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Polarization and Faraday rotation measure imaging at metre wavelengths with sub-arcsecond resolution: a foundational calibration strategy

R. J. van Weeren¹,¹★ J. M. G. H. J. de Jong^{1,2}, X. K. Le Saux¹, V. A. Chakawri¹, Q. W. E. van Zegveld¹, D. de Jong¹, S. P. O’Sullivan³, F. Sweijen⁴, V. H. Mahatma^{5,6}, E. De Rubeis^{7,8}, L. K. Morabito⁹, D. Alonso-López³, A. Bonafede^{8,10}, C. Horellou¹¹ and M. van der Wild⁴

¹Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, The Netherlands

²ASTRON, The Netherlands Institute for Radio Astronomy, Postbus 2, NL-7990 AA Dwingeloo, The Netherlands

³Departamento de Física de la Tierra y Astrofísica & IPARCOS-UCM, Universidad Complutense de Madrid, E-8040 Madrid, Spain

⁴Centre for Extragalactic Astronomy, Department of Physics, Durham University, Durham DH1 3LE, UK

⁵Cavendish Laboratory–Astrophysics Group, University of Cambridge, 19 JJ Thomson Avenue, Cambridge CB3 0HE, UK

⁶Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

⁷Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, D-21029 Hamburg, Germany

⁸INAF–Istituto di Radioastronomia di Bologna, Via Gobetti 101, I-40129 Bologna, Italy

⁹Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK

¹⁰Dipartimento di Fisica e Astronomia, Università di Bologna, via P. Gobetti 93/2, I-40129 Bologna, Italy

¹¹Department of Physics and Astronomy, Chalmers University of Technology, Onsala Space Observatory, SE-43992 Onsala, Sweden

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ABSTRACT

Low-frequency radio polarimetric observations provide a powerful probe of magnetic fields in astrophysical sources and the intervening medium, as well as magnetospheric emission from compact objects such as pulsars, magnetically active stars, brown dwarfs, and planetary aurorae. With baselines of up to 2000 km, LOFAR offers a unique opportunity to study the low-frequency polarized Universe at sub-arcsecond resolution. However, polarimetric studies with LOFAR have so far been limited to angular resolutions of ~ 6 arcsec, resulting in stronger beam depolarization. Here, we present a calibration strategy that enables full-resolution polarimetric imaging with the LOFAR pan-European array. Our method applies full-Jones corrections to the international stations using an in-field unpolarized calibrator. In addition, when a sufficiently bright polarized source is present in the field, multi-epoch observations can be aligned in Faraday depth using a visibility-based correction that accounts for polarization angle and rotation measure offsets. This approach enables deeper combined imaging and deconvolution. We apply this strategy to the LOFAR ELAIS-N1 field, combining four 8-h observations for a total integration time of 32 h. At 0.3 arcsec resolution, we detect two previously known polarized sources identified in lower-resolution studies, resolve additional polarized components, and localize emission regions with sub-arcsecond precision. We also identify a new polarized source and detect circularly polarized emission from the binary M-dwarf system CR Draconis, measuring its proper motion across epochs. These results demonstrate that sub-arcsecond polarimetry at metre wavelengths is now feasible with LOFAR, opening new science opportunities in the LOFAR2.0 era.

Key words: polarization – techniques: interferometric – techniques: polarimetric – surveys – galaxies: active.

1 INTRODUCTION

Radio waves arriving from astronomical sources carry an electric field that may exhibit oscillations with a preferred direction or rotational pattern; a phenomenon called polarization. This behaviour is described using the Stokes parameters: total intensity (I), linear polarization (Q and U), and circular polarization (V). Analysing these polarized components of the signal and

their wavelength dependence provides insight into the underlying emission mechanisms, the properties of the intervening medium, and the intrinsic characteristics of the source. This is information that cannot be obtained from total-intensity measurements alone.

Radio polarization observations provide a unique probe of magnetic fields, both within astrophysical sources and in the intervening medium through which the polarized emission propagates (e.g. B. J. Burn 1966; M. A. Brentjens & A. G. de Bruyn 2005; H. K. Vedantham et al. 2020; T. Vernstrom et al. 2023; J. R. Callingham et al. 2024; S. Hutschenreuter et al. 2024; S. Vander-

* E-mail: rvweeren@strw.leidenuniv.nl

woude et al. 2024). Polarization also helps to distinguish between different emission mechanisms in galaxies, such as contributions from star formation, AGN accretion, and jets (e.g. B. Sebastian et al. 2020), and provides insight into the orientation of radio galaxies and the structure of their hotspots (e.g. P. A. Hughes, H. D. Aller & M. F. Aller 1989; V. H. Mahatma et al. 2021). Large samples of linearly polarized sources, combined with measurements of Faraday rotation, serve as powerful statistical tools to study magnetic field properties in large-scale structures such as galaxy clusters (e.g. M. Murgia et al. 2004; A. Bonafede et al. 2010; E. Osinga et al. 2022; E. De Rubeis et al. 2024; F. Loi et al. 2025; E. Osinga et al. 2025), filaments and the cosmic web (e.g. E. Carretti et al. 2022, 2025; G. V. Pignataro et al. 2025), as well as in our own Milky Way’s magnetoionic environment (e.g. J. C. Brown et al. 2007; A. R. Taylor, J. M. Stil & C. Sunstrum 2009; S. Hutschenreuter et al. 2022; M. Unger & G. R. Farrar 2024). Compared to centimetre-wavelength observations, metre-wavelength measurements can yield Faraday rotation estimates that are up to two orders of magnitude more precise, owing to the λ^2 dependence of Faraday rotation. This allows probing weak magnetic fields and studying the magnetoionic structure of diffuse cosmic plasmas. Additionally, these low-frequency observations are highly sensitive to depolarization effects, providing further constraints on the properties of intervening media in the low-density regime.

