ASTRONOMY FROM WIDE-FIELD IMAGING

Part Six:

CALIBRATION: ASTROMETRIC AND PHOTOMETRIC

REFERENCE CATALOGUES — PRESENT STATUS AND FUTURE PROSPECTS

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ABSTRACT. The present celestial reference frame is represented by the positions and proper motions of the 4500 stars in the Fifth Fundamental Catalogue (FK5). For practical applications it is extended by the catalogues IRS (International Reference Stars) and PPM (Positions and Proper Motions). According to resolutions of the IAU the FK5 system will be replaced by a purely kinematically defined reference system defined by extragalactic radio sources in the near future. At optical wavelengths, the forthcoming Hipparcos Output Catalogue will be linked to the extragalactic system.

1. General Remarks

In a resolution adopted at the XXIst General Assembly at Buenos Aires (IAU 1991), the International Astronomical Union recommended that the future celestial reference frame be defined by a set of distant extragalactic objects. This is a revision to the resolution taken in 1976 (IAU 1976), where the celestial reference frame was defined to be represented by the FK5 (Fricke et al. 1988, 1991). This is more than just a replacement of one set of objects defining the system by another one; it is a conceptual change.

Following the outlines by Kovalevsky (1990, 1991), a reference system can be defined either dynamically or kinematically. In the dynamical definition, the equations of motion of celestial bodies should have no Coriolis or linear acceleration terms when written in the reference system. A physical realization is given by the Solar System governed by Newtonian mechanics (as the approximation to General Relativity). The reference frame is called the practical realization of that system by a set of fiducial points with their coordinates.

In the kinematical definition, the reference system is given by the ensemble of very distant bodies showing no global rotation. The adhering reference frame is given by a list of quasars with their coordinates.

The FK5, more or less, belongs to the first category of systems; the system defined by quasars, to the second, of course. Replacing FK5 by the quasar system means a transition from a dynamically defined system to a kinematically defined one. Practically, there will not be a change in coordinates, as the origin and the principal plane of the new frame should be as close as possible to the equinox and equator of FK5 at epoch J2000.0.

Apart from the general definition of a coordinate system, users are very much interested in retrieving the coordinate system on their recordings of the sky, be they photographic plates or

H. T. MacGillivray et al. (eds.), Astronomy from Wide-Field Imaging, 261–270.

CCDs. If we neglect CCDs for the contents of this paper, as it is our primary goal to discuss the desiderata for Wide-field Imaging, we may come out with a tentative list of items. To state it more specifically, the following is necessary or desirable for a reduction of Schmidt-plates with fields between 3 x 3 and 6 x 6 square degrees:

1) a dense net of stars representing the reference frame with more than ten stars per square degree is necessary to account for the deformations of the Schmidt plate;
2) these reference stars must cover a magnitude range adapted to the majority of objects to be measured. For reductions of plates with limiting magnitudes of 20 mag, reference stars in the range 14 to 16 mag would be desirable;
3) these reference stars should not reveal systematic deviations from the set of primary reference stars representing the frame;
4) the individual accuracy of the reference stars should not be worse than the accuracy to be obtained from the measurements on the plates.

At present, there is no reference catalogue fulfilling all these requirements; improvement of the situation during the next decade is expected.

3. FK5, IRS and PPM

FK5, the reference frame presently adopted by the IAU, has been constructed by applying dynamical as well as kinematical concepts (Schwan 1993). Details on the determination of the FK5 equator and equinox are given by Fricke (1982).

The FK5 consists of two parts, the 1535 classical fundamental stars, as in FK3 and FK4, and 3117 new fundamental stars, the so-called FK5 Extension. Figure 1 shows the magnitude distribution of the total of 4652 FK5 stars. Due to the Extension, the distribution now extends to the 9.5th visual magnitude. But the average star density is only 3 per 25 square degrees, which is still much too low for many practical purposes.

