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A COMPARISON AMONG SOLAR DIAMETER MEASUREMENTS CARRIED OUT FROM THE GROUND AND OUTSIDE EARTH'S ATMOSPHERE

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ABSTRACT

The solar diameter has been measured since the 17th century, using different methods and instruments, and without a clear strategy of measurement, which could explain the lack of coherence between the results obtained. The present study confirms that the discrepancies between solar diameter measurements are mostly due to differences in instrumental characteristics, the spectral domain of observation of each investigation, and atmospheric turbulence for ground measurements. We show that correcting the measurements for the effects introduced by the properties of each instrument reduces the differences between the radius measurements to the level of uncertainty of each instrument. This study makes use of simulated and real data. For the simulated data, we use an empirical model of the solar limb shape, and for observations, we use measurements carried out with the Solar Disk Sextant experiment, the CCD solar astrolabe of Calern Observatory, and the Michelson Doppler Imager on board *SOHO*.

Subject headings: atmospheric effects — Sun: photosphere — techniques: image processing

Online material: color figures

1. INTRODUCTION

The fundamental global parameters of the Sun measured with precision are (1) the total solar irradiance, which allows us to recover the solar luminosity; (2) the solar spectrum, which permits us to determine the composition of the solar atmosphere, to distinguish the origin of emission lines, and to determine the temperature as a function of altitude; (3) the oscillation modes and asphericity, which permit measurement of the rotation of internal layers that are not accessible to direct observation; (4) the form of the limb, which permits study of the chemical composition of the solar atmosphere and the temperature gradient; and (5) the solar diameter, which permits one to study the variations of the magnetic field and the dynamics of the convection zone (see, e.g., Sofia et al. 2005).

Even though the solar diameter has been the subject of careful measurements for 350 years, with gradually increasing accuracy, the results up to now do not allow one to determine without ambiguity its variation or its constancy, say, as a function of solar activity. Furthermore, different instruments provide different absolute values of the solar radius (Thuillier et al. 2005). For ground-based data, the different instruments and methods of measurement provide inconsistent results as a function of solar activity. Generally, to explain these differences the effect of atmospheric turbulence is invoked. To overcome the problem of the atmosphere, observations have been carried out from stratospheric balloons by the Solar Disk Sextant (SDS) experiment and in orbit by the Michelson Doppler Imager (MDI) on the *Solar and Heliospheric Observatory* (*SOHO*).

Some of the instruments that have been used to measure the solar diameter are listed in Table 1. The diversity of their designs suggests that the discrepancies in the results are likely due to (1) the wavelength and the spectral domain of observation, (2) Earth's atmosphere, (3) the point-spread function (PSF), (4) the spatial resolution and pixelization, and (5) the processing methods. The effect of this last item is discussed in Djafer et al. (2008), where it is shown that noise-filtering methods may introduce a bias in the measured solar diameter. The objective of this article is to study to what degree these causes can explain the discrepancies in the diameter values derived from measurements obtained with the SDS, MDI, and ground-based telescopes.

2. WAVELENGTH AND SPECTRAL DOMAIN OF OBSERVATION

The solar diameter is usually measured by determining the position of the inflection point of a series of solar limbs. The position of the inflection point varies if the slope of the solar limb changes. Consequently, the value of the diameter so determined also changes. This is why we have investigated all available information about the solar limb-darkening function.

Before 1970, most observations of the solar limb-darkening function were carried out photographically (Canavaggia & Chalonge 1946) and a few ones photoelectrically (Peyturaux 1955). Thanks to improvements in detectors and methods of observation, precise measurement of the solar limb-darkening function became possible, and several solar limb models were derived, such as those of Allen (1973), Pierce & Slaughter (1977) and Pierce et al. (1977), Mitchell (1981), Neckel & Labs (1994), and Hestroffer & Magnan (1998, hereafter HM98). These models, uncorrected for instrumental effects, show a variation of the solar limb darkening as a function of wavelength. To illustrate this dependence, we simulated a solar image seen through an optical system of constant PSF (independent of wavelength) and with a CCD detector that permits a spatial resolution of 0.01″ (the choice of these values is arbitrary, but it allows the determination of an inflection point for the limb and, consequently, the radius). For each wavelength for which the model is defined, we determine the corresponding solar image and calculate the mean solar radius. The results are presented in Figure 1 and show

