# MEASUREMENTS OF MAGNETIC FIELDS IN SOLAR CORONA AS BASED ON THE RADIO OBSERVATIONS OF THE INVERSION OF POLARIZATION OF LOCAL SOURCES AT MICROWAVES

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**Abstract.** The possibility of measuring magnetic fields of solar active regions at coronal heights up to $10^{10}$ cm by observing the inversion of circular polarization of local sources at microwaves is demonstrated. The observations by the radiotelescope RATAN-600 were accomplished with the angular resolution 17″–34″ in the wavelength range 2–4 cm. It is found that the inversion of polarization occured within a core of local source situated above the largest sunspot of Mc Math 14822. The inversion was followed during the period of June 30–July 3, 1977. The measured coronal magnetic field of $\approx 16$ G is found to be at the height $\approx 12 \times 10^9$ cm. This measured field proves to agree with a simulated potential structure of Mc Math 14822 coronal magnetic field. Our analysis of the inversion has been based on the theory of interaction (coupling) of the ordinary and extraordinary wave modes in the region of quasi-transverse propagation.

## 1. Introduction

Recent radio observations of the microwave local sources (for example Gelfreikh, 1981; Schmahl *et al.*, 1982) have succeeded in an evaluation of the magnetic field strength in the regions of gyroresonance emission. To evaluate coronal magnetic field well above the regions responsible for gyroresonance emission the radio observations of polarization inversion may be explored.

The inversion of the sense of circular polarization at microwaves were recorded both in local sources (Tanaka and Kakinuma, 1960; Peterova and Akhmedov, 1974) and in radio bursts (Kakinuma, 1958; Krüger, 1976). This early radio observations were carried out with an angular resolution of some arc min. More recently the phenomenon has been described with as high an angular resolution as a few arc seconds (Kundu *et al.*, 1977; Kundu and Alissandrakis, 1984).

As a rule, the investigators of the inversion phenomenon (Tanaka and Kakinuma, 1960; Peterova and Akhmedov, 1974) treat the observational features as an effect of quasi-transverse propagation. According to Cohen (1960), Zheleznyakov and Zlotnik (1963), the ordinary and extraordinary wave modes may interact (couple) in quasi-

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transverse magnetic fields, thereby conserving the sense of circular polarization. The degree of circular polarization depends much on the local value of the strength of magnetic field in a quasi-transverse region.

Peterova and Akhmedov (1974) applied the coupling theory and the geometry of local source 'occultation' to interpret radio observations with an angular resolution $1'$–$3'$. The measured coronal field of 15–25 G was found to be at a height of about $5 \times 10^9$ cm. This is in accordance with potential field extrapolations (Peterova and Ryabov, 1981). Kundu and Alissandrakis (1984) found that the dipole model holds for interpretation of polarization inversion.

This paper continues a series of examinations of the coronal magnetic fields of the active regions using polarization inversion in local sources at microwaves (Peterova and Akhmedov, 1974; Peterova, 1977; Peterova and Ryabov, 1981). A full spectral analysis and higher angular resolution would enable field strength to be measured at various coronal heights with a more accurate localization of the measured field in the solar atmosphere. To this end we have analysed RATAN-600 data at five wavelengths between 2 and 4 cm with an angular resolution of $17''$–$34''$.

## 2. Radio Observations

The microwave local source of the active region Mc Math 14822 was observed once a day with RATAN-600 from June 30 till July 3, 1977 at the five wavelengths of 2.0, 2.3, 2.7, 3.2, and 4.0 cm. The total intensity and circular polarization (Stokes parameters I and V) were recorded. The antenna has been used in the 'south + periscope' mode (Parijskij *et al.*, 1976). The half-power beamwidths are as follows: $17\overset{''}{.}0$, $19\overset{''}{.}5$, $24\overset{''}{.}0$, $27\overset{''}{.}3$, and $34\overset{''}{.}2$ in the horizontal direction and ranged from $13\overset{'}{.}$ to $25\overset{'}{.}4$ in the vertical direction at the five wavelengths, respectively.

