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In-Orbit Calibration of the Distortion of the SOHO/LASCO-C2 Coronagraph

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Abstract. This paper describes distortion calibration procedures for the *SOHO*/LASCO-C2 Coronagraph, based on in-orbit data and extensive image processing methods. It addresses specific problems of externally occulted coronagraphs (obstructed center of field-of-view, strong vignetting, and presence of stray light) and limitations inherent to space-based instrumentation (cosmic rays and limited number of reference points).

1. Introduction

The Large Angle Spectrometric Coronagraph (LASCO) is an instrument aboard the *SOHO* spacecraft, which routinely observes the solar corona in white light (Brueckner et al. 1995). It has now been in successful operation since January 1996 and has produced thousands of images of the corona. LASCO consists of three individual coronagraphs named C1, C2, and C3, each tailored to a specific field-of-view (respectively 3, 6, and 30 solar radii) in order to cope with the tremendous range of brightness of the corona (10^5) and with the problem of rejecting the stray light coming from the Sun. C2 and C3 are externally-occulted coronagraphs, where an external occulter blocks direct solar illumination of the objective. C2 suffers from moderate optical distortion, which must be corrected in order to properly locate the stars crossing its field-of-view (which are subsequently used for photometric calibrations), to retrieve critical attitude parameters, and to insure a correct overlapping of the region common to the C2 and C3 instruments. Practical considerations prevented an accurate calibration of the optical distortion before launch. In-flight calibration has been performed using stars as positional references, and the procedures are described in this paper.

2. Specific Constraints of the LASCO/C2 Instrument

The LASCO/C2 coronagraph has a field-of-view of 1.5° which is imaged onto a 1024×1024 pixels CCD detector so that the pixel field-of-view amounts to $11.5''$. It presents a classical barrel distortion, whose amplitude reaches 5 pixels in the corners of the images. The goal of the correction is to restore real positions to within a fraction of a pixel across the whole field-of-view.

Classical correction methods used by the photogrammetry, computer vision, and astronomy communities cannot straightforwardly be implemented for several reasons: (*i*) the lack of extensive ground calibrations (a few images of a grid pattern were obtained but later found unsuitable for analysis), and (*ii*) the central obstruction created by the external occulter which prevents access to the optical axis and the center of distortion.

As a consequence, we decided to rely on stars for absolute positional references. Although C2 is extremely sensitive and detects stars as faint as magnitude 9, a limited number of them (15 in the best cases) is available as reference points for a given image. Therefore, we had to use a large set of images to alleviate this limitation and introduce a sufficient number of reference points.

The calibration of the optical distortion is a particular case of the general calibration of an optical instrument, which consists in determining: (*i*) the so-called internal parameters, which define the correspondence between the ideal and the real images, and (*ii*) the so-called external parameters, which relate the internal coordinates of the ideal images to the outside world.

A favorable point is that we can apply a simple axi-symmetric model to relate the ideal, undistorted images with the real images, because it is able to represent the actual distortion of LASCO-C2 with sufficient accuracy. As a consequence, the shifts due to distortion are constant in moduli over circular annuli and directed to a common center. We can assume that this center coincides with the optical axis.

We adapted the "*Two-Step*" method introduced by Weng, Cohen, & Herniou (1992) as the most appropriate to our problem, given the above constraints. In its general form, this method involves a direct solution for most of the calibration parameters and an iterative solution for the other ones. In our case, we implemented the following procedure:

1. star detection by correlation of successive frames and star identification,
2. initial estimation of the optical parameters (e.g., focal length) and orientation of each individual frame, and
3. fine determination of the intrinsic distortion parameters and estimation of the external parameters from a large set of images.

3. Detection of Stars

Because the method relies on identified stars in image fields as absolute references, we need a reliable detection and identification procedure. Here we define detection as the determination of a star position on the CCD frame and identification as the link between detection (from frame) and star (from catalog).

