FAINT REFERENCE STARS

Thomas E. Corbin and Sean E. Urban

U.S. Naval Observatory

ABSTRACT: Three major reference star projects have been completed recently at the USNO: the Southern International Reference Stars (SIRS - 19,827 stars) the southern part of the Faint Fundamentals (1,169 stars) and the Astrographic Catalog Reference Stars (ACRS - 325,416 stars). The compilation of the mean positions and proper motions of each is discussed. Reports on the progress of the USNO's Pole-to-Pole Fundamental Program and the Working Group on Star Lists are also presented.

I. Introduction

For many years the U. S. Naval Observatory has contributed to the stellar positions and motions of the reference frame in two ways: Absolute observations, primarily of the fundamental stars, have been made on the USNO's transit circles, in particular the Six-Inch, since the beginning of this century. Both absolute and differential observations of large numbers of reference stars in the sixth through ninth magnitude range have been made on the Six-Inch, Seven-Inch and Nine-Inch. Since 1940 the reference star observations have been directed toward lists of evenly distributed stars with an average density of about one star/square degree. In the 1950's the USNO joined the Bergedorf, Bordeaux, Herstmonceux, Heidelberg, Nicolaiev, Ottawa, Paris and Pulkovo observatories in a cooperative program to observe the AGK3R (Scott 1963) in order to provide reference stars for the AGK3 (Dieckvoss 1975). This work was carried to the Southern Hemisphere in the 1960's and early 1970's in order to provide the Southern Reference Stars (SRS - Scott 1962) for the Cape astrograph plates. In this endeavor the USNO collaborated with Abbadia, Bordeaux, Bucharest, Nicolaiev, San Fernando and Tokyo in the north and Bergedorf (at Perth), Cape, Pulkovo (at Santiago), San Juan and Santiago in the south.

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The AGK3R was compiled on the FK4 system by the USNO (Scott and Smith 1971) and resulted in positions for 21,499 reference stars north of -5°. It had been realized by Scott (1962) that the AGK3R - SRS lists were more than just reference stars for particular astrographic programs. These lists had been chosen with care to ensure even distribution over the sky, and to give preference to the stars with the best observational histories. A large contribution to both AGK3R and SRS was made by the KSZ stars, compiled by Zverev (Scott 1955). The KSZ lists were originally compiled at Sternberg Astronomical Institute. Revisions to the original KSZ stars were made by Zverev at Pulkovo. At Pulkovo, Zverev replaced stars fainter than magnitude 9.1, and deleted stars with inappropriately large proper motions (Zverev 1956). The AGK3R and SRS were selected by international agreement. Thus Scott referred to the combined lists as the International Reference Stars (IRS) and envisioned a wide range of applications.

If these applications were to be realized, then the IRS needed good proper motions. Combining 97,624 meridian circle positions from 64 catalogs, Corbin (1978) compiled mean positions and proper motions for 20,194 of the AGK3R stars in the IRS. The average mean errors of the proper motions are 0".45/c in right ascension and 0".46/c in declination. Proper motions for the SRS portion of the list had to await the completion of the SRS catalog.

Fricke (1973) realized that the IRS could also be used to select stars for an extension of the fundamental catalog in the seventh to ninth magnitude range. Kopff (1954,1956) had first put forth a list of stars with which to extend the fundamental list in the FK3 Supp. These stars have been well observed in the intervening years, and about 1000 will be used for the extension to the FK5. However, very few of these stars are fainter than magnitude 7.0, and thus to extend the fundamental system to the ninth magnitude, it was necessary to select from the IRS. Using the results of the NIRS and preliminary results for SIRS, Corbin (1985) selected 2072 stars for the Faint Fundamental list. A small revision changed this to 2158 stars, and this list was transmitted to Fricke in 1986. However, the positions and motions in this list were final only for the northern portion since the final southern values had to await the completion of the southern IRS (SIRS).

In recent months there has been good progress toward improving the system of faint reference stars. Work on the SIRS and southern Faint Fundamentals has been completed. In addition, the IRS has been used to compile a high density reference star catalog, the Astrographic Catalog Reference Stars (ACRS), that contains 325,416 positions and motions of stars to the tenth magnitude and covering the whole sky. Finally, the Working Group on Star Lists (IAU Commissions 8 and 24) has been considering the question of how to extend the system of reference stars to even fainter magnitudes.

