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The diameter of the Sun over the past three centuries

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Abstract. 17th century measurements of the solar diameter indicate values which are about 10" (0.5 per cent) larger than the present figure of approximately 1920". The apparent enlargement is smaller (3") for measurements made during the 19th century. Has the diameter of the Sun diminished significantly over the past three centuries or is the reason for the difference located in the methods used or the instruments employed during the period? In this paper, a comparison of 30 series of measurements, obtained at various epochs over the last three centuries, is made with about 900 modern measurements applying early techniques and instruments. This investigation reveals the necessity of instrumental corrections, notably the effect of diffraction. When these corrections are taken into account, a homogenised database, extending over three centuries, can be considered. This does not reveal any sensible secular variation in the solar diameter and leads to a result for the semi-diameter at 1 AU of 960".0 $\pm$ 0".1.

Key words: Sun: fundamental parameters – Sun: activity

1. Introduction

The usage of early measurements to investigate long-term trends in the solar diameter commenced with the pioneering work of Eddy and Boornazian (1979). These authors deduced from the Greenwich meridian circle observations between 1836 and 1953 that the solar diameter had shown a secular decrease at a mean rate of 2".25/century. However, this result was disputed by Parkinson et al. (1980), who criticised Eddy and Boornazian's interpretation of the Greenwich data. In particular, Parkinson et al. demonstrated that different observers obtained discordant results with the same instrument. They also showed that analysis of series of timings of both Mercury transits and total solar eclipses since 1715 revealed no evidence of a secular change in the solar diameter. Soon afterwards, Gilliland (1981), by combining meridian circle measurements since 1836 with Mercury transit data since 1715, suggested that a secular decrease in the solar diameter by 0".1/century was "likely". Débarbat (1982) deduced that determinations of the horizontal diameter of the Sun at noon by Picard between 1666 and 1673 revealed irregularities of periodical nature. Subsequently Ribes et al. (1987) made an analysis of 50 years of measurements by Picard and La Hire between 1666 and 1718 which were in the form of annual means. These results indicate that around 1700 the solar diameter was some 4" greater than it is now. However, in reply Morrison et al (1988) demonstrated that careful observations of the edges of the shadow at the total solar eclipse of 1715 implied that at that date the solar diameter had essentially the present value. In order to try to resolve these difficulties, I have analysed extensive series of measurements of the solar diameter covering a long time scale - from 1660 to the present day - with the object of establishing a reliable database for the diameter of the Sun (Toulmonde 1995). The present paper is a summary of this work.

2. The measurements

Table 1 gives a list of measurements of the solar diameter available at the Paris Observatory library both in archives and documents from 1660 to 1995. Columns 1 to 4 contain respectively a reference number (1 to 30), name of author, date and method. Columns 5 to 7 give the number (N) of individual measurements, the calculated value of the semi-diameter at 1 AU (R1) and the estimated error (δR) for one individual measurement in each set. The contents of columns 8 to 10 will be discussed in Sects. 3 and 4 below. In the case of the 17th and 18th centuries (reference numbers 1 to 13), I have studied the measurements by comparing with modern theories and ephemerides. For each individual measurement made by each observer, I determined the value of R1 using the VSOP82 theory of Bretagnon (1982). In particular, this comparison has led to an explanation of the periodical term noted by Débarbat (1982); this proves to be a fictitious term related to the fact that the secular change in the eccentricity of the Earth's orbit produced by planetary action had not been taken into account. The error for each individual measurement (δR) was estimated, mainly on the basis of remarks by the observers, related to instrumental difficulties: micrometer, clock, reticule. The data dispersion (σ) could only provide a reasonable order of magnitude for the experimental uncertainties. In addition, similar observations have been made recently (Toulmonde 1995), either (i) using a well-preserved

