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The U.S. Naval Observatory pole-to-pole catalog: $\mathbf{W2_{J00}}$

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Abstract. Between the years 1985 and 1996 the U.S. Naval Observatory (USNO), using two transit circles, one located in Washington, DC (U.S.A.) and the other in Blenheim, New Zealand, conducted an ambitious program of absolute observations of positions of celestial objects completely covering both hemispheres. Over 737 000 individual observations were made, primarily of the International Reference Stars (IRS) and FK5 stars, as well as all the major planets (except Pluto) and thirteen minor planets. This included some 55 000 observations of day-time objects including the Sun, Mercury, Venus, and Mars.

The original objective was to form a traditional, all-sky catalog of absolute star positions which could be firmly linked to the dynamical system. However, with the success of the Hipparcos project and the adoption of the ICRF as the celestial reference frame, the primary focus of the pole-to-pole program changed. The stellar positions have been differentially reduced to the system of Hipparcos and these were used to tie the planetary observations into the ICRF. Thus the program has resulted in a body of high quality observational data (average standard deviation of a mean position of about 75 mas) that will provide important input for the production of ICRF-based ephemerides. This is particularly true for the outer and minor planets.

Key words: catalogs — astrometry

1. Catalog availability

The observed stellar and planetary positions from this catalog can be downloaded from the web at: www.usno.navy.mil/ad

2. Introduction

2.1. History

Plans for absolute observing programs concurrently covering both hemispheres using the USNO Six-inch and Seven-inch transit circles date back to the 1970's (Hughes 1978). The result was to be an all-sky, absolute catalog tied to the dynamical reference frame. This required each transit circle to observe in the daytime and be located at a latitude such that a fundamental determination could be made of the azimuth using circumpolar stars. It was also planned that the bulk of the stars, the program stars, would be observed in declination zones of 15° along with suitable distributions of reference stars to allow differential reduction on a semi-nightly basis. At this same time, during the 1970's, the European Space Agency (ESA) was studying the feasibility of the high precision astrometric satellite, Hipparcos (Høg 1978). Though the estimated accuracy of Hipparcos was a significant improvement over that of a transit circle, the plans were to reference the satellite's positions to FK5 (Fricke et al. 1988, 1991). By the late 1980's it was evident that the FK5 contained systematic errors and an improved global catalog was desirable. The USNO undertook the pole-to-pole project to address this need. Renovation and testing of the Seven-inch transit circle delayed the start of the observing program until 1985. The launch of the Hipparcos satellite took place in August, 1989. Even with a revised mission made necessary by the failure of the apogee booster, the satellite was able to operate until August, 1993. The Hipparcos Catalogue (ESA 1997) was released in mid-1997. In the end, the Hipparcos Catalogue was referenced to the International Celestial Reference Frame (ICRF, Ma et al. 1998) and not to FK5. Observations for the pole-to-pole project were completed in April, 1995 by the Six-inch transit circle and in February, 1996 by the Seven-inch transit circle. Instead of following the traditional procedures to form an absolute catalog, the stellar positions were differentially reduced using stars from the Hipparcos catalog and the resulting

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Table 1. Observations made by the Six-inch transit circle located in Washington DC, U.S.A., during 1985-1995

			Solar System Objects			
Stellar Objects			Sun and Planets		Minor Planets	
Star Class	Number of Obn's	Number in Class	Object	Number of Obn's	Object	Number of Obn's
IRS	141870	21509	*Sun	*1863	Ceres	481
Clocks	37486	230	*Mercury	*596	Pallas	396
FK5	94762	3234	*Venus	*1426	Juno	312
Refraction (LC)	5729	121	*Mars (day)	*134	Vesta	511
Azimuth (UC)	7607	23	Mars (night)	588	Hebe	288
Azimuth (LC)	7210	23	Jupiter	727	Iris	276
*Day	*9255	*84	Saturn	764	Flora	257
Radio	3176	106	Uranus	729	Metis	221
Miscellaneous	10349	874	Neptune	617	Eunomia	265
Totals	317444	26204	Totals	7444	Totals	3007

* Observations not reduced.
UC = Upper culmination.
LC = Lower culmination.

catalog is on the system of the ICRF. This project is the latest and largest of a long series of transit circle catalogs produced by the U.S. Naval Observatory. It is also, because of advancing technologies, certainly the last.

