THE DETERMINATION OF FUNDAMENTAL PROPER MOTIONS

Thomas E. Corbin

U. S. Naval Observatory

ABSTRACT Fundamental positions and proper motions are derived from absolute catalogs. Taking recent Washington Six-Inch and Seven-Inch Transit observing programs as examples, the observation and compilation of absolute catalogs are discussed. The roles of quasi-absolute and differential catalogs in the formation of fundamental catalogs are also examined. Finally, the current effort to extend the fundamental system to fainter magnitudes than are presently represented in the FK4 is described as well as the expected composition of the forthcoming FK5 catalog.

INTRODUCTION

The stellar positions and proper motions of the Fourth Fundamental Catalog (FK4), compiled by Fricke and Kopff (1963), form the reference frame that has been the basis of celestial coordinates for the past twenty years. At their respective epochs the mean positions are quite good north of -30 degrees with mean errors of only 1 to 4 milliseconds of time in right ascension and 2 to 5 hundredths of an arcsec in declination. However, south of -30 degrees the errors are generally two to three times as great. Even so, it is not these errors that are the main sources of difficulty in using the FK4 at current epochs, but rather the 60 to 75 years of proper motion that must be applied to the majority of the stars. For example, using the formal errors listed in the FK4, an error of 0.18 arcsec is to be expected at 1985 for star 452. Of this amount 0.17 arcsec is due to proper motion. In addition to this, modern observations have shown that the systematic and individual errors of the FK4 proper motions published in the FK4 are considerably larger than had been estimated, especially in the Southern Hemisphere (Schwan, 1985). This situation, combined with the early epochs of the FK4 positions, led Fricke and Gliese (1968) to propose the preparation of an FK5.

D. S. Hayes et al. (eds.), Calibration of Fundamental Stellar Quantities, 53–70.

A new fundamental catalog would not only take advantage of recent observations to reduce both random and systematic errors, but would also extend the fundamental catalog in its range of magnitudes and improve its distributions of stars over the celestial sphere. The improvement of the FK4 positions and motions involves three stages: 1.) The zero points of the system are redefined to more accurately represent the dynamically defined fundamental reference frame. To achieve this, absolute catalogs of observed stellar positions are required. These are also often referred to as fundamentally observed catalogs. 2.) Systematic errors of the FK4 positions and motions that cause distortions of the reference frame must be corrected. This step requires absolute and quasi-absolute catalogs. 3.) The individual random errors of the FK4 positions and motions are reduced through the application of the observed positions in absolute, quasi-absolute and differential catalogs. In addition, an extension to fainter magnitudes and an improved distribution of fundamental stars over the sky was proposed by Fricke (1973) and will involve the addition of stars from the "Catalog of 1987 Supplementary Stars to FK4" (FK4 Sup), Fricke (1963) and from the list of International Reference Stars (IRS), Scott (1962). It is the purpose of this review to discuss how absolute observations are currently made, how these are combined to produce absolute star positions and how these positions may be used to yield fundamental positions and proper motions. In addition, the role that the FK4 Sup and IRS stars can play in the FK5 will be examined.

1. OBSERVATIONS

It is appropriate to discuss the observations first because not only are they the first step in the process of determining fundamental positions and motions but also they are the most important. The ultimate quality of the fundamental catalog depends on observed absolute positions that are as free as possible of instrumental error and that are part of a program that has been conducted in such a manner as to allow the determination of a reference frame that is independent of existing catalog positions. Since transit circle observations have determined the reference frame in the past and will do so again in the FK5, they will be discussed here.

In order to make absolute observations the orientation of the telescope must be accurately known. In the Washington programs, the collimation, level, nadir point with respect to the local gravity and azimuth are measured every two to three hours, as is shown in Table I. In fact, during the W L-50 program at El Leoncito, Argentina (Hughes, Smith and Branham 1984), observers were encouraged to take the first two sets of instrumental constants after sunset only one hour apart because of the rapid temperature changes occurring then. Very small mechanical shifts in the mounting of the instrument or its optics can have serious effects on the observations if not corrected. A shift of

TABLE I

INSTRUMENTAL CALIBRATION FOR ABSOLUTE PROGRAMS

QUANTITY	FREQUENCY	ACCURACY
AZIMUTH OF MARKS	MONTHLY	±0″.08
MARKS – 1 TOUR	2 – 3 HOURS	.30
COLLIMATION	2 – 3 HOURS	.25
LEVEL	2 – 3 HOURS	.15
NADIR	2 – 3 HOURS	.35
CIRCLE –DIAM CORR	4 TIMES/PROGRAM	.07
– ONE READING	EACH STAR	.06
CLOCK CORRECTION	EACH TOUR	.10
REFRACTION	PUBLISHED TABLES	.03
TEMPERATURE	EACH STAR	.10 °C
DEW POINT	EACH STAR	1.0
BAROMETER	EACH STAR	.1 mm
VAR OF LATITUDE	BIH & SOLUTION	0″.03
FLEXURE	PROGRAM AVERAGE	.02
SCREW ERROR – RA	1 TIME/YEAR	.02
SCREW ERROR – DEC	1 TIME/YEAR	.02
PIVOT ERRORS	2 TIMES/PROGRAM	<.005
CLAMP DIFFERENCES	REVERSE MONTHLY	.02
EQUINOX CORRECTION	PROGRAM AVERAGE	.14
EQUATOR CORRECTION	PROGRAM AVERAGE	.02

only 10 microns in one of the mounting cages of the Washington Six-Inch Transit Circle can produce a shift of 2.3 arcsec in the azimuth. In addition, there are characteristics of a transit circle that need to be calibrated less frequently but with high accuracy. For example, the corrections to the divisions on the graduated circle are now measured four times during a program. In addition the circle is monitored every six months. This allows the corrections to be applied with an accuracy of 0.24 microns, corresponding to 0.07 arcsec in the pointing of the instrument in declination. (Rafferty and Klock, 1982) The instrument's pivots, micrometer screws and tube flexure must also be evaluated. Because a transit circle must operate under a wide range of environmental conditions a large number of calibrations will not necessarily lead to an accurate determination if they are not also taken over a similar range.

