Searching for a jet stream

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Abstract
We can imagine, under the term jet stream (sometimes also torsional oscillation), a layer where the rotational speed of the solar surface is higher than the average value. According to Birch and Kosovichev (1998) there is a difference of about 15 m s^{-1}. This layer is also an indicator of hypothetical processes that take place under the solar surface, and its location (heliographic latitude) is probably related with phase of the solar activity cycle. Therefore, it would be useful to routinely determine its position from observations.
We are trying to determine its position by using a series of images obtained from the AIA instrument onboard the SDO satellite. In this contribution we present a two-phase method, where the first phase includes the estimation of the rotational speed in a big range of latitudes and the second phase uses a hybrid algorithm combining PSO (Particle Swarm Optimization) and Snake algorithms for detecting, tracking and determining the rotation of coronal bright points. In the near future we plan to use this method to process significantly higher number of images from the AIA instrument and thus improve the knowledge about the properties of the differential rotation of the solar corona, as well as, to determine the heliographic latitude of the jet stream.

1. INTRODUCTION

Specifying the exact nature of the differential rotation of both the solar surface and the solar interior is still one of the most serious open issues of solar physics. The solar surface rotates differentially. However, the differential rotation (DR) mechanism, most likely caused by interactions between convection and overall rotation, is not exactly known. Rotational irregularities may also serve as indicators of hypothetical processes being in progress beneath the solar surface. One example could be the location of a layer where rotational speed changes abruptly (a *jet stream*, Fig. 1). Sometimes it is called a layer of torsional oscillation (Ulrich and Boyden, 2005). The location of this layer (its heliographic latitude) is likely related to the phase of the solar activity cycle. Therefore, it would be useful to have a tool for regular determination of its location. However, this implies the determination of the deviation from the average rotation speed with an accuracy of

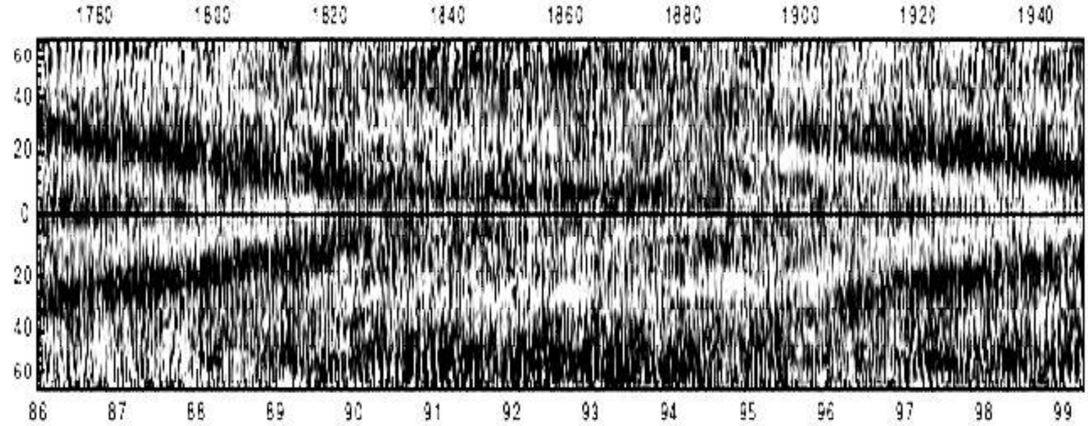

Figure 1. Differences in the rotational speed according to Birch and Kosovichev (1998). Differences between white and black area are around 15 m s^{-1}.

± 15 m s $^{-1}$, while the average speed in the latitude of 15° is around 1882 m s $^{-1}$. Therefore, it requires a relative accuracy of ± 0,8 %.

It is possible to achieve such precision by an interactive method of measurement as it was shown by Lorenc *et al.* (2012). Results on the study of differential rotation of the solar corona by observing Coronal Bright Points (CBPs) in images obtained by the *Atmospheric Imaging Assembly* (AIA) Instrument on board the space *Solar Dynamics Observatory* (SDO) on a PC monitor are presented in that paper, *i.e.* determining manually the position of CBPs in an interactive session of an image editor. However, this method of measurement is laborious and time-consuming, hence, it becomes practically unworkable on a large number of images. Therefore, we selected and developed an automatic method of estimation of the speed in a big range of latitudes. In the following section we describe the method and present some preliminary results and conclusions.

