$\mathbf{W2}_{J00}$

THE USNO POLE-TO-POLE OBSERVATIONS, 1985-1996 MADE BY THE SIX-INCH TRANSIT CIRCLE AND SEVEN-INCH TRANSIT CIRCLE

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Preface

The following text describes the observing techniques and reduction procedures used in the formation of this catalog. The information is presented in a very brief form; but, it is hoped, with enough detail to allow the knowledgeable investigator successfully to make use of this data. A much more complete description will be available later in the printed version. In the meantime we felt it important to make the catalog available to the user community, many members of whom have requested that we do so. It is recommended that those who may need more detailed discussions of the procedures used to form the catalog consult the references, in particular the WL_{50} (Hughes, 1992) and the $\mathrm{W5}_{50}$ (Hughes, 1982).

It should be pointed out that, unlike most previous USNO transit circle catalogs, the $\mathrm{W2}_{J00}$ is not an absolute catalog. It is, instead, a differential catalog, adjusted to the the International Celestial Reference Frame (ICRF) (Morrison, 1997) using positions from the Hipparcos Catalogue. This approach was adopted because we felt the positions from the $\mathrm{W2}_{J00}$ would be more useful on the ICRF rather than the traditional dynamical reference frame.

1 Introduction

1.1 History

Plans for an observing program 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 absolute catalog tied to the dynamical reference frame. This required both transit circles to be able to observe in the daytime and 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 zones of 15° declination along with a suitable distribution 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 an astrometric satellite called 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 Hipparcos positions to FK5. Since the FK5 exhibited known 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) and not to FK5. Observations for the $\mathrm{W2}_{J00}$ were completed in April, 1995 by the Six-inch transit circle and in February, 1996 by the Seven-inch transit circle. The $W2_{J00}$ 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.

1.2 Program

This catalog contains the combined results of observations made with the Six-inch Transit Circle in Washington, D.C. USA and the Seven-inch Transit Circle in New Zealand, between April 1985 and February 1996. This is the second Washington catalog to be referred to the Equinox of J2000.0 and will be named the $W2_{J00}$.

The majority of the celestial objects observed in this program fall into three categories; FK5 stars (Fricke, 1988 and 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 greatest number of the program stars were International Reference Stars (IRS) (Corbin, 1991), but also included in this class were AGK3R stars and SRS that were not in the IRS. For brevity's sake will shall denote this entire class as IRS.

Table 1

Six-inch Transit Circle Observing Program (1985-1995)				
Star Class	Number of Obn's	Number in Class	Solar System Object	Number of Obn's
IRS	141870	21509	Ceres	481
Clocks	37486	230	Pallas	396
FK5	94762	3234	Juno	312
Refraction (lower culmination)	5729	121	Vesta	511
Azimuth (upper culmination)	7607	23	Hebe	288
Azimuth (lower culmination)	7210	23	Iris	276
∗Day	∗9255	∗84	Flora	257
Radio	3176	106	Metis	221
Miscellaneous	10349	874	Eunomia	265
			∗Sun	∗1863
			∗Mercury	∗596
			∗Venus	∗1426
			∗Mars(day)	∗134
			Mars(night)	588
			Jupiter	727
			Saturn	764
			Uranus	729
			Neptune	617
Totals	317410	26189		10451

∗ observations not reduced

Table 2

Seven-inch Transit Circle				
Observing Program (1987-1996)				
Star Class	Number of Obn's	Number in Class	Solar System Object	Number of Obn's
IRS	174997	23552	Ceres	337
Clocks	29878	223	Pallas	361
FK5	102112	3078	Juno	335
Refraction (lower culmination)	9111	98	Vesta	386
Azimuth (upper culmination)	12295	49	Hebe	277
Azimuth (lower culmination)	11812	49	Iris	324
∗Day	∗38907	∗348	Flora	238
Radio	3687	117	Metis	189
Miscellaneous	10349	874	Eunomia	298
			Hygiea	284
			Melpomene	244
			Nemausa	68
			Amphitrite	269
			∗Sun	∗1166
			∗Mercury	∗461
			∗Venus	∗867
			∗Mars(day)	∗ 521
			Mars(night)	402
			Jupiter	391
			Saturn	446
			Uranus	581
			Neptune	561
Totals	400655	28186		8976

∗ observations not reduced

Because of the inherent high scatter of the daytime observations and the difficulty of putting them on the same system as the nighttime observations, these observations were not reduced.

