Astronomy
&
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The proper motions of fundamental stars

I. 1535 stars from the Basic FK5[⋆]

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Abstract. A direct combination of the positions given in the HIPPARCOS catalogue with astrometric ground-based catalogues having epochs later than 1939 allows us to obtain new proper motions for the 1535 stars of the Basic FK5. The results are presented as the catalogue *Proper Motions of Fundamental Stars* (PMFS), Part I. The median precision of the proper motions is 0.5 mas/year for $\mu_\alpha \cos\delta$ and 0.7 mas/year for μ_δ. The non-linear motions of the photocentres of a few hundred astrometric binaries are separated into their linear and elliptic motions. Since the PMFS proper motions do not include the information given by the proper motions from other catalogues (HIPPARCOS, FK5, FK6, etc.) this catalogue can be used as an independent source of the proper motions of the fundamental stars.

Key words. astrometry – reference systems – catalogs

1. Introduction

The proper motions in the HIPPARCOS catalogue (hereafter HIP) (ESA 1997) can be improved by combining the HIP and ground-based data. The reasons why this should be done are well-known. They are discussed, for example, in the description of recently realized FK6 catalogue, Part I, by Wielen et al. (1999). The FK6 is a combination of the HIP with FK5 (Fricke et al. 1988; Fricke et al. 1991). Part I contains 878 stars from the FK5 catalogue with little or no indication of duplicity. The FK6 shows non-linear motions of some of the stars, but it cannot provide details of such motions because the ground-based data are represented by the compilation catalogue FK5.

To investigate the proper motions with emphasis on non-linear motions of stars the *direct* combinations of the HIP with ground-based catalogues were proposed by Gontcharov & Kornilov (1997) as well as by Wielen et al. (1999) (see p. 6, 7) in their project "FK7". In the process the systematic errors in each ground-based catalogue have to be eliminated individually reducing of each catalogue to the HIPPARCOS system.

An advantage of this approach is that one can use the same procedure both for single and non-single, linearly and non-linearly moving stars. Therefore, proper motions of thousands of stars can be improved simultaneously. It would be reasonable to begin with 4638 stars common to the HIP and FK5 because they have been the most extensively observed from the ground. The *Proper Motions of Fundamental Stars* (PMFS) catalogue, Part I – 1535 stars from the Basic FK5 – is the result of our direct combination of the HIP with over 60 compiled and observational ground-based catalogues. The proper motions of the stars from the FK5 Extension will be considered in Part II of the PMFS.

2. Selection of ground-based catalogues

To trace the non-linear motions of the stars one should use the most precise observational catalogues with a spread in epoch, especially earlier ones. The catalogues should be evenly and closely (ideally annually) distributed over the time interval. Moreover, for correct estimation of the systematic errors every catalogue should contain reasonable number of stars and cover a rather wide interval of α and δ. For the last reason we rejected several zonal catalogues, some obtained with astrolabes and some others.

We have analyzed a hundred observational catalogues as described in Gontcharov & Andronova (1997),

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Andronova (1998) and Gontcharov et al. (1998). Hereafter we reject the observations made at zenith distances $> 70°$ as not being accurate enough. For the evaluation of the catalogues the mean absolute values of the differences $\Delta\alpha$ and $\Delta\delta$ in the sense "observational catalogue minus HIP at the observational catalogue epoch" were calculated twice for every catalogue: before and after the elimination of systematic errors as described in the section "Method". The procedure for the determination of the systematic errors was much less effective for older catalogues probably because of the degradation of the HIP positions at earlier epochs. In other words, the method of direct combination of the HIP with ground-based catalogues seems to be acceptable only for those catalogues with epochs at which the HIP (as the reference) is still several times more precise. It turns out that most catalogues observed after 1940 (as against a few observed before 1940) have mean absolute values of coordinate differences "catalogue minus HIP" <150 mas after elimination of systematic errors.

In order to get a uniform and dense set of observational catalogues, we decided to reject all catalogues observed before 1939 as well as those with mean absolute value of coordinate differences "catalogue minus HIP" <150 mas after elimination of systematic errors. The final list of catalogues used for positions includes 57 observational catalogues with epochs between 1939 and 1995 listed in Table 2 (hereafter denoted observational catalogues). It gives, on average, 20 observations per star spread over 40 years. This means that we can investigate the non-linear motions of stars with periods from about 10 to 100 years and amplitudes >100 mas. Apparently, the use of a few accurate catalogues observed before 1939 would add little to the investigation of non-linear motions of bright stars, but they may be appropriate for investigating fainter stars with poor observational histories.

