

RADIO MEASUREMENTS OF CORONAL MAGNETIC FIELDS IN FAN-SPINE CONFIGURATIONS ON THE SUN

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Recent interest of solar physicists in the analysis of the coronal mass ejections and circular solar flares in fan-spine magnetic configurations (FSCs) necessitates measurements of the corresponding coronal magnetic fields. A dominant sunspot with the circumjacent magnetic flux of opposite polarity produces a specific coronal region of the quasi-transverse (QT-) propagation of microwaves. We make use of the theory of QT-propagation to evaluate the strengths of coronal magnetic fields in the active regions NOAA 11579, 12242, and 12488 while they are non-flaring. Microwave polarization changes were observed with the RATAN-600 radio telescope, the Siberian Solar Radio Telescope, and the Nobeyama Radioheliograph. Changes in the sign of circular radio polarization provide the strengths of coronal fields in a QT-region if the coronal plasma density N_e and the length scale of magnetic field divergence L_d are known. We evaluate the length scale by means of the potential-field source-surface (PFSS) model and the coronal density from the Gaussian inversion of the differential emission measure (from the Solar Dynamics Observatory observational data), obtaining $N_e L_d = (0.46\text{--}0.64) \times 10^{10} \text{ m}^{-2}$. The resulting coronal fields of $1.4 \times 10^{-3} \text{ T}$ and $2.34 \times 10^{-3} \text{ T}$ are attributed to the heights of 100 Mm and 50.2 Mm. We discuss the validity and consistency of the involved values to draw conclusions on the feasibility of coronal radio magnetography of FSCs.

Keywords: *Solar magnetic field, solar microwave observations, Sun, sunspot.*

1. INTRODUCTION

Coronal magnetic fields are involved in practically all phenomena of solar activity and in shaping the structure of solar corona. Since those magnetographic measurements that employ the Zeeman effect on ion line emission are difficult to apply to faint coronal lines, radio polarization observations are preferred [1]. The detection of polarization changes due to the crossing of magnetic field lines by microwaves at an exactly or a nearly right angle (i.e., quasi-transverse, QT) can supply precise and well-localized radio measurement in the range from a few to one hundred gauss. Such measurements of coronal field in solar active regions (ARs) make use of the theoretical Eq. (1) and employ studies of observed changes of circular polarization due to QT-propagation of microwaves [2].

Here we present the radio measurements of coronal field in three cases of fan-spine magnetic field configurations (FSCs) and the preparatory work for future diagnostics of the QT-propagation of microwaves in the FSCs. In contrast to the elongated in latitude bipolar ARs, the FSCs investigated here represent a dominant sunspot with circumjacent magnetic flux of opposite polarity. The magnetic field structure of such an FSC is characterised by a magnetic null point, a spine line, and a dome-shaped fan surface that is also a separatrix surface [3]. Accordingly, there are two systems of field lines (Figs. 1d, 2e, and 3c): the lower-lying field lines surrounding the inner spine line and the overlying field lines surrounding the outer spine line.

When such ARs are close to the central solar meridian, the region of QT-propagation (QT-region) is dome-shaped for the lower-lying system, while not coincident with the fan dome. This shape determines the time evolution with solar axis rotation of polarization inversion in FSCs.

FSCs are regarded as locations of possible flaring activity and thus are important targets of investigations. Yet some essential characteristics of the coronal magnetic field structure such as field strength, gradients, scales of magnetic divergence, which are key values for energy estimates and modelling, are not measured; hence, coronal radio magnetography is of great potential value.

Since the magnetic fields of FSCs are believed to remain potential fields outside the periods of flaring activity [4], we use the potential-field source-surface model (PFSS) with the HMI synoptic maps of the radial component B_r as the boundary conditions. With the goal to reveal and analyse the non-potential components of the magnetic structure, some authors [5]–[9] have already investigated the sampled FSCs. In contrast, our work concerns the robust potential magnetic structure, which shows modifications of the QT-region in the course of solar axis rotation in accordance with the variations of the propagation angle. A stable potential configuration then reveals polarization changes that are expected in quiet time intervals and thus measured coronal fields are the undisturbed values useful for comparative analyses with the perturbed magnetic field values during the time of flaring.

