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Astrolabe Solar Observations

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Abstract. Since 1978 at the Calern Observatory-France and from 1996 at the Observatório Nacional (O.N.)-Brasil solar observations have been carried out, aiming primarily to study the solar diameter. The ensemble of these two series is noteworthy by the length of Calern's, which spans about two solar cycles, and by the high density of O.N.'s, with typically 20 observations per day, on each side of the meridian, all year around. The precision of a single measure is $0\overset{''}{.}15$ for the northern hemisphere observations and $0\overset{''}{.}2$ for the southern hemisphere observations.

The characteristics of the combined series enabled detailed searches for anomalous trends (*e.g.*, from atmospheric origin) and systematic bias (*e.g.*, from instrumental origin). The analysis show the series robust for either. Thus there is a possiblity to investigate the variable time of transit of the solar disc across the almucantars of observation.

The apparent solar time, defined by the actual diurnal motion of the Sun, shows variations because of the varying rate of motion of the Sun in hour angle. That is, due to the inequalities in the annual motion along the ecliptic and to the inclination of the ecliptic to the equator.

In this work we detail the series characteristics and discuss the determination of the hour angle of the true Sun, as exemplified by the equation of time. The accuracy of the determination varies with the solar declination and the length of the observed apparent orbit. Typical precisions follow those for the semi-diameter determinations.

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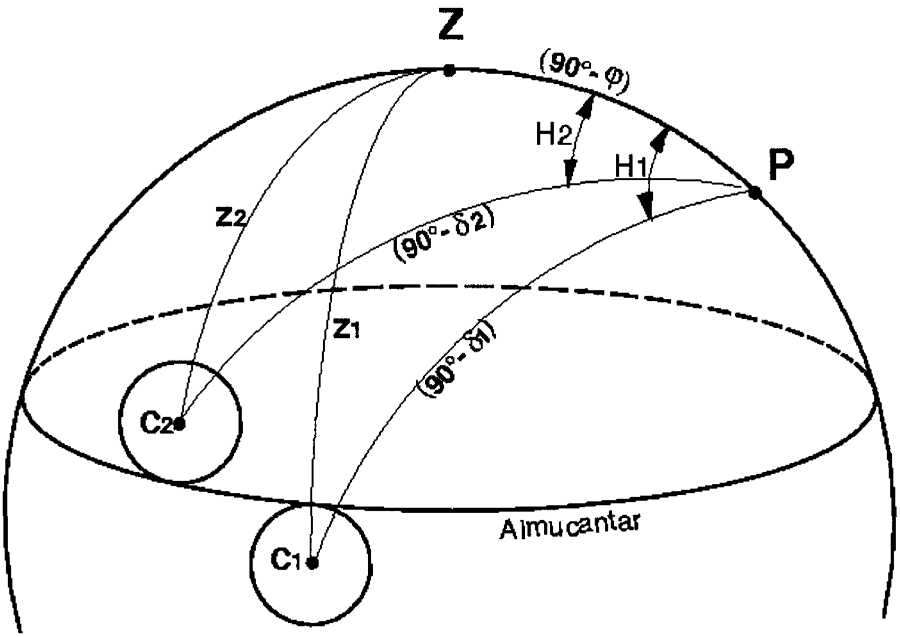

Figure 1. Geometry at solar crossing through an almucantar.

1. Sites and Equipment

CCD observations of the solar diameter with a Danjon astrolabe at the Observatório Nacional ($\phi = -22°53'42''.50$, $\lambda = +2^h52^m53^s.479$), were made with a variable angle prism, between 27° and 58° zenith distance (Jilinski *et al.*, 1998). The images are acquired by a COHU #4710 CCD camera, with a 512 × 512 matrix of 0''.7 pixels (vertically). The effective wavelength is 6400Åwith a 3000Åbandpass. Observations are taken daily, east and west of the solar meridian transit. The use of the variable angle prism, combined with the latitude of the astrolabe and usually uncloudy weather enabled us to get the measurements all year round.

