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SYSTEMATIC CORRECTIONS TO REDUCE CERTAIN SATELLITE POSITIONS TO THE FK4 SYSTEM

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BIOGRAPHICAL NOTE

After graduation from Swarthmore College, in 1958, Mrs. Haramundanis joined the Photoreduction staff of the Smithsonian Astrophysical Observatory. One of her first projects was to develop a method for publication of all photo-reduced data.

In 1962 she was transferred to the Data Division and appointed Supervisor of the SAO Star Catalog. After its publication in 1966, she prepared the SAO Star Charts for publication, and has recently been made head of the Precision Control Section of the division.

ABSTRACT

Prior to the observation date September 1, 1962, all precisely reduced positions of artificial satellites were reduced with star positions from a large number of inhomogeneous star catalogs. After this date, the SAO Star Catalog has been used for all star coordinates. For the years 1962.80 to 1963.99, the Star Catalog in the FK3 system was in use; subsequently the Catalog was put into the FK4 system. In order to bring early (prior to September 1, 1962) satellite positions into the same coordinate system as the final SAO Star Catalog (the FK4 system), it was necessary first to derive and then to apply the appropriate systematic corrections to the observed positions. This paper presents a brief discussion of the typical errors to be found in star catalogs, and uses the standard (Newcomb) method for deriving the systematic corrections. A complete table of the corrections is included, with an explanation for its use.

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K. Haramundanis

Inherent in the preparation of a star catalog is the accumulation of systematic errors. These errors may depend upon the time of year when observations are made and upon the position or, possibly, the magnitude of the observed objects. In this paper, a brief description of the types of systematic errors common to star catalogs is given as an introduction to the main body of the paper, which deals specifically with the derivation and application of certain systematic errors that should be applied to all precisely reduced Baker-Nunn satellite positions observed prior to September 1, 1962. Accidental or fortuitous errors are not considered.

There are three major causes for the occurrence of systematic errors in a given star catalog: a) errors in the various constants and methods adopted; b) instrumental and observational variations; and c) errors of unknown cause.

The adopted constants for precession and aberration, for example, of two catalogs produced at different times or at different observatories may differ according to convention; e.g., in France from 1850 to 1890 one set of these constants was in general use, while in England at the same period another set was adopted. Refraction tables, precession tables, or possibly the means of computing nutation might be unique at a given observatory. Tables used in reductions in the last century were rarely standardized, and

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not every catalog maker adopted the same method for computing the various corrections. In addition, some source of error that was not previously known may be discovered, such as polar motion, which introduces a variable but systematic error into the results of fixed meridian instruments.

Instruments themselves are liable to certain systematic errors, and while in general their errors are very thoroughly investigated before their use in an extended astrometric program, sometimes an instrumental error may not be entirely eliminated, or may subsequently be introduced into the instrument. For meridian instruments (visual telescopes fixed in the meridian, able to move in altitude only), which are used for observing selected stars in the preparation of a fundamental catalog, the usual errors are noncircularity of the pivots on which the declination (altitude) axis turns, and flexure (bending) of the telescope tube as it moves from zenith to horizon. For a complete and interesting discussion of meridian telescopes as investigated during modern observing programs, see Podobed (1965). For astrographs (photographic telescopes with long focal lengths) the usual errors are flexure and optical aberrations such as coma, astigmatism, distortion, and depth of field. A careful discussion of the various optical aberrations can be found in Linfoot (1955).

Only source a) can be corrected with relative certainty prior to the reduction of a catalog, and even then it may be subject to revision as new values for the various constants and tables are obtained. Most errors in b) are corrected by calibration techniques during observation or reduction, but residual errors in b) and those in c) are best determined by a comparison of catalogs of the same stars from various observatories.

Although each observatory produces catalogs of the highest possible accuracy, a comparison of positions of the same stars reduced by

different observatories often shows discrepancies of a systematic nature. To obtain a standard, many observatories in various parts of the globe have cooperated in compiling fundamental catalogs. A fundamental catalog is obtained from repeated, but independent, observations referred not to other stars but to the sun or minor planets, or directly to the earth (when observations are made with a fixed meridian instrument). The major fundamental catalogs were those by Auwers (1879), Kopff (1937, 1938), Fricke and Kopff (1963), Boss (1936), and Morgan (1952). For an exhaustive discussion of the significance and use of systematic corrections in star catalogs, see Newcomb (1898, 1960).

Since all the pioneering work in positional astronomy was carried out from the many observatories situated in the Northern Hemisphere, the present reference system is more rigorously defined in that area than in the Southern Hemisphere. The sky south of -30° has at best been observed by two or possibly three observatories capable of producing useful fundamental catalogs, and by these only at a comparatively recent date. Additionally, the individual motions of the stars so complicate the determination of an absolute reference system referred to the "fixed stars" that work outlined at the 1961 IAU meeting (Sadler, 1962) is now in progress to determine a reference with respect to the galaxies, which are so distant as to have virtually no "proper motion."

A comprehensive star catalog (Staff of SAO, 1964) on magnetic tapes reduced to a homogeneous reference system, the FK3 (Kopff, 1937, 1938), was completed in 1963. This catalog was used for all precisely reduced satellite photographs taken after September 1, 1962. Later, when the FK4 (Fricke and Kopff, 1963) was made available, the SAO Star Catalog was reduced to this system.

Baker-Nunn observations made prior to September 1, 1962, had been reduced by means of star positions and, where available, proper motions from a varied and inhomogeneous group of catalogs. Reconciliation of these observations with those reduced with the SAO Star Catalog in the FK4 system required an investigation of the catalogs and their systematic errors.

