1996SoPh..166..211L

MEASUREMENTS AND VARIATIONS OF THE SOLAR DIAMETER

F. LACLARE, C. DELMAS and J. P. COIN
OCA/CERGA (CNRS, URA 1360), Observatoire de Calern, 06460 St Vallier de Thiey, France

A. IRBAH
Observatoire d'Alger, C.R.A.A.G., BP63, Bouzareah, 16340 Alger, Algeria

(Received 12 July, 1995; in revised form 24 January, 1996)

Abstract. As a consequence of an astrometry program, conducted since 1975 on a solar astrolabe at the Calern Observatory (Observatoire de la Côte d'Azur), we have obtained a data set of apparent solar diameters which encompasses periods greater than one solar cycle. From a set of more than 5000 visual observations, made by the same observer between 1975 and 1994, the mean value of the semi-diameter was measured at $959.42'' \pm 0.01''$. Also, a set of CCD measurements made with the same instrument between 1989 and 1994 yields the mean value $959.40'' \pm 0.01''$. Both results obtained by raw measurements are consistent but significantly differ from values obtained by other methods and on other instruments. We discuss some systematic effects that can affect our visual measurements and their precision. Taking account of a zenith distance effect provides for the semi-diameter a mean value closer to the value of the ephemeris. Our observations also reveal deviations around the mean diameter in the royal zones and for high heliographic latitudes; their amplitudes reaching as much as $0.08''$. Finally, semi-diameter variations appear in our series; their origin is unknown but they may possibly be related to observed variations of magnetic activity or other solar parameters.

1. Introduction

Since the early nineteenth century, many authors have noted variations in the Sun's diameter, either secular, periodic, irregular or linked to solar activity.

This matter was raised anew when, on the grounds of a long series of meridian observations, Eddy and Boornazian (1979) announced that the Sun was 'shrinking' at the considerable rate of 2 arc sec per century. The mediocre precision of old measurements, the many causes of discontinuity in series such as changing observers or modifications to the instruments render this conclusion dubious. Moreover, the analysis of the Mercury transits observed between 1723 and 1973, or the solar eclipses between 1715 and 1966, do not allow the detection of a perceptible lessening of the diameter, but only a possible periodic variation of 80 years (Parkinson, Morrison, and Stephenson, 1980).

In the present work we obtained the value of the Sun's diameter by means of observations made with the solar astrolabe, in the framework of an astrometry program whose goal was the measurement of the equinox and several parameters of the Earth's orbit. This program, initiated in 1975 (by an initial test period), has been steadily pursued since 1978 on the Calern site (Observatoire de la Côte d'Azur, OCA, $\varphi = 43°44'55.9''$, $\lambda = -0^{h}27^{m}42.44^{s}$).

The instrument is a variant from the Danjon astrolabe. A set of 11 reflector prisms enables the measurement of the diameter up to 22 times a day. The zenith

Solar Physics **166:** 211–229, 1996.
© 1996 *Kluwer Academic Publishers. Printed in Belgium.*

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

distances are: 30°, 34°, 37.5°, 41.5°, 45°, 49°, 52.5°, 56.5°, 60°, 65°, and 70°. Observations at large zenith angles makes it possible to cover the whole apparent orbit of the Sun (Laclare, Demarcq, and Chollet, 1980; Laclare, 1983). We have obtained a series of measurements covering a complete cycle of solar activity; these measurements, carried out by the same observer with the same instrument, bestow a character of homogeneity to this set of data that is spread over some 15 years.

In Section 2, the principle of the measurement and data reduction is given and the agreement between CCD and visual measurements is discussed.

In Section 3, the mean value of the semi-diameter is estimated after more than 5000 visual measurements made between 1975 and 1994, and the influence of some systematic effects is considered, such as the zenith distance, the crossings before and after the meridian or the heliographic latitude of the observed diameter.

In spite of Danjon's improvements with which this instrument evolved to a 'quasi-impersonal' level, there remained an uncertainty linked with the visual estimate of the measurements by each observer. Since 1989, the use of a CCD Camera has removed all 'personal' bias and provided an improved definition of the observed Sun's limb (Laclare and Merlin, 1991). Here we give the first results obtained by this new type of acquisition. To put our mean value of the semi-diameter in perspective with other results, we recall also in this section the values obtained these last 25 years by different methods.

Section 4 deals with the changes that affect this series of visual measurements. An oscillation of $0.10''$ semi-amplitude and 10.4-year period might be out of phase with the activity cycle. Other variations occur that could be related to some parameters of solar activity or neutrino flux.

2. Measurement Principle

The principle of the instrument, the techniques of observing the Sun, as well as the method of data reduction (which is much simpler if the diameter is the only unknown parameter) have already been presented previously (Laclare, Demarcq, and Chollet, 1980; Chollet, 1981; Kovalevsky, 1994). Here, we briefly review the salient points of the method.

Let us recall that observing a transit requires the recording of the time when both images of the Sun's edge, i.e., the direct one and its reflection on the mercury surface, become tangent to each other. At this instant, the Sun's edge crosses the parallel of altitude (almucantar) defined in the instrument by the angle of the reflector prism and also by the refraction and other terms computed or measured by the observer: curvatures of the parallel of declination and the almucantar, position of the focal plane, symmetry of the images during the crossing.

The recorded time coincides with the crossing by the Sun's center of a parallel of altitude whose spherical radius is increased (or decreased) by the apparent semi-diameter value for an upper (or lower) edge (Figure 1).

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

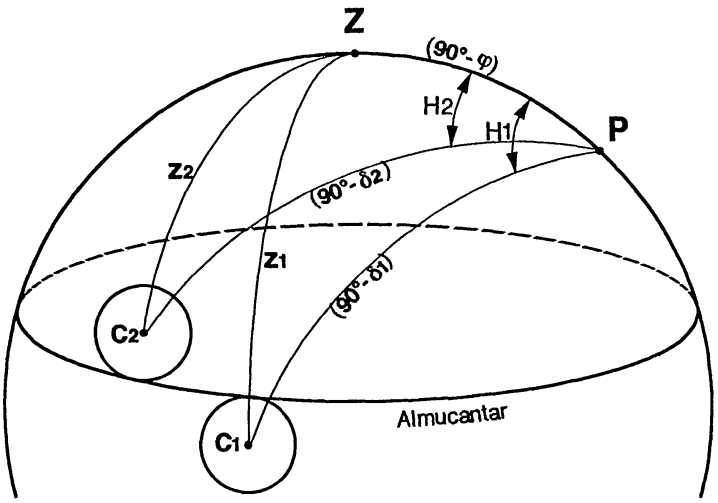


Figure 1. Measurement principle. An eastern transit is shown. P stands for the celestial pole and Z for the zenith. φ is the latitude and $H = ST - \alpha$ is the hour angle of the Sun appearing in formula (1). The almucantar is the parallel of altitude. The solar diameter is obtained from making the difference of the zenith distances z_1 and z_2, computed at the times of the crossings of the same almucantar by the upper edge (Sun in C_1) and lower edge (Sun in C_2). For the two instants, the center of the Sun, in C_1 and C_2, is located on two close parallels of declination, $\delta 1$ and $\delta 2$, which are not drawn.

