High-frequency very long baseline interferometry rotation measure of eight active galactic nuclei

J. C. Algaba*

Academia Sinica, Institute of Astronomy and Astrophysics, PO Box 23-141, Taipei 10617, Taiwan, R.O.C.

ABSTRACT
We have studied very long baseline array (VLBA) polarimetric observations of eight sources, including quasars and BL Lacertae objects, at 12, 15, 22, 24 and 43 GHz. We present high-frequency rotation-measure maps. We find typical values for the rotation measure in the very long baseline interferometry core of several thousand rad m$^{-2}$. These values are higher than the values given in the literature at lower frequencies. Assuming a dependence of the form $RM \propto \nu^a$, where $RM$ is the rotation measure, we obtain an average value of $a = 3.6 \pm 1.3$, which is larger than that expected using theoretical considerations. Rotation measures are detected in the jets of only two sources, and we find that only 0906+430 (and possibly 1633+382) show indications of a robust gradient. We discuss the Faraday-corrected polarization properties of the sources. Our interpretation supports the presence of helical magnetic fields with new, unresolved, components affecting the intrinsic direction of polarization close to the base of the jet of some objects.

Key words: polarization – galaxies: active – radio continuum: galaxies.

1 INTRODUCTION
The emission associated with jets in active galactic nuclei (AGNs) is a result of synchrotron radiation over a wide range of the electromagnetic spectrum, including radio frequencies. The emission is generally highly linearly polarized, more than 50 per cent in some optically thin jet regions (e.g. Lister & Homan 2005), indicating the presence of highly ordered magnetic fields. In several cases, it has been found that this polarization is perpendicular to the direction of the jet (Gabuzda, Pushkarev & Cawthorne 2000, and references therein) or has a spine/sheath structure (Attridge, Roberts & Wardle 1999; Pushkarev et al. 2005); see also numerous examples in the MOJAVE data base (Lister & Homan 2005).

Although this can be interpreted as a series of shocks in the jet, which enhance the perpendicular component of the magnetic field, and/or the interaction of the jet with the surrounding media (Laing 1980), the presence of polarization – either parallel or perpendicular to the jet – can also be easily explained with a helical magnetic field. There is evidence that helical magnetic fields seem to be present in, at least, a fraction of AGNs. Gabuzda (2006) has summarized different observational polarization tests in order to distinguish between helical magnetic fields and alternative explanations, and has concluded that there are a number of sources for which there is reasonable evidence of helical jet magnetic fields.

One way to study the structure of the intrinsic magnetic field is to analyse the rotation-measure distribution across the source. The polarization angle $\chi$ rotates following the relation $\chi = \chi_0 + RM \lambda^2$. Here, $\chi_0$ is the intrinsic polarization angle, $\lambda$ is the wavelength and $RM$ is the rotation measure, given by

$$RM \propto \int n_e B \, dl.$$  \hfill (1)

Here, $n_e$ is the electron density and $B \, dl$ is the magnetic field along the line of sight.

The first implication is that the intrinsic polarization (and hence the inferred direction of the magnetic field giving rise to it) will be altered by the effects of the Faraday rotation. Because the rotation measure depends on the component parallel to the line of sight of the magnetic field, in general, we have a variable alteration of the polarization direction across the source. Thus, if we want to properly understand the intrinsic properties of the magnetic field, we need to map the rotation measure across the source in order to adequately subtract its effects in the different regions.

If we have a helical magnetic field, its toroidal component will produce a rotation-measure change across the jet, giving rise to a gradient (Blandford 1993). In the simplest case, with the jet perpendicular to the line of sight in the observer’s rest frame, we would observe an antisymmetric distribution of the rotation measure, with positive values on one side of the jet, negative values on the other and a null rotation measure in the centre. As the viewing angle decreases, there will be an offset of the absolute value of the rotation-measure values and, if the viewing angle turns out to be
smaller than the pitch angle, we will observe only positive values for the rotation measure (Asada et al. 2002; Uchida et al. 2004).

Such rotation measures have already been detected. Zavala & Taylor (2003, 2004) have studied the rotation measures in a sample of AGNs. Asada et al. (2002, 2008) have found a time-variable rotation-measure gradient over more than 100 pc along the jet in 3C 273, the origin being, quite probably, the sheath around the ultrarelativistic jet. Gabuzda, Murray & Cronin (2004) have also found rotation-measure gradients ranging from negative to positive values across the jet in 0745+241. However, the stability of the rotation-measure structures is still unclear. Zavala & Taylor (2001) have found time variability of the rotation measure in 3C 273 and 3C 279, but Gómez et al. (2011) have found that, although there were changes in the linear polarization of 3C 120, the underlying rotation measure remained unaltered between 2 and 5 mas from the core over several years.

Previous results have been based on observations obtained with the Very Long Baseline Array (VLBA) using, with the exception of few cases, low-frequency bands (typically in the range of 8–15 GHz), based on a compromise between resolution and sensitivity. Only Gómez et al. (2011) and Attridge, Wardle & Homan (2005) have obtained results for frequencies as high as 86 GHz for the radio galaxies 3C 120 and 3C 273, respectively. Thus, we seek to obtain more measurements at higher frequencies, so that we can study the behaviour and structure of the rotation measure closer to the base of the jet in a larger number of cases. We can then compare our results with those obtained at lower frequencies.

In this paper, we study the rotation measure of eight sources observed with the VLBA from 12 to 43 GHz. In Section 2, we summarize the observations and data reduction. In Section 3, we present our results. In Section 4, we discuss our findings. We present our conclusions in Section 5. An analysis of the robustness of rotation-measure gradients is presented in the Appendix.

2 OBSERVATIONS AND DATA REDUCTION

The polarization observations of six radio quasars (0133+476, 0420–014, 0745+241, 0906+430, 1633+382 and 1954+513) and two BL Lacertae (BL Lac) objects (0256+075 and 1823+568) were carried out in a 24-h session on 2008 November 2, using the VLBA. The frequencies selected were 12.039, 15.383, 21.775, 23.998 and 43.135 GHz, each with two intermediate frequencies with a bandwidth of 8 MHz and a bit rate of 128 MB s⁻¹. The sources were observed in a snapshot mode, with 8–10 scans lasting for several minutes for each frequency and object spread in time, so that the resulting ultraviolet (UV) coverage was uniform. The data reduction and imaging were carried out with the National Radio Astronomy Observatory (NRAO) Astronomical Image Processing System (AIPS) using standard techniques. The reference antenna used was Los Alamos. Simultaneous solutions for the instrumental polarizations for the compact source 1954+513 were derived using the AIPS task LPCAL.