As the star density in FK5 is so low, photographic sky surveys obtained with classical astrographs, such as the Astrographic Catalogue, AGK2, AGK3, the Yale Zones or others cannot directly be linked to FK5. A denser net of reference stars has to be provided first by observations with meridian circles. In the northern hemisphere, projects like AGK2A (Kopff & Peters 1943) and AGK3R (Scott 1968) were carried out as international cooperations; the same is true for SRS (Smith et al. 1990) in the southern hemisphere. To derive proper motions for stars in the above catalogues, observations of these stars were located in quite a number of meridian circle catalogues distributed over a long period of time. This finally resulted in the IRS catalogue (Corbin 1991) with its total of 36,000 stars (or 0.9 per square degree). The candidate stars for IRS, taken from AGK3R and SRS, were selected only in the 50s and 60s of this century, so the observational history for individual stars, which determines the quality of the proper motions, is varying. So, the IRS is given in 2 parts, the first with good observational history, the second with poor observational history. Average individual accuracy for present-day positions and for proper motions are given in Table 1. The individual accuracy of even Part I in the IRS is already worse than what can be obtained by measurements of photographic plates with modern measuring machines. As a rule of thumb, we shall use as a typical value of the measuring accuracy 60 mas, which comes from the assumption that one has an astrograph with a scale of 60 arcsec/mm and a measuring accuracy of 1 micron.

The step from FK5 to IRS meant an increase of the star density by a factor of about 10. The

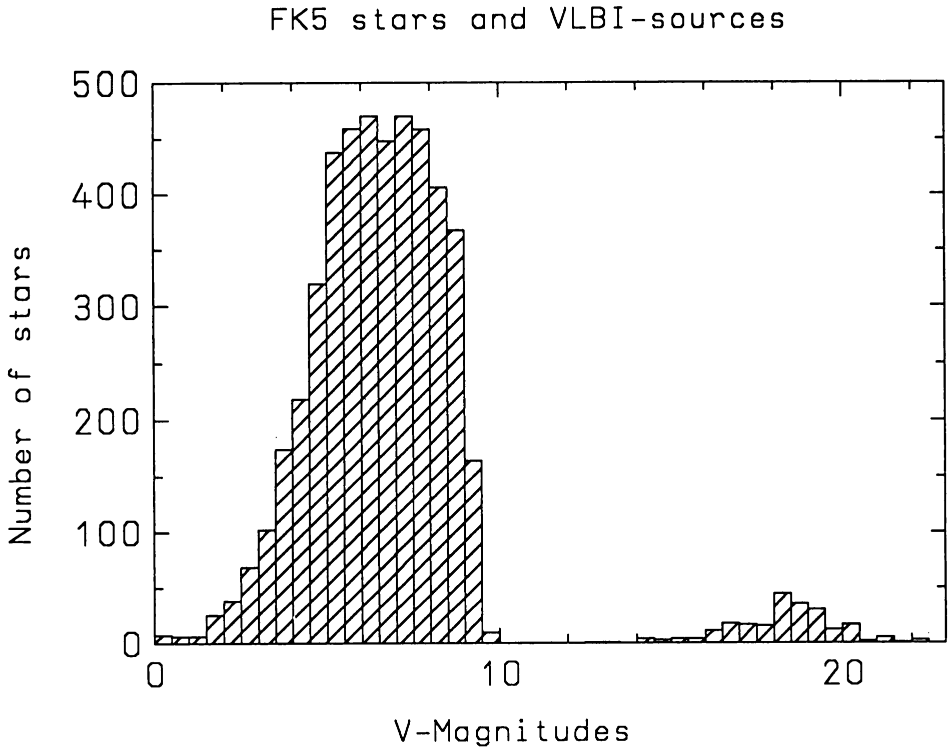

Figure 1. The distribution of V-magnitudes in the FK5 for stars brighter than magnitude V = 10 mag, and in the list of extragalactic radio sources from Argue et al. (1984) for objects fainter than V = 14 mag.

third step in this hierarchy of reference catalogues is the construction of a catalogue based on photographic astrometry with again a ten times higher star density. During the last century several large mappings of the sky with astrographs have been carried out. The first and largest in this series is the Astrographic Catalogue, an international cooperation of 20 observatories. In the northern hemisphere the observatories at Hamburg and Bonn produced AGK2 and AGK3. In the southern hemisphere we mention the CPC and CPC2, photographed at the Cape of Good Hope, and the very recently completed FOKAT-S catalogue, a collaboration of the Pulkovo observatory with Bolivian astronomers. Yale observatory has performed an almost full sky coverage, the so-called Yale Zone Catalogues. All these catalogues have in common a limiting magnitude of the plates of B = 11 to 13, with the result that the bright reference stars from IRS are not overexposed and can be measured satisfactorily. For an extensive description of all this photographic work see Eichhorn (1974).

