Chapter 3
DCP – A Utility Tool for HSOS Data Reduction

3.1 Introduction

The DCP (Direction, Current & Projection) is a line-menu software for use with the reduction of solar magnetogram data taken with SMFT at HSOS, which is programmed using Fortran-77 with PGPLOT graphics subroutine library on Sun Station. The program was originally designed in 1993 for the study of vector magnetic fields and electric currents in solar active region, mainly solving the problems of vector magnetogram calibrations, removing the 180^o ambiguity of the transverse field, deriving current distribution, and correcting projection effect. Now it has been developed to a practical software with miscellaneous functions adding in calculations of the potential field, angular shear, magnetic flux, current intensity, image processing and so on. In the past years, DCP has been proved very valuable to solar researchers who are interesting in HSOS data. Using this tool amounts of significant results were published in a various of scientific journals at home and abroad. It plays a key role in raising the utilizing efficiency of the HSOS data. In the next, we will present the fundamental principles and methods used in DCP.

3.2 Removal of the 180^o Ambiguity in Vector Magnetic Field Measurements

We know the ambiguity results from the fact that the transverse measurements of the magnetograph provides only the plane of linear polarization (Harvey 1969). To resolve this ambiguity, it requires an additional constraint on the field azimuth either from other theoretical considerations or from independent observations. A number of techniques have been developed to date, which we summarize as follows:

1. *The potential method*—This technique selects the azimuth of the observed field closest to the azimuth of the potential field derived from the longitudinal field (Harvey 1969; Hagyard & Teuber 1978; Sakurai et al. 1985; Aly 1989).

2. *The gradient method*—In this technique, the gradient of the longitudinal (or vertical) field, $\mathbf{B_T} \cdot \nabla_\mathbf{T} \mathbf{B_Z} \leq \mathbf{0}$ determines the selection of the azimuth direction (Kotov 1971; Aly 1989).

3. *The pseudo-gradient method*—That is, a magnetic charge method. In this technique, selected points are given from which the transverse field either converges or diverges (Gary & Hagyard 1990).

4. *The linear force-free field methods*—In this technique, the least-squared solution of the constant-α force-free field model is used to derive the global α value which determines the azimuth (Sakurai et al. 1985; Kress 1987).

5. *The vertical gradient methods*—In this technique one applies the relation $B_z \left(\frac{\partial B_x^2}{B_x \partial x} + \frac{\partial B_y^2}{B_y \partial y} \right) \geq 0$ to assign the azimuth direction (Hagyard et al. 1983; Wu & Ai 1990; Cuperman et al. 1993), which is derived from the divergence-free condition on assuming a decreasing

vertical field magnitude.

6. *The divergence-free method*—In this technique $\nabla \cdot \mathbf{B} = 0$ permits determination of the azimuth if the vertical field is measured at two levels in the atmosphere (Harvey 1969; Li, Cuperman, & Semel 1993).

7. *The consistency method*—In this technique the observer selects the azimuth most consistent with some intuitive model, e.g., conformity of nearest neighbors (Aly 1989; Canfield et al. 1993).

8. *The observational methods*—These techniques use either independent observations, such as Hα fibrils and the history of the field evolution, or separate Zeeman lines formed at two different heights (Sakurai 1989).

9. *The synthesized methods*—This technique combines several of the above methods (Wang & Lin 1993; Canfield et al. 1993; Wang 1994; Zhang & Wang 1994).

10. *The simulated annealing method*—This technique simultaneously minimizes both the divergence of the magnetic field and electric current density using a simulated annealing process to determine the azimuth (Metcalf 1994).

11. *The nonlinear optimization method*—This technique uses a function of the transverse field (e.g., $F[j_z^2] = \int\int j_z^2(x,y)dxdy$) to select the direction by minimization of this function (Gary & Démoulin 1995).

In DCP, a synthesized method is adopted to solve the ambiguity through the multi-steps. First, the technique (1 or 2) determines the direction for a whole region, then use (7,8) to modify the orientation unsuitable in some high-sheared areas. For active regions away from the disk center, the validity of field arrangements after eliminating the projection effects also provides an evidence to check if the azimuth is solved correctly. Applied with DCP, the obtained result for AR6659 (Zhang & Wang 1994) was well consistent with that given by the method (11).

3.3 Calculations of the Vertical Electric Current

Electric current systems are a key component in understanding solar activity. The free magnetic energy which drives much of the variation is directly connected to the magnitude of the electric currents in the solar atmosphere (Wang et al. 1996, and references therein). The vertical current can be derived from vector magnetograms, via the curl of the magnetic intensity as

$$j_z(x,y) = \frac{1}{\mu_0}\left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right), \qquad (\mu_0 = 4\pi \times 10^{-3} GmA^{-1}), \tag{3.1}$$

or

$$j_z = \frac{1}{\mu_0 S}\oint_L \mathbf{B}_\perp \cdot d\mathbf{r}, \tag{3.2}$$

where S is the surface enclosed by contour L. The current systems also can be inferred approximately from modelling the observed tracers such as the twisted Hα fibrils or the transverse field arrangements by a constant- α force-free field (Levine 1976; Schmahl 1982; Seehafer 1985; Gary et al. 1987).

