Research Article

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Possibilities of velocity field analysis from Hinode SOT/SP data

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Abstract: The possibility of analyzing the line of sight (LOS) velocity and its gradient at each point of the Hinode SOT/SP maps using bisector analysis is revealed. A technique for obtaining such gradient is described. To estimate the velocity gradient, it is necessary to know both the velocity value and the layer height to which the bisector point is responded. We have constructed and tested a method to determine this height. We found velocities at the same heights for lines Fe I λ 6301, 6302 Å averaged over the whole map. It turned out that these velocities have some difference that changes with height and time. The error in the estimating of average velocity for the whole map is $2 \text{ m}\cdot\text{s}^{-1}$. It follows that the wavelengths of lines 6301 and 6302 given in the NIST tables may differ from the real ones at $5.5 \text{ m}\text{\AA}$. Or there is an inaccuracy in the spectrograph dispersion specified in the FITS files. As an example, the curves of changes with the height of the LOS velocity and its gradient were constructed both for points of the whole map and for subsets of the hottest and coldest points.

Keywords: solar photosphere; line profiles; bisectors; effective heights

1 Introduction

The spectropolarimeter of the solar telescope (Lites *et al.* 2013) of the HINODE mission (Kosugi *et al.* 2007) receives observational data. These data are Stokes profiles, each of which includes 112 points in the wavelength range $\lambda\lambda$ 6300.9 – 6303.3 Å for individual pixels on the maps of the solar surface. The Hinode mission team processes the data and uploads maps of the magnetic field vector to the Internet. However, the data, in addition to the magnetic field, make it possible to consider other physical quantities, in particular, to analyze the velocity fields. Our research is exploring this possibility and also serves as the basis for our other works (Mozharovsky 2021a,b). All calculations performed in our work were done using a software package written in Delphi 7.

A similar study was carried out by (Oba *et al.* 2017a). There is a fairly detailed review of the literature on the topic.

2 Bisectors construction

Spectral line bisectors provide information on the LOS velocity gradient. Hinode data make it possible to construct bisectors that consist of a small number of points (due to rare wavelength step). We will receive these points as the centers of gravity of trapezoids cut from the intensity profile at line depth levels $d = 0-20, 20-40, 40-60, 60-80, 80-100\%$, where $d = (I_{\text{CONT}} - I)/(I_{\text{CONT}} - I_0)$, I_0 and I_{CONT} – these are intensities at the center of the line profile and at the level of the continuous spectrum, respectively. Let's designate the segments with indices 1 ($d = 0.1$), 3, 5, 7 and 9 ($d = 0.9$). Segment 1 refers to the wings of the line, segment 9 – to its core.

Figure 1. To the explanation of the bisector construction algorithm, see text

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In Figure 1 the horizontal lines divide the profile into 5 trapeziums – 5 segments of equal height $0.2 d$ each, (d is the line profile depth). Inside each segment we find the position of the wing $b = x_1 + S_1/S \cdot \Delta x$, where S_1 is indicated on the graph, $S = \Delta x \cdot \Delta y$, $\Delta x = x_2 - x_1$, $\Delta y = y_2 - y_1$. The vertical lines along the Y -axis at “ b ” (bound)-position and the profile line form pairs of triangles of equal area (red and blue triangles). The positions of the halfsums $b_n = (b_{\text{blue}} + b_{\text{red}})/2$ are the points of the bisectors. And the values $w_n = (b_{\text{red}} - b_{\text{blue}})$ are the absolute widths of the profiles in the segments $n = 1..9$, w_5 we can consider as FWHM.

Let's note that segments 1 and 9 have some problems in accurately determining the wavelength. For segment 1 in some cases, we start (or we end) segment not at the I_{CONT} intensity level, but at a given distance from the center of the line (350 mÅ), this difference contaminates results. For segment 9 there is a phase problem – the real line core wavelength falls into the interval between two points of the scanned profile. When the center of the line and the point of the profile coincide exactly, this will be phase 0, when the center falls exactly between two points, this is phase ± 0.5 . The wavelength of the b_9 bisector will partially depend on this phase.

