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On 2D Linear Polarimetry in Prominences

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Abstract. An approach for high-precision 2D linear polarimetry is briefly described. The key components are reducing random errors, reducing systematic errors, and obtaining 2D distributions of the linear polarization degree, p, and polarization angle, χ (deviation of the polarization plane from the direction tangential to the solar limb).

Keywords. Sun: prominences, Sun: magnetic fields, techniques: polarimetric

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1. 2D linear polarimetry with actual accuracy $< 2\%$ and $< 2^\circ$

Significant noise is inevitable for the near-limb filter linear polarimetry. We suggest an approach aimed at obtaining the polarization "images": 2D distributions of p, χ, and the sign of χ. The main components are the following (Kim *et al.* 2011): low sky brightness (a), low-scattered light telescopes (b), identity of the polarizer performance for any "point" of the image (c), reducing random errors by the use of 24 successive orientations of the polarizer corresponding to its full turnover instead of traditional three (d), reducing systematic errors by the use of a special algorithm of data reduction (e), obtaining the polarization "images" (f). We note that items $(d)-(f)$ are the key ones. The polarization p- and χ-images of H_α-prominence of March 29, 2006 (centered at position angle of 307°) were presented in Figure 2 by Suyunova *et al.* (2013), they illustrate the relative accuracies $< 2\%$ and $< 2^\circ$.

Main "steps" of the final corrected version of the algorithm (e) are given here. The use of I, p, and $\chi-$parameters with different dimensions before statistical procedures results in systematic errors. Parameters of the Stokes vector (I, U, Q) have the same dimension, the intensity. $I = I_*$(non-polarized) + $I_\updownarrow$(linearly polarized). The alternating-sign Q and U are the projections of $I_\updownarrow$ on the axes of the Cartesian coordinates chosen randomly in the sky plane. $I_\updownarrow = \sqrt{Q^2 + U^2}$ and is oriented at an angle φ: $\tan\varphi = U/Q$. So, $p = I_\updownarrow/I$, and $\chi = \varphi/2$. The intensity of partially linearly polarized light passed through an ideal polarizer is described by the expression

$$S \sim I_* + 2I_\updownarrow \cos^2(\chi - \alpha) = (I_* + I_\updownarrow) + I_\updownarrow \cos(2\chi - 2\alpha) = I + Q\cos 2\alpha + U \sin 2\alpha, \quad (1.1)$$

where α is the orientation of the polarization plane in the χ coordinate system. The intensities I, Q and U depend on the coordinates (i, j), i.e., the frames $\mathbf{I} \equiv \mathrm{I(i,j)}$, $\mathbf{Q} \equiv \mathrm{Q(i,j)}$, and $\mathbf{U} \equiv \mathrm{U(i,j)}$. α differs in successive frames by $2\pi/24 = 15^\circ$, and $\alpha_k = \alpha_0 + \pi k/12$ in the $k-$frame, where α_0 is the orientation in the initial frame. Thus, there are 24 equations for each pixel with the (i, j) coordinates based on 24 successive frames $\mathbf{S_k}$:

$$\mathbf{S_k} \equiv \mathrm{S_k(i,j)} = \mathbf{I} + \mathbf{Q}' \cos\frac{\pi \mathrm{k}}{6} + \mathbf{U}' \sin\frac{\pi \mathrm{k}}{6}, \qquad \mathrm{k} = 0, 1, \ldots, 23, \quad (1.2)$$

where the $(\mathbf{Q}', \mathbf{U}')$ vector is related to the $(\mathbf{Q}, \mathbf{U})$ vector by rotation by $2\alpha_0$:

$$\begin{pmatrix} \mathbf{Q}' \\ \mathbf{U}' \end{pmatrix} = \begin{pmatrix} \cos 2\alpha_0 & \sin 2\alpha_0 \\ -\sin 2\alpha_0 & \cos 2\alpha_0 \end{pmatrix} \begin{pmatrix} \mathbf{Q} \\ \mathbf{U} \end{pmatrix}; \quad \begin{pmatrix} \mathbf{Q} \\ \mathbf{U} \end{pmatrix} = \begin{pmatrix} \cos 2\alpha_0 & -\sin 2\alpha_0 \\ \sin 2\alpha_0 & \cos 2\alpha_0 \end{pmatrix} \begin{pmatrix} \mathbf{Q}' \\ \mathbf{U}' \end{pmatrix}. \tag{1.3}$$