Circularly polarized emission at low radio frequencies typically originates from compact objects such as pulsars, magnetically active stars, brown dwarfs, and aurorae from planets, including potentially extrasolar planets (for an overview, see J. R. Callingham et al. 2024). This emission is often generated by coherent mechanisms, such as the electron cyclotron maser instability (ECMI), and can serve as a diagnostic of star–planet interactions or extrasolar coronal mass ejections. In the context of star–planet interactions, ECMI emission is expected to peak in the MHz regime, with the cutoff frequency directly tracing the magnetic field strength of the planet (e.g. P. Zarka 2007; S. L. G. Hess & P. Zarka 2011). As such, low-frequency polarimetric observations are crucial for detecting and characterising this emission. They provide a powerful pathway to study and constrain exoplanetary magnetospheres, offering insights into magnetic field strengths, rotation, and the surrounding plasma environment (e.g. H. K. Vedantham et al. 2023).

In recent years, the number of polarization studies of the low-frequency sky has steadily increased. For example, using the Murchison Widefield Array (MWA; S. J. Tingay et al. 2013), C. J. Riseley et al. (2018, 2020) reported 512 linearly polarized sources in the sky south of declination $+30^\circ$, at a resolution of a few arcminutes. With LOFAR (M. P. Haarlem et al. 2013), several polarization studies have been conducted at similar arcminute-scale resolution, primarily focusing on Galactic foreground emission (e.g. M. Iacobelli et al. 2013; V. Jelić et al. 2015, 2018; C. L. Van Eck et al. 2017, 2019; A. Erceg et al. 2022, 2024). An overview of some polarization-related aspects of LOFAR is provided by M. A. Brentjens (2018).

However, LOFAR also offers significantly higher angular resolution at metre wavelengths. A systematic search for linearly polarized sources in the LOFAR Two-metre Sky Survey Data Release 2 (LoTSS DR2; T. W. Shimwell et al. 2022) was performed by S. P. O’Sullivan et al. (2023), detecting 2461 sources at 20 arcsec resolution across 5720 deg^2 , with a median noise of $0.08 \text{ mJy beam}^{-1}$ in the Faraday spectra. This represents the deepest large-area low-frequency polarization survey to date. Additional studies based on LoTSS data have also been carried out (e.g. S. P. O’Sullivan

et al. 2020; C. Stuardi et al. 2020; V. H. Mahatma et al. 2021; V. Heesen et al. 2023). A large-area search for circularly polarized sources was carried out at 20 arcsec resolution at 144 MHz by J. R. Callingham et al. (2023), resulting in the detection of 68 sources within the LoTSS DR2 footprint. The median noise level in the Stokes V images was approximately $140 \text{ } \mu\text{Jy beam}^{-1}$.

The ELAIS-N1 field has become one of the best-studied regions in low-frequency polarization, as it is one of LOFAR’s deep extragalactic survey fields (C. Tasse et al. 2021; T. W. Shimwell et al. 2025). Galactic polarized emission in this field has been explored at 3–4 arcmin resolution by V. Jelić et al. (2014) and I. Šnidarić et al. (2023). Discrete sources were investigated by N. Herrera Ruiz et al. (2021) at 20 arcsec resolution, achieving a median noise of $26 \text{ } \mu\text{Jy beam}^{-1}$ and detecting 10 sources, corresponding to a polarized source density of 0.8 deg^{-2} . More recently, S. Piras et al. (2024, 2025) probed the field at the full angular resolution of LoTSS (6 arcsec) using 152 h of LoTSS deep-field data, detecting 31 sources with a median noise of $19 \text{ } \mu\text{Jy beam}^{-1}$, yielding a polarized source density of 1.24 deg^{-2} .

Since the first LoTSS data release (T. W. Shimwell et al. 2017), we have known that the majority of radio sources detected by LOFAR at 6 arcsec resolution remain unresolved (see also F. Sweijen et al. 2025). This lack of spatial resolution limits our ability to study the polarization structure across sources and may result in significant beam depolarization, thereby reducing the number of polarized sources that can be detected (e.g. S. P. O’Sullivan et al. 2018). LOFAR’s international (European) baselines, extending up to 2000 km, provide significantly higher angular resolution, reaching $\sim 0.3 \text{ arcsec}$ within the typical LoTSS observing band of 120–168 MHz (e.g. L. K. Morabito et al. 2022, 2025; F. Sweijen et al. 2022). This enables sub-arcsecond resolution polarimetric studies and, for example, allows structures on sub-kpc scales to be probed at $z = 0.1$, typically resolving the hotspots of radio galaxies into complex morphologies. However, until now, no comprehensive strategy for full-polarization calibration and imaging at this resolution has been developed or demonstrated.