A general application of Eq. (1) for coronal magnetography requires the knowledge of the degree of circular polarization for the emitted radiation ρ_θ before crossing the QT-region. However, for an FSC a given emission source may remain covered by the dome-shaped QT-region during the whole observation period of several days, thus making the measurement of ρ_θ impossible. The use of zero-polarization observations avoids this complication. Here we present the coronal locations in the QT-regions where radio

polarization turns to zero and thus makes the radio measurements indifferent to the initial microwave polarization.

In this work we use the imaging and the spectral-polarization radio observations of FSCs to perform radio measurements of coronal fields. In particular, we analyse radio scans in Stokes V at a set of observational frequencies taken with the RATAN-600 radio telescope (angular resolution $\Theta = 20''$ at 12.9 GHz [10]) to diagnose the

strong dependence of polarization changes on observing frequency. Imaging polarization observations with the Nobeyama Radio-heliograph (NoRH; angular resolution $\Theta = 15''$ at 17 GHz [11]) and the Siberian Solar Radio Telescope (SSRT; angular resolution $\Theta = 20''$ at 5.7 GHz [12]) are used to localize the radio measurements in the plane of view. Finally, we note the characteristic features of polarization changes and discuss the results of radio measurements.

2. RADIO MEASUREMENTS OF THE MAGNETIC FIELD

Our radio measurements of coronal magnetic fields are based on the effects of QT-propagation determined by Eq. 1. Let ρ_0 be the degree of the circular polarization of emitted radio waves before crossing

a QT-region, where the propagation angle $\alpha = 90^\circ$. The authors [13] gave the following degree of the circular polarization ρ after crossing the QT-region:

$$\rho = \rho_0 \cdot (2 \cdot \exp(-1.15 \times 10^3 B^3 N_e L_d \lambda^4) - 1), \quad (1)$$

where B is the strength of coronal magnetic field, N_e is the electron density, L_d is the scale of coronal field divergence along the wave path, and λ is the known observing wavelength at the corresponding frequency $F = c/\lambda$.

To evaluate both B and the product $N_e L_d$ directly from radio observations one needs a detection of the full Stokes vector of radio intensities with high angular and frequency resolution [14]. There authors deduced $B = (1.28-1.12) \times 10^{-3}$ T and $N_e L_d = (1.4-2.1) \times 10^{10} \text{ m}^{-2}$ from the radio observations made by [15].

Otherwise, the most sensitive radio measurements of coronal field correspond to the detection of nearly zero circular polarization. For the case of $\rho = 0$, one can immediately evaluate B , given the product $N_e L_d$. At the observing frequencies of 17 GHz (NoRH) and 5.7 GHz (SSRT) the corresponding fields of about 8.4×10^{-3} T and 2×10^{-3} T are measurable, assuming $N_e L_d = 10^{10} \text{ m}^{-2}$.

When attempting coronal radio mag-

netography of FSCs in the $\rho \neq 0$ cases, a common difficulty is the unknown initial polarization ρ_0 , since the observed microwave source might be affected by QT-propagation during the whole observation period. That is why we do not construct 3D coronal magnetograms but evaluate the coronal field only in some locations within the QT-regions.

Regarding the unknown product $N_e L_d$, it should be noted that in some FSCs plasma density varies by two orders of magnitude during a coronal rain [8]. Similarly, the scale of the magnetic field divergence L_d is expected to be a few orders of magnitude smaller near null points. For the time intervals of no flaring in FSCs, we adopt the maps of the differential emission measure (DEM) of the Solar Dynamics Observatory

(SDO) AIA observational data in the Integrated Data & Operation Center (IDOC) database and estimate N_e in the region of radio measurements with the assumed hydrostatic scale length of $Z_H = 47$ Mm [16]. The column emission measure EM is used as a rough estimate of electron density, $N_e = (EM/Z_H)^{0.5}$. The scale length L_d of the magnetic field divergence is estimated with the help of the PFSS model (Table 1).