The solution of the overdetermined system of 24 equations $\mathbf{S_k}$, with respect to $\mathbf{I}, \mathbf{Q}'$ and $\mathbf{U}'$ by the least square method minimizes the systematic errors and is given by

$$\mathbf{I} = \frac{1}{24}\sum_{\mathrm{k}=0}^{23} \mathbf{S_k}, \qquad \mathbf{Q}' = \frac{1}{12}\sum_{\mathrm{k}=0}^{23} \mathbf{S_k} \cos\frac{\pi \mathrm{k}}{6}, \qquad \mathbf{U}' = \frac{1}{12}\sum_{\mathrm{k}=0}^{23} \mathbf{S_k} \sin\frac{\pi \mathrm{k}}{6}. \tag{1.4}$$

The possible input of the steep brightness gradient is reduced by the use of the $\mathbf{q}'$ and $\mathbf{u}'$ frames which are alternating-sign components of p, so that the module of $\mathbf{p} = \sqrt{\mathbf{q}'^2 + \mathbf{u}'^2}$.

$$\mathbf{q}' \equiv \mathrm{q}'(\mathrm{i},\mathrm{j}) = \mathbf{Q}'/\mathbf{I}, \qquad \mathbf{u}' \equiv \mathrm{u}'(\mathrm{i},\mathrm{j}) = \mathbf{U}'/\mathbf{I}. \tag{1.5}$$

The polarization vector $(\mathbf{q}', \mathbf{u}')$ transfer to local coordinates is carried out by turning by $2\psi \equiv 2\psi(i,j)$: $\cos 2\psi = \frac{i^2 - j^2}{\sqrt{i^2+j^2}}$ and $\sin 2\psi = \frac{2ij}{\sqrt{i^2+j^2}}$. Tangential $\mathbf{t}'$ and radial $\mathbf{r}'$ frames are derived from $\mathbf{q}'$ and $\mathbf{u}'$ cartesian projections by the following transformations

$$\begin{pmatrix} \mathbf{t}' \\ \mathbf{r}' \end{pmatrix} = \begin{pmatrix} \cos 2\psi & \sin 2\psi \\ -\sin 2\psi & \cos 2\psi \end{pmatrix} \begin{pmatrix} \mathbf{q}' \\ \mathbf{u}' \end{pmatrix}. \tag{1.6}$$

The angle α_0 is determined with sufficient accuracy under the assumption that the radial component of polarization, $\langle \mathbf{r} \rangle$, averaged around the limb equals zero: $\tan 2\alpha_0 = \langle \mathbf{r}' \rangle / \langle \mathbf{t}' \rangle$. Turning the $(\mathbf{t}')$ and $(\mathbf{r}')$ frames by $2\alpha_0$ results in the $(\mathbf{t})$ and $(\mathbf{r})$ frames with the averaged $\mathbf{r}$ of zero. Finally the $(\mathbf{t})$ and $(\mathbf{r})$ frames are used to obtain p and χ.

The described method was applied to Hα-prominence to obtain 2D distributions of polarization parameters (Suyunova *et al.* 2013). On the average, our p-values are 1-6% more than the values of non-eclipse coronagraphic filter linear polarimetry in Hα quiescent prominences for the same height range (Bommier *et al.* 1994). Several factors can be responsible for the difference: the underestimation of the observed p in the presence of large-angle stray light (Chae *et al.* 1998) inevitable for non-eclipse polarimetry, the input of the continuum corona for total solar eclipse polarimetry, our accuracies, and a possible change of [I, Q, U] during 5 seconds (the polarizer full turnover period). The latter factor was indicated by V. Bommier (private communication during IAU S300). This will be discussed in a separate article.

Summary. The application of the approach to non-eclipse coronagraphic filter linear polarimetry in two lines looks promising for study of magnetic structure of prominences.

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