During the passage across the solar disc the sunspot group under consideration was of the C-, D-, and H-types (Zürich sunspot classification, *Solar Geophysical Data*, 1977). The maximum strength of the sunspot magnetic field varied between 2200 and 3600 G according to *Solnechnye Dannye Bulletin* (1977). The inversion of the sense of circular polarization is given in Figure 1. The effect of polarization inversion started on July 1 at the longest wavelength (4 cm) and thereafter occured successively at all the wavelengths down to the shortest one (2 cm) on July 3. On June 30 the degree of circular polarization of the sunspot-associated component ranged between 64 and 23% at $\lambda\lambda = 2.0$–$3.2$ cm, but it dropped to $\approx 15\%$ of opposite sign on July 3. On the intermediate day of July 2 (Figure 1(c)) approximately zero-circular polarization has been recorded at $\lambda = 2.3$ cm.

## 3. Magnetic Field Measurement

According to the coupling theory (Cohen, 1960; Zheleznyakov and Zlotnik, 1963) the conditions of the quasi-transverse propagation of microwaves are described by the

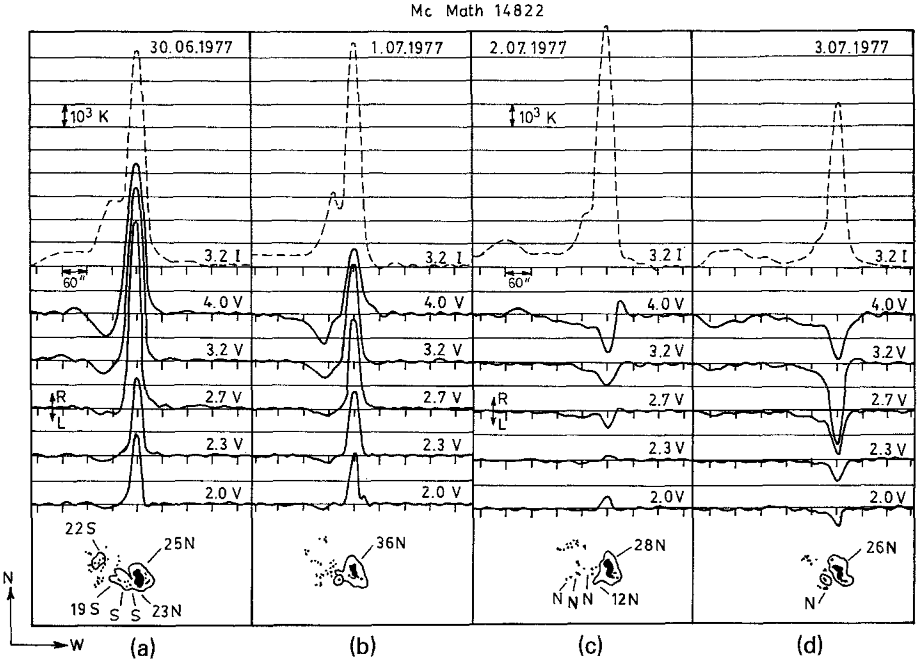


Fig. 1a–d. Radio scans of Mc Math 14822 of the total intensity I (dashed line) and circular polarization $V$ (solid line) at the five wavelengths given in cm on (a) June 30, (b) July 1, (c) July 2, and (d) July 3, 1977. The angular scale can be determined from the 60″ spacing between the fiducial marks on the axis. The polarization inversion in the main core of the local source continues from July 1 till July 3, i.e., 2–3 days after central solar meridian passage of the active region (CMP on June 29).

