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IN-FLIGHT DETERMINATION OF THE PLATE SCALE OF THE EXTREME-ULTRAVIOLET IMAGING TELESCOPE

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ABSTRACT

Using simultaneous observations of the Michelson Doppler Imager and Extreme-Ultraviolet Imaging Telescope (EIT) on board the *Solar and Heliospheric Observatory* spacecraft, we determined in flight the plate scale of the EIT. We found a value of $2''.629 \pm 0''.001$ pixel^{-1}, in fair agreement with the $2''.627 \pm 0''.001$ pixel^{-1} value deduced from recent laboratory measurements of the focal length and much higher by 7 σ than the $2''.622$ pixel^{-1} value of the preflight calibrations. The plate scale is found to be constant across the field of view, confirming the negligible distortion level predicted by the theoretical models of the EIT. Furthermore, the 2 σ difference between our results and the latest laboratory measurements, although statistically small, may confirm a recent work suggesting that the solar photospheric radius may be 0.5 Mm lower than the classically adopted value of 695.99 Mm.

Subject headings: instrumentation: miscellaneous — Sun: fundamental parameters

1. INTRODUCTION

The precise knowledge of the plate scale (i.e., the angular size of the pixels) of the Extreme-Ultraviolet Imaging Telescope (EIT; see Delaboudinière et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*; see Domingo, Fleck, & Poland 1995) is a fundamental parameter in various applications such as in the astrometric measurements or coalignment of its observations with other instruments. Although the plate scale was measured during the preflight calibrations, two offpoint maneuvers of the *SOHO* spacecraft (north-south and east-west) featuring several intermediate steps were performed on 1996 April 3 and 4 and gave us the opportunity to measure it in flight. Indeed, using couples of shifted EIT images, with the amplitudes of these shifts in arcseconds known from another source, we deduced a more reliable plate scale of the telescope. The Sun sensor of *SOHO* could provide these amplitudes, but unfortunately and for unknown reasons, it turned out to give inconsistent results. Instead, we used the Michelson Doppler Imager (MDI; see Scherrer et al. 1995) continuum images, the plate scale of which is known with a good precision, to determine the angles between the different pointing positions.

2. MEASUREMENTS

The basic geometrical principle of the plate-scale measurements is illustrated on Figure 1. Considering a couple of MDI images and a couple of EIT images taken at two different pointing positions, we name (x_{M1}, y_{M1}) and (x_{M2}, y_{M2}) the coordinates of the centers O_{M1} and O_{M2} of the solar disks in the MDI images, and we name (x_{E1}, y_{E1}) and (x_{E2}, y_{E2}) the coordinates of the centers O_{E1} and O_{E2} of the solar disks in the EIT images. The plate scale P_E of the EIT is then equal to the ratio of the distances $\overline{O_{M1}O_{M2}}$ and $\overline{O_{E1}O_{E2}}$ between the shifted MDI and EIT images multiplied by the plate scale P_M of the MDI:

$$P_E = P_M \frac{\overline{O_{M1}O_{M2}}}{\overline{O_{E1}O_{E2}}} = P_M \sqrt{\frac{(x_{M1} - x_{M2})^2 + (y_{M1} - y_{M2})^2}{(x_{E1} - x_{E2})^2 + (y_{E1} - y_{E2})^2}}. \quad (1)$$

In order to achieve a great level of precision in the determination of the plate scale of the EIT, this simplistic view must be refined. Indeed, in equation (1), the product $P_M \overline{O_{M1}O_{M2}}$ is supposed to represent the angle between two pointing positions of the EIT. This is true only if we assume (there is no way to make sure of it) that the offpoint maneuvers induced only negligible mechanical flexions between the two instruments, for otherwise the pointing of the MDI would not reflect the pointing of the EIT. Furthermore, due to the optical distortions at the focal plane and to the aspect ratio of the pixels, the plate scale of the MDI is variable across the field of view. The MDI images must therefore be corrected before the distance $\overline{O_{M1}O_{M2}}$ between two shifted images could be measured and converted into an angle with the constant factor of proportionality P_M. This constant is therefore the operational plate scale of the corrected MDI images and not the real plate scale of the raw images. To the contrary, the distance $\overline{O_{E1}O_{E2}}$ between two EIT images must be measured in raw images, for the detection of variations in the plate scale P_E would reveal the presence of distortions in the EIT images.