3. Method

We used the positions and parallaxes from the HIP; radial velocities from the HIPPARCOS input catalogue (HIC) (Turon et al. 1993); the proper motions from the HIP and best ground-based compilations: GC (Boss 1937), N30 (Morgan 1952), FK5, N70E (Kolesnik 1997), CMC9 (Carlsberg Meridian Catalogue # 9 1997), KSV2 (Time Service Catalogue 2) (Gorshkov & Scherbakova 1998); and the positions from the observational catalogues. All mentioned ground-based catalogues were transferred to the equinox J2000.

Since the discrepancies between HIP and ground-based proper motions of non-linearly moving stars may be great (sometimes >50 mas/year), proper motions from the HIP, GC, N30, FK5, N70E, CMC9 and KSV2 were used for the calculation of mean weighted proper motions as initial values for the main procedure. These ground-based compilation catalogues were first adjusted to the HIPPARCOS system: the proper motion differences in the sense "catalogue minus HIP" were approximated by polynomials, which were then eliminated from the ground-based proper

motions. The weights were calculated from an intercomparison of the catalogues by the method described by Zverev et al. (1980). We did not need a more rigorous reduction of these catalogues because these mean proper motions were used only as initial values for the first of three iterations. The proper motions from these catalogues have no influence on the final result.

The main procedure was:

1. All stars were divided into linearly moving ones (mainly single stars, classes "S" and "W" discussed later), non-linearly moving ones (class "A" discussed later) and stars with doubtful results (class "C" discussed later). Among the non-linearly moving stars are those with calculated proper motion components differing from the HIP by >7 mas/year ($\Delta\mu$ binaries in terms of the FK6). Thus, the lists of linearly and non-linearly moving stars were revised as the proper motions were recalculated in every iteration;

2. The calculated proper motions together with positions and parallaxes from the HIP and radial velocities from the HIC were used to calculate the positions for the epochs of the observational catalogues following the procedure described in (ESA 1997, vol. 1, Sect. 1.5.5);

3. The differences $\Delta\alpha$ and $\Delta\delta$ in the sense "observational catalogue minus HIP at the observational catalogue epoch" for every *linearly moving* star in every observational catalogue were calculated;

4. The systematic behaviour in these differences was approximated by Legendre-Hermite-Fourier functions of α and δ. After elimination of the systematic curve the autocorrelation function of the residuals on the sphere was calculated as described by Gubanov & Titov (1993). The γ-criterion was used to test the separation of the systematic and accidental components as described by Zverev et al. (1980);

5. The approximating functions were eliminated from the coordinates of *all* stars in the observational catalogues. Thus, the observational catalogues were reduced to the HIPPARCOS (ICRS) system with mean errors in the range 30–200 mas, varying from catalogue to catalogue as tested by the intercomparison of the catalogues with close epochs. The weights of the catalogues were calculated from their mean errors. It turns out from the comparison of these weights that three long series of observations made with the Washington 6-inch transit circle, Hamburg meridian telescope at Perth and Carlsberg meridian circle at La Palma are of exceptional importance in our investigation;

6. The mean weighted proper motions were recalculated using the series of the reduced ground-based positions together with the HIPPARCOS position for 1991.25;

7. These proper motions were then used for the next two iterations (steps 1–6) until the obtained improvements were insignificant.

The advantage of the obtained PMFS proper motions over ground-based ones (such as from the FK5) is that the PMFS proper motion system is very close to the HIP one.

It shows itself in the fact that the differences "PMFS minus HIP" do not indicate noticeable systematic dependence on the equatorial coordinates. On the other hand, the advantage of the PMFS proper motions over HIP ones is that they reflect the star motions over decades, not only in the course of 3.36 years of the mission. Namely, the non-linear motions of 134 stars were directly separated into their proper motions and periodical motions of the photocentres around barycentres, and the proper motions of some other 200 stars were separated from their non-linear motions which were implicit in large differences between the PMFS and HIP proper motions of the stars.

4. Stellar systems

There are many double and multiple stellar systems in the Basic FK5. The stars are divided into 4 classes. 760 stars can be considered as single. They are marked as the class "S". All the pairs with separation >10 arcsec and >10 000 AU are likely to be common proper motion stars or optical pairs. Their bright components are also marked as single stars.