At the C.E.R.G.A. (Plateau de Calern, Observatoire de la Côte d'Azur), ($\phi = +43°44'55''.89$, $\lambda = -0^h27^m42^s.442$), the Danjon Astrolabe used for the visual measures has received several improvements for enhanced performance (Laclare *et al.*, 1996). The CERGA series has been pursued steadily since 1975, starting with visual observations to the current CCD apparatus and a set of 11 reflector prisms enables the measerement of the diameter up to 22 times a day. The zenith distances are: 30°, 34°, 37°, 41°, 45°, 49°, 52°, 56°, 60°, 65° and 70°. Observations at large zenith angles make it possible to cover the whole apparent orbit of the Sun.

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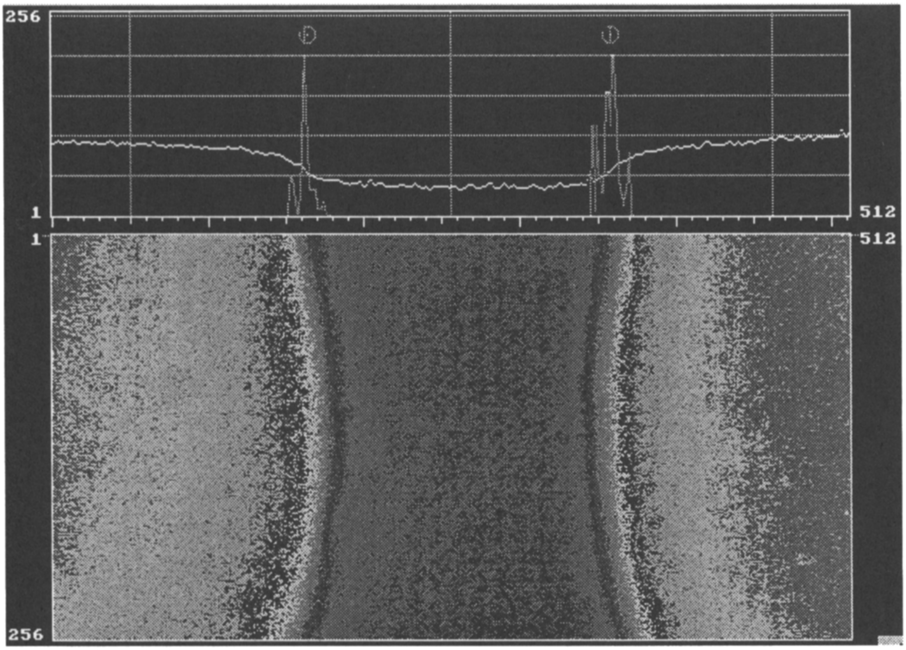

Figure 2. Solar observation at the CCD Astrolabe of Observatório Nacional.

2. Data Reduction

The accurate timing of the transit of the upper and lower solar limb enables us to calculate the solar diameter. Corrections are applied to refer the topocentric measures to the Earth's center, at 1 a.u. Also corrections to the curvature of the solar parallel and to the curvature of the almucantar are considered.

Following the Observatoire de Paris digital acquisition system software (Sinceac *et al.*, 1998), the solar limb edge, at each CCD line, is represented by the inflection point of the luminosity curve along the line. The observed solar limb can be adequately represented by a parabola that fits the set of inflection points. In each frame, the characteristic parabola's maximum provides a horizontal tangent parallel to the CCD columns and is recorded as (Y,t), where Y is the ordinate and t, the corresponding UTC. The two series of maxima, from the direct and reflected twin images, are adjusted by least squares to two crossing lines in the (Y,t) plane. The location of the point of intersection of these lines gives the instant of crossing of the almucantar by the observed limb. The observation of the crossing of the same almucantar by the second border enables the determination of the Sun's diameter, from the difference between the two instants.