parameter (Zheleznyakov, 1977)

$$Q = \frac{\omega v u^{3/2}}{c\left|\frac{\mathrm{d}\alpha}{\mathrm{d}l}\right|} \approx 4.59 \times 10^{-25} N B^3 L_\alpha \lambda^4 , \tag{1}$$

in cgs units, where $v = (\omega_p/\omega)^2$; $u = (\omega_B/\omega)^2$; $\omega_B$ is the electron gyrofrequency, $\omega_p$ is the plasma frequency; $\omega$ is the frequency and $\lambda$ is the wavelength of the emission; $L_\alpha = \alpha\,|\mathrm{d}\alpha/\mathrm{d}l|^{-1}$ is the characteristic length of magnetic field divergence along the direction $l$ of the propagation, $N$ is the electron number density and $B$ is the strength of the magnetic field in the quasi-transverse region. When $Q \gg 1$, the two wave modes (the ordinary and extraordinary) are uncoupled. The sense of circular polarization reverses when the emission passes through the quasi-transverse region. When $Q \ll 1$, the sense of circular polarization is unchanged when the wave passes through the quasi-transverse region. The strength of coronal magnetic fields can be specified by a measurement of the wavelength $\lambda_t$ at which the circular polarization becomes zero. At this particular wavelength the values of $N$, $B$, and $L_\alpha$ are related by the condition $Q = 1$. Under reasonable assumptions for $N$ and $L_\alpha$ the strength of the magnetic field $B$ can be evaluated in the quasi-transverse region.

This method was applied to the western core (sunspot-associated component) of the local source on July 2. Figure 1(c) shows the inversion of the core polarization within the wavelength range from 2 to 4 cm, the lowest degree of circular polarization $\rho_c \lesssim 1.4\%$) being at $\lambda_t = 2.3$ cm. To estimate the strength $B$ of the magnetic field in the quasi-transverse region we use the relation:

$$B \approx 1.57 \times 10^8 \lambda_t^{-1} (NL_\alpha \lambda_t)^{-1/3} . \tag{2}$$

Because the values of $N$ and $L_\alpha$ vary with the 1/3 power, approximate values do not markedly affect the result. Assuming $N = 10^9$ cm$^{-3}$, $L_\alpha = 3 \times 10^{10}$ cm and neglecting variation of the $\lambda_t^{-1/3}$ term (Gelfreikh, 1981),

$$B(G) \approx 50/\lambda_t \,(\text{cm}) . \tag{3}$$

The relation (3) with $\lambda_t = 2.3$ cm yields $B = 22$ G. Note that usually the cores of a local source are compact, strongly polarized and easily resolved in the wavelength range 2–4 cm.

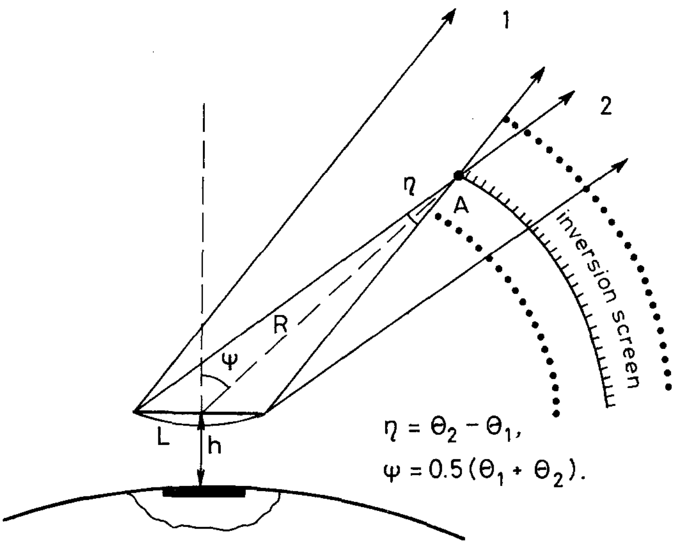


Fig. 2. Geometry of an 'occultation' of local source of the size $L$ by an inversion screen ($\alpha = 90°$, $Q \lesssim 1$) due to the solar rotation. The angular displacements of the local source from the solar disk center are equal to $\theta_1$ (at the start of 'occultation') and $\theta_2$ (at the completion of 'occultation').