We calibrated the electric vector position angles (EVPA) using the VLBA D-Terms (Gómez et al. 1992). A comparison of the D-terms against a set of tabulated values (previously calibrated by other means) has proven to be a reliable method for calibrating the absolute L–R phase offset in VLBA observations. We have been able to obtain two sets of calibrated data with either the same or nearly the same frequencies (S. P. O’Sullivan, private communication; A. Reichstein, private communication). So, it has been possible for us to apply this method to our data.

To ensure the reliability of this method, we have performed a series of extra checks. First, we compared the independent results given by the two comparison sets of D-terms for consistency. Secondly, we compared our new images with our previous images (Algaba 2010). Thirdly, for some frequencies, we were also able to compare the resulting polarization angles with images from MOJAVE, the University of Michigan Radio Astronomy Observatory Database (M. Aller, private communication) and the 7-mm monitoring by the Boston University Blazar Group’s data bases. Fourthly, we obtained the EVPAs of several sources in the optically thin jet regions and checked for consistency with modest Faraday rotation. We estimate the overall error in the EVPA calibration to be about 4° for all frequencies.

After the initial construction of total intensity maps, we made new versions at 12, 15, 22, 24 and 43 GHz using the best calibrated data, but convolving all frequencies with a circular version of the beam obtained for the 15-GHz map. This beam was chosen as a compromise between the lower (12 GHz) and higher (43 GHz) resolution maps, superresolving 12 GHz only by a modest amount. Then, we made the maps for the Stokes parameters Q and U, which we used to construct the polarized flux, \( p = \sqrt{Q^2 + U^2} \), and the polarization angle, \( \chi = (1/2) \arctan(U/Q) \), with their respective noise maps, using the AIPS task COMB. Because information about the absolute position is lost during the calibration process, and given the core shift at different frequencies (Lobanov 1998), first we had to properly align the different maps at various bands. For this, we used the program developed by Croke & Gabuzda (2008), which is based on the cross-correlation of optically thin regions of the jet.

For the construction of the rotation-measure maps, because the current version of the AIPS task RM is limited by a maximum of four input frequencies, we used a modified version obtained from R. Zavala, which can construct rotation-measure maps using up to 10 frequencies. The distribution of the rotation measure was obtained in the regions where the error in the input maps was smaller than 15°. We have found that the results are very similar, compared to when we blank those regions with the error on the rotation measure exceeding 100 rad m⁻², except that the blanking edges appear smoother in the former case. In order to check the goodness of the \( \chi^2 \) fit, we have used the AIPS task RMUFB, also included in R. Zavala’s package, which allows us to plot a grid of rotation-measure fits and to obtain fit parameters, such as the rotation-measure fit error, \( \chi^2 \), the correlation coefficient and the \( Q \) value.

For 0420–014, 0745+241, 1823+568 and 1954+513, we used all five available frequencies. The case of 0133+476 is very complex (see Algaba, Gabuzda & Smith 2012), including the possible integration of different polarization components or the frequency variability of the rotation measure. Thus, we decided to fit only our three highest frequencies. In the cases of 0256+075 and 0906+430, the polarization structure becomes more complicated when reaching the highest frequency in our observation. Consequently, the 43-GHz EVPA value significantly departs from the trend seen in other frequencies. This indicates that we are either probing a different region or that we are integrating over different non-resolved components. Hence, we do not consider these values to be representative of the region we have studied in the rest of the frequencies, and we have decided not to include 43 GHz in our rotation-measure maps. For 1633+382, the 43-GHz angles have larger errors, and
thus we exclude this frequency from our study. In Table 1, we summarize the frequencies used in each source for the calculation of the rotation-measure maps.

There are a number of factors that might alter the orientation of the polarization angles in our maps. For example, a transition in the optical depth of the source can induce a 90° change in the polarization angle. Also, 180° ambiguities are inherent to the polarization jumps. We investigated these in Algaba et al. (2012), where we analysed the total and polarized intensity properties of the sources. We found that all sources were either only optically thin or only optically thick in the regions where we find the rotation measure. Hence, we are confident that there is no 90° jump, resulting from a thin-thick transition, invalidating our results. In the same way, we have studied the possibility of 180° ambiguities in the polarization angles in the region close to the core, and these have been taken into account in the calculations.

In order to double-check our results, various rotation-measure maps were created for each source using different blanking methods and/or a different set of frequencies. We compared the fits both by eye and by checking the goodness of the fit using the task RMCLASS. We noticed that, for sources such as 0256+075, this implied the addition of noisy areas in the rotation-measure map, and, in some cases such as 0133+476, the emergence of patchy areas.

In cases such as 0256+075 and 0906+430, if we included 43 GHz, this resulted in the fit not passing through all the data, and it tilted the slope to a wrong value. Because we excluded 43 GHz in these cases, the goodness of the fits improved from $R^2 \sim 0.35$ and 0.86 to $R^2 \sim 0.95$ and 0.96 for 0256+075 and 0906+430 respectively. For other sources, such as 1633+382, the rotation-measure map did not change significantly, but because of the error associated with the additional frequency, the fit turned out to be worse.

We have also checked the consistency of the rotation-measure maps when a shift on any of the input maps was applied. For this, we considered input maps with and without a core shift (Lobanov 1998), as well as horizontal or vertical shifts up to 200 mas, and we found no significant difference in the output rotation-measure maps.