The measurement of the diameter will then be given as the difference between the zenith distances computed at the times of two successive crossings. The resolution of the spherical triangle at the time of observation yields the geocentric zenith distance of the center of the Sun. The topocentric apparent zenith distance is written as

$$z = \text{arc cos}(\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos(ST - \alpha)) + \rho\varpi \sin z^* + R +$$

$$+\Delta F + \Delta C + \Delta D \pm P_j \,, \qquad (1)$$

where φ is the latitude of the instrument given in the Introduction, α, δ are the equatorial coordinates of the Sun computed at the time of observation, ST is the sidereal time of observation recorded in UTC, $\rho\varpi \sin z^*$ is the parallax altitude correction where ρ is the geocentric radius of the instrument, ϖ is the solar horizontal parallax, z^* is the approximate zenith distance at the time of observation, R is the atmospheric refraction computed at the time of observation, and ΔF is the correction to the focal plane position. This measurement is done, before and after the observations, by autocollimation on a plane mirror set in front of the objective lens. This correction is afterwards interpolated for the time of observation. The average variation of ΔF between two successive edges, about 3 min apart, is $0.05''$ and has no systematic character. Further, ΔC is a correcting term dealing with the curvature of the declination and altitude parallels. This second-order effect is evaluated during the observation by the eccentricity of the transit in the instrument field. This correction has no systematic character and is nearly always under $0.05''$. ΔD is a

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

correcting term dealing with the attitude of the reflector prism edge which should be in the horizontal plane. As well as ΔC, it is evaluated during the observation, by the distance in a vertical plane between both direct and reflected images. This correction, of a systematic character, lessens the value of the observed diameter and can reach $0.3''$. P_j is the 'personal' error, changing sign with the observed edge.

The observed semi-diameter, S.D., given by half of the difference of zenith distances, has been reduced to become geocentric at one astronomical unit:

$$\text{S.D.} = \tfrac{1}{2}\{|z_1 - z_2| - s\rho\varpi \cos z^*\}r + P_j \ , \tag{2}$$

where z_1 and z_2 are the zenith distances of the center for the upper and lower edge transits; s is the geocentric apparent semi-diameter of the Sun, $\rho\varpi \cos z^*$ is the correction of parallax of the observed diameter, and r is the Earth–Sun distance at the mean time of the observation.

The computation of the Sun's diameter by the differences of zenith distances obviously assumes a true stability of the almucantar during that observation. This condition is fulfilled by using zerodur types of ceramic reflector prisms affected by quasi-nought dilatation and a mercury mirror which establishes the horizontal plane. The astronomical refraction, computed at the time of observation, enters the definition of the zenith distance: an error in the model used for the computation directly affects the solution of Equation (1) but does not alter the semi-diameter drawn on the differences (2). Only unmeasured instrumental and/or unmodelled refraction variations, during the few minutes that span the successive crossings of both Sun's edges, could affect the radius of the almucantar and consequently the measurement of the solar diameter.

In spite of the 'impersonal' micrometer devised by Danjon, the analysis of long series of stellar or, more recently, solar observations reveals the existence of systematic effects due to observers. The visual estimate of the tangency of the Sun's images actually seems to be a characteristic of each observer. The semi-diameter measurement depends on how the observer estimates the touching of images, whether they are distinct or overlapping. In other words, the images are estimated tangent before or after the edge crosses the almucantar (Figure 1). Several series of measurements made with the same instrument suggest that this correction is a constant for a specified observer. Only long-term follow-up of the visual and photoelectric measurements that we have initiated will confirm the time-independance of this unknown.

To clear the measurements of the personal bias and to define better the observed edge, we developed an acquisition system equipped with a CCD camera (699×580 pixels) at the focal plane of this instrument. The size of a pixel on the sky is $0.6''$ (Laclare and Merlin, 1991).

We define the limb as the point where the intensity distribution on a CCD line, which we call the solar limb function, has its inflection point. It is determined by analog methods as the zero of the second derivative of the solar limb function

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

(experiments are being performed to determine the limb digitally). For each frame, the limb is reconstructed by a least-square adjustment of a parabola through the inflection points. The entire sequence consists of 100 images in 20 s. The integration time of a single image is 20 ms.

The results obtained during the 1989–1994 period, although affected by the seeing effect, show a very good agreement between the new technique and visual observations (compare Tables I and II, see Figure 7).

The differences between visual and CCD measurements are small. This implies that an observer makes good estimates of the neighborhood of the inflection point of the solar limb function. If this accord is confirmed over a longer period, we shall be able to link our visual observations to those of the CCD program whose superiority is obvious.

Also, the new measurements will permit a comparison of the results with those obtained with other instruments, whether they are similar or based on a different principle. A bi-dimensional analysis of the digitized image should, in addition, allow evaluation of the possible atmospheric contribution to the variations of the apparent solar diameter.

3. Mean Value of the Observed Semi-Diameter

The mean value of the semi-diameter, observed by the same observer on more than 5000 visual measurements spanning 1975 to 1994 is $959.42'' \pm 0.01''$. These measurements were performed in the visible spectral region using a broad (200 nm) bandwidth centered on 540 nm. The increase in the number of annual data points arises from the growing number of observed zenith distances (Table I).

Since 1989, the CCD acquisition program has run concurrently on the same instrument, and 981 CCD measurements spanning the period 1989–1994 give the mean value $959.40'' \pm 0.01''$ (Table II).

The set of visual measurements is large enough to study the influence of some effects on the observed diameter and possibly to evaluate a 'seeing effect' to correct the mean value that we measured. Conversely, the distribution of CCD measurements is nowadays insufficient for this type of study; the evaluation of atmospheric effects on CCD observations is a matter for other studies (Irbah *et al.*, 1994).

3.1. East–West Effect

The observations made the same day at the same zenith distance can be far apart in time. For instance, around the summer solstice, about 9 to 10 hours span east and west crossings of an observation of the Sun at 60° from the zenith. During this time, the atmospheric warming conditions between morning and evening can change drastically. Similarly, the instrument and elements that are used for computing

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

Table I

Annual mean value of the visual semi-diameter, including east and west measurements (observer: F. Laclare)

Year	n	Mean semi-diameter	N	SD_{east}	N_E	SD_{west}	V_W
1975	1	$959.88'' \pm 0.07''$	62				
1976	1	$959.50'' \pm 0.06''$	52				
1978	3	$959.31'' \pm 0.04''$	118	$959.21'' \pm 0.05''$	66	$959.44'' \pm 0.06''$	52
1979	3	$959.16'' \pm 0.03''$	113	$959.32'' \pm 0.04''$	60	$959.19'' \pm 0.05''$	53
1980	3	$959.38'' \pm 0.03''$	168	$959.35'' \pm 0.04''$	95	$959.42'' \pm 0.05''$	73
1981	3	$959.30'' \pm 0.03''$	174	$959.31'' \pm 0.03''$	104	$959.27'' \pm 0.04''$	70
1982	3	$959.30'' \pm 0.03''$	238	$959.29'' \pm 0.03''$	145	$959.30'' \pm 0.04''$	93
1983	5	$959.53'' \pm 0.02''$	265	$959.56'' \pm 0.02''$	166	$959.47'' \pm 0.03''$	99
1984	9	$959.38'' \pm 0.02''$	364	$959.38'' \pm 0.02''$	219	$959.37'' \pm 0.03''$	145
1985	10	$959.51'' \pm 0.01''$	464	$959.54'' \pm 0.02''$	279	$959.47'' \pm 0.02''$	185
1986	10	$959.57'' \pm 0.02''$	370	$959.60'' \pm 0.02''$	225	$959.52'' \pm 0.03''$	145
1987	11	$959.50'' \pm 0.02''$	341	$959.49'' \pm 0.02''$	201	$959.52'' \pm 0.03''$	140
1988	11	$959.42'' \pm 0.02''$	414	$959.42'' \pm 0.02''$	258	$959.42'' \pm 0.03''$	156
1989	11	$959.33'' \pm 0.01''$	484	$959.34'' \pm 0.02''$	303	$959.30'' \pm 0.02''$	181
1990	11	$959.38'' \pm 0.02''$	353	$959.37'' \pm 0.02''$	254	$959.41'' \pm 0.04''$	99
1991	11	$959.44'' \pm 0.02''$	266	$959.43'' \pm 0.02''$	187	$959.45'' \pm 0.03''$	79
1992	11	$959.40'' \pm 0.02''$	293	$959.40'' \pm 0.02''$	220	$959.39'' \pm 0.03''$	73
1993	11	$959.39'' \pm 0.01''$	347	$959.39'' \pm 0.02''$	262	$959.39'' \pm 0.03''$	85
1994	11	$959.47'' \pm 0.02''$	267	$959.44'' \pm 0.02''$	192	$959.56'' \pm 0.04''$	75
Mean		$959.42'' \pm 0.01''$	5153	$959.42'' \pm 0.01''$	3236	$959.41'' \pm 0.01''$	1803

n is the number of reflector prisms and N the number of observations.

