WEDNESDAY 22 APRIL, AFTERNOON SESSION

Peter van de Kamp presiding

STATUS AND PROBLEMS OF THE INTERNATIONAL REFERENCE STAR PROGRAMS

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INTRODUCTION

One of the major projects in positional astronomy now in progress is the cooperative effort of 18 transit circles throughout the world to relate the positions of 20,000 reference stars in each hemisphere of the sky to the fundamental system. It is intended that these reference stars will serve as intermediaries in concurrent photographic surveys to relate the positions of upwards of 300,000 stars to the 9th magnitude to the fundamental system.

The reference star work in the northern hemisphere is known as the AGK3R program and that in the southern hemisphere as the SRS program.

THE AGK3R PROGRAM

The AGK3R Catalog. By the end of year 1964 approximately 300,000 observations made with 11 transit circles had been collected at the U.S. Naval Observatory for use in the compilation of a catalog of final positions of the AGK3R stars. This task was completed by July 1967. The mean errors of the final positions were $\pm 0^{s}.0050 \sec\delta$ and $\pm 0''.116$ in right ascension and declination, respectively.

Proper Motions of the AGK3R Stars. Corbin (1968) derived proper motions free of magnitude errors for 2679 stars in the zone -4° to +30° declination by use of the AGK3R and other star catalogs observed since 1900 in which the observer had made some positive effort to minimize personal and magnitude errors.

Mean positions and proper motions were derived by a method of successive approximations in which the weight assigned a catalog depended on its agreement with other catalogs after allowing for proper motion. This method decreased the weights of those catalogs for which it was difficult to obtain a good reduction to the FK4.

Table 1 enables one to compare the mean errors of Corbin's proper motions with those of other well known sources. All data therein refer to

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the zone -4° to +30° declination. The 930 GC stars are those that were in common with Corbin's study.

Table 1

Comparison of Average Mean Errors of Centennial Proper Motions

Source	Stars	M. E. μ_α	M. E. μ_δ
FK4	$6.5 \leq m < 7.5$	$\pm 0''.21$	$\pm 0''.22$
Corbin	2679 stars, $\bar{m} = 8.0$	± 0.42	± 0.42
N 30	$6.5 \leq \bar{m} < 7.5$	± 0.44	± 0.42
FK3	$6.5 \leq m < 7.5$	± 0.46	± 0.43
N 30	$7.5 \leq m$	± 0.55	± 0.54
GC	930 stars, $\bar{m} = 7.2$	± 1.05	± 0.92

Table 2 shows the results of a comparison of Corbin's proper motions with those given in the GC. The magnitude differences in both coordinates appear to have some significance in spite of the large mean errors associated with them. The large mean errors are due mainly to uncertainties in the GC proper motions as might be inferred from Table 1.

Table 2

Magnitude Errors of GC Centennial Proper Motions (Corbin - GC)

Magnitude Range	R. A.	m. e	Decl.	m. e.
$m < 7.0$	$+0^s.0036$	$\pm 0^s.0027$	$-0''.113$	$\pm 0''.037$
$7.0 \leq m < 8.0$	$+0.0036$	± 0.0031	-0.077	± 0.043
$8.0 \leq m$	$+0.0052$	± 0.0049	$+0.151$	± 0.065

Comparison of the AGK3R Positions with Other Star Catalogs. A comparison of the AGK3R positions with the SAO was presented by Scott and Smith (1968) at a Conference on the Photographic Astrometric Technique.

In addition to the comparisons made by Corbin in his proper motion study, the AGK3R positions have been compared with the FK4 indirectly through use of positions of 939 PZT stars observed 1962-1965 by Hughes (1966) and by use of two star catalogs observed in recent years with the U.S. Naval Observatory six-inch transit circle, W2.50 (Watts et al 1952) and W3.50 (Adams et al 1964).

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Hughes' positions of the PZT stars were reduced to the fundamental system on a nightly basis by use of concurrent observations of FK4 stars in a narrow zone surrounding each PZT list. A comparison of his results with the AGK3R positions is shown in Table 3. Proper motions from various sources were used to reduce the AGK3R from 1958 to 1963.5, the epoch of the PZT positions.