In this work, we present a strategy to perform full-polarization calibration using LOFAR’s international baselines. We apply and validate this approach using observations of the ELAIS-N1 field. This field was previously imaged by J. M. G. H. J. Jong et al. (2024) at resolutions of 1.2, 0.6, and 0.3 arcsec over the full LOFAR international station’s field of view ($2.5^\circ \times 2.5^\circ$), reaching a central Stokes I map noise of $14 \text{ } \mu\text{Jy beam}^{-1}$ at 0.3 arcsec resolution.

The paper is structured as follows. Section 2 describes the ELAIS-N1 observations used in this study. In Section 3, we outline the calibration steps required, building upon the framework developed by J. M. G. H. J. Jong et al. (2024) and J. M. G. H. J. Jong et al. (2025a). The results are presented in Section 4, followed by discussion and conclusions in Sections 5 and 6, respectively.

2 DATA

We make use of four calibrated 8-h LOFAR observations from the ELAIS-N1 Deep Field, originally analysed by J. M. G. H. J. Jong et al. (2024). These observations, L686962, L769393, L798074, and L816272, were taken between 2018 and 2021 and selected based on having international LOFAR stations and good ionospheric conditions, as detailed in J. M. G. H. J. Jong et al. (2024)’s section 2. The observations include baselines up to 1980 km in length and frequencies from 115 to 166 MHz. All four observations use 3C 295 as the primary calibrator. Two of the data sets (L798074 and L816272) were originally archived with a 2 s time resolution,

which is twice the typical 1 s resolution for LOFAR, introducing additional time smearing effects at larger angular distances from the pointing centre (see fig. 1 in J. M. G. H. J. Jong et al. 2024). Due to the calibration on the in-field calibrator (see Section 3.1), the astrometric accuracy achieves median offsets in right ascension and declination of less than 0.1 arcsec. The flux density is also consistent with radio maps made at the same frequencies with LOFAR at 6 arcsec resolution by J. Sabater et al. (2021) and T. W. Shimwell et al. (2025). With the calibrated visibility data retained, we can re-image the observations at different resolutions, explore different Briggs weightings, and adjust other imaging parameters using the WSCLEAN imager with its WGRIDDER module (A. R. Offringa et al. 2014; P. Arras et al. 2021; H. Ye et al. 2022).

3 CALIBRATION

The polarization calibration of LOFAR international baseline data consists of several steps. These include a station-based correction for ionospheric Faraday rotation, based on a global ionospheric model using RMEXTRACT (M. Mevius 2018).¹, which is a standard part of LOFAR processing carried out by LINC² and is not specific to international baseline observations. A subsequent step is a full-Jones polarization calibration for the Dutch LOFAR stations, performed by the LoTSS DDF-pipeline³ (C. Tasse 2014a, b; O. M. Smirnov & C. Tasse 2015; T. W. Shimwell et al. 2019; C. Tasse et al. 2021). The final steps are specific to the international baselines and are discussed below for both an unpolarized and a polarized calibrator.

3.1 Unpolarized calibrator

As part of the LOFAR calibration strategy for observations including international stations, a high-signal-to-noise-ratio (S/N) in-field calibrator is selected from the Long-Baseline Calibrator Survey (LBCS; N. Jackson et al. 2022). This source is typically among the brightest objects in the field, providing sufficient S/N on the international baselines. Given the high-S/N requirement for calibrating at a fine time and frequency resolution, driven by the rapidly varying ionosphere, such a source is well suited not only for correcting scalar Stokes I effects but also for solving for polarization leakage terms.

For polarization calibration, the in-field calibrator must be unpolarized ($\ll 1$ per cent) in the HBA band (about 115–170 MHz). For the ELAIS-N1 observations, the Seyfert 2 galaxy ICRF J160607.6+552135 was selected as the calibrator (P. Charlot et al. 2020; R. O. Sexton et al. 2022), and has previously been shown to be unpolarized at LOFAR frequencies in linear and circular polarization (N. Herrera Ruiz et al. 2021; J. R. Callingham et al. 2023). In addition, the source remains unpolarized in higher frequency Very Long Baseline Array (VLBA) observations (S. E. Tremblay et al. 2016). Furthermore, the source is unresolved at the longest LOFAR baselines and has a flux density of about 0.3 Jy in the LOFAR HBA band.

We now highlight a few key calibration steps that are discussed in detail by J. M. G. H. J. Jong et al. (2024) and are specific to polarization calibration. The direction-independent