So, to increase the number of homogeneous bisector points, we introduced the segments 2, 4, 6 and 8, that cut trapezoids from the intensity profile at levels $d = 10\text{--}30$, $30\text{--}50$, $50\text{--}70$ and $70\text{--}90\%$, respectively (that is, with 50% overlap of segments 1, 3, 5, 7, 9).

3 Determination of the continuous spectrum level and the line core position

Before constructing bisectors, we should determine the intensity of the continuum and the line core position.

Usually, the intensity of the spectrum band in which there are no absorption lines is taken as the level of the continuum. However, there is no blend-free region in the Hinode SOT/SP spectral range in the spectrum of sunspot umbra. Therefore, for the sake of generality of the approach, we simply take the entire profile, smooth it with a Gaussian width of 90 mÅ (approximately 4.5 points of the profile along the wavelength scale), and then take the intensity of the brightest point as the level of the continuum I_{CONT} .

To determine the exact line core position, we choose 3 or 4 or 5 points closest to the center of the profile. Then using the least squares method for all three sets of points we fit the nearest Gaussian to the points. In the current

version of the algorithm, the squares of the deviations are selected for 7 points, however, the points farthest from the center ($7 - 5$, $7 - 4$ or $7 - 3$ points) are assigned smaller weights – $1/50$ and $1/350$ when calculating the sum of the squares of the deviations. Three Gaussian parameters used for the fit are the intensity of the core I_0 , its wavelength λ_0 and the width of the Gaussian $\Delta\lambda$. The λ_0 gives us three more values of the LOS velocity, which we designate as c_3 , c_4 , c_5 .

4 The maps of LOS velocities vertical distribution in the photosphere

If we know that the line core is formed higher in the atmosphere, and the wings are formed deeper, then we can obtain the distribution of line-of-sight velocities in height in the photosphere layer.

The Figure 2 shows the LOS velocity maps for the layers that correspond to the bisectors b_1 , b_7 ($d = 0.1, 0.7$) and core position c_4 , (wavelength λ_0 of the Gaussian fit for 4 points), that is, in the first three frames we rise from deep layers towards the surface in velocity map. The fourth frame shows the LOS velocity gradient between the layers b_7 and b_3 ($d = 0.7$ and 0.3):

Figure 2. Three left frames – LOS velocity maps for the layers b_1 , b_7 , c_4 (line wing, above half maximum position and line core respectively). Dark areas correspond to downflow. Right frame – the LOS velocity difference between b_7 and b_3 , layers that is proportional to LOS velocity gradient $\Delta v_{\text{LOS}}/\Delta h$. Hinode observation session 20191109_1334, $\cos(\theta) = 0.985$. Fe I $\lambda 6301 \text{ Å}$ line

5 Evaluation of the relative position of layers

Having 9 bisector points and 3 ways of finding the line core position, we have 12 different levels, twelve effective heights from which we receive data. If we talk about maps,

then these are twelve map layers for each of Fe I 6301 and 6302 Å lines. The LOS velocities at all these heights can be compared with some common dependent parameter. Let us choose the intensity of the continuum for comparison, bearing in mind that in the bright centers of the granules the substance floats up, and in the dark intergranular lanes it sinks, see Figure 3.

Figure 3. The scatterplots for the LOS velocity against the continuum intensity for different layers of the photosphere (in the analysis of statistics, the points for which longitudinal field $B_{||} > 10$ G were discarded). R – the correlation coefficient between v_{LOS} and I_{CONT}

From Figure 3, we can notice that the correlation R between the v_{LOS} and I_{CONT} gradually changes smoothly with a layer change, that is, with a change in the effective height h_{eff} at which the velocity is measured. Therefore, we can draw the dependence of the correlation on the layer index (Figure 4, *Left*). And then find for each point its position on a uniform scale, see Figure 4, *Right*. The given values 0.0 and 10.0 set the bounds of uniform scale.