Every effort was made to obtain 6 good observations of each star distributed equally between clamps and circles (the terms clamp and circle will be defined later). 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.

1.3 Personnel and acknowledgments

The program was carried out under the leadership of J.A. Hughes (1985-1992), C.A. Smith (1993), and F.S. Gauss (1993-1998), directors of the Astrometry Department. The observing program was overseen by T.E. Corbin (1985-1993) and T.J. Rafferty (1993-1996). The operations of the Black Birch station in New Zealand were directed by M.D. Robinson (1985-1989), E.R. Holdenried (1989-1990), T.J. Rafferty (1990-1992), and C.S. Cole (1992-1996). Many Department members served as observers and are listed in Tables 3 and 4.

Table 3

Six-inch Transit Circle

Observers (1985-1995)

Name	Tenure				
C. S. Cole	February	1987	to	March	1991
T. E. Corbin	April	1985	to	April	1995
H. E. Crull	December	1988	to	April	1995
S. J. Dick	April	1987	to	January	1988
J. C. Doty	February	1987	to	April	1995
R. Etheridge	November	1985	to	August	1986
F. S. Gauss	April	1985	to	April	1989
M. E. Germain	October	1993	to	April	1994
D. M. Hall	September	1986	to	April	1995
G. S. Hennessy	October	1993	to	November	1994
J. L. Hershey	April	1985	to	March	1988
R. B. Hindsley	December	1986	to	June	1994
E. R. Holdenried	April	1985	to	April	1995
E. S. Jackson	April	1985	to	April	1995
I. Jordan	June	1988	to	March	1990
V. Kallarakal	April	1985	to	April	1995
J. C. Martin	May	1990	to	January	1995
J. M. Muse	November	1990	to	October	1991
R. J. Miller	April	1985	to	April	1995
M. D. Robinson	May	1991	to	April	1995
T. J. Rafferty	April	1985	to	April	1995
C. B. Sandy	February	1990	to	January	1993
D. K. Scott	May	1985	to	November	1986
C. A. Smith	April	1985	to	March	1991
S. E. Urban	September	1985	to	April	1995
G. L. Wycoff	September	1985	to	April	1995
Z. G. Yao	April	1985	to	April	1995

Table 4

Seven-inch Transit Circle					
Observers (1987-1996)					
Name	Tenure				
C. S. Cole	May	1991	to	February	1996
W. B. Dunn	June	1987	to	November	1987
W. Durham	December	1988	to	September	1991
E. R. Holdenried	July	1987	to	June	1990
R. Hudson	April	1992	to	February	1996
I. Jordan	May	1990	to	September	1995
T. Love	January	1994	to	February	1994
B. R. Loader	June	1987	to	February	1996
R. Millington	June	1987	to	February	1996
J. Priestley	September	1993	to	September	1993
M. D. Robinson	June	1987	to	December	1995
T. J. Rafferty	June	1987	to	March	1992
R. C. Stone	June	1987	to	December	1988
A. Wadsworth	November	1991	to	September	1995

The preliminary daily reductions and editing of the data were carried out by a team composed of various observers and included at one time or another Holdenried, Miller, Rafferty, Urban, Wycoff, Hall, Crull, Dick, Loader, and Jordan. The final reductions were carried out by Holdenried and Rafferty with close and frequent consultation with C.A. Smith and T.E. Corbin.

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

2 Instrumentation, accessories, and procedures

2.1 The USNO Six-inch transit circle

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 as used during the previous programs, the $W5_{50}$ (Hughes, 1982) and the $W1_{J00}$ (Holdenried and Rafferty, 1997).

2.2 The USNO Seven-inch transit circle

The Seven-inch transit circle was built by the USNO Instrument Shop in 1948. It's previous program, the WL_{50} (Hughes, 1992), was a visual catalog made from El Leoncito, Argentina. For the $W2_{J00}$, the telescope was located on the Black Birch ridge at an elevation of 1350m, 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°44′ 41.″4 and a longitude of 173°48′ 11.″99 East.

2.3 New equipment

For the $W2_{J00}$ it was decided to make observations with the Six-inch transit circle visually because of it's long and continuous series of excellent catalogs made in this mode. The major changes made to the Six-inch prior to the start of the $W2_{J00}$ observing program included; a second glass circle, two additional magnitude screens, and an upgrade to the photoelectric circle scanning system. At the beginning of Circle Two the photoelectric scanners were replaced with CCD devices (Rafferty, 1986).