II. The Southern IRS

With the completion of the Southern Reference Star catalog (Smith et. al. 1989), it was possible to begin work on the proper motions of these stars. While the observational histories of the stars in the SRS are somewhat poorer than those in the AGK3R (Corbin 1986), this is partly offset by the epoch of the SRS being about ten years later than AGK3R. As in the north, the problem was to reduce the stars fainter than the sixth magnitude in each catalog to the system of the FK4.

A. The Southern Base System (SBAS): In the Northern Hemisphere it was possible to compare the FK4 directly with ten catalogs for which screens had been used in making the observations. This permitted a system of 5590 faint star positions and motions to be compiled that provided the basis for the reduction of the 54 other catalogs. This was called the Base System, or BAS (Corbin 1974). Unfortunately, the observational data in the Southern Hemisphere are such that this can be done only north of -30°. Table 1 shows the southern catalogs that can be compared directly with the FK4. Combining these catalogs with the SRS produced a system of 3801 stars with proper motion mean errors of ±0".38/century in each coordinate. Table 2 shows the the resulting numbers of SBAS stars by declination. Quite clearly, no systematic reductions in the far south are possible with these stars. Something additional is required.

TABLE 1. Catalogs used for the SBAS

Catalog	Number of Stars in SRS
AGK2A	1039
AGK3R	3360
Albany 10	1801
Bonn 00	283
Cape II-50	1092
Katalog von 3,356 Schwachen Sternen	234
San Luis 1910	2082
SRS	20488
Tokyo Zodiacal 1950	681
Washington 00	1363
Washington 20	1130
Washington 25	784
Washington 40	741

TABLE 2. Numbers of SBAS by 10° Zones of Declination

Declination	-80	-70	-60	-50	-40	-30	-20	-10	0	+10
no. of stars	105	12	17	91	330	281	416	534	1091	924

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B. Removal of Magnitude Equation South of -30°: The situation described above required that the FK4 be included in determining the systematic differences south of -30°. Schwan's Analytical Method (1986) of making systematic reductions gives very good results when the reference stars cover the magnitude and declination ranges of the catalog to be reduced. Unfortunately, such is not the case in this instance. The faint stars (SBAS) do not cover the declination range and the FK4 does not cover the magnitude range. The solution to this dilemma was found in the characteristics of the catalogs themselves. Using the Greenwich catalogs: Catalog of Stars for 1910.0 (Gr 10), Second Nine-Year Catalog of Stars (9Y2), First Greenwich Catalog of Stars for 1925.0 (Gr I-25), Second Greenwich Catalog of Stars for 1925.0 (Gr II-25) and First Greenwich Catalog of Stars for 1950.0 (GR I-50) in combination with the NIRS and the FK4, it was determined that those catalogs observed with fixed-wire micrometers show magnitude equations that vary with declination. Those observed with moving-wire micrometers, however, generally do not. Thus it was possible to select southern catalogs for which a magnitude equation can be determined between -5° and -30° and for which the magnitude equation can be used farther south. These catalogs are listed in Table 3.

TABLE 3. Catalogs added to SBAS to form SBAS2

Catalog	Number of Stars in SRS
Cape 1 - 25	240
Cape 2 - 25	1912
Cape Standard Stars -76° to -82°	145
Cordoba Cat. of 6249 Reference Stars	801
La Plata Cat. of 3710 Galactic Stars	332
La Plata General Catalog for 1950	885
Sydney Cat. of 1499 Intermediate Stars	236

Since H. Schwan had very kindly provided the USNO with a copy of his improved positions and motions of the FK4 SUP stars (ISUP), it was possible to use these, transformed to B1950.0, in combination with the FK4 and SBAS to determine the magnitude equations for each catalog. The procedure for each catalog was:

1. Tabular systematic differences (FK4-catalog), similar to those used for the NIRS, were computed using the FK4, ISUP and SBAS. An average magnitude was determined for each tabular value.

2. The differences were interpolated for each star in the catalog that was used in step 1 and subtracted from that star's individual difference. The result of this was combined with the difference between the star's magnitude and the average tabular magnitude at the star's coordinates.

3. Analysis of the differences from step 2 then gave the corrections in each coordinate as a function of magnitude. Some catalogs show magnitude equation in both coordinates.

4. The final step was to interpolate a tabular correction and a magnitude-based correction for each star in the catalog, and apply the corrections to the observed coordinates.

Combining the catalogs in Tables 1 and 3 produced a set of positions and motions (SBAS2) that are much stronger south of -30° than the SBAS, as Table 4 shows. The average mean errors of the proper motions are ±0".36/c in RA and ±0".38/c in DEC, about the same as the SBAS.