N.B. The 1975 and 1976 measurements had an experimental character.

Table II

CCD measurements

Year	Semi-diameter	N
1989	$959.41'' \pm 0.03''$	100
1990	$959.43'' \pm 0.02''$	106
1991	$959.37'' \pm 0.02''$	129
1992	$959.41'' \pm 0.02''$	148
1993	$959.39'' \pm 0.02''$	272
1994	$959.40'' \pm 0.02''$	226
Mean	$959.40'' \pm 0.01''$	981

N.B. These results put together eleven zenith distances measurements.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

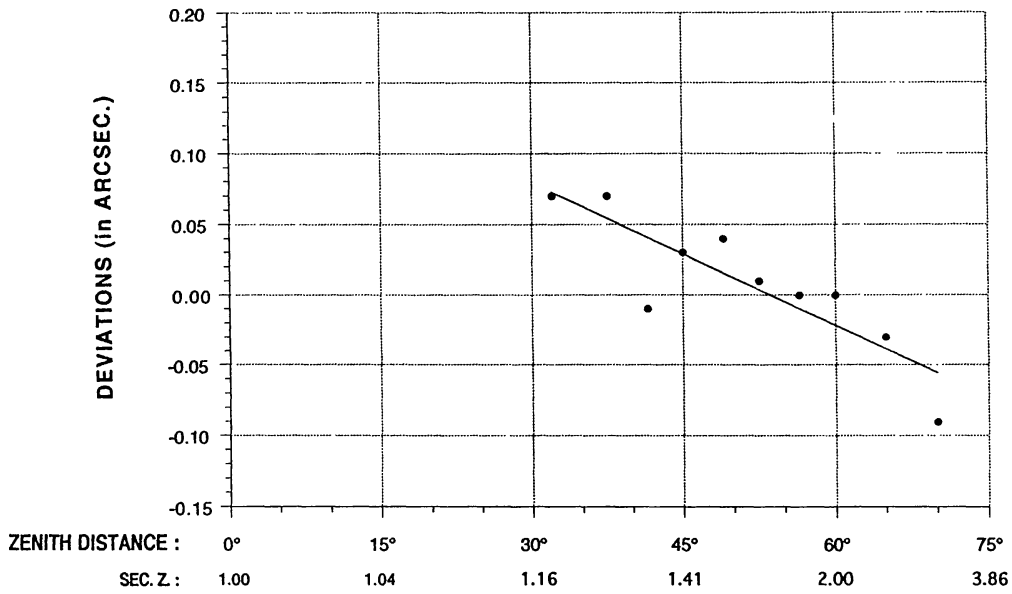


Figure 2. Deviation from the mean semi-diameter as a function of zenith distance, z. The semi-diameter is systematically smaller for higher zenith distances. Please note that we put together the data from the 30° and 34° prisms whose number of observations is lower than average. A bold (linear) extrapolation would give 959.58″ for $z = 0$.

refraction are affected. The annual mean values listed in Table I separately for east and west do not display the systematic effects that might be anticipated. The lower number of crossings observed in the west are due to cloudy afternoons; the larger errors are due to the lower numbers of measurements and partly to a lower quality of afternoon observations.

3.2. ZENITH DISTANCE EFFECT

The use of 3 reflector prisms for 3 almucantars in 1978 was extended since 1987 to 11 prisms for 11 almucantars.

By the method of equal altitudes applied to the opposite sides of the Sun, the differential refraction should not affect the measurement of the vertical diameter. Nevertheless, the thickness of the atmosphere changes noticeably with zenith distance, and we can expect a link between the observed diameter and altitude.

The deviations from the mean, Figure 2, display a correlation between the measured diameter and the altitude of observation. The measured diameter systematically decreases when the zenith distance increases. This fact, that we might compare with the increase of the standard deviations with zenith distance (see Figure 3), just reflects the inward shift of the inflection points, which occurs when the image of the Sun's limb is broadened by seeing/blurring (Rösch and Yerle, 1983; Neckel, 1995).

The apparent correlation that we observe in Figure 2 might lead us to evaluate the 'observed' semi-diameter at the zenith as 959.58″ ± 0.05″ instead of

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

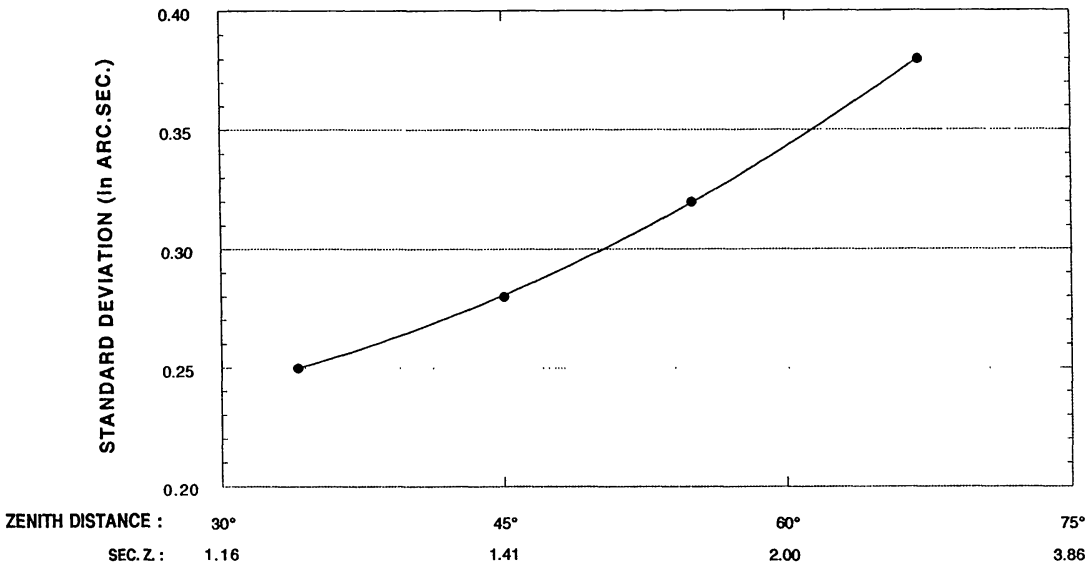


Figure 3. Dependence of mean standard deviations on zenith distance. Each point gathers data from several prisms: (30°, 34°, 37.5°), (41.5°, 45°, 49°), (52.5°, 56.5°, 60°) and (65°, 70°).

$959.42'' \pm 0.01''$. We nevertheless consider that the uncertainty coming with a wide extrapolation from known measurements does not endow the extrapolated value with a satisfactory level of confidence. Only semi-diameter measurements closer to the zenith will confirm or not the correction thus evaluated.

3.3. ACCURACY OF MEASUREMENTS

The standard deviation of a single semi-diameter from the monthly average of about 40 measurements ranges from $0.27''$ to $0.30''$. We notice that the measurements made the same day, for all zenith distances, agree to within 1 arc sec.

According to what might be expected, the quality of the results is affected by the altitude of observation. Beyond a zenith distance of 60° (sec $z \geq 2$), the standard deviation of the measurements clearly increases to obtain about $0.4''$ at a zenith distance of 70° (sec $z = 2.9$) (Figure 3).

In this figure, mean data are considered and the points put together data that were obtained with different prisms.

The mean standard deviation for visual measurements reckoned 'day to day' is about $0.18''$ for one year, whereas for CCD measurements this standard deviation does not exceed $0.10''$.