Figure 4. *Left:* Correlation between the v_{LOS} and I_{CONT} depending on the layer on which the v_{LOS} is measured. These data are averaged over 8 Hinode maps for the same area 20191109_1334 – 20191109_1444, total >140000 points (points with $|B_{||}| > 10$ G have been discarded). *Right:* Performing layer height estimation

So, using the operation shown in the Figure 4, *Right*, we get the Table 1, “Relative h ” columns.

We cannot determine the relative height of the b_1 ($d = 10\%$) level because the monotonicity of the $R(d)$ dependence of the correlation coefficient R for this level is vio-

Table 1. The relative positions of the layers on height scale

Line:	Fe I λ 6301 Å		Fe I λ 6302 Å	
Layer	Relative h	Model h , km	Relative h	Model h , km
b_1	?	81	?	92
b_2	0.00	97	0.28	114
b_3	0.24	119	0.52	130
b_4	0.64	140	0.88	146
b_5	1.24	164	1.33	163
b_6	2.04	194	1.85	186
b_7	3.20	235	2.49	217
b_8	4.82	289	3.34	261
b_9	7.17	372	4.42	322
c_5	6.02	-	3.11	-
c_4	10.00	-	5.40	-
c_3	9.61	-	5.15	-

lated. We can also see that the c_4 level is located above the c_3 level. This is probably due to the fact that, in going from c_3 to c_4 and to c_5 , the thickness of the layer that is responsible for the formation of this fragment of the line profile changes greatly.

Model heights, that is, heights calculated from a numerical simulation, we will discuss in the following section.

6 Is the “relative height” linearly related to geometric height in kilometers?

Numerical simulation can be used to calculate the heights of the response of various bisector segments $b_1 - b_9$ to LOS velocity variations. I used the 1-d photosphere model (Grevesse and Sauval 1999) and a program, that calculate a line profile by the Runge-Kutta method without taking into account non-LTE effects. The method for calculating the response function (RF) that will now be described can be named the “probe layer” method. In a layer 5 km long, we set the LOS velocity to change by $+0.5 \text{ km s}^{-1}$, and the height of this probe layer changed step by step from -100 to 850 km. From the calculated intensity profiles, bisectors were constructed for 9 profile segments. The wavelength positions of the bisector points are plotted in the graphs in Figure 5. The effective heights of the response (indicated by inverted triangles in the graphs) were obtained as the values of the centers of gravity of the resulting RF curves.

We named the calculated effective heights as “Model h ” and you can see them in Table 1. Now we can plot the relative and model heights on one graph (Figure 6, *Left*)

Figure 5. The response of the segments of bisectors $b_1 - b_9$ to LOS velocity variations at $+0.5 \text{ km} \cdot \text{s}^{-1}$ in 5 km long “probe layer” and determination of effective heights of response. *Left:* For 6301 line. *Right:* For 6302 line

and make sure that the relationship between these heights is not far from a linear relationship.

The bending of the curves near the model heights of 100–140 km can be explained by the fact that the scale of granular structures below heights of 150 km turns out to be less than the resolution of the telescope, see (Oba *et al.* 2017b). This makes the velocity-intensity correlation coefficient R less accurate. That is, here the values of “relative heights” are less reliable.

The curves for the two lines 6301 and 6302 diverge significantly starting from a height of 220 km. As we will see from Figure 7 *Left*, obtained from experimental data, the correspondence between the “relative heights” of the two lines for levels b_7, b_8, b_9 ($h = 5, 6, 7$) remains quite good. Hence it follows that, specifically, the RF centers of gravity are not the best thing for determining the effective height, and this method of determining effective heights for model simulations requires improvement.

The ratio between “relative” and model heights is close enough to linear, whereas in Figure 6 *Right*, we see that the dependence of the height on the number of the bisector segment is closer to a parabolic dependence than to a linear one. Recall that separately for lines 6301 and 6302

Figure 6. *Left:* Close to linear relation between “relative” and model heights. *Right:* Close to quadratic dependence between the model height and the intensity of the profile wings, linked to bisector segment. The data taken from Table 1

the bisector number is linearly related to the intensity of its profile fragment.