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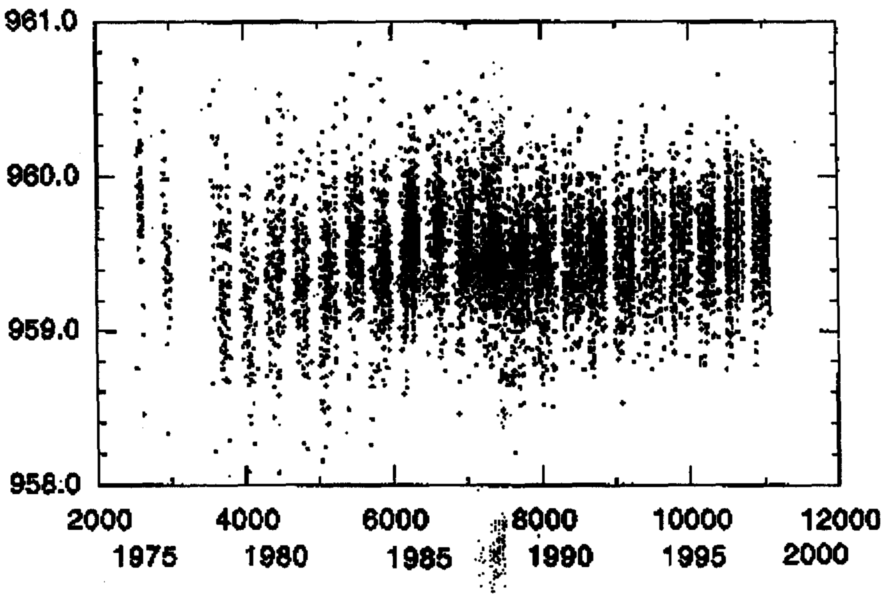

Figure 3. Calern visual measures for the solar semi-diameter (given in arc seconds).

3. The Solar Diameter Time Series

At Calern, the standard deviation of a single semi-diameter from the monthly average of about 40 measurements ranges from 0.″27 to 0.″30. The quality of the results is affected by the altitude of observation. Beyond the zenith distance of 60° the standard deviation of the measurements increases to 0.″4 at the zenith distance of 70°. Also, a linear dependence of the observed semi-diameter on the zenith distance is evaluated and its effect upon the results is considered.

4. Parabola Adjustment

At the Observatório Nacional, the varying angle frontal prism enables us to obtain several measurements (either east or west), keeping the observational zenith distance interval typically below 20°. On the other hand, the stability of the prism's angle needs to be high and was investigated. No dependence was found on zenith distance, UT of observation or length of the observation.

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Table 1. CALERN AVERAGE RESULTS

	Calern Visual				Calern CCD	
Year	N	Mean	East	West	N	Mean(″)
1975	62	959.88±0.07				
1976	52	959.50±0.06				
1978	118	959.31±0.04	959.21±0.05	959.44±0.06		
1979	113	959.16±0.03	959.32±0.04	959.19±0.05		
1980	168	959.38±0.03	959.35±0.04	959.42±0.05		
1981	174	959.30±0.03	959.31±0.03	959.27±0.04		
1982	238	959.30±0.03	959.29±0.03	959.30±0.04		
1983	265	959.53±0.02	959.56±0.02	959.47±0.03		
1984	364	959.38±0.02	959.38±0.02	959.37±0.03		
1985	464	959.51±0.01	959.54±0.02	959.47±0.02		
1986	370	959.57±0.02	959.60±0.02	959.52±0.03		
1987	341	959.50±0.02	959.49±0.02	959.52±0.03		
1988	414	959.42±0.02	959.42±0.02	959.42±0.03		
1989	484	959.33±0.01	959.34±0.02	959.30±0.02	100	959.41±0.03
1990	353	959.38±0.02	959.37±0.02	959.41±0.04	106	959.43±0.02
1991	266	959.44±0.02	959.43±0.02	959.45±0.03	129	959.37±0.02
1992	293	959.40±0.02	959.40±0.02	959.39±0.03	148	959.41±0.02
1993	347	959.39±0.01	959.39±0.02	959.39±0.03	272	959.39±0.02
1994	267	959.47±0.02	959.44±0.02	959.56±0.04	276	959.40±0.02
1995	273	959.48±0.02	959.47±0.02	959.51±0.03		
1996	313	959.47±0.02	959.46±0.02	959.51±0.04		
1997	392	959.52±0.02	959.52±0.02	959.53±0.04		
1998	357	959.52±0.01	959.52±0.01	959.52±0.04		
MEAN	6487	959.44±0.01	959.44±0.01	959.44±0.01	981	959.40±0.01