Table 1. Observations in chronological order and R1 values. In column 2, names in parenthesis are those of authors who have analysed the observations and not the observers themselves. Methods are given in col. 4: PP = projected transit time, MI = micrometer, DP = observed transit time, HE = heliometer, ME = transit time at meridian circle, AS = solar astrolabe.

no	author	date	method	N	R1(")	δR(")	D(cm)	β(")	Rc(")
1	Mouton	1660	PP	86	959.4	3.3	1-2	+8	951.7
2	Auzout	1666	MI	2	965.2	2		+5	960.5
3	**Picard**	1670	MI	304	964.6	2	2-3	+5	959.9
4	Richer	1672	DP	26	961.9	5.2	2-3	+5	957.2
5	**Picard**	1674	DP	154	962.9	3.5	2-3	+5	958.2
6	La Hire	1683	MI	14	963.2	2.8	2-3	+5	958.5
7	**La Hire**	1684	DP	304	965.4	3.8	2-3	+5	960.7
8	La Hire	1701	DP	6980	963.6	3.8	2-3	+5	958.9
9	Louville	1724	DP	10	962.4	2		+3.3	959.4
10	Bouguer	1753	HE	14	957.3	2	4.3	+1	956.6
11	**Mayer**	1759	DP	105	960.4	1.2	5	+3.2	957.5
12	Lalande	1760	HE	12	961.1	1.5	4.3	+1	950.4
13	Lalande	1764	HE	12	961.4	1.5	4.3	+1	960.7
14	**Bessel**	1824	ME	1698	960.90	0.5		+1.2	959.7
15	**(Airy)**	1837	ME	92	962.25	1.4		+1	961.3
16	**Goujon**	1842	ME	1575	962.20	0.6	15	+0.9	961.3
17	(Smith-M.)	1877	ME	1363	961.45	0.7		+1	960.5
18	**Auwers**	1880	HE	2840	959.63	0.5		-0.3	959.9
19	(Gething)	1895	ME	10302	961.04	0.44		+1	960.0
20	**Schur**	1896	HE	760	960.07	0.55	15	-0.3	960.4
21	**Ambronn**	1897	HE	920	959.9	0.55	15	-0.3	960.2
22	(Cimino)	1907	ME	27249	961.34	0.54		+1	960.3
23	(Smith-M.)	1946	ME	3468	961.34	0.20	15	+0.9	960.4
24	**Wittmann**	1974	DP	246	960.00	0.8	45	+0.3	959.7
25	**Wittmann**	1978	PP	2159	960.29	1.8	45	+0.3	960.0
26	**(Ribes)**	1981	ME	349	961.20	0.5	19	+0.7	960.5
27	**Leister**	1984	AS	804	959.4	0.8	5	-0.3	959.7
28	**Journet**	1986	AS	1176	959.03	0.4	5	-0.3	959.3
29	**Laclare**	1987	AS	8000	959.4	0.3	5	-0.3	959.7
30	**Noël**	1991	AS	189	960.8	0.6	5	-0.3	961.1

historical instrument (dated 1677) or (ii) with the aid of a small modern telescope which was assumed to be similar to that used by early observers. Both series of measurements enable the past observations to be better assessed, considering the timing for the solar limb (eye and ear method) and the friction of the micrometer screw. Astrometric instruments around 1700 had a very small objective (2 to 3 cm in diameter) and with a focal length from 2 to 3 m. For micrometric measurements, the full disk of the solar image was seen in the field of view; the objective had only a single lens, which was often employed with a diaphragm to diminish the geometric and chromatic aberrations. In my detailed analysis of these observations, I showed that the measurements made with such instruments gave results for the solar diameter some 10" (0,5 per cent) larger than the standardised values calculated using modern ephemerides. For the data from the 19th and 20th centuries, analyses by various authors have been divided into two groups. Items numbered 14 to 23 in Table 1 are based on the measurements from the beginning of the 19th century up to the middle of the 20th century; those numbered 24 to 30 relate to the most recent measurements. It should be noted that in many instances, the period covered by any specific series of measurements covered several decades, with observations made by different personnel, using a variety of instruments at the same observatory.