A brief survey was made of the catalogs used in SAO's Photoreduction Division and a chart constructed indicating all areas of discrepancy (Table 1). On the basis of this chart the systematic errors between the various systems were computed to the mean epoch of 1960.0. The use of this mean epoch rather than the actual epoch of satellite observation has a negligible effect upon the results. Use of different equinoxes in the original catalogs posed no problem, since Newcomb's constant was invariably employed in reductions from older equinoxes to that of 1950.0. Note that SAO has adopted the standard equinox of 1950.0 for its precisely reduced observations, but each satellite is partially reduced to epoch of date by the application of proper motions (to an epoch never more than 0.5 year from the true epoch of date), and by the application of the annual aberration computed for the position of a fictitious star at the position of the satellite. Complete reduction to epoch of date is made during orbital analysis. Differential effects are thus not generally accounted for.

Conversion of an original catalog to the FK4 system required several intermediate steps. Reduction of a Yale catalog, for example, called for:

$$\text{Yale}_{\text{system}} \text{ to } \text{GC}_{\text{system}} \text{ to } \text{FK3}_{\text{system}} \text{ to } \text{FK4}_{\text{system}} .$$

The system used by each original catalog is indicated in Table 1.

Table 1. Catalogs and systems used by Photoreduction prior to September 1, 1962.

δ	Catalog	Mean epoch	System	Corrections required
+90				
+85	Yale 261	1951.34	Yale; μ applied	$\Delta\alpha, \Delta\delta, \Delta\mu, \Delta\mu'$
+80	AGK2	1928.07		
+75	AGK2	1927.38		
+70	AGK2	1926.64	FK3; no μ applied	$\Delta\alpha, \Delta\delta, \bar{\mu}, \bar{\mu}'$
+65	AGK2	1925.17		
+60	AGK2	1927.55		
+55	Yale 27	1941.82	Yale; μ applied	$\Delta\alpha, \Delta\delta, \Delta\mu, \Delta\mu'$
+50	Yale 26II	1941.89		
+45	AGK2	1927.73		
+40	AGK2	1927.12		
+35	AGK2	1927.22	FK3; no μ applied	$\Delta\alpha, \Delta\delta, \bar{\mu}, \bar{\mu}'$
+30	AGK2	1927.13		
+25	Yale 24	1925.36	FK3; μ applied	$\Delta\alpha, \Delta\delta, \Delta\mu, \Delta'$
+20	Yale 25	1924.38		
+15	Yale 18	1933.11		
+10	Yale 19	1934.88		
+09	Yale 22II	1933.80		
+05	Yale 22I	1934.88		
+01	Yale 20	1931.82		
-02	Yale 21	1932.11	Yale; μ applied	$\Delta\alpha, \Delta\delta, \Delta\mu, \Delta\mu'$
-06	Yale 17	1929.38		
-10	Yale 16	1929.62		
-14	Yale 11	1929.87		
-18	Yale 12I	1930.49		
-20	Yale 12II	1929.96		
-22	Yale 13I	1930.44		
-27	Yale 14	1930.65		
-30	Yale 13II	1929.92		
-35	Cape 17	1929.11	FK3; μ applied	$\Delta\alpha, \Delta\delta, \Delta\mu, \Delta\mu'$
-40	Cape 18	1930.28		
-52	Cape Zn	1902.56	Cape; Cape μ applied	$\Delta\alpha, \Delta\delta, \Delta\mu, \Delta\mu', \Delta\alpha_m$
-56	Cape 19	1931.24		
-59	Cape 20	1938.17	FK3; μ applied	$\Delta\alpha, \Delta\delta, \Delta\mu, \Delta\mu'$
-64		1937.04		
-65	La Pla. C	1920.0	La Plata; no μ applied	$\Delta\alpha, \Delta\delta, \bar{\mu}, \bar{\mu}'$
-72	La Pla. D	1920.0		
-90	GC	1895.29	GC; μ applied	$\Delta\alpha, \Delta\delta, \Delta\mu, \Delta\mu'$

To compute the systematic correction from system A to system B, we used the following equations:

$$\overline{\Delta\alpha} = \Delta_{\alpha_\alpha} + \Delta_{\alpha_\delta} + \Delta\mu_\alpha(\tau) + \Delta\mu_\delta(\tau), \qquad (1)$$

$$\overline{\Delta\delta} = \Delta\delta_\alpha + \Delta\delta_\delta + \Delta\mu'_\alpha(\tau) + \Delta\mu'_\delta(\tau), \qquad (2)$$

where $\overline{\Delta\alpha}$ = correction to right ascension from system A to system B,

$\Delta\alpha_\alpha$ = change in right ascension according to right ascension,

$\Delta\alpha_\alpha$ = change in right ascension according to declination,

$\Delta\mu_\delta$ = change in proper motion of right ascension according to declination,

τ = difference in years from the epoch of catalog observation to 1960.0,

μ, μ' = proper motions in right ascension and declination, respectively,

and similarly in declination.

The initial values for $\Delta\alpha_\alpha$, $\Delta\mu_\alpha$, etc., were taken from tables of systematic corrections published by Barney (1951), Boss (1936), Fricke and Kopff (1963), Gyllenberg (1948), Kopff (1939), and Williams (1947).

The only magnitude errors (systematic errors depending upon magnitude) that were determined as significant, and therefore included in our computations, affected the right ascensions of the Cape Zone

Catalogue ($\Delta\alpha_m$ where m = visual magnitude). Magnitude errors between the FK3 and FK4 were not applied, since the catalogs used at SAO were not affected by the same magnitude errors.

