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PROCESSING METHOD EFFECT ON SUN DIAMETER MEASUREMENT WITH CCD SOLAR ASTROLABE

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ABSTRACT

Photometric Sun diameter measurement is based on the calculation of the inflection point of the solar limb. In ground measurement, this point is located at a position on the solar limb where the signal-to-noise ratio is very high, which necessitates the appropriate filtering techniques to eliminate the noise while preserving its position. In this paper, we compare the filtering method currently in use to process the CCD solar astrolabe data, the FFTD method widely used, with a different method that we propose. Using the acquired data from the CCD astrolabe at Calern, France during 1997, we can obtain a mean difference of 130 mas in the measured radii.

Key words: methods: data analysis – methods: numerical – Sun: general – Sun: photosphere – techniques: image processing

Online-only material: color figure

1. INTRODUCTION

Solar diameter has been the subject of careful measurements for the last 350 years; gradually, accuracy has increased. Most measurements yield different values of the diameter of the Sun. Thuillier et al. (2005) and Djafer et al. (2008a) have emphasized that no unique strategy exists to measure the solar diameter and that different methods are used, mostly based on photometric recordings of the solar-limb profile using CCDs as detectors. One of these widely used instruments is the solar astrolabe. The description of the visual and CCD generation of this instrument and the results obtained for the diameter of the Sun are given by Laclare et al. (1991, 1996, 1999), Delmas et al. (2006), Andrei et al. (2004), Gölbaşı et al. (2000, 2001), Jilinski et al. (1999), Penna et al. (2002), and Kilic et al. (2005).

The most typical definition of solar diameter is based on the determination of the position of the inflection point of the solar-limb profile. This point is situated in a region where the light intensity is less than that of the disk's center, which leads to a smaller signal-to-noise ratio. This ratio can be further decreased by the dark current, parasitic light and the presence of sunspots. Under these conditions, the position of the inflection point is difficult to determine. Table 1 shows the methods used most to determine the inflection point. All the methods necessitate a reliable noise filtering. Djafer et al. (2008a, 2008b) have presented in detail the filtering methods and their effects on the measurement of the diameter of the Sun using the solar disk sextant (SDS) data. With a CCD solar astrolabe, the filtering method currently being used is based on a smoothing process of 1, 3, 5, and 7 pixel windows. The size of the smoothing windows is chosen according to the noise level in the acquired image. So, the filtering process is not automatic.

The aim of this work is to show that an inadequate filtering method introduces a bias in the calculated solar diameter. To show this, we compare three filtering methods using the CCD solar astrolabe data, i.e., the proposed method (see Djafer et al. 2008b) based on the compact wavelet that automatically determines the amplitude of the noise present in the image and eliminate it without changing the inflection point position, the FFTD method (see Sofia et al. 1983, 1994; Egidi et al. 2006),

and the method actually used with the CCD solar astrolabe (see Chollet & Sinceac 1999; Sinceac et al. 1998; Jilinski et al. 1999; Kilic et al. 2005).

2. PROCESSING METHOD EFFECT

Our filtering method is based on the compact wavelet. Its one-dimensional version is applied to SDS data; more detail is given in Djafer et al. (2008b). In the present work, we use the two-dimensional version of this method and apply it to the solar images acquired by the CCD astrolabe.

The method for CCD measurements of the solar diameter with the astrolabe has been described in detail by Sinceac et al. (1998). The diameter value of the Sun depends on the difference between the two instants of transition of the Sun through the height circle defined by the astrolabe. These two instants are determined as follows: (1) we extract the edge of the acquired image of the Sun by determining the inflection points that define its limb and (2) we fit this set of points using a parabola to determine its summit. The set of these summits is used to determine the trajectory of the direct and reflected images. The intersection of these two trajectories defines the instant of the upper and lower transitions of the Sun through the height circle defined by the instrument.

We will use the three methods to filter the noise of the acquired images of the Sun, the compact wavelet method, the FFTD method, and the actual solar astrolabe filtering method. For the FFTD method, the position of the inflection point is highly dependent on the value of the parameter a . The optimal value of a is 4 pixels (Djafer et al. 2008b). For the solar astrolabe method, a window of 5 pixels is used. This 5 pixel window value may not be sufficient to eliminate the present random noise and to easily determine the inflection point position. As the window size for the smoothing process is increased, the inherent noise is filtered out, but the position of the inflection point is displaced, resulting in a smaller solar radius determination (Djafer et al. 2008b).

