual AGK3R – AGK3 differences for each spectral type bin. The coefficients B — so derived — agree to within 10 per cent with theoretical values derived from atmospheric dispersion and the spectral energy distribution of the stars and photographic plates. Today this effect is well known in photographic astrometry, and one tries to minimise it by using yellow-sensitive plates.

The proper motion system of AGK3 is simply given by the difference AGK3 – AGK2, where modifications to the original AGK2 were introduced by Heckmann *et al.* (1975) in order to reduce AGK2 to FK4. It must be suspected, however, that differential colour refraction was not considered in the reduction of AGK2 also, meaning that the proper motion system is essentially unaffected by

https://doi.org/10.1017/S0074180900087349 Published online by Cambridge University Press

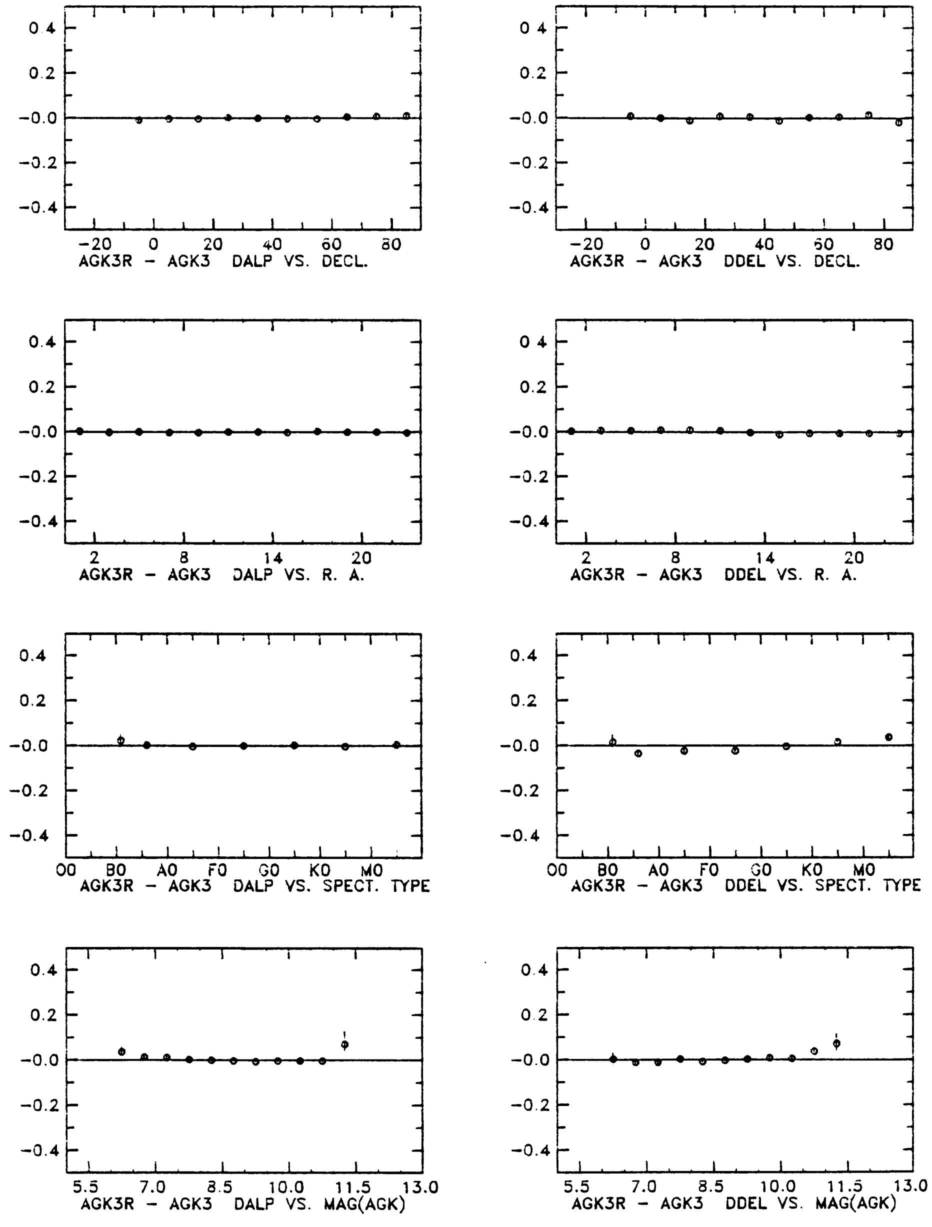

Figure 1. Systematic differences AGK3R – AGK3 (after Schwan's corrections) in right ascension times cos δ (*left*) and declination (*right*). From top to bottom the differences depending on declination, right ascension, spectral type and magnitude are shown. Units are sec of arc.

this effect. This problem is further discussed below, where we compare AGK3 with CMC.