In cases where proper motions had not been applied, $\bar{\mu}(\tau)$ was substituted for $[\Delta\mu_\alpha(\tau) + \Delta\mu_\delta(\tau)]$, and similarly in declination. We ascertained the average proper motions $\bar{\mu}$, $\bar{\mu}'$ (see Table 2) by tallying all proper motions in the finished SAO Star Catalog (FK3 system), taking the mean value in each area, and reducing this value to the FK4 system.

For convenience, the final corrections (Tables 3 and 4) were set up in sky areas of 1 hour of right ascension by 5° declination. Where the published systematic corrections did not coincide with such divisions, we took smoothed and weighted means of all the necessary corrections.

In order to apply the corrections, we added tabular values algebraically to the appropriate satellite positions. Table headings for declinations specify both upper and lower limits for each tabular row, i.e., +40° to +45°; for right ascensions, only the upper limit is given above each tabular column; i.e., 1 = 0^h to 1^h, 22 = 21^h to 22^h. This should be borne in mind when entering the table to extract a correction. Note that the table in right ascension is in the form $\Delta\alpha$, not $\Delta\alpha(\cos\delta)$, throughout, for ease in applying the corrections. Two typical examples are worked out below.

Example 1:

α	$13^h\ 55^m\ 53^s.530$	δ	+46° 49' 55".70
$\Delta\alpha$	-.015	$\Delta\delta$	-.32
α'	53.515	δ'	55.38

Example 2:

α	$21^h\ 05^m\ 24^s.590$	δ	-59° 37' 48".30
$\Delta\alpha$	+.016	$\Delta\delta$	-.23
α'	24.606	δ'	48.53

where α, δ = original satellite position; α', δ' = corrected position.

Table 2. Average $\bar{\mu}$, $\bar{\mu}'$ used in systematic corrections.

δ	$\bar{\mu}^*$	$\bar{\mu}'$
+80 to +85	-0.^{s}0092	-0.''008
+75 +80	-0.0056	-0.005
+70 +75	-0.0080	-0.005
+65 +70	-0.0200	-0.006
+60 +65	-0.0225	-0.006
+45 to +50	-0.0004	-0.009
+40 +45	-0.0004	-0.009
+35 +40	-0.0003	-0.016
+30 +35	-0.0003	-0.016
-64 to -65	+0.0003	-0.013
-65 -70	-0.0000	-0.012
-70 -72	+0.0001	-0.012

* $|\delta| > 60° = \bar{\mu} \cos \delta$

Table 3. Corrections in seconds of arc to declination, unit = 1".

DEC IN DEG	RA IN HOURS 1	2	3	4	5	6	7	8	9	10	11	12
90 TO 85	.20	.05	.02	-.01	-.13	-.11	-.04	.06	.06	.09	.10	.16
85 TO 80	-.30	-.26	-.24	-.24	-.20	-.20	-.24	-.28	-.24	-.18	-.14	-.14
80 TO 75	-.23	-.19	-.17	-.17	-.14	-.14	-.17	-.22	-.18	-.11	-.08	-.08
75 TO 70	-.23	-.20	-.18	-.17	-.16	-.16	-.23	-.24	-.19	-.14	-.13	-.14
70 TO 65	-.25	-.23	-.21	-.20	-.19	-.20	-.25	-.27	-.22	-.17	-.16	-.17
65 TO 60	-.21	-.21	-.20	-.18	-.18	-.23	-.23	-.18	-.16	-.17	-.17	-.18
60 TO 55	-.08	-.07	-.03	-.06	-.05	-.04	0	.04	-.04	-.07	-.02	.05
55 TO 50	-.19	-.19	-.11	-.29	-.30	-.23	-.20	-.20	-.24	-.15	-.18	-.23
50 TO 45	-.29	-.29	-.29	-.29	-.26	-.24	-.23	-.21	-.20	-.21	-.24	-.27
45 TO 40	-.29	-.29	-.30	-.30	-.27	-.25	-.25	-.25	-.23	-.23	-.23	-.24
40 TO 35	-.51	-.51	-.52	-.52	-.49	-.47	-.47	-.47	-.45	-.45	-.45	-.46
35 TO 30	-.52	-.52	-.52	-.52	-.50	-.49	-.49	-.49	-.48	-.45	-.46	-.46
30 TO 25	.01	.01	.01	.01	.04	.06	.07	.07	.08	.11	.12	.12
25 TO 20	-.04	0	.02	.01	.01	.01	.05	.03	.03	.04	.05	.06
20 TO 15	.66	.63	.66	.59	.50	.37	.30	.31	.34	.30	.20	.18
15 TO 10	.37	.28	.29	.29	.32	.39	.28	.27	.26	.18	.11	.02
10 TO 5	.37	.28	.22	.11	.08	.17	.19	.22	.18	.11	.04	-.03
5 TO 0	.44	.27	.28	.37	.42	.34	.22	.13	.06	.08	.03	-.03
0 TO -5	.33	.18	.17	.22	.28	.29	.23	.10	.17	.19	.12	.05
-5 TO -10	.34	.32	.33	.47	.47	.37	.20	.11	.24	.32	.18	.02
-10 TO -15	-.52	-.45	-.39	-.31	-.23	-.20	-.37	-.59	-.54	-.36	-.37	-.39
-15 TO -20	-.21	-.39	-.52	-.43	-.36	-.38	-.36	-.30	-.25	-.37	-.59	-.45
-20 TO -25	.58	.47	.45	.46	.45	.37	.30	.28	.34	.38	.28	.27
-25 TO -30	-.10	-.04	-.04	-.15	-.16	-.12	-.18	-.25	-.37	-.45	-.50	-.45
-30 TO -35	-.26	-.31	-.29	-.25	-.25	-.25	-.23	-.23	-.22	-.21	-.22	-.25
-35 TO -40	-.38	-.41	-.33	-.31	-.31	-.25	-.23	-.22	-.22	-.22	-.23	-.26
-40 TO -45	.33	.24	.23	.35	.41	.28	.21	.59	.06	-.12	-.16	-.12
-45 TO -50	.33	.24	.23	.35	.41	.28	.21	.59	.06	-.12	-.16	-.12
-50 TO -55	-.34	-.37	-.30	-.36	-.36	-.29	-.27	-.21	-.21	-.25	-.18	-.11
-55 TO -60	-.37	-.48	-.50	-.48	-.39	-.27	-.27	-.30	-.30	-.30	-.23	-.19
-60 TO -65	-.33	-.45	-.47	-.45	-.36	-.24	-.24	-.27	-.27	-.26	-.20	-.15
-65 TO -70	-.30	-.32	-.34	-.38	-.43	-.46	-.46	-.49	-.53	-.51	-.51	-.50
-70 TO -75	.02	-.01	0	-.01	-.03	.10	.15	.17	.18	.27	.36	.38
-75 TO -80	.04	.10	.03	-.02	-.01	.13	.12	.12	.24	.34	.40	.34
-80 TO -85	-.03	.03	-.04	-.09	-.08	.06	.05	.05	.17	.27	.33	-.27
-85 TO -90	-.01	-.02	0	-.10	-.11	.04	.02	-.08	.03	.15	.37	.53