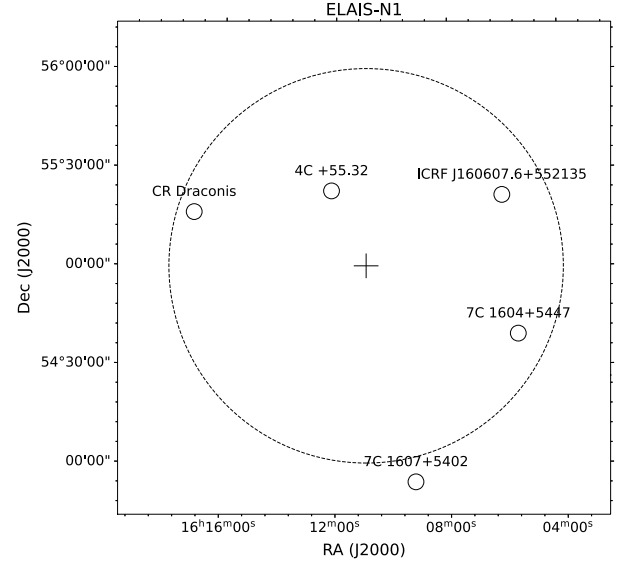


Figure 1. Location of the sources discussed in this work within the ELAIS-N1 field. The unpolarized calibrator is ICRF J160607.6+552135, and the polarized calibrator is 7C 1604+5447. The cross marks the field centre, while the dashed circle indicates a radius of 1° .

full-Jones solutions from the DDF-pipeline were carried over as a starting point for the calibration of the other international LOFAR stations. These stations were calibrated with FACET-SELFAL (R. J. Weeren et al. 2021)⁴, using a point-source sky model of ICRF J160607.6+552135. The model incorporates a well-constrained radio spectrum derived from multiple radio surveys, together with a precise astrometric position from P. Charlot et al. (2020), accurate to approximately 2 mas in both right ascension and declination. The location of this source within the $2.5^\circ \times 2.5^\circ$ ELAIS-N1 field is indicated in Fig. 1. The first calibration step corrects for differences between right-handed (RR) and left-handed (LL) circular polarizations by solving for their relative phase offset, which can include contributions from differential Faraday rotation. In a circular polarization basis, differential Faraday rotation reduces to a simple phase difference between the two circular hands. For the ELAIS-N1 field, this calibration was applied using 8-min solution intervals with a frequency smoothness kernel of 10 MHz. After polarization-independent phase and amplitude corrections, a longer time-scale full-Jones correction for instrumental leakage effects was applied to also correct the RL and LR cross-hands. This was done with a solution interval of 20 min and a frequency smoothness kernel of 5 MHz. Since full-Jones corrections for the Dutch LOFAR stations from the DDF-pipeline were already carried over, these stations were constrained to have the same solutions for the full-Jones solve. During calibration, short baselines were ignored by using a uv -limit of 20 k λ , which corresponds to a largest angular scale of about 10 arcsec at 140 MHz. In addition, for these steps the data are phase-shifted and averaged to a frequency resolution of 488 kHz and a time resolution of 32 s. Both this averaging and the exclusion of short baselines during the calibration solve help mitigate the effects of incomplete sky models arising from other sources within the station's primary beam, as these sources are suppressed through fringe washing. This includes potentially

¹<https://pypi.org/project/RMextract/>; Predecessor of spinifex (<https://pypi.org/project/spinifex/>).

²<https://git.astron.nl/RD/LINC/>

³<https://github.com/mhardcastle/ddf-pipeline>

⁴github.com/rvweeren/lofar_facet_selfcal

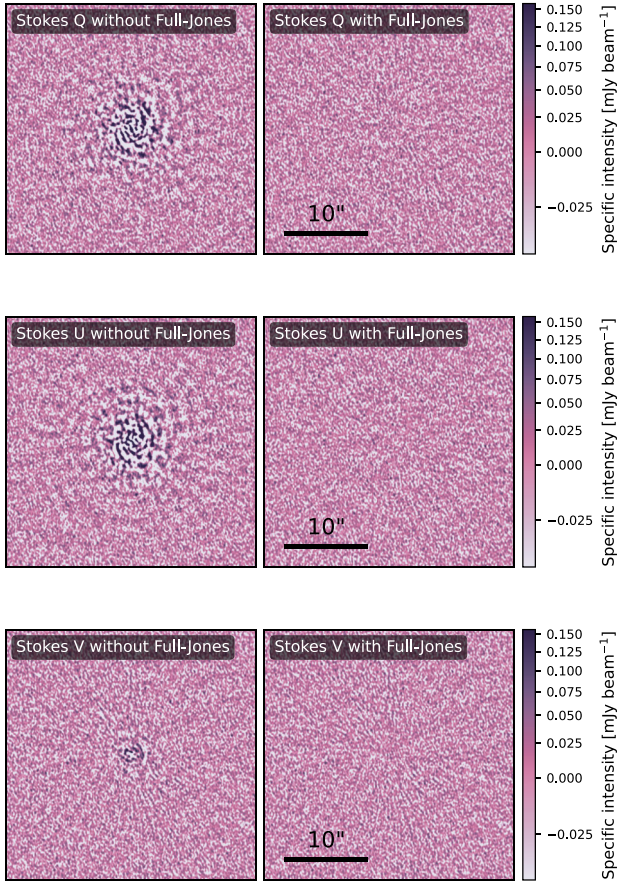


Figure 2. Stokes Q , U , and V images of the unpolarized infield calibrator ICRF J160607.6+552135 with full-Jones calibration applied (*right panels*) and without (*left panels*). A $10''$ scale bar is added in the right panels.

polarized sources. The core stations can also be phased up into a superstation to further suppress contributions from sources elsewhere in the primary beam and to reduce processing time (L. K. Morabito et al. 2022); however, this was not necessary for the ELAIS-N1 field observations.