### Table 1. Parameters used for the maps.

<table>
<thead>
<tr>
<th>Source</th>
<th>$I_{\text{peak}}$ (Jy beam$^{-1}$)</th>
<th>Bottom contour (mJy beam$^{-1}$ mas$^{-1}$)</th>
<th>Polarization sticks (mJy beam$^{-1}$ mas$^{-1}$)</th>
<th>Frequencies used for rotation measure (GHz)</th>
<th>Rotation-measure range (rad m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0133+476</td>
<td>3.19</td>
<td>3.2</td>
<td>50</td>
<td>22, 24, 43</td>
<td>-4000 to 1000</td>
</tr>
<tr>
<td>0256+075</td>
<td>0.32</td>
<td>1.0</td>
<td>50</td>
<td>12, 15, 22, 24</td>
<td>1000 to 2000</td>
</tr>
<tr>
<td>0420–014</td>
<td>3.72</td>
<td>5.6</td>
<td>200</td>
<td>12, 15, 22, 24, 43</td>
<td>-1000 to 1000</td>
</tr>
<tr>
<td>0745+241</td>
<td>1.39</td>
<td>1.4</td>
<td>40</td>
<td>12, 15, 22, 24, 43</td>
<td>500 to 3000</td>
</tr>
<tr>
<td>0906+430</td>
<td>0.69</td>
<td>1.4</td>
<td>10</td>
<td>12, 15, 22, 24</td>
<td>-2000 to 2000</td>
</tr>
<tr>
<td>1633+382</td>
<td>2.18</td>
<td>2.2</td>
<td>20</td>
<td>12, 15, 22, 24, 43</td>
<td>-500 to 1000</td>
</tr>
<tr>
<td>1823+568</td>
<td>1.18</td>
<td>2.4</td>
<td>100</td>
<td>12, 15, 22, 24, 43</td>
<td>500 to 1500</td>
</tr>
<tr>
<td>1954+513</td>
<td>1.21</td>
<td>1.2</td>
<td>40</td>
<td>12, 15, 22, 24, 43</td>
<td>-15000 to -13000</td>
</tr>
</tbody>
</table>

3 RESULTS

The rotation-measure maps, derived for all eight sources studied here, are shown in the top panels of Fig. 1. Here, the contours correspond to the total intensity of the convolved version of the map for 15 GHz, and the colour levels indicate the rotation measure found. Peak and bottom intensity contours, corresponding to $3 \times$ rms, are given in Table 1, together with the frequencies used for the Faraday rotation $\lambda^2$ fit, and the rotation-measure scale for all sources. In all maps, contours increase in steps of $\sqrt{6}$, the colour code for the rotation measure is shown at the top and the beam is shown in the bottom-left corner of the image.

The rotation measure is typically found in the VLBA core region (i.e. close to the base of the jet). In 0745+241, some rotation measure that extends slightly further from the core is found. Only in 0906+430 does the rotation measure extend continuously from the core up to a distance of 2 mas into the jet. In 1633+382 and 1954+513, we have also found rotation measures in the knots located at 4 and 3.5 mas from the core, respectively. Typical values for the rotation measure are of the order of some krad m$^{-2}$, with 1633+382 and 1954+513 showing the most extreme values.

In order to investigate the observed rotation measures, we made slices to analyse the rotation measure across the jet. Plots of the rotation measure across the jet are shown below the rotation-measure maps in Fig. 1, indicating the region taken for the slice with a thick black line in the map. (Note that for 0420–014 and 0745+241 no slices are shown, because these sources do not present any indications of variations of the rotation measure across the jet.) In all cases, the direction for the slice is taken to be from left to right and, in case of confusion (e.g. 1633+382), from top to bottom. The horizontal axis of the rotation-measure slice plot has been zeroed at the beginning of the slice. A line in the bottom of the slice indicates the size of the beam. Note that, for the case of 0133+476, the slice is smaller than the beam size. We discuss the significance of these gradients following the criteria given in the Appendix.

0133+476 is a quasar showing the rotation measure in the boundaries of the very long baseline interferometry (VLBI) core. The values obtained for the rotation measure span from -4000 to 1000 rad m$^{-2}$. Although the slice taken shows a very clear gradient with a large signal-to-noise ratio (S/N), $\sigma \sim 15$, the region where a possible gradient is seen is very limited, less than one beam width, making this very ambiguous. According to the simulations performed in the Appendix, and together with the fact that it is located in the core, this is not a reliable gradient.

0256+075 shows a gradient in the core region spanning slightly more than a single beam size and forming an angle with the direction of the jet. The values for the rotation measure found in this source vary monotonically from 2000 rad m$^{-2}$ in the upper region of the core to about 1000 rad m$^{-2}$ as we approach the upstream region of the jet. However, this gradient is too small, in both size and slope, to be considered reliable.

0420–014 shows no indications of variations transverse to the jet but it does show the rotation measure monotonically decreasing from positive ($\sim +1000$ rad m$^{-2}$) to negative ($\sim -1000$ rad m$^{-2}$) values as we move further from the central region.
Figure 1. Rotation-measure maps. For each of the sources, the top panel shows the rotation-measure map and the bottom panel shows a slice of the rotation measure along the thick black line taken on the rotation-measure map. This figure can be seen in colour in the online version.
0745+241 shows a behaviour similar to that of 0420–014 with higher values of the rotation measure (∼3000 rad m$^{-2}$) closer to the core and a monotonic decrease to ∼1000 rad m$^{-2}$ at a distance of ∼1 mas.

0906+430 has an almost null rotation measure in the core, whereas it takes positive values (+2000 rad m$^{-2}$) on one side of the jet, decreasing gradually and changing sign down to −2000 rad m$^{-2}$ on the other side of the jet. This is the source that shows the clearest rotation-measure gradient spanning two beam widths along the jet. The slope is about three times larger than the typical error and its profile is very smooth, in agreement with all the requirements discussed. Also, the gradient is clearly visible at around one beam size away from the core, in agreement with simulations performed by Broderick & McKinney (2010). We consider this rotation-measure gradient to be robust.

1633+382 shows a very high ($RM = 22$ krad m$^{-2}$), featureless rotation measure in the core, but displays an interesting gradient in the knot located at about 4 mas from the core. We discuss the reliability of this gradient in Section 4.4.2. We note that, in Fig. 1(d), we have set the rotation-measure range to enhance the rotation-measure features in the knot for clarity in the discussion. Because high values of the rotation measure are not included in the scale, the map is saturated for the values occurring in the core.