TABLE 4. Numbers of SBAS2 by 10° Zones of Declination

Declination	-80	-70	-60	-50	-40	-30	-20	-10	0	+10
no. of stars	108	160	238	355	368	322	571	561	1101	924

C. The Final SIRS: With the compilation of the SBAS2 it was possible to reduce most of the remaining catalogs. These catalogs contain a large amount of data for they include the Cordoba and La Plata zone catalogs. Since analysis of these catalogs showed that many have large magnitude equations, it was decided that the procedure outlined above would be used rather than making reductions with the faint stars alone, as was done in the NIRS. There are two advantages to this: First, the combination of SBAS2 with FK4 and ISUP gives a much larger range of magnitudes upon which to determine the magnitude equation than using the SBAS alone. Second, the resulting higher density of reference stars makes a stronger determination of the systematic differences. Using this approach, 52 more catalogs were systematically reduced, and when combined with the 20 listed above a system of 13,375 stars resulted. There were, however, 24 catalogs remaining that have too low densities of SBAS2, FK4 and ISUP to give good reductions. These last few were reduced by combining the 13,375 stars just mentioned with the FK4 and ISUP. The final body of SIRS obtained by combining these catalogs with the other data consists of 19,827 mean positions and proper motions.

The SIRS will be made available in two parts: Part I consists of 15,088 positions and motions formed from three or more catalog positions. Part II contains 4739 positions and motions that either result from only two catalog positions or have high mean errors. The average mean errors of the proper motions in Part I are ±0".43/c in RA and ±0".44/c in DEC, and their distribution is shown in Figure 1. The SIRS positions and motions have also been transformed to FK5 J2000.0 and will be available from the U. S. Naval Observatory either on this system or FK4 B1950.0.

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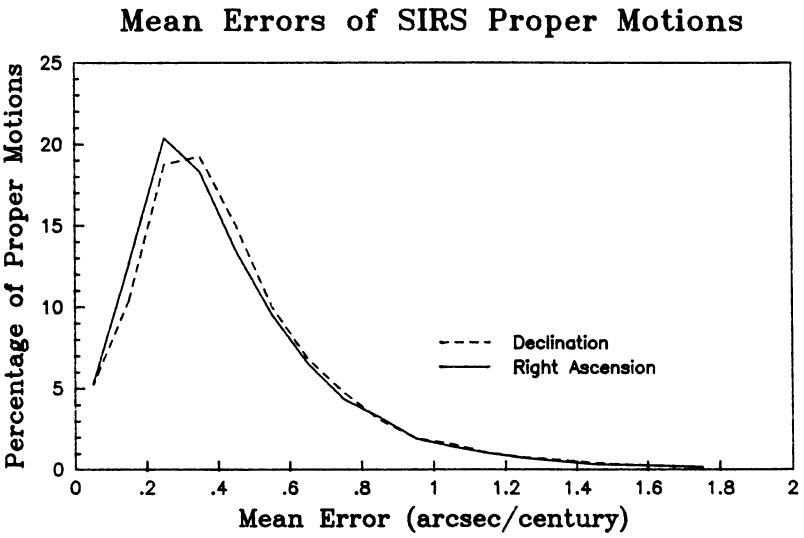

Figure 1. Frequency Distribution of the centennial mean errors of the SIRS proper motions.

III. The Southern Faint Fundamentals

There are 1169 Faint Fundamentals south of +5°, which is the northern limit of the SRS. Since the SRS added considerable weight to the determination of the positions and motions of all IRS in the SRS-AGK3R overlap zone, -5° to +5°, the final values of the Faint Fundamentals south of +5° are all taken from the SIRS. No change was made in the list of selected stars, and the details of the selection have been published (Corbin 1985). The final values have now been sent to Schwan at the Astronomisches Rechen-Institut for inclusion in the FK5, Part II. The distributions of the mean errors of the proper motions are given in Table 5, and they average ±0".28/c in RA and ±0".29/c in DEC.

TABLE 5. Faint Fundamentals - Numbers of stars by intervals of mean error of proper motion (arcsec/century)

	0.0/0.1	0.1/0.2	0.2/0.3	0.3/0.4	0.4/0.5	0.5/0.6
RA	20	228	453	303	163	2
DEC	27	169	408	387	177	1

IV. The Astrographic Catalog Reference Stars

For many years the USNO has participated in the effort to convert the published volumes of x-y measures of the Astrographic Catalog to a usable catalog. This involves first converting the measures to machine readable

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form and then using a suitable reference system to reduce the plates. The first of these tasks was begun by Lacroute and Valbousquet (Valbousquet 1977) when they prepared the region from -2° to +31°. Thus far the USNO effort has focused on the Perth and Cape zones, -32° to -52° and the San Fernando and Tacubaya zones, -3° to -16°.