Since we thought of this use of an offpoint of the *SOHO* spacecraft only after the fact, there was no coordination between the observations of the MDI and those of the EIT during the maneuvers. However, the two instruments recorded simultaneous images at 24 of the intermediate steps, with a total of four images at 17.1 nm, 15 at 19.5 nm, five at 28.4 nm, and four at 30.4 nm. In order to measure the position of the solar disk in the EIT and MDI images, an iterative limb-fitting routine was developed. It starts with some initial Sun-center coordinates, and then it finds the position of the maximum of the radial gradient of intensity along 10,000 directions (using a three-point Lagrangian interpolation), taking into account the distortion in the case of the MDI images (the distortion of the MDI is well known and tabulated). Then it fits the resulting profile with a circle for the EIT images and with an ellipse for

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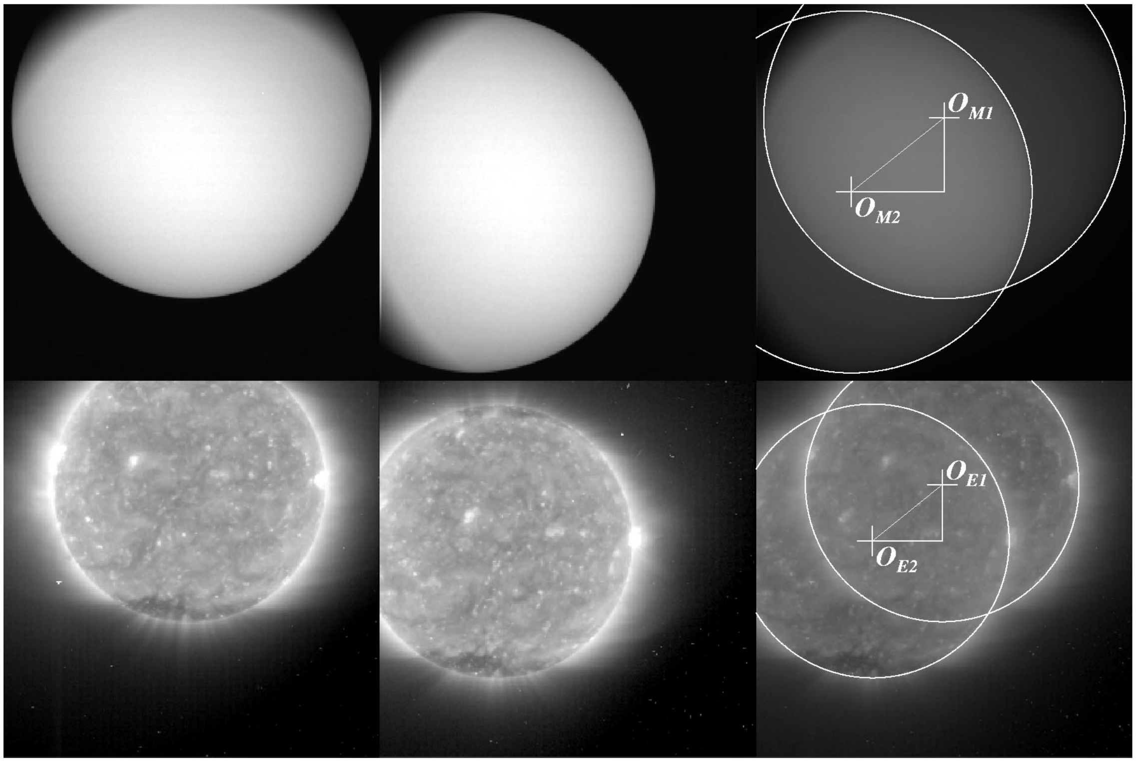