TABLE 1

Photometric and CCD Measurements of the Solar Diameter

Site/Instrument	λ (nm)	$\Delta\lambda$ (nm)	Period	D (cm)	r (arcsec pixel^{-1})	R (arcsec)	P	Reference
Mount Wilson	525.02	0.014	1970–2003	30.48	9.6 × 13.1, 12.9 × 20.1[a]	959.486 ± 0.005	B	Ulrich & Bertello 1995, Lefebvre et al. 2006
Calern:								
11 prisms[b]	540	200	1989–1995	10[c]	0.60	959.590 ± 0.010	C	Laclare et al. 1999
11 prisms	538	200	1996	10[c]	0.74	959.360 ± 0.030	C	Sinceac et al. 1998
Prism[d]	850	160	1996	10[c]	0.74	959.385 ± 0.035	C	Sinceac et al. 1998
11 prisms	538	200	1996–1997	10[c]	0.74	959.630 ± 0.080	C	Chollet & Sinceac 1999
DORaySol	548	60	2001	10[c]	0.50	959.509 ± 0.014	C	Andrei et al. 2004
Rio de Janeiro:								
Prism[e]	563.5	168	1997–1998	10[c]	0.50	959.200 ± 0.020	C	Jilinski et al. 1999
			2001	10[c]	0.50	959.190 ± 0.013	C	Andrei et al. 2004
Antalya:								
2 prisms	550	180	1999–2000	10[c]	0.78	959.030 ± 0.070	C	Gölbaşı et al. 2001
			2001–2003	10[c]	0.78	959.290 ± 0.010	C	Kılıç et al. 2005
Boulder (SDM)	800	10	1981–1986	10	1	959.680 ± 0.018	E	Brown & Christensen-Dalsgaard 1998
Locarno/Izaña	475.8	2.1	1997	45	0.179	959.73 ± 0.050	A	Wittmann 1997
	486	2.1	1997	45	0.179	959.81 ± 0.030	A	Wittmann & Bianda 2000
	583	2.1	2000	45	0.179	960.09 ± 0.040	A	Wittmann & Bianda 2000
Kitt Peak	329.8–660	2	1981	152	0.925	959.620 ± 0.030	C	Neckel 1995
SDS	620	80	1992–1996	13	0.128	959.561 ± 0.111	E	Egidi et al. 2006
						959.658 ± 0.091	C, E	Djafer et al. 2008
MDI	676.78	0.0094	1996–2006	15	2	959.283 ± 0.150	C	Kuhn et al. 2004

Notes.—Listed are wavelength λ, bandpass $\Delta\lambda$, telescope diameter D, spatial resolution r, the Sun's radius R, and the processing method, P: (A) the solar limb is defined by the point having maximal slope; (B) the solar limb is defined by the point at 25% of intensity to the Sun disk center; (C) the solar limb is defined by the barycenter of points around the point of the maximum of the first derivative; (E) the solar limb is determined by the finite Fourier transform definition.

[a] The instrument uses two resolutions; data are combined to use the best resolution.

[b] Analogical CCD measurement.

[c] The real aperture of the telescope is about 5 cm × 8 cm.

[d] Motorized variable prism.

[e] No motorized variable prism.

that for all models, the calculated solar radius increases with wavelength. We note that for the model of Pierce et al. (1977), there is a difference of 12 mas between the radius at 500 nm and that at 1000 nm. This difference is 13 mas for the Neckel & Labs (1994) model, and 19 mas for the HM98 model.

This dependence of the solar radius on wavelength has not been rigorously verified experimentally. The only instruments that have measured the solar diameter at different wavelengths are the Gregory coudé telescopes of Locarno (Switzerland) and Izaña (Tenerife) (Wittmann 1997; Wittmann & Bianda 2000). Table 1 lists these CCD measurements for three wavelengths. We note that the radius increases with wavelength.

According to Table 1, we also note the absence of consensus on the choice of the spectral domain of observation. Certain instruments observe in the continuum at different wavelengths, while others observe in the center of a Fraunhofer line, as does the Mount Wilson instrument (Ulrich & Bertello 1995; Lefebvre et al. 2006). In addition, there are instruments that use a narrow bandpass, such as MDI (0.0094 nm) and Mount Wilson (0.014 nm), whereas others use a wide spectral domain on the order of hundreds of nanometers, as do, for example, the CCD astrolabes.

The behavior of the intensity of Fraunhofer lines over the solar cycles is not the same for all lines (Livingston 1992; Livingston & Holweger 1982; White & Livingston 1978). Therefore, in the case of wide-bandpass observations, where Fraunhofer lines are present the chromospheric emission associated with these lines may modify the value of the solar diameter determination and thus affect the study of its variability as a function of solar activity.

The effect of the presence of Fraunhofer lines is illustrated by the physical model of Haberreiter & Schmutz (2003), which shows that the chromospheric contribution of Fraunhofer lines increases the value of the determined solar diameter. This model gives a difference of 314 mas between the position of the inflection point of a solar limb profile calculated in the center of the Fe I Fraunhofer line at 607.85 nm and that in the continuum at 606.9 nm. Correcting for the intensity variation of the Fraunhofer lines present within the bandpass is an uncertain task, as the observations of weak and moderately strong lines show a slight increase in strength at the limb, whereas the strongest lines show a decrease (Pierce & Allen 1977). Neckel (1995) concluded after calculating the solar radius in 1981 and between 1986 and 1990 that the solar radius differences will exceed 0.1″ if the observations are undertaken in spectral bands that contain Fraunhofer lines.