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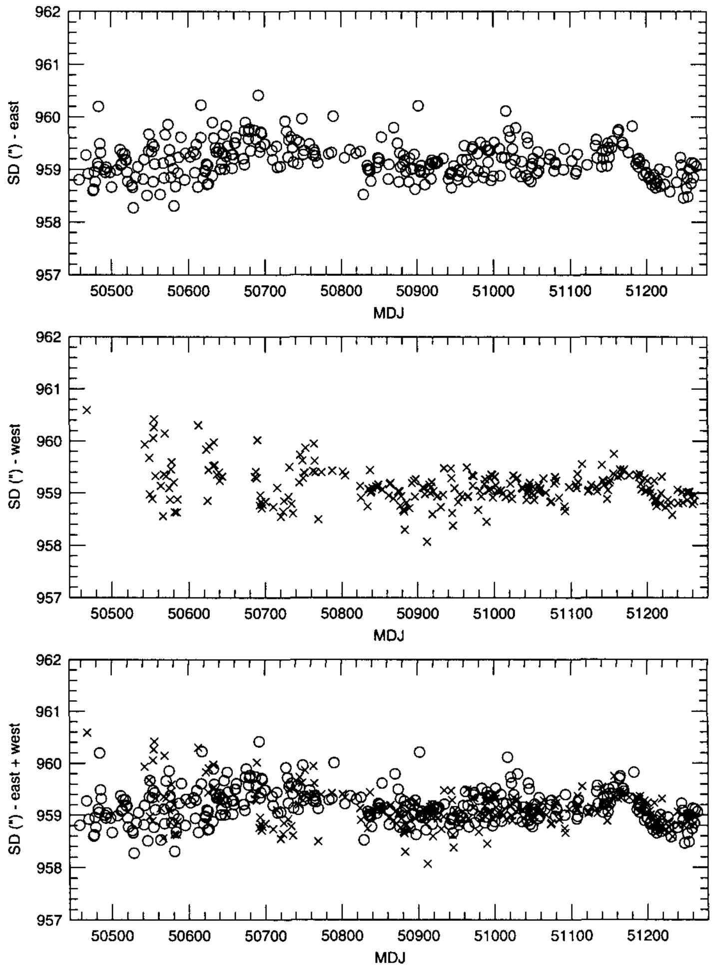

Figure 4. Observatório Nacional CCD measures for the solar semi-diameter. Circles denote a.m. observations and crosses p.m. observations.

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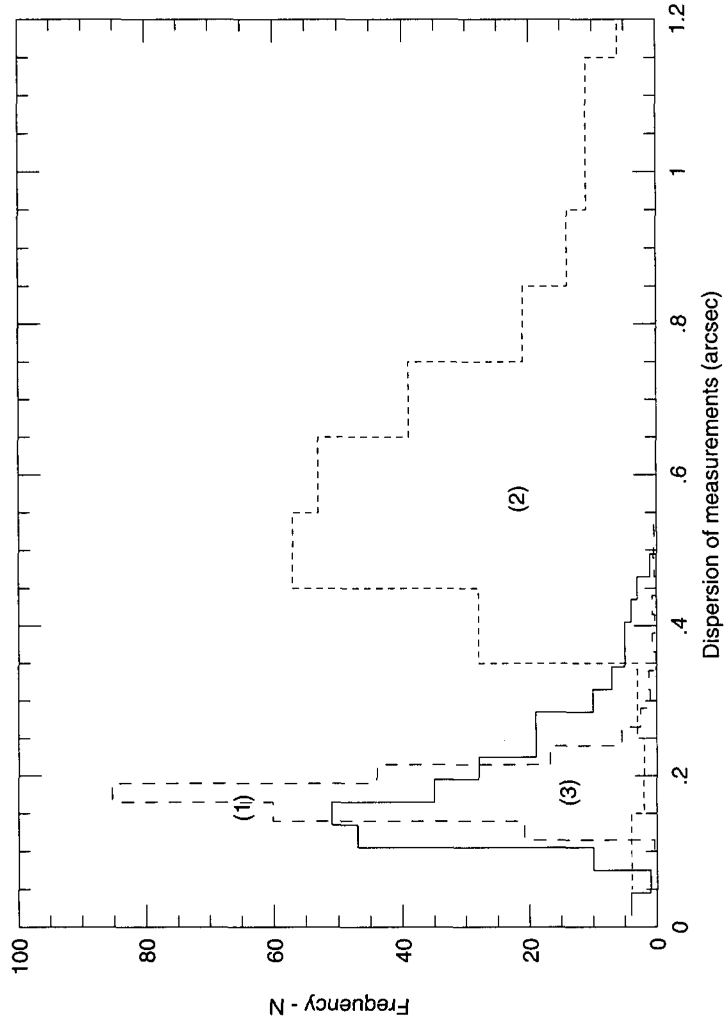

Figure 5. Distribution of internal and external errors for the O.N. CCD observations. (1)- error on the image treatment; (2)- single measure standard deviation; (3) - dispersion of the single measure about the daily average.

