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CERRO TOLOLO INTER-AMERICAN OBSERVATORY

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GEODETIC AND ASTRONOMICAL COORDINATES OF THE CERRO TOLOLO INTER-AMERICAN OBSERVATORY

By

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INTRODUCTION

Cerro Tololo Inter-American Observatory (CTIO) is located about 34 miles ESE of La Serena, Chile. Approximate coordinates, taken from a topographic sheet based on the 1924 International Reference Ellipsoid and the 1956 Provisional South American Datum, are longitude W70°48'16", latitude S30°9'56", altitude 2210 meters. However, since the systematic errors of the above datum are not known and can be significant, the true location of the observatory has been uncertain.

The GEOS series of satellites have been launched for geodetic purposes, and they carry strobe lights that can be programmed to flash at precisely determined times. Therefore observations of these satellites should permit station location determinations, particularly since these satellites are well tracked and there dynamics are well known. Further, if simultaneous observations from existing tracking stations that have well-determined coordinates can be obtained, a solution can be considerably strengthened by triangulation. Satellite observations give true geocentric coordinates; transforming through the standard ellipsoid will give true geodetic coordinates. The difference between astronomic coordinates (coordinates with respect to the vertical), and the true geodetic coordinates represent the local deflection of the vertical.

THE SATELLITE

GEOS - II (1968-002A = SDC #3093 = Explorer 36) was launched 11 Jan 1968, with a perigee height of 1077 km, an apogee height of 1569 km, an eccentricity of 0.03, an inclination of 105°8, and period of 112.1 minutes. This period produces a resonance in the motion, in that the satellite makes almost exactly 77 revolutions in 6 days.

The satellite is gravity-gradient stabilized to point towards the center of the earth. It carries storage cells and solar panels for power sources, and has four strobe units which insure almost uniform apparent flash brightness for a large range of zenith distance. A flash has a total duration of 1.4 milliseconds, and a flash sequence consists of seven flashes every four seconds, starting on an even minute.

This satellite and its predecessor, GEOS I, have been used extensively for determining locations of tracking stations in various networks (Marsh *et al*. 1971). In particular, NASA makes optical observations of this satellite with MOTS cameras as part of their mini-track network, one station of which is near Peldehue, just north of Santiago, Chile. This station has well-determined coordinates and is capable of simultaneous observations with CTIO, being only 332 km away. The geodetic coordinates of the MOTS camera at Peldehue are latitude S33°9'7".655, longitude W70°40'8".651 (1927 North American Datum), with an elevation above sea level of 693.4 meters, a geoid height of +270 meters, and a height above the ellipsoid of 963 meters. The astronomic coordinates are S33°9'7".87, W70°40'28".41, giving a deviation of 16".72 towards an azimuth of 269°.

THE TELESCOPE

The University of Michigan's Curtis Schmidt telescope, on loan to CTIO, was used for this experiment. The scale of the instrument, which has an f/3.5 focal ratio, is 96.7 arc secs per mm, and it uses 8x8-inch plates covering a field of 5°.4x5°.4.

To attempt to determine the characteristics of the field of this instrument, several plates of the Pleiades cluster were obtained in January and February 1971. The Pleiades is not a good cluster for such work at CTIO, since its zenith distance is always at least 54°. However, there are no good astrometric clusters in the Southern Hemisphere. Measures were made not only of general field stars, but also of most fainter cluster stars, whose positions are known more accurately. It was from these plates that the above cited scale was obtained. The standard distortion was found to be about 0.4 arc secs per degree^3. It was found that there could be severe field distortion not dependent on distance from plate center; it is assumed that this is due to emulsion wrinkling produced by bending the plate in the plate holder. Such effects were minimized in the present study by the choice of very small reference frames close to the object in question.