From consideration of an 'occultation' of a local source by an inversion screen (Figure 2), the position of the measured field can be determined. The inversion screen is defined as an imaginary surface with $\alpha = 90°$ and $Q \gtrsim 1$. That is, the wave propagation is orthogonal to the direction of the magnetic field and the coronal magnetic field is strong enough to reverse the sense of circular polarization at $\lambda$. According to the occultation geometry shown in Figure 2, the distance $R$ between the position of the measured magnetic field and the 'occulted' core of the size $L$ can be expressed in terms of the duration of the polarization inversion (Peterova, 1975):

$$R = 0.5L[\text{ctg}(0.5\eta) + \text{tg}\,\psi]\cos\psi\,, \qquad \eta = \theta_2 - \theta_1\,, \qquad \psi = (\theta_1 + \theta_2)/2\,, \tag{4}$$

where $\theta_1$, $\theta_2$ are angular displacements from the solar disk center at two inversion moments, that is, at the start and at the completion of inversion, respectively.

The use of relation (4) demands high-angular resolution observations in order to detect the polarization inversion in a resolved core and to evaluate the size of the core. Using such observations with RATAN-600 which satisfy these requirements, we get $L = 2 \times 10^9$ cm, $\theta_1 \approx 30°$, and $\theta_2 \approx 37–44°$ from consequent recordings at $\lambda = 3.2$ cm (Figure 3). Thus we obtain $B \approx 16$ G from (3) and $R = 7–14 \times 10^9$ cm from (4), since $\theta$ is only measured once per day. Our daily radio observations do not allow a more precise determination of the confine moments of the inversion phenomenon.

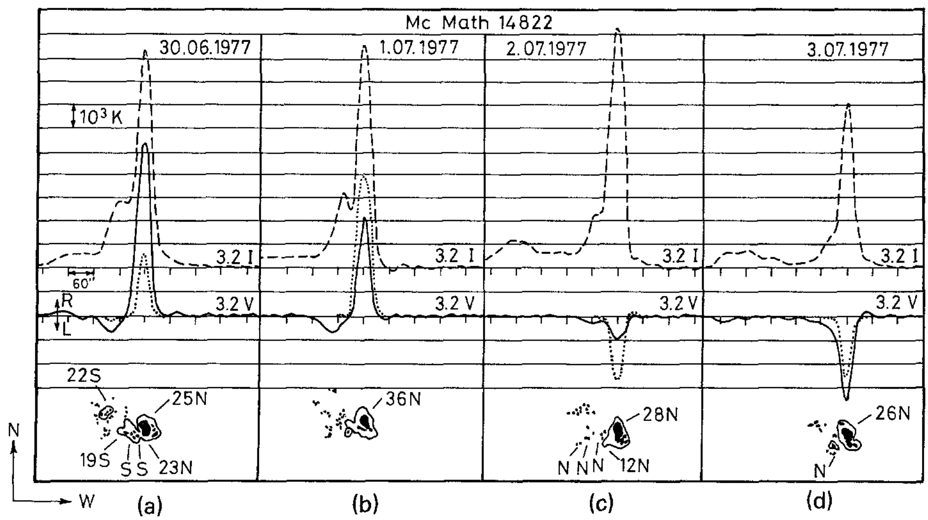


Fig. 3a–d. The polarization inversion in the main core of the local source at $\lambda = 3.2$ cm in time: (a) June 30, (b) July 1, (c) July 2, and (d) July 3, 1977, recorded with the RATAN-600 in circular polarization $V$ (solid line). The model brightness distribution of the circularly polarized emission of the local source at $\lambda = 3.2$ cm after convolution with the RATAN-600 beam pattern is represented by dotted line.

## 4. Model Computations

In this section the model POLAR 2 (Peterova and Ryabov, 1981) is employed to compute the coronal magnetic field of the active region Mc Math 14822, the gyroresonance emission of the cores of the local source, and the quasi-transverse propagation of microwaves. The circularly polarized emission of a core source is taken to be due to gyroresonance in the wavelength range 2–4 cm. The expressions relating to the optical depth are taken from Zlotnik (1968).