In constructing the proper motion system of PPM we were guided by the idea that only the most reliable catalogues should be used and, especially, the system should represent FK5 as precisely as possible at present epoch. This led to the following conclusion: the system of PPM is determined by AGK3R at epoch 1958 and by CMC (1985-88) at epoch 1986.5.

The comparison with the CMC catalogues is described below. Although the systems of the individual CMC catalogues differ slightly from each other, we discuss them as one entity after reducing them individually to the FK4 system using Schwan's (1988) results. Then AGK3 was compared with CMC (on FK4). This comparison is shown in Fig. 3, which has the same scheme as Fig. 1. Let us first consider the magnitude dependence. In right ascension we note a flat region of almost zero systematic difference between magnitudes 6 and 10.5, where the bulk of PPM stars lies. All stars brighter than 6 mag fall in the first bin in Fig. 3. There the observed r.a. in CMC are systematically larger than those computed from AGK3 for this epoch. But only 770 stars or 0.4 per cent of our ensemble lie in this magnitude range. In the majority these stars are bright blue stars, which are difficult objects in photographic astrometry, as can also be seen from the plots showing the dependence on spectral type in this Figure. This should be remembered if one uses data for these stars from PPM. For stars fainter than 10.5 a systematic difference between CMC and AGK3 of about 0.″1 can be found. It is quite possible, that this effect is due to errors in the AGK3 proper motion system, but there is no final proof. For this magnitude range, the number of stars in CMC which can

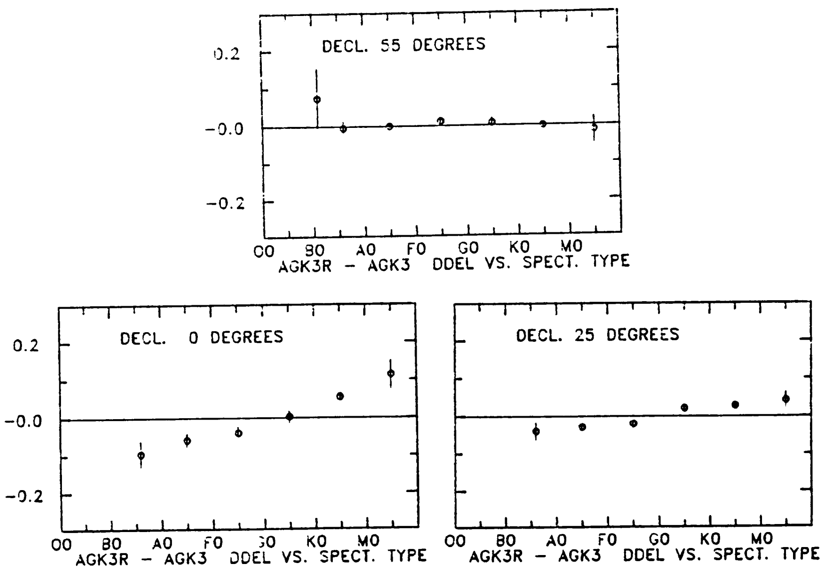

Figure 2. Systematic differences Δδ AGK3R – AGK3 depending on spectral type for declinations 0, 25 and 55 degrees. Units are sec of arc.

https://doi.org/10.1017/S0074180900087349 Published online by Cambridge University Press