DEC IN DEC	RA IN HOURS 13	14	15	16	17	18	19	20	21	22	23	24
90 TO 85	.19	.10	.07	.07	.10	.17	.14	.09	.12	.17	.11	.15
85 TO 80	-.18	-.22	-.22	-.22	-.24	-.26	-.28	-.30	-.32	-.32	-.30	-.30
80 TO 75	-.12	-.16	-.16	-.16	-.18	-.19	-.22	-.24	-.25	-.25	-.24	-.24
75 TO 70	-.16	-.14	-.13	-.15	-.18	-.20	-.22	-.24	-.25	-.25	-.25	-.24
70 TO 65	-.19	-.17	-.16	-.18	-.21	-.23	-.25	-.27	-.28	-.28	-.28	-.27
65 TO 60	-.21	-.19	-.15	-.15	-.18	-.19	-.19	-.16	-.17	-.19	-.22	-.23
60 TO 55	.13	.22	.17	.07	.04	.02	.03	.11	.14	.11	.07	0
55 TO 50	-.13	-.06	.06	.14	.10	.06	.05	0	-.07	-.12	-.17	-.22
50 TO 45	-.30	-.32	-.31	-.29	-.28	-.27	-.25	-.25	-.27	-.29	-.31	-.31
45 TO 40	-.25	-.31	-.33	-.30	-.28	-.28	-.28	-.30	-.31	-.31	-.31	-.30
40 TO 35	-.47	-.53	-.55	-.52	-.50	-.50	-.50	-.52	-.53	-.53	-.53	-.52
35 TO 30	-.48	-.52	-.55	-.51	-.48	-.53	-.54	-.54	-.54	-.53	-.52	-.52
30 TO 25	.08	.01	-.03	.03	.07	0	-.01	-.01	-.01	.01	.02	.02
25 TO 20	.01	0	0	.02	.02	-.03	-.02	-.01	-.02	-.06	-.08	-.07
20 TO 15	.22	.21	.27	.41	.44	.36	.45	.61	.69	.70	.72	.71
15 TO 10	-.01	0	.04	.12	.13	.13	.23	.40	.46	.39	.36	.38
10 TO 5	-.13	-.22	-.16	-.03	.05	.09	.21	.39	.50	.46	.43	.41
5 TO 0	-.02	-.01	.02	.09	.11	.18	.27	.44	.47	.46	.51	.33
0 TO -5	.10	.17	.18	.23	.30	.42	.46	.50	.45	.38	.40	.36
-5 TO -10	-.01	-.02	.02	.14	.28	.38	.49	.62	.65	.58	.48	.41
-10 TO -15	-.26	-.13	-.14	-.20	-.26	-.21	-.14	-.11	-.17	-.11	-.19	-.41
-15 TO -20	-.17	-.04	-.06	-.15	-.15	-.09	.01	.07	.07	-.04	-.06	-.08
-20 TO -25	.28	.16	.07	.02	.05	.08	.30	.49	.53	.61	.61	.60
-25 TO -30	-.36	-.30	-.36	-.28	-.28	-.24	-.12	-.13	-.17	-.29	-.32	-.31
-30 TO -35	-.20	-.14	-.12	-.08	-.04	-.04	-.03	-.03	-.11	-.15	-.15	-.18
-35 TO -40	-.24	-.19	-.16	-.18	-.20	-.16	-.12	-.10	-.14	-.18	-.19	-.18
-40 TO -45	.10	.05	-.07	.23	.38	.66	.68	.63	.66	.62	.48	.52
-45 TO -50	.10	.05	-.07	.24	.38	.66	.68	.63	.66	.62	.48	.52
-50 TO -55	-.18	-.16	-.16	-.19	-.19	-.15	-.15	-.15	-.17	-.16	-.20	-.27
-55 TO -60	-.23	-.26	-.23	-.20	-.18	-.20	-.20	-.10	-.14	-.23	-.28	-.31
-60 TO -65	-.20	-.23	-.20	-.16	-.15	-.17	-.17	-.07	-.10	-.20	-.25	-.27
-65 TO -70	-.38	-.35	-.45	-.44	-.46	-.43	-.34	-.22	-.26	-.36	-.29	-.31
-70 TO -75	.49	.50	.42	.39	.33	.32	.37	.20	.22	.09	.12	.16
-75 TO -80	.01	.54	.55	.48	.18	.19	.34	.30	.25	-.08	.16	.09
-80 TO -85	-.06	.47	.48	.41	.11	.18	.27	.23	.18	-.15	.09	.02
-85 TO -90	.56	.56	.45	.27	.09	.18	.20	.22	.18	.25	-.09	.03

Table 4. Corrections in seconds of time to right ascension, unit = 1^s.