Table 3

(AGK3R - HUGHES) for PZT Stars

PZT List	ϕ	No. of Stars	$\Delta\alpha \cos\delta$	m. e.	$\Delta\delta$	m. e.
Richmond	+25°.6	45	$+0^s.0030$	$\pm 0^s.0014$	-0".039	± 0".023
Tokyo	+35.7	47	+0.0017	0.0017	-0.053	0.028
Washington	+38.9	43	-0.0006	0.0011	+0.040	0.025
Ottawa	+45.4	36	-0.0023	0.0011	-0.006	0.022
Neuchatel	+47.0	18	-0.0032	0.0022	-0.033	0.052
Herstmonceux	+50.9	40	-0.0004	0.0011	+0.015	0.022
Hamburg	+53.5	43	-0.0033	0.0011	+0.035	0.023
Moscow	+55.8	40	-0.0003	0.0014	+0.044	0.025
Pulkovo	+59.8	33	+0.0052	0.0018	-0.064	0.033

Each of the Washington catalogs, W2.50 and W3.50, contain approximately 2000 stars in common with the AGK3R. These catalogs being fundamental in nature, it was necessary to compare each catalog with the AGK3R and then reduce the results to the FK4 through the use of tables based on the bright stars. The results of these comparisons will be published in the AGK3R catalog. In general, they are small and seldom exceed their mean errors. SAO proper motions were used to reduce the AGK3R to the epochs of the Washington catalogs.

SOUTHERN REFERENCE STAR (SRS) PROGRAM

Status of the SRS Program. The status of the SRS Program as of 1 July 1969 is shown in Table 4. Work has progressed steadily at all observatories since that date. It should be noted that the Felix Aguilar Observatory of the University of Cuyo, San Juan, Argentina has joined the program and is making excellent progress with its commitment.

On the basis of projections made by several observatories, it is quite likely that most of the SRS commitments will be completed by the end of the year 1973.

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Table 4

Status of SRS Program - 1 July 1969

Observatory	Zone	Commitment Stars	Commitment Obs'ns	Completed Obs'ns
Abbadia	+ 5° to -15°	1560	4	100%
Bordeaux	+ 5 to -15	1560	4	89
Bucharest	+ 5 to -10	1176	4	100
Nicolaiev	0 to -20	5984	2	100
San Fernando	-10 to -30	3709	4	80
Tokyo	-10 to -30	3560	4	99
USNO 6-inch	+ 5 to -30	8706	2	60
		1233	4	
Cape	-30 to -40	10082	4	90
	-40 to -50			100
	-50 to -90			0
Santiago-Pulkovo	-25 to -47	11496	4	90
	-47 to -90			100
Bergedorf (Bickley)	+ 5 to -90	20495	4	43
USNO 7-inch (El Leoncito)	+ 5 to -20	7683	2	25
	-20 to -75	12121	4	
	-75 to -75SP	1382	4	
San Juan	-40 to -90	7190	2	2

PROBLEMS OF THE SRS PROGRAM

One of the requirements of the SRS Program is that observations of the fundamental stars be made concurrently with the reference stars for the purpose of relating the reference stars to the fundamental system as well as for improving the fundamental system itself.

Our limited experience at the U. S. Naval Observatory with the reductions of twenty months of observations made with the seven-inch transit circle at El Leoncito, Argentina has led us to believe that our results would be greatly improved if we developed an instrumental system by use of our observations, before carrying out the final steps in the reduction of the reference stars. The end results of such a procedure, of course, would not be on the system of the FK4. They would, in our opinion, be somewhat smoother in the systematic sense and, therefore, more amenable to a good reduction to an improved fundamental system at a later date.

Problems in Right Ascension. Our most critical problem in right ascension arises from the lack of meridian marks for the determination of fundamental values of Bessel's n. The values of n resulting from the use of the FK4

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and FK4 Supp. right ascensions are affected with inordinately large mean errors; the median value of the mean error of a single determination of $\underline{n}$ being $\pm 0^{s}.032$. As a very preliminary step towards obtaining more accordant values of $\underline{n}$, the corrections to the FK4 right ascensions of the circumpolar stars observed during the first twenty months at El Leoncito were introduced in the determination of $\underline{n}$. This step alone reduced the median value of the mean error of a single determination of $\underline{n}$ to $\pm 0^{s}.017$. The latter value is comparable to the mean error of a single determination of the azimuth constant with the six-inch transit circle at Washington by use of FK4 positions of the northern circumpolar stars.