Major changes made to the Seven-inch transit circle after it's completion of the WL_{50} and prior to the beginning of the $W2_{J00}$ observing program included the replacement of the visual micrometer with a new one using an image dissector as the detector (Hughes, 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, at the beginning of Circle Two the circle scanning system was upgraded to use CCD's (Rafferty, 1986).

2.4 Accessories

2.4.1 Data acquisition and control system

Hewlett Packard HP1000 computers were used to acquire data and to perform preliminary reductions for both transit circles.

2.4.2 Environmental data

Air temperature was measured to $0.^{\circ}1C$ using Hy-cal platinum resistance probes. Air pressure was measured to $0.1mm$ of mercury using Setra barometers. Dewpoint was measured to $5.^{\circ}0F$ using Honeywell probes treated with lithium chloride activation solution and dried.

2.5 Clock system

Cesium frequency standards were used for both transit circles. A once per second pulse from the clocks was used to trigger an interrupt-driven routine in the data acquisition computer that maintained the time in a common area accessible to all programs and accurate to approximately 30 microseconds.

2.6 Procedures

2.6.1 Instrument reversal

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°0 in azimuth), thus changing clamp, approximately every 30 days. This was done to mitigate any clamp-dependent systematics.

2.6.2 Circle rotation

The wheels of the graduated circles of each of the transit circles were rotated 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".

2.6.3 Observing tours

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 clock, azimuth, and refraction. In addition, a subset of stars, following a concept developed by Kustner and henced referred to as Kustner stars, distributed over the entire sky was observed during a 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 nightly differential reductions. 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 monitor the quality of the observations in that time frame. Differential observations also are an effective method of reducing the random and systematic errors in the data.

2.6.4 Star Selector

The requirement imposed by the even distribution in time and zenith distance of the clock, azimuth, refraction, and Kustner 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 actual coding was done by F.S. Gauss.

3 Right ascension

3.1 The right ascension screw of the micrometer

The Six-inch traveling micrometer was driven by a screw to which was attached a circular encoder for measuring the micrometer's position. Therefore it was necessary to determine and apply corrections for the error in the screw to the encoder output. The position of the Seven-inch traveling micrometer, although driven by a screw, was directly measured by a linear encoder. Thus these measures did not have to be corrected by the application of screw errors. The Six-inch micrometer screw errors were measured three times; in 1984, at the change between Circles in 1989, and finally at the end of the program in 1995. The errors determined from the measures in 1984 and 1989 agreed closely enough that they were combined. Progressive and periodic errors were found. Both the progressive and the periodic errors derived from the 1995 measures differed significantly from the 1989 results. It, therefore, was decided that time interpolated values of the screw errors (progressive and periodic) would be calculated for observations taken between the 1989 and 1995 sets (i.e. all observations on Circle Two), and applied to each micrometer encoder reading.

3.2 Inclination

Normally the micrometer of a transit circle is adjusted so that the scale by which right ascension is measured exhibits no inclination with respect to the sky. That is, if vertical wires are used to measure an object's position in right ascension, then these wire are parallel to the meridian. In the case of the Six-inch, during the change from Circle One to Circle Two, these wires were incorrectly adjusted leaving them inclined to the meridian and resulting in a significant correction that must be applied to the right ascension measures and is dependent on the vertical place in the field of the object observed. The micrometer was correctly adjusted after the third clamp on Circle Two. In the case of the Seven-inch, it appears from an analysis of the observations that an inclination was also introduced when changing from Circle One to Circle Two. In this case the initial adjustment of the wires was correct, but some kind of relaxation phenomenon caused them to shift later. The inclination was derived from star observations and found to vary with clamp. Thus, for Circle Two, a clamp dependent correction for the inclination is applied to the right ascension measures.

3.3 Irregularities of the pivots

In the case of the Six-inch, pivot irregularities were measured on four different occasions after the the pivots were re-ground in 1963, the last measures being taken in 1989 at the break between circles. No significant change was detected so all measures were averaged and applied as a function of the pointing of the telescope. The pivot irregularities of the Seven-inch were measured in 1973, and at the break between circles in this program in 1992. No significant change was evident so a mean was formed and applied as described above.

3.4 Collimation of the telescope

The collimation of each telescope was determined at intervals of between two and three hours by means of horizontal collimating telescopes mounted to the north and south of the main telescope but within the telescope pavilion. A mean collimation was formed for a tour and applied to each observation.