DEC IN DEG	RA IN HOURS 1	2	3	4	5	6	7	8	9	10	11	12
90 TO 85	.367	-.206	-.481	-.665	-.550	-.183	.023	.183	.115	.069	.069	.220
85 TO 80	-.023	-.046	-.069	-.084	-.069	-.054	-.038	-.023	-.008	-.008	-.015	-.031
80 TO 75	.032	.018	.005	-.005	.005	.014	.023	.032	.042	.042	.037	.028
75 TO 70	.017	.020	.027	.023	.017	.013	.017	.030	.040	.040	.033	.017
70 TO 65	.037	.039	.044	.042	.037	.034	.037	.047	.055	.055	.050	.037
65 TO 60	-.028	-.022	-.022	-.026	-.030	-.032	-.028	-.015	-.006	-.009	-.013	-.024
60 TO 55	-.035	-.055	-.080	-.076	-.058	-.031	-.009	.001	-.005	-.016	-.022	-.025
55 TO 50	.007	.001	-.009	-.016	-.020	-.022	-.022	-.026	-.033	-.039	-.036	-.041
50 TO 45	-.007	-.004	-.009	-.016	-.018	-.016	-.012	-.005	-.001	.001	-.001	-.006
45 TO 40	-.008	-.007	-.010	-.016	-.017	-.013	-.009	-.007	-.005	-.004	-.006	-.008
40 TO 35	-.006	-.005	-.008	-.014	-.015	-.011	-.007	-.005	-.003	-.002	-.004	-.006
35 TO 30	-.008	-.006	-.007	-.010	-.013	-.011	-.009	-.008	-.006	-.005	-.006	-.007
30 TO 25	.010	.011	.008	.002	-.002	.001	.005	.008	.011	.012	.009	.007
25 TO 20	.010	.010	.009	.005	.002	.002	.003	.007	.012	.013	.011	.007
20 TO 15	.022	.015	.010	.006	.001	.002	.002	-.006	-.009	-.010	-.013	-.015
15 TO 10	.002	-.012	-.020	-.017	-.013	-.003	-.001	.008	.011	.009	.007	.001
10 TO 5	.014	.009	.004	.002	-.001	-.005	-.004	-.005	-.009	-.011	-.014	-.011
5 TO 0	.014	.007	-.002	-.004	-.001	0	0	-.004	-.014	-.010	-.010	-.004
0 TO -5	-.010	-.010	-.024	-.029	-.030	-.035	-.035	-.029	-.023	-.016	-.013	-.013
-5 TO -10	-.023	-.019	-.020	-.028	-.029	-.032	-.022	-.010	0	-.003	-.001	-.002
-10 TO -15	-.034	-.014	-.005	-.014	-.017	-.025	-.023	-.014	-.019	-.022	-.022	-.021
-15 TO -20	-.021	-.015	-.010	-.013	-.005	-.010	-.015	-.009	-.004	-.004	-.011	-.019
-20 TO -25	-.008	-.004	-.003	-.016	-.010	-.017	-.016	-.001	-.001	-.008	-.020	-.026
-25 TO -30	.009	.032	.010	-.008	-.004	.002	-.004	-.009	-.010	-.008	-.009	-.005
-30 TO -35	.020	.022	.015	.008	0	-.007	-.006	.002	.004	.002	-.002	-.002
-35 TO -40	.025	.025	.021	.015	.013	.013	.014	.021	.022	.013	.001	.004
-40 TO -45	-.017	-.003	-.038	-.105	-.116	-.116	-.128	-.123	-.126	-.110	-.097	-.096
-45 TO -50	-.004	.007	-.020	-.079	-.087	-.089	-.094	-.084	-.099	-.097	-.085	-.085
-50 TO -55	.022	.018	.018	.019	.021	.022	.026	.031	.037	.016	.010	.009
-55 TO -60	.011	.011	.012	.015	.018	.021	.023	.020	.007	-.003	-.007	-.008
-60 TO -65	-.024	.024	.026	.032	.039	.045	.050	.043	.015	-.006	-.015	-.017
-65 TO -70	.233	.196	.157	.107	.071	.031	0	.013	-.042	-.044	-.068	-.071
-70 TO -75	.156	.150	.153	.073	.057	.023	.003	.037	.057	0	.020	-.040
-75 TO -80	.171	.139	.028	.046	.023	-.028	.028	.116	.194	.083	.051	-.097
-80 TO -85	-.100	-.153	-.337	-.306	-.299	-.337	-.276	-.192	-.061	-.245	-.299	-.544
-85 TO -90	.665	.825	-.046	-.138	-.459	-.734	-.504	-.115	.344	-.092	-.115	-.711