The question of the required reference system was addressed by Corbin and Urban (1988). Due to the small size of the AC plates, 2° x 2°, a reference catalog with about 8 stars per square degree is required. The AGK3 has such a density, but as has been pointed out (Corbin and Urban 1989) there are problems with using the AGK3 at such early epochs as the AC plates, which are mostly earlier than 1915. The IRS has the required accuracy, but the density is too low, about one star per square degree.

The IRS is ideal, however, to make systematic corrections to the existing photographic catalogs so that they can be combined to yield a high density reference system. Since the NIRS was already available, work was begun at the USNO in 1987 on the Northern Hemisphere. The successful completion of this work (Corbin and Urban 1989) led to the conclusion that the ACRS could be compiled for the whole sky.

The compilation of the SIRS, described above, has allowed the northern and southern parts of the IRS to be combined, and now the IRS can be used as a whole system. In order to avoid any discontinuity in the system the IRS has been used to make new reductions of all catalogs, meridian circle and photographic, that contain any stars between -5° and +5°. In all, a total of 1.59 million catalog positions from 124 meridian circle catalogs, the Yale Photographic zones, the first Cape Photographic Catalog (CPC1), the AGK2, the Sydney Southern Star catalog, the Sydney zone catalog from -48° to -54°, and the Paris zone catalog from +17° to +25° were reduced to the FK4 system. The AGK3R, SRS, AGK3 and Second Cape Photographic Catalog (de Vegt 1989) already conform well to the FK4 and need no further reduction.

Weights and residual limits were determined in the manner described by Corbin (1977), and the data combined to give the mean positions and proper motions. There was a large variation in the numbers of catalog positions per star. Table 6 summarizes this quantity.

TABLE 6. Distribution of the Numbers of Catalog Positions

no. of cat. pos.	2	3	4	5	6	7	8	9	10 & more
no. of stars (thousands)	60	76	66	38	24	18	13	9	21
avg. epoch (+1940)	7.6	7.1	7.0	6.1	7.6	9.5	10.9	11.7	9.9

All stars are either in the AGK3 or the CPC2. Since the epoch of the CPC2 is about seven years later than the AGK3, this partly compensated for the generally poorer observational histories in the south. The results of the computation of the proper motions are summarized by zone in Table 7

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and globally in Figures 2 and 3. The total number of mean positions and proper motions is 325,416 and the average mean errors for the stars with three or more catalog positions are ±0".49/c in RA and ±0".47/c in DEC. Like the IRS the system will be converted to FK5 on J2000.0 and will be available on either this system or FK4 B1950.0 from the USNO. When the IRS is rediscussed on FK5 and the final CPC2 is available a definitive version on FK5 will be produced and made available.

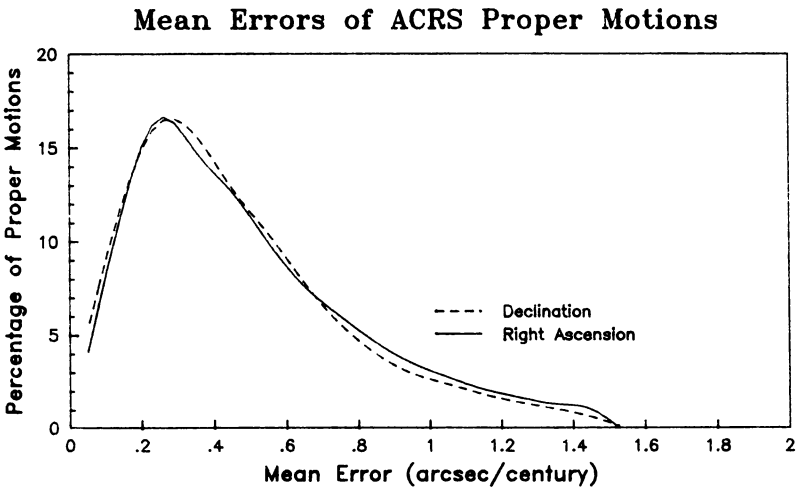

Figure 2. Mean errors of ACRS proper motions in Right Ascension and Declination.