1823+568 shows a very flat rotation measure in the core, with values of ∼1200 rad m$^{-2}$. As we move away from the VLBI core, there are some indications of a transverse gradient taking only positive values. This is in general agreement with the idea that finite-beam effects blend different regions and make it impossible to detect reliable features of the rotation measure in the core.

1954+513 shows indications of a gradient across the core region that seem to be faded out (or inverted) as we move less than one beam size away. This case is similar to one of the simulations of Broderick & McKinney (2010), where spurious rotation measures and sign changes occur. Thus, we do not consider this gradient reliable.

In general, we find rotation measures to be of the order of several krad m$^{-2}$, the core of 1633+382 being the most extreme case. Variations of the rotation measure in the optically thick core are, in general, not reliable and give rise to unrealistic gradients (Broderick & McKinney 2010; Taylor & Zavala 2010). Thus, such variations of the rotation measure are not discussed.

4 DISCUSSION

4.1 Comparison with previous results

The source 0256+075 has been previously studied by Mahmud & Gabuzda (2008), who claimed to have found a rotation-measure gradient in the VLBA core, with a gradient reversal that they explained using magnetic tower models proposed by Lynden-Bell & Boily (1994) and Lynden-Bell (1996). However, their gradient was found very close to the core and with a width not significantly exceeding the beam size. Thus, it is likely that the gradients they observed are also a result of rotation-measure fluctuations in the core.

0420–014 was one of the sources for which a rotation-measure analysis was carried out using the MOJAVE programme. Almost no rotation measure was found by Hovatta et al. (2012) for this source in 2006 October, with only small patchy traces within one beam size from the core. The difference in the rotation-measure detection could be a result of the increase of both polarization and the degree of polarization by a factor of 2 in the epoch we study here, which allows us to obtain a better S/N with a similar sensitivity.

Venturi & Taylor (1999) performed observations of 0906+430 in 1996 November and also found a clear rotation measure over a long distance from the core in this source. The rotation measure they found in the core is of the order of 100 rad m$^{-2}$, about one order of magnitude smaller than the results presented here. No rotation measure of this source is shown in the Faraday rotation studies of Hovatta et al. (2012).

Hovatta et al. (2012) and Gabuzda et al. (2004) studied the rotation measures in the sources 0133+476 and 1823+568, and 0745+241, respectively. The features and signs of the rotation measures are different when compared with our work. Although this could be because of some time variation, given their location (optically thick core) and extension (generally, less than 1.5 beam sizes), it is also likely that they might have a non-negligible contribution from a spurious rotation measure because of noise in the data.
4.2 Increase of core rotation measure with frequency

As we observe at higher frequencies, the core rotation measure is expected to increase. This is because of the apparent change in location of the central engine with frequency (i.e. core shift) because of optical depth effects. Thus, observations of the VLBI core at higher frequencies probe regions closer to the central engine, where both the magnetic field and particle densities increase. Hence, the core rotation measure is expected to increase with frequency following the formula $RM \propto \nu^2$ (Jorstad et al. 2007). Theoretical estimations provide $a = 2$ under the assumption of a toroidally dominated magnetic field and electron density in equipartition, scaling as $B \propto d^{-1}$ and $n_e \propto d^{-2}$, respectively, where $d$ is the distance from the central engine, and the outflow is a spherical or conical wind. This value is also in general agreement with estimations for $a$ on other similar sources by Jorstad et al. (2007) and O’Sullivan & Gabuzda (2009a).

We have compared our measurements with previous results on the core rotation measure in the literature at other frequencies. For our data, we have used the core rotation measure obtained by Algaba et al. (2012). For data from the literature, we have used the fitted data for the core that authors have supplied. If unavailable, we estimated the core rotation measure based on their rotation-measure map. We note that, for the case of 0420–014, Hovatta et al. (2012) were not able to find the rotation measure in the VLBI core, and so we have used the value they found upstream in the jet as the lower limit. To the best of our knowledge, there are no previous VLBI rotation-measure data for 1954+513.

Our results are summarized in Table 2. Column 1 indicates the source. Columns 2, 3 and 4 give the reference of the lower-frequency rotation-measure data, the frequency used in the literature and the core rotation measure found for that frequency, respectively. Columns 5 and 6 give the lowest frequency that we have used from our data to determine the rotation measure and its value. Column 7 gives the value for $a$ that we obtain when we compare previous data with our data at higher frequency.

We find that the values obtained are around $a = 3$, with a lower limit being $a < 1.2$ for 0420–014 and the highest value $a = 11.2$ for 1633+382. If we exclude these two values, we find the average ($\bar{a}$) = 3.6 $\pm$ 1.3. Except for the case of 1633+382, with exceptionally high $a$, these values are similar to those found by O’Sullivan & Gabuzda (2009b), ranging from 0.9 $< a < 3.8$, but slightly larger than those found by Jorstad et al. (2007). The average value found here is not compatible with the theoretical estimation $a = 2$ and, indeed, only the value for 0133+476 matches this value to within 1$\sigma$. Two possible explanations for this include time variations or convolution effects.

Our observations were taken roughly two years later than several of the lower-frequency observations we are comparing. During this time, several changes might occur in the innermost regions of the jet, causing a change of the core rotation measure. Indeed, Zavala & Taylor (2001) found changes in the core rotation measure in 3C 273 and 3C 279 during a period of about 1.5 yr. In our case, this is particularly true for 0745+241, 0906+430 or 1823+568, which are sources that show a change in the sign of the rotation measure for the two epochs. Such changes in the sign of the rotation measure have been detected before for 0133+382, 0745+241 and 1633+382 when compared with another set of observations (Algaba et al. 2012).

A different reason for our relatively high $a$ value could be that convolved rotation measures are, in general, smaller than the true values and a function of the beam size (Murphy & Gabuzda 2012). As we observe at higher frequencies, the beam size becomes smaller, and thus this effect becomes less important. In practice, this implies that the rotation measure observed at lower frequencies was underestimated (or, at least, more so than the values of the rotation measure studied here), thus producing an artificial increase of the $a$ parameter. However, the range of observed frequencies is relatively small, and so the effects due to deconvolution on the rotation measure are expected to be similarly small.