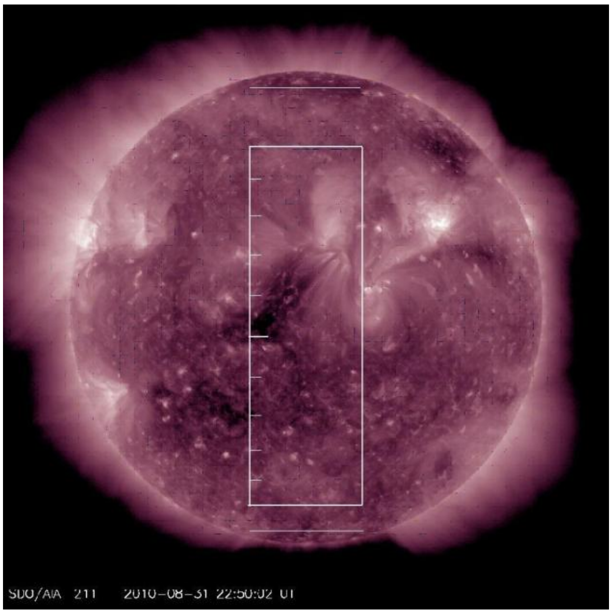

Figure 2. Selection window in the SDO/AIA 211 image for further processing.

2. METHOD OF DETERMINATION OF THE ROTATIONAL SPEED

We used cross-correlation method for bulk data processing. The input data are the observations of the Solar Dynamics Observatory (SDO)/AIA instruments at 21.1 nm wavelength. We choosed for further processing a series of 148 images from 1st and 2nd of September 2010. We used the jpeg images with a resolution of 1024 x 1024 pixels. For each picture we defined a rectangular window, for intensity data selection, with size in the range of140 to 890 pixels in direction N - S and from 412 to 612 pixels in the direction E - W (Fig. 2).

For each pixel in the selection window of individual images, we determine the heliographic coordinates *b* and *Δl* and transform the whole file into a rectangu-lar matrix with a range of ± 50° in width, with a reso-lution of 0.5° and ± 14° in longitude and with a resolu-tion of 0.1°. Then, we correlate lines with each other at a particular latitude in the whole series of images (1-2, 1-3, 1-4, 1-5; the time interval between adjacent images is around 15 minutes), with a shift of *n* x 0.1° and search a shift with maximum matching (Fig. 3 and Fig. 4). The cross-correlation function, defined by points, is approximated by a third degree parabola, because it is usually asymmetric. The position of its top provides the difference of longitudes in a particular latitude, which a certain point undergo, between two consecutive images. Their ratio, corrected by the Earth movement, determines the sidereal rotational speed for each particular point and time. After this processing we obtain 201 time series with duration of 48 hours.

