CORONAL MAGNETIC FIELD STRUCTURE IN SOLAR ACTIVE REGIONS

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Abstract

We analyzed the structure of the magnetic field in active regions at coronal altitudes, determined using multiwavelength observations of polarized radio emission in the microwave range at the radiotelescope RATAN-600. The observations were compared with the current-free magnetic field extrapolation of the photospheric field. It is shown that the measured magnetic field is always larger than the reconstructed field at the same height. The slopes of the tubes obtained by this method corresponds to the slopes obtained for the reconstructed field, although the degree of the slope differ significantly. The measured magnetic field structure is probably more complicated than the structure obtained by the reconstruction. Comparison of our measurements with previous measurements of radio astronomical heights at fixed frequencies showed good match.

1 Introduction

Knowledge of the coronal magnetic field plays a key role for eruptive phenomena such as coronal mass ejections, flares and eruptive prominences. Unfortunately, the direct measurement of the coronal magnetic field (see e.g. [Lin et al., 2004]) is extremely difficult by optical methods. Many authors have modeled the coronal magnetic field, using the extrapolation of the observed photospheric magnetic field mainly on the basis of the potential and force-free (linear and nonlinear) approximations (see e.g. [Wiegelmann, 2004]). However, in the case of flares and active regions these approximations do not work perfectly, because they do not contain free energy. Application of stereoscopy applied to microwave observations from RATAN-600 [Bogod and Yasnov, 2009], the VLA [Aschwanden and Bastian, 1994] and the OVRO [Aschwanden et al., 1995] give the opportunity to determine the heights of the radio sources. Numerous attempts to measure magnetic fields using radio observations at selected wavelengths should be noted [Akhmedov et al., 1982; Marsh and Hurford, 1982; Lang and Wilson, 1983; Shibasaki, 1986]. There is

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the method for the measurement of the coronal magnetic field by using MHD coronal seismology [Nakariakov et al., 2001].

This paper presents the results of stereoscopic measurements of height structure of the magnetic field in the lower solar corona, obtained at a large number of wavelengths (56) with simultaneous spectral and polarization observations by RATAN-600 in the range of 6-18 GHz with frequency resolution of about 1%. The large number of simultaneously used wavelengths enables more precise measurement of the magnetic field height structure. Possible systematic errors in height measurements are eliminated by comparing with the reconstructed magnetic fields in the region of maximum magnetic field strength, i.e. fields measured at the shortest wavelengths.

2 Method of the Magnetic Field Determination

Methods of the magnetic field structure measurment is described in details in Bogod and Yasnov [2009]. Scans of the polarized radiation give us the opportunity to single out separate structures with different magnetic field signs in the active regions. By processing the solar scans, we obtain the frequency dependence of the position of the selected part of the active region in the polarized emission from the observation date and time. The method involves rather long trigonometric calculations that take into account the peculiarities of the solar rotation and passing of the radio telescope diagram through active region. First, the theoretical value of the position the selected source part on the solar disk in the radioscan coordinate system was retrieved – $x_{theor}(h, \lambda(\phi, t_i), t_i)$. Here, h – the height of the source above the photosphere, λ —the helio longitude, ϕ – the helio latitude, t_i – the time of observation. Further, for obtaining the required values of h and λ the following expression was minimized

$$\sum_{i=1}^{n}(x_{theor}(h, \lambda(\phi, t_i), t_i) - x_{exp}(t_i))^2,$$

where $x_{exp}(t_i)$ – the position of the selected source part on a radio scan, N – the number of used data series (observation days). To reduce errors of the telescope radiator installation to a minimum value and to obtain a uniform data, we linked the height of the magnetic field maximum strength (i.e. measured at the shortest wavelengths) with the height of the reconstructed field. Since the point of maximum magnetic field is low enough in the solar atmosphere compared to the total height range of magnetic field structure, the use of a such method for eliminating the systematic error in the installation of the radio telescope radiator does not introduce significant errors in its determination. We used the method of magnetic field reconstruction proposed in Wiegelmann [2004]. This method is based on the functional minimization

$$L = \int_V w(x, y, z)\,[B^{-2}\,|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2 + |\nabla\mathbf{B}|^2]\,dxdydz \tag{1}$$

by the volume V with some weight function w. Here B is the magnetic field strength. The functional is minimized by gradient iterations method (see e.g. Landweber [1951]).