In the case of wide pairs (separation >10 arcsec but <10 000 AU, no orbital motion) the fainter component usually does not affect the ground-based or space astrometry of the brighter one. In this case the method used and the obtained proper motions are acceptable. 187 such stars are marked as the class "W". Closer pairs need some special consideration.

The parameters (resolving power, field of view etc.) of the astrometric telescopes are so different that whereas one of them may resolve a pair and observes the brighter component, another resolves the pair and observes its photocentre, while yet another does not resolve the pair and observes its photocentre. Therefore, any combination of the results of different telescopes (in our study also) may be doubtful for some pairs, mainly with the separation from 1 to 10 arcsec. 35 such stars are marked as class "C".

Some of the stars have been known as spectroscopic, eclipsing, close visual binaries or even single ones, but in the series of astrometric observations with different epochs they appear as non-linearly moving photocentres of astrometrically unresolved stellar systems with some hidden (i.e. faint) massive components. Such stellar systems are known as astrometric binaries (see ESA 1997). The class "A" (astrometric binaries) in the PMFS includes 551 stellar systems with 553 brighter components in the Basic FK5 for which the astrometrically observed photocentre moves, or *can move*, non-linearly with an amplitude > 1 mas:

1. the visual or photocentre orbit is well-known (in fact it means a period ≪1 000 years), or
2. suspected revolution period is <200 years, or
3. the distance between components is <75 AU (one suspect a rather short period in this case), or

Table 1. The format of the catalogue of proper motions of fundamental stars

Bytes	Format	Units	Explanations
1–6	I6		[122,118322] HIPPARCOS number
7–11	I5		[1,1670] FK5 number
12–19	F8.1	mas/year	[−3629.0,4141.8] $\mu_\alpha \cos\delta$
20–23	F4.1	mas/year	[0.4,2.0] Mean error of $\mu_\alpha \cos\delta$
24–31	F8.1	mas/year	[−5811.1,3267.5] μ_δ
32–35	F4.1	mas/year	[0.3,2.0] Mean error of μ_δ
36–36	I1		blank
37–37	A1		[ACSW] Class of stellar system

4. a spectroscopic or eclipsing component is known and we suspect the photocentre periodic motion amplitude >1 mas, or
5. the distance between components is <1 arcsec (in this case many astrometric telescopes did not resolve the system and observe its photocentre), or
6. the HIP Double/Multiple System flag (field H59) is O, G, V or X, or
7. the HIP solution quality (field H61) is S, or
8. the absolute difference between the HIP and PMFS proper motions is >7 mas/year for either $\mu_\alpha \cos\delta$ or μ_δ, or
9. we found a non-linear motion of the photocentre.

One would expect a significant diversity of the proper motions of these stars and stellar systems in different catalogues. The PMFS proper motions are the linear motions of the barycentres of these systems. Some parameters of a periodic motion of their photocentres around barycentres have been obtained also and combined with the parameters known from other sources in a separate catalogue of astrometric binaries, which will be published elsewhere.

5. Statistics and format of the catalogue

The PMFS catalogue gives the proper motion components $\mu_\alpha \cos\delta$ and μ_δ in mas/year, their mean errors and classification of the stellar systems by the type of duplicity. The PMFS is presented in Table 3 deposited in machine-readable form at the CDS. The mean error of the proper motion components varies from 0.3 to 2.0 mas/year. The median precision is 0.5 mas/year for $\mu_\alpha \cos\delta$ and 0.7 mas/year for μ_δ.

The format of the catalogue is given in Table 1. The stars are listed in order of HIP number.

6. Comparison with the FK6

The proper motions of the fundamental stars in the PMFS and FK6 are quite independent. Therefore, it will be very interesting to make a detailed comparison of these catalogues when all parts of the FK6 have been completed. At present we restrict our comparison to the proper motions