2.2. Observing program

This catalog contains the combined results of observations made with the Six-inch Transit Circle in Washington, DC U.S.A. and the Seven-inch Transit Circle in New Zealand, between April 1985 and February 1996. This is the second USNO catalog to be referred to the Equinox of J2000.0 and will be named the $\mathrm{W2_{J00}}$. The Six-inch transit circle was built by the Warner and Swasey Company and has operated from the U.S. Naval Observatory in Washington, DC since 1897. The visual, two axis micrometer was the same one used during the previous programs, the $\mathrm{W5_{50}}$ (Hughes & Scott 1982) and the $\mathrm{W1_{J00}}$ (Holdenried & Rafferty 1999). The Seven-inch transit circle was built by the USNO Instrument Shop in 1948. One of its previous program, the $\mathrm{WL_{50}}$ (Hughes et al. 1992), was a visual catalog made from El Leoncito, Argentina. For the $\mathrm{W2_{J00}}$, the telescope was located on the Black Birch ridge at an elevation of 1350 m, 20 km southwest of the city of Blenheim, New Zealand. The station, referred to as the Black Birch Astrometric Observatory, was at a latitude of $-41^\circ\ 44'\ 41''.4$ and a longitude of $173^\circ\ 48'\ 11''.99$ East.

For the $\mathrm{W2_{J00}}$ it was decided to continue to make observations with the Six-inch transit circle visually because of the long and continuous series of excellent catalogs made in this mode (its observations formed the backbone for the FK3, FK4, and FK5 catalogs). The major changes made to the Six-inch just prior to the start of the $\mathrm{W2_{J00}}$ observing program included; a second glass circle, two additional magnitude screens, and an upgrade to the photoelectric circle scanning system. Midway through the observing program, the photoelectric scanners were replaced with CCD devices (Rafferty & Klock 1986). Major changes made to the Seven-inch transit circle after its completion of the $\mathrm{WL_{50}}$, and just prior to the beginning of the $\mathrm{W2_{J00}}$ observing program, included the replacement of the visual micrometer with a new one using an image dissector as the detector (Hughes et al. 1986), the installation of a new temperature compensating objective built by the Farrand Optical Corporation of New York, the installation of new graduated glass circles mounted on steel wheels fabricated by Heidenhain Corporation of Germany, and the installation of a new photoelectric system for scanning the graduated circles. As in the case of the Six-inch, the circle scanning system was upgraded to use CCDs (Rafferty & Klock 1986) midway through the observing program.

Both transit circles were equipped with clamping devices that prevented any motion of the telescope in altitude during an observation. These devices were located near one of the pivots of the instrument and provide a convenient way of referencing the orientation of the telescope; that is the telescope could be in either a "Clamp East" or "Clamp West" orientation. Both transit circles were reversed (rotated 180° in azimuth), thus changing clamp, approximately every 30 days. This was done to mitigate any clamp-dependent systematics.

The wheels of the graduated circles of each of the transit circles were rotated about 10° with respect to the tubes midway through the observing program. Observations taken before this circle rotation were referred to as from "Circle One" and after the rotation from "Circle Two".

Most of the celestial objects observed in this program fall into three categories; FK5 stars (Fricke et al.

Table 2. Observations made by the Seven-inch transit circle located near Blenheim, New Zealand, during 1987-1996

Stellar Objects			Solar System Objects			
			Sun and Planets		Minor Planets	
Star Class	Number of Obn's	Number in Class	Object	Number of Obn's	Object	Number of Obn's
IRS	174997	23552	∗Sun	∗1166	Ceres	337
Clocks	29878	223	∗Mercury	∗461	Pallas	361
FK5	102112	3078	∗Venus	∗867	Juno	335
Refraction (LC)	9111	98	∗Mars (day)	∗521	Vesta	386
Azimuth (UC)	12295	49	Mars (night)	402	Hebe	277
Azimuth (LC)	11812	49	Jupiter	391	Iris	324
∗Day	∗38907	∗348	Saturn	446	Flora	238
Radio	3687	117	Uranus	581	Metis	189
Miscellaneous	17856	672	Neptune	516	Eunomia	298
					Hygiea	284
					Melpomene	244
					Nemausa	68
					Amphitrite	269
Totals	400655	28186	Totals	5351	Totals	3610

∗ Observations not reduced.
UC = Upper culmination.
LC = Lower culmination.