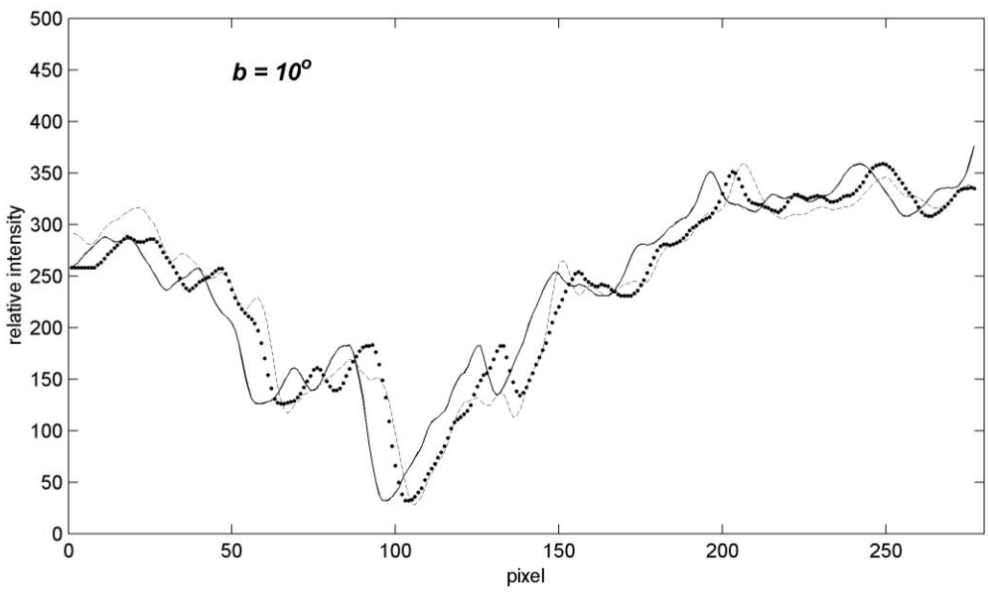

Figure 3. Variation of relative intensity at latitude b = 10° for consecutive images.

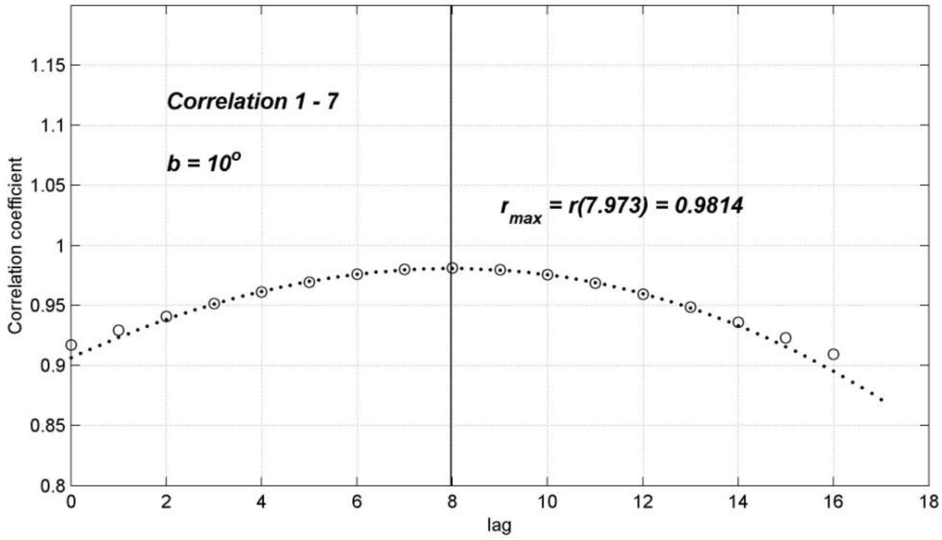

Figure 4. Cross-correlation of intensity variations in the images 1 and 7 at latitude b = 10°.

2.1. Preliminary Results

In general, the average rotation speed for a particular latitude differs only slightly from the values referred in other papers (Fig. 5). Its values vary from 14.5 °/day at equator to 12.5 °/day at latitudes around 50° with standard deviation around 4%. Unfortunately, it is not enough for fulfilling the task and longer time series will be necessary.

The novelty of this method is the temporal variation of rotation for different latitudes and different levels of solar activity at a particular point. The amplitude of these changes varies from 0.5°/day in quiet regions to approximately 4°/day in active regions (Fig. 6). In an active region, if we are able to distinguish it by this temporal resolution, the change of rotational speed occurs rapidly, up to 2°/hour.