Although the introduction of corrections to the FK4 pole star right ascensions greatly diminished the influence of $\Delta\alpha_{\delta}$ type errors and large individual errors, $\Delta\alpha_{s}$, in the computation of $\underline{n}$, they did not diminish the influence of errors of the form,

$$\Delta\alpha_{\alpha} = a \sin\alpha + b \cos\alpha .$$

If nothing further was done, the lack of meridian marks in the determination of $\underline{n}$ would cause errors in the FK4 positions of the circumpolars to be carried over into $\underline{n}$ and thence into all observed right ascensions.

To reduce the effect of a carry-over of the above type, we propose, at the end of the program, to develop an instrumental system in right ascension according to the following steps: (1) use the mean observed corrections to the FK4 right ascensions of the circumpolar stars to improve the $\underline{n}$'s for each tour of observing. The improved $\underline{n}$'s would be used to re-reduce all observations of FK4 stars in the circumpolar zone and in the clock star zone, ±30° declination. (2) Using only those tours having a good distribution of fundamental stars in the zone ±30° declination, a solution would be made of (O - FK4)'s in right ascension from each tour for a constant and a $\Delta \underline{n}_{\delta}$, the latter being a correction to the $\underline{n}$ computed for the corresponding tour in the first step. The resulting constants and $\Delta \underline{n}_{\delta}$'s would then be used to correct the observed right ascensions of the circumpolar stars. The resulting right ascensions should be quite free of the errors in the FK4 in that part of the sky. (3) The corrected right ascensions would then be used to revise the nightly $\underline{n}$'s for use in a final reduction of all observations. The resulting right ascensions, after reduction to the mean clamp position of the instrument, would be the instrumental system to which the reference stars would be reduced.

It is advisable that the process just described be repeated at least once to ensure that the resulting right ascensions have converged to an acceptable instrumental system. The advantage of the method is that at each step one would always be working with the most accurate data possible. It is believed that this might enable the detection of errors and systematic trends which otherwise might go unnoticed.

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Before solving the Δn_{δ} it may be advisable to consider correcting the FK4 positions of the equatorial stars. On the basis of recently published star catalogs, the $\Delta\alpha_{\delta}$ errors of the FK4 equatorial stars could introduce a systematic error in Δn_{δ} of about $0^{s}.005$.

Trial solutions of 413 observing tours having at least five FK4 stars with a declination spread of 30° or more in the zone ±30° declination, indicate that the mean error of a single Δn_{δ} is $\pm 0^{s}.021$. The fact that individual Δn_{δ}'s will not be determined with high precision will be partly overcome in the end due to the fact that fifty or more of them will be involved in deriving the position of each circumpolar.

Problems with the Declinations. Our problems with the El Leoncito declinations are due mainly to the atmospheric refraction. These problems are of two kinds: (1) the correction for atmospheric refraction per se and (2), the derivation of corrections to the adopted latitude and constant of refraction from declinations observed above and below pole.

A part of the first problem arises from the local conditions at El Leoncito. The station is situated in a rough, desert-like terrain at an elevation of 7,800 feet. A preliminary examination of some of the declination observations indicates that the Pulkovo Refraction Tables do not give as satisfactory corrections for refraction at El Leoncito as they do at Washington.

The second problem is not a new one for observatories engaged in the improvement of the fundamental system of declinations. The problem is, however, considerably more difficult to resolve at El Leoncito because of its low latitude, -31°.8. At this latitude it is very difficult to obtain a good separation of the unknowns in the refraction solution.

One form of the equation relating corrections to the adopted latitude and constant of refraction to the difference between the declinations of a star observed below pole and above pole is,

$$2\,\Delta\phi + 2\,\Delta r \sin\phi \cos\phi / (\sin^2\delta - \cos^2\phi) = (\delta' - \delta) - 2\,\Delta f \cos\phi \sin\delta,$$

where δ' is the below pole declination and $\Delta\phi$, Δr and Δf are corrections to the adopted latitude, constant of refraction, and flexure, respectively.