Table 3. Estimated standard deviations of the selected right ascension tour adjustments models. Nine different models were tested to adjust each tour's observations of a set of Hipparcos reference stars and the one providing the best fit was used to differentially adjust all the observations from that tour

Estimated standard deviations of the models					
Right Ascensions (units = arcseconds)					
Telescope	Circle	Median	Minimum	Maximum	No. of Tours
Six-inch	Circle One	0.186	0.022	0.469	1969
Six-inch	Circle Two	0.182	0.010	0.430	2719
Seven-inch	Circle One	0.194	0.052	0.383	1452
Seven-inch	Circle Two	0.201	0.046	0.421	1853

Table 4. Estimated standard deviations of the selected declination tour adjustment models. Twenty one different models were tested to adjust each tour's observations of a set of Hipparcos reference stars and the one providing the best fit was used to differentially adjust all the observations from that tour

Estimated standard deviations of the models					
Declinations (units = arcseconds)					
Telescope	Circle	Median	Minimum	Maximum	No. of Tours
Six-inch	Circle One	0.221	0.017	0.596	1947
Six-inch	Circle Two	0.216	0.010	0.644	2714
Seven-inch	Circle One	0.274	0.060	0.757	1447
Seven-inch	Circle Two	0.293	0.020	0.648	1854

1988; 1991), the program stars and solar system objects. Tables 1 and 2 give the number of stars in each category and the number of observations made. The program stars, primarily, consisted of International Reference Stars (IRS) (Corbin & Warren 1991), but also included in this class were AGK3R stars and SRS that were not in the IRS. For brevity's sake we shall denote this entire class as IRS. The magnitude range of the majority of the stars in this catalog extends from the brightest FK5 stars down to, on the faint end, about 10th magnitude. The Seven-inch transit circle was able to reach as faint as 11th magnitude which allowed it to observe the fainter minor planets, SRS and radio stars.

Table 5. Weights applied when combining observations from the two transit circles to form a single position

Weights for combined observations		
Zenith Distance	RA obs.	Dec. obs.
80.0	0.00	0.00
75.0	0.16	0.03
70.0	0.29	0.14
65.0	0.42	0.24
60.0	0.56	0.34
55.0	0.68	0.43
50.0	0.78	0.53
45.0	0.87	0.62
40.0	0.93	0.72
35.0	0.97	0.82
30.0	0.98	0.89
25.0	0.99	0.94
20.0	1.00	0.97
15.0	1.00	0.99
10.0	1.00	1.00
5.0	1.00	1.00
0.0	1.00	1.00

Every effort was made to obtain 6 good observations of each star distributed equally between clamps and circles. However, some stars were added to the program too late to obtain that ideal distribution. For the late arrivals it was decided that a minimum of three good observations in right ascension and declination would be required. Of course, the FK5 stars that served as clock, azimuth, refraction, IRS reference, and day stars accrued many more than the minimum number of observations.

3. Discussion

3.1. Procedures

Traditional corrections were applied for the inclination of the micrometer, irregularities of the pivots and the micrometer screw, clamp and circle differences, circle diameter corrections, variation of latitude, and refraction, as well as collimation, level, azimuth, and nadir.

Measurements of the instrumental flexure determined from the horizontal collimators were made for each transit circle but these exhibited very large variations. Since a more consistent determination of the flexure can be determined from the star observations (Holdenried & Rafferty 1997), the flexure determined from the horizontal collimators was not applied.

Since the formation of the most recent absolute catalog from the Six-inch, the $W1_{J00}$, showed that a more consistent determination of the flexure can be extracted from star observations (Holdenried & Rafferty 1997), this method was tried with the $W2_{J00}$ observations. Although excellent results were obtained from the Six-inch observations, the results from the Seven-inch were not satisfactory, showing a systematic error that was a function of zenith distance. The method involved using FK5 stars to solve for corrections to the flexure and refraction, and using circumpolar stars to solve for a correction to the latitude. This last step was necessary for an absolute program such as the $W1_{J00}$; however, in the case of the Seven-inch data, it was felt that the below pole observations of the circumpolar stars were the source of the systematic errors. Therefore, another method was employed, fitting a cubic spline to reduce the residuals of all Hipparcos stars but excluding the below pole observations (which are not necessary for the differential reductions). This new appoarch gave nearly identical results for the Six-inch as the other method and it removed the systematic differences seen in the Seven-inch observations. For consistency the cubic spline method was used on both the Six-inch and Seven-inch $W2_{J00}$ observations.