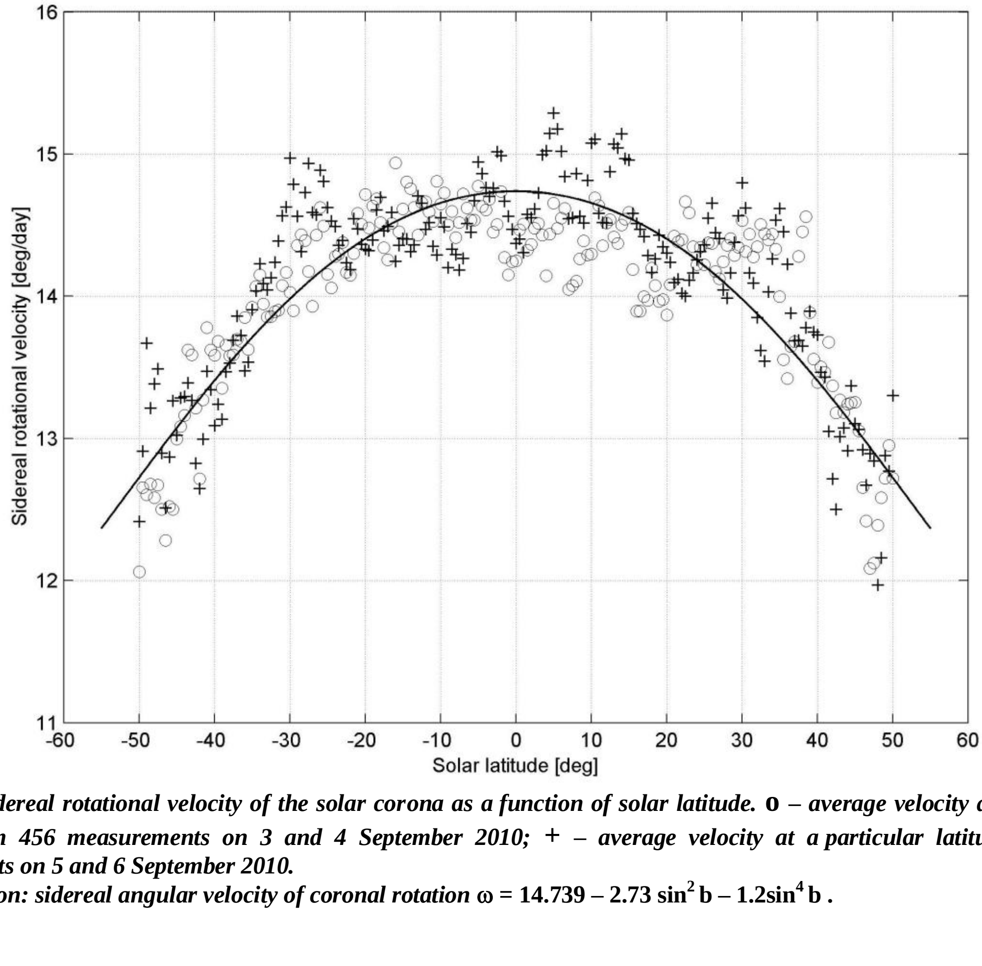

Figure 5. Sidereal rotational velocity of the solar corona as a function of solar latitude.* o *– average velocity at a particular latitude from 456 measurements on 3 and 4 September 2010;* + *– average velocity at a particular latitude from 536 measurements on 5 and 6 September 2010.
***Approximation: sidereal angular velocity of coronal rotation* $\omega = 14.739 - 2.73 \sin^2 b - 1.2 \sin^4 b$.**