DEC IN DEG	RA IN HOURS 13	14	15	16	17	18	19	20	21	22	23	24
90 TO 85	.252	-.092	-.069	.183	.596	.825	.779	.665	.757	.779	.504	.390
85 TO 80	-.069	-.100	-.123	-.130	-.115	-.115	-.123	-.123	-.123	-.115	-.092	-.046
80 TO 75	.005	-.014	-.028	-.032	-.023	-.023	-.028	-.028	-.028	-.023	-.009	.018
75 TO 70	0	-.010	-.020	-.027	-.030	-.033	-.033	-.033	-.033	-.027	-.013	.003
70 TO 65	.024	.016	.008	.003	0	-.003	-.003	-.003	-.003	.003	.013	.026
65 TO 60	-.032	-.039	-.045	-.050	-.054	-.058	-.056	-.050	-.048	-.048	-.045	-.039
60 TO 55	-.029	-.032	-.029	-.029	-.028	-.025	-.021	-.019	-.027	-.031	-.034	-.024
55 TO 50	-.043	-.037	-.030	-.026	-.025	-.023	-.017	-.004	-.008	-.016	-.013	0
50 TO 45	-.012	-.015	-.016	-.018	-.022	-.024	-.021	-.016	-.015	-.021	-.021	-.013
45 TO 40	-.009	-.010	-.011	-.012	-.013	-.012	-.011	-.009	-.011	-.016	-.017	-.013
40 TO 35	-.007	-.008	-.009	-.010	-.011	-.010	-.009	-.007	-.009	-.014	-.016	-.011
35 TO 30	-.007	-.007	-.009	-.012	-.009	-.005	-.003	-.003	-.005	-.008	-.011	-.011
30 TO 25	.007	.008	.005	.001	.006	.014	.019	.019	.017	.013	.007	.007
25 TO 20	.006	.004	.002	.001	.005	.012	.017	.020	.019	.017	.014	.011
20 TO 15	-.009	-.004	.001	.005	.004	.003	0	.001	.002	.008	.013	.021
15 TO 10	.001	.008	.019	.029	.027	.020	.014	.012	.011	.009	.004	.012
10 TO 5	-.008	.004	.017	.011	.012	.009	.006	.002	-.002	-.003	.013	.016
5 TO 0	-.003	.001	.009	.012	.011	-.002	-.001	-.001	-.008	.017	.022	.018
0 TO -5	-.016	-.017	-.011	-.005	-.013	-.023	-.029	-.023	-.018	-.017	-.011	-.013
-5 TO -10	-.003	-.003	0	-.011	-.003	-.021	-.025	-.023	-.022	-.025	-.027	-.026
-10 TO -15	-.012	.001	.018	.015	.010	.005	-.006	-.005	-.007	-.018	-.038	-.045
-15 TO -20	-.019	-.011	-.004	-.003	-.002	-.010	-.020	-.019	-.020	-.014	-.017	-.021
-20 TO -25	-.020	-.011	-.010	-.013	-.015	-.018	-.016	-.006	-.005	-.003	-.007	-.011
-25 TO -30	.009	.012	.005	.002	.013	.017	.016	.008	-.002	-.004	.001	.001
-30 TO -35	.008	.007	.003	.003	.004	.006	.004	.018	.024	.021	.015	.013
-35 TO -40	.016	.015	.008	.005	.003	.004	.009	.010	.030	.028	.021	.021
-40 TO -45	-.081	-.077	-.052	-.039	-.029	-.005	-.018	-.033	-.031	-.003	.009	-.006
-45 TO -50	-.083	-.078	-.044	-.016	.005	.033	-.020	-.009	-.004	.026	.045	.028
-50 TO -55	.010	.012	.015	.018	.021	.023	.024	.027	.030	.030	.029	.027
-55 TO -60	-.008	-.006	.002	.009	.014	.014	.012	.012	.014	.016	.014	.011
-60 TO -65	-.017	-.013	.004	.019	.030	.030	.026	.026	.030	.035	.030	.024
-65 TO -70	-.021	.047	.115	.272	.253	.308	.337	.334	.337	.308	.295	.272
-70 TO -75	-.040	.003	.033	.027	.047	.103	.133	.123	.123	.120	.143	.180
-75 TO -80	-.129	-.046	-.014	.023	.051	.079	.157	.134	.060	.079	.125	.143
-80 TO -85	-.598	-.460	-.406	-.345	-.299	-.253	-.123	-.161	-.283	-.253	-.299	-.268
-85 TO -90	-.779	-.344	-.206	-.115	-.138	-.183	.229	.344	.115	.183	-.160	-.069

Large quantities of the same sign were often canceled by large quantities of the opposite sign, in agreement with the supposition that the large Yale-minus-GC values were caused by errors in the GC system. Final corrections were thus minimized, but the trends were systematic within bands, and rather more divergent from band to band (see Figures 1 to 3).

Figures 1 to 3 illustrate the errors in the uncorrected coordinate system. The tabular values in α were converted to seconds of arc (multiplied by cos δ). The zone divisions adopted in these figures were those judged most appropriate for this illustration. Figure 1 pertains to the errors in δ depending upon right ascension ($\Delta\delta_\alpha$); Figure 2, to the errors in α depending upon right ascension ($\Delta\alpha_\alpha$); Figure 3, to the errors in both α and δ depending upon declination ($\Delta\delta_\delta$, $\Delta\alpha_\delta$).