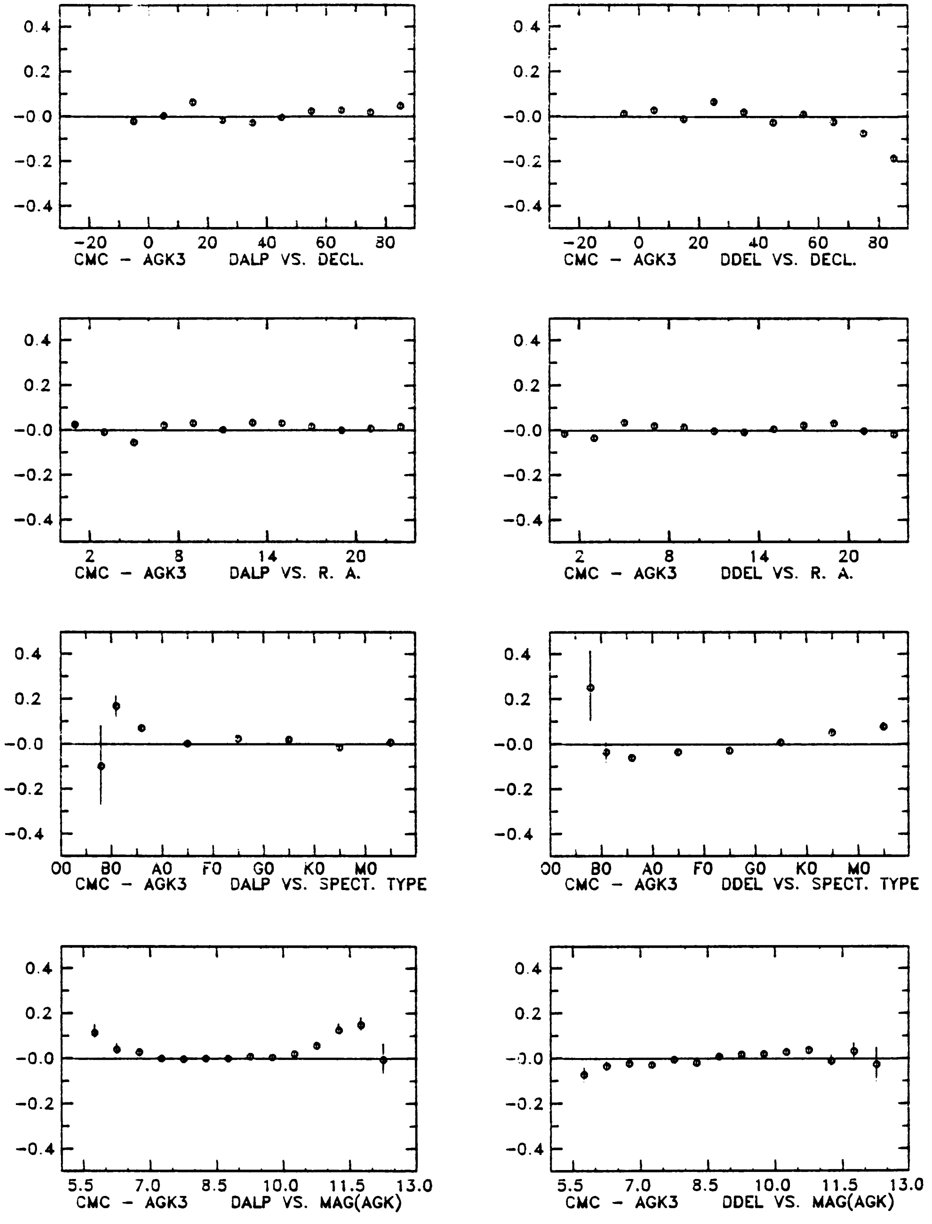

Figure 3. Systematic differences CMC (on FK4) – AGK3 (after Schwan's corrections) in right ascension times cos δ (*left*) and declination (*right*). From top to bottom the differences depending on declination, right ascension, spectral type and magnitude are shown. Units are sec of arc.

https://doi.org/10.1017/S0074180900087349 Published online by Cambridge University Press

be used for a comparison strongly decreases. For stars brighter than 10 mag, the ratio CMC/PPM is about 0.1; it decreases to 0.05 between $m = 10$ and $m = 10.5$ and to 0.03 for stars fainter than 10.5 mag. This means that the systematic corrections would be determined from a relatively small number of comparison stars. We did therefore not correct the PPM system for this effect. But any user of PPM is free to do so, of course, using Fig. 3 for this purpose.

In declination we note a very smooth slope from the bright to the faint end. The size of the slope is 16 milli-arcsec/mag, which is so small that we did not apply this correction.

The results shown in Fig. 3 are rather remarkable. It is by no means straightforward, that in comparing the proper motions of a photographic catalogue AGK3/2 with a present-day photoelectric meridian circle catalogue magnitude-dependent effects are so minute. As the differences in epoch AGK3 – AGK2 and CMC – AGK3 are almost the same, the comparisons above are essentially comparisons between CMC and AGK2 modulo the sign. The smallness of all the effects in Fig. 3 is a proof for the good work done in the compilation of AGK2.