3. EFFECT OF EARTH'S ATMOSPHERE

On the ground, atmospheric turbulence modifies the observed shape of the Sun's limb, and this effect is always considered to be the source of the discrepancies among the diameter determinations. We used the HM98 solar model and the characteristics of the *Définition et Observation du Rayon Solaire* (DORaySol) instrument of Calern (Delmas et al. 2006) to simulate the mean solar limb, and the Kolmogorov model to represent the atmospheric effects (Lakhal et al. 1999). Figure 2 shows the PSFs of the atmosphere and their effect on the displacement of the position of the inflection point for several values of Fried's parameter r_0. We note from Figure 2*b* that the position of the inflection point of the measured limb is subject to a displacement that increases with turbulence. This displacement is on the order of 0.123″ for r_0 = 5 cm, and 1.21″ for r_0 = 1 cm. These values are obtained with the assumptions that we observe with a long

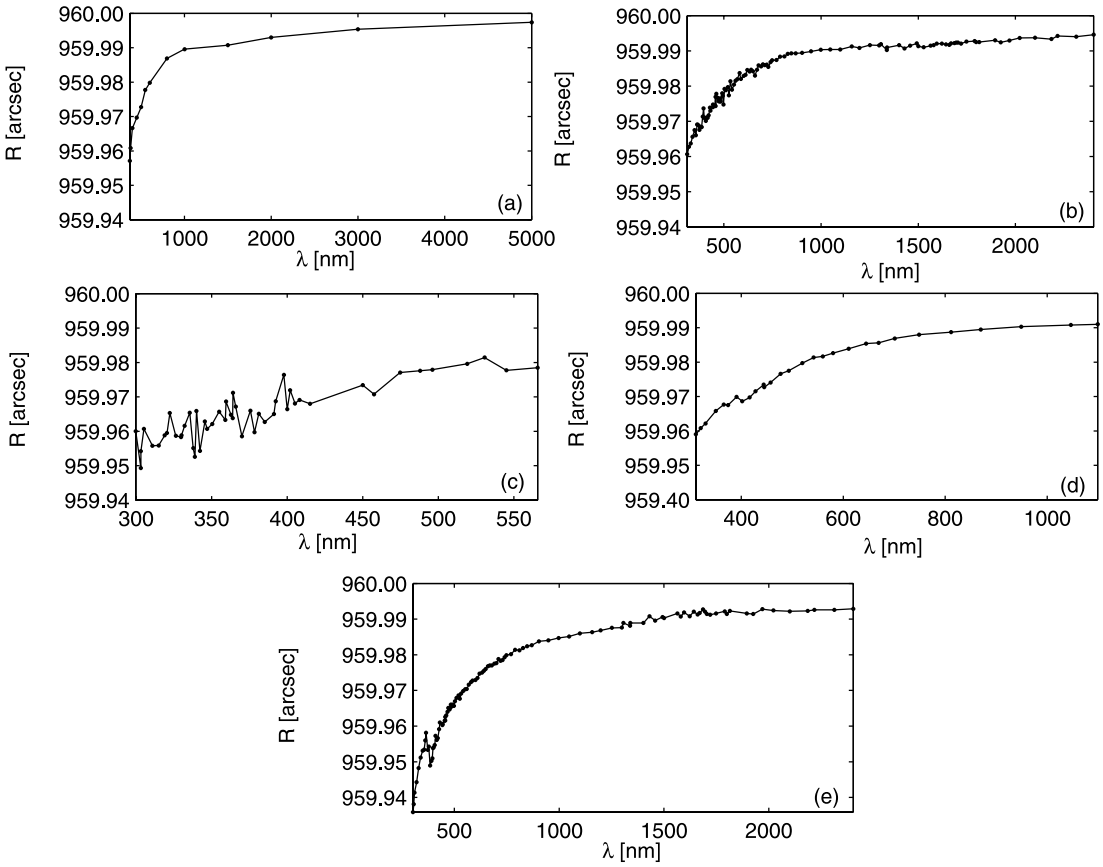

FIG. 1.—Variation of the calculated solar radius (R) as a function of wavelength suggested by five solar models: (a) Allen (1973), (b) Pierce & Slaughter (1977) and Pierce et al. (1977), (c) Mitchell (1981), (d) Neckel & Labs (1994), and (e) HM98. [*See the electronic edition of the Journal for a color version of this figure.*]

