Inversion of Zeeman polarization for solar magnetic field diagnostics

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HIGHLIGHTS

- We develop a new inversion code based on Zeeman effect to obtain solar magnetic maps.
- We deeply analyze the dependence of the results on the signal-to-noise ratio.
- We compare our code with the HAO MERLIN code (USA).
- Using our numerical code, we interpret Fe I line observed at IRSOL in Locarno.

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ABSTRACT

The topic of magnetic field diagnostics with the Zeeman effect is currently vividly discussed. There are some testable inversion codes available to the spectropolarimetry community and their application allowed for a better understanding of the magnetism of the solar atmosphere. In this context, we propose an inversion technique associated with a new numerical code. The inversion procedure is promising and particularly successful for interpreting the Stokes profiles in quick and sufficiently precise way. In our inversion, we fit a part of each Stokes profile around a target wavelength, and then determine the magnetic field as a function of the wavelength which is equivalent to get the magnetic field as a function of the height of line formation.

To test the performance of the new numerical code, we employed "hare and hound" approach by comparing an exact solution (called input) with the solution obtained by the code (called output). The precision of the code is also checked by comparing our results to the ones obtained with the HAO MERLIN code. The inversion code has been applied to synthetic Stokes profiles of the Na D_1 line available in the literature. We investigated the limitations in recovering the input field in case of noisy data. As an application, we applied our inversion code to the polarization profiles of the Fe I λ 6302.5 Å observed at IRSOL in Locarno.

1. Introduction

In the quiet Sun, where the magnetic field is weak, the Zeeman splitting can be smaller than the Doppler width of the spectral lines; in these conditions the Zeeman effect cannot be observed and one must use the Hanle effect technique to obtain the solar magnetic field (e.g. Stenflo, 1982; Landi Degl'Innocenti, 1983; Sahal-Bréchot et al., 1986; Trujillo Bueno et al., 2004; Derouich et al., 2006; Faurobert et al., 2009; Derouich et al., 2010). However, in the active regions where the magnetic field is sufficiently strong, the Zeeman effect produces a measurable splitting of the atomic levels and a subsequent polarization of the emitted light (e.g. Harvey et al., 1972; Jefferies et al., 1989; Socas-Navarro et al., 2000; Asensio et al., 2012).

Rigorous interpretation of the Zeeman effect on the spectral polarization can be a crucial source of information about the Sun's magnetic field. It is necessary to apply suitable theoretical and numerical methods to extract the physical information from spectropolarimetric solar observations. To this aim, from the beginning of the70s of the 20th century, vigorous theoretical and numerical efforts have been made to develop non-linear inversion codes that are able to reliably derive information about the magnetic properties of the solar plasma. The present work is a new contribution to these efforts. Our aim is to illustrate a new inversion procedure in order to search for new possibilities to determine the structure and distribution of the solar magnetic field. The inversion technique uses the equations established by Landi Degl'Innocenti and Landi Degl'Innocenti (1972), and later by Jefferies et al. (1989); Stenflo (1994).

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In this work, we focus on the accuracy of the fitting algorithms of the Stokes profiles to ensure maximum performance of the inversion technique. In fact, for the familiar Zeeman effect, the responsible physical mechanisms are typically already well understood.[1] Therefore, the advances in the inversions codes, which are based on the Zeeman effect, should be mainly concentrated on how to fit the Stokes profiles in order to deduce the magnetic field. It is the intention of this paper to find out the best fitting strategy. Careful fitting of the Stokes profiles allows to reduce significantly the error bar on the determination of the magnetic field. This work proposed useful methods to achieve a proper fit of the Q, U, V, and I-profiles.

In order to validate our numerical code, through a controlled and pragmatic strategy, we adopt "hare & hound" approach consisting of the following steps:

(1) We make use of synthetic Stokes profiles of the Na I λ 5896 Å line available in the literature (Uitenbroek, 2001, 2003, 2011; Leka et al., 2012). The magnetic maps which served to generate these Stokes profiles, with the aid of 3D NLTE radiative transfer models, are also available and are called *input*.

(2) We analyze the synthetic Stokes profiles using our inversion code, and attempt to retrieve the magnetic maps (called *output*).

(3) We compare the exact solution (input) with the solution provided by the inversion code (output).

(4) We analyze the dependence of the results on the signal-to-noise ratio. Different levels of expected noise are then simulated to evaluate their impact on the precision of our results. This allows us to determine the needed polarimetric sensitivity and estimate the error bars in the determination of the solar magnetic field.

In addition, the precision of the code is also checked by comparing our results to the ones obtained with the HAO MERLIN code. The comparison is based on the level 1 and level 2 data available online at the Community Spectro-polarimtetric Analysis Center.[2] Finally, using our numerical code we interpret Fe I λ 6302.5 Å observed at IRSOL in Locarno.