Table 2. The observational ground-based catalogues used for star positions

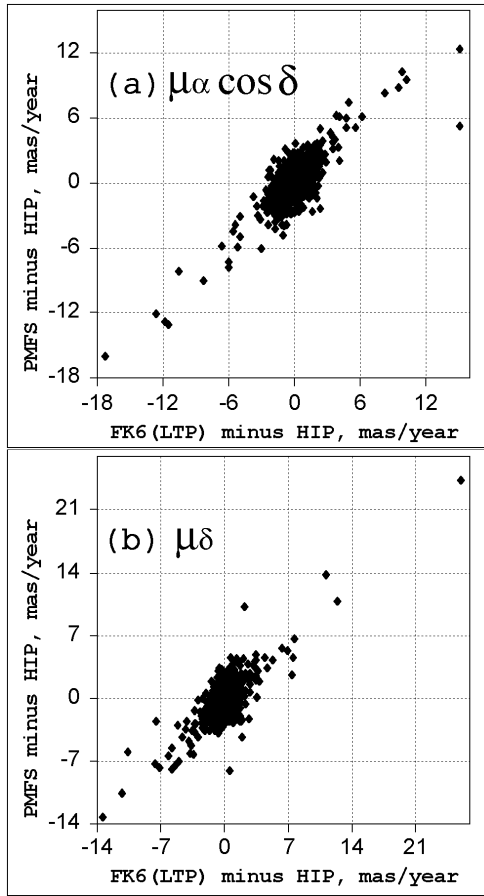| Abbreviation	Name in CDS	Observatory	Telescope	Reference	Epoch
W150	I/100A	Washington	6-inch transit circle	Watts & Adams (1949)	1939
W250	I/100A	Washington	6-inch transit circle	Watts et al. (1952)	1945
W350	I/100A	Washington	6-inch transit circle	Adams et al. (1964)	1953
W450	I/100A	Washington	6-inch transit circle	Adams et al. (1968)	1960
W550	I/100A	Washington	6-inch transit circle	Hughes & Scott (1982)	1967
W1j00		Washington	6-inch transit circle	Holdenried & Rafferty (1997)	1980
WL50		El Leoncito	7-inch transit circle	Hughes et al. (1992)	1971
PU55A		Pulkovo	Tepfer meridian circle	Bedin et al. (1983)	1955
PU58A		Pulkovo	Pulkovo large transit circle	Nemiro et al. (1977)	1958
PU58D		Pulkovo	Ertel-Struve vertical circle	Bagildinsky & Kossin (1966)	1958
PU72D		Pulkovo	Ertel-Struve vertical circle	Bagildinsky et al. (1986)	1972
SPU66D		Cerro Calan	photographic vertical circle	Naumov (2000)	1966
PVC96	I/242	Pulkovo	photographic vertical circle	Bagildinsky et al. (1998)	1991
SPF1A	I/82	Cerro Calan	Repsold meridian circle	Anguita et al. (1975)	1965
SPF1DS	J/A+AS/67/1	Cerro Calan	Repsold meridian circle	Carrasco & Loyola (1987)	1965
SPF1DP		Cerro Calan	Repsold meridian circle	Gnevysheva & Zverev (1983)	1965
SPF2	I/44	Cerro Calan	Repsold meridian circle	Baturina et al. (1986)	1966
SPF3	I/78	Cerro Calan	Zeiss transit instrument	Loyola & Shishkina (1974)	1964
Santiago67	I/89A	Cerro Calan	Repsold meridian circle	Carrasco & Loyola (1981)	1967
SantiagoFC83	J/A+AS/95/355	Cerro Calan	Repsold meridian circle	Carrasco & Loyola (1992)	1983
SPU71A		Cerro Calan	Pulkovo large transit circle	Varin et al. (1981)	1971
Nikolaev60A		Nikolaev	transit circle	Markina & Petrov (1969)	1960
Nikolaev60D		Nikolaev	vertical circle	Bozhko & Zimmermann (1977)	1960
Goloseevo81D		Goloseevo	vertical circle	Lazorenko (1985)	1981
Brorfelde68	I/30	Brorfelde	Carlsberg meridian circle	Olsen Fogh et al. (1973)	1968
Brorfelde73	I/99	Brorfelde	Carlsberg meridian circle	Helmer & Olsen Fogh (1982)	1973
Brorfelde82	I/99	Brorfelde	Carlsberg meridian circle	Helmer et al. (1983, 1984)	1982
CMC1	I/126	La Palma	Carlsberg meridian circle	CMC (1989)	1984
CMC2	I/126	La Palma	Carlsberg meridian circle	CMC (1989)	1985
CMC3	I/133	La Palma	Carlsberg meridian circle	CMC (1989)	1986
CMC4	I/147	La Palma	Carlsberg meridian circle	CMC (1989)	1987
CMC5	I/170A	La Palma	Carlsberg meridian circle	CMC (1991)	1989
CMC6	I/189	La Palma	Carlsberg meridian circle	CMC (1992)	1990
CMC7	I/205	La Palma	Carlsberg meridian circle	CMC (1993)	1991
CMC8	I/213	La Palma	Carlsberg meridian circle	CMC (1994)	1993
CMC9		La Palma	Carlsberg meridian circle	CMC (1997)	1994
Perth70	I/62C	Perth	Hamburg meridian teles.	Høg & von der Heide (1976)	1970
Perth75	I/97	Perth	Hamburg meridian teles.	Nikoloff & Høg (1991)	1975
Perth83	I/168	Perth	Hamburg meridian teles.	Harwood (1990)	1984
BMC74	I/63	Bordeaux	meridian circle	Mazurier et al. (1977)	1974
BMC89		Bordeaux	meridian circle	Requieme (1993)	1989
Beograd69D		Beograd	vertical circle	Sadzakov & Saletic (1972)	1969
Beograd84	J/A+AS/77/411	Beograd	meridian circle	Sadzakov & Dacic (1989)	1984
CPASJ2	J/A+AS/136/1	San Juan	Beijing astrolabe	Manrique et al. (1999)	1994
PACP4	I/182	Beijing	photoelectric astrolabe	Lu Lizhi (1991)	1987
PPCP3		Beijing	transit instrument	Lu Lizhi (1990)	1982
PPCP4		Beijing	transit instrument	Wang & Lu Lizhi (1991)	1990
QAC2	J/A+AS/103/427	Quito	Danjon astrolabe OPL-13	Kolesnik & Davila (1994)	1970
SAC1	J/A+AS/18/135	Cerro Calan	Santiago Danjon astrolabe	Noël et al. (1974)	1969
SAC2	J/A+AS/106/441	Cerro Calan	Santiago Danjon astrolabe	Noël (1994)	1980
CERGA92	J/A+AS/96/477	CERGA	photoelectric astrolabe	Vigouroux et al. (1992)	1990
Calern99	J/A+AS/137/269	Calern	photoelectric astrolabe	Martin et al. (1999)	1995
GCA	J/A+AS/31/159	various	various astrolabes	Billaud et al. (1978)	1967
KSV (TSC)		various	various	Pavlov (1971)	1958
KSV2 (TSC2)		various	various	Gorshkov & Scherbakova (1998)	1982
GCPA	I/180	various	various astrolabes	GCPA (1992)	1979
GCPA2	I/181	various	various astrolabes	Lu Lizhi (1992)	1987