An example is the determination of flexure in the Washington transit circles. For many years, measures of the coefficient of the flexure were made on cloudy nights when the instruments were not otherwise occupied. However, during the recently completed W 6-50 program a flexure measure was made with each collimation. This practice has permitted an extensive examination of the behavior of the flexure covering the same range of conditions as the observations, including the important daytime observatons. Miller (1984) has found that in previous programs the flexure has been treated too simply and that if the temperature and even the rate of change of the temperature are not taken into account then errors in computing the flexure can amount to as much as ±0.55 arcsec.

In order for an observing program to produce absolute results, several requirements should be met. To obtain independent determinations of the azimuth of the instrument, observations of circumpolar stars must be made twelve hours apart. Generally, these can be made only between the autumnal and vernal equinoxes. During the other six months the meridian marks must be relied upon to monitor the azimuth. Since the marks are usually viewed through several hundred feet of air near the surface of the ground, it is important that there be one north and another south of the instrument. It has recently been determined at the Washington site that the images move several arcseconds with periods of around one or two minutes. Fundamental stars within 20 to 30 degrees of the equator should be observed at a rate of one every 30 to 40 minutes. Each night's observing should have a good distribution of these stars in declination. If the program is to contribute to the determination of the equator and equinox of a fundamental reference frame, then either the Sun, Mercury and Venus or the minor planets must be observed. It is, of course, preferable to observe both groups. Mars and Jupiter can contribute to the equator correction (Branham, 1984), but observations of Saturn, Uranus and Neptune mainly contribute to improved orbits for these objects. The Moon should also be observed. Branham concludes that, theoretically, the Moon can contribute strongly to the equinox determination, but that the difficulty of observing the lunar limb and applying the appropriate corrections reduces the lunar contribution. Finally, if the goal of a program is to provide new absolute positions for the improvement of a fundamental catalog, then each observing tour should contain stars from the catalog well distributed over declination as well as right ascension. This allows the $\Delta\alpha_\delta$ and $\Delta\delta_\delta$ terms to be corrected. In the forthcoming Washington Six-Inch/Seven-Inch program, each observing tour will contain at least two FK5 stars for every 15 degrees of declination.

2. FORMATION OF AN ABSOLUTE CATALOG

In order for a program to give absolute positions the observing tours must be reduced in such a way that the results are independent of any existing catalog. Two recent programs will serve to illustrate this process. In the W 5-50 program (Hughes and Scott, 1982) FK4, IRS from -30° to $+5^\circ$, the stars of IAU Resolution No. 17 and several small lists were observed. The observations of the azimuth stars in the September through March period served two purposes. First the upper and lower culmination observations served to establish the azimuth of the instrument independent of the FK4, and second, these same observations served to correct the stars' positions for determining the azimuth of the instrument during the summer. Averaging this value on a monthly basis, the average value of the azimuth of the marks was then determined for each similar time period. This, combined with the mark measures made during the tours allowed an azimuth independent of the FK4 to be applied to each object observed in each tour, the marks now serving as interpolating devices. At this point the right ascension system of the observations is independent of the FK4 as far as the azimuthal orientation of instrument is concerned, but is tied to the FK4 with respect to origin and systematic errors of the type $\Delta\alpha_{\alpha}$. This is because each tour has been reduced using a clock correction that is derived from the FK4 positions of the selected clock stars between +30° to -30°. However, due to the high quality of modern clocks and the accurately calibrated orientation of the instrument it is possible to pair tours either during the same night or morning-evening of consecutive nights to derive periodic corrections to the clock star system. In the Six-Inch Programs these corrections have been given the form:

$$\Delta\alpha = A \sin(\alpha) + B \cos(\alpha) + C \sin(2*\alpha) + D \cos(2*\alpha).$$

Note that this solves for periodic errors within the FK4 right ascension system but cannot correct the origin. The periodic corrections were added to each star's position and then new clock corrections were computed for each tour. Additional individual corrections to the clock stars were determined by differencing each star in a tour with the improved mean clock correction for that tour. Thus final corrections of periodic plus individual corrections could be determined for each clock star and applied. At this point final clock corrections were computed and applied to all of the observations in each tour. Since the instrument can operate with its pivots first in one position and then reversed, every object was observed in both positions. (These positions are called clamp east and clamp west.) Reversals were made monthly. Comparing the results made on the two clamp positions and averaging the results gave the final positions on the instrumental system with the FK4 equinox as the origin.