7 How the LOS velocity and its gradient change with the “relative height”

Knowing the LOS velocity at each point of the Hinode SOT/SP map, we can find the average value of v_{LOS} for each of the 11 levels (since the b_1 level is excluded) for each of the two lines and plot this average value on the graph, see Figure 7, *Left*. We can also see how the gradient changes with height – Figure 7, *Right*.

The relative height h obtained by correlating Δv_{LOS} and I_{CONT} makes it possible to fairly well compare the velocities and their gradients for two spectral lines 6301 and 6302 at the same heights.

Figure 7. *Left:* Averaged (mean) v_{LOS} versus relative height h for >140000 points of maps. Red and blue graphs – the data for >12000 points of respectively brightest ($I_c > 1.145$) and darkest ($I_c < 0.94$) points. *Right:* Correspondent averaged $\Delta v_{\text{LOS}} / \Delta h$ values. We see that the combination of levels for which the velocities were determined in different ways (b and c), generates steps on the right graph

8 The difference between the velocities measured in the lines Fe I λ 6301 and 6302 Å, referred to the same heights

As we can see from Figure 7, *Left*, the velocities obtained for 6301 and 6302 lines are shifted relative to each other. This is easy to explain if we assume that the exact wavelengths for lines 6301 and 6302 are somehow incorrectly set.

Note that the layer velocities in Figure 7 are calculated by subtracting the position of the center of gravity (COG) of the whole line profile, averaged over the entire map, from the wavelength positions of the bisector points. That is, for each of the lines 6301 and 6302, we have calculated its center of gravity averaged on the map. If real wavelengths of the lines are 6301.5008 and 6302.4932 Å according to NIST data, see (Löhner-Böttcher *et al.* 2019), then the averaged COG wavelength difference correspond to the velocity difference $v_{6302} - v_{6301}$ changed from 200 to 260 $\text{m}\cdot\text{s}^{-1}$ for 8 maps of same area for Hinode sessions 20191109 (13:34,13:44,13:54,14:04,14:14,14:24,14:34 and 14:44), see Figure 8.

The changes over time of the $v_{6302} - v_{6301}$ values do not look random. Maybe these changes are associated with processes on the Sun, for example, with 5-minute oscillations? We divided the X-axis of each of the 8 maps into two equal halves and repeated the calculations. It turned out that the graphs for the halves are similar. This means that the changes in Figure 8 are caused not due to 5-min oscillations, but by the fact that the spectropolarimeter data is unstable over time. Instability manifests itself when determining the transition point from the line profile to the level of the continuous spectrum. It follows that our algorithm for determining the centers of gravity of lines needs to be changed. The integration should stop not too far from the

Figure 8. The differences of averaged over the whole map 6302 and 6301 COG velocities for 8 maps. The standard error for each map is $2 \text{ m}\cdot\text{s}^{-1}$

center of the line. At the other hand we see that the standard statistic error $2 \text{ m}\cdot\text{s}^{-1}$ is combined with the instrumental systematic error which can reach $\pm 30 \text{ m}\cdot\text{s}^{-1}$.

The velocities of the bisector points of both lines, referred to the same heights, must coincide or have the same convective blue-shift. The discrepancy indicates any errors in the method for determining the velocities and allows us to evaluate the quality of this method. From Figure 9, we see that the scatter of values from map to map in the most reliable fragment, where bisectors are compared, is approximately $\pm 0.1 \text{ m}\text{\AA}$, which corresponds to $\pm 5 \text{ m}\cdot\text{s}^{-1}$. Exceeding the value of $6302.4932 - 6301.5008 = 0.9924 \text{ \AA}$ by $0.0055 \text{ \AA}$ can be explained by an inaccuracy in the NIST data. But it is more likely that the difference in wavelengths between pixels in the Hinode SOT/SP spectrum is inaccurately known. If we take as spectral resolution value $21.668 \text{ m}\text{\AA}$ per pixel instead of 21.549 , as recorded in the Hinode FITS files, then the problem disappears. Velocity data in line wings (relative $h < 1$) is obviously less reliable. As noted in (Oba *et al.* 2017b), the size of the photospheric elements in the deepest observed layers is approximately two times smaller than the diffraction limit of the SOT/SP instrument. Mixing radiation from different elements spoils the result. In Figure 9, a step is noticeable in the area of relative $h = 3.3$. This is the point where the heights of type *b* and type *c* are joined – that is, determined using the bisector and the method of the line core fit with a Gaussian. The reason of the step is that, as we said earlier, there is a difference not only in the effective height, but also in the thickness of the layer, which is responsible for the formation of a specific fragment of the line profile. The difference $\lambda_{6302} - \lambda_{6301} - 0.9924$ in Figure 9 changes along the relative height according to a certain pattern. In this work, we will not explore this pattern.