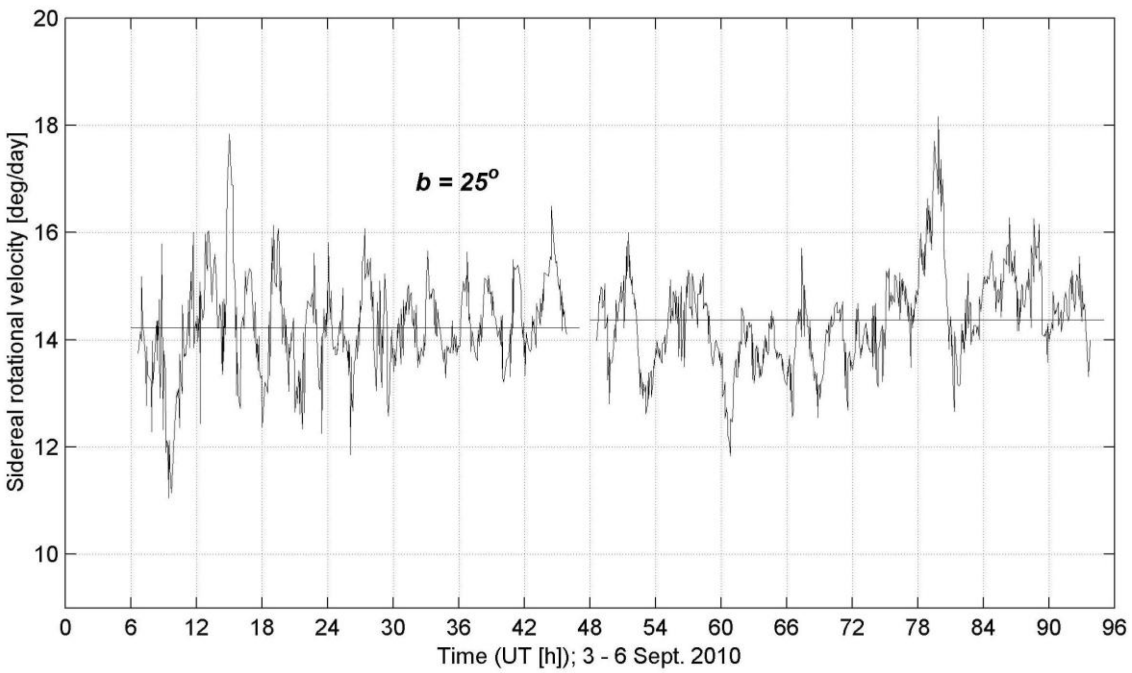

Figure 6. Temporal evolution of the sidereal rotational velocity **ω(t)** ***of two time series of measurements at latitude b = 25° where the time lag between used images is less than 15 minutes:***

a) ***3 - 4 September 2010, 456 measurements with an average*** **ω = 14.22°/day,**

b) ***5 – 6 September 2010, 536 measurements with an average*** **ω = 14.37°/day.**

We can see that rapid changes in **ω** ***can achieve also more than*** **5°/day (1°/day = 127 m/s** ***at the given latitude.***

3. AUTOMATIC TRACKING ALGORITHM

The method described in section 2 is capable of estimating the rotational speed in a big range of latitudes, determined by a rectangular selection window (100° in latitude and 14° in longitude) and identifying a region with abrupt change of the rotational speed. Once the region of interest is identified, there is a need for automatic detection and precise tracking software tools. These tools will enable us to track a CPB that occurs near a region of abrupt change of the rotational speed and to determine its heliographic coordinates and rotational speed over its lifetime.

Therefore, we propose to use a hybrid algorithm for automatic detection and tracking of CBPs. The algorithm for identification and tracking of CBPs has been already tested on sunspots (Shahamatnia et al., 2012). This algorithm is a merger of a Snake model and Particle Swarm Optimization (Shahamatnia and Ebadzadeh (2011), henceforth called S-PSO.

The Snake model, also known as Active Contour Model, is an energy minimization algorithm induced not only by low level image features such as image gradient or image intensity, but also with higher level information such as object shape, continuity of the contour and user interaction (Kass *et al.* 1987). Given an approximation of the object boundary, the snake model will be able to find the precise boundary of that object.

The second part of the tracking approach is the Particle Swarm Optimization (PSO) algorithm, which is an evolutionary optimization technique consisting of a number of particles, each representing a potential solution to the problem (Kennedy and Eberhart, 1995). The Swarm is initialized with random solutions, i.e. random positions and velocities for the particles.

As mentioned before, the tracking approach used here is built on the authors' previous work (S-PSO) and combines advantages of high-level object detection capacities of the snake model with the PSO algorithm to achieve a promising system for automatic CBP tracking. The **main steps** of the S-PSO algorithm are as follows:

- **Step 1. Initialization.** Preprocessing of images (if required), i.e. normalizing the size of images, correcting the orientation and contrast of images, etc.
- **Step 2. Initial contour.** An operator has to draw the initial contour (snake) around the area of interest. For most cases a rough estimation of the initial contour is enough. This step is done only once when the CBP appears in the image.
- **Step 3. Internal parameters set-up.** The weight parameters for the S-PSO algorithm are initialised in this step.
- **Step 4. Snake force calculation.** The external force (image force) is calculated, once for every image.
- **Step 5. Calculation of social and cognitive parts.** In this step we update the pbest value (the best velocity the snaxel ever experienced)

and the best value as average of velocities of neighbouring particles.

- **Step 6. Moving snaxels.** For each snaxel its velocity is evaluated and then each snaxel velocity and position are updated.
- **Step 7. Snake detection.** This step checks the convergence of the snake contour to the CBP outline, i.e. choosing the snake with the lowest total energy calculated. If the results are not satisfactory, the algorithm goes back to step 5 and repeats until it converges. The outcome of this step is the CBP contour for an image frame.
- **Step 8. Tracking CBPs.** This step tracks the same CBP in the next image by feeding the subsequent image frame to the system as input. The algorithm loops back to step 4, and passes the specifications of the detected CBP.
- **Step 9. Stopping tracking.** Tracking of a CBP ends when a CBP disappears, e.g. when it shrinks below a threshold limit, or when it reaches the solar limb.