The iteration step is chosen rather small to guarantee minimization of L. The weight function w is intended to exclude the effect of the boundaries of the integration over V. In our case, the weight function of the integration region ($40 \times 40 \times 20$ points) was defined as a constant within the integration region ($30 \times 30 \times 15$ points) and linearly falling down to the boundaries of the region. As an initial approximation, we chose the linear force-free approximation, which was easily defined by the photospheric data. This linear force-free approximation was suggested, for example, in [Seehafer, 1978].

Magnetic fields were reconstructed on the basis of data obtained from the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO) mission. The magnetogram geometry was first adjusted to fit the active region position on the solar disk. We neglected the difference between the magnetic field components along the line of sight compared to the component normal to the photosphere (this assumption is acceptable for regions quite distant from the limb).

Of course, we cannot as, for example, in the EUV range to reveal the exact horizontal structure of the magnetic field. The spatial resolution of RATAN-600 at 15 GHz is 18 arcsec. We can only hope that our measurements are associated to the most powerful structure (loop), with smaller the horizontal size.

3 Calculation Results

Figures 1-3 present the results of the measurements for the AR NOAA 10933, observed in January 2007. The magnetic field strength is obtained on the assumption that the emission occurs at the third gyrofrequency harmonic. As shown by many model calculations the microwave emission is effectively generated at this harmonic (see e.g. [White, 2004]). These figures show the restored magnetic field structure, and relevant the measured magnetic field. The force line emanating from the region with maximum magnetic field strenght at the photosphere was chosen for comparison. Figures 1-3 also show that the altitudinal structure and slope of magnetic flux tubes in the period January 6-8, 2007 have changed significantly compared to the period January 2-3, 2007.

Note that the slope of the flux tube, obtained by the proposed method, corresponds to that obtained by the reconstruction, although the degree of slopes in some cases differ considerably. Our proposed method also leads to higher magnetic field strengths at the same altitude.

In the same period an other active region (NOAA 10935) was observed, the magnetic structure of which for the period of January 3-4, 2007 is shown in Figure 4: a) the dependence of the magnetic field on the height, b) the magnetic field structure. Squares - the method proposed in this paper, triangles - the reconstructed magnetic field.

We carried out similar calculations of the dependence of the magnetic field on the height for the active region NOAA 10940 observed on February 2007 at different times (during February 2-3, 2007 and during February 4-5, 2007), as presented in Figure 5. The field restoration is shown for 2, 3, 4 and 5 February 2007. Figure 6 for the region NOAA 10940 shows the magnetic field structure as well as a one-dimensional scan, obtained by the

RATAN-600. It is seen that the maximum intensity of the radio emission corresponds to the open field line emanating from the point with the strongest magnetic field at the photosphere. Figure 7 presents the results for ARs NOAA 10953 and 10963. It can be seen that the flux tube is directed upwards with some bending. In Figure 7b one can see two-dimensional projection of the flux tube with helical shape. It should be mentioned that this structure is not unique. For NOAA 10933 during January 6-7, 2007 (Figure lb) and NOAA 10935 (Figure 4b) one can also see the structure, which may reflect the helical structure in the two-dimensional plane. AR NOAA 10953 has unipolar structure at the photosphere, therefore, it is natural that the flux tube tends perpendicularly to the photosphere. However, the nature of this tendency is apparently helical.

In general, we can see some agreement between radio observations and the reconstruction. In two cases (January 7-8, 2007 for NOAA 10933 and January 3-4, 2007 for NOAA 10935), we have noticeable differences between the observation and reconstruction of the height-dependence of the magnetic field. In part this may be associated with a significant distance of regions from the central meridian and, accordingly, with possible distortions of the reconstructed magnetic field.