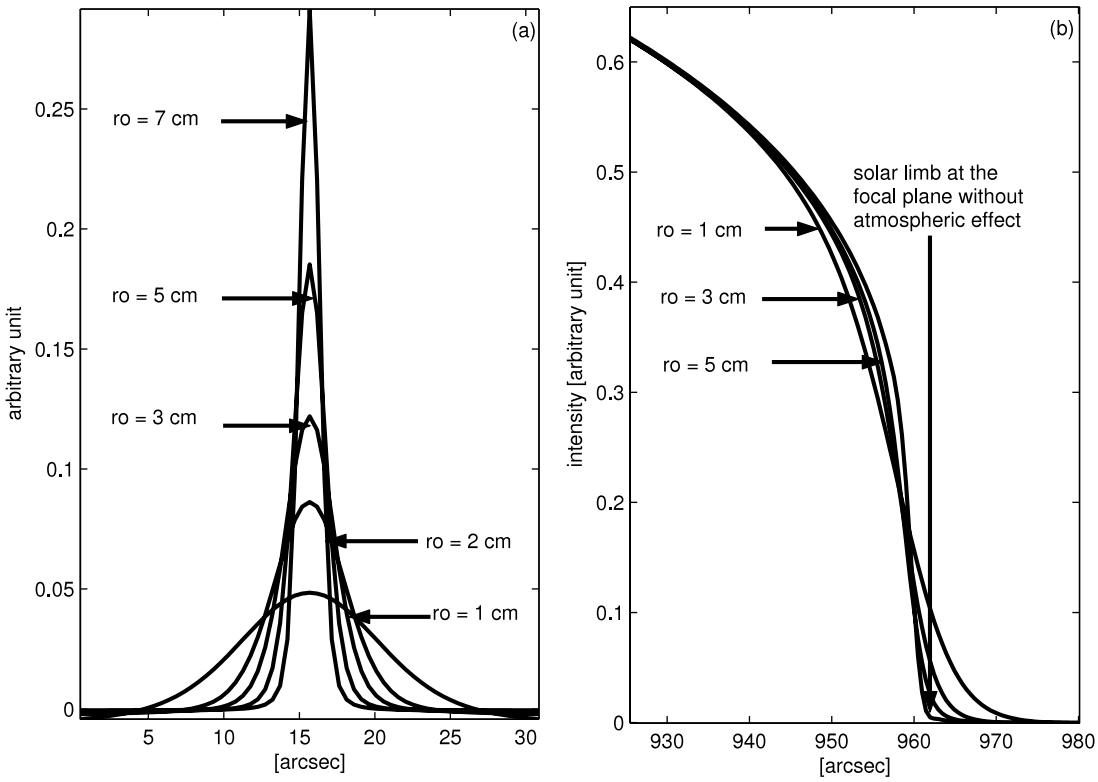

FIG. 2.—(a) PSF for several values of Fried's parameter r_0 according to the Kolmogorov turbulence model, through a telescope having the instrumental characteristics of the DORaySol instrument; (b) effect of atmospheric turbulence on the solar limb. [*See the electronic edition of the Journal for a color version of this figure.*]

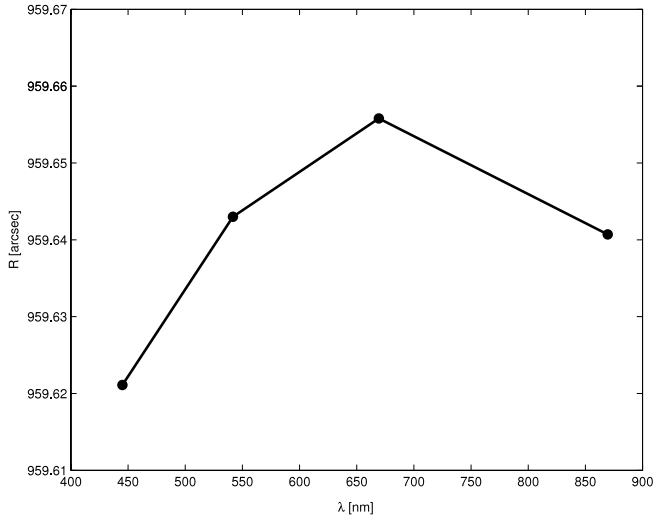

FIG. 3.—Instrumental and physical effects of wavelength on solar diameter measurement. The value of the reference radius used in the simulation is 960″. [*See the electronic edition of the Journal for a color version of this figure.*]

exposure time and the instrumental PSF is independent of detector pixel position.

4. INSTRUMENTAL EFFECTS

Instrumental effects depend on the characteristics of each telescope. Among them are the PSF, the spatial resolution, and the pixel size. This section addresses their respective effects.

4.1. *Point-Spread Function*

The FWHM of the PSF is proportional to λ/D, where λ is the wavelength of observation and D is the pupil diameter. Therefore, for a given value of the wavelength, if D increases, the FWHM of the PSF decreases, and consequently the calculated diameter increases. Thus, two instruments with different D will measure different solar diameters if this instrumental effect is not taken into account. However, for a given instrument (D), if λ increases, the FWHM of the PSF increases, and consequently the calculated diameter decreases. Therefore, for a given instrument there are two opposing effects due to wavelength: first, the instrumental effect that states that if λ increases, the measured solar diameter decreases, and second, the physical effect (as suggested by the solar model and the few measurements) that states that if λ increases, the solar diameter increases.