Observations were grouped into "tours". Usually two tours were taken per night, dividing the night in half between two observers. Each tour contained determinations of the collimation, level, nadir, azimuth, and flexure taken at two to three hour intervals for the nighttime tours. For the Seven-inch transit circle, azimuth determinations were made hourly due to apparent motions of the piers. For each tour, observations were made of selected groups of stars to determine corrections to the sidereal time, azimuth, and refraction. In addition, a subset of stars, following a concept developed by Küstner and henced referred to as Küstner stars, distributed over the entire sky was observed during each tour to check for nightly variations of the instrument or atmosphere over large angles. The IRS were grouped in zones of 15° of declination and were observed with FK5 reference stars to allow differential reductions for each tour. As was explained previously, although the catalog was planned to be absolute, the IRS were observed in such a way as to allow differential reductions. Because the differential reductions could be carried out in almost real-time, they provided an opportunity to closely monitor the quality of the observations. Differential observations also are an effective method of reducing the random and systematic errors in the data.

The requirement imposed by the even distribution in time and zenith distance of the clock, azimuth, refraction, and Küstner stars as well as the need to choose IRS and their reference stars while maintaining a balance of all observations over the Clamps and Circles necessitated the development of an automatic method of selecting the stars to be observed for each tour. The logical criteria for this Star Selector software were constructed by T. Corbin, while the software and system development was done by F.S. Gauss.

Table 6. Mean right ascension positional errors for each transit circle as well as the mean errors and epochs for the final positions

Right ascension errors

	Six-inch			Seven-inch			Total			
Declination Range	σ mas	$\bar{\sigma}$ mas	n stars	σ mas	$\bar{\sigma}$ mas	n stars	mean epoch	σ mas	$\bar{\sigma}$ mas	n stars
+90 to +85	234	68	97				1990.80	234	68	97
+85 to +80	218	71	265				1990.73	218	71	265
+80 to +75	203	70	435				1990.70	203	70	435
+75 to +70	208	74	577				1990.73	208	74	577
+70 to +65	203	72	736				1990.76	203	72	736
+65 to +60	203	74	874				1990.80	203	74	874
+60 to +55	197	72	1018				1990.79	197	72	1018
+55 to +50	197	72	1156				1990.86	197	72	1156
+50 to +45	193	71	1277				1990.83	201	74	1277
+45 to +40	192	71	1416				1990.83	192	71	1416
+40 to +35	188	70	1533				1990.86	188	70	1533
+35 to +30	188	70	1579	128	94	16	1990.79	188	70	1579
+30 to +25	190	72	1765	165	63	191	1990.84	189	71	1765
+25 to +20	191	70	1748	181	55	236	1990.87	191	69	1748
+20 to +15	199	74	1782	187	48	228	1990.84	199	73	1782
+15 to +10	192	72	1811	191	45	210	1990.85	193	71	1811
+10 to +5	191	71	1827	193	44	244	1990.90	192	70	1827
+5 to 0	193	73	1820	209	76	1792	1991.51	208	55	1822
0 to −5	194	74	1727	208	74	1796	1991.58	208	55	1802
−5 to −10	189	52	282	206	72	1825	1992.14	205	70	1822
−10 to −15	185	48	207	200	70	1829	1992.13	200	69	1831
−15 to −20	183	52	204	200	70	1842	1992.14	200	69	1841
−20 to −25	163	51	200	199	69	1701	1992.13	199	69	1701
−25 to −30	149	56	186	198	68	1596	1992.12	196	68	1596
−30 to −35	123	98	67	196	69	1787	1992.16	196	69	1787
−35 to −40				199	69	1832	1992.16	199	69	1832
−40 to −45				200	69	1657	1992.23	200	69	1657
−45 to −50				198	70	1644	1992.21	198	70	1644
−50 to −55				201	70	1329	1992.15	201	70	1329
−55 to −60				204	71	1184	1992.27	204	71	1184
−60 to −65				201	70	1034	1992.21	201	70	1034
−65 to −70				205	70	799	1992.24	205	70	799
−70 to −75				208	70	648	1992.22	208	70	648
−75 to −80				222	73	494	1992.25	222	73	494
−80 to −85				229	70	310	1992.30	229	70	310
−85 to −90				237	65	111	1992.26	237	65	111