3.5 Level

The level of each telescope was measured by auto-collimating on the reflection of the micrometer wires in a basin of mercury placed beneath the instrument in the direction of the nadir. The amount of displacement from the collimation point was the value taken as the level. It was measured at intervals of between two and three hours, a linear rate computed, and the value interpolated to the time of transit.

3.6 Azimuth

The azimuth of the mires (pin-hole light sources mounted several hundred meters to the north and south of each transit telescope) with respect to each telescope, was measured at intervals of between one and three hours depending on the telescope. Because of indications of an unstable azimuth, the azimuths of the mires of the Seven-inch were measured much more frequently (as often as once an hour) than were the azimuths of the Six-inch, which were observed about every two to three hours. The azimuth of the mires with respect to the celestial pole was determined by observations of a special set of circumpolar stars (azimuth stars). The azimuth of the mires with respect to the telescope was added to the azimuth of the mires with respect to the celestial pole to form the azimuth of the telescope. A linear rate was computed from the difference between consecutive observations of the azimuths of the mires and the value interpolated to the time of transit.

3.7 Sidereal time

The sidereal time at each telescope was maintained by clocks driven by cesium beam frequency standards. The clock time was corrected for the variation of longitude (provided by IERS), the Equation of the Equinoxes, and a correction derived from observations of a special set of stars (clock stars). The clock stars for both telescopes consisted of a set of 203 FK5, Part I, stars evenly distributed in right ascension and declination between declinations $-30°$ and $+30°$. A clock correction was derived from the mean (O-C) of clock stars observed during a tour. On the average between 5 and 9, and never less than 4, clock stars were observed per tour.

3.8 Clamp differences

Differences between the right ascension (O-C)'s of the same stars observed on Clamp East and Clamp West were grouped in $5°$ zones of zenith distance and averaged. Half of the average zonal difference was added to or subtracted from all observations in that zone depending on the clamp on which the observations were made.

3.9 Circle differences

Differences between the right ascension (O-C)'s of the same stars observed on Circle One and Circle Two were grouped in $5°$ zones of zenith distance and averaged. This was done after the clamp differences were applied. Half of the average zonal difference was added to or subtracted from all observations in that zone depending on the circle on which the observations were made.

3.10 Tour Adjustments

Differential adjustments were applied to each tour from a least squares fit to a set of Hipparcos reference stars. This set of stars was distributed over the entire sky and consisted of those Kustner stars in the tour that were observed by Hipparcos and were not found to exhibit multiplicity. A number of models incorporating coefficients that depended on various combinations of the zenith distance, the sine and cosine of the zenith distance, and arguments of time and and powers of time, were tested for each tour. The one providing the best fit was used. After the tour corrections were applied, the (O-C)'s of the Hipparcos stars, when averaged by star and collected as a function of declination, exhibited slight systematic deviations about zero. A cubic spline was fit to these deviations and applied to all observations as a function of declination. Table 5 presents information about the estimated standard deviation of the models for the tour corrections.

Table 5

Estimated Standard Deviation 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

3.11 Image Dissector

It was discovered after the program had been under way for a considerable time that an error in the image dissector processing software was causing a systematic offset in the observations of the Seven-inch, that depended on observed magnitude. The amount of this offset was one pixel, and only occurred under certain conditions. This problem was corrected after the circle rotation but affected all of the data from Circle One. A correction for the effect was developed from a statistical analysis of the Circle One observations and applied to the data. However, because it is a statistical correction, individual observations may be biased, although at a reduced level, by some residual error.

4 Declination

4.1 Corrections to declination micrometer screw

For the Six-inch transit circle, the progressive screw error was measured before the observing program began and after it ended, and was judged not to have changed significantly between the two determinations; therefore the two sets were averaged. This averaged screw error was applied to the mean declination screw value of each observation. No periodic screw error was detected. Corrections for the inclination of the micrometer wires and reduction to the meridian were also applied to the mean screw value. The micrometer of the Seven-inch telescope had no movable declination slide so no corrections were necessary.

4.2 Nadir

The nadir point, in conjunction with the level, was determined by auto-collimating over a mercury basin. This was done at intervals of between two and three hours, a linear rate computed, and the value interpolated, as a function of time, to the time of transit.