To show the resulting effect, we simulated a solar image according to the HM98 solar model for four wavelengths (445.125, 541.76, 669.4, and 869.6 nm), observed through an optical system having a pupil diameter of 10 cm and a sampling spatial frequency of 0.1″. For each wavelength, we determine the mean solar radius of the corresponding solar image. Figure 3 shows the results. We note that the calculated solar radius (R) increases under the physical effect and then decreases as soon as the instrumental effect becomes more important. Therefore, in order to compare the solar diameters measured by different instruments, and to study the wavelength dependence, it is very important to take into consideration the instrumental effect and to correct it accordingly.

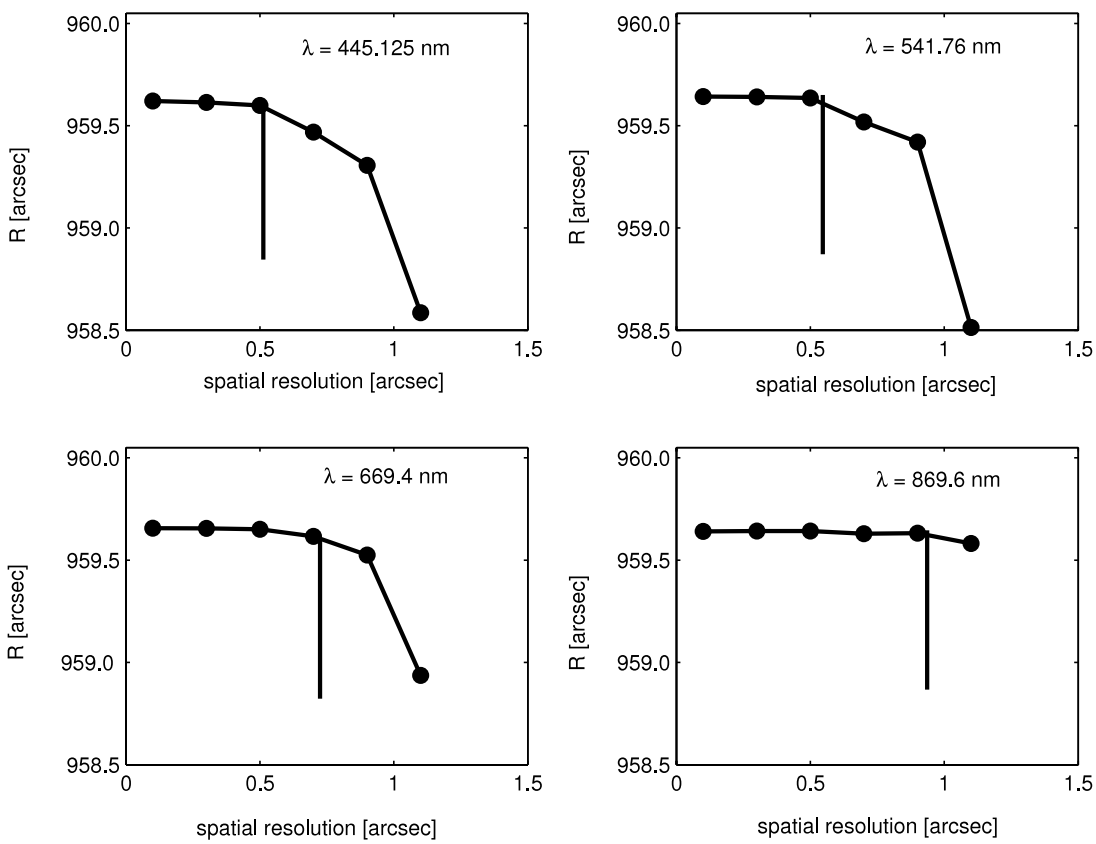

FIG. 4.—Effect of spatial resolution on solar diameter measurement. The vertical lines indicate the diffraction limit. The reference radius used in the simulation is 960″. [*See the electronic edition of the Journal for a color version of this figure.*]