3.2. Tour adjustments

Differential adjustments were applied to each tour from a least squares fit to a set of Hipparcos reference stars. Numerous models (9 in right ascension and 21 in declination) were tested for each tour, and the one providing the best fit was used. The models incorporated coefficients that depended on zenith distance, the tangent and sine of the zenith distance, and arguments of time. Tables 3 and 4 present the median, minimum, and maximum estimated standard deviations (average mean error of a single observation) of the selected models for each transit circle.

3.3. Combined observations

The locations of the two transit circles allowed nearly 70° overlap in the declinations accessible to each telescope. For those stars in this overlap region, the observations were combined in a weighted mean. The weights (given in Table 5) were based on the mean standard deviation of a single observation as a function of zenith distance and were an attempt to account for the degradation suffered by observations made through large air masses.

3.4. Mean errors of the observation and positions

The weighted standard deviation of the mean is given with the position of each star. For the stars observed with both transit circles, the mean positions and their standard deviation of the mean as determined by each instrument are given as well as the weighted mean and weighted standard deviation of the mean of the combined data.

Table 7. Mean declination positional errors for each transit circle as well as the mean errors and epochs for the final positions

Declination errors

	Six-inch			Seven-inch			Total			
Declination Range	σ mas	$\bar{\sigma}$ mas	n stars	σ mas	$\bar{\sigma}$ mas	n stars	mean epoch	σ mas	$\bar{\sigma}$ mas	n stars
+90 to +85	251	72	97				1990.76	251	72	97
+85 to +80	226	73	265				1990.72	226	73	265
+80 to +75	216	74	435				1990.68	216	74	435
+75 to +70	212	75	577				1990.71	212	75	577
+70 to +65	215	76	736				1990.73	215	76	736
+65 to +60	213	78	874				1990.76	213	78	874
+60 to +55	206	74	1018				1990.74	206	74	1018
+55 to +50	209	76	1156				1990.83	209	76	1156
+50 to +45	201	74	1277				1990.80	201	74	1277
+45 to +40	194	71	1416				1990.80	194	71	1416
+40 to +35	200	73	1533				1990.83	200	73	1533
+35 to +30	201	75	1579	142	189	16	1990.76	201	75	1579
+30 to +25	201	75	1765	210	114	191	1990.80	202	75	1765
+25 to +20	207	76	1748	227	91	236	1990.82	209	76	1748
+20 to +15	206	77	1782	219	72	228	1990.80	208	77	1782
+15 to +10	209	81	1811	218	65	210	1990.82	211	80	1811
+10 to +5	201	79	1827	216	58	244	1990.85	203	78	1827
+5 to 0	194	80	1820	217	93	1792	1991.45	215	64	1822
0 to −5	186	80	1727	218	87	1796	1991.58	211	63	1802
−5 to −10	183	59	282	227	86	1825	1992.15	225	84	1822
−10 to −15	179	57	207	220	80	1829	1992.16	218	80	1831
−15 to −20	173	62	204	223	80	1842	1992.16	221	79	1841
−20 to −25	173	70	200	221	78	1701	1992.14	219	77	1701
−25 to −30	165	86	186	221	76	1596	1992.14	220	76	1596
−30 to −35	124	148	67	217	77	1787	1992.18	217	77	1787
−35 to −40				220	77	1832	1992.17	220	77	1832
−40 to −45				225	78	1657	1992.25	225	78	1657
−45 to −50				222	78	1644	1992.22	222	78	1644
−50 to −55				222	77	1329	1992.16	222	77	1329
−55 to −60				227	79	1184	1992.27	227	79	1184
−60 to −65				228	79	1034	1992.22	228	79	1034
−65 to −70				235	81	799	1992.25	235	81	799
−70 to −75				247	83	648	1992.21	247	83	648
−75 to −80				266	87	494	1992.26	266	87	494
−80 to −85				275	84	310	1992.30	275	84	310
−85 to −90				298	79	111	1992.23	298	79	111