By creating Stokes Q , U , and V images before and after applying the full-Jones calibration, we confirm that this step successfully corrects the data, forcing the Stokes Q , U , and V emission of the calibrator source to zero, as intended. Fig. 2 shows the corresponding images with and without the full-Jones calibration, clearly demonstrating the removal of calibration artefacts. In Section 4.3, we assess the sensitivity of the Stokes I to the linear and circular polarization leakage using the source 4C +55.32, which has the highest integrated Stokes I flux density in the field.

When working with sources other than the in-field (unpolarized) calibrator, such as the sources discussed in Sections 3.2 and 4, we always apply the additional direction-dependent corrections derived in J. M. G. H. J. Jong et al. (2024). These are scalar corrections and are therefore not polarization specific. We do not apply direction-dependent differential Faraday rotation corrections, as the bulk of this effect is already removed through the in-field calibrator. The remaining direction-dependent differential Faraday rotation terms are expected to be very small, with magnitudes $\ll 1$ rad, and therefore do not require additional correction.

3.2 Polarized calibrator

Although each of the four LOFAR observing epochs was corrected for the bulk ionospheric Faraday rotation, residual offsets in the polarization angles between epochs may remain, at the level of ~ 0.1 – 0.3 rad m^{-2} (e.g. C. Sotomayor-Beltran et al. 2013), larger than the typical rotation measure (RM) precision obtained with these data.

To correct for these residual offsets, the observations must be aligned in Faraday depth using a linearly polarized reference source (e.g. C. A. Hales 2017; S. Piras et al. 2024). This polarized source needs to have an $|\text{RM}| \gtrsim 1$ rad m^{-2} to avoid potential confusion with any leftover polarization leakage from imperfect calibration contaminating the region around zero Faraday depth.

We selected the source 7C 1604+5447 to carry out the Faraday depth alignment. This was the source with the highest S/N in polarized intensity previously detected with LOFAR in this field by S. Piras et al. (2024). The location of 7C 1604+5447 within the ELAIS-N1 field is indicated in Fig. 1. For this source, S. Piras et al. reported an RM of 6.062 ± 0.003 rad m^{-2} . We applied the solutions derived from the unpolarized in-field calibrator, including the necessary correction using the full-Jones station beam model. We then phase-shifted the data to the position of 7C 1604+5447, again applying the station beam correction, now evaluated in the direction of 7C 1604+5447. Since the full-Jones correction does not commute with the station beam correction, these terms must be applied in the correct order (for details, see section 3.3.1 of J. M. G. H. J. Jong et al. 2024).

As 7C 1604+5447 has an angular extent of approximately 15 arcsec and is well resolved on the long baselines of LOFAR, we first performed RM-synthesis to identify more precisely the region from which the polarized emission originates. From the resulting maximum linearly polarized intensity map, we find that the vast majority of the polarized emission arises from the southern hotspot. For further details on the RM-synthesis procedure and the scientific results for this source, we refer the reader to Sections 3.3 and 4.2, respectively.

We extracted integrated Stokes Q and U flux densities from 125 channel maps by summing the flux within the southern hotspot region for each channel. Using these measurements at 125 frequencies, we plot in Fig. 3 the polarization angle χ ,

$$\chi = \frac{1}{2} \arctan\left(\frac{U}{Q}\right), \quad (1)$$

as a function of wavelength squared (λ^2) for the four observing epochs. We adopt observation L686962 as the reference epoch, as it provided the highest data quality and the lowest noise levels.

For a single Faraday-rotating screen, the polarization angle varies with wavelength squared as

$$\chi(\lambda^2) = \chi_0 + \text{RM} \lambda^2, \quad (2)$$

where χ_0 is the intrinsic polarization angle in the absence of Faraday rotation.

As can be seen in Fig. 3, the polarization angles of the four observing epochs are not aligned with respect to the reference observation, exhibiting systematic offsets. To quantify these offsets⁵, we fit the following parametrisation to the observed $\chi(\lambda^2)$ for each epoch:

$$\chi(\lambda^2) = \chi_{\lambda_0^2} + \text{RM}(\lambda^2 - \lambda_0^2), \quad (3)$$

⁵these are also called Xf-terms in CASA (J. P. McMullin et al. 2007)

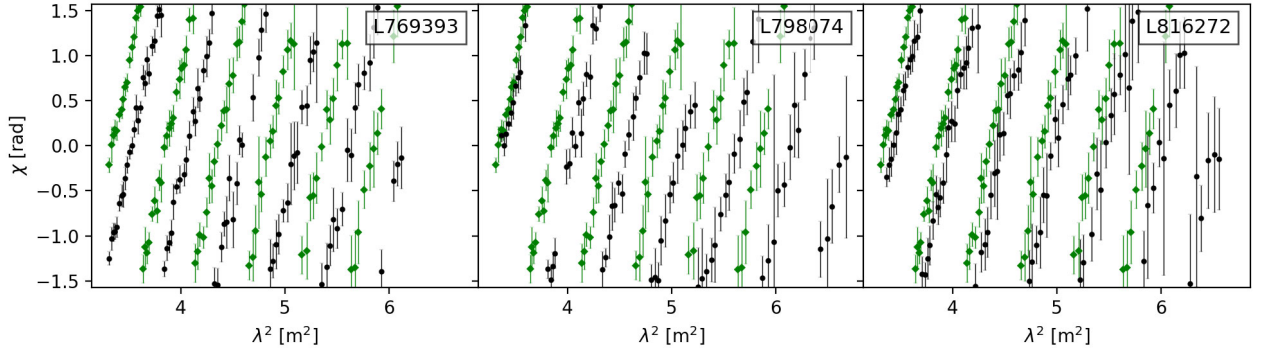


Figure 3. The polarization angle (χ) as a function of the wavelength squared (λ^2) for our reference observation L686962 in green and the three other observations in black.