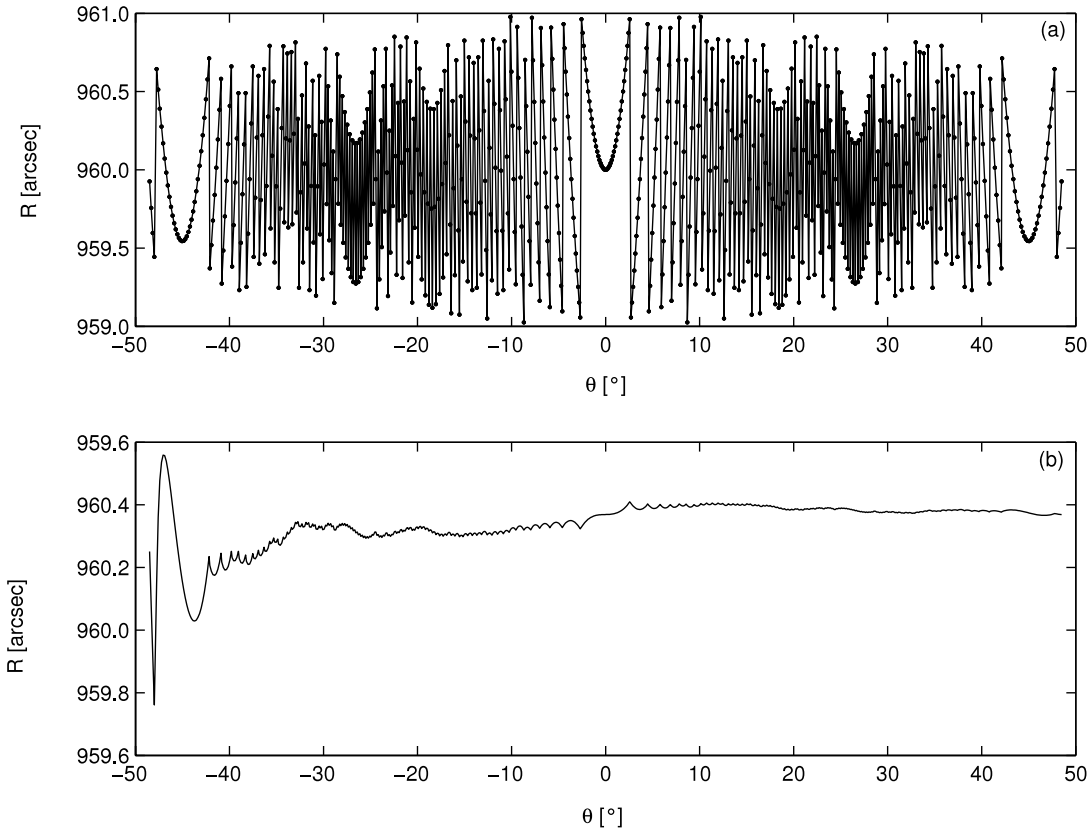

Fig. 5.—(*a*) Effect of pixelization on solar radius measurement; (*b*) mean value of the solar radius as the number of integrated individual radius values increases from $\theta = -50°$. The reference radius used in the simulation is 960″. [*See the electronic edition of the Journal for a color version of this figure.*]

4.2. *Spatial Resolution*

For any instrument, the Shannon (1949) condition must be satisfied. This requires that the PSF must cover at least two sensing elements, that is to say, 2 pixels when using a CCD. Furthermore, the spatial resolution (r) must be less than or equal to $F(\lambda/2D)$, where F is the instrument's focal length.

To illustrate a case in which the Shannon condition is not satisfied, we simulated a solar image according to the HM98 model, for four wavelengths (445.125, 541.76, 669.4, and 869.6 nm), seen through an optical system having a pupil diameter D equal to 10 cm. These values correspond respectively to diffraction-limit values of 1.072″, 1.366″, 1.687″, and 2.192″. For each wavelength, we vary the spatial resolution between 0.1″ and 1.1″ and we determine the mean solar radius of the corresponding image. In the present study, the atmospheric effect is not considered. Figure 4 shows the variation of the calculated solar radius (R) with spatial resolution for a given wavelength (λ). We note that whenever the Shannon condition is not satisfied we lose resolution, and the measured diameter decreases and loses precision. However, this effect decreases with wavelength.

4.3. *Pixelization*

The effect of pixelization depends on the pixel dimensions and on the number of measurements used to determine the mean value of the solar radius. To illustrate this effect, we simulated a spherical solar image according to the HM98 model for $\lambda =$ 676.78 nm seen through an optical system having a pupil diameter of 10 cm and a sampling spatial frequency of 2″. Figure 5*a* represents the calculated radius for a sector of 100° of the simulated image. We note that the pixelization effect depends on the polar position (R, θ) of the inflection points that define the figure of the Sun. We also note that the calculated radius varies by $\pm 1''$, according to the pixel position. To determine the solar figure, we use the set of radii, which tends to reduce the pixelization effect as soon as the number of measurements increases, as illustrated by Figure 5*b*.

5. RESULTS AND DISCUSSION

This study identifies a number of effects that may explain discrepancies in measurements of the solar diameter carried out by various instruments. These are applied in this section to the absolute diameters obtained, during the same period of time, by three different instruments: the Solar Disk Sextant (Sofia et al. 1984), the Michelson Doppler Imager (Kuhn et al. 2004), and the CCD astrolabe of Calern (Laclare & Merlin 1991; Laclare et al. 1996, 1999).

Table 2 shows the characteristics of each instrument, the measured absolute radius, and the calculated radius according to the HM98 model using the characteristics of each instrument.

TABLE 2
Comparison of the Solar Radius as Measured by Three Instruments

Quantity	Calern CCD Astrolabe	SDS	MDI
λ (nm)	538	620	676.78
$\Delta\lambda$ (nm)	200	80	0.0094
r (arcsec)	0.74	0.128	1.987
d (m)	0.10	0.13	0.15
R_m (arcsec)	959.628 ± 0.075	959.789 ± 0.091	959.283 ± 0.150

Note.—Here λ is the central wavelength of observation, $\Delta\lambda$ is the passband, d is the diameter of the telescope, r is the spatial resolution, and R_m is the absolute measured solar radius.