Tables 6 and 7 group the average standard deviations of a single observation, the average standard deviation of the mean, and the number of stars into five degree zones of declination. The average standard deviation of a single observation was close to 200 mas in right ascension and 215 mas in declination. The average standard deviation of the mean position for a star varied by the number of observations. Since the majority of stars in each zone were IRS, which averaged six (two on Circle One and four on Circle Two) observations each, the average standard deviation of the mean was close to 70 mas in right ascension and 77 mas in declination. In the declination zone −5° to +5° the Six-inch and Seven-inch observed the same IRS stars thus doubling the number of observations each received, and this manifests itself in a sharp drop in the average standard deviation of the mean.

3.5. Epochs

The average epoch of a position in right ascension is 1991.53 and in declination 1991.52. However, because the Seven-inch started observing about a year after the Six-inch, there is a pronounced dependence on declination of the epochs of individual stars. Tables 6 and 7 show the epochs averaged over the same 5° zones in declination that were used in the groupings for the errors.

Table 8. Additional phase corrections applied to Mars, Jupiter, and Saturn

		Additional phase corrections		
Mars	-	Six-inch	-	$\pm 0.15 + \text{phase corr}_\alpha \times 0.282$
	-		-	$\pm 0.10 + \text{phase corr}_\delta \times 1.290$
	-	Seven-inch	-	± 0.88
	-		-	$\text{phase corr}_\delta \times 3.450$
Jupiter	-	Six-inch	-	$\text{phase corr}_\alpha \times 1.901$
	-		-	$\text{phase corr}_\delta \times 6.426$
	-	Seven-inch	-	$\pm 0.25 + \text{phase corr}_\alpha \times 4.250$
	-		-	$\pm 0.15 + \text{phase corr}_\delta \times 4.445$
Saturn	-	Six-inch	-	$\text{phase corr}_\alpha \times 7.000$
	-	(limb obs)	-	none
	-	Six-inch	-	none
	-	(ring obs)	-	none
	-	Seven-inch	-	none
	-		-	none

3.6. Double stars

A few double stars observed by both transit circles showed significant differences. For example, in some cases the image dissector on the Seven-inch transit circle could not split doubles that the observers on the Six-inch transit circle were able to resolve. In those situations, where it was clear that each telescope observed a particular double differently, the observations by one instrument or the other were dropped. Double stars outside the overlap zone for the two telescopes, of course, can not be compared in this way and may have undetected errors in their positions.

3.7. Planetary observations

The purpose of the daytime observations of the Sun, Mercury, Venus, Mars, and bright stars was to create an absolute catalog tied to the dynamical reference frame. Because these observations were not necessary for the link to the ICRF and the quality of these observations makes it difficult to adjust them to the nighttime system, the daytime observations were not reduced.

The same corrections that were developed for the observations of the stars also were applied to the nighttime planetary observations. It is necessary to apply additional corrections to the observations of most of the planets due to their orbital motions, appearances, and distances. These additional corrections must be calculated using data from an ephemeris. For the major planets, ephemeris data from JPL's DE405 (1998) were used, and for the minor planets, USNO (Hilton 1999) provided the ephemerides.

Corrections for orbital motion were applied to bring the mean, measured position into coincidence with the meridian.

$$\mathrm{OMCorr}_\alpha = (\mathrm{TimeObs}_\alpha - \mathrm{ObsRA}) \times \frac{\mathrm{SSMTD}}{\mathrm{SSMTD} \times \mathrm{OM}_\alpha} \quad (1)$$

and

$$\mathrm{OMCorr}_\delta = \frac{\mathrm{ClpSw} \times \mathrm{MicEq}_\alpha \times \mathrm{MPoB} \times \mathrm{OM}_\delta}{\mathrm{SSMTD} \times \cos(\mathrm{ObsDec})} \quad (2)$$

where:

OMcorr_α = right ascension orbital motion correction;
$\mathrm{TimeObs}_\alpha$ = time of observation;
ObsRA = observed right ascension;
SSMTD = sidereal seconds per Mean Time Day;
OM_α = motion in RA per Mean Time Day;
OMcorr_δ = declination orbital motion correction;
ClpSw = clamp switch;
(+1 for East Clamp and −1 for West);
MicEq_α = right ascension micrometer screw equivalent;
MPoB = mean place of bisection (mean measured position minus the collimation);
ObsDec = observed declination;
OM_δ = motion in Dec per Mean Time Day.