EXPERIMENTAL PROCEDURE

Preliminary bearings (altitudes and azimuths) of the satellite from Cerro Tololo were provided by the Smithsonian Astrophysical Observatory. These covered all passes of the satellite visible during the period of interest (28 April 1971 through 13 May 1971) for which the Sun would be more than 12° below the horizon. Assuming a minimum of 4 minutes recycle time for both satellite and telescope, flash times were picked arbitrarily except so as to yield as many sequences per pass as possible. Bearings at the beginning and the end of a flash sequence were obtained by interpolation, and these were converted to equatorial coordinates for setting the telescope. The plate center coordinates were taken as the mean of the first and last coordinates if the entire sequence fell on the given plate; otherwise the coordinates were taken 2° down track from the first flash.

Since an appreciable time was required for the exposures, only two sequences could be handled per satellite pass. Three exposures were taken per sequence. For the first sequence, two 30-second exposures of the field were taken, separated slightly in right ascension. The telescope was then shifted slightly in declination for the satellite exposure, which began three seconds before the first flash and ran for 30 seconds to three seconds after the last flash. For the second sequence the procedure was reversed, with a satellite exposure, followed by two field exposures, off-set in declination. Thus each star formed three images in a small right triangle, while the satellite images were single. Further, the stellar images formed during the satellites flash exposure could be unambiguously identified.

Fourteen nights were scheduled, of which two were cloudy. Plates were taken with the assistance of A. Gomez and R. González. For the first five nights, filterless Eastman Kodak 103a0 plates were used; Eastman Kodak 098-02 plates were used for the remaining nights to obtain a higher band-pass. It would have been desirable to restrict the pass-band by use of a filter and/or a more band-pass restrictive emulsion, since the flashes are from xenon tubes, which are different in color from the star in the reference frames; hence dispersion will produce a small color dependent shift in position, which has not been allowed for.

The provisional ephemeris was found to have an error of almost 2° in right ascension (mostly cross-track), so not all flashes were recorded. In addition, moonlight unduly blackened some plates and also the satellite malfunctioned several nights.

Nevertheless, 26 measurable flashes were recorded on 7 plates taken on 5 nights.

All plates were measured on the semi-automatic measuring machine at the U.S. Naval Observatory of Washington, D. C. The details of the measurement and reduction procedure are given by Harrington and Mintz (1972). The reference catalogue used was the SAO catalogue, which, for the southern hemisphere at this epoch, has an accuracy of a single position of about one arc sec. Since the telescope-measuring machine configuration is capable of an accuracy of about 0.1 arc sec, the present limitation to this procedure is the accuracy of reference star positions. Only linear plate constants were used in reducing measures to spherical coordinates.

The final positions, equator and equinox of 1950, are given in Table I. In this table are given the year, month, day, hour, minute, and nominal second of the flash, the right ascension and declination, along with internal estimates of their errors, and the number of reference stars. The number of reference stars is generally smaller than desirable, since reference frames were kept smaller than one degree in diameter, because of the random field distortion mentioned earlier.

ASTRONOMIC COORDINATES

The astronomic coordinates of the observatory were determined by a method closely related to that suggested by Mintz (1955). In this technique times of transit of known stars through a fixed (unknown) zenith distance are determined to establish local coordinates. Usually many observations are made, and coordinates are determined from some estimation procedure, such as least squares.

Let ϕ, λ, Z be the latitude, longitude, and zenith distance of the transit; it is assumed that approximate values of these are known and that corrections must be derived. Let α and δ be the apparent place of the star observed, and let $h = t - \lambda - \alpha$ be the local hour angle of the star, where t is the sidereal time of the observation. Then, from the astronomical triangle,

$$\cos z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h, \qquad (1)$$

which if differentiated yields

$$\begin{aligned} - \sin Z \, dz = {} & (\cos \phi \sin \delta - \sin \phi \cos \delta \cos h) \, d\phi \\ & - \cos \phi \cos \delta \sin h \, dh. \end{aligned} \qquad (2)$$

Since $dh = dt - d\lambda$ the above can be rewritten:

$$dt = d\lambda + \left[\frac{\tan \delta}{\sin h} - \frac{\tan \phi}{\tan h}\right] d\phi + \frac{\sin Z}{\cos \phi \cos \delta \sin h} dz. \qquad (3)$$

Approximating differentials by differences, this equation can be solved by least squares for the corrections $\Delta\lambda$, $\Delta\phi$, ΔZ. The residual Δt is the difference between the observed sidereal transit time and that computed from the assumed λ, ϕ, Z. ΔZ is of no real interest but must be included in the solution because of the wide field of vision of the theodolite used in the observations.