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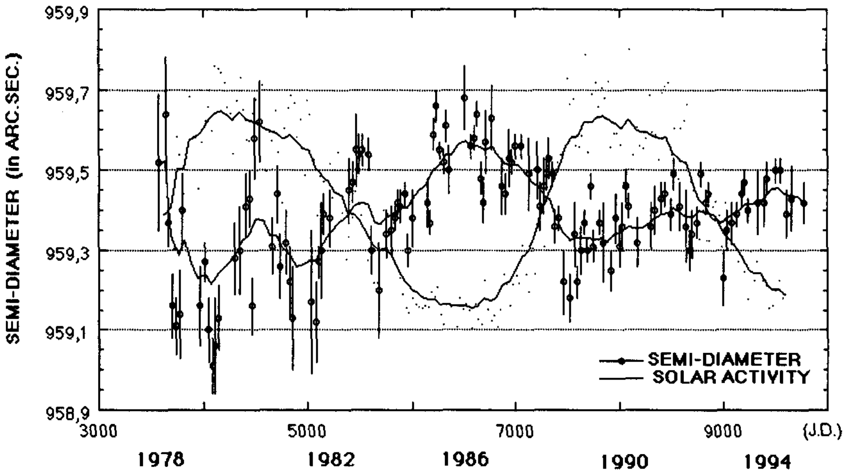

Figure 6. Correlation between the sunspot number and the measured semi-diameter on the Calern series.

Table 2. O.N. AVERAGE RESULTS

	OBSERVATÓRIO NACIONAL - CCD			
Year	N	Mean($''$)	East($''$)	West($''$)
1997	2656	959.27±0.03	959.25±0.03	959.32±0.06
1998	3917	959.12±0.02	959.17±0.02	959.07±0.02
1999	2279	958.95±0.02	958.93±0.03	958.96±0.02
MEAN	8852	959.13±0.01	959.15±0.02	959.10±0.02

5. Signature of Solar Origin on the Results

A long term variation of the measured semi-diameter with the sunspot number was detected in the Calern series (Laclare *et al.*, 1996). The Calern series was also successfully compared with the frequency shifts of low-degree solar p-modes (Jimenez-Reyes *et al.*, 1998), and with neutrino flux (Gavryuseva *et al.*, 1994).

Both the Calern and O.N. series show comparable results concerning a modulation of the results with the heliographic latitute. The density of measures at O.N. enabled us to verify the Akimov *et al.* (1996) suggestion that the presence of faculae on the solar limb should increase the measured solar radius by up to $0\rlap{.}''14$. (See Table 2 and 3).

6. Astrometry Using the Astrolabe's Solar Diameter Measurements

The classical astrolabe's solar measurements had already produced very precise assessments of the parameters of the Earth's orbit and the dynamical reference

