LINEAR FORCE-FREE MAGNETIC FIELD OVER AN ACTIVE REGION WITH DUE REGARD FOR CORONAL MAGNETIC FIELD

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ABSTRACT

A numerical code for the reconstruction of the linear force-free magnetic field in a bounded domain (as a rectangular box Ω) is presented here. Dirichlet boundary value problem for the Helmholtz equation is solved for B_z component specified at the Ω boundary.

Chebyshev's iteration method with the optimal rearrangement of the iteration parameters sequence was used. The solution is obtained as for the positive-definite, so for the non-sign-definite difference analogue of the differential operator $\nabla^2 u + \alpha^2 u$. Specifying two scalar functions B_x and B_y on the intersection of the lateral part of the Ω boundary with one selected plane $z = const$ and using B_z inside the Ω, we have found B_x and B_y throughout the Ω. The root-mean-square deviation of the analytic solution $\mathbf{B}$ from the calculated $\mathbf{B}'$ does not exceed 1.0%.

The routine is applied here to the AR NOAA 7216. For that the B_z component of the photospheric field was used, the available information about coronal magnetic fields being taken as a complimentary data. It is shown that the coronal magnetic field of the AR 7216 (4 July 1992 at about 00:35 UT, N12, E17) was non-linear force-free one with positive α decreasing with height. The electric current density in coronal loops decreases with height. The sense of the twisting of the coronal field (clockwise) is untypical for active regions in the northern hemisphere.

Subject headings: solar magnetic field, modelling

1. Introduction

It is well known that in the modeling of linear force-free field (LFFF) above an active region (AR) it is impossible to calculate the magnetic field uniquely using only the B_z component of the magnetic field $\mathbf{B}$ at the photosphere (Chiu and Hilton 1977). One should have some additional information. The using of the transverse field components on the photosphere is not desirable due to their non-force-freeness (Klimchuk et al. 1992). So it is very desirable to use in the modeling the *a priori* information about the coronal magnetic fields, especially when taking into account the fact that just coronal magnetic structures seems to be force-free or current-free ones.

We propose the numerical routine (Sec. 2) allowing to calculate the LFFF using *a priori* information about the coronal magnetic fields (say, potentiality of external loops of an AR). The application of the routine to the AR NOAA 7216 (Sec. 3) allowed to construct a reliable model of its coronal magnetic field.

2. Mathematical Formulation

The algorithm renders it possible to calculate the linear force-free field **B** in a bounded volume (as a rectangular box Ω with the boundary G) provided B_z are specified at G. So, for B_z we have to solve the Dirichlet boundary-value problem (DBVP) to the Helmholtz equation:

$$\nabla^2 B_z + \alpha^2 B_z = 0, \tag{1}$$

$$B_z|_G = \psi \tag{2}$$

We proposed to solve this DBVP using the Chebyshev's iteration method (Samarsky and Nikolaev 1978) with the optimal rearrangement of the iteration parameters sequence (Abramenko and Yurchishin 1996). Two kinds of the routine were devised: a) for the positive-defined operator $\tilde{A}$ – the difference analogue of the differentiation operator $Au \equiv \nabla^2 u + \alpha^2 u$ on our grid (for the case $\alpha^2 < \delta$); b) for the non-sign-defined $\tilde{A}$ (for the case $\alpha^2 > \delta$). Here δ denotes the minimum eigenvalue of the 3D Laplacian on our grid. This allowed us to calculate the LFFF not only under the restriction $\alpha^2 < \delta$, as in the most existing LFFF routines (see, e.g., the review by Sakurai (1989)), but also in the case of $\alpha^2 > \delta$, except for one requirement: $|\alpha|$ must not coincide precisely with any eigenvalue of the 3D Laplacian. So, it becomes possible to broad the Ω without the $|\alpha|$ reduce.

As soon as B_z are calculated throughout the volume of integration Ω one can calculate B_x and B_y is the same volume. For that B_x and B_y must be specified at the intersection C of the lateral sides of the Ω with the plane $z^\star = const$. The 2D modification of the same Chebyshev's iteration scheme can be used (for detail see Abramenko and Yurchishin 1996).

The code ensures a good enough accuracy of the LFFF reconstruction: in the test the root-mean-square deviation of the analytic solution from the calculated one does not exceed 1.0%.

3. Application to the AR NOAA 7216

The method was applied to the AR NOAA 7216 observed on 4 July, 1992. The vector-magnetogram of this large, strong bipolar active region was obtained with the Huairou videomagnetograph of Beijing Astronomical Observatory, China (Wang et al. 1996) in the photospheric spectral line FeI 5324.19 Å. The magnetogram was recorded at the period of best seeing conditions at 00:29 – 00:33 UT (Fig. 1). According to our H-alpha observations there were no regular large-scale vortex structures around the main spots. Soft X-ray coronal loops by YOHKOH/SXT at 00:29 UT were used here. They are shown by dotted lines on the Fig. 2. We started our coronal field modeling from the potential approach. We made sure that external X-ray loops of the AR practically coincide with the potential lines of force (Fig. 2a). This allowed us to make a reasonable assumption that at some distance (corresponding to the height of the external loops) from the main spots the field becomes potential. So, we can use this fact in the LFFF-modeling as an additional a priori information, namely: we can specify the potential field values $B_z(pot)$ as boundary conditions at the lateral and top sides of the Ω. For B_x, B_y calculations we made only one assumption: as a boundary condition, we took $B_x(pot)$ and $B_y(pot)$ at the frame C at the height $z^\star$ being equal to the height of the Ω.