2.1. AR 12488 on 26 January 2016: A Single Polarization Inversion

The authors of [8], [9] confirmed null point topology of AR 12488 magnetosphere (at the height of $H_{NP} \approx 112$ Mm) during the next solar rotations of the AR. A long-last-

ing coronal rain along the spine line (for 59 hours on March 13) and an immediate reappearance of the filament after its eruption on 27 February were analysed.

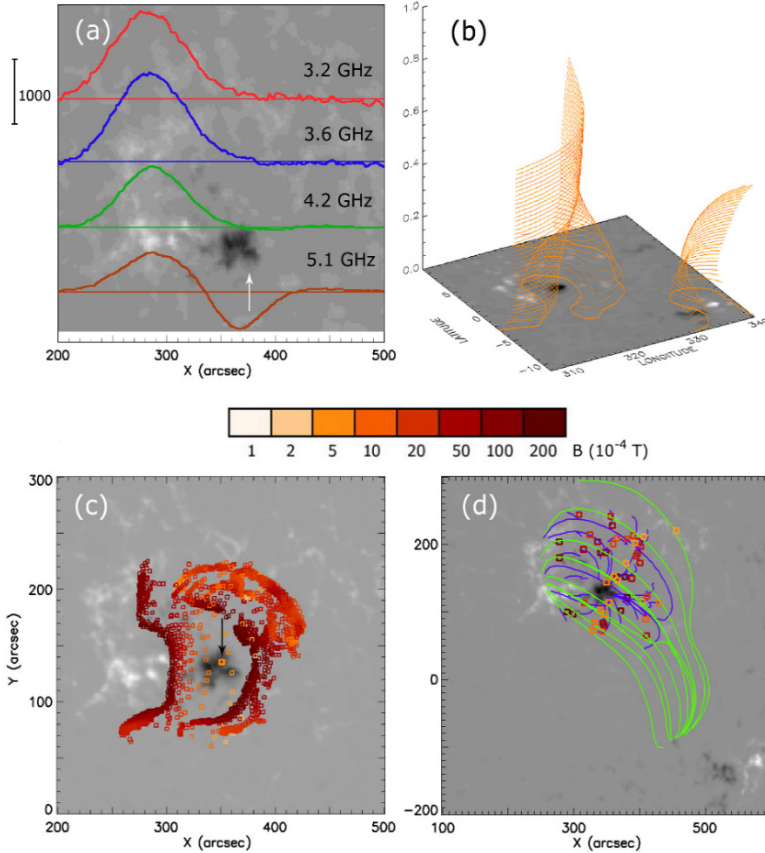


Fig. 1. (a) The RATAN-600 1D radio scans in circular polarization at four frequencies. (b) 3D surfaces of QT-propagation. (c) Colour-coded coronal field strengths at some crossings of the QT-region. (d) Field lines of the FSC surrounding the inner spine line (blue colour) and the outer spine line (green colour).

On 26 January 2016, the sign of circular polarization above the dominant sunspot of negative magnetic polarity inverted at frequencies shorter than 3.6 GHz. During the next two days the inversion extended to frequencies $F < 7.3$ GHz and $F < 10$ GHz, respectively. Earlier, near the eastern solar limb, the RATAN-600 scans showed polarization inversions of the microwave sources of positive magnetic polarity closest to the limb. These characteristics of polarization inversions in microwave are typical for the extended in latitude bipolar ARs [2]. It seems that like the QT-region of this FSC is a tall dome-like surface that at larger heights mimics the QT-region of a typical bipolar AR.