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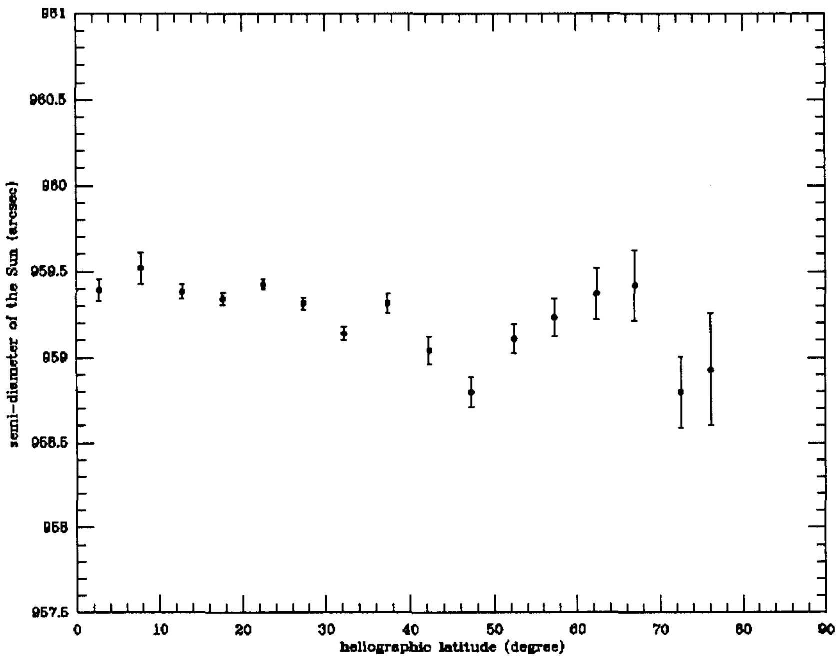

Figure 7. Dependence on the heliographic latitude for the O.N. results. Comparable results are displayed for the Calern Series, in agreement with the Khun *et al.* (1988) model for the solar shape.

Table 3. East Observations

Sunspots on limb		Without Sunspots on limb	
N days	SD(″)	N days	SD(″)
59	959.30±0.05	179	959.06±0.02

Table 4. West Observations

Sunspots on limb		Without Sunspots on limb	
N days	SD(″)	N days	SD(″)
52	959.14±0.03	193	959.02±0.02

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system (Penna *et al.*, 1997). Since the metrological qualities of the instrument are the same for diameter measurements a discussion is presented concerning the astrometric capabilities of these measurements. The basic observable is the timing of the time-length of transit of the Sun by the almucantar of observation.

7. Adjustment of Daily Observations

A second possibility is to adjust the daily results, which are symmetrical relative to the meridian crossing of the true (observed) Sun. The spherical trigonometry expression $\Delta z = \sin A \cos\phi \Delta t$ (where Δz stands for the solar diameter and Δt for the time of transit through the almucantar) shows, that the precision on the placement of the local meridian depends on the length of the observed arc of the true Sun's parallel.

For the typical conditions (ΔH = 4h and σ(S)daily = 10^{-1} arcsec) the precision on the instant of the meridian crossing of the true Sun is of the order of 10^{-3} s. The estimate varies by a factor of 10, depending on the quality of the fit and on the precision of the observations.

8. Parabola Adjustment

For the sake of simplicity and directness of interpretation of the results, the Δt versus H lines where adjusted by a parabola — or, in the few cases where the Δt variation was too small, by regression lines.

A Monte Carlo simulation, for 100,000 trials, revealed that for a Gaussian error ($\sigma = 0''.4$) for the time of transit of the almucantar, the corresponding error for the meridian's hour angle varied between 10^{-1} and 10^{-3} seconds. This is equivalent to the analysis of the analytical expression.

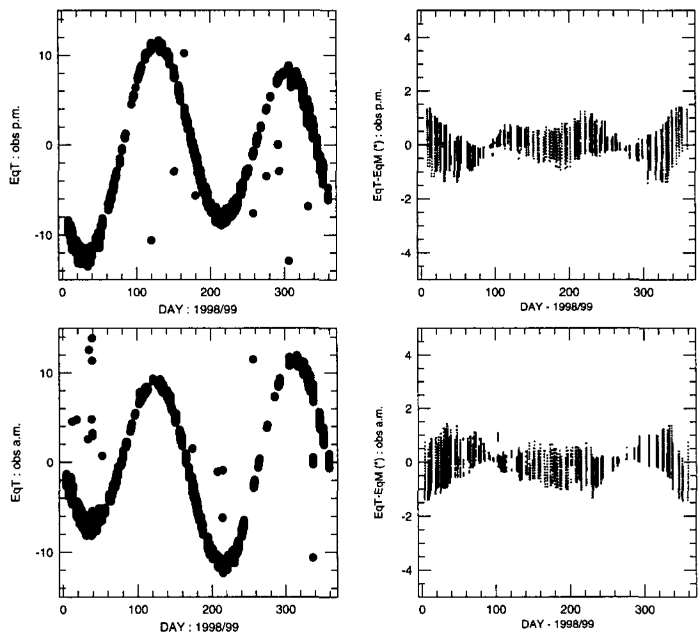

Figure 8. On the left, the Equation of Time as adjusted by the Observatório Nacional eastern and western measurements. On the right, residuals from the adjusted solutions to the standard curve (in arcsec).