2. Inversion method

The inversion formalism is based on the equations obtained by Landi Degl'Innocenti and Landi Degl'Innocenti (1972), and later by Jefferies et al. (1989) and Stenflo (1994). According to these equations, the Stokes parameters are related in a simple way to the magnetic field vector under the weak field approximation. The domain of validity of these equations was reviewed and presented in Table 9.1 of a monograph by Landi Degl'Innocenti and Landolfi (2004). The inversion **code** allows us to deduce the magnetic field by fitting theoretical profiles to the observed ones.

2.1. Fitting of the I-profiles

We adopted, the well known Voigt line shape to fit the intensity profiles. Voigt function depends on five parameters: the continuum of the profile, the line strength, the damping parameter, the Doppler width, and the value of the line center. The fitting consists of the determination of these five parameters. Our fitting strategy is divided into three steps. The first step consists of obtaining a first guess. In this first step we use a uniform weighting to all points in the profile. Using the results of the initial analysis, as a second step, we change the weights of some points in the sense of improving the determination of the continuum intensity, the line strength and the line center. The inversion method developed in this work permits the magnetic field determination in a given target wavelength $\delta\lambda_B$. Therefore, in the third step only
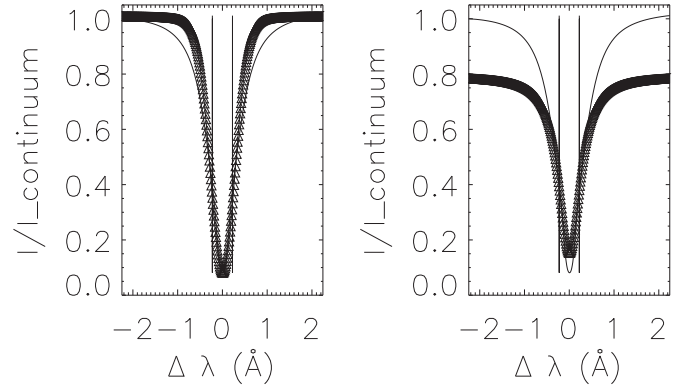
Fig. 1. A plot representing a Voigt function fit of the intensity profile of an umbra pixel. This fit is performed as follows. The open triangles ($\triangle$) represent the theoretical profile resulted from the fitting procedure. Left: the weighting is taken in a manner to improve the determination of the continuum intensity, the line strength and the line center. The vertical line represents the place of the target wavelength $\delta\lambda_B$ = 0.224520 Å. Right: the weighting is changed in a way to obtain the best Voigt-fitting around the target wavelengths where the magnetic field will be determined.

a part of the intensity profile surrounding $\delta\lambda_B$ is well fitted. With this aim, the choice of weighting is done in such a manner as to obtain the best Voigt-fitting around the target wavelengths where the magnetic field is determined. The third step permits especially the determination of the Doppler width and the Doppler damping. Fig. 1 represents an example of the fitting of an intensity profile where the second and the third steps are illustrated.

Now one uses the results of the fitting of the I-profile to obtain the Voigt function $H(a, v)$ and the Faraday–Voigt function $F(a, v)$; $H(a, v)$ is associated to the absorption coefficient which is proportional to the imaginary part of the complex refractive index and $F(a, v)$ is associated to the real part of the complex refractive index. Note that $F(a, v)$ indicates the measurable consequences of the changes of the phase velocity of the wave in the atmosphere. Here a is the Voigt parameter and $v = \delta\lambda_B/\delta\lambda_D$, where the target wavelength $\delta\lambda_B$ represents the shift in wavelengths due to the Zeeman effect of the magnetic field and $\delta\lambda_D$ is the Doppler width of the intensity profile. In addition, one can determine the values of $H'(a, v) = \frac{\partial H}{\partial v}$, $H''(a, v) = \frac{\partial^2 H}{\partial^2 v}$ and $\frac{\partial I}{\partial \lambda}$ which gives the variation of the intensity I (in arbitrary units) for a small variation $d\lambda$ (in Angström) along the I-profile. Considering that S designates the line strength, in the Voigt fitting case, one can show that,

$$\frac{\partial I}{\partial \lambda} = -2S \times [2 \quad a \quad F(a,v) - v \quad H(a,v)]/\delta\lambda_D \tag{1}$$

2.2. Fitting of the polarization profiles

Once the intensity profile is well-fitted, we fit the Stokes parameters Q, U, and V. The fitting of Stokes Q, U and V is obtained with the Singular Value DeComposition (SVDC) and Singular Value SOLve (SVSOL) routines. The SVDC expands the original data that we are trying to fit in a 4-dimensions basis. We checked other possible dimensions and we found that a 4-dimensions basis is more appropriate. After that, the SVSOL uses the results of the expansion generated by SVDC in order to fit the polarization profiles, i.e. obtaining the solution which corresponds to the minimization of the χ^2. An example of the result of the fitting of the polarization profiles is given in the Fig. 2.

It is worth noticing that the fitting of the Stokes parameters is performed after convolution of the original spectra. The convolution is typically needed to smooth the profile and to decrease the effect of the noise. Generally, one can perform the convolution with a rectangle or kernel functions, or with an instrumental profile.