In this experiment the mean places of the stars observed were taken from the SAO catalogue. Apparent places for a given night were computed at the same time the estimates of universal time and azimuth for each observation were derived. Observing runs were broken into sequences mostly of no more than one hour duration, and the instrument, a Wild-T2 theodolite, was releveled as often as possible, generally between each star observed. Taking stars brighter than 5th magnitude permitted an average of 20 stars per hourly sequence. The primary constraints on the instrument are that the zenith distance, though only approximately known, must be maintained constant for a given sequence, and the instrument must be accurately level. Any deviation from level will produce a corresponding error in position. A good distribution in azimuth of observations should be obtained, though the number of transits in the North and South are generally fewer and harder to time, thus weakening the latitude solution. On the other hand, the longitude solution is weakened by its greater sensitivity to timing errors.

For these observations the transit was mounted on a fixed reinforced pier 1″.1 North and 1″.2 East of the Curtis Schmidt. Two persons were required, one observing at the transit and the other recording the time at a voice mark from the observer. The timing error is estimated to be about half a second or less.

A total of 17 sequences were observed on 4 nights in May and 3 in October of 1971. The mean solution weighted by the inverse square of the internal errors and reduced to the site of the Schmidt is:

$$\lambda = W70^{\circ}48'52''.7 \quad \pm\ 2''.0$$
$$\varphi = S30^{\circ}09'55''.5 \quad \pm\ 1''.4$$

The distribution of the individual sets about their weighted mean are shown in Fig. 1.

SATELLITE OBSERVATION REDUCTIONS

The observed coordinates, $\vec{C}$, of a satellite are functions of the geocentric coordinates, $\vec{X}$, of the satellite, the geocentric coordinates, $\vec{X}$, of the observing station, and the parameters, $\vec{P}$, of the force model. The satellite coordinates are in turn functions of the elements, $\vec{E}$, of the satellite orbit at some epoch, and the time interval, T, from that epoch. Thus $\vec{C}=\vec{C}(\vec{X},\vec{E},T,\vec{P})$. With estimates of $\vec{X},\vec{E},\vec{P}$, assuming T is exactly known, predicted values of $\vec{C}$ can be computed. The residuals in $\vec{C}$ are then related to the errors of the estimates through a first order Taylor's expansion (assuming reasonably good estimates) as follows:

$$\Delta\vec{C} = \vec{C}_o - \vec{C}_c = \Delta\vec{X}\,\frac{\partial C}{\partial X} + \Delta\vec{E}\,\frac{\partial C}{\partial E} + \Delta\vec{P}\,\frac{\partial C}{\partial P}\,.$$

With a sufficient number and good distribution of observations, a simultaneous solution can be made for all unknowns; in practice usually just a sub-set of the unknowns is solved for.

For the problem at hand the reduction was done in two steps. First, observations over the time interval of interest were collected from the regular tracking network, whose stations have well-determined coordinates. Assuming the force parameters are known, solutions were made for elements to represent short arcs (of a few days each) of the orbit. Then, using the known orbit and the observations from CTIO, a solution was made for corrections to the station coordinates.

GEOS-II had reasonably good laser and range-rate, as well as optical, coverage during the period of observation from CTIO, so good orbits were obtained. For the final solution the orbit was broken into two 8-day arcs, and observations made with the MOTS camera were included for comparison (there were not enough simultaneous observations to permit direct triangulation). Santiago station coordinates were held fixed, and orbital elements were fixed for the first arc but allowed to float for the second (showing very little change). The coordinates on the SAO C-6 Earth derived for CTIO, and related pertinent parameters, are given below.