Figure 1(a) shows the superposition of Sun edges obtained by the three methods, with the smoothing method using a window of 5 pixels, with the FFTD equal to 4 pixels, and with the

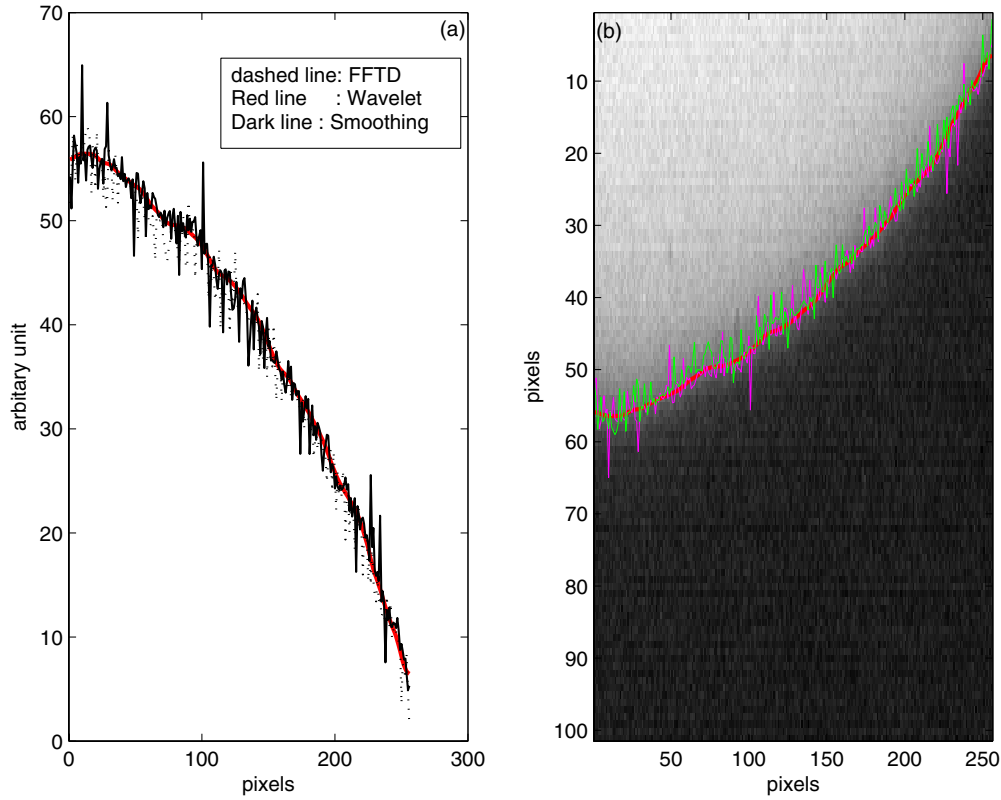


Figure 1. (a) Superposition of the Sun image edges obtained by the three methods, and (b) the acquired Sun image superposed to the three obtained edges. (A color version of this figure is available in the online journal.)

Table 1
Processing Methods to Determine the Inflection Point Position

| Site/Instrument | Method of Measurement | Reference |
|------------------------|-----------------------|--------------------------------------|
| Calern, France | | |
| 11 prisms ^a | C | Laclare et al. (1999) |
| 11 prisms | C | Sinceac et al. (1998) |
| Prism ^b | C | Sinceac et al. (1998) |
| 11 prisms | C | Chollet & Sinceac (1999) |
| DORaySol | C | Andrei et al. (2004) |
| Rio | | |
| Prism ^c | C | Jilinski et al. (1999) |
| Prism ^c | C | Andrei et al. (2004) |
| Antalya | | |
| 2 prisms | C | Gölbaşı et al. (2001) |
| 2 prisms | C | Kilic et al. (2005) |
| SDM | E | Brown & Christensen-Dalsgaard (1998) |
| Mount Wilson | B | Lefebvre et al. (2006) |
| Locarno and Izāna | A | Wittmann (1997) |
| | A | Wittmann & Bianda (2000) |
| Kitt Peak | C | Neckel & Labs (1994) |
| SDS | E | Egidi et al. (2006) |
| | C, E | Djafer et al. (2008) |
| MDI | C | Kuhn et al. (2004) |

Notes. Photometric and CCD measurements of the solar diameter.

^a Analog CCD measurement.

^b Motorized variable prism.