The dependence of the electron temperature and density on height is taken from Reimers' (1971) model of the quiet solar atmosphere. To simulate an active region atmosphere the temperature is increased by a factor of 2 and the density by a factor of 6. The maximum coronal temperature attains $2.8 \times 10^6$ K. The chromosphere-corona transition region has a width of about 200 km.

The coronal magnetic fields of an active region are composed of fields of horizontal (in regard to the photosphere) current loops (Oster, 1963; Sakurai and Uchida, 1977). The loops are submerged to the depths $d_i$ beneath the photospheric level, where $d_i$ is taken to be proportional to the diameter of the relevant sunspot or plage (Table I). This proportion is a free parameter of the POLAR 2 model. The free parameter is determined by comparing polarization distribution of the model with the observed distribution, so that the shape of the model distribution (after convolution with the RATAN-600 beam pattern) provides the best fit to the radio scan of the local source in the wavelength range of 2–4 cm.

TABLE I

Location and parameters of the model current loops for Mc Math 14822

| Date 1977 | Loop No. | Location | | Diameter ($10^9$ cm) | Depth of submergence ($10^9$ cm) | Magnetic field[a] ($10^2$ G) | Relative magnetic moment |
|---|---|---|---|---|---|---|---|
| 30 June | 1 | N14.5 | W07.8 | 1.97 | 1.97 | +25 | +0.97 |
| | 2 | N16.2 | W01.8 | 1.28 | 1.28 | −22 | −0.25 |
| | 3 | N14.2 | W04.0 | 1.23 | 1.23 | −19 | −0.20 |
| | 4 | N14.0 | W11.2 | 10 | 10 | +1 | +13 |
| | 5 | N16.0 | W04.2 | 10 | 10 | −1 | −13 |
| 1 July | 1 | N14.5 | W21.0 | 2.05 | 2.05 | +36 | +1.056 |
| | 2 | N14.0 | W24.4 | 10 | 10 | +1 | +13 |
| | 3 | N16.0 | W17.4 | 10 | 10 | −1 | −13 |
| 2 July | 1 | N14.5 | W34.2 | 2.14 | 2.14 | +28 | +1.063 |
| | 2 | N14.0 | W37.6 | 10 | 10 | +1 | +13 |
| | 3 | N16.0 | W30.6 | 10 | 10 | −1 | −13 |
| 3 July | 1 | N14.5 | W47.4 | 2.05 | 2.05 | +26 | +1.055 |
| | 2 | N14.0 | W50.8 | 10 | 10 | +1 | +13 |
| | 3 | N16.0 | W43.8 | 10 | 10 | −1 | −13 |

[a] Maximum photospheric magnetic field of a current loop.

If the coronal plasma is rarefied and isotropic enough (see Zheleznyakov *et al.*, 1979 for details), a linear interaction (coupling) of the ordinary and extraordinary wave modes occurs in a quasi-transverse region. The amplitudes of the wave modes in front of the quasi-transverse region are connected with those behind the region by the equations given by Zheleznyakov and Zlotnik (1963). This provides additional opportunities to evaluate $Q$ (thus providing field strength $B$) when circular polarization is partly reduced in the quasi-transverse region. Two-dimensional distributions of the circularly polarized emission have been computed for this case. As RATAN-600 produces one-dimensional radio scans, the computed two-dimensional brightness distributions were converted into one-dimensional distributions by convolution equation (Figure 3).

Our comparisons indicate that plage magnetic fields contribute significantly to the overall coronal magnetic structure of the active region. In some cases (Peterova and Ryabov, 1981) no qualitative agreement had been achieved without taking the plage into account. The height dependence of the coronal magnetic field of the active region Mc Math 14822 according to the model POLAR 2 is depicted in Figure 4, where the error is estimated to be less than 20% provided $Q \approx 1$. The error is mainly due to the uncertainty in the accepted model of the active region atmosphere (especially of the electron density).