With all this material available, new reference catalogues containing positions and proper motions for more than a quarter of a million stars could be compiled. One project, ACRS (Corbin & Urban 1991) was carried out at the USNO at Washington. This catalogue contains the above photographic catalogues with the exception of the Astrographic Catalogue and the FOKAT–S. Additionally, some 100 small-sized meridian circle catalogues went into ACRS.

Table 1. Global statistical properties of the reference catalogues discussed in this paper. FK5, IRS and PPM are published; for Hipparcos and TRC the expected year of publication is given in brackets. The columns give the names of the catalogues, the total number of stars, the number of stars per square degree, the average rms error (per coordinate) in position at epoch 1990 in milliarcseconds and the average rms error in proper motion in milliarcseconds per year.

Name		N	Stars per sq. deg.	Sig (1990) mas	Sig(P.M.) mas/year
FK5	Basic	1,535	0.04	35.	0.7
	Extens.	3,117	0.08	130.	2.6
IRS	Part 1	29,163	0.75	190.	4.2
	Part 2	7,064	0.18	290.	6.5
PPM	North	181,731	9.	270.	4.2
	South	197,179	10.	110.	3.0
Hipparcos	(1997)	120,000	3.	2.	2.0
TRC	(1998)	1,000,000	25.	30.	2.5

At the Astronomisches Rechen-Institut, Heidelberg, Roeser and Bastian constructed the PPM catalogue (Roeser & Bastian, 1991; Bastian, Roeser et al. 1993). All the photographic catalogues mentioned above plus a small number of important meridian circle catalogues were used to derive mean positions and proper motions. A description of the properties of PPM is given by Roeser & Bastian (1993). The inclusion of the Astrographic Catalogue as an accurate early epoch was decisive for the determination of proper motions of some 380,000 stars, 50 per cent more than in Part I of ACRS, which is of comparable accuracy. For the astrometric reduction of photographic plates taken at present epoch, the accuracy of the positions of PPM stars is important. Figure 2 shows the distribution of rms-errors of PPM declinations at epoch 1990. Due to the different observational history in the northern and southern hemisphere, the distribution is rather inhomogeneous. In the northern hemisphere, the distribution is bimodal. The bulk of the stars has AGK3 (around 1960) as the latest observational epoch. Present-day positions of these stars are less accurate than the positions of stars that profit from recent observations with the Carlsberg meridian circle on La Palma. In the southern hemisphere, the present-day accuracy of all stars has the same quality as the High Precision Subset in the north due to the recent epoch of the FOKAT-S catalogue. The distribution of the rms errors in right ascension look very much the same as those for declination. It is the first time in the history of astrometry that the southern hemisphere has a better quality than the northern one. In Table 1 global properties of PPM can be compared with FK5 and IRS. Comparisons of PPM positions with preliminary Hipparcos results (Turon et al. 1992) show that the error estimates in PPM are rather reliable.

Even more important than the individual accuracy of stars is the question of the inertiality of the reference catalogues. This has two aspects, the global rotation of the system and its internal

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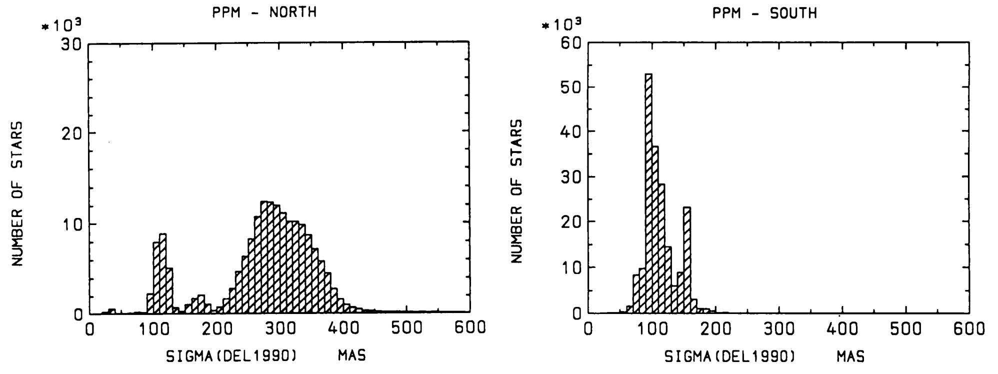

Figure 2. The distribution of individual rms-errors in declination for epoch 1990. Left: PPM-north, Right: PPM-South. Note the different scales in the ordinates. The distribution in right ascension looks essentially similar.

rigidity. The second part can be tested by comparison with the Hipparcos sphere which is assumed to be much more rigid than FK 5. Lindegren (1992) carried out such comparisons for the system of positions at present epoch for FK5 and PPM. After subtraction of a global rotation, the systematic differences between Hipparcos and FK5 are generally less than 100 mas; only in some small regions on the sky may 200 mas be reached. These values correspond to the estimates of zonal systematic accuracy in FK5.