Table 2. Main corrections (over to 0".1) to the horizontal diameter of the Sun

- atmospheric refraction	0".6
- seeing	~ 1"
- personal equation	1" to 2"
- diffraction of the objective	12" (~ 1680), 6" (~ 1750)
	2" (~ 1850), 1".4 (~ 1900)

3. Corrections to measurements

The measures analysed here, considering the horizontal diameter, have been corrected for various factors (the vertical diameter is more affected by refraction). The main corrections (which

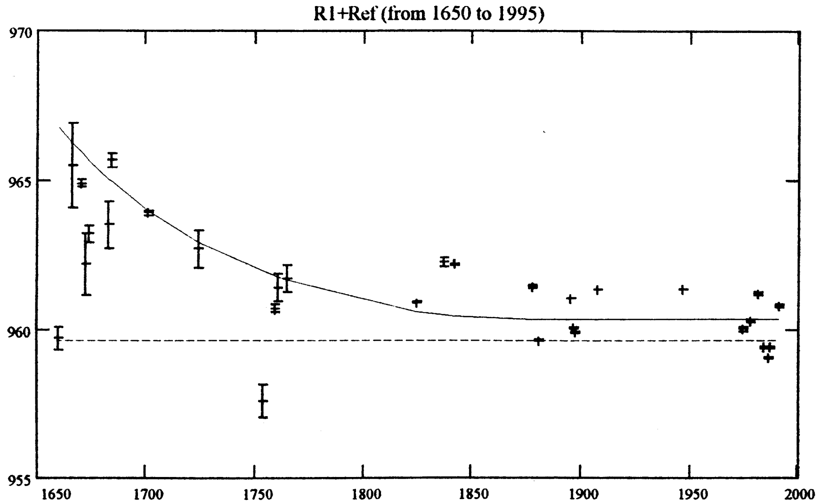

Fig. 1. Representation of $R1 + Ref$ from 1650 to 1995 (from Table 1). The solid line (959".63 + β) represents the effect of applying a diffraction correction to the mean semi-diameter of 959".63 of form $\beta \sim$ 15"$/D$ (where D is in cm) up to 1870 and later $\beta \sim$ +0".7

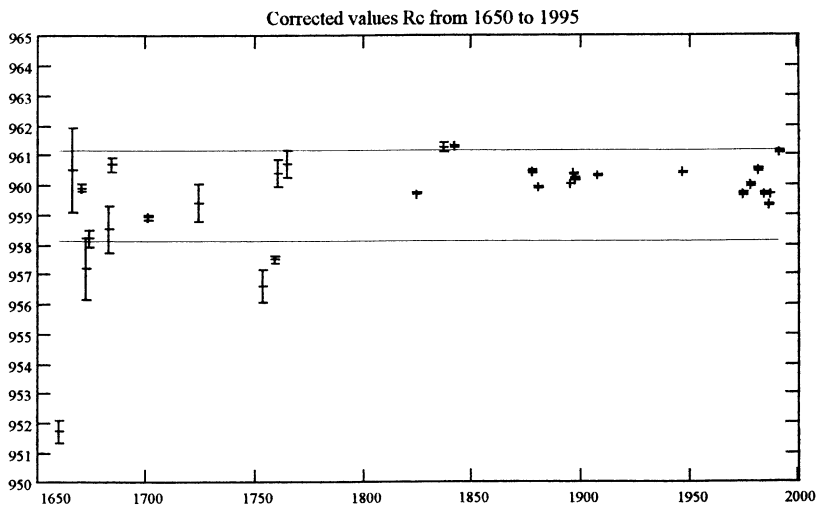

Fig. 2. Representation of $Rc = R1 + Ref - \beta$. Horizontal lines correspond to R = 959".63 ± 1".5