where $\chi_{\lambda_0^2}$ is the polarization angle at a central wavelength squared λ_0^2 .

The fit is performed using `scipy.optimize.curve_fit` by modelling the fractional Stokes parameters

$$q(\lambda^2) = p \cos \left\{ 2 \left[\text{RM}(\lambda^2 - \lambda_0^2) + \chi_{\lambda_0^2} \right] \right\}, \quad (4)$$

$$u(\lambda^2) = p \sin \left\{ 2 \left[\text{RM}(\lambda^2 - \lambda_0^2) + \chi_{\lambda_0^2} \right] \right\}, \quad (5)$$

and minimizing the combined residuals of q and u , where p is the polarization fraction with $p = \sqrt{Q^2 + U^2}/I$. The fractional polarizations $q = Q/I$ and $u = U/I$ are therefore insensitive to the absolute Stokes I intensity. The fractional polarizations q and u were computed by dividing the measured Stokes Q and U values by a model for Stokes I , rather than by the measured Stokes I value in each channel, to avoid propagating noise or systematic errors present in I but not in Q and/or U . The Stokes I model was obtained by fitting a simple power-law spectrum of the form $S_\nu = S_0 \nu^\alpha$, where S_ν is the Stokes I flux density and α is the spectral index. We note that an alternative approach would be to derive the RM and polarization angle directly from the peak of the Faraday dispersion function. This approach is advantageous when multiple Faraday components are present, for example, due to a significant leakage signal. However, this is not the case for 7C 1604+5447 (see Fig. 5), and we therefore adopt the ‘*qu*-fitting’ approach described above.

We adopt $\lambda_0^2 = 4.5 \text{ m}^2$, corresponding approximately to the mean λ^2 of our observations. From the fitted parameters, we compute the differences relative to the reference observation L686962 as

$$\Delta\chi_0 = \chi_0 - \chi_0^{\text{ref}}, \quad \Delta\text{RM} = \text{RM} - \text{RM}^{\text{ref}}. \quad (6)$$

The required correction to the visibility cross-hand phase as a function of wavelength squared is then given by

$$\theta_{\text{corr}}(\lambda^2) = 2 \left[\Delta\chi_0 + \Delta\text{RM}(\lambda^2 - \lambda_0^2) \right] \quad (7)$$

$$= 2 \left(\Delta\chi_0 - \Delta\text{RM} \lambda_0^2 \right) + 2 \Delta\text{RM} \lambda^2 \quad (8)$$

where $\theta_0 = 2(\Delta\chi_0 - \Delta\text{RM} \lambda_0^2)$ is the intercept of the cross-hand phase correction.

In Table 1, we give the RM and θ_0 values that we found for each of the observations. Applying the corresponding frequency-dependent corrections on the visibilities allows us to align all observations (C. A. Hales 2017). An advantage of applying these corrections directly to the visibilities is that it enables deep polar-

Table 1. RM and θ_0 values for different observations. The reference observation ID is highlighted in bold. The three other observations are then corrected (equation 8) to match the reference observation so that all observations can be jointly imaged.

Observation ID	RM (rad m ⁻²)	θ_0 (deg)
L686962	6.30 ± 0.02	0.9 ± 1.5
L769393	5.97 ± 0.02	-6.9 ± 1.6
L798074	5.69 ± 0.02	-17.6 ± 1.6
L816272	6.11 ± 0.01	1.6 ± 1.3

ization imaging with visibility data from all observations together. This contrasts with imaging observations separately and applying corrections in image space, followed by image stacking, as done for example by N. Herrera Ruiz et al. (2021); S. Piras et al. (2024), where the fainter polarized signal only detected in the deeper combined data would not be deconvolved during imaging.

3.3 RM-synthesis

To search for linearly polarized emission, we performed RM-synthesis, which enables an efficient search for polarized emission as a function of Faraday depth (M. A. Brentjens & A. G. de Bruyn 2005). We used the RM-TOOLS package to perform the RM-synthesis (C. R. Purcell et al. 2020; C. L. Van Eck et al. 2026).

The input to the RM-synthesis consists of Stokes Q and U channel maps. In this work, the number of frequency channels per observation ranges between 115 and 125, reflecting the slightly different frequency coverage of the four observing epochs, although all observations share the same channel width. When combining the full 32 h data set, we therefore produced Q and U channel maps using WSCLEAN with the option `-pol QU -channels-out 125`, where the 125 channels correspond to the full frequency coverage when the four observations are jointly imaged. For the alignment of the individual observing epochs, described in Section 3.2, the number of output channels was adjusted to match the actual channel count of each observation.