Another possibility is that the assumptions for the theoretical derivation of $a = 2$ are not adequate for these sources. As discussed in Algaba et al. (2012), it is a reasonable assumption to consider that these are in equipartition. However, it is not yet clear how magnetic and electron densities actually scale with distance from the central engine. If these scale in a different way, this could lead to a theoretical prediction for $a$ that is closer to our measured value. For example, if the electron density decays as $n_e \propto d^{-3}$, with the rest of the parameters left unchanged, then the theoretical estimate would be $a = 3$. Further investigation of rotation measures at different wavelengths should be performed in order to clarify this.

4.3 Rotation-measure gradients

Although rotation measures have been studied for several decades, it is still not clear when the observed variations and gradients of rotation measures are reliable, and only recent studies and simulations have dealt with this question. Taylor & Zavala (2010) have introduced a series of criteria to discern when a gradient is reliable. Broderick & McKinney (2010) have discussed jet rotation measures from theoretical magnetohydrodynamic simulations. Hovatta et al. (2012) have simulated errors of Faraday rotation for their

Table 2. Increase of rotation measure with frequency.

<table>
<thead>
<tr>
<th>Source</th>
<th>Reference</th>
<th>$\nu_1$ (GHz)</th>
<th>Core rotation measure ($\nu_1$) (rad m$^{-2}$)</th>
<th>$\nu_2$ (GHz)</th>
<th>Core rotation measure ($\nu_2$) (rad m$^{-2}$)</th>
<th>$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0133+476</td>
<td>H12</td>
<td>8</td>
<td>-216</td>
<td>22</td>
<td>-2500</td>
<td>3.4 ± 0.4</td>
</tr>
<tr>
<td>0256+075</td>
<td>M09</td>
<td>4</td>
<td>50</td>
<td>15</td>
<td>1530</td>
<td>2.6 ± 0.5</td>
</tr>
<tr>
<td>0420–014</td>
<td>H12</td>
<td>8</td>
<td>&gt;548</td>
<td></td>
<td></td>
<td>&lt;1.2</td>
</tr>
<tr>
<td>0745+241</td>
<td>G04</td>
<td>5</td>
<td>-120</td>
<td>12</td>
<td>2550</td>
<td>3.5 ± 0.5</td>
</tr>
<tr>
<td>0906+430</td>
<td>V99</td>
<td>4.8</td>
<td>100</td>
<td>12</td>
<td>-3200</td>
<td>3.8 ± 0.5</td>
</tr>
<tr>
<td>1633+382</td>
<td>H12</td>
<td>8</td>
<td>-235</td>
<td>12</td>
<td>22040</td>
<td>11.2 ± 0.4</td>
</tr>
<tr>
<td>1823+568</td>
<td>H12</td>
<td>8</td>
<td>-121</td>
<td>12</td>
<td>1250</td>
<td>5.8 ± 0.4</td>
</tr>
<tr>
<td>1954+513</td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>-13800</td>
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</tr>
</tbody>
</table>

References: V99, Venturi & Taylor (1999); G04, Gabuzda et al. (2004); M09, Mahmud & Gabuzda (2008); H12, Hovatta et al. (2012).
observations. We discuss these studies and perform similar simulations in the Appendix.

In general, the rotation measures we find are located in the cores of the sources. In this region, the rotation-measure structure is less reliable and is subject to several blending effects (Broderick & McKinney 2010). Thus, we do not consider variations of the core rotation measure. We have found indications of a reliable rotation measure across the jet in two of the sources studied here: 0906+430 and possibly 1633+382.

The quasar 0906+430 displays a constant rotation-measure gradient that spans along the jet up to a distance of 2 mas. At a redshift of $z = 0.67$ and its cosmology-corrected scale $6.831 \text{ pc mas}^{-1}$, this implies a rotation-measure gradient extending at least $\sim 14$ pc. The amount of rotation of the polarization angles that we find is greater than 90° (Algaba et al. 2012) and the fractional polarization, although relatively weak ($<1$ per cent at 12 GHz), is smoothly increasing with frequency. Hence, we can estimate that the contribution of internal Faraday rotation, if any, is negligible. In turn, this indicates that the screen producing the Faraday rotation gradient must be external.

The quasar 1633+382 shows a rotation measure at about 4 mas from the core. If we take into account the errors, the rotation measure runs from around 1000 rad m$^{-2}$ to zero (or possibly negative values). Unlike the case of 0906+430, this rotation measure is located in a knot of the source, where both total intensity and degree of polarization are enhanced. The range of the rotation measure indicates that, as in 0906+430, it is dominated by external Faraday rotation.

The case of 1633+382 is indeed close to the limits of what we would consider a reliable gradient: it spans over about 1.5 beams across the jet with a significance $\sigma \approx 2$. As we state in the Appendix, there is a chance of about $\sim 1$ per cent for this gradient to be a false detection. It is possible to have spurious gradients of up to $\sim 230$ rad m$^{-2}$ beam$^{-1}$ over 1.5 beams (see Fig. A4b). This would lead to a contribution of $\sim 345$ rad m$^{-2}$ as a result of the noise, which is about 25 per cent of the gradient observed in this source. Therefore, the existence of a physical gradient is possible, although we discuss it with caution.

The rotation measure is also found in the jet of this source in the Faraday studies of Hovatta et al. (2012). The typical value they have found in the region we are studying here is $RM \approx 200$ rad m$^{-2}$, which is about five times smaller than the values we find. In their study, Hovatta et al. (2012) have not found strong indications of a gradient. If the rotation-measure gradient we detect is real, we suggest that it might be a result of the evolution of the region (see below).

### 4.4 Polarization structure of the jets

Once we have obtained rotation-measure maps, it is possible to correct for Faraday effects on these regions. We show Faraday-corrected electric-field (E-field) maps in Figs 2–4. Here, contours indicate total intensity at 12 GHz, as in Fig. 1, and the direction and longitude of the sticks indicate the direction of the Faraday-corrected E-field direction and polarization intensity, respectively. Note that we do not show the E-field for the regions where we have not found rotation measures, because we are unable to correct it for Faraday rotation. A longitude of 1 mas in the polarization sticks corresponds to the number of mJy beam$^{-1}$ indicated in column 4 of Table 1.