Table 1: Parameters of force-free loops: maximal height above $z = 0$ plane, magnetic field strength and electric current density.

$\alpha, arcsec^{-1}$	$h,\ 10^3 km$	$B,\ Gauss$	$j,\ A \cdot km^{-2}$
0.0	100	3.5	0.0
0.001	90	5.7	0.6
0.005	40	27.0	15.0
0.007	15	150.0	115.0

We have chosen a set of positive α and run several LFFF models (negative values of α yielded unacceptable fit with observed X-ray loops). Some of them are shown in Fig. 2(b-d). One can see that the stronger the α, the more short and more low X-ray loop coincides in the best way with the LFFF model. At the every panel of the Fig. 2 the observed loop showing the best fit with the model is denoted by the open circles; their parameters are shown in the Table. The higher the loop the weaker electric current in it. Moreover, the density of electric current decreases with height more rapidly than in any linear model. These results allow to suggest that coronal magnetic field above a stable, large, strong bipolar active region seems to be force-free, but not *linear* forse-free one. This coincides qualitatively with results obtained by Klimchuk et al. (1992) and by Schmieder et al. (1996).

4. Conclusions

The new numerical code for the LFFF modeling in a bounded domain above an active region was applied here to the AR NOAA 7216. The code uses the B_z- component of the magnetic field at the photosphere as main data and the information about coronal fields as supplementary data. In the considered case of AR 7216 the potentiality of external X-ray coronal loops was used. The potential B_z substitution at the non-photospheric sides of the considered volume as boundary conditions secured a good modeling of the coronal field of the AR 7216.

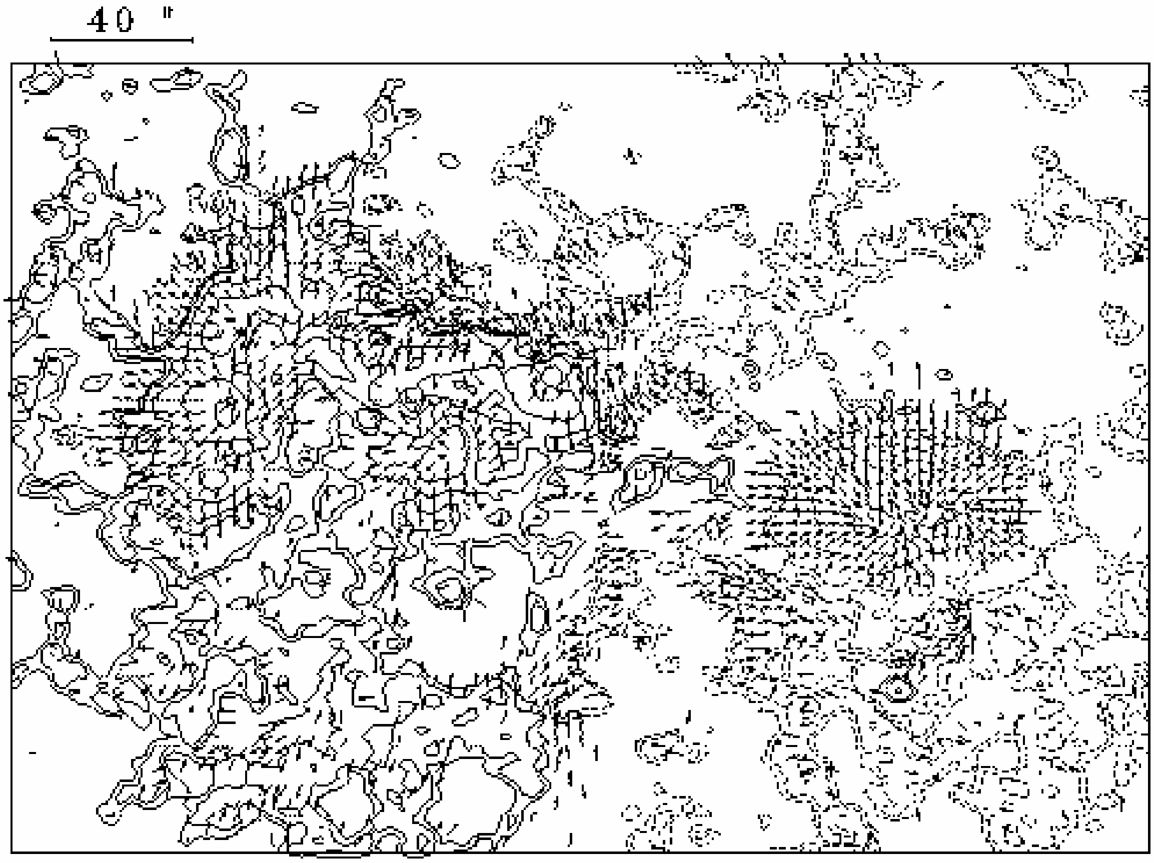

Fig. 1.— Photospheric vector magnetogram of the AR NOAA 7216 at 00:29-00:33 UT 4 July,1992 (image plane). Contour levels correspond to 100, 200, 500, 1500 G.