The investigation of colour-dependent effects shows similar features as in the comparisons with AGK3R. The differences $\Delta\alpha \cos\delta$ show no colour dependence for spectral types from late B to M, and we already mentioned that stars earlier than B2 are problematic in PPM. As in the comparison with AGK3R, the influence of neglecting the colour refraction is inherent in the declination differences. It is larger than in the case of AGK3R suggesting that AGK3 proper motions also carry this defect. This would indicate that in AGK2 the effect of atmospheric dispersion differs from that in AGK3, contrary to our expectation above. This could be studied in a new reduction of AGK2 using a suitable reference catalogue. We did not do this and therefore left the PPM proper motion system unchanged in this respect.

The remaining plots in Fig. 3 show the position-dependent systematic differences between AGK3 and CMC on FK4. These are determined and removed with the moving-average-filter method explained in section 3. Again, it is noteworthy that these systematic differences are rather small with only one minor exception. This refers to $\Delta\delta$ for declinations larger than about +75 degrees. There is a difference between CMC (on FK4) and AGK3 of about $-0''.2$. From the comparison CMC – NIRS (see CMC, 1986) we find $\Delta\delta$ about $-0''.1$, and Schwan (1988) determined $+0''.1$ for the resp. difference CMC – FK4. This explains this relatively large discrepancy between CMC (on FK4) and AGK3.

5. Systematic Reductions of Individual Catalogues

PPM is constructed from the following source catalogues (see Roeser and Bastian, 1989): The Astrographic Catalogue (AC), AGK1, Yale zone catalogues, AGK3, AGK2, AGK3R and CMC. The reduction of AC, AGK1 and Yale is briefly described below.

For the reduction of the 12070 AC plates a single-plate, second-order polynomial fit algorithm was selected. Each observatory's AC zone was then investigated with respect to higher-order distortions, "coma", magnitude and/or spectral type dependent systematic deviations from AGK3, and corrected.

The reductions of the Yale and AGK1 zones are performed with the methods of catalogue comparison described in section 3.

6. Conclusion

The individual steps for the derivation of the PPM system can be summarized as follows: As starting hypothesis the system of AGK3 positions and proper motions on equinox 1950.0 was selected. First, the corrections found by Schwan (1985) were applied. This is an intermediate system, nominally on FK4, from which systems of position at epoch 1958.0 and 1986.5 can be computed.

The 1958.0 positional system was compared with AGK3R, the only correction applied to this system is the correction in declination due to the effect of differential colour refraction (see Figures 1 and 2).

The 1986.5 positional system was compared with CMC. Spatial systematic differences in right ascension and declination as found from the comparison were applied, and, also at this epoch, the same declination correction due to colour refraction as above must be performed. No correction for magnitude effects has been made as explained above.

The system of positions and proper motions on FK4, equinox 1950.0, is then given by the 1986.5 and the 1958.0 systems and their difference.

The final transformation from FK4 system at equinox and epoch 1950.0 to the FK5 system at equinox and epoch J2000.0 was performed in exactly the same way as in the construction of FK5.

It is a rather difficult undertaking to estimate the systematic errors of the PPM system of position and proper motions. But, it seems appropriate to give here at least rough figures even if they are uncertain. Let us assume that both AGK3R and CMC have a systematic accuracy of their positional system of $0\overset{''}{.}04$. It can be concluded from Figure 1, that the systematic difference between AGK3R and PPM is smaller than $0\overset{''}{.}04$, and after applying the systematic differences to CMC derived from Figure 3, the deviation of PPM from CMC (on FK4) is also less than $0\overset{''}{.}04$. Then we immediately find the mean epoch of the PPM system to be 1972, and we may expect typical systematic errors of position at mean epoch of $0\overset{''}{.}03$, and a typical error of the proper motion system of 0.20 arcsec/century.

References

CMC (1985-1987): *Carlsberg Meridian Catalogue La Palma*, Numbers 1 to 3. Copenhagen University Observatory, Royal Greenwich Observatory and Real Instituto y Observatorio de la Armada, San Fernando.

CMC (1988): *Carlsberg Meridian Catalogue La Palma, Number 4*. Copenhagen University Observatory, Royal Greenwich Observatory and Real Instituto y Observatorio de la Armada, San Fernando. Private communication.

