Vector Magnetic Field Inversions of High Cadence SOLIS-VSM Data

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Abstract. We have processed full Stokes observations from the SOLIS VSM in the photospheric lines Fe i 630.15 nm and 630.25 nm. The data sets have high spectral and temporal resolution, moderate spatial resolution, and large polarimetric sensitivity and accuracy. We used the LILIA, an LTE code written by Socas-Navarro (2001) to invert the data. We also applied the non-potential magnetic field calculation method of Georgoulis (2005) in order to resolve the 180 degree ambiguity. The output are maps of the full magnetic field vector at the photospheric level. Here we present the first inversions of the active region NOAA 10808 during an X-class flare, which occurred on 13 September 2005.

1. Introduction

With instruments such as the ground-based SOLIS Vector-Spectromagnetograph (VSM) and the Japanese Hinode satellite producing large amounts of polarimetric data, we need to find a fast and accurate way of deriving the atmospheric parameters to study the magnetic field and its dynamics. We make use of the LTE inversion code LILIA (LTE Inversion based on the Lorien Iterative Algorithm) to create a pipeline for fast and effective analysis of Stokes profiles. This publicly available inversion code from the High Altitude Observatory derives the thermodynamic properties of the atmosphere, as well as the magnetic field strength with its corresponding inclination angle, azimuth angle and stray light factor. The code is based on the SIR inversion code (Stokes Inversion based on Response functions) introduced by Ruiz Cobo & del Toro Iniesta (1992).

2. Observations

On 13 September 2005 the active region NOAA 10808 (see Fig. 1) produced one of its strongest flares (1.5 X), starting at 19:19 UT and peaking at 19:27 UT. In the following 1.5 hours the X-ray flux, as recorded by the GOES instrument, started to rise again resulting in a second X-class flare that peaked at around 20:05 UT, with the flaring ending at around 21:00 UT. We have data from the SOLIS VSM instrument (see Keller et al. 2003, for details on the instrument) covering the period of this second flare from 19:36 UT until 20:57 UT. The SOLIS VSM provides us with the full Stokes profiles (I, Q, U, and V) of the two iron lines, Fe i 630.25 nm and Fe i 630.15 nm, with a polarization sensitivity of a few times $10^{-4}$. A high temporal sampling of approximately 5 minutes for a
Figure 1. NOAA 10808 recorded by the SOLIS VSM on 13 September 2005. The image on the left was generated from the continuum intensity of the Stokes I profiles. The active region showed a delta configuration with the two umbrae sharing a common penumbra. The right image shows the magnetogram obtained from Stokes V profiles. The black areas denote magnetic flux pointing away from the viewer and the white area is magnetic flux in the direction toward the viewer.

339 arcsec × 2176 arcsec area showing the complete active region was achieved for this data set. The spatial pixel size was 1.125 arcsec.

3. Data Analysis

Inversion codes synthesize Stokes profiles from a given initial atmospheric model and fit the observed profiles by changing the atmospheric parameters until a satisfactory fit is achieved. The LILIA code employs a Levenberg-Marquardt algorithm to minimize the merit function $\chi^2$ describing the difference between the observed and the synthesized profiles. The necessary perturbations of the atmospheric model are found with the help of response functions, which express the sensitivity of the profiles to changes in the various atmospheric parameters. The atmosphere producing the best fit is assumed to describe the real atmosphere under the assumption of (in the case of LILIA) hydrostatic equilibrium and local thermodynamic equilibrium. LILIA has the advantage over other inversion codes in employing a height-dependent model atmosphere and therefore being able to fit asymmetries in the Stokes profiles. Apart from the starting atmospheric model, the code accepts also a straylight profile, with straylight percentage as an additional fitting parameter, and the heliocentric angle. We grouped the profiles into umbra, penumbra and plage profiles. The inversion was performed using corresponding initial atmospheric models. We used the semi-empirical models derived from non-LTE inversions of high-resolution spectropolarimetric observations of four Ca and Fe lines obtained by Socas-Navarro (2007). The averaged Stokes I profile of 10 quiet sun pixels surrounding the active region was chosen as the straylight profile. We obtained in this way the temperature, electron pressure, magnetic field and its inclination and azimuth angle, microturbulent and macroturbulent velocities, line of sight velocity and straylight factor. The reduced $\chi^2$ value returned by the code gave us an idea of the quality of the obtained fit. Typical values for the reduced $\chi^2$ were in the range from 1 to 3. The results for the magnetic field strength and the inclina-
Figure 2. The magnetic field strength in Gauss (at optical depth \( \log(\tau_{500\text{nm}}) = -1 \)) retrieved by the inversion. The inverted area is 644 arcsec times 339 arcsec large. The stripes in the center of the images are due to noise in the original spectra, which was caused by a deteriorating polarization modulator.

Figure 3. The inclination angle of the magnetic field in degrees (at optical depth \( \log(\tau_{500\text{nm}}) = -1 \)). The stripes are again due to noise in the raw data.

The inclination angle at optical depth \( \log(\tau_{500\text{nm}}) = -1 \) for the time step at 20:05 UT are shown in Figs. 2 and 3. The azimuth angle derived by the inversion code is still affected by the 180 degree ambiguity. We therefore applied the non-potential magnetic field calculation method of Georgoulis (2005). This code is based on the iterative minimization of the vertical electric current \( J_z \). It requires a good proxy of \( J_z \) for the disambiguation. We used the result of the previous data set as an initial proxy for the next time step. With the knowledge of the magnetic field strength, the inclination angle and the azimuth angle, we were then able to produce vector maps such as the one shown in Fig. 4.
Figure 4. After applying the data analysis steps including the disambiguation step, we obtained this magnetic field vector map of the umbra and surrounding of NOAA 10808 at optical depth \( \log(\tau_{500\text{nm}}) = -1 \). The bright arrows represent magnetic field vectors in the direction outward of the image plane and the black arrows point into the image plane. The vector length is proportional to the magnetic field strength whereas the thickness of the arrows is determined by the stray light factor.

4. Future Work

After having inverted the data, we are now in a position to work on a detailed temporal analysis of the various atmospheric parameters (temperature, magnetic field vector, velocity, etc.) of the NOAA 10808 data set. The magnetic field information will be used as a boundary condition for magnetic field extrapolations to estimate the magnetic field topology in the upper atmosphere where the actual flare occurred. Another aim is to analyze Hinode spectropolarimeter quiet sun data with essentially the same pipeline.

Acknowledgments. This research project has been supported by a Marie Curie Early Stage Research Training Fellowship of the European Community’s Sixth Framework Program under contract number MEST-CT-2005-020395.

References