At first glance, it seems that the variation in the direction of the E-field in the core region is smaller and smoother when corrected for Faraday effects. This is particularly true for sources 0256+075, 0420−014 and 1823+568. However, in sources such as 0133+476, 0745+241 or 0906+430, there appear to be two differentiated components in the direction of the E-field: one in the VLBI core and one upstream in the jet. We suggest that this second component is caused by an unresolved feature in the jet.

In several sources, the E-field in the core seems to be either perpendicular (0745+241 and 1954+513) or parallel (0133+476, 0256+075, 0420−014 and 0906+430) to the direction of the jet. This bimodal configuration has been observed previously (e.g. Gabuzda et al. 2000, and references therein) and can be interpreted as reflecting the presence of helical magnetic fields associated with the jets. We observe polarized emission from both the front and the rear of the emitting regions, but the polarization angles will have a 180° offset. When both contributions are vectorially added, the result will depend on the pitch angle of the jet. With a small pitch angle, the azimuthal component of the magnetic field dominates and the vectorial addition will produce polarization perpendicular to the jet. However, with a large pitch angle, the toroidal component dominates and the polarization will be parallel to the jet (Asada et al. 2002).

Only in two sources (1633+382 and 1823+568) is there an evident misalignment between the E-field and jet directions. One explanation for this, as above, is the presence of an unresolved (in this case, even in polarization) component. Other possibilities include opacity effects on the magnetic field direction or differential Doppler boosting, which would twist the electric vector pattern (Roberts & Wardle 2012). Oblique shocks with arbitrary angles can also cause arbitrary observed polarization angles.

Because of sensitivity limits, we have been able to detect the rotation measure and significant polarization at high frequencies in the jets of only two sources: 0906+430 and 1633+382. We study these two cases below.

#### 4.4.1 0906+430

Fig. 3 shows the polarization structure of this source. The top panel shows the polarization map as detailed above. The bottom panel shows the degree of polarization $m$ of the map at 12 GHz across the width of the jet in the direction of the rotation-measure slice shown in Fig. 1. The axis has been zeroed at the centre of the jet. In the degree of polarization slice, areas shaded in grey indicate the regions with polarized flux density below $3 \times \text{rms}$ in the polarization images.

There seem to be two regions with different E-field directions along the jet. Close to the VLBI core, the E-field appears to be forming an angle with the direction of the jet, whereas further downstream it becomes perpendicular to the direction of the jet, as in the core. As discussed above, this might be caused by an unresolved component, opacity or relativistic effects. If we investigate the 43-GHz intensity map, we can identify a resolved component located at $\sim 1$ mas from the core, and we think this might make a significant contribution to the change of the polarization direction.

There have been previous studies (e.g. Marscher et al. 2010) where a rotation of the optical polarization angle has been seen, presumably because of a structure following a spiral path through a helical magnetic field where the flow accelerates. One of the possibilities is that we are observing a snapshot of the radio counterpart here, with this structure rotating the polarization angle or the region around it.
When we study a cut of the degree of polarization $m$ along the direction of the gradient (i.e. across the jet), we find a minimum in the centre of the jet and indications of an increase as we move towards the edges. However, the errors become rapidly large and, after 0.5 mas from the jet centre, the errors dominate and the polarization drops below $3 \times \text{rms}$. In the region of the rotation-measure gradient, even if we take into account the errors, $m$ seems to have a concave shape across the jet.

Overall, one possible way to explain the structure of 0906+430 could be the following. A new component (only resolved at 43 GHz in total intensity) is emerging from the VLBI core and following the path along the intrinsic helical magnetic field, thus altering the direction of the observed polarization closer than 1 mas to the core. Further away, we find three aspects (rotation-measure gradient, spine structure of the polarization and shape of $m$ across the jet) that point towards a helical shape of the magnetic field.

We note (Contopoulos et al. 2009) that a spine–sheath polarization structure is not a necessary condition to pinpoint a helical magnetic field, because the observed structure depends on parameters such as viewing and/or pitch angles.

### 4.4.2 1633+382

Fig. 4 shows the polarization structure of this source. The top panel shows the polarization map. The middle panel shows the degree of polarization $m$ of the map across the width of the jet in the direction of the rotation-measure slice, zeroed at the centre of the jet. The bottom panel shows $m$ along the jet zeroed at the core. As before, in the degree of polarization slices, areas shaded in grey indicate the regions with polarized flux density below $3 \times \text{rms}$ in the polarization images.

In the region of the jet where we have been able to correct for Faraday rotation, the E-field seems to form an angle with the direction of the jet. When we take a slice perpendicular to the direction of the jet in order to study the polarization structure of this feature, we find hints of a complex W-shape. However, given the errors in both total and fractional polarization, the only significant feature is a peak of the fractional polarization in this region.

A smooth sheath around the jet cannot produce a region of enhanced polarization. Hence, based on the total intensity and polarization maps, we speculate that the reason for this shape is a component arising from the polarization of the knot itself. Indeed, the local peak of the degree of polarization is coincident with the intensity peak of the knot, and both shapes also agree within the errors. We note that this is not unique, and has also been observed in other sources (Algaba et al., in preparation). We also note that magnetic fields do not need to be perpendicular to the direction of the jet to be caused by a shock: oblique shocks with arbitrary angles, leading to different directions of the magnetic field are also possible.

In order to check if such a knot is compatible with the observations, we have obtained a slice of $m$ along the jet. We observe a
very low value of $m$ near the core, but a peak of $m \sim 20$ per cent at a distance of $\sim 3.5$ mas (corresponding to $\sim 700$ pc, deprojected), coincident with the location of the knot. According to Liu et al. (2010) and MOJAVE data, this component has been moving at a velocity of $\sim 0.32$ mas yr$^{-1}$, gradually decelerating until reaching its current position around 2003, where it appears to have remained steady.

One possibility is that this is a component that has been gradually decelerated by interaction with the surrounding media and that has developed a shock front with compressed magnetic field. Given the degree of polarization, we can conclude that the underlying magnetic field is highly ordered. Compression across the jet will produce an enhancement of the transverse component of the magnetic field. Algaba et al. (2012) have found that, for this source, the magnetic field at 1 pc from the central engine is $B(1 \text{ pc}) = 0.7$ G. If we assume $B \propto R^{-1}$, which is in agreement with equipartition arguments and which can be used to describe the observed synchrotron emission in compact regions of VLBI jets, we find that the corresponding magnetic field strength in the region of the knot is around $B(1 \text{ pc}) \sim 1$ mG. This is a relatively high magnetic field strength but it does agree with those found in other sources at similar scales (e.g. Owen, Hardee & Cornwell 1989).