FIG. 1.—*Left and center columns*: Simultaneous MDI continuum (*top*) and EIT 19.5 nm (*bottom*) images recorded at two different pointing positions during the offpoint maneuvers of 1996 April 3 and 4. The darkenings at the edges of the MDI images are due to a strong vignetting. *Right column*: Geometrical principle of the measurements drawn on overlays of the left images. The plate scale of the EIT is equal to the ratio of the distances $\overline{O_{M1}O_{M2}}$ and $\overline{O_{E1}O_{E2}}$ between the shifted MDI and EIT images multiplied by the plate scale of the MDI.

the MDI images (for its pixels are rectangular). This allows the corrected coordinates to be obtained, which then become the new initial ones, and so on until they converge. The MDI *y*-coordinates were then corrected for the aspect ratio of the pixels, which are given by the ratio between the equatorial and polar radii of the fitted ellipse, assuming that the photosphere is perfectly circular (which is true at least to a 10^{-4} level). The aspect ratio was found to be 1.00101 ± 0.00001. Once we had measured the coordinates of the Sun center for each pointing position, we computed the distances in pixels between the images for all the different possible combinations of pointing positions (six at 17.1 nm, 102 at 19.5 nm, nine at 28.4 nm, and six at 30.4 nm). Then the distances between MDI images were converted into angles by multiplying them by the operational plate scale P_M of the corrected MDI images. This plate scale is different from the tabulated plate scale of $1\farcs9779$ pixel^{-1}, which is an average value for uncorrected images. The operational plate scale was obtained by dividing the measured solar radius by the classically adopted value of the photospheric radius $R_\odot = 695.99$ Mm (Allen 1976) and found to be $P_M = 1\farcs97644 \pm 0\farcs0001$ pixel^{-1}. This computation is well validated, for the same operation on uncorrected images gives a result of $1\farcs97785 \pm 0\farcs0001$ pixel^{-1}, exactly the tabulated value. Once we had the value of P_M, we could compute the plate scale of the EIT according toequation (1). The results are discussed in the next section.

3. RESULTS AND DISCUSSIONS

Figure 2 shows for all four wavelengths the plate scale of the EIT deduced from each couple of images plotted versus the angle between the images. The error made on the pointing measurements being constant, the larger the angle, the better the precision on the plate scale. Within the error bars and whatever the wavelength, the plate scale is independent of the angle between the images, which means that no distortion is detected in the EIT images at a level of precision of 10^{-3} (neither optical nor due to rectangular pixels, since the measurements were made with data recorded during both the north-south and the east-west offpoints). Furthermore, the plate scale is identical in the four wavelengths. These results confirm the theoretical models showing that the optical distortions of the EIT are negligible, which is expected for a low-aperture telescope ($F/D = 14$).

The values plotted in Figure 2 were calculated with the MDI plate scale deduced from the classical photospheric radius $R_\odot = 695.99$ Mm. However, recent results (Brown & Christensen-Dalsgaard 1998) show that this value may have to be reduced by about 0.5 Mm. In this case, the operational plate scale of the MDI becomes $1\farcs97507$ pixel^{-1} instead of $1\farcs97644$

TABLE 1

PLATE SCALE OF EIT IMAGES AT ALL FOUR WAVELENGTHS AND THE AVERAGE OVER THE WAVELENGTHS[a]

Wavelength (nm)	EIT Plate Scale (arcsec pixel^{-1})	
	$R_\odot = 695.99$ Mm	$R_\odot = 695.508$ Mm
17.1	2.6296 ± 0.0010	2.6278 ± 0.0010
19.5	2.6285 ± 0.0010	2.6267 ± 0.0010
28.4	2.6296 ± 0.0010	2.6278 ± 0.0010
30.4	2.6286 ± 0.0010	2.6268 ± 0.0010
Average	2.6291 ± 0.0010	2.6273 ± 0.0010

[a] Given for the two values of the photospheric radius used to determine the plate scale of the MDI images.