N.B. The lower quality of measurements made after the meridian passage is obvious: the standard deviation of a measurement at an altitude of 45° increases from $0.24''$ in the morning to $0.28''$ in the afternoon.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

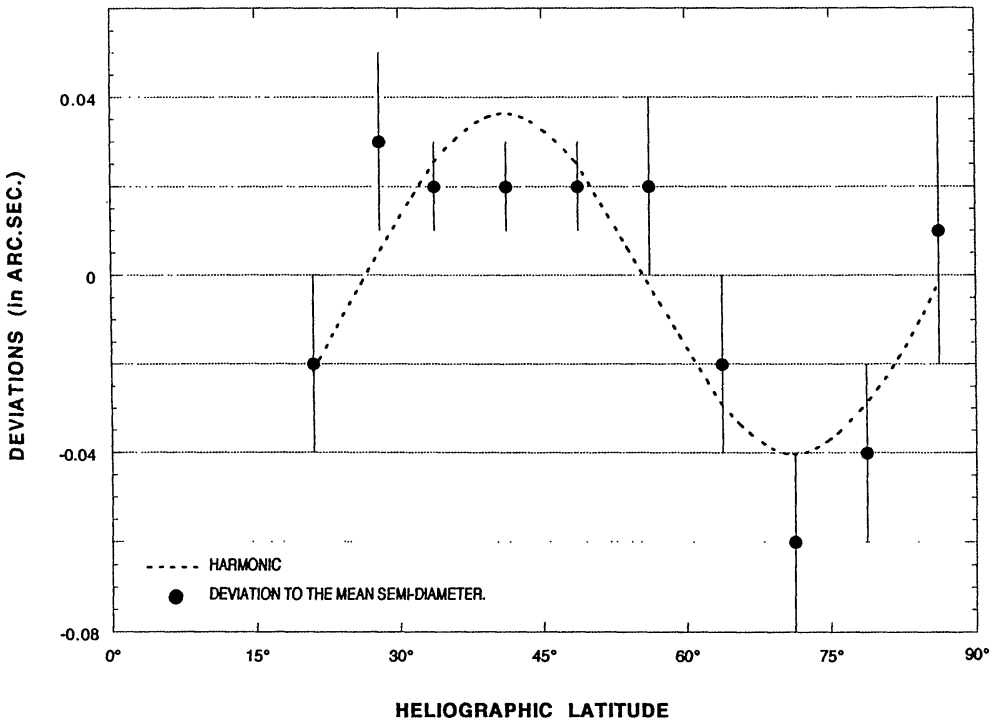


Figure 4. Apparent dependence of semi-diameter on heliographic latitude. The measurements being sorted into classes of heliographic latitude, from 1978 to 1994, it is noticed that the apparent semi-diameter is larger in the royal zone whereas the lower values are found at around 75° of heliographic latitude. The amplitude of these differences might reach 0.08″.

3.4. HELIOGRAPHIC LATITUDE EFFECT

The heliographic latitude of the vertical diameter observed with the astrolabe changes during the year and also with a given zenith distance, according to the direction of observation, east or west. This variation of inclination can amount to 50° the same day. The apparent movement of the Sun allows us to observe at our site only zones inclined to the Sun's equator at an angle of more than 15°.

To study a possible variation of the semi-diameter with heliographic latitude, the observed data were corrected for the zenith distance effect (we reduced all data to $z = 45°$) and sorted into 10 classes of inclination. The result is shown in Figure 4, which seems to indicate that the solar radius possibly varies with heliographic latitude: the largest radii are found for the royal zone, the smallest radii near 75°.

The amplitude is about 0.08″. The analysis of measurements at different epochs of the activity cycle (increasing and decreasing, maximum and minimum) seems to point to an apparent stability of this effect. Currently, we are reluctant to interpret these deviations in terms of solar oblateness or a change in the global figure of the Sun, because of the limited quality of measurements, and their non-simultaneity.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

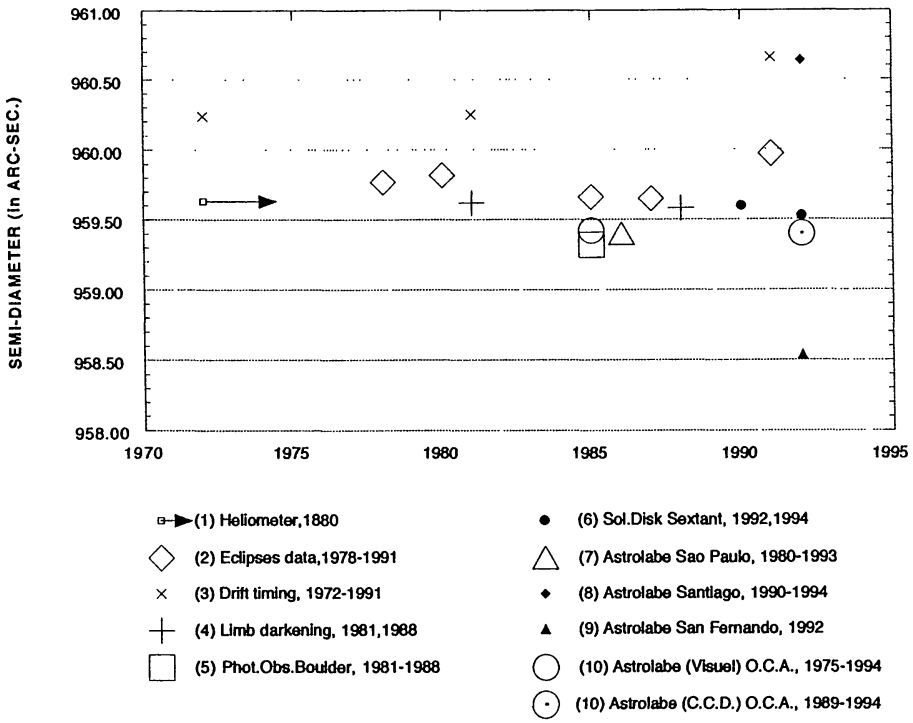


Figure 5. Solar semi-diameter results. With the exception of (3), (8), and (9), the mean value is about 959.60″.

3.5. COMPARISON WITH OTHER RESULTS

In Table III and Figure 5, we compare our results with other data which were obtained during the last twenty-five years from various authors by using different instrument types and different methods.

This great disparity of the ground-based results exemplify the difficulties of measuring the solar diameter. These arise from the difficulty of defining the observed solar limb, the systematic effects of instrumental and/or atmospheric origins, and, of course, from the bias introduced by visual observations.

Several comments are relevant to Table III and Figure 5.

– Our global result is lower by about 0.3″ than those derived from eclipse observations or limb-darkening measurements. Such a difference might be explained by the fact that these results are either free from or corrected from seeing effects.

– All measurements from the bottom of atmosphere necessarily yield smaller solar radii. This shortening of the radius can easily be of the order of 0.1″ to 0.3″, and it depends on the seeing and the limb-darkening function (Neckel, 1995).

– The personal bias is another source of systematic errors for visual observations.

– Uncertainties linked to the instrument affect equally the results presented in Table III, in the more or less systematic manner.