^c No motorized variable prism; (A) the limb is defined by the point with the maximal slope; (B) the limb is defined by the point at 25% of the intensity to the disk center of the Sun; (C) the limb is defined by the barycenter of points around the point of the maximum of its first derivative; and (E) the limb is defined by the finite Fourier transform definition.

compact wavelet method using a low pass filter of 7 pixels. We note that the edge obtained with the compact wavelet method is smooth, while those obtained with the FFTD method and the 5 pixel window still contain residual high frequencies. Figure 1(b) shows an acquired edge of the Sun superposed to the three obtained edges.

Figure 2 shows a set of successive edges of the Sun for the filtered direct and reflected images acquired using the compact wavelet. The edges of Figure 2(a) are used to determine the instant of the upper transition and those of Figure 2(b) determine the instant of the lower transition. Figure 3 shows the intersection of the two trajectories that define the instant of the transition of the Sun. We note that the precision of the transition instants depends on the processing method by which the inflection points are determined.

3. RESULTS AND DISCUSSION

We use the data acquired by the CCD solar astrolabe from Calern, France between May and July 1997. Table 2 summarizes the radius values of the Sun obtained by the three methods. Figure 4 shows the values obtained using the compact wavelet method (circle) superposed to those obtained using the FFTD (stars) and Calern CCD astrolabe (squares) methods.

We note that the values of the radius of the Sun obtained with the compact wavelet method are greater than those obtained with the two other methods. This result is expected because both of the other two methods filter the noise on the one hand but displace the position of inflection point on the other hand, leading to a smaller radius of the Sun. A mean difference of 30 mas is found between the radius value of the Sun calculated

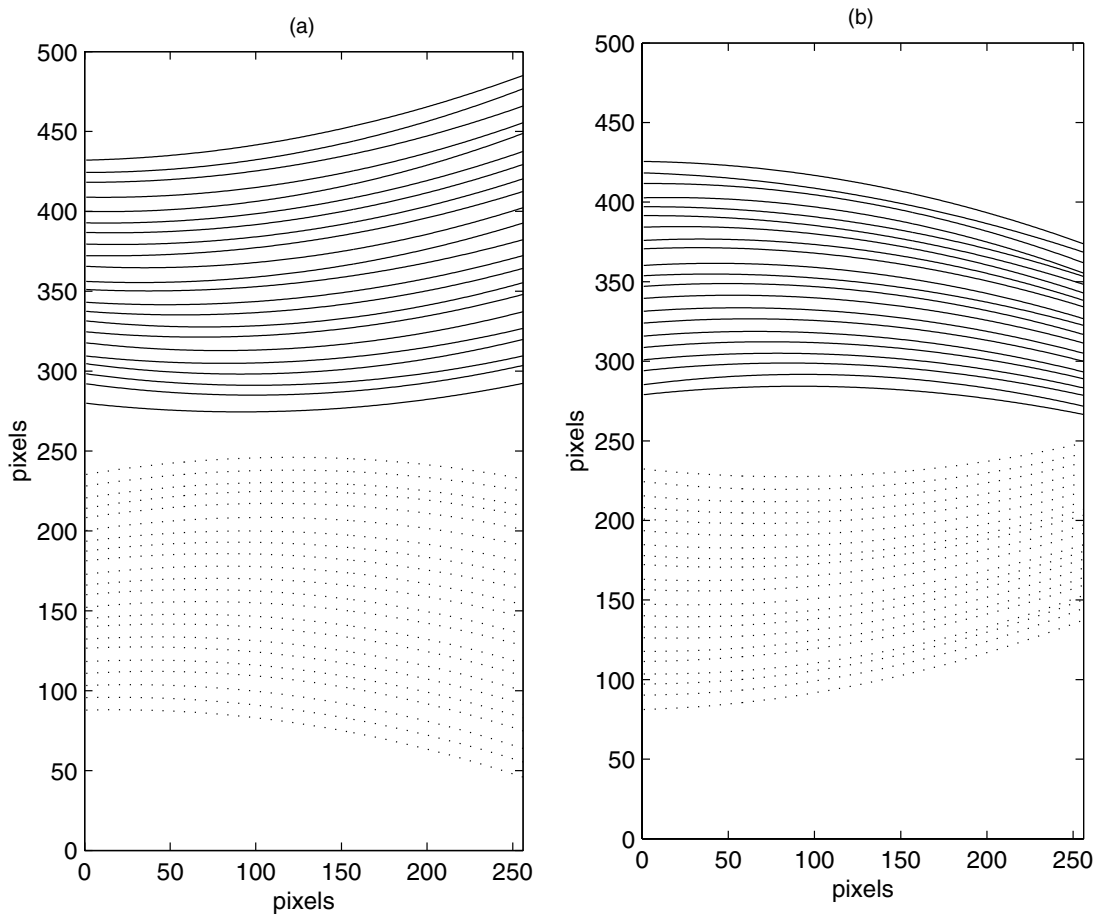


Figure 2. (a) Extracted Sun edges of a set of acquired images of the Sun during the upper transition, and (b) extracted edges of a set of acquired images of the Sun during the lower transition.