In the second case, the W L-50 observations, it was possible to determine the corrections to the positions of the azimuth stars in a much more rigorous manner. In the W 5-50 program the large number of partly cloudy nights made it necessary to combine upper and lower culmination observations of the azimuth stars on a monthly basis. At El Leoncito the many clear nights made it possible for most tours observed during the fundamental azimuth period to be paired with at least one other. This was important for two reasons: the positions of the southern azimuth stars are much poorer than those in the north and Leoncito is a seismically active area. Thus it was possible to confirm the stability of the marks over periods as short as 24 hours. Again, analysis of the paired upper and lower culmination observations resulted in corrections to the catalog positions of the azimuth stars that were linked only to the FK4 equinox. These corrections were then used to compute improved azimuths of both summer and winter tours leading to improved clock corrections for the tours. In turn, the improved clock correction was used to further refine the azimuth. In all cases three iterations of the azimuth were sufficient to reduce the change between the last two iterations to ±0.0005 second of time. Finally, the observations of the clock stars were analyzed by pairing tours only from the same night. No functional fit was assumed, but rather new corrections to the individual stars were computed relative to the nightly mean clock correction. Included in the analysis were personal equations of the observers. Surprisingly, several showed significant values for the program, ranging from $+0^{s}.017$ to $-0^{s}.012$. New clock star residuals were computed for each night by applying the individual corrections to each star, personal equations, if any, and change in the equation in the equinox. Only three iterations of this process were necessary. From this, a final value of the clock correction for each tour was derived and applied to each object observed in the tour. Again, the point is reached where the results represent a system that is independent of the FK4 except for the zero point in right ascension. The adherence to the FK4 equinox was checked by summing the final observed minus computed residuals of the FK4 stars that were not clock stars. The result was $+0^{s}.0015$.

In reductions of the declinations, the starting points are the assumed latitude of the instrument and the readings of the nadir taken each tour. The observed positions in declination are related to the zenith point through the circle of the instrument and the individual corrections to its inscribed divisions. In addition, a model of the atmospheric refraction must be applied to the observed zenith distances. In the W 5-50 and W L-50 the Pulkovo Refraction Tables were used, the third and fourth editions, respectively. The variation of latitude used in the W 5-50 was taken from the results of the Washington PZT. Errors in the assumed latitude, refraction and flexure are determined by an analysis of the circumpolar FK4 stars observed at upper and lower culmination. The success of such an analysis depends strongly on the latitude of the observing site. At the Washington site (+38° 55') it was possible to separate all three variables, and so the flexure measured from the collimators was not used. The El Leoncito site (-31° 48') is even closer to the Equator than Washington and the flexure term (sin z) becomes inseparable from the refraction (tan z), where z is the zenith distance. Thus a large number of flexure measures were made and the coefficient so determined was used without further correction. Otherwise the the same procedure was used as in the W 5-50 to compute preliminary declinations. In both programs these procedures yielded declinations independent of the FK4 system.

At this stage the results are not yet absolute. In right ascension the zero points are tied to the FK4 equinox. In declination it will be seen that residual errors in the solutions for the corrections to latitude and refraction cause the positions to be on a system that is in each case free of the FK4 but that should not be used to correct the FK4 declinations.

To make the results in each coordinate absolute, observations of solar system objects are required. In the W 5-50 the results of observing the Sun, Mercury, Venus, Mars and Jupiter were used to correct the equinox and equator of the catalog. The Sun, Mercury and Venus were observed in conjunction with FK4 stars bright enough to be seen in the daytime. These stars were used to connect the daytime observations with those made at night. The observations of Mars and Jupiter made in each tour were reduced along with the stars in that tour. Differences between the observed and ephemeris positions of the Sun and planets were then used to compute corrections to the catalog's equator, equinox and to the orbital elements of the planets and the Earth. This resulted in corrections of $+0''.431 \pm 0''.033$ in right ascension and $-0''.347 \pm 0''.032$ in declination. The right ascension correction also represents the correction to the FK4 equinox at the mean epoch of the catalog. The declination correction was used to adjust all of the declinations in the catalog by defining the final correction to the latitude, refraction and flexure. The provisional system was established by using a measured coefficient of the flexure of $+0''.0123$ and initial adjustments of the latitude and variation of latitude determined from the upper and lower culminations of the circumpolar stars. The provisional correction to declination is

$$\Delta\delta = +0''.353 - 0''.057 \tan z + 0''.012 \sin z.$$

This gives the adjustment determined at the pole. The adjustment determined at the equator, from the solar system objects, is

$$\Delta\delta = -0''.193 + 0''.015 \tan z + 0''.225 \sin z.$$

The sum of these,

$$\Delta\delta = +0''.193 + 0''.015 \tan z + 0''.225 \sin z,$$

is then the total adjustment to the declination system. This includes the correction to the preliminary value of the coefficient of the flexure, and the three values are the final corrections to the latitude, refraction and flexure, respectively. It is seen from this that the final correction to the declinations retains the location of the pole that was defined by the upper and lower culmination observations and yet brings the system into agreement with the dynamically defined equator. The W L-50 reductions generally followed the above procedure but differed in a few important details. First, and most important, the Sun and planets were not observed in this program. The minor planets Ceres, Pallas, Juno and Vesta were observed, however, and the large number of clear nights at El Leoncito permitted over a thousand minor planet observations to be taken during the six year course of the program. This strong body of data allowed Branham (1979) to conclude that equinox and equator corrections could be derived from these observations alone. Another difference was that after the provisional corrections to the refraction and latitude were applied to the declinations a catalog mean <O-C> was formed for each FK4 star and the FK4 <O-C>'s of each tour were compared to this mean. This comparison showed no zenith distance variations, but a number of tours had large zero point differences in declination relative to the mean. The average difference for each tour was applied to all of the observations. The final equinox correction derived from the minor planets is $+0''.713 \pm 0''.138$, and the equator correction is $-0''.056 \pm 0''.016$. Again, the equator correction was used to correct the latitude and refraction in such a way that the fundmentally determined pole remains unchanged and the correction at the equator is $-0''.056$.