– For unknown reasons, some data show extremely large deviations from the overall mean: namely, in Figure 5, data from drift timing (3) as well as those of

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

Table III
Solar semi-diameter results

Reference	Mean epoch	Semi-diameter	Remarks
Auwers, 1891	1880	$959.63''$	From heliometer measurements
Sofia, Dunham, and Fiala, 1980	1978	$959.77'' \pm 0.06''$	From solar eclipses data
Kubo, 1993	1980	$959.82'' \pm 0.02''$	
Bode, Büchner, and Mushardt, 1995	1985	$959.66'' \pm 0.04''$	
Sato and Soma, 1989	1987	$959.64'' \pm 0.10''$	
Wan Lai and Zhao Jun-Liang, 1989	1987	$959.65'' \pm 0.02''$	
Akimov *et al.*, 1993	1991	$959.97'' \pm 0.04''$	
Wittmann, 1973	1972	$960.24'' \pm 0.16''$	From drift timing in Izaña and Locarno
Wittmann *et al.*, 1981	1981	$960.25'' \pm 0.02''$	
Wittmann *et al.*, 1991, 1993	1991	$960.66'' \pm 0.02''$	
Neckel, 1995	1981	$959.62'' \pm 0.03''$	From the limb darkening observations at Kitt Peak Observatory in 1981 and 1986–1990
	1988	$959.58'' \pm 0.02''$	
Ribes *et al.*, 1991	1985	$959.32'' \pm 0.02''$	From photoelectric measurements made at HAO, Boulder, in 1981–1988
Maier, Twigg, and Sofia, 1992	1990	$959.60'' \pm 0.10''$	From measurements made by the solar disk sextant, on balloon flights
Sofia, Heaps, and Twigg, 1994	1992	$959.53'' \pm 0.06''$	
Leister and Benevides Soares, 1990 Leister *et al.*, 1995	1986	$959.40'' \pm 0.05''$	From astrolabe observations in 1980–1993 at São Paulo Observatory
Noël, 1995	1992	$960.64'' \pm 0.10''$	From astrolabe observations in 1990–1994 at Santiago Observatory
Sanchez *et al.*, 1995	1992	$958.54'' \pm 0.12''$	From astrolabe observations in 1992 at San Fernando Observatory (Cadiz)
Laclare *et al.*, present work	1985	$959.42'' \pm 0.01''$	From visual observations (1975–1994. Raw values)
	1992	$959.40'' \pm 0.01''$	From CCD measurements (1989–1994. Raw values)
	1985	$959.58'' \pm 0.05''$	From visual observations (1975–1994, after correction of zenith distance effect). With the solar astrolabe at Calern Observatory (OCA)

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

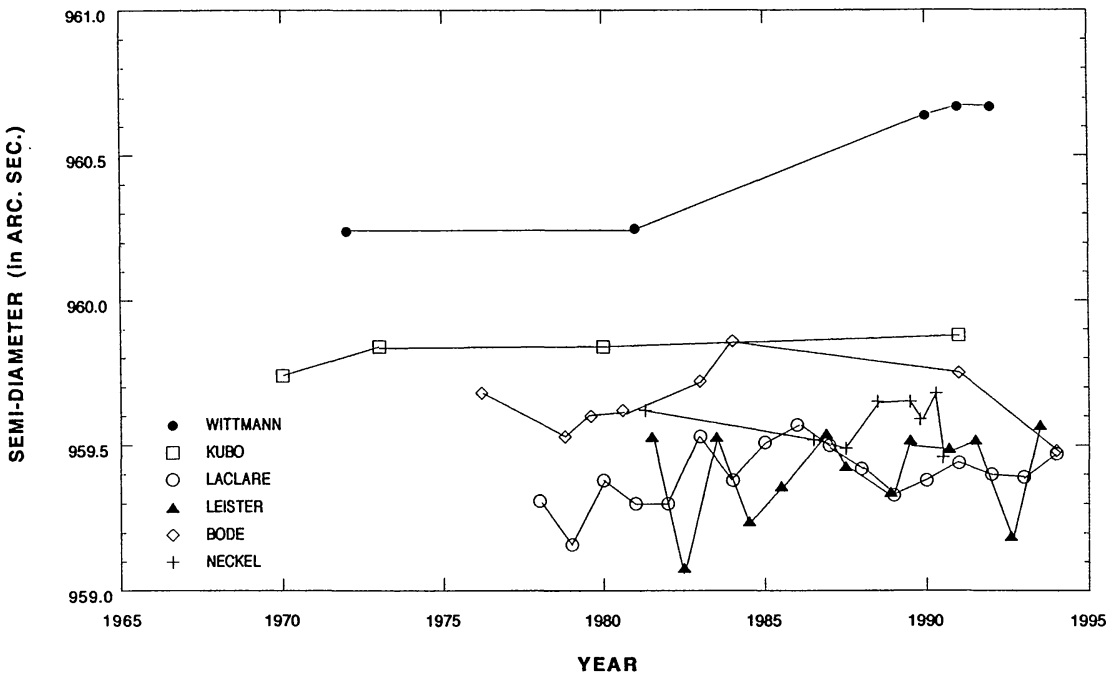


Figure 6. Long-term trend for the solar semi-diameter. Except for the Wittmann measurements, that show a 0.4″ increase between 1972 and 1991, a significant long-term variation cannot be seen in other series.

Santiago (8) and San Fernando (9) astrolabes. Nevertheless, these two astrolabes are less specialized in solar programs than those of São Paulo (7) and OCA (10).

– If we except the (3), (8), and (9) measurements, the set of data fits in a 0.5″ wide band and their mean value is 959.60″ (Figure 5).

– Finaly, we must stress that our extrapolated value of 959.58″ for a 'zenith observation' does not have the weight of other (observed) data.

4. Semi-Diameter Variations

Only the visual measurements series was considered for the study of eventual variations of the semi-diameter: the CCD measurement series cannot yet cover a long enough span of time for such a quest.

Concerning variations of the semi-diameter, our visual measurements, along with other recent ones (see Table III), do not span a long enough period of time to be able to reveal a long-term trend which might be of any significance.

In a recent paper, Wittmann detected an increase of the solar semi-diameter of 0.4″ over ten years (Wittmann, 1993). Accordingly, we tried to evaluate a possible solar radius variation in our series as well as in the recent ones that span more than ten years and the results are presented in Figure 6.

For the six selected sets, we obtained a rate of variation over ten years from 0″ to +0.25″:

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

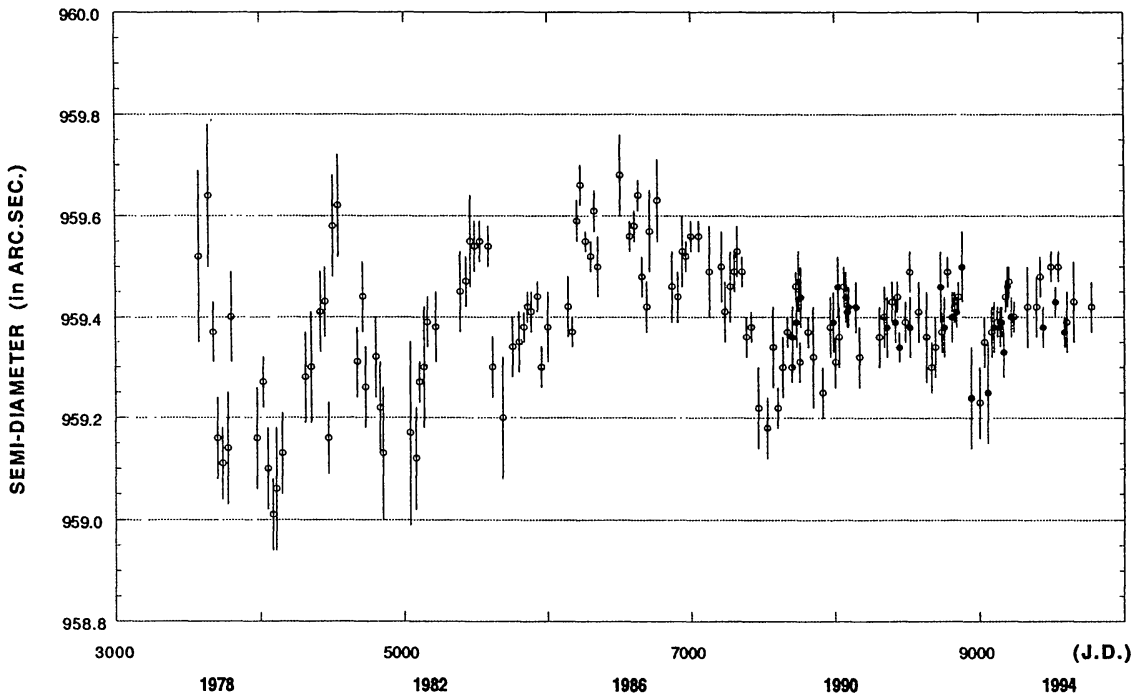


Figure 7. Monthly measurements of the observed semi-diameter. Circles are the visual and dots are the CCD measurements. The number of observed zenith distances increased from 3 in 1978 to 11 since 1987, which accounts for the improvement of the precision. This series hints at some variability of the observed semi-diameter between 1978 and 1994.

