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Gradient Path Labelling method and tracking method for calculation of solar differential rotation using coronal bright points

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ABSTRACT

With new space missions, such as Solar Dynamics Observatory (SDO), solar images are being produced in unprecedented volumes. To derive, as much as possible, information on evolution of solar activity from those huge datasets, the scientific community needs a new generation of software tools for automatic and efficient data processing. In the last decade, several research teams have been developing tools for obtaining more precise estimations of the solar rotation profile, but more are needed to improve knowledge about solar activity. We applied here a segmentation algorithm called Gradient Path Labelling (GPL), used originally to identify drusens in medical retinal images, to detect and track the coronal bright points (CBPs) using images from the AIA instrument onboard the SDO satellite. The CBPs have a tendency to change shape and size along time, to disappear and reappear at a corresponding heliographic position, therefore, decision trees were also included in the tracking solution. Since our CBP detection algorithm uses an active region mask to filter out the CBPs, whose centroid is inside the active regions, the number of identifications clearly depends on the level of solar activity. Our approach uses the commonly applied fitting relation to the latitudinal dependence of the rotational velocity, which resulted in calculation of the optimum fit parameters as well as the Gegenbauer orthogonal polynomials. Comparison of these parameters with the results presented in recent papers on this topic shows that our rotational velocity profile indicates slightly lower rotational velocities than the profiles obtained with other approaches. We also calculate the meridional motion of the CBPs, but comparison with other authors results, clearly show that a 3-day time interval is too short to estimate the latitudinal dependence of the CBP meridional motion. Distributions of the rotational velocity and meridional motion velocity uncertainties show that 85% of uncertainty values are lower than 1 degree/day. The evaluation of our test results shows that the applied algorithm is a promising tool that can help to refine the solar rotational profile.

1. Introduction

One of the main problems in digital image processing is image segmentation, for which several algorithms have been developed (Morel and Solimini, 1995). Huge amounts of high resolution solar images, acquired by instruments onboard satellites, require efficient automatic image processing tools to detect and track solar activity features. Tracer methods are based on observation of locations of a prominent detail on the solar surface or in the atmosphere at exactly determined time intervals resulting in rotational speed determination in dependence on the latitude (differential rotation). Sunspots have been used widely in the past (mainly before the space instrumentation era) to estimate the solar differential rotation profile mainly because they were easier to detect than other solar features, observable using ground-based telescopes. With the advent of instruments onboard satellites now small and bright structures can be observed in the extreme ultraviolet (EUV) part of the solar spectrum, called coronal bright points (CBPs), and provide more precise tracing of the solar rotation. Opposed to sunspots, known to be found concentrated in two bands around the equator, the CBPs can be found all over the Sun, even appearing at the poles and in coronal holes. Hence, CBPs have been proven very good tracers since they also appear at much higher latitudes than sunspots and they are quite numerous in all phases of the solar cycle while, for example, sunspots are often absent in the minimum of the cycle Brajša et al. (2001) and Sudar et al. (2015). CBPs are suitable tracers for the determination of the solar differential rotation also for the reason that they are small localized

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objects, very well distributed over the solar disk (Brajša et al., 2014). Moreover, the short lived CBPs are more numerous than long lived ones (Brajša et al., 2008).

Long-term series of images available from ground-based solar instruments represent a valuable source of data for investigation of characteristics of the solar differential rotation over several solar cycles. Poljančić Beljan et al. (2014) presented results of the solar differential rotation behaviour, during solar cycles no. 20 and no. 22, derived from Kanzelhöhe sunspot drawings. Wöhl et al. (2010) measured the solar differential rotation by tracing small bright coronal structures in EIT (Delaboudinière et al., 1995) images from the SOHO (Solar and Heliospheric Observatory Extreme Ultraviolet Imaging Telescope) mission. McIntosh and Gurman (2005) developed a method of automatically detecting EUV bright points and applied it to the archive of EIT data from the launch of the SOHO. They produced a database of all detected bright points that can be used to extract numerous diagnostics of the solar corona over the 23rd solar cycle till 2005. Jurdana-Šepić et al. (2011) have found a dependence of the solar rotation on the phase of the solar cycle. During the 24th solar cycle, even higher resolution solar images from the AIA (Atmospheric Imaging Assembly instrument; Lemen et al., 2012) onboard the SDO (Solar Dynamics Observatory; Pesnell et al., 2012) are already available. Since 2010, the SDO/AIA instrument provides images with a resolution of 4096 × 4096 pixels. Therefore, several authors continue to investigate the solar differential rotational profile. Nowadays, the high cadence enables to track and measure velocities of the short lived CBPs, which could not be detected or accurately tracked by the comparatively long time interval between successive images from the SOHO/EIT instrument — its 28.4 nm channel had a regular cadence of four images per day (Wöhl et al., 2010), i.e., images were usually taken every 6 h. Wöhl et al. (2010) found also a more differential rotation profile of CBPs than of sunspots and sunspot groups. The high data density (high spatial resolution of the SDO data in addition to the high cadence of solar images) requires the use of an automatic algorithm to detect and track various solar features such as developed e.g. by Zharkova et al. (2005), Martens et al. (2012), Sudar et al. (2015), among others. Ashamari et al. (2015) developed a series of enhanced segmentation algorithms to detect and calculate the area coverages of specific magnetic features from MDI intensitygrams and magnetograms. These algorithms are part of their Automated Solar Activity Prediction (ASAP) tool.