Figure 1 demonstrates the correspondence between the microwave polarization inversion at 3.6 GHz (Fig. 1a) and the coronal field at the site of the modelled

region of QT-propagation (Fig. 1c). With $N_e L_d = 4.6 \times 10^9 \text{ m}^{-2}$ (Table 1), the observing wavelength $\lambda = 8.32 \times 10^{-2} \text{ m}$ ($F = 3.6$ GHz), and observed depolarization $\rho = 0$ (vertical marked with the white arrow) one gets by means of Eq. 1 the coronal field $B = 1.4 \times 10^{-3} \text{ T}$. The height of the QT-crossing in the PFSS model is $H = 100 \text{ Mm}$ (this site is marked with the black arrow). This coronal site is located in the outer field line system of the FSC overlying the sunspot-associated microwave source on 26 January 2016. We focus only on a short segment inside the line of depolarization bearing in mind that the knife-like diagram of the RATAN-600 is 70.8 angular second wide at 3.6 GHz. Nevertheless, it is enough to evaluate the possibility of employing radio observations to estimate the coronal magnetic fields in FSCs through the QT-propagation of microwaves.

2.2. AR 11579 on 3 October 2012: Stripes of Inverted Polarization

The authors in [5] analysed the non-potential components of the magnetic structure near the dominant sunspot of AR 11579. The authors revealed the links between the magnetic flux cancellation and the formation of UV bursts on 30 September 2012.

On 1 and 3 October 2012 the SSRT maps of circular polarization at 5.7 GHz started to show the development of stripes of opposite polarity (Figs. 2a and 2b). On 5 October 2012 (not shown), the sign of polarization at 5.7 GHz inverted completely for the sunspot-associated microwave source despite the lack of any considerable changes in the photospheric magnetic field. Such an inversion with the sunspot approaching the solar limb is a clear indication of the effect of QT-propagation of microwaves, while the stripes of the inverted polarity is an unexpected feature. In the case of a bipolar AR elongated in latitude, the QT-region is expected to be a surface with a monotone

decrease of magnetic field intensity with height while the original unaffected distribution of circular polarization ρ_0 above a sunspot-associated microwave source would be of a horseshoe shape [18].

We attribute appearance of these stripes in polarization to a fragmentation in the circumjacent sources of opposite magnetic polarity. Figure 2d shows a field line representing one of the fragmentations in the magnetic structure owing to the fragmented sources of circumjacent opposite magnetic polarity. The black arrow points to the coronal site where microwaves cross this field line transversally at $B = 2.34 \times 10^{-3} \text{ T}$ (Table 1). The form and size of QT crossings vary during the course of the solar rotation. For an equidistant grid of the starting points in the PFSS model the representative crossings of the QT-region form rings in the volume of the lower-lying field lines and stripes in over-lying field lines (Figs. 2c, 2d).