During run time the operator can interact with the system adding or removing CBPs to be tracked. The simulations were implemented in MATLAB 2009b software and tested on several AIA solar images from the SDO archive (http://sdo.gsfc.nasa.gov/data/aiahmi/browse.php) for the same period (from 14 September 2010 to 20 October 2010) as in the manual interactive method described in (Lorenc *et al.*, 2012).

3.1. Illustrative Examples

In this section the potential and performance of the proposed tracking algorithm (S-PSO) is demonstrated with some simple illustrative examples. More results can be found in (Shahamatnia et al., 2012).

Figure 7. Initial snake in the SDO/HMI image from 18th June 2011.

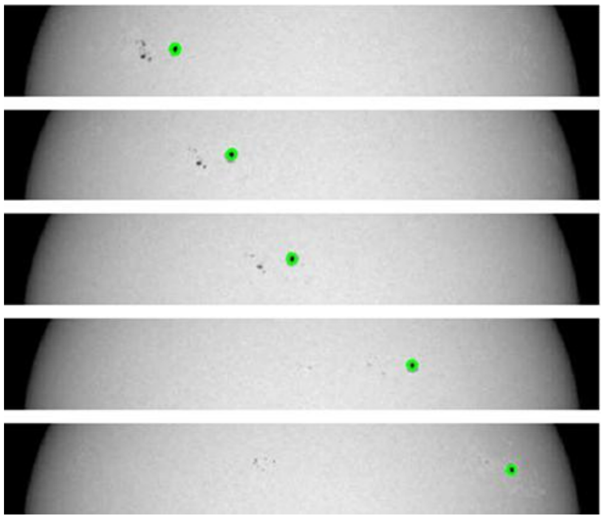

Figure 8. Tracking of a sunspot in SDO/HMI images from 18 to 24 of June 2011.

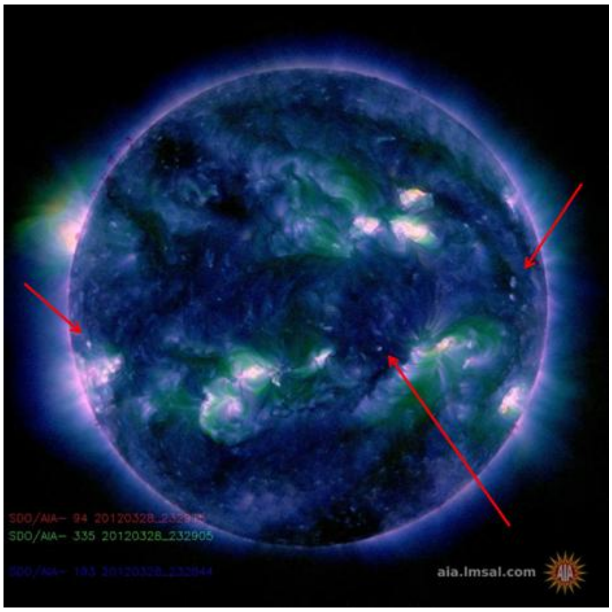

Figure 9. The proposed hybrid software tool (S-PSO) is being tested on CBPs (SDO/AIA images).

4. DISCUSSION AND CONCLUSIONS

Based on the results presented in (Lorenc *et al.* 2012), we infer that tracers may have rotational speeds sufficiently stable during the whole day and that the (interactive, manual) tracer method is sufficiently precise, hence the obtained values of rotational speed are reliable. However, the method is laborious and with a large number of images becomes unworkable for practical reasons. Therefore, we developed two automatic image processing tools (first one is an automatized method of estimation of the speed in a big range of latitudes and the second one is a hybrid Snake/PSO algorithm for detection and tracking features in the solar atmosphere). The obtained results confirmed the potential of the proposed approach as a promising tool for investigating the evolution of solar activity and also for processing any solar image archives.

Considering that there are many solar images available online, in the jpeg2000 format with a cadence of approximately 1 minute and with more than 1000 images per day, we plan to use them to create and analyze a three month time series and later to introduce a patrol determination of the rotational speed.

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