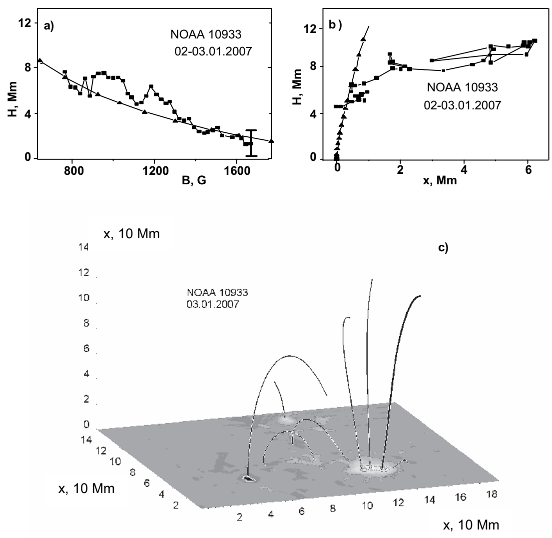

Figure 1: The calculation results for the NOAA 10933, observed during January 2-3, 2007. a) the dependence of the magnetic field on the height (squares - the method proposed in this paper, triangles - the reconstructed magnetic field), b) the magnetic field structure ; c) the three-dimensional structure of the reconstructed magnetic field on January 2, 2007. The force line from the field with a maximum magnetic field at the photosphere is in bold. The vertical segment marks the systematic error in radio measurements associated with quality of the antenna diagram installation.

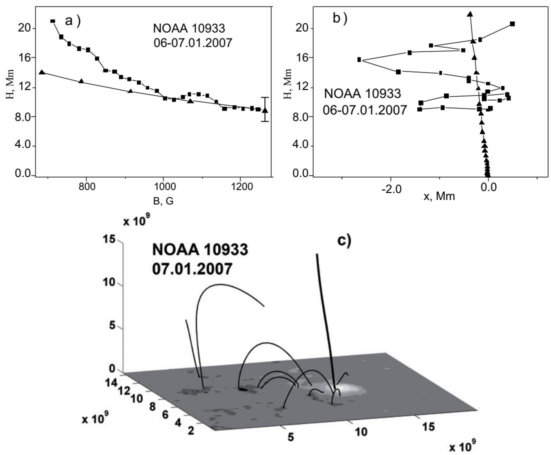

Figure 2: The calculation results for the NOAA 10933, observed on January 6-7, 2007. Notations same as in Figure 1.

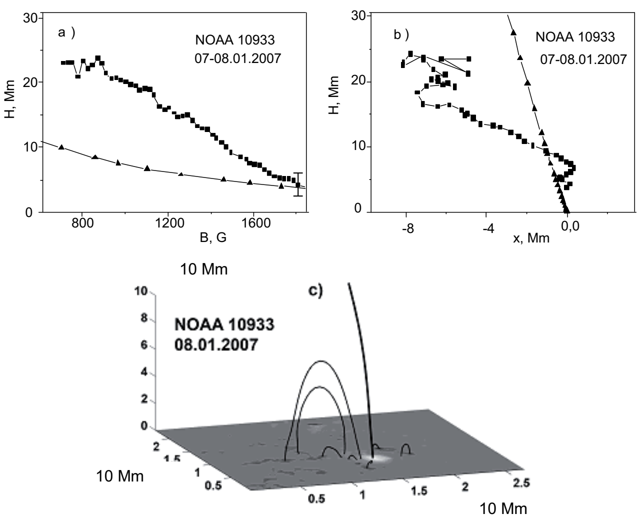

Figure 3: The calculation results for the NOAA 10933, observed on January 7-8, 2007. Notations same as in Figure 1.

4 Discussion and Conclusions

A detailed discussion on the method and results of magnetic field determination using radioastronomical data were reported in Bogod and Yasnov [2009]. It was shown that the magnetic field strength of about 1000 G is found in a suficiently high altitudes in the

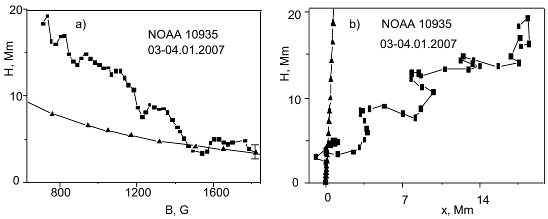

Figure 4: The calculation results for the NOAA 10935, observed on January 3-4, 2007. Notations same as in Figure 1.