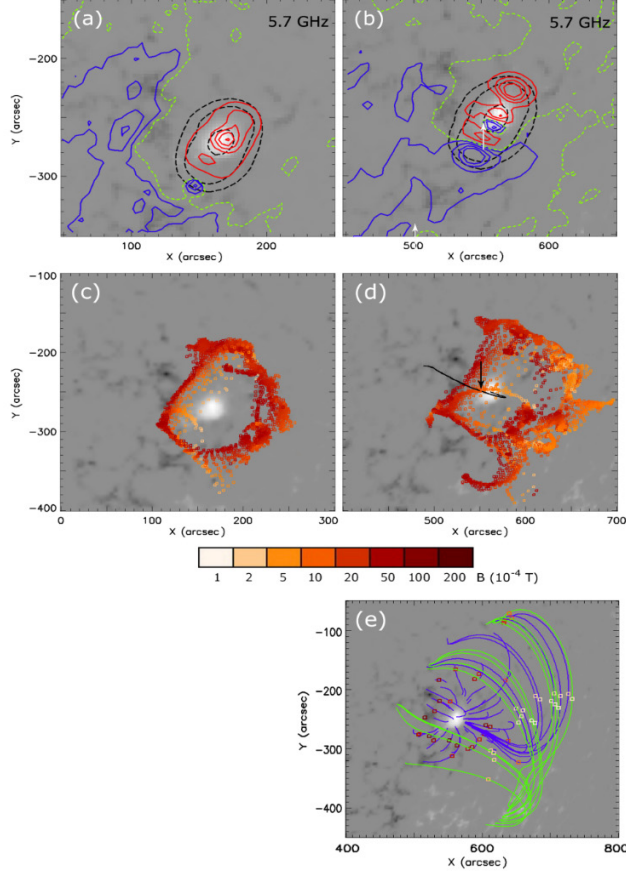


Fig. 2. (a) The SSRT radio map in total intensity (black dashed contours) and circular polarization (red and blue contours) on 1 October and (b) on 3 October 2012. (c) Color-coded coronal field strengths at selected crossings of the QT-region on 1 October and (d) on 3 October 2012. (e) Field lines of the FSC surrounding the inner spine line (blue colour) and the outer spine line (green colour).

With $N_e L_d = 6.4 \times 10^9 \text{ m}^{-2}$ (Table 1), the observing wavelength $\lambda = 5.2 \times 10^{-2} \text{ m}$ ($F = 5.7 \text{ GHz}$), and the observed depolarization $\rho = 0$ (site marked with the white arrow) one gets by means of Eq. 1 coronal field $B = 2.34 \times 10^{-3} \text{ T}$. The height of the QT-crossing in the PFSS model is $H = 50.2 \text{ Mm}$

(the site is marked with the black arrow). Again, the model location of the depolarized 5.7 GHz emission does not precisely correspond to the observed one but is sufficient to evaluate the possibility of using the radio observations for measurements of the coronal fields of FSCs.

2.3. AR 12242 on 18 December 2014: A Double Polarization Inversion

In [4], [6], and [7] the non-potential components of the magnetic structure near the dominant sunspot of AR 12242 on 17 December 2014 were analysed. The findings of [4] were as follows: (a) the potential field extrapolation reproduced a fan-spine

topology at the time of no flaring and (b) the circular ribbon flare was caused by the unstable outer loops, which conveyed the spine field line. In [6] the authors studied the circular ribbon flare using NoRH radio observations and found that radio polar-

ization sign reversed in the central region of the positive magnetic polarity, which implied a magnetic breakout-type eruption in the FSC. The authors of [7] concluded from non-linear force-free field extrapolations that the magnetic null pointed at the height of about 36 Mm did not project itself

on any part of the sunspot on 17 December. The EUV remote brightening confirmed the closed outer spine line as inferred from the magnetic field extrapolation. The evolving flux rope started eruptive expansion when it reached the height of ≈ 30 Mm.