Dorotovič et al. (2007) applied the watershed software tool (Beucher and Meyer, 1993) for automatic image processing and feature recognition of sunspots in the Coimbra Ca II K spectroheliograms. The Watershed transform is constructed by implementing a flooding process on the solar gray-tone image, which identifies the most active areas on the solar image, and delimits the area related with each sunspot. In a study performed by Lorenc et al. (2012), were the CBP structures in solar images from the AIA instrument marked through a manual procedure directly on a PC monitor (in an interactive session), and then the sidereal rotational speed of individual CBPs is automatically calculated. However, this manual method is extremely laborious and with the availability of large number of images it becomes unworkable for practical reasons. High data density of the input solar dataset requires unconditionally to use an automatic procedure. Shahamatnia et al. (2016a) published results of applying the PSO/Snake hybrid algorithm for automatic tracking the CBPs and calculating solar differential rotation. Preliminary results, using benchmark SDO/AIA images, for both the PSO/Snake hybrid algorithm and the Gradient Path Labelling (GPL) segmentation method (proposed by Mora et al., 2011), are already discussed in Shahamatnia et al. (2016b). In this paper we improved the GPL segmentation method with a post-processing algorithm to merge neighbour regions that have similar amplitudes, associated with a region matching process to identify the CBPs, and tested it on a larger set of SDO/AIA images. The remainder of this paper is organized as follows: the description of input data and the pre-processing methods is in Section 2. Section 3 provides details on the CBP detection algorithm while Section 4 deals with the CBP tracking method. Section 5 reviews the determination rules applied for the rotational speed and the meridional motion, respectively. The results are presented in Section 6 followed by their discussion in Section 7. Finally, conclusions are provided in Section 8.

2. Data

We used high spatial resolution solar images taken by the AIA (Lemen et al., 2012) on-board the SDO (Pesnell et al., 2012) in the EUV channel 19.3 nm (Fe XII, 1.25 MK). For the time interval of 3 days 432 images with temporal cadence of 10 min were exploited (August 9–11, 2010). Raw AIA data in full resolution (4096 × 4096 pxs, 0.6 arcsec/px) were corrected for the effect of the instrument PSF function using data and method provided by Poduval et al. (2013). After, the basic photometric reduction was performed (*aia prep.pro* routine) and intensities were normalized to 1 s exposure time. Finally image noise filtering was applied using Lee box algorithm (Lee, 1986).

3. CBP detection algorithm

For the detection of the CBPs in the SDO images the Gradient Path Labelling (GPL) segmentation algorithm was used. This algorithm was initially designed and proposed by Mora et al. (2011) to segment retinal images but its accuracy and flexibility made it suitable to be applied in the domain of the microscopy image analysis (Häkkinen et al., 2013). Shahamatnia et al. (2016b) confirmed that the segmentation and tracking of the CBPs in solar images is also a promising domain for the application of the GPL, since the CBPs are higher intensity regions with distinguishable boundaries. The GPL segmentation method uses the image gradient as the basis for a pixel labelling procedure which groups ascending paths that belong to the same regional maximum. Its segmentation result is comparable to the watershed transform, with the advantage of having a lower over-segmentation effect, good computation efficiency and customizable segmentation effect. Together with GPL a post-processing algorithm is applied to merge neighbour regions that have similar amplitudes. The method produces an image segmented in several intensity regions that are then filtered to match the relevant solar features.

The approach to detect the CBPs follows a three-step process (Fig. 1) that starts by creating a mask of the active regions, followed by the GPL segmentation. Finally, the generated segmentation regions are filtered to select the region that matches a CBP, and the centroid and maximum intensity locations are determined. More details on the GPL image segmentation part for CBP detection can be found in Shahamatnia et al. (2016b), and CBP matching and GPL configurations can be found in Coelho (2017).

In addition, an active regions mask was introduced to filter out the CBPs whose centroid is inside the active regions. This mask is obtained by applying an Otsu threshold (Otsu, 1975) and performing a morphological open operation with a 3 × 3 full size structuring element. The open operation consisted in 15 erosions and dilations to clear small manifestations with less than 15 pixels, followed by 5 dilations to emphasize the active regions and potentially reject CBPs on the active region borders (Fig. 2).

Due to the large data volume of images of the solar disk and the GPL segmentation algorithm complexity – GPL is proportional to the images resolution – the authors decided to split the image into several smaller regions (in total to 4 × 4 regions) and apply the segmentation in each one separately. This approach enables faster