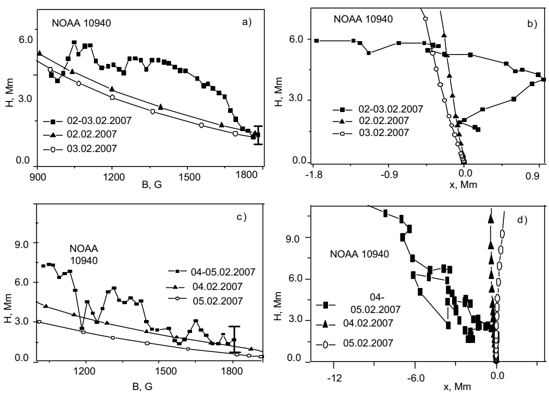

Figure 5: The calculation results for the NOAA 10940, observed on February 2-5, 2007. Notations same as in Figure 1, triangles and circles correspond to the results of the field restoration for 2-3 February 2007 (a, b) and 4-5 February 2007 (c, d).

solar atmosphere consistent with observations in ultraviolet [Klimchuk, 2000] for which the divergence of the flux tubes is small (not more than 15% in the tops of magnetic loops). The magnetic field strength corresponds well to the previously obtained radio measurements of the magnetic field in active regions using OVRO, WSRT, and VLA [Felli et al., 1981; Lang et al., 1983; Shibasaki, 1986; Aschwanden et al. 1995].

In Aschwanden et al. [1995], the heights of the sources at 10-14 GHz (which corresponds to H = 1190-1670 G) are 3-11 Mm. In our case, where a magnetic field of 1400 G occurs at heights of 5-13 Mm. Observations with the VLA [Felli et al., 1981; Lang et al., 1983] showed that a field of 600 G is located at altitudes from 20 to 35 Mm, and with the WSRT a field of 600 G is located at the height of 12 Mm. In our case, a 700 G magnetic field is at heights 12-23 Mm.

The slope of the flux tubes obtained by the proposed method, corresponds to that obtained from the reconstruction, although the degree of slopes differs significantly. The magnetic field structure can be much more complex than that obtained from the reconstruction.

The magnetic field structure obtained from radio observations differs from that obtained

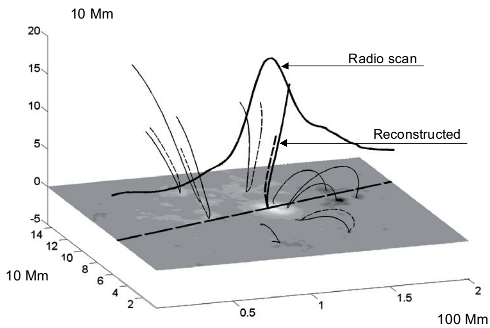

Figure 6: Comparison of the magnetic fields for the NOAA 10940 on February 3, 2007, reconstructed by the method of [Wiegelmann, 2004] (solid line) and by the method of [Seehafer, 1978] (dotted line). The structure of the magnetic field is spatially aligned with the radio-emission intensity scan obtained with the RATAN-600 (solid line); straight dotted line corresponds to the scan projection on the photosphere surface.

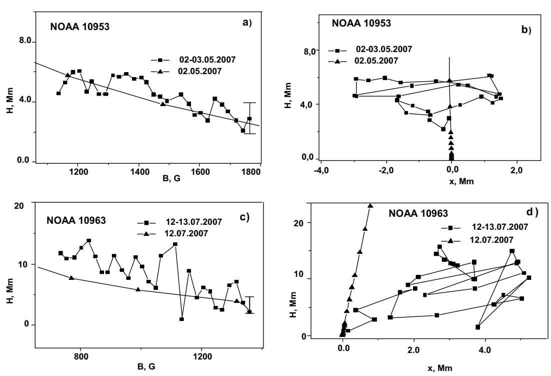

Figure 7: The results of calculations for the NOAA 10953, observed on May 02-03, 2007 and for the NOAA 10963, observed on July 12-13, 2007. Notations same as in Fig. 1

by force-free reconstruction. The proposed method leads to a higher magnetic field strength at given heights than that obtained by the reconstruction. This means that or the observed magnetic field is not force-free or there are problems in the method of reconstruction of the magnetic field. The problem is rather in the method of reconstruction of the magnetic field. For example, we used only the longitudinal component of photospheric magnetic field (due to lack of data on the transverse component), that is certainly not sufficient for exact reconstruction of the magnetic field.

Topology of the flux tube emitting microwaves may have a helical structure in some cases. The estimated helical twist seems too strong and well above Kruskal-Shafranov instability criterion [Srivastava, 2010]. Therefore, it could be unstable to kink instability.

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