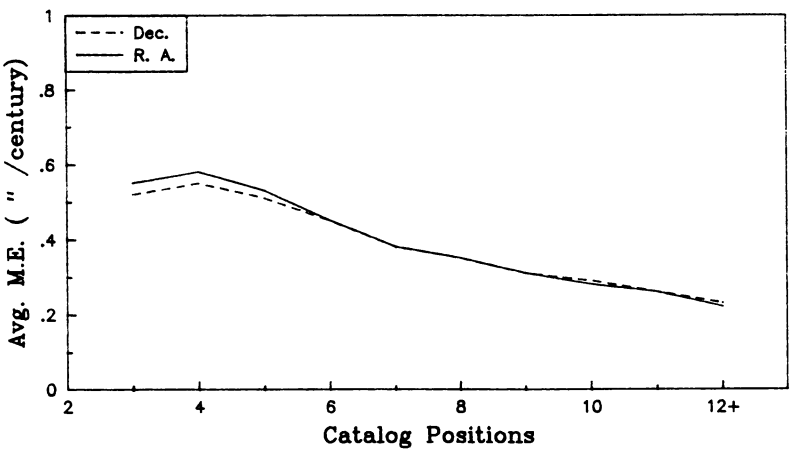

Figure 3. Mean errors of proper motions as a function of number of catalog positions.

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TABLE 7. Characteristics of the ACRS by Declination

Declination	Number of Stars	Average Epoch	Mean Errors of PM RA	DEC
+70 to +90	11723	1942.9	0.44	0.43
+50 to +70	30578	1944.6	0.52	0.52
+30 to +50	47282	1943.5	0.52	0.50
+10 to +30	54187	1941.9	0.50	0.46
-10 to +10	53169	1947.5	0.46	0.44
-30 to -10	45086	1950.0	0.45	0.42
-50 to -30	42380	1951.5	0.46	0.45
-70 to -50	30519	1958.1	0.43	0.42
-90 to -70	10492	1958.5	0.53	0.53

V. Current Observations

The USNO continues with its effort to make absolute observations of the FK5, IRS and Radio Stars and differential observations of the IRS. This is the Pole-to-Pole Fundamental Program involving the Six-Inch Transit Circle in Washington and the Seven-Inch in Black Birch, New Zealand. In April of this year the first circle of the Six-Inch program was completed with a total of 122,054 observations. The second circle will begin shortly and will require a similar number. The first circle of the Seven-Inch should be completed in late 1990 with a higher total than the Six-Inch because of the larger number of daytime observations. It is anticipated that both programs will include third circles.

VI. Report from the Working Group on Star Lists

There is a general consensus among the Working Group that fundamental stars fainter than the Faint Fundamentals should be selected so that the observational efforts are coordinated. The question of reference stars fainter than the IRS has produced several responses. Some feel that reference stars to at least the 13^{th} magnitude should be selected while others worry about the observing load that such a list, in combination with the IRS, would generate. Still others feel that reference stars of this brightness should be selected, but only in selected areas, generally around objects of special interest. The group is in general agreement that the question of fundamental and reference stars fainter than 15^{th} magnitude should be deferred for the time being. Since there is good general agreement on the identification of fainter fundamental stars, work will begin in this area. The Hipparcos Input Catalog will provide the basic list for the selection of these stars. Morrison (RGO) will identify candidate stars in the 9^{th} to 11^{th} magnitude range, and Corbin will work on the 11^{th} to 13^{th} magnitude portion. About 2000 stars in all will be selected and submitted to the WG members for review. Stars that have been observed at La Palma and Bordeaux will be given highest priority. Double stars and large proper motion stars will be avoided as much as possible. It is hoped that the WG will have agreed on a final list by the time of the next General Assembly of the IAU.

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Discussion

RÖSER: Could you comment on the accuracy for proper motions of about 0.48 arcsec/century on the northern sky? Our experience with PPM suggests that only by including the Astrographic Catalogue with its high accuracy could we achieve such precision.

CORBIN: First, 190,000 of the ACRS proper motions come from four or more catalog positions. Secondly, the AC has many problems and requires a rigorous reduction of its plates to yield the best results possible. That is one reason that we have compiled the ACRS.

WALTER: (1) How many of the "High Priority Radio Stars" are already among the "Astrographic Catalogue Reference Stars" or in any other of your observation programmes? (2) What kind of identifiers are provided for the ACRS in order to facilitate data retrieval of selected stars?

CORBIN: (1) All objects brighter than magnitude 10 should be in ACRS. We are observing 154 of these stars in our 6-inch/7-inch program. (2) Most of the ACRS have Durchmusterung numbers.