To enable deep cleaning, we used the WSCLEAN options `-join-polarization`, `-join-channels`, `-squared-channel-joining`, and `-fit-rm`. In addition, we applied a Gaussian uv -taper, chosen to correspond to a specific angular scale on the sky, to achieve a similar angular resolution across all channel maps. The images were subsequently restored with

identical beams. These Q and U channel maps were then used as input for the two-dimensional RM-synthesis⁶.

Following M. A. Brentjens & A. G. de Bruyn (2005), the maximum observable Faraday depth to which one has more than 50 per cent sensitivity is given by

$$|\phi_{\max}| = \frac{\sqrt{3}}{\delta\lambda^2}, \quad (9)$$

where $\delta\lambda^2$ (0.0254 m^2) is the width in λ^2 corresponding to a single frequency channel. For our data, this gives $|\phi_{\max}| = 68 \text{ rad m}^{-2}$, computed from the channel frequency resolution (390.625 kHz) at the average observing frequency of 140.2 MHz. The original data have a frequency resolution that is at least four times finer, which would in principle allow a search up to $\pm 272 \text{ rad m}^{-2}$. However, note that well below this value, depolarization effects already become important. Thus, for studies in which one expects large RMs, or in cases where there are no previous estimates of them, the loss in S/N can be quite significant due to the bandwidth depolarization effect (M. A. Fine, C. L. Van Eck & L. Pratley 2023). Therefore, as a general rule, it is advisable to choose a tailored channel width that minimizes S/N losses to maximize polarization detection. This can be estimated with the `rmtools_bwpredict` tool in RM-Tools, based on the adjoint transform method developed in M. A. Fine et al. (2023) (see fig. 6 in their paper).

The largest scale in Faraday depth to which our data are sensitive is given by

$$\text{max-scale} = \frac{\pi}{\lambda_{\min}^2}, \quad (10)$$

where $\lambda_{\min}^2$ corresponds to the shortest wavelength (1.8145 m) of the observations. This value is 0.95 rad m^{-2} . Since this value is comparable to the resolution in Faraday depth space, the data are only sensitive to Faraday-thin (i.e. unresolved) emission.

For the RM-synthesis, we sampled the Faraday dispersion function in steps of 0.3 rad m^{-2} over the range -30 to $+30 \text{ rad m}^{-2}$. Previous studies (N. Herrera Ruiz et al. 2021; S. Piras et al. 2024, 2025) show that essentially all detected radio sources in the ELAIS-N1 field have RM values of $\lesssim \pm 20 \text{ rad m}^{-2}$. A larger Faraday depth range could be explored in future work. The input Stokes Q and U images were weighted by the inverse of their variances in order to optimize the sensitivity to faint polarized emission in Faraday depth space. In Fig. 4, we show the Rotation Measure Spread Function (RMSF) of our data.

We applied RM-CLEAN (G. Heald, R. Braun & R. Edmonds 2009) to remove sidelobes introduced by the RMSF. The clean components were restored with a Gaussian of full width at half maximum (FWHM) of 1.09 rad m^{-2} , corresponding to the resolution in Faraday depth space and the adopted ‘variance’ parameter in RM-Tools. Within RM-Tools, we used a cleaning threshold of 0.15 mJy , a standard gain of 0.1 , and a maximum of 1000 clean iterations.

For polarized source components detected in the Faraday cubes, we performed an additional one-dimensional RM-synthesis step on each detected feature, rather than on a per-pixel basis as described above. This approach allows for summation of the signal and finer sampling along the Faraday depth axis over a larger Faraday depth range, enabling more accurate decon-

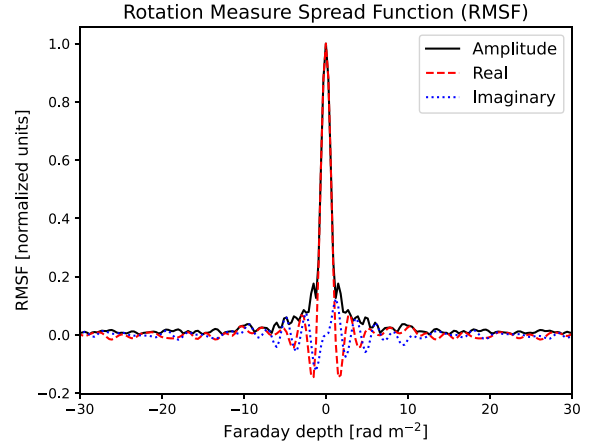


Figure 4. Rotation measure spread function (RMSF) corresponding to the observations used in this work. The RMSF amplitude is shown by the black solid line. The real component is indicated by the red dashed line, and the imaginary component by the blue dotted line.

volution and deeper cleaning. Performing this at full resolution with a two-dimensional RM-synthesis would otherwise result in prohibitively large data cubes.

We summed the Stokes Q and U flux densities over the relevant pixels to obtain integrated spectra, which were then provided to RM-Tools to perform a one-dimensional RM-synthesis using ‘variance’ weighting with a sampling of 0.11 rad m^{-2} over a Faraday depth range of -60 to 60 rad m^{-2} . RM-CLEAN was applied, with the cleaning going down to a threshold of $3 \sigma_{\text{rms}}$.