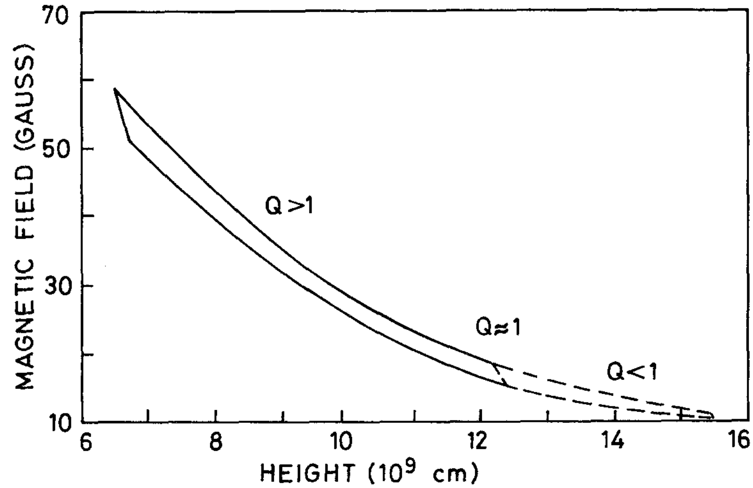


Fig. 4. Height dependence of the Mc Math 14822 coronal magnetic field. The strength of the field is measured by the effect of the polarization inversion on the base of the observations with the radiotelescope RATAN-600 and computations with the POLAR 2 model (error of the measurement 20% at the level of $Q \approx 1$).

## 5. Discussion and Conclusion

In Section 3 we found $B \approx 16$ G at the distance $R = 7\text{–}14 \times 10^9$ cm from radio source, the values being in accordance with the potential approximation of the active region coronal magnetic field (Section 4). The conception of the inversion screen 'occulting' the local source during the solar rotation enabled the determination of $R$.

Calculations indicate that as a rule the inversion screen has a sharp upper border ($\alpha = 90°$, $Q \approx 1$). The sharpness of the upper border of the screen implies narrowness of the region with weak circular polarization in the source (the region of $\rho_c \lesssim 1\%$ being narrower than $\sim 10^8$ cm at $\lambda\lambda = 2$–$4$ cm; cf. Bandiera, 1982). The lower border of the inversion screen is identical with the neutral line of the photospheric longitudinal component $B_l$. On both sides of the inversion screen there are quasi-transverse regions extending to distances of $2\pi^{-1} L_\alpha \sqrt{u} \sim 10^8$ cm (Kravtsov and Naida, 1976). If no new magnetic fluxes appear in an active region the shape of the inversion screen will be modified only due to solar rotation.

The results of this paper support our conception of the inversion phenomenon in spite of the failure to obtain a complete quantitative coincidence of the polarization brightness distribution of the model with the observed one. The above discrepancy may result, firstly, from the simplifications of the solar atmosphere and the coronal magnetic field model and, secondly, from the elimination of bremsstrahlung absorption.

An important result is the conclusion that the potential (current-free magnetic field) is a good approximation of the coronal field of the active region at heights $\sim 10^9$–$10^{10}$ cm (where $Q \approx 1$ for microwaves). The minimum scale length of the coronal field accessible to the analysis is determined by the angular resolution of the radiotelescope (being of the order $10^9$ cm in the case of RATAN-600). For the above heights and scales no deviations from the current-free magnetic field have been found in the Mc Math 14822 coronal magnetic structure. Some of the published data (Lang, 1974; Kundu *et al.*, 1982) appear to imply non current-free fields on a limited scale $\lesssim 5 \times 10^8$ cm. These have been acquired by radio observations of flaring active regions with high-angular resolution.

A remarkably large contribution of the magnetic flux from the plage to the coronal magnetic structure of the active region at heights of some $10^9$ cm is another result of general interest. This result confirms similar finding of Peterova and Ryabov (1981).

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