A global rotation of the FK5 system is not easy to detect, because at present there is nothing to compare with. But some basic constants implicitly connected with FK5 can be tested as the following example illustrates. The proper motions in FK5 are consistent with the IAU(1976) constant of precession. Any change in this constant causes an induced rotation of the FK5 proper motion system. According to Fricke (1977), the rms error of the determination of this constant corresponds to 1.5 mas/year. Recent observations by VLBI and Lunar Laser Ranging techniques (see Fukushima 1991) estimate the correction to the IAU(1976) value to be -2.5 mas/year. This has to be compared with the size of the angular velocity of the Galaxy at the position of the Sun, the difference of Oort's constants A and B, which is 5.2 mas/year. So, artificial rotations of the FK5 system can be of the same order of magnitude as fundamental kinematical quantities of our galaxy. This calls for progress towards a more inertial coordinate system.

3. Towards an Extragalactic Reference System

Ground-based observations, mainly with meridian circles over more than a century, finally resulted in the construction of the FK5. Using these classical techniques, progress towards a more nearly inertial system in the next decades is ruled out. As we have seen above, FK5 is not a purely dynamically defined system. The construction of such a system would imply highly accurate, of the order of milliarcseconds or better, optical observations of stars and solar system objects over a period of at least a decade. Even Hipparcos cannot solve this problem.

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For this reason, the International Astronomical Union in its Resolution A4 (IAU 1991) recommended to move to a purely kinematically defined new reference system represented by a number of extragalactic objects. It is implied that these represent the rotation of the universe which is assumed to be zero.

In 1984, Argue et al. (1984) proposed a first list of 234 extragalactic radio sources as candidates for this new system. The visual magnitudes of the Argue sources typically range from V = 16 to V = 20 mag. Their magnitude distribution is also shown in Fig. 1. This figure illustrates the problem of implementing the coordinate system for practical usage. Now the representative objects are in the right magnitude range for large sky surveys with Schmidt telescopes, but they are only one tenth in number compared with FK5. The bridging of the gap in magnitude and the extension to more grid points is discussed in the next section. These extragalactic objects meanwhile have been observed using VLBI techniques by groups at GSFC, JPL, and USNO. As an example, Ma et al. (1990) published the observations of 182 sources with typical internal rms errors < 1 mas. In the same paper, a first link between radio positions of the QSOs and the optical positions of the FK5 stars is reported. Three steps are needed for this link. First, IRS is taken as representative of FK5. Second, with astrographs, intermediate stars of 12th to 14th magnitude are measured and reduced with IRS as reference. In the third step, those are used to reduce the Schmidt plates around the positions of the optical counterparts of the VLBI sources; 28 sources were treated by this procedure, too few to show any internal systematic inconsistencies in the FK5 system.

On an annual basis the International Earth Rotation Service (IERS) is collecting VLBI observations from various groups and is compiling a catalogue. In its annual report for 1992 (IERS 1993) a total of 504 sources is listed with internal positional accuracies from 0.25 mas to 3 mas, 10 per cent of the sources show rms errors larger than 3 mas. The distribution of sources on the sky is shown in Fig. 3. As usual, the number of sources is smaller and the accuracy is less