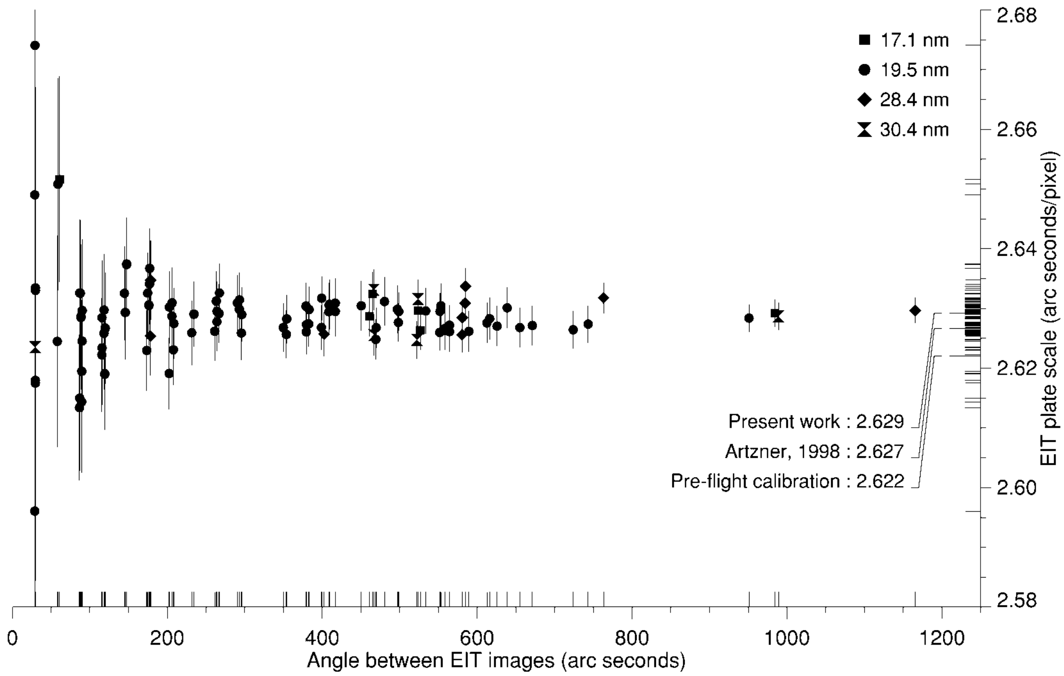

FIG. 2.—Plate scale of the EIT at the four wavelengths plotted vs. the angle between the EIT images. Within the error bars, the plate scale is identical at the four wavelengths and constant across the field of view, showing that the optical distortions of the EIT are negligible. The two previous determinations of the plate scale are quoted on the vertical axis for comparison with the average of the present measurements.

pixel^{-1}, which leads to smaller angles between pointing positions and therefore smaller values of the plate scale of the EIT. In Table 1, the median value of the plate scale at each wavelength and the average over the wavelengths are given for both the classical photospheric radius and the determination of Brown & Christensen-Dalsgaard. The two previous determinations of the plate scale are quoted on the vertical scale of Figure 2 for comparison with the average of the present measurements. The preflight calibration value of the plate scale, based on a 1.652 m focal length, was 2″.622. This is significantly lower than the present results, whatever the photospheric radius adopted to determine the plate scale of the MDI. The latest laboratory measurements of the focal length (Artzner et al. 1999) gave a result of 1.6491 ± 0.0005 m. Assuming that the pixels have their nominal size of 21 μm, this corresponds to a 2″.627 ± 0″.001 plate scale. This value is slightly lower than the value calculated with the classical photospheric radius but fits exactly with the value calculated with the determination by Brown & Christensen-Dalsgaard. Therefore, considering the great accuracy of the laboratory measurements of Artzner et al., the present result may show, as suggested by Brown & Christensen-Dalsgaard, that the photospheric radius is lower by about 0.5 Mm than the classically adopted value of 695.99 Mm. However, the statistical difference between the two values of the plate scale is only 2 σ, and having no confirmation of a smaller photospheric radius from another source, we recommend the value of 2″.629 ± 0″.001 pixel^{-1} for the plate scale of the EIT.

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