There is another possibility that could also give rise to an intrinsic Faraday-corrected polarization forming an apparent angle with the jet in this region. If we analyse the structure of this source at higher frequencies, a component close to the core ($\sim 0.5$ mas) is observed.
in the north-west direction (e.g. see the 7-mm monitoring by the
Boston University Blazar Group). This could be an indication that
the direction of the jet has actually changed and that new com-
ponents are now being ejected in a direction that is tilted with respect
to the previous direction. Alternatively, the component located at
0.5 mas might be a standing component (Liu et al. 2010), thus in-
dicating the truly intrinsic direction of the jet and showing that the
actual jet is curved. If this is the case, polarizations in both the core
and the knot might be showing the true direction of the jet in these
regions (i.e. the E-field would be parallel to the direction of the jet).

We have obtained new slices of $m$, assuming that the local di-
rection of the jet is the one shown by the E-field vectors. We find
that the previous discussion does not significantly change (i.e. the
W-shape across, and the peak along, the local direction of the jet
in the polarization are still found). Under this interpretation, the
possible rotation-measure gradient found would be parallel to the
local direction of the jet. This could still be explained in terms of
a shock, if we assume that we have a strong compression shock
where the E-field is enhanced, followed by a dissipation zone pro-
ducing the rotation-measure gradient. This shock might have been
formed recently, based on the proper motion of this component,
which could explain why such a gradient was not observed by
Hovatta et al. (2012), because their observations were carried out in
2006 September, more than two years prior to ours.

However, we are currently unable to distinguish between these
scenarios. According to Hovatta et al. (2009), the viewing angle for
this source is only 2.5°, and so we are looking at it almost head-on;
this makes it difficult to adequately study its deprojected features.
Also, observations with more sensitivity would be necessary at
higher frequencies in order to discover the actual direction of the jet
at different scales. Further observations of the knot studied here are
necessary in order to understand its motion and E-field evolution in
future years.

5 CONCLUSIONS

We have obtained polarimetric VLBA observations of eight AGNs
and we have presented an analysis of their rotation measures. Far-
day rotation is found in the VLBA cores, with typical values for
the rotation measures of the order of some thousands of rad m$^{-2}$,
except for the sources 1633$+$382 and 1954$+$513, with core rota-
tion measures up to 22 and $-13$ krad m$^{-2}$, respectively. Because
of sensitivity limits, the jet rotation measure is detected only in the
jets of two sources: 0906$+$430 and 1633$+$382.

The core rotation measures found here are larger than in previous
studies performed for the same sources at lower frequencies. If we
assume a dependence of the form $RM \propto \nu^a$, derived by Jorstad et al.
(2007), we find an average of $a = 3.6 \pm 1.3$, in agreement with es-
timations made for similar sources (Jorstad et al. 2007; O’Sullivan
& Gabuzda 2009b). However, most of the individual values are
higher than the theoretical estimations that provide $a = 2$ under the
assumption of a toroidal-dominated magnetic field and electron den-
sity in equipartition. Different explanations for this include a time
variability of the rotation measure (supported in some sources by a
sign change over different epochs) or a convolution effect, causing
rotation measures to be underestimated at lower frequencies.

In order to discuss the reliability of the rotation measures found
here, we have performed simulations based on our multifrequency
data. Our simulations indicate that in order for variations of the
rotation measure to be robust, they have to span over at least 1.5
beam sizes with $S/N > 3$. However, we have found that these
conditions can be slightly relaxed because stable gradients over

a few beam sizes should not arise because of random variations or
beam effects. These results agree with previous discussions by
Taylor & Zavala (2010) and Hovatta et al. (2012).

The Faraday-corrected direction of the core magnetic field is,
in general, either aligned or parallel with the direction of the jet.
This can be interpreted as an indication of an underlying helical
magnetic field. Two sources seem not to follow this trend. For
1633$+$382, there were various possibilities, including a change of
the jet direction, and for 1823$+$382, we propose that the rotation
of the polarization angle might be the result of an unresolved com-
ponent. This interpretation is supported by observations at higher
frequencies and slices of the degree of polarization, revealing this
component.

In some sources (i.e. 0133$+$476, 0745$+$241 and 0906$+$430), we
observe two different regions for the polarization angle. Based on
the previous interpretation, we suggest that this is because of the
unaltered E-field in the core plus an additional component that,
being still unresolved at 12 GHz, has moved away from the core
enough to be detectable in polarization.

We find that the rotation-measure gradient in the jet of 0906$+$430
(and possibly 1633$+$382) is reliable. The combination of the results
from the rotation measure, the spine polarization structure and the
concave shape of the degree of polarization across the jet seem to
indicate the presence of a helical magnetic field in 0906$+$430
beyond 1 mas away from the core. The case for 1633$+$386 is unclear,
and different possibilities, such as a compression shock or diffusion
of enhanced magnetic field, are given.

ACKNOWLEDGMENTS

This research has made use of data taken by the VLBA. The VLBA
is operated by the NRAO, and the NRAO is a facility of the National
Science Foundation operated under cooperative agreement by As-
sociated Universities, Inc. The author thanks M. Inoue, K. Asada,
M. Nakamura and the anonymous referee for very useful comments
that have substantially improved this manuscript.

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models by setting them to be a known I\(\xi\)rms. This is consistent with sim-
\(\sim\)20, this implies a resolvable size of one-third
Slices transverse to the jet in 1633
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4, the
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\(\langle\theta\rangle\) fraction of the synthesized beam size, because in the calibration
position accuracy of polarized intensity images is below a small
about a gradient. However, this requirement is too restrictive. The
requirements here.