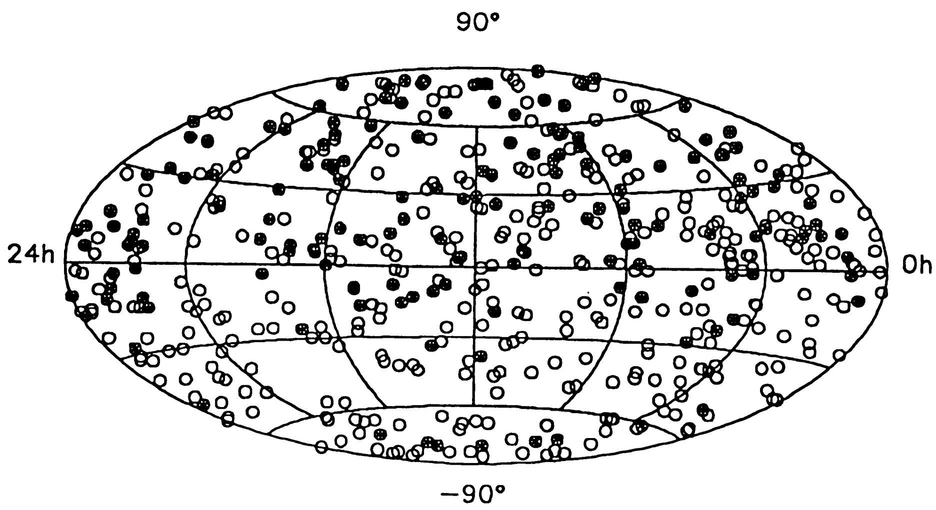

Figure 3. Distribution on the sky of 504 radio sources from IERS (1993). The filled circles represent the 158 sources with formal internal rms-errors less than 0.25 mas.

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in the southern hemisphere compared to the northern one.

A Working Group of the IAU will present a list of some 400 candidates as primary sources of the Extragalactic Reference Frame at the next General Assembly in 1994.

With these 400 sources defining the new system, practical applications such as reductions of Schmidt plates are not possible. Although having the right magnitude range, they are far too few by number. An extension to a denser net is called for. This is discussed in connection with Hipparcos, and its link to the Extragalactic Reference System in the next section.

4. Hipparcos and Tycho

After the end of the Hipparcos measurements in August 1993, one may expect the final Hipparcos catalogue in about 3 years. Despite the unfortunately bad orbit, the Hipparcos mission has turned out to be so successful that the original goals will be met or even surpassed. The global properties of the Hipparcos catalogue are also given in Table 1 for comparison. Hipparcos will supply a rigid sphere in positions as well as in proper motions, an enormous advance in rigidity, and in the number of stars compared to FK5. But Hipparcos cannot measure extragalactic sources directly. Therefore the link to the Extragalactic System must be performed by other methods.

The Tycho experiment on Hipparcos will produce a catalogue of 1 million stars brighter than B = 12 with an accuracy of 30 mas (Hoeg et al. 1992). Combining the Tycho positions with those from the Astrographic Catalogue will give proper motions of typically 2.5 mas/year. This is called the Tycho Reference Catalogue (TRC — Roeser & Hoeg 1993). Main statistics for this catalogue are also given in Table 1. The rms errors of the proper motions deteriorate the positions as one leaves the central epoch of a reference catalogue towards the future or the past. This is shown in Fig. 4. The big progress, that which Hipparcos and TRC will give for the next decades, can be clearly seen. TRC will supply a dense net of 11th to 12th magnitude stars on the Hipparcos system, quite suited for the reduction of Schmidt plates, even though fainter stars would be desirable, of course.

The Hipparcos catalogue and TRC must be linked to the Extragalactic Reference System. This can be done by three methods (Argue 1991), as follows:

1) radio stars. Many radio stars are bright enough to be observed by Hipparcos. These stars are also observed by VLA or VLBI techniques relative to the quasars of the Extragalactic System. Under the assumption that 50 radio stars are available for this link, Froeschle & Kovalevsky (1982) estimate the accuracy of this link to be 0.7 mas/yr;
2) ground-based optical astrometry of quasars. Here we have exactly the problem as can be seen from Fig. 1: bridging the gap in magnitude between Hipparcos (typically brighter than V = 10 mag) and the quasars (typically fainter than V = 16 mag). The linking can be done in the same way as in Ma et al. (1990), described above. First, wide-field astrographs are used for intermediate stars, which then are taken as references on small-field or Schmidt plates with quasars;
3) absolute proper motion surveys. The Lick Northern Proper Motion (NPM) programme is nearing completion (Klemola 1990). The programme has 19,000 stars in common with the Hipparcos Input Catalogue. In the southern hemisphere, the Yale-San Juan Proper Motion programme complements the Lick survey. It will have 12,000 stars in common with Hipparcos (van Altena et al. 1990). But this programme is only in the measuring phase, and will not be ready, when the Hipparcos catalogue will be completed.