4.3 Circle diameter corrections

The Høg method (three microscope diameters) of determining the circle diameter corrections was used. Changes in the circle diameter corrections for both transit circles were noticed after the rotation of the circles midway through their observing programs and different sets of circle diameter corrections were used for each Circle

4.4 Assumed latitude and variation

An assumed latitude of $+38^\circ\ 55'\ 14''.257$ was used in the reductions for the Six-inch transit circle (Hughes, 1975) and $-41^\circ\ 44'\ 41''.4$ was used for the Seven-inch transit circle. Corrections for the variation of latitude were provided by the IERS.

4.5 Refraction

Corrections for refraction came from the Fourth Edition of Pulkovo Refraction Tables (see WL_{50} for details, Hughes, 1992).

4.6 Clamp differences

Differences between the declination (O-C)'s of the same stars observed on Clamp East and Clamp West were grouped in 5° zones of zenith distance and averaged. Half of the average zonal difference was added to or subtracted from all observations in that zone depending on the clamp on which the observations were made.

4.7 Circle differences

Differences between the declination (O-C)'s of the same stars observed on Circle One and Circle Two were grouped in 5° zones of zenith distance and averaged. This was done after the clamp differences were applied. Half of the average zonal difference was added or subtracted to all observations in that zone depending on the circle on which the observations were made.

4.8 Flexure determined from horizontal collimators

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, 1997), the flexure determined from the horizontal collimators was not applied.

4.9 Latitude, constant of refraction, and flexure corrections

The new method, developed for the $W1_{J00}$, to determine the corrections to the constant of refraction and flexure using all FK5 stars, and the correction to the assumed latitude from the circumpolar observations (Holdenried, 1997) was not used for the $W2_{J00}$. Although Six-inch transit circle observations gave excellent results, when used with the Seven-inch observations systematic differences as a function of zenith distance were still apparent. The source of these differences was not discovered. Instead a cubic spline was used to adjust the observed positions to the Hipparcos system. For consistency the same method was used on the Six-inch observations.

4.10 Tour adjustments

Differential adjustments were applied to each tour from a least squares fit to a set of Hipparcos reference stars. A number of models 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 time. Table 6 presents information about the estimated standard deviation of the models for the tour corrections.

Table 6

Estimated Standard Deviation 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

4.11 Image Dissector

As with the right ascensions, it was discovered after the program had been under way for a considerable time that an error in the image dissector processing software was causing a systematic offset in the observations of the Seven-inch, that depended on observed magnitude. This problem was corrected after the circle rotation but affected all of the data from Circle One. A correction for the effect was developed from a statistical analysis of the Circle One observations and applied to the data. However, because it is a statistical correction, individual observations may be biased, although at a reduced level, by some residual error.

5 Combined Observations

The locations of the two transit circles allowed for a 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 using:

$$\bar{o} = \frac{\sum_{i=1}^{n} w_i o_i}{\sum_{i=1}^{n} w_i}$$

where:

o_i	-	single observation
w_i	-	weight for o_i based on its zenith distance
$\bar{o}$	-	mean observed position

The weights (given in Table 7) 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.

Table 7

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

6 Errors

6.1 Mean Errors of the Observation and Positions

The weighted standard deviation of a single observation was determined using:

$$\sigma_o = \sqrt{\frac{\sum_{i=1}^{n} w_i(o_i - \bar{o})^2}{(n-1)}}$$

and the weighted standard deviation of the mean using:

$$\bar{\sigma}_{\bar{o}} = \sqrt{\frac{\sum_{i=1}^{n} w_i (o_i - \bar{o})^2}{(n-1)n}}$$

where:

o_i	-	single observed position
w_i	-	weight for o_i based on its zenith distance
$\bar{o}$	-	mean observed position
σ_o	-	standard deviation of a single observation
$\bar{\sigma}_{\bar{o}}$	-	standard deviation of the mean

The standard deviation of the mean is given with the position of each star. For the stars observed with both transit circles, the mean position and 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.

Tables 8 and 9 group into five degree zones of declination: the average standard deviations of a single observation, the average standard deviation of the mean, and the number of stars. 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° , both the Six-inch and Seven-inch observed the same IRS stars doubling the number of observations each received, and this manifests itself in a sharp drop in the average standard deviation of the mean.

Table 8

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

Table 9

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

7 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. This is shown in Table 10 where the epochs have been averaged over the same 5° zones in declination that were used in the preceding tables for the errors.