TABLE 3

Estimate of the Instrumental Effects and Determination of the Corrected Value of the Absolute Radius

Quantity	Calern (arcsec)	SDS (arcsec)	MDI (arcsec)
R_s	959.969	959.973	959.977
R_a	959.786	959.864	959.555
D	0.183	0.109	0.422
R_m	959.628 ± 0.075	959.789 ± 0.091	959.283 ± 0.150
$R_{m,c}$	959.811 ± 0.075	959.898 ± 0.091	959.705 ± 0.150

Note.—R_s is the calculated radius according to the HM98 solar model without the instrumental effects, R_a is the calculated radius according to the HM98 model with the instrumental effects, D is the difference between R_s and R_a, R_m is the absolute solar radius measured by the three instruments, and $R_{m,c}$ is the absolute radius measured by the three instruments and corrected for the instrumental effects.

The absolute radius value for the Calern astrolabe is the mean value corrected for the effect of seeing, corresponding to observations from 1996 to 1997 (Chollet & Sinceac 1999). That for the SDS is the mean value obtained from the observations in 1996 (Djafer et al. 2008). For MDI, it is the mean value obtained from the observations between 1996 and 2003 (Kuhn et al. 2004). In the case of MDI, we have considered the solar radius of 1996 and 1997 as the mean value of the 8 years' measurements, since no evidence of a secular trend in solar radius variability at any level above 15 mas has been revealed (Kuhn et al. 2004). We note that even though the measurements took place during the same period of time, a difference of 161 mas exists between Calern and SDS, and there is a difference of 506 mas between SDS and MDI.

To understand these differences, we have to quantify the effects studied in § 3 for the three instruments. To accomplish this, we use the empirical HM98 solar model, and we proceed for each instrument as follows: (1) We use the central wavelength and the passband to determine the interval of wavelengths for which we determine the limb's shape according to the model. (2) For each wavelength (j) in this interval, we simulate the corresponding solar image and then determine the mean radius, $R_{s,j}$, of the obtained image. (3) For each wavelength in this interval we simulate another solar image but in this case as seen through the corresponding instrumental PSF, and then we determine its mean radius, $R_{a,j}$. (4) We repeat steps 2 and 3 for the number of wavelengths determined in step 1, and finally we calculate the mean values of R_s and R_a. (5) We then calculate the difference (D) between R_s and R_a, and (6) we use this difference to determine the solar radius corrected for the instrumental effects, $R_{m,c}$.

Table 3 summarizes the results. The first row contains the calculated mean radius (R_s). This represents the radius without the instrumental effects. It takes into account only the physical effect due to wavelength. Figure 6*a* shows this radius. We note that the calculated radius increases with wavelength as suggested by the model (see Fig. 1*e*). The second row of the table represents the calculated mean radius (R_a) with the instrumental effects. Figure 6*b* compares this radius with the absolute measured one. We note that the two radii show the same trend with wavelength (the shift of about 200 mas between the measured and calculated radii is due to the arbitrary choice of solar radius used in the simulation). The third row is the difference (D) between R_s and R_a. This difference quantifies and represents the bias induced by the instrumental effects. We add D to the measured radius R_m to determine the measured radius without instrumental effects