Declinations were corrected for horizontal parallax using the following:

$$\mathrm{ParCorr} = \mathrm{EarthRV} \times \mathrm{HorPar} \times \sin(\mathrm{gLat} - \mathrm{ObsDec}) \quad (3)$$

where:

ParCorr = parallax correction;
EarthRV = Earth's radius vector;
HorPar = horizontal parallax;
gLat = geocentric latitude;
ObsDec = observed declination.

Corrections for the visual appearance of each solar system object were based on their appearance in the transit circle and the method of measurement used.

The Seven-inch, observing with the image dissector, used digital centering algorithms developed by Stone (1990). Changes to these algorithms have caused the observations of Mars, Jupiter, and Saturn made between 1987 and 1992 to be dropped. The algorithm also had difficulty with Saturn as the rings tilted edge on during the last year of the program and these observations were also dropped. For Uranus, Neptune, and the minor planets the center of light was observed.

The Six-inch, observing visually, dealt with the planetary objects as follows:

Mars - The four limbs were observed for all the nighttime observations, except for three when the center of light was taken. Corrections for phase were applied using:

$$\text{phase corr}_\alpha = \frac{240}{(1-\lambda)(\cos\delta)} \times q \times \left(\frac{1}{2}\sin^2 Q - \frac{1}{16}(1-\cos i)\sin^2 2Q\right) \tag{4}$$

and

$$\text{phase corr}_\delta = q \times \left(\frac{1}{2}\cos^2 Q - \frac{1}{16}(1-\cos i)\sin^2 2Q\right) \tag{5}$$

where:

phase corr_α = right ascension correction for phase;
phase corr_δ = declination correction for phase;
λ = planet's orbital motion;
δ = declination;
q = defect of illumination;
Q = position angle of the defect of illumination;
i = angle at planet between Earth and Sun.

Minor Planets - No visual appearance corrections were applied as all presented point source images.

Jupiter - The four limbs were observed. Corrections for phase were applied using the same equations as were given for Mars.

Saturn - The four limbs of Saturn were observed about 65% of the time, otherwise the edges of the rings were taken. Even though in previous catalogs no phase corrections were applied to the observations of Saturn, plots of the (O−C)s from the limb observations showed a systematic offset symmetrical around oppositions indicating the need for such an adjustment. The (O−C)s from the ring observations showed no such systematic offsets. Corrections for phase were applied to the limb observations using the same equations used for Mars and Jupiter.

Uranus and Neptune - Center of light was observed and no corrections for phase were applied.

Plots of the (O−C)s as functions of the phase corrections determined from equations above show systematic offsets symmetrical around opposition even after phase corrections given above were applied. The equations used for the Six-inch data, as well as the algorithms developed for the Seven-inch data, are based on the geometric changes in the appearances of these planets. The failures to account for all the phase effects are likely the result of limb darkening or other illumination effects. Empirically correcting for these residual effects is the cause for some concern in that the effects may be in the ephemeris rather than in the observations themselves. However, the Six-inch results for Saturn were able to clarify the situation when the observations of Saturn's limbs showed the systematic offsets while the observations of the rings did not (no such phase corrections could be determined for the Seven-inch Saturn observations because the algorithm used was fitted to both the limbs and rings). The empirically determined, additional phase corrections for Mars, Jupiter, and Saturn are shown in Table 8.

4. Conclusion

Using the positions of the Hipparcos catalog stars to differentially adjust the individual tours made significant improvements to the final results of the program. The resulting catalog is free of most of the systematic errors that would have remained if the original plan of absolute reductions had been followed. In addition the random errors have also been diminished. The value of this catalog to stellar astrometry has certainly been reduced by the outstanding success of Hipparcos. However the observations of the major planets and asteriods should be able to make an important contribution to their astrometry. Improvements to the phase corrections for Mars, Jupiter, and particularly Saturn are significant.

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James Hughes died before the completion of this project. His planning, leadership, and prescient efforts in this undertaking played an important role in its success. It is our wish to present this catalog as a memorial to him.

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