Corbin, T. (1978): "The proper motions of the AGK3R and SRS stars". *IAU Colloquium No. 48*, Eds. F.V Prochazka and R.H. Tucker, 515.

Fricke, W., Schwan, H., Lederle, T. (1988): *Fifth Fundamental Catalogue (FK5)*. Part I. The Basic Fundamental Stars. *Veröff. Astron. Rechen-Institut Heidelberg* Nr.32.

Heckmann, O., Dieckvoss, W., Kox, H., Günther, A. and Brosterhus, E. (1975): *AGK3. Star catalogue of positions and proper motions north of –2.5 declination.* Hamburg-Bergedorf 1975.

Roeser, S. and Bastian, U. (1989): *PPM - Positions and Proper Motions of 181731 stars north of –2.5 degrees declination.* Astronomisches Rechen-Institut, Heidelberg, 1989.

Scott, F. P. (1968): "The AGK3R, SRS and related projects", In: *Highlights of Astronomy*, ed. L. Perek. International Astronomical Union. Reidel, Dordrecht, 279.

Schwan, H. (1985): "The systems of the positions and proper motions in star catalogues AGK3, AGK3RN, and N30", *Astron. Astrophys.* **149**, 50.

Schwan, H. (1988): Private communication.

de Vegt, Ch. (1988): "Status of Photographic Catalogs: Available Material and Future Developments", *Proc. IAU-Symp. 133 Mapping the Sky*. Eds. S. Débarbat, J.A. Eddy, H.K. Eichhorn and A.R. Upgren. Kluwer, Dordrecht.

Discussion

COLE: (1) The transformation from FK4 to FK5 is magnitude dependent. How did you handle this problem? (2) I note that a slightly different approach was used for the SRS. The average magnitude of FK4 stars in the neighborhood of the SRS star was used. I do not know if there is any significant difference in those two approaches.

RÖSER: (1) We have to perform this transformation for stars fainter than those in the FK5. Nothing is really known about such a transformation for these faint stars. So, we made this transformation for the fainter stars using Schwan's transformation functions at $m_v = 6.5$, which is the faintest realistic point. (2) I have not in mind the size of the magnitude dependent term in this transformation. The average magnitude in the FK5 is $m_v = 4.7$, so we can calculate the size of this effect in comparing the transformation functions at 4.7 and at 6.5 magnitudes.

SMITH: In applying Schwan's analytic functions to reduce a catalog of faint stars which was referred to the FK4 system (such as the AGK3R catalog) to the FK5 system, to what extent do you think the average magnitude of the FK4 stars in the vicinity of the particular AGK3R star should be used as an input argument to the analytic function — in preference to some constant value far from the average magnitude of the FK4 stars?

RÖSER: In order to study the size of the effect, I will go home and look into the transformation function. I will send my response to the editor.

[*Written Response*]

First, the FK4 system is only well-defined for $m_v < 6.5$ mag. At present the FK5 system given by the basic FK5 (Fricke *et al.*, 1988) is also not defined for faint magnitudes. So the transition between FK4 and FK5 at magnitudes fainter than $m_v = 6.5$ is, in principle, undefined.

Second, in constructing the PPM on FK5 we made the transition at $m_v = 6.5$ for all stars fainter than that. Your question refers to magnitude dependent effects correlated with the position on the sky. Checking these effects on Schwan's tables for the transition, the only noticable effect occurs in proper motions in right ascension. There the position dependent difference between $m_v = 5$ and $m_v = 7$ is at its maximum 0.015 arcsec/cy, which is so small, that it does not matter at which magnitude the transition is made.

RATNATUNGA: After all the corrections for systematic effects which reduce the catalogs to a single proper motion system of FK5, how do you ensure that this is an inertial frame of reference?

RÖSER: We do not know how "inertial" the FK5 is. We tried the best we could do to reduce our catalogue to the FK5. It can, of course, not be "more inertial" than the FK5. It would be highly desirable to have an instrument able to measure large angles between a great number of stars free of systematic errors like the HIPPARCOS mission as it was originally conceived.

BASTIAN: PPM, aiming to be a representation of the FK5 at higher star density and fainter magnitude — aiming to be on the system of the FK5 as closely as possible — it cannot be better than the FK5. This would be the ultimate limit. And from the discussions today we know that the FK5 is not perfectly inertial.