In the first scheme, since the observed transverse field has a relatively large noise, the partial derivatives intensify the noise severely, sometime even lead to the distribution at some sites with little physical meaning. To reduce the high-frequency noise, Wang (1993) proposed a discrete FFT method to calculate the vertical current. In the Fourier domain,

$$\hat{J}_z(m,n) = \hat{B}_y(m,n)\left[\frac{sin(2\pi m/I)}{\mu_0 h_x}\cdot i\right] - \hat{B}_x(m,n)\left[\frac{sin(2\pi n/J)}{\mu_0 h_y}\cdot i\right] \tag{3.3}$$

where $\hat{B}_x$, $\hat{B}_y$, and $\hat{J}_z$ are relevant Fourier transformations, h_x and h_y are distances between adjacent pixels. For the similar purpose, Wang et al. (1997) first do a filtering on the observed transverse field before operate the numerical derivatives for calculation. A Fourier filter can be performed as

$$B^*_{x,y}(x,y) = \sum_u \sum_v F(u,v)\hat{B}_{x,y}(u,v)e^{2\pi i(xu+yv)} \qquad F(u,v) = \frac{1}{1+k(u,v)/k_c} \tag{3.4}$$

where $k(u,v) = 2\pi(u^2+v^2)^{1/2}$, and k_c is the lowpass cutoff frequency. Using this technique, one can readily obtain the interested characteristic scale of current density by selecting the k_c. In another way, Abramenko et al. (1991) use (3.2) to determine the current density, where the contour L enclosed an area 5×5 pixels around the central point. They argued that comparing with the FFT method (Wang 1993), the main current structures obtained for the same active region are quite similar, but in their routine peaks are more sharp and structures are more jagged. On the other hand, we notice that an inappropriate determination of the azimuth of the transverse magnetiograms is also a key reason to result from the large noise for current calculation with (3.1). So the techniques coupling with selection of the azimuth, such as the simulated annealing method (Metcalf 1994) and the nonlinear optimization method (Gary & Démoulin 1995) may have more advantages. As in most of cases we put our interests on the properties of large-scale current structures in an active region, DCP hence reduces the noise simply through a 10×10 box smooth average on the current density distribution. The effect is compatible with that of the 5×5 integral method (Abramenko et al. 1991). For a typical active region, DCP gives the maximum current density in range of $1.0 \sim 2.0 \times 10^{-2}$A/m^2, the total current magnitude in range of $10^{12} \sim 10^{13}$A.

3.4 Elimination of Projection Effects

The analysis of vector magnetograms obtained away from the center of the solar disk poses special problems requiring great care in the elimination of projection effects (Venkatakrishnan et al. 1988; Wilkinson et al. 1989). Because the observed magnetograms in geometry and field characteristics are distorted distinctly due to projection effect (Gary & Hagyard 1990), which influence us to approach the essential properties of field configuration or current structure evolution for an active region (Wang et al. 1994). Eliminating projection effects includes a combination of two aspects. One is the geometric transformation of the image plane (Venkatakrishnan et al. 1988), equivalent to correcting the active region at the solar edge into the center to observe; in DCP, the second-order effect of the grid, i.e. the curvature of solar spherical surface, is considered. The other is the vector field transformation (Hagyard 1987), which transforms the image-plane field components into the heliographic field components. Based on the above theories, DCP can eliminate the projection effects for both vector magnetograms and the filtergrams such as Hβ, or the white images observed with SMFT.

The theoretical methods in eliminating projection effects are not complicate; however, when they are applied to deal with an actual region, some knotty problems concerning vector magnetogram measurement are encountered. For example, whereas the line-of-sight field is measured in the line wing, the transverse field is measured near the line center (Ai & Hu 1982), so the inconsistency of relative calibration between the line-of-sight and transverse fields readily results from the invalidity of the new magnetograms transformed into the heliographic surface. Another key factor is the ambiguity of the

azimuth of the observed transverse magnetograms; although many techniques have been developed to solve this problem, no one can work with success completely even if assuming the active regions at the disk center. For off disk-center regions, most of the techniques work with a poor effect, and the fundamental models for selections of the azimuth–the potential calculations–also meet with problems (Venkatakrishnan & Gary 1989). This is because the field properties of the distorted vector magnetograms due to projection effect already cannot be described by these selection criterions. In one word, the projection effects complicate the determination of the azimuth, thus make the correction of off-center magnetograms involving with more problems which need to be considered carefully (Allen & Hagyard 1990). It is worthwhile mentioned that in the simulated annealing method (Metcalf 1994), three problems of the azimuth determination, current calculation and projection effect correction are combined together to solve; it is a greatly inspiring method to us.

3.5 Summary

A special software, DCP, designed for reduction of HSOS vector magnetograms are introduced. Using DCP, one can readily process the raw data of polarization into the calibrated magnetic field components (in Gauss) with FITS format. DCP is a convenient tool to study the field properties of an active region, such as magnetic shear, current structure and nonpotential evolution. We review the backgrounds of the problems which DCP is designed to solve, including the 180^o-ambiguity of the transverse magnetogram measurements, the vertical electric current calculations and the elimination of projection effects for off disk-center active regions. We also present some comments on the relevant methods.