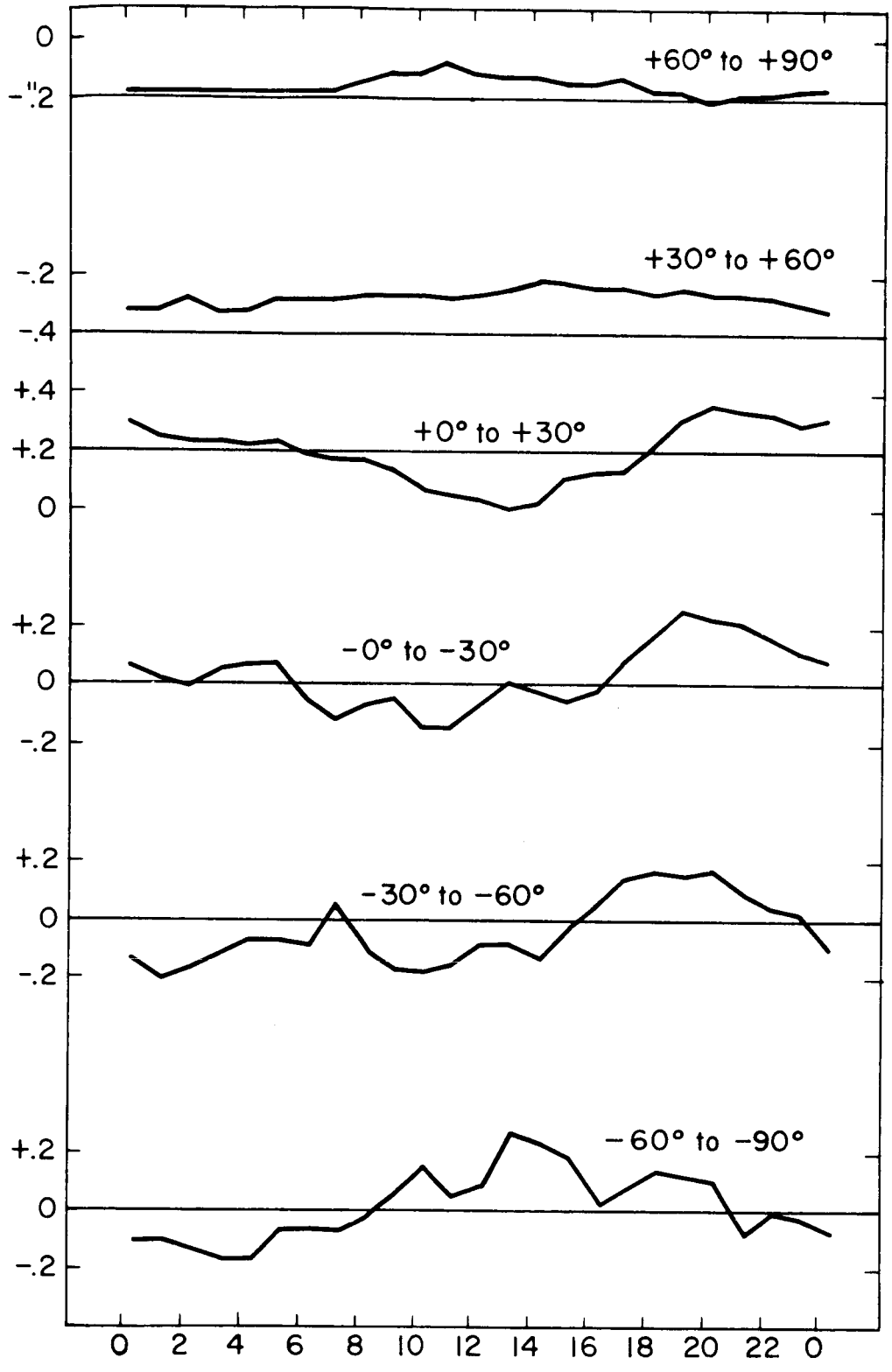

Figure 1. Systematic corrections according to α, FK4 − SAO observations; abscissa = α^h, ordinate = mean $\Delta\delta$.