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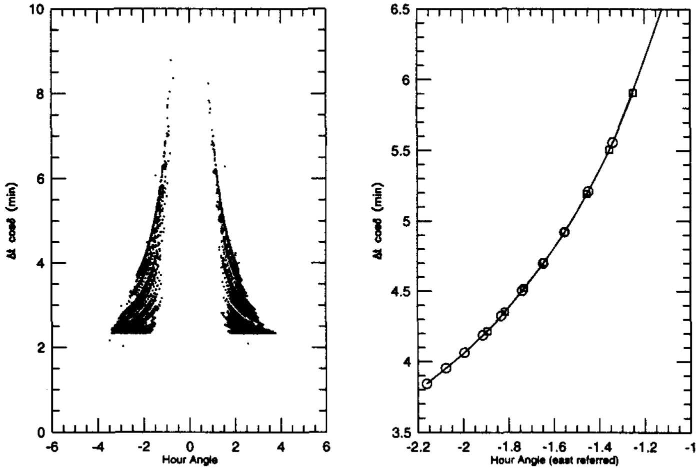

Figure 9. On the left, the time interval of the solar transit by the observation almucantars for each of the 131 pairs of east and west observations made on the same day. On the right, the fitting line for a typical pair. East observations are indicated by the circles, while the squares indicate the west observations (mirrored in hour angle in order to be comparable with the east ones).

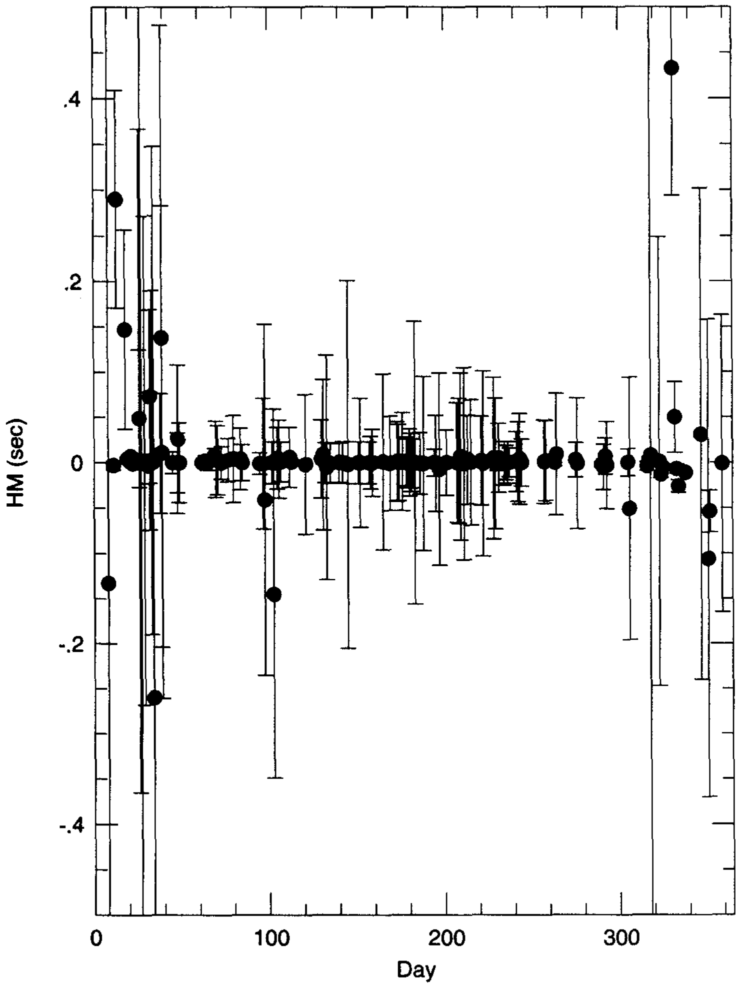

Figure 10. Correction to the hour angle of the meridian's transit of the true Sun, for 131 days with east and west observations at the Observatório Nacional, during 1998/99.

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