Wittmann	1972–1991	+0.25″	Correlation coefficient = 0.9
Laclare	1978–1994	+0.09″	0.4
Leister	1980–1993	+0.09″	0.2
Kubo	1970–1991	+0.05″	0.8
Bode	1976–1994	0.00″	0.1
Neckel	1981–1990	0.00″	0.1

On such a short-term set of data, the significance level of that trend is low. Moreover, these observation programs generally do not display enough continuity to allow the comparison of year to year variations between the series, except for São Paulo and OCA measurements (Leister and Benevides, 1990).

Nevertheless, our series of measurements made with the solar astrolabe by a single observer between 1978 and 1994, and framed in monthly averages, reveals some sense of variability of the apparent observed semi-diameter (Figure 7).

This figure suggests a long-term variation upon which are superimposed other large amplitude variations, dampened since 1986.

Several low-frequency oscillations were detected over the first ten years of measurements (Delache, Laclare, and Sadsaoud, 1985). The analysis then displayed a significant term corresponding to the solar cycle, a period of some 1000 days, and other diameter variations of lower amplitudes.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

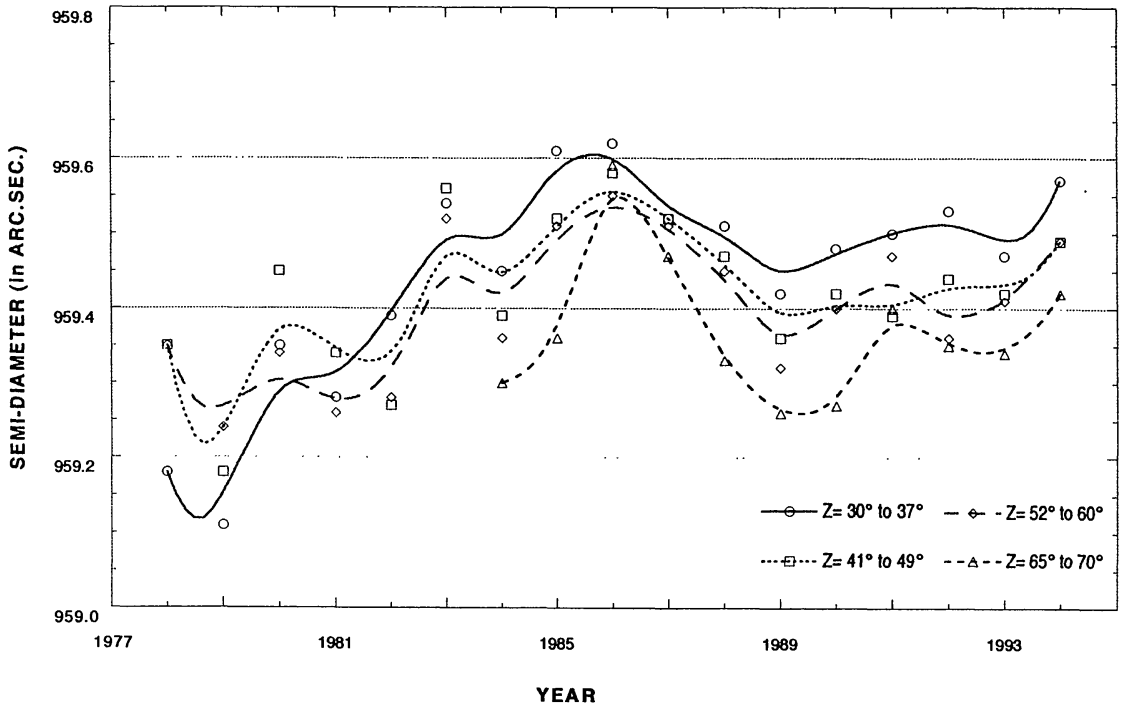


Figure 8. Semi-diameter variations and zenith distances. The apparent semi-diameter variations do not seem to depend on the thickness of the atmosphere crossed. The zenith distance effect mentioned in Figure 2 can also be recognized.

This oscillation of approximately 1000 days arose as early as 1982 (Laclare, 1983). Its amplitude then estimated at 0.18″ still largely dominated the low frequency spectrum computed from all the measurements of 1975 to 1984. We recall that an oscillation of the same phase was detected between 1980 and 1987 in the São Paulo series of measurements by Leister (Leister and Benevides Soares, 1990).

We thought that the origin of that oscillation could be atmospheric and linked with the existence of the quasi-biennial oscillation (Q.B.O.). But the vanishing of that oscillation after 1986 weakens such an explanation.

Another possible explanation of the changing character of that variation was recently offered by Wolff (1992). Grounded on the combination of g-mode pulsation frequencies, the reccurence period of that 1000-day oscillation might be 35 years.

We remark that these variations of the apparent diameter occur and are in phase with one another for any zenith distance of observation (Figure 8). This might prove that the observed variations are independent of the thickness of the atmosphere crossed.

The harmonic analysis over the whole 1978–1994 data set displays a large amplitude term whose period is close to the activity cycle:

$$R = 959.40'' + 0.04'' \sin(2\pi t/T) + 0.10'' \cos(2\pi t/T) ,$$

where t = J.D. − 6120.5 and T = 10.4 years.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

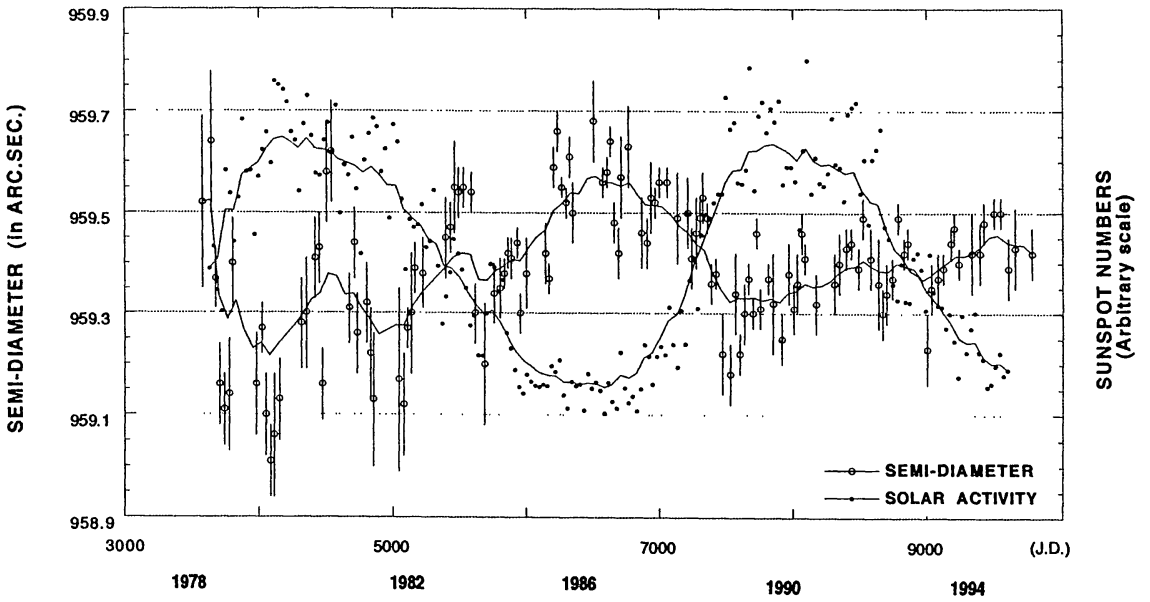


Figure 9. Semi-diameter variations and sunspot numbers. The raw data of the semi-diameters with their error bars are plotted together with solar activity given by the sunspot data. Respective smoothings are also shown. We notice an apparent opposing phase between semi-diameter and sunspots variations.

This variation has nearly an opposite phase relative to the solar activity given by the Sunspot Index Data Center (Pierre Cugnon (ed.), Brussels).