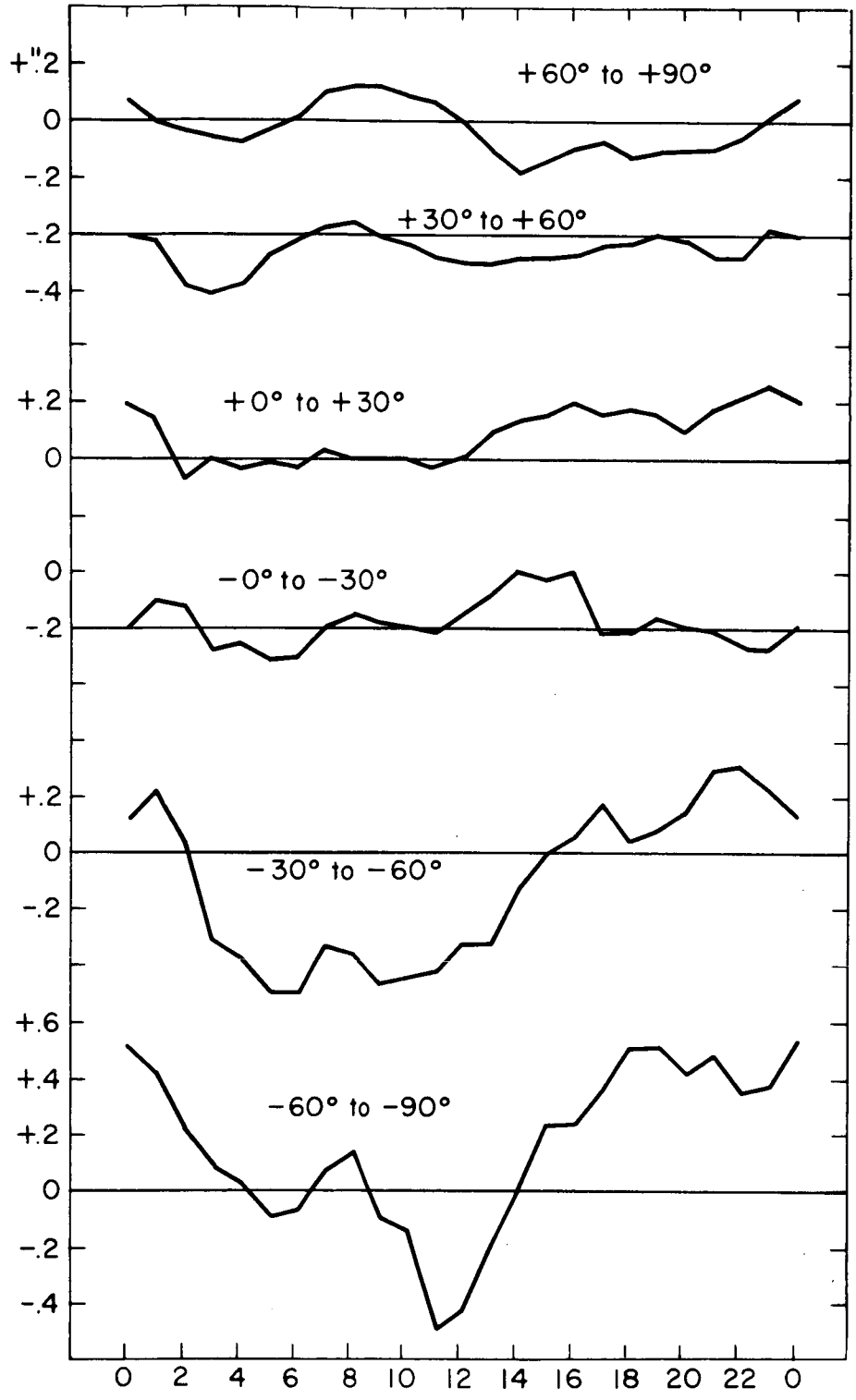

Figure 2. Systematic corrections according to α, FK4 – SAO observations; abscissa = α^h, ordinate = mean $\Delta\alpha(\cos\delta)$.

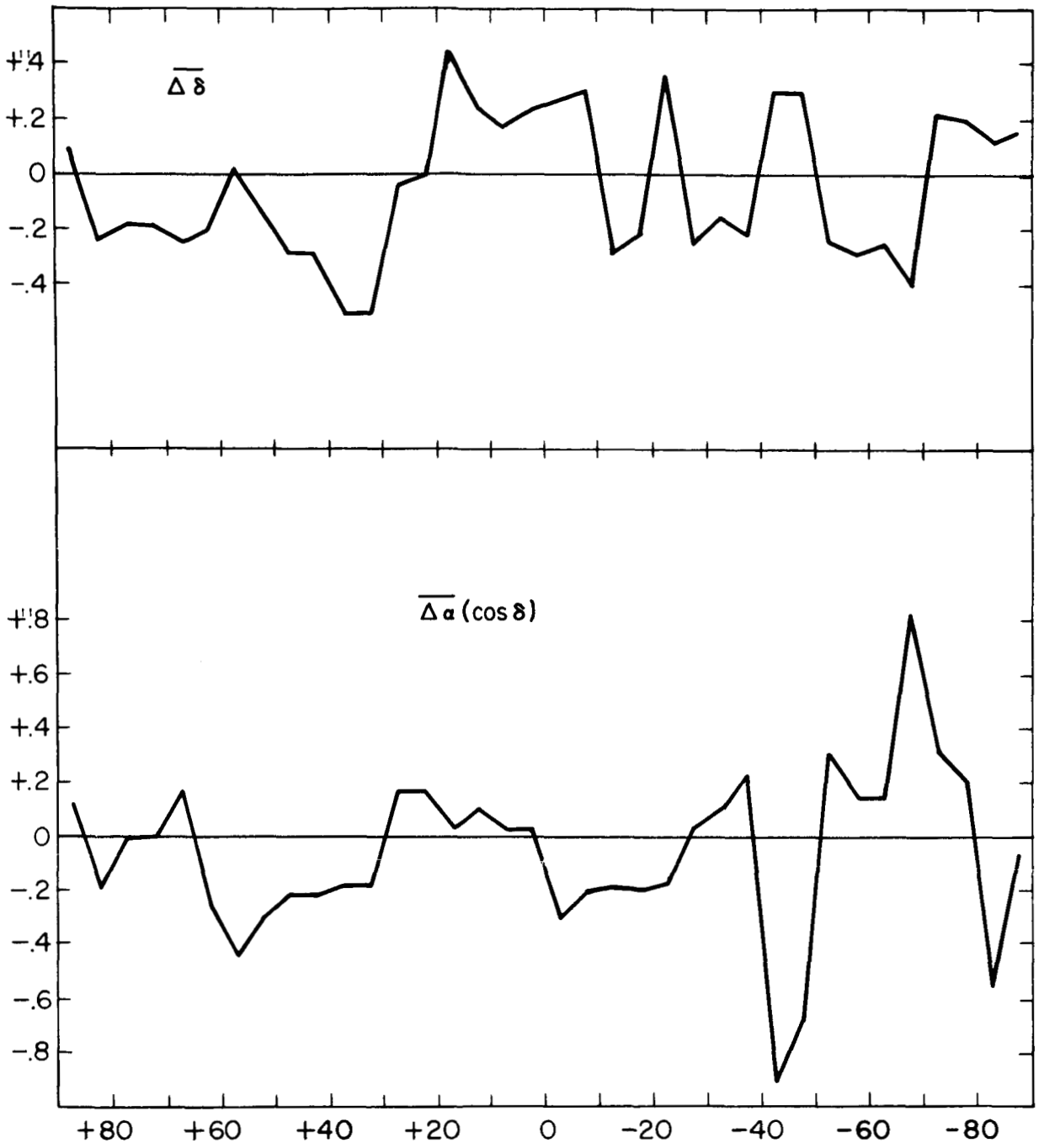

Figure 3. Systematic corrections according to δ, FK4 − SAO observations; abscissa = δ°, ordinate as on graph.

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