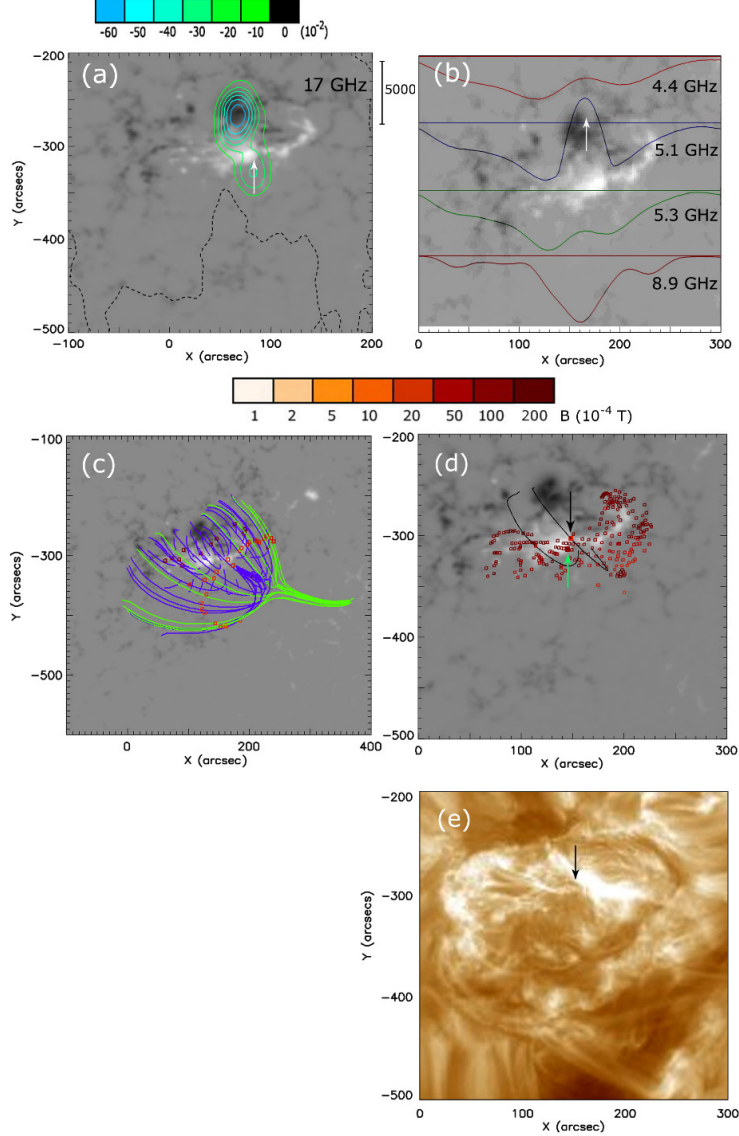


Fig. 3. (a) The NoRH radio map in the degree of circular polarization. (b) The RATAN-600 1D radio scans in circular polarization at four frequencies. (c) Field lines of the FSC surrounding the inner spine line (blue colour) and the outer spine line (green colour). (d) Color-coded coronal field strengths at representative crossings of the QT-region (the green arrow points to radio measurements at $H = 3.45 \times 10^7$ m; the black arrow points to radio measurements at $H = 6.6 \times 10^7$ m). (e) The SDO/AIA EUV image in the emission lines of Fe XII, XXIV (the black arrow points to the hot coronal loops).

In this AR, a total of three cases of polarization inversion is observed. First, the southern sunspot of positive magnetic polarity (white colour in Fig. 3) displays reversed from expected sign of circular polarization at 17 GHz at all times during its passage across the solar disc due to solar axis rotation. Such behaviour is different from that observed with elongated in latitude bipolar ARs. As seen in Fig. 3c, the sunspot is enclosed by the low-lying field lines of the FSC and the resulting QT-surface. It remains the case during the whole passage and, as a result, we do not know the initial polarisation p_0 for the radiation emitted from this region. The depolarization line at 17 GHz (dashed line in Fig. 3a) is located at a distance from these microwave sources and is not affected by the QT-propagation of 17 GHz emission. Nevertheless, we calculated the minimal strength of coronal field in the QT-region as the prerequisite for the sign inversion of circular polarization at 17 GHz, $B > 37.2 \times 10^{-4}$ T (green arrow in Fig. 3d) assuming zero polarization for a sunspot of positive magnetic polarity at this site.

Second, polarization inversion above the sunspot of positive magnetic polarity is the inversion recorded by RATAN-600 at about 5.2 GHz (Fig. 3b). According to PFSS modelling and coronal density estimate, the coronal field at the second cross-

ing of the QT-region (black arrow in Fig. 3d) equals 19.9×10^{-4} T at $H = 6.6 \times 10^7$ m.