In Figure 9, instead of drawing this harmonic, we prefer to give the raw data of the semi-diameters with error bars and the sunspot numbers along with their respective smoothings.

This result confirms the work of Gilliland (1981) which was established using observations from Washington and Greenwich. We want to stress the necessity of following up this type of program since this slow variation of the semi-diameter, which seems to be connected with solar activity, is contained only once in the series of measurements that we carried out.

Finally, we remark on Figure 10 that if the observed diameters are sampled according to their heliographic latitude, larger and smaller than 45°, the variations are the same for both classes.

The similarity of the variations of the diameters of both classes of inclination can *a priori* be interpreted in two ways: their origin is to be found either in the atmosphere, in the instrument, or in the Sun. We cannot now interpret this phenomenon which remains an observational fact.

On the other hand, we know that irradiance and solar activity are correlated (Mecherikunnel, 1994); it is then no surprise to recognize the same link between the diameter and irradiance.

Similarly, we would like to recall that, as early as 1984, Delache linked the variations of the observed diameter with the neutrino flux measurements (Delache, Laclare, and Sadsaoud, 1988), and that in 1988 Gough mentioned an eventual

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

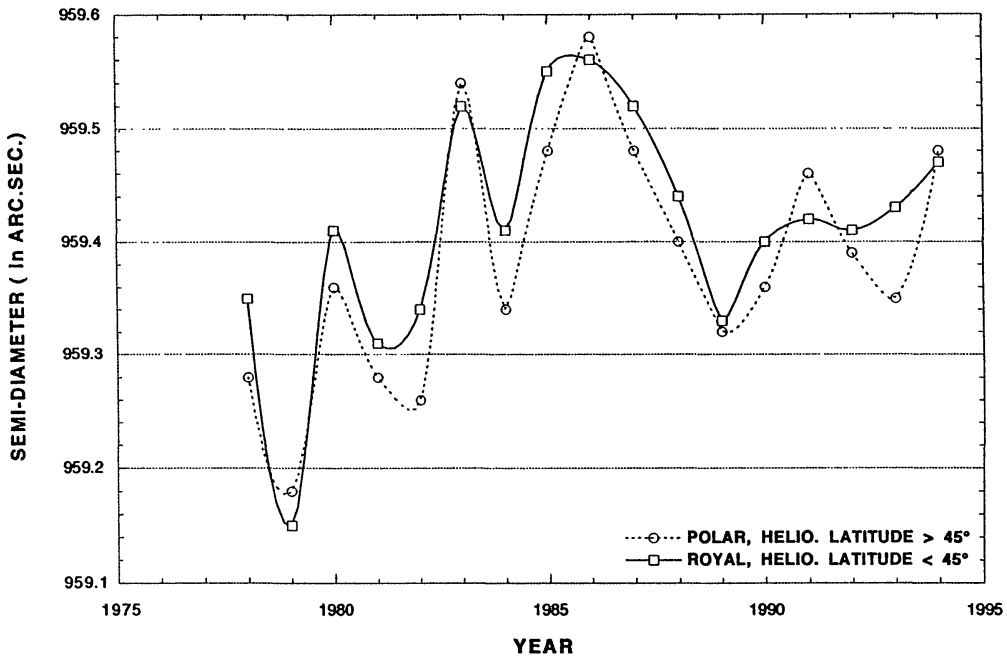


Figure 10. Semi-diameter variations and heliographic latitude. We can notice a good coherence between the semi-diameter variations of both heliographic inclinations, poleward and equatorward of 45°.

'causal connection' between sunspot number, solar neutrinos and diameter (Gough, 1988).

Naturally, this 'troublesome similarity' between the observed variations of the diameter and the solar neutrino flux could be chance. We feel nevertheless that it is worth mentioning. This connection between diameter and neutrino flux seems to be corroborated (Gavryusev, Gavryuseva, and Roslyakov, 1991; Gavryuseva and Gavruysev, 1994) as we see in Figure 11.

Finally, we would like to recall the relationship between our diameter measurements and the drift of frequencies of pressure modes (Delache *et al.*, 1993).

5. Conclusion

5.1. The mean semi-diameter that we obtain from the raw visual observations, i.e., $959.42'' \pm 0.01''$, is appreciably smaller than the one in use in the ephemeris ($959.63''$). It is different as well from values proposed by other authors that were obtained from different instruments with different methods.

The bandwidth of the observation, the spreading of the image resulting from atmospheric and instrumental effects, the uncertainty of the visual estimate of measurements account on the whole for the differences in the published results. Taking into account the zenith distance effect might provide a mean value of the semi-diameter of $959.58'' \pm 0.05''$. If this value is confirmed, it would be close to

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

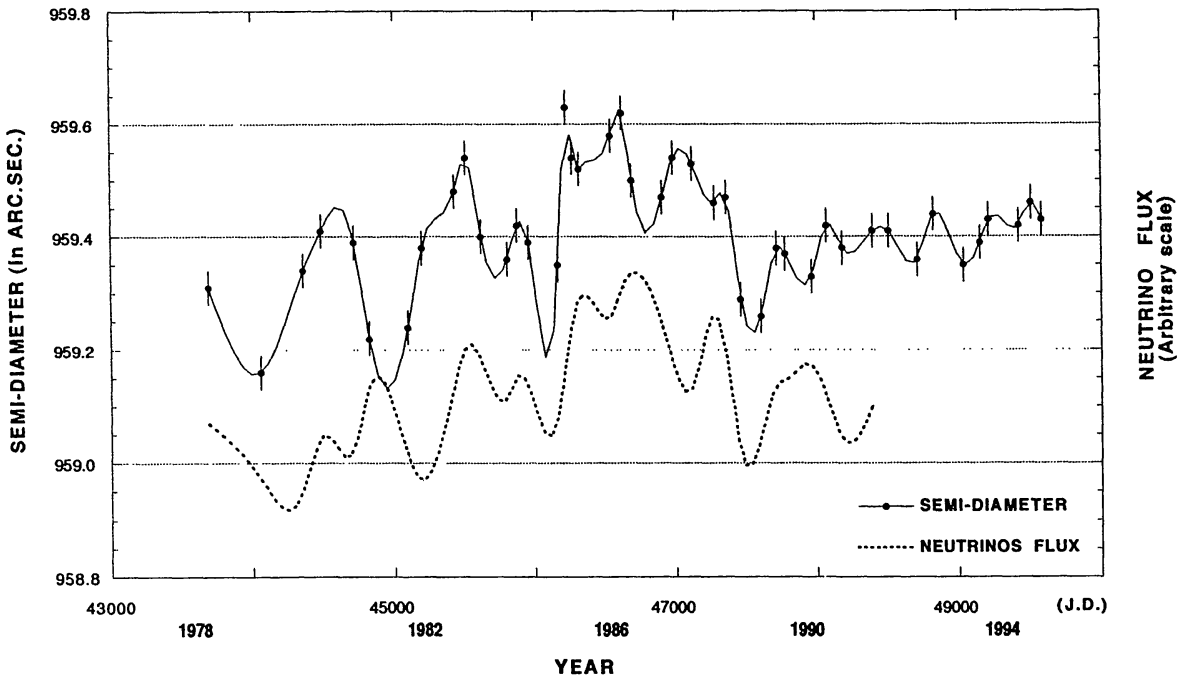


Figure 11. Semi-diameter variations and neutrino flux. The black dots averaging 140 measurements, we can notice a rather good likeness between the variations of the observed diameter and the data smoothing performed by the Gavryusevs on the homestake neutrino flux series.

the one in use in the ephemeris or those obtained by other methods free from or corrected the seeing effects.

For the last few years, we have been alternating on the solar astrolabe visual measurements with a series of CCD acquisitions. The raw mean value from the CCD program (981 measurements from 1989 to 1994) is $959.40'' \pm 0.01''$. The good agreement between the two types of acquisitions reduces the defect linked with the 'personnal bias' that goes with visual observations. On the other hand, we initiated an evaluation of the effects of atmospheric turbulence on the diameter from CCD observations (Irbah *et al.*, 1994). These studies are necessary for a better definition of the limb and consequently a better evaluation of the solar semi-diameter.