values greater than 0".1), are given in Table 2; these relate to atmospheric refraction and turbulence, personal equation of the observer and diffraction at the objective. In particular, this last correction could be very important for instruments having a small objective - such as those employed during the 17th and 18th centuries. By the 19th century, instruments have larger diameters so that diffraction would not be so important. More than a century ago, André (1876, 1877) studied this aspect. Allowing for refraction and diffraction, the corrected value of the semi-diameter of the Sun at unit distance (Rc) can written in the form $Rc = R1 + Ref - \beta$, where Ref is the correction for refraction and β is the correction for diffraction. The diffraction correction, of the order of $1.22\lambda/D$, corresponds to 16"$/D$ (red filter) or 14"$/D$ (green filter), where D is the diameter of the objective in cm. When D is not known, I have used an empirical formula $D \sim 2,5.exp[(year - 1680)/82]$; this is valid up to 1870. After 1870, the diameter is considered to be 20 to 25 cm. The different values of β are summarised in Table 2 and are listed in column 9 of Table 1 following the estimated value of D in column 8. As seen from this table, for the heliometer and astrolabe when observing two limbs of the Sun, the assumed correction ranges from about +1" to -0.3". The refraction correction Ref (equal to +0".3 for the semi-diameter), is applied to all R1 values deduced from the observations made up to the end of the 18th century. It is assumed that during the 19th and 20th centuries, the necessary correction was properly applied.

4. The corrected measurements

Values of R1 and the derived results for Rc are given in Table 1 (column 10) for the 30 series, which in total contain 71000 measurements. Fig. 1 shows the values of R1 corrected only for refraction; it is evident that the results in the 17th and 18th centuries exceed the conventional value 959".63 due to Auwers (1891) - represented by a broken line in the diagram - by 5" at the beginning of this period and 2" at the end. The solid line (959".63 + β) represents the effect of applying a diffraction correction to the mean semi- diameter of 959".63 of form $\beta \sim$ 15"$/D$(where D is in cm) up to 1870 and later $\beta \sim$ +0".7. It is evident that there is a close correlation between the values of $R1+Ref$ and 959".63+β for the whole of the period between 1660 and 1995. Fig. 2 plots the values of Rc listed in Table 1. It also shows two solid lines corresponding to a semi-diameter

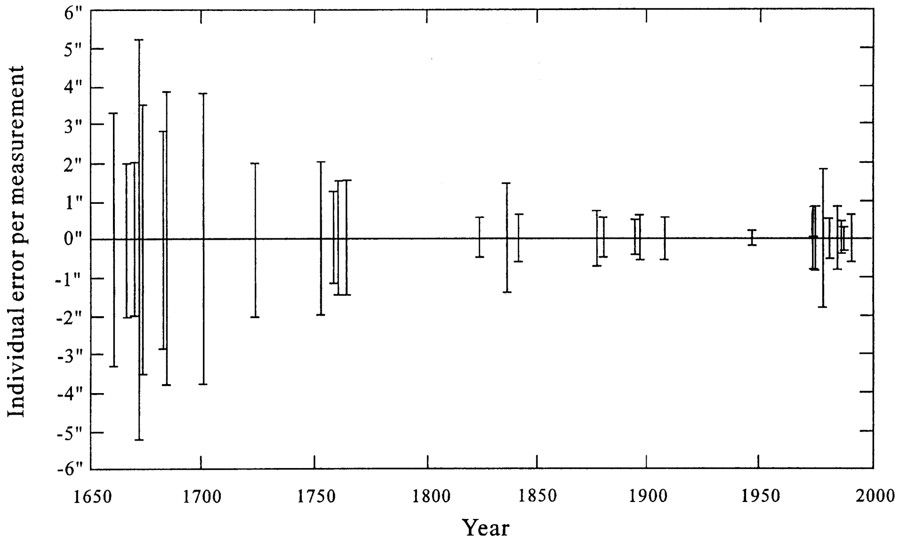

Fig. 3. Representation of error (δR) for one measurement of the semi solar diameter