Third, it can be seen at 4.4 GHz that the polarization assumes the initial sign of circular polarization, which implies an additional inversion. However, we find no model crossings of QT-region corresponding to the observed change of the sign of circular polarization between 5.1 GHz and 4.4 GHz (see the vertical along the white arrow in Fig. 3b).

We suppose that a different mechanism not due to QT-propagation is responsible for the rapid with frequency polarization changes at the short frequencies below 5.1 GHz. It might be due to propagation of microwaves through the hot plasma with negative gradient along the wave path. The above polarization inversion measurements are from a location (black arrow in Fig. 3d) where a flux rope of hot plasma erupted during the impulsive phase of a flare on 17 December 2014 at 04:18 UT [7]. On 18 December 2014 10:05 UT, the central temperature of DEM parametrization, which gives an indication of mean plasma temperature along the line of sight, 7.4×10^6 K, is still high (black arrow in Fig. 3e). As proposed by [19], some hot coronal loops can produce multiple polarization inversions in relatively narrow frequency bands due to negative gradient of plasma temperature along the wave path.

3. RESULTS AND DISCUSSION

We present radio measurements of coronal magnetic field at the sites where the sign of the observed circular polarization changed due to the QT-propagation of microwaves. Given the plasma density N_e (evaluated from the DEM in six EUV bands) and the scale of field divergence L_d (calculated by means of the PFSS model)

we find that the measured strengths of the coronal magnetic fields lie in the range $(1.4\text{--}2.34) \times 10^{-3}$ T. The heights of the locations where the coronal fields are measured, were calculated with the PFSS model and were found to be in the range of 100–50.2 Mm.

Table 1. Overview of the Three Analysed Fan-Spine Magnetic Configurations

Time	AR number	Telescope	F , GHz	Ne , 10^3 m^{-3}	B , 10^{-4} T	Ld , 10^7 m	H , 10^7 m
				Parameters from observations		Parameters from the PFSS model	
2016 Jan 26 09:43 UT	12488	RATAN-600	3.6	1.41	14	0.325	10
2012 Oct 3 05:00 UT	11579	SSRT	5.7	1.74	23.4	0.37	5.02
2014 Dec 18 03:00 UT	12242	NoRH	17	2.6	> 37.2	4.71	3.45

- This work is the first attempt to measure coronal magnetic fields in FSCs using the sites of depolarisation at microwave frequencies in the QT-regions. We have investigated QT-propagation of microwaves only at several locations where the product $NeLd$ varies in the range of $(0.46\text{--}0.64)\times 10^{10} \text{ m}^{-2}$ and have avoided the assumption of constant $NeLd$ as practiced for the elongated in latitude bipolar ARs by specifying the parameters for each FSC.
- The measured coronal fields are consistent with the parameters Ne and Ld in the sense that these independently evaluated parameters provide reasonable values of the measured coronal field B (cf. [20]).

We try to avoid the post-eruptive structures for the validity of the above parameters for the potential magnetic structures.

- We regard two systems of field lines in FSCs: the lower-lying field lines underneath the fan surface dome and the overlying field lines. An additional third system is formed by the large overlying loops [21]. Each system produces a specific shape and height of the QT-region and some distinct features of polarization changes in the microwave wavelength range for the first two systems and at decametric wavelengths (not analysed here) for the large overlying loops.

4. CONCLUSIONS

The results of the three case studies do not permit us to arrive at an explicit formulation of diagnostics of QT-propagation in FSCs. There is a set of various polarization and time evolution features, which are different from those of the elongated in latitude bipolar ARs [2]. In particular, we observe the stripes of inverted polarization (the case of AR 11579) and polarization inversion of

a sunspot-associated source persistent with solar rotation (the case of AR 12242). The main conclusion we draw is the confirmation of the possibility to augment radio measurements with PFSS modelling for FSCs in quiet non-flaring state. A broader range of samples is required to formulate the general diagnostics for the recognition of the QT-propagation in FSCs.

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