Each circumpolar observed at both culminations gives rise to an equation of the above form. Normal equations are formed in the usual way and solved by the method of least squares. The solution of the normal equations adopted at the end of the program, to a large extent, establishes the degree to which the resulting declinations may be regarded as fundamental. The adoption of a solution is not a simple matter due to complications introduced by uncertainties in the sine flexture of the instrument.

The nature of the difficulties of the refraction solution may be illustrated quite well if integrations are used to derive expressions for the coefficients of typical sets of normal equations of the form,

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$$A_{11}\,\Delta\phi + A_{12}\,\Delta r = Q_1 + A_{13}\,\Delta f$$
$$A_{11}\,\Delta\phi + A_{22}\,\Delta r = Q_2 + A_{23}\,\Delta f.$$

The determinacy of the solution of the normal equations for $\Delta\phi$ and Δr may be easily estimated if we regard them as equations of straight lines and calculate the angle between them. For El Leoncito and Washington these angles are approximately 0°.25 and 0°.62, respectively, for circumpolars observed to a zenith distance of 75°.

The indeterminacy of the refraction solution reflects itself in the weights of the unknowns. If the weight of Δr at Washington is taken as unity, then its weight at El Leoncito is only 0.31. The corresponding weights of $\Delta\phi$ are 0.38 and 0.08, respectively.

From the foregoing it is evident that a correction, Δf, to the adopted sine flexure of the instrument cannot be introduced as an additional unknown in the refraction solution at El Leoncito. To do so would make the solution impossible because of the strong correlations that would develop among the unknowns. The best way to deal with Δf is to carry it along on the right hand side of the equation and try to find some other way of determining its value.

If $\Delta\phi_o$ and Δr_o result from a solution of circumpolar declinations reduced with a slightly erroneous sine flexure, then the true values of Δr and $\Delta\phi$ may be computed from the relations,

$$\Delta\phi = \Delta\phi_o + \frac{d\phi}{df}\,\Delta f,$$
$$\Delta r = \Delta r_o + \frac{dr}{df}\,\Delta f,$$

once Δf has been determined. One method for determining Δf is by use of the observations of the minor planets.

To be of value for this purpose, the minor planets should have a good distribution of observations from quadrature to quadrature at each opposition and should be reduced in the same manner as the stars. If $\Delta\phi_o$ and Δr_o from the refraction solution are applied to them, then an analysis of their observations will yield a value of $\Delta\delta_o$, a correction needed by all declinations observed with the instrument in the neighborhood of the equator. If it is now assumed that $\Delta\delta_o$ arose from an error in the flexure and its influence on the refraction and latitude solution, then one may write,

$$\Delta\delta_o = \Delta f\left(\frac{d\phi}{df} - \frac{dr}{df}\tan z - \sin z\right)$$

from which Δf may be obtained.

In practice, the coefficient of Δf should be computed for each observational equation for the circumpolar stars so as to obtain correct values

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of A_{13} and A_{23} in normal equations. If this is done, proper values of $d\phi/df$ and dr/df will evalue as the refraction solution progresses. It is estimated that Δf should be about $2\,\Delta\delta_o/3$ at El Leoncito.

Although the method proposed for deriving instrumental declinations from our El Leoncito results is simple and straight forward, it must be used with caution. For example, one should have some confidence that $\Delta\delta_o$ is due to flexure and not to a fortuitous error in the refraction solution before equating it to Δf.

After the adoption of preliminary values of $\Delta\phi$, Δr and Δf, it is highly advisable that they be used as the starting point for another approximation. It is always possible that quantities such as $\Delta r \tan z$ and $\Delta f \sin z$, correlate with corrections to some of the elements of the orbits of minor planets and, thereby, indirectly modify $\Delta\delta_o$ and all quantities deduced from it.

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DISCUSSION

Fricke: May I make a few remarks? First of all, I would like to thank all astronomers, particularly those in the audience who took part in these programs. All these big programs would not have been possible without your help; that deserves some applause. We have seen on the board how you have handled the results from many observatories; each with different wishes and different techniques, different people and different kinds of systematic errors. It has been done in a wonderful way. Forty years ago for the AGK2, it was Kopff who did the same task. Now, I would like to make two remarks concerning the results. Is it not so that, again, we have seen that effects of $0.^{\prime\prime}2$ do appear between the brighter stars and those of ninth magnitude. It does not seem to be unusual. Has not H.R. Morgan already found such magnitude equations in GC? He could not derive them accurately. He could not do it in such a nice way as you, but I would feel that it is quite all right. The next comment concerns the accuracy that you mentioned. I must say that I have a feeling that the system is on the FK4 within the errors which I put on the greenboard this morning. Remember I got $0.^{s}0003$ and $0.^{\prime\prime}02$ in declination. That is just about what I have seen here.