The series of measurements reveals deviations from the mean semi-diameter that could affect the royal or the high heliographic latitude zones; their amplitude could reach $0.08''$. The existence of these deviations is nowadays questionable. To decide for or against our result requires simultaneous and more global measurements achieved by other means (Sofia, 1994; Rösch *et al.*, 1996).

5.2. The series of observations made by a single observer on the same instrument for about twenty years displays a homogeneous character that permits the study of an eventual variability of the solar semi-diameter.

The series of measurements that we present here is plainly too short to enable the detection of an eventual secular trend. But variations are found in our series, whose amplitude ranges from $0.2''$ to $0.5''$ and is clearly larger than the error bars.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

The origin of these variations is currently unknown. It is then quite natural to put our measurements together with those which were done at the same time and linked either with the atmospheric circulation or solar activity.

A 1000-day oscillation, with an amplitude up to $0.20''$, was found three times in a row in the series of 1978 to 1986. The damping, let us say the disappearance, of that oscillation in our measurements cast doubt on a possible atmospheric origin such as the existence of QBO in the higher atmosphere.

We also observe a variation of the semi-diameter with $0.2''$ amplitude that has an opposite phase relative to the solar magnetic activity. This result corroborates in size and sign another source (Gilliland, 1981). We have to notice that these apparent semi-diameter variations that we detect seem to be independent of the zenith distance and the heliographic latitude of the observed diameter.

Lastly, we mention some similarities between the variations of the observed solar radius and other parameters with a solar origin and linked to the internal structure, such as the neutrino flux.

In spite of the still too short span of time covered by this series of measurements, these first results already allow a wide prospect for investigations. Their value can only increase with the improvement of the instrumental performance along with long-term observations and the launching of survey programs from space. Such a program of survey of the solar diameter conducted on the ground over a long period of time with the help of automatic instrumentation remains useful. Moreover, the observations parallel to those done from space (SOHO) will allow us the modelling of the effects which alter the observed limb and in this way will permit a better calibration of the measurements.

Acknowledgements

Philippe Delache (1937–1994) was an outstanding scientist who was especially interested in solar physics. Nothwithstanding his many responsibilities, he always spared time to give this observational program his full attention. Along with all those who were fortunate enough to meet him, we grieve his untimely loss. We express our thanks to Nelson Leister, who recently sent us a set of his reanalysed 1990 data. Our colleague Jean-Pierre Rozelot kindly communicated the last estimate of the quadrupole moment of the Sun, measured with the Pic-du-Midi heliometer and referenced in Rösch *et al.* (1996). Finally, the authors would like to express their appreciation for the sustained and profitable cooperation with Vladimir Gavryusev and Elena Gavryuseva with the neutrino production data analysis (from the Davis series at Homestake). Many thanks are also due to Peter Lawson and Michael Hrynevych for comments on the text.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1996SoPh..166..211L

References

Akimov, L. A., Belkina, I. L., Dyatel, N. P., and Marchenko, G. P.: 1993, *Kinematics Phys. Celest. Bodies* **9**, No. 3.

Auwers, A. A.: 1891, *Astron. Nachr.* **128**, 361.

Bode, H. J., Buchner, R., and Mushardt, M.: 1995, *Sterne und Weltraum* **34**, 646.

Chollet, F.: 1981, Thesis, Paris VI University.

Delache, Ph., Laclare, F., and Sadsaoud, H.: 1985, *Nature* **317**, 548.

Delache, Ph., Laclare, F., and Sadsaoud, H.: 1988, in J. Christensen-Dalsgaard and S. Frandsen (eds.), 'Advances in Helio- and Asteroseismology', *Proc. 123rd IAU Symp.*, p. 223.

Delache, Ph., Gavryusev, V., Gavryuseva, E., Laclare, F., Régulo, C., and Roca Cortés, T.: 1993, *Astrophys. J.* **407**, 801.

Eddy, J. A. and Boornazian, A. A.: 1979, *Bull. Am. Astron. Soc.* **11**, 437.

Gavryusev, V., Gavryuseva, E., and Roslyakov, A.: 1991, *Solar Phys.* **133**, 161.

Gavryuseva, E. and Gavryusev, V.: 1994, *Proc. 6th Int. Workshop Neutrino Telescopes-94*, Venice, p. 319.

Gilliland, R. L.: 1981, *Astrophys. J.* **248**, 1144.

Gough, D.: 1988, *Nature* **336**, 618.

Irbah, A., Laclare, F., Borgnino, J., and Merlin, G.: 1994, *Solar Phys.* **149**, 213.

Kovalevsky, J.: 1994, *Modern Astrometry*, Springer-Verlag, Berlin.

Kubo, Y;: 1993, *Publ. Astron. Soc. Japan* **45**, 819.

Laclare, F.: 1983, *Astron. Astrophys.* **125**, 200.

Laclare, F. and Merlin, G.: 1991, *C.R. Acad. Sci. Paris* **313 SII**, 323.

Laclare, F., Demarcq, J., and Chollet, F.: 1980, *C.R. Acad. Sci. Paris* **291B**, 189.

Leister, N. V. and Benevides Soares, P.: 1990, *C.R. Acad. Sci. Paris* **313 SII**, 399.

Leister, N. V., Poppe, P. C. R., Emilio, M., and Laclare, F.: 1995, *Poster in IAU Symposium* **172**, Paris, France, and a private communication from N. Leister.

Maier, E., Twigg, L., and Sofia, S.: 1992, *Astrophys. J.* **389**, 447.

Mecherikunnel, A. T.: 1994, *Solar Phys.* **155**, 211.

Neckel, H.: 1995, *Solar Phys.* **156**, 7.

Noël, F.: 1995, *Astron. Astrophys. Suppl. Series* **113**, 131.

Parkinson, J. M., Morrison, L. V., and Stephenson, F. R.: 1980, *Nature* **288**, 548.

Ribes, E., Beardsley, B., Brown, T. M., Delache, Ph., Kuhn, J. R., Laclare, F., and Leister, N. V.: 1991, in C. P. Sonett, M. S. Giampapa, and M. S. Matthews (eds.), *The Sun in Time*, University of Arizona, p. 94.

Rösch, J. and Yerle, R.: 1983, *Solar Phys.* **82**, 139.

Rösch, J., Rozelot, J. P., Deslandes, H., and Desnoux, V.: 1996, *Solar Phys.* **165**, 1.

Sanchez, M., Parra, F., Soler, M., and Soto, R.: 1995, *Astron. Astrophys. Suppl. Ser.* **110**, 351.

Sato, I. and Soma, M.: 1989, in H. Kinoshita and H.Yoshida (eds.), *22d Symposium in Celestial Mechanics*, Tokyo, Japan, p. 20.

Sofia, S., Dunham, D. V., and Fiala, A. D.: 1980, in R. O. Pepin, J. A. Eddy, and R. B. Merril (eds.), *Proc. Conf. Ancient Sun*, p. 147.

Sofia, S., Heaps, W., and Twigg, L. W.: 1994, *Astrophys. J.* **427**, 1048.

Wan Lai and Zhao Jun-Liang: 1989, *Acta Astron. Sinica* **30**, No. 4, 355.

Wittmann, A. D.: 1973, *Solar Phys.* **29**, 333.

Wittmann, A. D., Bonnet Navarro, J. A., and Wöhl, H.: 1981, in L. E. Cram and J. H. Thomas (eds.), *The Physics of Sunspots*, Proc. 5th SPO Summer Workshop, National Solar Observatory, Sunspot, NM, p. 424.

Wittmann, A. D., Alge, E., and Bianda, M.: 1991, *Solar Phys.* **135**, 243.

Wittmann, A. D., Alge, E., and Bianda, M.: 1993, *Solar Phys.* **145**, 205.

Wolff, C. L.: 1992, *Solar Phys.* **142**, 187.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System