3. FUNDAMENTAL POSITIONS AND PROPER MOTIONS

The intention of the somewhat lengthy discussion above, illustrating how absolute catalogs are observed and reduced, has been to stress the necessity of freeing the results from systematic error as much as possible and rigorously relating them to a dynamically defined inertial system. If these processes are not successfully carried out, no amount of analysis or modeling can prevent a catalog's results from adversely affecting a fundamental catalog if they are included in the solutions for the fundamental system. This has become especially true in the past twenty years when there have been so few observatories producing absolute results.

3.1 Determination of the Equinox and Equator

The system of FK4 positions and proper motions, combined with Newcomb's precession, define a reference frame at any given dates of epoch and equinox. Using absolute catalogs it is possible to compare the FK4 at the date of each catalog with the FK4 stars in that catalog in order to evaluate the corrections needed to the FK4 equinox and equator. Relying primarily on observations of the Sun made at Cape, Greenwich, Washington, Ottawa, Breslau and Pulkovo in combination with results of lunar occultations and minor planet results, Fricke (1982) compared the FK4 equator and equinox with absolute determinations over a range of epochs from 1906 to 1971. Figure 1 shows this comparison. Fricke found that not only does the right ascension zero point represented by the FK4 at 1950.0 need correction, but that the the correction is also epoch-dependent. Thus the error in the FK4 equinox is found to be

$$E(T) = +0^{s}.035 \pm ^{s}.003 + (0^{s}.085 \pm ^{s}.010)\ (T - 19.50)$$

where T is in centuries from 1950. A similar study of the FK4 equator showed no need for correction. Thus the absolute catalogs are used to correct the zero points of the fundamental system. It should be noted that the correction derived to the FK4 equinox is really defined only over the range of declinations covered by the Sun and Moon, but is assumed to apply at all declinations. Deviations from this assumption are corrected at a later step. (See section 3-b.)

Correcting the FK4 equinox in order to define that of the FK5 has the great advantage of making the transition to an improved fundamental system with as little discontinuity as possible. However, Smith (1985)

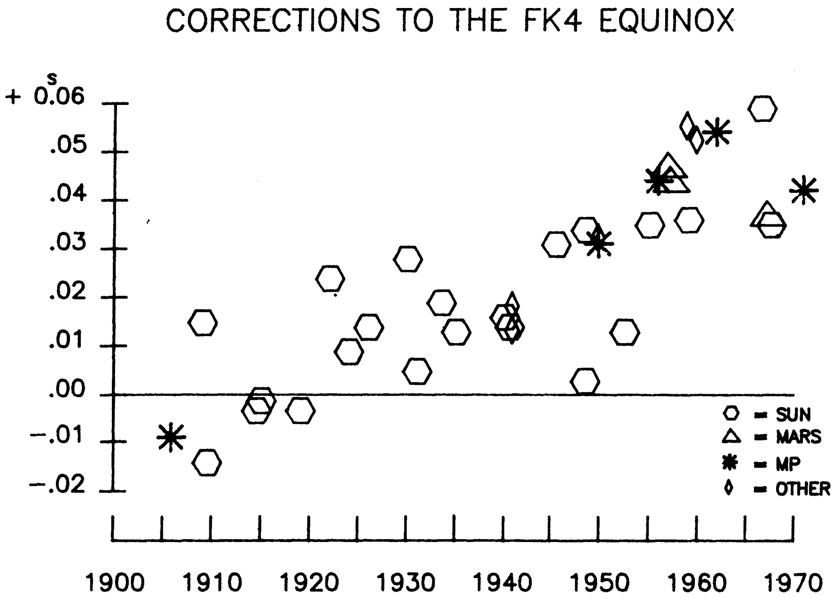

Fig. 1. Corrections to the FK4 equinox plotted by epoch. (Data from Fricke, 1982)

---

points out that new observing programs will make an independent fundamental catalog possible. Currently the U. S. Naval Observatory is making preparations to observe the FK5 and the IRS in a simultaneous program involving the Six-Inch Transit Circle in the Northern Hemisphere and the Seven-Inch Transit Circle in the Southern Hemisphere (Hughes, 1982). The Sun Moon, planets and minor planets will also be observed, and one of the intended results of the program will be absolute positions of the FK5 and IRS stars. With estimated mean epochs around 1989 these positions could be combined with the other absolute catalogs observed after 1900 to produce an independent fundamental catalog. In this case the zero points would be determined by first removing the effect of the error in Newcomb's value of the lunisolar precession (Fricke, 1977) from each of the absolute catalogs. This is done by precessing the observations of the Sun, planets and minor planets to the date of observation with the precession that was used to compile the catalog and then precessing to J2000. Using a modern ephemeris, new solutions for the equinox and equator corrections are made. Also, other time-dependent corrections can be made at this point, eg. elliptic aberration and inaccuracies in the variation of latitude that was initially applied to the catalog observations. The mean observed positions of the stars are brought to J2000 by the same route and the equator and equinox corrections applied. The zero points of the fundamental reference frame are then defined at any given epoch by combining all of the corrected catalogs and solving for the mean positions and proper motions.

3.2 The Fundamental Mean Positions and Proper Motions

Thus far the discussion has centered about the absolute catalogs for only they can define the zero points of the fundamental frame. Once these points are established, however, the quasi-absolute catalogs can make a valuable contribution to the fundamental system. The quasi-absolute catalogs are observed and reduced in much the same manner as the absolute catalogs. However, they lack the observations of solar system objects required to make the solutions for the corrections to the equinox and equator and so cannot contribute to defining the zero points of the fundamental system. These catalogs are independent of the FK4 otherwise and as such can help define the corrections to the FK4 system once they are brought into agreement with the improved equinox and equator. A combination of the absolute and quasi-absolute catalogs will result in the definition of the fundamental system over the entire sky. Now the zero point of the right ascension system is defined not only at the equator but at all declinations. This is only possible if the catalogs have been observed and reduced in such a way that errors of the form $\Delta\alpha_\delta$ have been avoided. Again, the dependence of the fundamental system on proper observational and reduction techniques is seen.