First, the Stokes I model of the CLEANed source was used. Then,
we created fiducial \(Q\) and \(U\) models by setting them to be a known
fraction of Stokes I (which leads to a constant EVP and polarization
across the source). Following this, we produced the UV data
based on these models and added random independent noise with a
normal distribution to the data. Using this method, we produced 500
sets of UV data for each frequency, which were used then to derive
new \(Q\), \(U\) polarized and respective noise maps. We checked that
the resulting maps had noise levels and distributions statistically
compatible with the real observations.

We created simulated rotation measures and rotation-measure
noise maps using the values of the polarization angles from the
simulated 12-, 15- and 22-GHz maps, to which we added a random
value between \(\pm 4\) to account for EVP correction errors. Errors on
the rotation measure were obtained by the quadratic sum of
different terms, namely the errors from the noise map, estimated
from the variance–covariance matrix of the linear fit as the error of

For a typical \(S/N \sim 20\), this implies a resolvable size of one-third
of the beam size (i.e. \(\sim 0.25\) mas for our case).

Murphy & Gabuzda (2012) have argued that a rotation-measure
gradient can change its value when convolved with different beams,
but the gradient itself is not destroyed, even when the jet is unre-
solved, although they do not take into account spurious gradients
arising from noise. Hovatta et al. (2012) have performed a series
of simulations specifically dealing with this issue, which indicate
and we created fiducial \(Q\) and \(U\) models by setting them to be a known
fraction of Stokes I (which leads to a constant EVP and polarization
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We created simulated rotation measures and rotation-measure
noise maps using the values of the polarization angles from the
simulated 12-, 15- and 22-GHz maps, to which we added a random
value between \(\pm 4\) to account for EVP correction errors. Errors on
the rotation measure were obtained by the quadratic sum of
different terms, namely the errors from the noise map, estimated
from the variance–covariance matrix of the linear fit as the error of
the slope, and the simulated propagated errors from the polarization maps. This is done because, although errors from the covariance matrix alone are adequate for each pixel, we still need to take into account the fact that pixels are not independent. Note that we do not include the EVPA calibration errors, because these will have no effect in rotation-measure gradients (Mahmud, Gabuzda & Bezrukovs 2009), in which we are interested. Fig. A1 shows a sample of a simulated rotation-measure map.

The typical error in the rotation measure is about \( \sim 150 \text{ rad m}^{-2} \), which is slightly smaller than the error in the real rotation measure in our observation at the same position (\( \sim 250 \text{ rad m}^{-2} \)). We estimate that there is a probability of \( \sim 5 \) per cent to obtain a simulated rotation measure with an error similar or larger than the observed rotation measure. Thus, it is possible that our observation is within this case. It might also be possible that this difference arises because of the underestimation of the non-thermal errors, as a result of the procedure in creating the \( Q \) and \( U \) models, or the evaluation of the pixel dependence. After carefully checking our estimations, we do not believe that this is the case.

Fig. A2 shows the distribution of obtained values of the rotation measure at a point in the jet for the source 1633+382, close to the area where the actual rotation measure is observed. Values are about a third smaller than the values in the actual observation, around a few hundred rad m\(^{-2}\). The distribution of the values of the rotation measures found is as follows. The average and the most probable values are \( \sim 8 \) and \( \sim 9 \) rad m\(^{-2}\), respectively, consistent with a distribution that has no rotation measure. The standard deviation of the distribution is 104 rad m\(^{-2}\).

For each of the simulated rotation-measure maps, we took a slice across the jet, as shown in Fig. A1 by the straight line. Ideally, we would like to take different slices of various sizes separated by at least one beam width to ensure that they are independent. However, given the structure of the source, this is not possible, particularly for slices smaller than \( \sim 2.5 \) beams. In order to overcome this issue, we have used the following procedure.

First, we set the longitude of a single slice to 1, 1.5, 2, 2.5 and 3 beam sizes, respectively (here, note that one beam corresponds to 0.75 mas), all centred around the jet spine. In total, we obtained 2500 slices that were used to calculate simulated rotation-measure gradients as follows. We fitted a simple line to the slice. We estimated the gradient error as the maximum between the error in the slope fit and the largest error bar in the rotation-measure slice. Because this method does not provide independent measurements, we repeated this process for another two different slices, shown by dashed lines in Fig. A1, as a consistency check. We find that the results are similar for all three slices. Fig. A3 shows the distribution of rotation-measure gradients obtained by this method for the straight slice, which is taken along our observed rotation measure. In all cases, the simulated rotation measure is centred at \( \sim 0 \) rad m\(^{-2}\), as expected, with the standard deviation decreasing as we move to slices larger than one beam size.

![Figure A2. Distribution of simulated rotation measures in the jet of 1633+382.](https://academic.oup.com/mnras/article-abstract/429/4/3551/1020194)

![Figure A3. Distributions of the 2500 simulated rotation-measure gradients.](https://academic.oup.com/mnras/article-abstract/429/4/3551/1020194)
To study when these rotation-measure gradients are significant, we have analysed their S/N by dividing them by their error, defined as above. The results can be seen in Fig. A4, where the number of rotation-measure gradients is plotted in terms of their S/N. We note that none of these rotation-measure gradients is real. However, when a slice with the size of only one beam is analysed, there is still a significant number of spurious gradients with $\sigma = S/N > 3$.

The number of these gradients decreases dramatically as we study slices with 1.5 beam sizes or larger: only four sources for 1.5 beam sizes and none for larger beam sizes had $\sigma > 3$ in our simulation.

This is clearly shown in Fig. A5, where we plot the number of false positives (i.e. the proportion of sources that exceed $1\sigma$, $2\sigma$ and $3\sigma$, respectively) against the size of the slice. This fraction goes rapidly to zero as we increase the number of error limits $\sigma$ that are imposed. In general, $1\sigma$ gradients will not be reliable, even for large slices, but a level of $2\sigma$ will be enough when the width of the slices used is at least two beams. In most cases, even a $2\sigma$ detection level over 1.5 beams will be reliable, with a chance of finding false gradients in only 0.8 per cent of these.

Summarizing, the results of our simulations agree with the results shown by Hovatta et al. (2012) and the suggestions given by Taylor & Zavala (2010), although we consider the latter too restrictive. While slices with three beam widths are optimal for a reliable detection of a rotation-measure gradient, in the most general case smaller slices can also provide a reliable gradient, provided the error treatment and S/N are adequate.