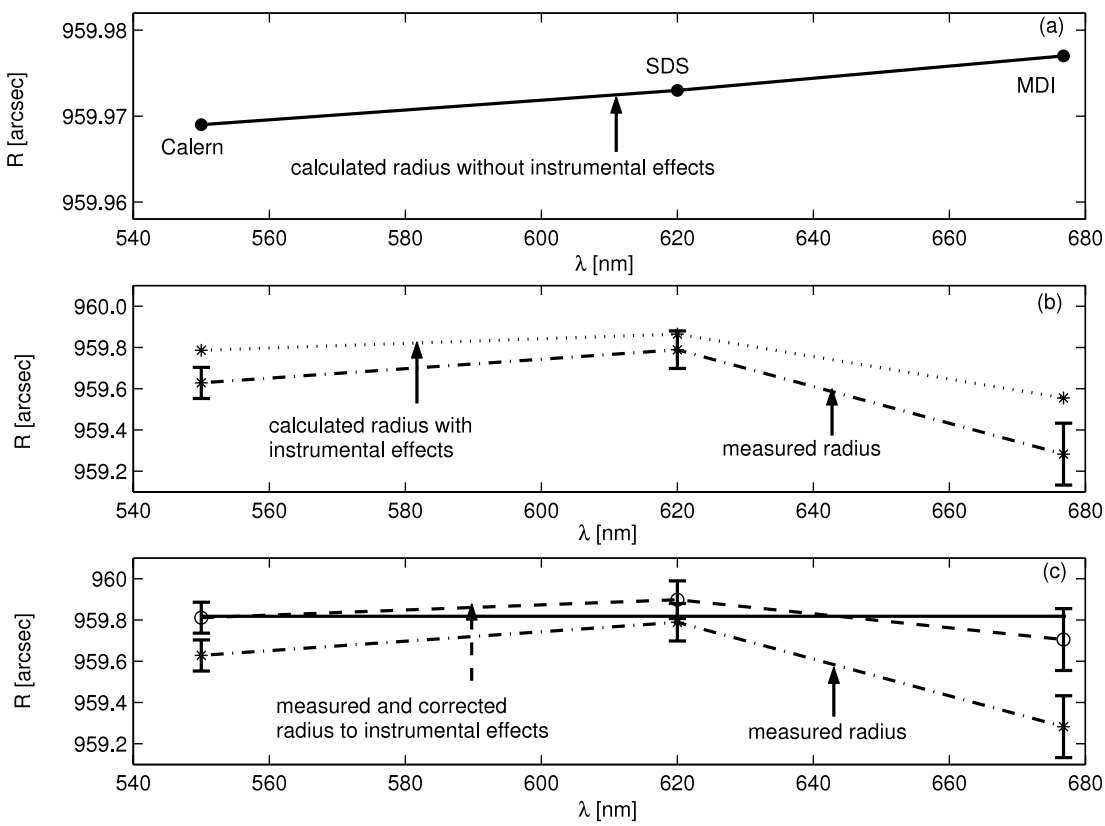

Fig. 6.—(*a*) Calculated radius without instrumental effects at the wavelengths of the three instruments (Calern CCD astrolabe, SDS, and MDI); (*b*) comparison between the radius calculated by simulation using the HM98 model and the measured values; (*c*) comparison between the radius measured by the three instruments and the corresponding ones corrected for instrumental effects. [*See the electronic edition of the Journal for a color version of this figure.*]

($R_{m,c}$). The values of these two radii are given respectively in the fourth and fifth rows and shown in Figure 6*b*.

We note that after correcting for the instrumental effects, the absolute values of the solar radius have increased (which means that the instrumental effects produce more or less an inward displacement of the position of the inflection point) and the difference between the three measurements is on the order of the uncertainties. The difference is about 87 mas between SDS and Calern (instead of 161 mas), and 193 mas between MDI and SDS (instead of 506 mas). Therefore, we can consider that the three instruments provide the same solar radius, as shown by the solid line in Figure 6*c*, without dependence on wavelength, since its physical effect is small (see Fig. 6*a*). It is about 4 mas, due to the fact that the three wavelengths are close, and with bandpass overlap in the case of Calern and SDS. The MDI value is a mean over 8 yr, and if we admit the anticorrelation between radius and solar activity shown by the SDS results, the MDI value of 1996 would be greater than 959.283″, which could explain a part of the difference between SDS and MDI compared with the difference between SDS and Calern.

6. CONCLUSION

The solar diameter is measured by different methods and instruments, and the set of the values obtained show a lack of coherence for several reasons: (1) there is no consensus on the choice of wavelength (the empirical models and the few existing measurements suggest that the solar diameter depends on wavelength); (2) certain instruments observe in the center of Fraunhofer lines, while others observe in domains of different spectral width, which may contain Fraunhofer lines whose intensity may vary with solar activity, thus affecting the value of the diameter; (3) for ground measurements, atmospheric effects are site-dependent; (4) there is diversity of the instrumental characteristics such as the PSF, the spatial resolution, and the effect of pixelization; and (5) no uniform processing method is employed (certain methods may induce a displacement of the inflection point).

Using the empirical solar model of Hestroffer & Magnan (1998), we have studied most of these effects. The results show that the instrumental effects produce a decrease of the measured diameter, and the physical effect of the wavelength produces an increase of measured diameter with wavelength. We have tested these results on solar diameter measurements obtained during the same period of time by the MDI and SDS instruments, as well as the CCD astrolabe of Calern after correcting for the effect of seeing. The absolute values of the solar radius determined by the three instruments show a difference of hundreds of milliarcseconds (161 mas between Calern and SDS, 506 mas between SDS and MDI, and 445 mas between Calern and MDI). After evaluating the instrumental effects and performing the correction, the three instruments provide the same solar radius within their uncertainties.

Given the importance of the solar diameter to solar physics, it is necessary to have a strategy in the near future to overcome all these difficulties in solar diameter measurements. It is essential to (1) use the same definition of solar diameter, (2) use a bandpass free of Fraunhofer lines, (3) use the same processing method, (4) use an internal or external reference to calibrate the instrument, (5) quantify the effect of seeing at the moment of measurement for ground measurements, and (6) perform solar diameter measurements using the same instrument to observe in narrow bandpasses at several wavelengths that are sufficiently separated to study the dependence of the diameter on wavelength.

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