3.3 The Final Mean Positions and Proper Motions

Unfortunately the majority of observed catalogs of stellar positions are neither absolute nor quasi-absolute but are differential. A good example is the AGK3R (Scott, 1963), which contains the northern half of the IRS. A differential catalog is one in which a list of stars is observed in conjunction with fundamental stars. The orientation of the instrument is determined each observing tour, but this is to assist in bringing the observations into the system of the fundamental catalog. When reductions are made the purpose is to duplicate the fundamental system as closely as possible in the observed positions of both the fundamental and list stars. This is not to say that the positions of the fundamental stars are reproduced, but rather the goal is to adhere to the fundamental system in an average way in each part of the sky. Within this average there are differences between the observed positions of the individual fundamental stars and their catalog positions. Thus while differential catalogs cannot contribute to improving the fundamental system, they can help improve the positions and motions of the individual stars within the system. In order to do this a differential catalog must be first brought into the improved fundamental system that has been defined by the absolute and quasi- absolute catalogs. To accomplish this the positions of the improved system are brought to the equinox and individual epochs of the fundamental stars' observed positions in the differential catalog. Individual differences are then computed and these are averaged to give systematic differences over regions of the sky. Right ascension and declination differences are treated separately. Bien et al. (1978) have developed a very elegant treatment of this problem which not only functionally maps the differences with respect to right ascension and declination but also with respect to magnitude. The systematic differences are then applied to the observed positions in the differential catalog to bring it into the improved fundamental system. At this stage the catalog can assist in determining the mean positions and proper motions of the individual stars within the improved system. The data from the absolute, quasi-absolute and differential catalogs are then combined to give the final mean positions and proper motions of the improved fundamental catalog. Table II summarizes the attributes of these three types of catalogs.

TABLE II

CHARACTERISTICS OF OBSERVED CATALOGS

TYPE OF CATALOG	OBSERVATIONS REQUIRED	CONTRIBUTION TO THE FUNDAMENTAL SYSTEM
ABSOLUTE	CONSTANTS 2 – 3 HOURS MERIDIAN MARKS FUNDAMENTAL AZIMUTH PAIRED CLOCK CORRECTIONS SOLAR SYSTEM OBJECTS FLEXURE MEASURES CIRCUMPOLAR SOLUTION FOR LATITUDE AND REFRACTION	EQUINOX & EQUATOR CORRECTION OF SYSTEMATIC ERRORS IN THE EXISTING SYSTEM IMPROVEMENT OF MEAN POSITIONSITIONS AND PROPER MOTIONS
QUASI–ABSOLUTE	SAME AS ABSOLUTE EXCEPT SOLAR SYSTEM OBJECTS ARE NOT OBSERVED	SAME EXCEPT DO NOT CONTRIBUTE TO EQUATOR & EQUINOX
DIFFERENTIAL	INSTRUMENTAL CONSTANTS AZIMUTH AND CLOCK STARS FUNDAMENTAL STARS AS PART OF THE OBSERVING LIST	IMPROVEMENT OF MEAN POSITIONS AND PROPER MOTIONS

4. THE FAINT FUNDAMENTAL EXTENSION

The stars in the FK4 as a group have better observing histories than any others that could be used to define a reference frame. They also are bright with apparent magnitudes that average 4.85. In fact, only 13% of the FK4 is fainter than apparent magnitude 6.0. This situation has often made it difficult to use the FK4 because the objects to be referred to the FK4 system are usually somewhat fainter than this. Another difficulty is that the distribution of FK4 stars over the celestial sphere is not even. These conditions exist because the growth of the fundamental catalog from Auwers' FC (1879) with 539 stars to the FK4 with 1535 stars has generally been controlled by the lists of stars that the observatories happened to select for their programs. Until the appearance of the FK4 Sup there has never really been a list to guide observing efforts toward the requirements of future fundamental catalogs. Fricke (1973) realized that the FK5 would afford the best opportunity to both extend the magnitude range of the fundamental system and improve the distribution over the sky. An extension would also help focus observing efforts. The extension stars are to be selected from two lists: the FK4 Sup and the IRS. The FK4 Sup contains almost 1100 stars in the range 5.5 > m > 6.5 out of a total of 1987 stars. The IRS on the other hand has 32,000 stars in the range 7.0 > m > 9.0, or 84% of the total. (See Table III.)

TABLE III

CHARACTERISTICS OF THE IRS

MAGNITUDE		SPECTRAL TYPE	
< 6.5	0.9 %	B & O	2.6%
6.5 – 7.0	4.1	A	12.8
7.0 – 7.5	9.2	F	14.3
7.5 – 8.0	16.4	G	17.3
8.0 – 8.5	26.4	K	49.7
8.5 – 9.0	31.6	M & OTHER LATE TYPES	3.2
9.0 – 9.5	11.0		
9.5 –10.0	0.5		

FAINT FUNDAMENTAL CANDIDATES
SOUTH OF –30 DEGREES DECLINATION

MAGNITUDE		SPECTRAL TYPE	
< 6.5	0.3 %	B & O	0.6 %
6.5 – 7.0	1.7	A	5.0
7.0 – 7.5	17.6	F	10.7
7.5 – 8.0	33.2	G	18.6
8.0 – 8.5	30.3	K	60.2
8.5 – 9.0	12.6	M & OTHER LATE TYPES	4.8
> 9.0	4.4		