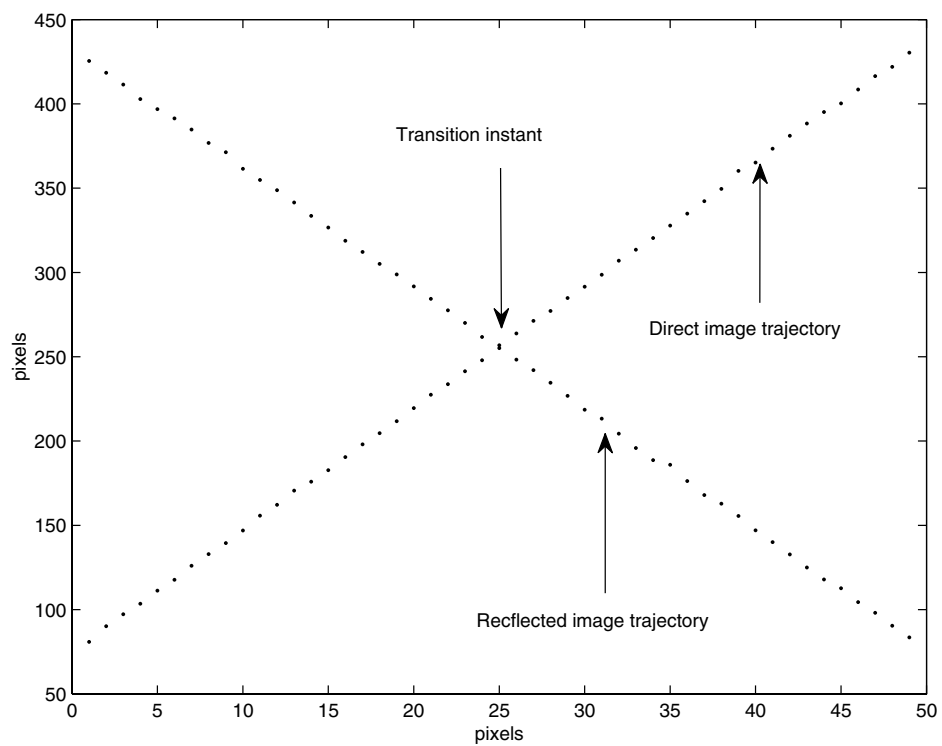


Figure 3. Determination of the transition instant of the Sun through the height circle defined by the astrolabe.

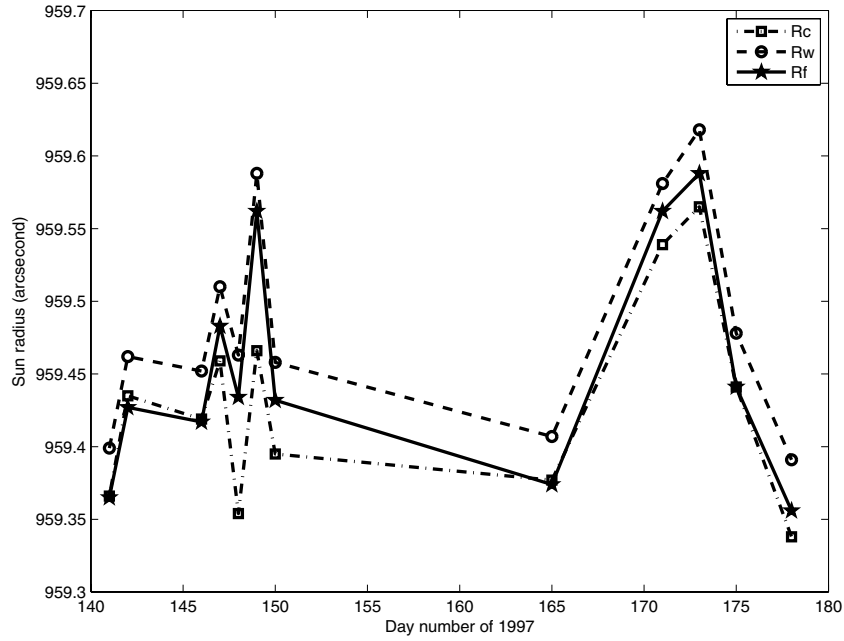


Figure 4. Values of the radius of the Sun obtained using the compact wavelet method (Rw, circle) superposed to those obtained with the FFTD (Rof, stars) and the Calern CCD astrolabe (Rc, squares) methods.