Geodetic Latitude	S30°10'8".2 ± 0".4
Longitude	W70°48'21".1 ± 0".4
Height above ellipsoid	2399m ± 10m
Redn. of S. T.	$+46^{s}.53$
$\rho \sin \phi'$	-.49980
$\rho \cos \phi'$	.86561
$\tan \phi'$	-0.57740
Δxy	-369
Δz	-213

The solution was carried out using the NONAME orbit reduction system of the geodesy section at Goddard Spaceflight Center, NASA. The errors of these coordinates are estimated from both the internal scatter of the data and from external estimates of the model errors. The latitude solution was essentially independent of those for longitude and height, while the longitude and height solutions were correlated. This is to be expected, since the satellite tracks were essentially South to North and were always in the eastern sky.

The residuals from the solution for the CTIO observations are given in Table II. Residuals for simultaneous Santiago observations are also given where appropriate. Since the Peldehue coordinates were kept fixed, the corresponding residuals indicate both the quality of the orbit and the degree of fit obtainable; inspection reveals the CTIO observations are comparable in quality. Mean residuals and the dispersion around that mean were formed for each sequence. The means indicate systematic errors, due chiefly to uncertainties in the orbit (typically estimated to be of the order of 1"). Since the CTIO observations were reduced using essentially independent reference frames, the dispersions are external estimates of the astrometric accuracy; these should be compared with the internal estimates in Table I. These residual dispersions reflect the catalogue error of 0".5 to 1".0.

CONCLUSIONS

Standard medium and large aperture astrographs can be used in conjunction with GEOS-type satellites to obtain accurate optical positions of the satellite and thus to obtain accurate geodetic coordinates. The limitations of the orbital knowledge to the dynamical solution and of the catalogue errors to the astrometry are comparable. Because astronomic astrographs have small field compared to tracking cameras, care should be taken to obtain raliable prediction ephemerides for experiments such as this one. The observing itself presents no serious problems, apart from the time limitations, except that short exposure emulsions, of a type not generally used by astronomers, should be used to avoid reciprocity failures with the short satellite flashes. An experiment of this type is only possible with flashing light satellites, since there is no other way to determine the time of exposure with the necessary accuracy.

The astronomic coordinates of the Curtis Schmidt telescope can be compared to the above geodetic coordinates to obtain the deflection of the vertical. This deflection amounts to 30″.1 ± 1″.7 towards an azimuth of 295° ± 3°, which corresponds to approximately 930 meters on the ellipsoid surface. The error of the datum if the existing chart coordinates are correct is +12″.2 = 377 meters in latitude and -5″.1 = -136 meters in west longitude.

ACKNOWLEDGEMENTS

We would like to thank J.G. Marsh, of the Trajectory Analysis and Geodynamics Division, Goddard Spaceflight Center, NASA, and his colleagues, for their assistance in this project. They provided real-time information on the status of the satellite during the experiment, prediction ephemerides for the last two days, and accurate up-dated ephemerides to assist in locating the flashes on the plates. They also carried out all of the satellite observation reductions described. We would also like to thank E.M. Gaposchkin, of Smithsonian Astrophysical Observatory, for supplying most of the prediction ephemerides.