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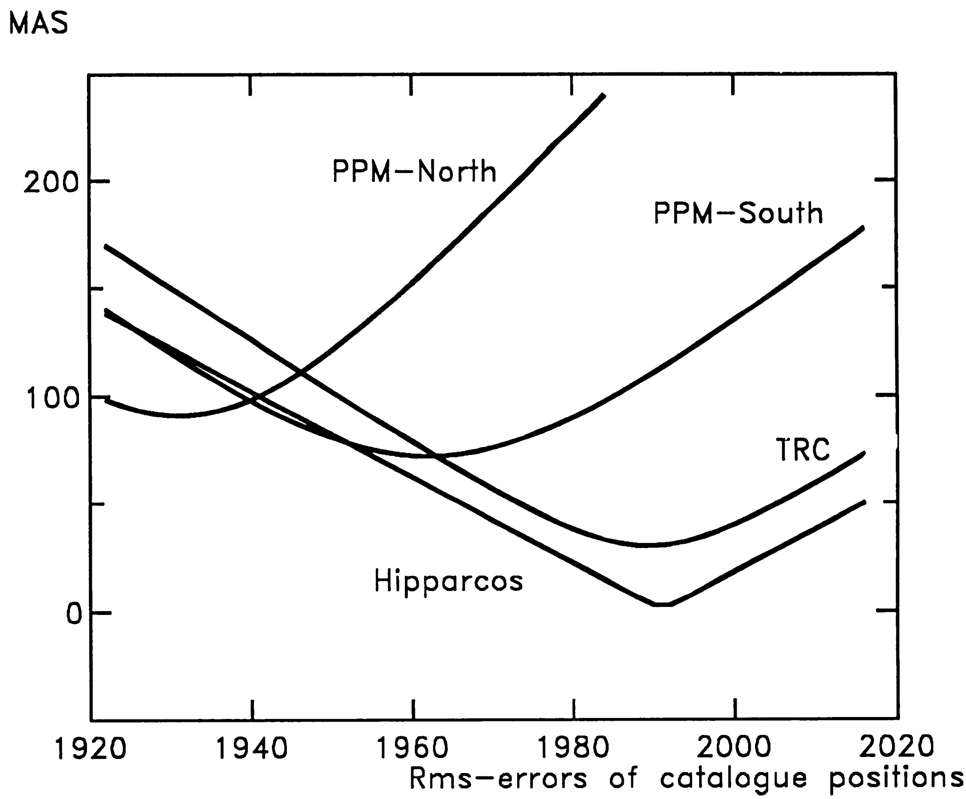

Figure 4. The rms position errors in mas (right ascension or declination) as a function of time in the catalogues Hipparcos, TRC and PPM. The progress to be expected from Hipparcos and TRC in the future can clearly be seen.

All the programmes above will give better links as time increases. At the time of completion of the Hipparcos catalogue, we expect the remaining rotation of the proper motion system of Hipparcos with respect to quasars to be less than 1 mas/year.

As a final topic, the filling of the gap in magnitude between Hipparcos and quasars by a dense net of references is touched. This can be done best by meridian circles equipped with CCDs or with telescopes like the Spacewatch telescope (Gehrels 1991). The 8-inch meridian circle at the Flagstaff station of USNO (Stone 1993) is presently equipped with a 1024 x 1024 CCD. If this instrument is operated in scanning mode, i.e. drive off, about 9000 stars per hour can be measured. The internal consistency of a star position within a typical scan is about 50 mas over a magnitude range of 5 magnitudes. At the bright end, stars are saturated; at the faint end the accuracy drops due to photon noise. Once the Hipparcos catalogue is available, these CCD scans can be accurately calibrated, and a measurement strictly relative to the Hipparcos sphere is possible with a few tens of mas accuracy. This enables us to extend the Hipparcos system of positions to fainter magnitudes.

5. Conclusions

The present celestial reference system is represented by the positions and proper motions of the 4500 FK5 stars.

This system is extended by the catalogues IRS (International Reference Stars) and PPM (Positions and Proper Motions) to higher star densities and fainter magnitudes. PPM contains a total of 380,000 stars.

This system is limited in inertiality. A remaining rotation of the frame may be of the order of 1 mas/year.

This frame cannot be significantly improved in the near future by classical astrometry.

The future kinematically defined reference system will be represented by the positions of distant extragalactic radio sources.

The forthcoming optical Hipparcos and TRC catalogues will be linked to this extragalactic reference system.

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