In addition each of these catalogs is generally composed of the best-observed stars in its respective magnitude range. During the past year the U. S. Naval Observatory has selected a list of 2160 Faint Fundamentals in collaboration with our colleagues at the Astronomisches Rechen-Institut. These are IRS stars in the magnitude range 6.5 to 9.5. To select the stars the sky was divided into blocks of 22 square degrees. The IRS star with the best observational history was usually chosen, although considerable effort was given to balancing the distributions in apparent magnitude and spectral type as well. In the Southern Hemisphere the selection was rather difficult to make. The primary reason for this can be seen in Figure 2. South of -30 degrees the observational histories of the IRS are poor. Whereas in the north only 4% of the stars selected

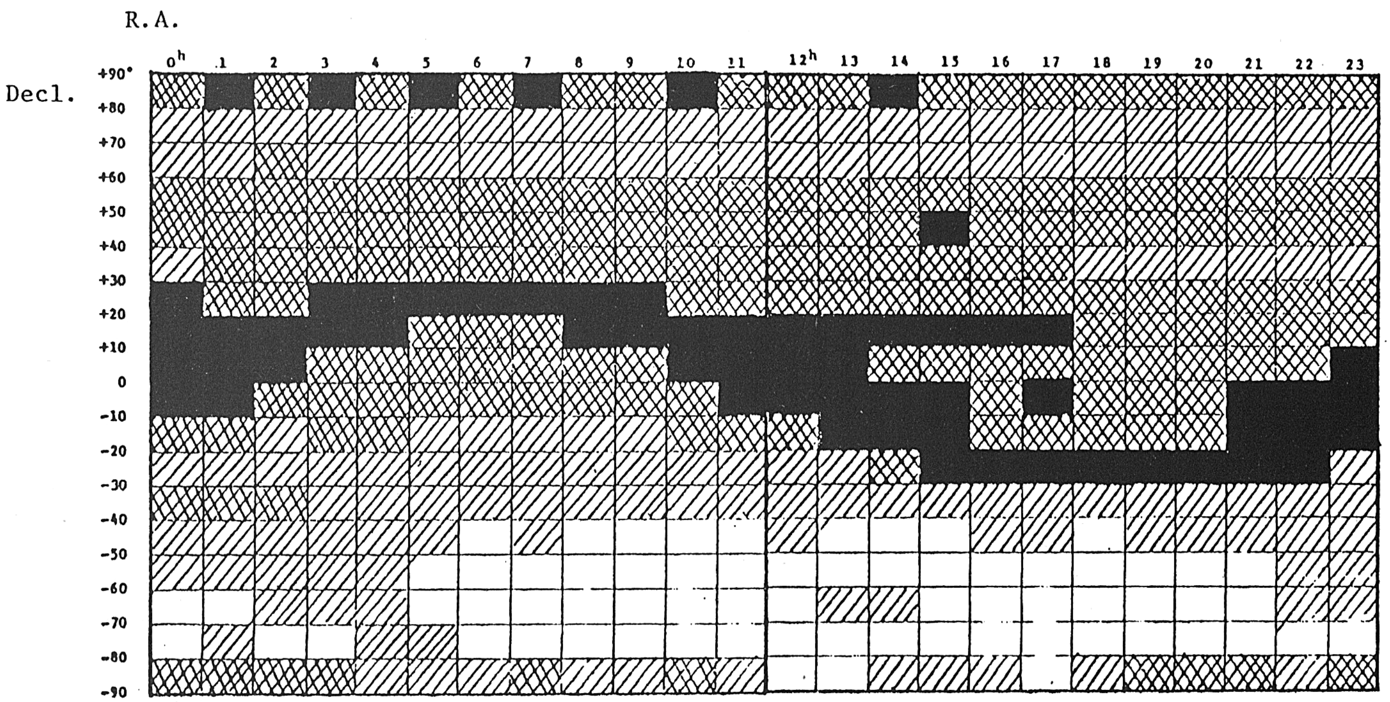

Fig. 2. The observational histories of the International Reference Stars. The averages are for blocks of 1^h in right ascension by 10° in declination.

CODE

■ = 5 OR MORE CATALOG POSITIONS PER STAR

▧ = 3 TO 4

▦ = 4 TO 5

□ = 3 OR LESS

have observational histories of 5 catalog positions, in the south 30% of th stars chosen have histories of 4 or 5 catalogs, mostly from the zone south of -30 degrees. It was also difficult to select a list that was balanced in magnitude and spectral type in this part of the sky. A look at Table III shows the reason; the IRS south of -30 deg., selected at the Cape Observatory, is heavily populated with late-type stars and concentrated in the 7.5 < m < 8.5 range. Stars within one degree of an FK4 star were generally not selected, and double stars with separations under 50" and a magnitude difference $m_2 - m_1 < 4.0$ were also excluded. In the polar regions additional stars have been selected in order to provide sufficient stars for evaluating $\Delta\alpha_\alpha$ terms in making catalog comparisons. The general characteristics of the Faint Fundamental list are shown in Table IV.