Gliese: We saw the list of observatories taking part in the SRS Program. Which observatories are really observing absolute positions?

Scott: The 6-inch transit circle at Washington is one. We are doing the best we can with the 7-inch in Argentina. However, we are going to have to use what I call a "bootstrap route" to obtain quasi-fundamental or semi-fundamental results. We are trying to set up, as best we can, an independent instrumental system, but it will not be as independent as we commonly regard instrumental systems in Washington. It will be a little bit subordinated to the method of correcting I described here. However, we will be as nearly fundamental as we can. I think something constructive may be expected from the Bergedorf people at Bickley. I know they are getting lots of observations. I believe they are also observing the minor planets which should give them an opportunity to do something in declination by establishing the equator. I hope they do so; it would be a help.

Vasilevskis: I hear that Chilean and Russian observers are also doing semi-fundamental work.

Scott: Yes, they are also doing fundamental work. Their methods are similar to those used at Pulkovo. They are a little different from those used at Washington.

Vasilevskis: And, do you know anything about observations at La Leona?

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Scott: No, I do not. All I know is that they conducted a program of observations of declinations. I really cannot say anything about it.

Dieckvoss: Do you observe the sun?

Scott: No, we are not observing the sun; however, we are observing the four brighter minor planets. We are trying to base whatever degree of fundamentality the work will have on the minor planets; not on the sun.

Eichhorn: Could you please say if, in your opinion, the observation of the sun has any intrinsic advantage for the establishment of the fundamental equator and equinox over the observation of the major planets and the minor planets?

Scott: I really should let Dr. Fricke take up that question. I do not think the major planets, during a single program, would be very helpful. In fact, they would be useless. I think the sun, though, has been the traditional, or one of the principal objects used in the traditional method for establishing the equator and equinox. The mean error of a single observation of the sun is very high, and I think it is affected by the kind of terms that Dr. Fricke was mentioning. I also believe that observations of the sun are affected by errors in refraction. Such errors, flexure and refraction, may be the cause of some of the problems the celestial mechanics people are now having with the secular rate of change in the obliquity. It is my opinion that annual terms in the refraction, especially for objects far south for northern observatories, could produce something like that. The minor planets, however, are not the solution to everything. The article that Dr. Clemence published was one in which he imagined a nice distribution from quadrature to quadrature. But you do not get that. Half the quadratures occur in the summertime when you cannot see the planet until as much as two hours after morning quadrature, and the same amount before evening quadrature. Thus, we do not achieve the distribution idealized in Clemence's paper. However, the minor planets are good for determining the position of the equator. They are not as good for the equinox, in my opinion.

Dieckvoss: Just a small remark in regards to observations of the sun. It cannot be attached to the bright stars in the daytime. In Perth they can observe the sun, but they cannot observe the stars - the clock stars.

Scott: Well, that is also our problem in Washington. We are not able to observe daytime clock corrections. The only thing we can do is observe the daytime stars and statistically determine the difference between day and night observations. The success of the present six-inch at Washington depends upon the long history of observations it has had. Each program adds to this history, thus improving our knowledge of day minus night and

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how it progresses with time. I think it would be hopeless for a new instrument to undertake observations of the day stars at Washington unless its aperture was considerably larger than that of the conventional transit circle.

Comment: On the comment on Eichhorn's question. You asked about the accuracy of observation of these minor planets. I would say, first, and most important, is that the theory of the motion of the asteroids is really the proof, and that masses can be determined and probably so by these observations we are now doing.

Eichhorn: The main point of my question was whether the observations of the major planets is almost just as valuable for the establishment of the equinox as the sun is.

Comment: Yes, sure. And the utility of the minor planets for the same equinox is guaranteed if one has a good theory for the motion of these planets. And, so far, that was not the case, but we will have that soon. And also maybe we will get masses.

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