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TABLE I

SATELLITE POSITIONS

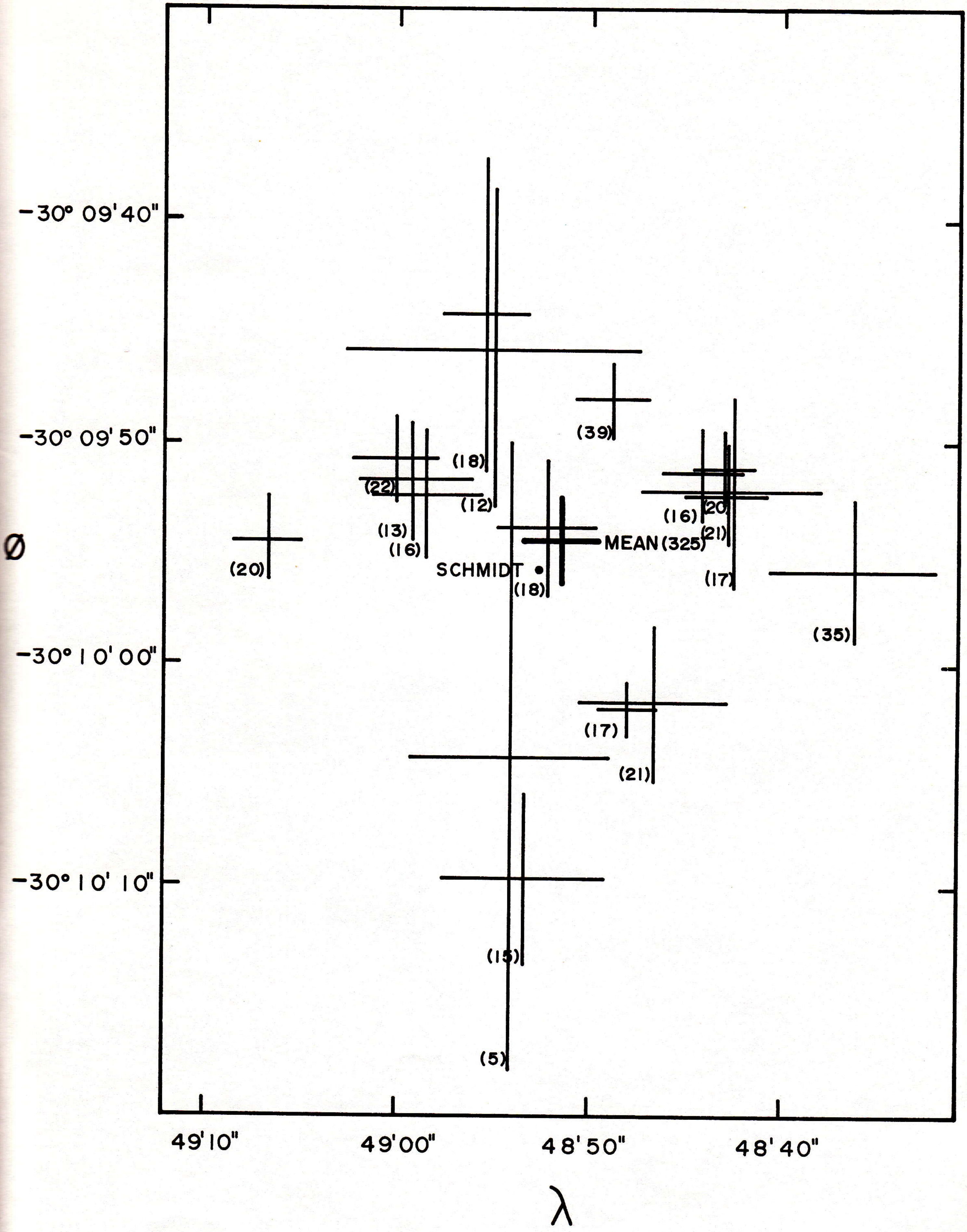
Y	M	D	H	M	S	α	Error	δ	Error	N*S
71	4	29	8	53	0	$0^h\ 3^m\ 5^s.12$	± $0^s.03$	-25" 49' 23".9	± 0".6	5
71	4	29	8	53	4	0 1 14.12	0.02	-25 21 49.0	0.4	7
71	4	29	8	53	8	23 59 23.35	0.04	-24 53 49.9	0.6	5
71	4	29	8	53	12	23 57 32.81	0.06	-24 25 24.3	0.4	6
71	4	29	8	53	16	23 55 42.47	0.06	-23 56 34.2	0.4	9
71	4	29	8	53	20	23 53 52.40	0.05	-23 27 21.1	0.3	6
71	4	30	9	15	0	22 38 23.41	0.02	- 5 3 34.8	0.4	6
71	4	30	9	15	4	22 36 26.02	0.03	- 4 15 24.5	0.4	8
71	5	6	9	17	0	0 45 48.58	0.06	-30 19 43.0	0.5	6
71	5	6	9	17	4	0 43 36.97	0.03	-29 50 57.0	0.2	6
71	5	6	9	17	8	0 41 25.35	0.03	-29 21 38.6	0.4	5
71	5	6	9	17	12	0 39 13.97	0.13	-28 51 47.5	0.3	5
71	5	6	9	17	16	0 37 2.95	0.09	-28 21 24.2	0.5	6
71	5	6	9	22	0	22 23 21.76	0.02	+21 15 27.9	0.3	6
71	5	6	9	22	4	22 21 50.61	0.01	+21 55 14.5	0.2	6
71	5	6	9	22	8	22 20 19.97	0.01	+22 34 36.5	0.3	6
71	5	6	9	22	12	22 18 49.81	0.02	+23 13 36.0	0.1	5
71	5	6	9	22	16	22 17 20.34	0.01	+23 52 12.1	0.2	7
71	5	9	10	15	0	23 51 50.36	0.03	-59 38 52.9	0.1	6
71	5	9	10	15	4	23 45 58.69	0.02	-59 4 15.1	0.3	5
71	5	9	10	15	8	23 40 11.84	0.07	-58 27 52.4	0.2	4
71	5	9	10	20	0	20 6 13.36	0.02	+21 6 20.4	0.7	8
71	5	9	10	20	4	20 4 52.46	0.03	+21 50 36.1	0.4	8
71	5	9	10	20	8	20 3 32.63	0.02	+22 33 53.8	0.5	8
71	5	14	10	2	0	23 53 14.44	0.03	-26 38 39.9	0.3	8
71	5	14	10	2	4	23 50 7.50	0.04	-25 40 53.4	0.4	8