of 959".63 ± 1".5. This uncertainty of 1".5 includes certain of the quantities given in Table 2: personal equation (1" to 2") and seeing (1") - both relative to the solar diameter. It can be seen that this zone of width 3" embraces nearly all of the individual values Rc in Table 1; the only exceptions are the results from the observations by Mouton (ref no. 1), Bouguer (no. 10) and Mayer (no. 11), for which the following comments are relevant. Mouton (1670) had an unusually large personal equation; Bouguer (1753) was not satisfied with his 14 measurements made using the recently designed heliometer; perhaps Mayer (1826) had already applied a correction for irradiation of approximately -2" to his results (Rc actually being 959".9 instead of 957".5).

5. Evolution of errors of measurement

Fig. 3 shows the evolution over the past three centuries of the error for one measurement δR as listed in Table 1. The error diminished by a factor 10 during that time. The diminution is more sensible in the case of the transit timings and is here due to the increasing diameter of the instruments and the use of better pendulum clocks and later chronographs. To obtain a better assessment of the old measurements, experiments have been made according to the original techniques (Toulmonde 1995): (i) duration of transit by projection similar to Mouton's experiments or using a cross-wire placed in a small telescope with a diaphragm of 5 cm; (ii) with the aid of an historical micrometer dated 1677.

6. Results for the solar diameter

The Rc values, from Table 1, which are plotted in Fig. 2, show that for two different observers using the same technique around the epoch 1680, some results are in considerable discord with one another. These measurements were made by Picard (1666) (ref nos. 3 and 5) and La Hire (1683) (ref nos. 6 and 8). This comparison shows that there are some difficulties in deducing a value for the solar diameter at this early period. The 30 Rc values listed in Table 1 (derived from 71000 measurements) considered as a unit lead to a mean value for the solar diameter $R1c$ = 960".02 ± 0".11 (σ = 0".59). If the very long series of observations (more than 10000 measurements or longer than 20 years with several observers, and a possible personal bias) or the very short sets (less than 90 measurements) are rejected, 17 sets remain. These are numbered in bold type in Table 1 and include in total 22000 individual measurements. The mean value for the solar diameter derived from this restricted data set is $R1c$ = 959".93 ± 0".13 (σ = 0".52). These two results are very close and taking into account the possible errors, the most probable value for the solar semi-diameter at 1 AU is $R1$ = 960".0 ± 0".1. This value is the same as that given by Wittmann et al. (1981), and exceeds by 0".6 Laclare's value (1993): 959".4. From the present data analysis, there is no evidence of any secular variations in the solar diameter when diffraction at the objective lens is taken into account. This result supports those of Morrison, Parkinson and Stephenson (1980 and 1988) which indicate that the solar diameter exhibits long-term stability. However, the findings of this investigation are in clear discord with those obtained by Eddy and Boornazian, and by Ribes et al. which indicate a major secular decrease in the solar diameter: the secular decrease from Eddy and Boornazian would bring to a variation of 7" after three centuries; as the apertures of 17th century refractors increased from 2.0 to 2.5 cm, the diffraction correction decreased by about 3".

7. Conclusion

It may be concluded from the present investigation that the available measurements of the solar diameter, which extend from the 17th century to the present day, reveal no evidence of any secular variation. However, the presence of shorter term fluctuations cannot be ruled out. A further result of this paper is that the mean solar semi-diameter at 1 AU over the past 300 years is 960".0 ± 0".1. On the question of the constancy of the solar diameter, the remark made by Lalande (1792) seems particularly relevant today: “ *Quoi qu’on ait trouvé le diamètre du Soleil de plus en plus petit depuis un siècle, je ne crois pas qu’il ait réellement diminué.*”

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