TABLE IV

CHARACTERISTICS OF THE FAINT FUNDAMENTAL LIST OF 2160 STARS

MAGNITUDE		SPECTRAL TYPE	
< 6.5	0.8 %	B & O	6.3 %
6.5 – 7.0	9.0	A	19.7
7.0 – 7.5	20.1	F	16.8
7.5 – 8.0	21.4	G	19.8
8.0 – 8.5	22.0	K	32.5
8.5 – 9.0	19.9	M & OTHER LATE TYPES	4.9
9.0 – 9.5	6.9		

INTERVALS OF MEAN ERROR OF PROPER MOTION ("/CENT)

	0.0/0.1	0.1/0.2	0.2/0.3	0.3/0.4	0.4/0.5	0.5/0.6	>0.6
RA	2 %	14 %	37 %	29 %	13 %	5 %	1 %
DEC	1	11	34	32	15	6	1

AVERAGE MEAN ERRORS OF THE PROPER MOTIONS

RIGHT ASCENSION: 0.31 ARCSEC/CENTURY
DECLINATION: 0.33 ARCSEC/CENTURY

The selection of the FK4 Sup stars for the extension has yet to be made. It is intended that about 1200 of these stars will be included in the FK5. The anticipated result of combining the FK4, 1200 FK4 Sup stars and the selected 2160 Faint Fundamentals is shown in Figure 3. Such a list should greatly improve the capability of the fundamental system to provide a reference frame at least to the ninth magnitude with a good distribution of stars in all parts of the sky.

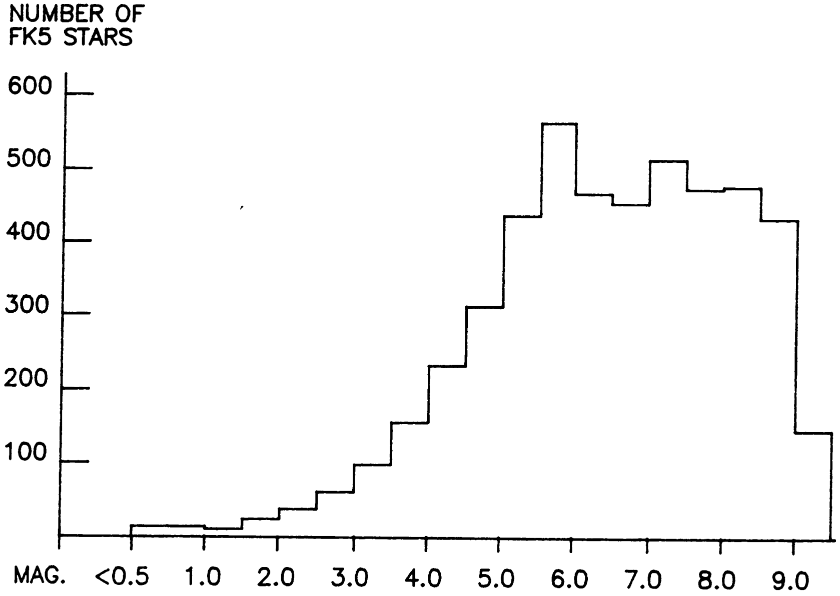

Fig 3: Predicted distribution of magnitudes in the FK5 from combining the FK4, Faint Fundamentals and 1200 FK4 Sup stars.

Finally, it is important to point out that the extension stars cannot be used to define the system of the FK5. They do not have sufficiently extensive observational histories to have their positions and motions determined from only the absolute and quasi-absolute catalogs. Although the FK4 Sup stars are better represented in these catalogs than the Faint Fundamentals, they have nevertheless received special attention in the observing programs for only about the past 20 years. Thus the extension stars will have their FK5 positions and motions computed by first reducing their observed positions in catalogs to the FK4 system. These positions will then be used to compute positions and motions on the FK4 system for the extension stars. The improved positions and motions (FK5 system) of the FK4 stars will be compared to the FK4 in order to define the conversion from FK4 to FK5, and this conversion will then give the positions and motions of the extension stars on the FK5 system.

5. THE RADIO FRAME

In recent years it has become clear that radio interferometry has the potential to make a substantial contribution to the fundamental reference frame. There is no doubt that a selected list of radio sources with optical counterparts at great distances that are not affected by 1. noticeable proper motion, 2. time variable structure such as jets or hot spots which develop, radiate intensely and then disappear, 3. wavelength dependent differences in the location of the radio-image center or 4. other astrometrically unacceptable characteristics such as the eccentricity of the radio image relative to the optical image, could provide an order of magnitude improvement in the precision of the fundamental reference frame defined in terms of those individual sources. Such a frame, however, must be linked with the stellar and planetary systems of observations. At present there is a program underway to do just this. First, transit circle observations are made of reference stars that surround selected radio sources (Dick and Holdenried 1982). Next, these fields are photographed with the USNO twin 20-cm astrograph. The star positions from these plates then provide a reference for the USNO 1.55-m astrometric reflector, which is capable of photographing the faint optical counterparts of the radio sources (Harrington et al., 1983). This effort is guided by the lists provided by the IAU-Commission 24 Working Group on Optical / Radio Astrometric Sources for the Establishment of an Inertial Reference Frame (Witzel et al., 1982). In the future, the proposed Hipparcos and Space Telescope astrometry may be able to provide such a link with the radio system at a very high level of accuracy. Indeed, optical positions at accuracies better than 0.01 arcsec will be needed if the full potential of the radio system to contribute to the fundamental reference system is to be realized.

6. ACKNOWLEDGEMENTS

I would like to thank our colleagues at the Astronomisches Rechen-Institut, especially W. Fricke and H. Schwan, for many useful discussions and exchanges of information concerning the FK5 and the Faint Fundamental stars. I would also particularly like to thank the following U. S. Naval Observatory personnel: C. Smith, J. Hughes and S. Gauss for their many helpful comments and discussions during the preparation of this paper, and E. Holdenried, R. Miller and T. Rafferty for their help in the preparation of Table I.