Table 10

	Epochs	
Declination Range	R.A	Dec.
+90 to +85	1990.80	1990.76
+85 to +80	1990.73	1990.72
+80 to +75	1990.70	1990.68
+75 to +70	1990.73	1990.71
+70 to +65	1990.76	1990.73
+65 to +60	1990.80	1990.76
+60 to +55	1990.79	1990.74
+55 to +50	1990.86	1990.83
+50 to +45	1990.83	1990.80
+45 to +40	1990.83	1990.80
+40 to +35	1990.86	1990.83
+35 to +30	1990.79	1990.76
+30 to +25	1990.84	1990.80
+25 to +20	1990.87	1990.82
+20 to +15	1990.84	1990.80
+15 to +10	1990.85	1990.82
+10 to +5	1990.90	1990.85
+5 to 0	1991.51	1991.45
0 to −5	1991.58	1991.58
−5 to −10	1992.14	1992.15
−10 to −15	1992.13	1992.16
−15 to −20	1992.14	1992.16
−20 to −25	1992.13	1992.14
−25 to −30	1992.12	1992.14
−30 to −35	1992.16	1992.18
−35 to −40	1992.16	1992.17
−40 to −45	1992.23	1992.25
−45 to −50	1992.21	1992.22
−50 to −55	1992.15	1992.16
−55 to −60	1992.27	1992.27
−60 to −65	1992.21	1992.22
−65 to −70	1992.24	1992.25
−70 to −75	1992.22	1992.21
−75 to −80	1992.25	1992.26
−80 to −85	1992.30	1992.30
−85 to −90	1992.26	1992.23

8 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.

9 Solar system 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 dropped.

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 were used, and for the minor planets, James Hilton provided the ephemerides.

9.1 Orbital motion corrections

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

$$OMCorr_\alpha = (TimeObs_\alpha - ObsRA) \times \frac{SSMTD}{SSMTD \times OM_\alpha} \quad (1)$$

and

$$OMCorr_\delta = \frac{ClpSw \times MicroEq_\alpha \times MPoB \times OM_\delta}{SSMTD \times cos(ObsDec)} \quad (2)$$

where:

$OMcorr_\alpha$	-	right ascension orbital motion correction
$TimeObs_\alpha$	-	time of observation
$ObsRA$	-	observed right ascension
$SSMTD$	-	sidereal seconds per Mean Time Day
	-	($SSMTD = 886636.555368$)
OM_α	-	motion in RA per Mean Time Day
$OMcorr_\delta$	-	declination orbital motion correction
$ClpSw$	-	clamp switch (+1 for East Clamp and -1 for West)
$MicroEq_\alpha$	-	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

9.2 Visual appearance corrections

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 R.C. Stone (Stone, 1990). Changes to these algorithms have caused the observations of Mars, Jupiter, and Saturn made between 1987 and 1992 to be dropped. Problems developed with the algorithm for Saturn as the rings tilted edge on caused problems during the last year of the program and these observations were also dropped. Uranus, Neptune, and the minor planets were observed center of light.

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:

$$phase\ corr_\alpha = \frac{240}{(1-\lambda)(cos\ \delta)} \times q \times (\frac{1}{2}sin^2 Q - \frac{1}{16}(1 - cos\ i)sin^2 2Q) \quad (3)$$

and

$$phase\ corr_\delta = q \times (\frac{1}{2}cos^2 Q - \frac{1}{16}(1 - cos\ i)sin^2 2Q) \quad (4)$$

where:

$phase\ corr_\alpha$	-	right ascension correction for phase
$phase\ corr_\delta$	-	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. Corrections for phase were applied to the limb observations made by the Six-inch 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 (3) and (4) show systematic offsets symmetrical around opposition. Equations (3) and (4) 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 a result of limb darkening or other illumination effects. The use of (O-C)s caused some concern that the residual effect was in the ephemeris rather than in the observations themselves. The Six-inch results for Saturn clarified the situation, the observations of Saturn's limbs showed the systematic offsets whereas 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 are as follows:

Table 1

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

9.3 Parallax correction

In declination, a correction based on the horizontal parallax at the time of the observation, the Earth's radius vector, and the difference between the geocentric latitude and observed declination was applied.

$$ParallaxCorr = EarthRV \times HorPar \times sin(gLat - ObsDec) \qquad (5)$$

where:

$ParallaxCorr$	-	parallax correction
$EarthRV$	-	Earth's radius vector
	-	(for Six-inch = 0.998691
$HorPar$	-	horizontal parallax
$gLat$	-	geocentric latitude
	-	(for Six-inch = 38.732576)
$ObsDec$	-	observed declination

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