Fig. 1. The proper motion differences in mas/year in the sense "FK6 minus HIP" versus "PMFS minus HIP" for 878 stars from the FK6, Part I: $\mu_\alpha \cos\delta$ **a)**, μ_δ **b)**

in HIP, FK6 and PMFS of the 878 stars in Part I of the FK6.

The PMFS proper motions are derived from over 40 years of astrometric observations and can be considered as a "long-term" prediction of coordinate variations. Therefore, as recommended by Wielen et al. (1999) in Sect. 8 of the FK6, the PMFS proper motions should be compared with the long-term prediction mode of the FK6 (hereafter FK6(LTP)).

The median precision of the FK6(LTP) and PMFS is: 0.46 versus 0.50 mas/year for $\mu_\alpha \cos\delta$ and 0.45 versus 0.60 mas/year for μ_δ. The standard deviation of the differences "FK6(LTP) minus HIP" and "PMFS minus HIP" is: 1.9 versus 2.1 mas/year for $\mu_\alpha \cos\delta$ and 1.9 versus 2.2 mas/year for μ_δ. Thus, formally the PMFS is only about 15% less accurate than the FK6. One should expect such a situation for these linearly moving stars because the ground-based data used in the FK5 cover a longer period. However, the inverse error budget may occur for non-linearly moving stars in the other parts of the FK6.

The standard deviation of the difference "PMFS minus FK6(LTP)" is 1.3 mas/year for $\mu_\alpha \cos\delta$ and 1.5 mas/year for μ_δ. Thus, the PMFS and FK6 are closer to one another than to the HIP. A strong correlation of the differences

"FK6 minus HIP" and "PMFS minus HIP" for individual stars is evident from Fig. 1.

We conclude that, although the accuracy of the PMFS and FK6 seems overestimated, the proper motions in both catalogues compare favourably with the HIP.

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