REFERENCES

Bien, R., Fricke, W., Lederle, T. and Schwan, H. 1978, Veroff. Astron. Rechen Inst. Heidelberg, **29**.

Branham, R. 1979, Astron. J., **84**, 1399.

Branham, R. 1984, "Equator and Equinox Determinations from Simulated Planetary Observations", in press.

Dick, S. and Holdenried, E. 1982, Astron. J., **87**, 1374.

Fricke, W. 1963, "Preliminary Supplement to the FK4 (FK4 Sup)," Veroff. Astron. Rechen Inst. Heidelberg, **11**.

Fricke, W. 1973, Mitteilungen des Astron. Rechen Inst. Heidelberg, Serie A, No. 68.
Fricke, W. 1977, Veroff. Astron. Rechen Inst. Heidelberg, **28**.
Fricke, W. 1982, Astron. Astrophys., 107, **L13**.
Fricke, W. and Gliese W. 1968, Highlights of Astronomy, ed. L. Perek (Reidel: Dordrecht), p. 301.
Fricke, W. and Kopff, A. 1963, "Fourth Fundamental Catalog (FK4)," Veroff. Astron. Rechen Inst. Heidelberg, **10**.
Harrington, R., Douglass, G., Kallarakal, V., Smith, C. and Guetter, H. 1983, Astron. J., **88**, 1376.
Hughes, J. 1982, Southern Stars, **29**, 245.
Hughes, J. and Scott, D. 1982, "Results of Observations Made with the Six-Inch Transit Circle 1963-1971," Publ. U.S. Naval Obs., Ser. 2, part III.
Hughes, J., Smith, C. and Branham, R. 1984, "Results of Observations Made with the Seven-Inch Transit Circle at El Leoncito, Argentina 1967-1973," Publ. U.S. Naval Obs., in preparation.
Miller, R. 1984, private communication.
Rafferty, T. and Klock, B. 1982, Astron. Astrophys., **114**, 95.
Schwan, H. 1985, in IAU Symposium 109, Astrometric Techniques, ed. H.K. Eichhorn (Reidel, Dordrecht), in press.
Scott, F.P. 1962, Astron. J., **67**, 690.
Scott, F.P. 1963, "The System of Fundamental Proper Motions," in Basic Astronomical Data, ed. K. Strand, (Univ. of Chicago Press, Chicago), p. 11.
Smith, C. 1985, IAU Symposium 109, Astrometric Techniques, ed. H.K. Eichhorn (Reidel, Dordrecht), in press.
Witzel, A. and Johnston, K. 1982, Abhandlungen aus der Hamburger Sternwarte, Band X, Heft 3.

DISCUSSION

GLIESE: T. Corbin mentioned the weakness of the FK4 in southern declinations (declinations < -50°). I will not discuss here the possible sources of such errors. Only one point: we have fairly reliable catalogues of absolute positions observed since 1960 but probably not only is the fundamental proper motion system south of -50° in the FK4 erroneous but also the positions at the mean epoch of the FK4 system (at about 1930). We need these positions again for deriving the proper motion system of the FK5. Therefore, I have some doubt whether we may succeed in producing an "ideal" proper motion system for the FK5 even if the system of positions of the FK5 should be correct at its mean epoch.

CORBIN: The effect that Dr. Gliese refers to is found mostly in the early catalogues, in which the stars were observed as they passed by fixed wires. Since these observations were not usually made using screens to dim the light of the bright stars, the observer's judgement as to when a star crossed each wire was often affected by the magnitude of the star - whence the term "magnitude equation" in these catalogues.

WILLS: Hipparcos will measure about 100000 stars of magnitude down to about B = 12 and after 2.5 years of observation will provide for stars of B = 9 positions and parallaxes accurate to 0.002 seconds and proper motions accurate to 0.002 seconds/year.

POPPER: Why is it necessary to observe solar system objects for defining the equator in addition to the definition of the pole using circumpolar stars. Diffraction? Too large an arc to measure?

CORBIN: The upper and lower culmination observations define the pole, but for purposes of contributing to the equator solution of the fundamental system it is best to use the dynamically defined value derived from observations of solar system objects because: 1) Flexure north and south of the zenith is not necessarily the same. 2) The same may be true of refraction. 3) The equator may not be 90° from the pole as measured by the circle of the instrument. Thus using the solar system objects as well as circumpolar observations defines the declination in a fundamental way at two points on two sides of the zenith and is a much stronger solution.

POPPER: Are recent techniques, such as photoelectric timing of transits and an Atkinson type instrument being introduced or do they represent too great a departure from the techniques used previously?

CORBIN: The instrument that observed the Perth 70 Catalogue had a photoelectric micrometer that employed a series of slits. This instrument was quite successful - especially in right ascension. The U.S. Naval observatory is about to begin a program with the 7" transit circle in New Zealand in which an image disector will replace the observer. The El Leoncito program has shown that it is very desirable to replace the observer with a detector because the observer generates heat and the observers show personal equations, especially in right ascension in spite of the "impersonal" micrometer.

FRACASTORO: I agree that photoelectric multislit measures with transit instruments are much more precise than the so called impersonal measurements.

BESSELL: Is there any published measurement of the relative reliability of the various southern catalogues, i.e. G. C., Cape, New Yale, Sydney?

CORBIN: Not really. This has been one of the great problems in the southern hemisphere. A comparison using Perth 70 would give differences around epoch 1970, but for a definitive comparison, especially for the proper motions in these catalogues, one should wait for the southern IRS Catalogue. I hope this will be available within a year.