Table 2
Radius Values of the Sun (R) Obtained by Three Processing Methods

| Date (day Nb) | R Calern ($''$) | R Wavelet ($''$) | R FFTD ($''$) | No. of Measurements |
|------------------|------------------------|-------------------------|----------------------|---------------------|
| 141 | 959.366 | 959.399 | 959.365 | 15 |
| 142 | 959.435 | 959.462 | 959.427 | 8 |
| 146 | 959.419 | 959.452 | 959.417 | 15 |
| 147 | 959.459 | 959.510 | 959.483 | 19 |
| 148 | 959.354 | 959.463 | 959.434 | 15 |
| 149 | 959.466 | 959.588 | 959.562 | 10 |
| 150 | 959.395 | 959.458 | 959.432 | 09 |
| 165 | 959.377 | 959.407 | 959.374 | 08 |
| 171 | 959.539 | 959.581 | 959.562 | 08 |
| 173 | 959.565 | 959.618 | 959.588 | 19 |
| 175 | 959.441 | 959.478 | 959.441 | 10 |
| 178 | 959.338 | 959.391 | 959.356 | 09 |
| Mean value | 959.346 | 959.484 | 959.453 | |

with the compact wavelet and FFTD. This difference is mainly due to the effect of the value of the parameter a . A mean difference of 138 mas is obtained between the radius value of the Sun calculated with the compact wavelet and the smoothing methods used in Calern (Chollet & Sinceac 1999; Sinceac et al. 1998). Our method uses a procedure to automatically estimate the noise present in each acquired image of the Sun. The constant and the Gaussian threshold values, used in the filtering process, clean the image while preserving the position of the inflexion point (Djafer et al. 2008b).

The uncertainty of our method is negligible. When applied to a set of 1000 noisy solar-limb profiles, it shows a bias in the inflection point position of about 2 mas and an uncertainty of 17 mas (Djafer et al. 2008b) using the second-derivative method. When applied to the SDS data, it shows a difference in the radius of the Sun that ranges between 64 mas and 114 and an amplitude variation with solar activity of 197 mas instead of 221 mas with respect to the FFTD method (Djafer et al. 2008b). Applying the

smoothing method using a window of 5 pixels to these 1000 noisy profiles, we found a bias of 315 mas in the inflection point and an uncertainty of about 40 mas.

The difference of 138 mas in the radius of the Sun between the compact wavelet and the smoothing methods partly explains, in addition to the experimental effects (Djafer et al. 2008a), the difference between the mean radius of the Sun measured during 1996 with the SDS and at Calern during the same period. The mean value of the radius of the Sun with the SDS is 959.788 ± 0.091 mas and 959.628 ± 0.075 mas at Calern (Djafer et al. 2008b; Chollet & Sinceac 1999).

According to solar astrolabe measurement, the variation of the solar radius with solar activity is about 200 mas (Laclare et al. 1999), and, according to physical solar models, the dependency to wavelength is about 20–30 mas (Thuillier et al. 2011). Therefore, to validate these dependencies, especially the dependency to wavelength, one of the requirements is to have results without the effect of the processing method.

4. CONCLUSION

The solar diameter has been measured for the last 350 years through the use of different methods and instruments. Its optical measurements use the position of the inflection point as a reference. This point is usually defined as the passage through zero of the second derivative of the solar-limb profile. In the presence of noise, the position of this point is difficult to locate, and the use of a filtering process that does not modify this position is necessary. An inadequate filtering method leads to systematic differences in the calculated values of the solar diameter. The proposed method based on the compact wavelet has been used to process the acquired data of the CCD astrolabe of Calern. We compared the values of the radius of the Sun obtained using this processing method with the method actually used with the CCD solar astrolabe. We obtained a mean difference of 138 mas. Even though the bias induced by the filtering process will only affect the absolute value of the diameter of the Sun and not its variation with time, it is necessary to use the same processing method in the future so that the comparison between the radius values of the Sun obtained by different instruments will not be affected by the method used.

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