TABLE II

SATELLITE RESIDUALS

Y	M	D	H	M	S	α (CTIO)	δ	α (STGO)	δ
71	4	29	8	53	0	2″5	-0″3		
			8	53	4	2.4	0.1		
			8	53	8	2.4	-0.5		
			8	53	12	2.2	0.4		
			8	53	16	1.3	0.8		
			8	53	16	0.4	-0.6		
				mean		1.9±0″8	0.0±0″5		
71	4	30	9	15	0	-1.6	0.1	0.0	-0.3
			9	15	4	-2.2	-0.3	-0.5	0.9
				mean		-1.9±0.4	-0.1±0.3	-0.2±0.4	0.3±0.8
71	5	6	9	17	0	-3.4	-4.0		
			9	17	4	-1.0	-2.2		
			9	17	8	-1.7	-1.1		
			9	17	12	-2.1	-0.4		
			9	17	16	-0.6	-0.8		
				mean		-1.8±1.1	-1.7±1.4		
71	5	6	9	22	0	-2.0	4.8		
			9	22	4	-1.3	5.4		
			9	22	8	-1.4	4.6		
			9	22	12	-2.9	4.6		
			9	22	16	-2.4	4.6		
				mean		-2.0±0.7	4.8±0.3		
71	5	9	10	15	0	4.4	2.2		
			10	15	4	4.1	2.2	5.7	-2.4
			10	15	8	3.3	1.2	2.1	-0.9
				mean		3.9±0.6	1.9±0.6	3.9±2.5	-1.6±1.1
71	5	9	10	20	0	4.9	-2.6		
			10	20	4	3.8	-1.7		
			10	20	8	3.8	-1.9		
				mean		4.2±0.6	-2.1±0.5		
71	5	14	10	2	0	-1.7	4.8		
			10	2	4	-2.2	4.9		
				mean		-2.0±0.4	4.8±0.1		

FIGURE 1. Plot of individual astronomic coordinate determinations with error bars. The mean and the corresponding Schmidt coordinates are also shown. The number of stars in each set is given in parentheses.


-30° 09'40"
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