The actual detection procedure looks for local maxima above local thresholds. However, the CCD images are spoiled with many cosmic ray traces, and the stars are severely sub-sampled, so that it is impossible to reliably detect stars in isolated frames without external information. To validate local maxima as star detections, we overlap detections from successive frames, applying the shift due to their relative displacement which results from the motion of the Sun on the sky. The operational procedure builds up a map of local maxima for each frame. It shifts and adds up five successive maps (centered on the third map). A maximum found in at least three maps is considered a positive detection.

4. Star Identification

Reference stars are obtained from a catalog of star positions limited to the equatorial band spanned by the LASCO-C2 telescope during the year, and limited to visual magnitude 8.5. Typically, 5 to 15 stars are detected in each frame for the period between 2 February 1996 and 29 April 1996.

Each reference map is scaled to the image frame using the initially estimated parameters (internal and external) and identifications are performed using a proximity criterion.

5. First Estimates of Linear Parameters and Distortion

To avoid the mutual interference between distortion and linear parameters, the procedure divides the field (bound by a circle of diameter 24 mm in the focal plane) in four concentric annuli of increasing radius (7, 8, 9, and 10 mm) and fixed width (2 mm) and assumes for each of them a constant equivalent focal length, to be determined later. Then, for each annulus, a minimum linear squares regression (MLSQ) between the reference stars and their associated detections is applied over the full set of images. The process yields estimates of the four equivalent focal lengths, one for each annulus.

The simple model[1] $\delta(\rho) = \rho_m - \rho = a_0\rho + a_1\rho^3$ gives us a first estimate of the radial distortion.

6. Refinement Process

In order to improve the above estimates, we rescale the star map by applying the distortion law and we redo the identification process over the full frame (i.e., without introducing the four annuli). This new association, together with a MLSQ determination of external parameters (residual translation and rotation), allows refining the values of the orbital attitude parameters of LASCO and of the distortion differences between the linearly rescaled references and their related detections. Finally a MLSQ regression of these distortion differences to the polynomial expression $\delta(\rho) = \rho_m - \rho = a_0\rho + a_1\rho^3 + a_2\rho^5 + ...$ produces the final improved estimates of the distortion coefficients.

The above method could be repeated iteratively to improve the estimation. In our case this was found unnecessary, as the residuals were small enough (i.e., ≤ 1 pixel) for our purpose.

7. Results

The procedure was applied to a set of 250 images of size 1024×1024 pixels. They were chosen for the same instrumental configuration of parameters (filter, polarizers, size, and exposure time). The initial estimate yielded the pixel[2]

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[1] note the addition of the term $a_0\rho$ to the classical formula, in order to allow for positive and negative differential distortions with respect to the mean radial distance $\rho = (-a_0/a_1)^{1/2}$ where the equivalent focal length is nominal (i.e., 364 mm)

[2] The bottom left corner pixel has coordinates (0,0)

(512,506) for the optical center and distortion parameters $a_0 = 4.6881.10^{-3}$ and $a_1 = -1.084.10^{-4}$ (where ρ is in mm).

The evolution of the estimation for successive refinements and for different data sets are given in the following table:

Period	Itera tion	a_0	a_1	a_2	Number of references
Apr 1996	0	$4.6881.10^{-3}$	$-1.0840.10^{-5}$	-	1589
Apr 1996	1	$6.5404.10^{-3}$	$-1.4441.10^{-5}$	$2.2103.10^{-7}$	1589
Apr 1996	2	$6.0619.10^{-3}$	$-1.4672.10^{-5}$	$2.0899.10^{-7}$	1589
Mar 1996	1	$5.1344.10^{-3}$	$-1.2234.10^{-5}$	$1.0979.10^{-7}$	1115
Feb 1996	1	$4.4836.10^{-3}$	$-1.1276.10^{-5}$	$0.5996.10^{-7}$	1477

8. Conclusion

In this article, a specific method for determining the distortion parameters of an externally occulted coronagraph from in-orbit images has been described. Good sensitivity and stable pointing over a long period of time, in order to get a significant number of reference points, were of critical importance. The method has been successful in correcting the images with an accuracy better than one pixel.

References

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