Figure 9. The differences between bisector points at the equal “relative” heights for 6302 and 6301 lines. Solid line – mean values, others – values for individual maps

Figure 10. Absolute LOS velocities for statistical collections of map points, filtered by specified conditions. A gravitational shift of $635 \text{ m}\cdot\text{s}^{-1}$ and a shift associated with the rotation of the Sun of $-340 \text{ m}\cdot\text{s}^{-1}$ are taken into account. All 6302 velocities are shifted to the blue at $260 \text{ m}\cdot\text{s}^{-1}$. *Left:* LOS velocities for all points in 8 maps and for hottest and coldest populations. *Center:* LOS velocities for the upflow points with maximum deceleration, for the downflow points with maximum acceleration, and for cells that move without acceleration. Acceleration Δv is measured as the difference in 6301 LOS velocities for levels b_6 and b_4 . *Right:* Scatter plot that explains why curves for upflow points $I_c > 1.145$ and $\Delta v > 0.21$ are different

9 Absolute LOS velocities for statistical collections of map points, filtered by specified conditions

In section 7 we looked at velocities, each of which was calculated relative to the average velocity across the map. In this section, we will consider the absolute velocities, taking into account the gravitation shift and the LOS velocity associated with the rotation of the Sun, see Figure 10. The blue graphs, in Figure 10 *Left* and *Center* refer to cold columns that are sinking, and the red graphs refer to hot areas that are floating up. As we can see, the red graphs are very different in Figure 10 *Left* and *Center*. This means that the hottest points (*left*) and the points that experience the most deceleration (*center*) are different points, see Figure 10 *Right*. The red and blue graphs in Figure 10, *Center* intersect at a relative $h = 6$, which corresponds to geometrical height about 350 km. The Figure 10, *Center* and the intersection in particular can be explained by horizontal flow, see (Oba *et al.* 2020), which carries matter from floating elements to falling ones.

10 Conclusion

This article is not the first to describe a technique for analyzing the velocity field in Hinode data using bisectors, see (Oba *et al.* 2017a; Ishikawa *et al.* 2020). We discovered some results that other authors did not have.

- We have established a numerical match between the heights of the layers related to different levels of the bisectors of 6301 and 6302 lines.
- We used a gaussian curve fit of the line core points to analyze the highest layers.
- We tried to use not small “interesting” areas of the Sun’s surface, but to collect large statistics, if necessary, combining data from different observation sessions. Large statistics allow obtaining velocity values averaged over a 140×190 -point map with a standard error of about $2 \text{ m}\cdot\text{s}^{-1}$.
- We found a change in the difference between the velocities determined by the centers of gravity of lines 6301 and 6302 averaged on whole map over time, that seems is result of instrumental instability.
- We came to the conclusion that the NIST data on the wavelengths 6301 and 6302 may differ significantly from the real ones (up to 5.5 mÅ for the difference in wavelengths). Or the value of the spectrograph dispersion given in the FITS files is incorrect (the FITS Header field CDEL1=0.021549 should be replaced by CDEL1=0.021668). Hinode’s SOT/SP integrated data allow one to obtain a velocity difference between measurements in two lines up to $1 \text{ m}\cdot\text{s}^{-1}$, which requires knowledge of the wavelength difference between 6301 and 6302 lines with an accuracy of 0.02 mÅ (which, however, can be distorted by any systematic error).

My goal was to show the possibilities of the method. In order to obtain end results describing in detail the processes in the solar photosphere, it is necessary to include in the data processing a careful calibration, such as that described in (Lites and Ichimoto 2013).

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