4 RESULTS

In this section, we evaluate the results obtained from the full 32 h data set after applying the polarization angle alignment procedure described in Section 3.2. We begin with an overview of the achieved noise levels in Stokes Q , U , and V . We then demonstrate the performance of our polarization calibration strategy through an analysis of the polarization angle calibrator 7C 1604+5447, the brightest radio source in the field, 4C +55.32, and an additional polarized source 7C 1607+5402, previously detected by LOFAR.

For the circular polarization Stokes V , we investigate the properties of CR Draconis, the only source detected in circular polarization in the LoTSS data for this field (J. R. Callingham et al. 2023). A systematic search for and characterisation of all polarized sources in the ELAIS-N1 field at sub-arcsecond resolution will be presented in future work.

4.1 Polarization image depth

To directly compare the image depths between the Stokes I images from J. M. G. H. J. Jong et al. (2024) and our Stokes Q , U , and V images, we imaged the central region of the field. In Table 2, we provide the different RMS levels for Stokes I , Q , U , and V for the three different resolutions from J. M. G. H. J. Jong et al. (2024). The close agreement between the four Stokes parameters indicates that the images are effectively thermal-noise limited (given the visibility weighting scheme), with minimal contamination from polarization leakage. The same noise levels in Stokes Q and U suggest that cross-hand calibration and primary beam polariza-

⁶Here, ‘two-dimensional’ refers to the fact that we perform RM-synthesis on two-dimensional images with right ascension and declination axes.

Table 2. RMS noise levels for different Stokes parameters at different resolutions in $\mu\text{Jy beam}^{-1}$.

Resolution	I	Q	U	V
0.3 arcsec	14	14	14	14
0.6 arcsec	21	22	22	21
1.2 arcsec	40	39	39	37

tion corrections are performing well. At 1.2 arcsec resolution, we find the largest difference between the rms noise levels of Stokes *I* and Stokes *V*. This likely arises because the calibration was performed at 0.3 arcsec, and residual calibration artefacts, particularly due to issues with calibrating the Dutch remote stations and possibly due to gaps in the uv-coverage (H. Ye et al. 2024), become more pronounced at the coarser 1.2 arcsec resolution in Stokes *I*. This issue has recently been addressed by J. M. G. H. J. Jong et al. (2025a), who implemented an improved calibration strategy for the Dutch LOFAR stations when combined with the international LOFAR stations.

In general, the LOFAR point spread function (PSF) deviates strongly from a simple Gaussian shape. Its structure depends on the adopted weighting scheme, any applied *uv*-tapers, and whether stations are phased up, in combination with the highly non-uniform distribution of stations on different spatial scales. To optimize for different science goals, it is therefore beneficial to tailor the weighting scheme to maximize the signal-to-noise ratio of the polarized emission of interest. For example, simply convolving an image with a Gaussian to a lower angular resolution to enhance sensitivity to extended emission may yield different detectability than adopting an alternative weighting scheme that modifies the PSF structure in a more complex way.

4.2 7C 1604+5447

The polarization angle alignment calibrator 7C 1604+5447 is an FR II type (B. L. Fanaroff & J. M. Riley 1974) radio galaxy (B.-Q. Lao et al. 2024) with a largest angular extent of 15 arcsec. Hotspots are visible for both the northern and southern lobes in our LOFAR 0.3 arcsec resolution Stokes *I* image, see Fig. 5 (left panel). The source is located at a spectroscopic redshift of $z = 0.7683$ (DESI Collaboration 2025). Polarized emission from this source has been previously reported at 1.4 GHz (J. J. Condon et al. 1998; A. R. Taylor et al. 2007; A. R. Taylor et al. 2009; J. K. Grant et al. 2010; J. S. Farnes, B. M. Gaensler & E. Carretti 2014). At 144 MHz at 6 arcsec resolution, the source has an integrated flux density of 1.572 Jy and is catalogued as ILT J160538.32+543922.6 (T. W. Shimwell et al. 2022). LOFAR observations at 20 arcsec resolution by N. Herrera Ruiz et al. (2021) showed polarized emission from the southern lobe, which was imaged in more detail at 6 arcsec resolution by S. Piras et al. (2024, 2025).

In our 0.3 arcsec LOFAR linearly polarized intensity image (left panel Fig. 5), the polarized emission predominantly originates from the southern hotspot, with additional faint emission extending northwards. At a resolution of 6 arcsec, this emission could not be spatially separated from that of the southern hotspot, see Fig. 6. We also detect faint polarized emission from the northern hotspot. For the southern hotspot, we measure an RM of $6.285 \pm 0.008 \text{ rad m}^{-2}$ (right panel Fig. 5). For the faint lobe emission located just north of the southern hotspot, we find an RM of $5.65 \pm 0.05 \text{ rad m}^{-2}$, indicating a significant difference with respect to the RM of the southern hotspot. This slightly lower RM is also visible in the Faraday depth spectrum shown in Fig. 5 (right panel), where the blue spectrum peaks at a lower Faraday depth than the black spectrum. For the northern hotspot, we measure an RM of $6.05 \pm 0.08 \text{ rad m}^{-2}$. A RM map of the

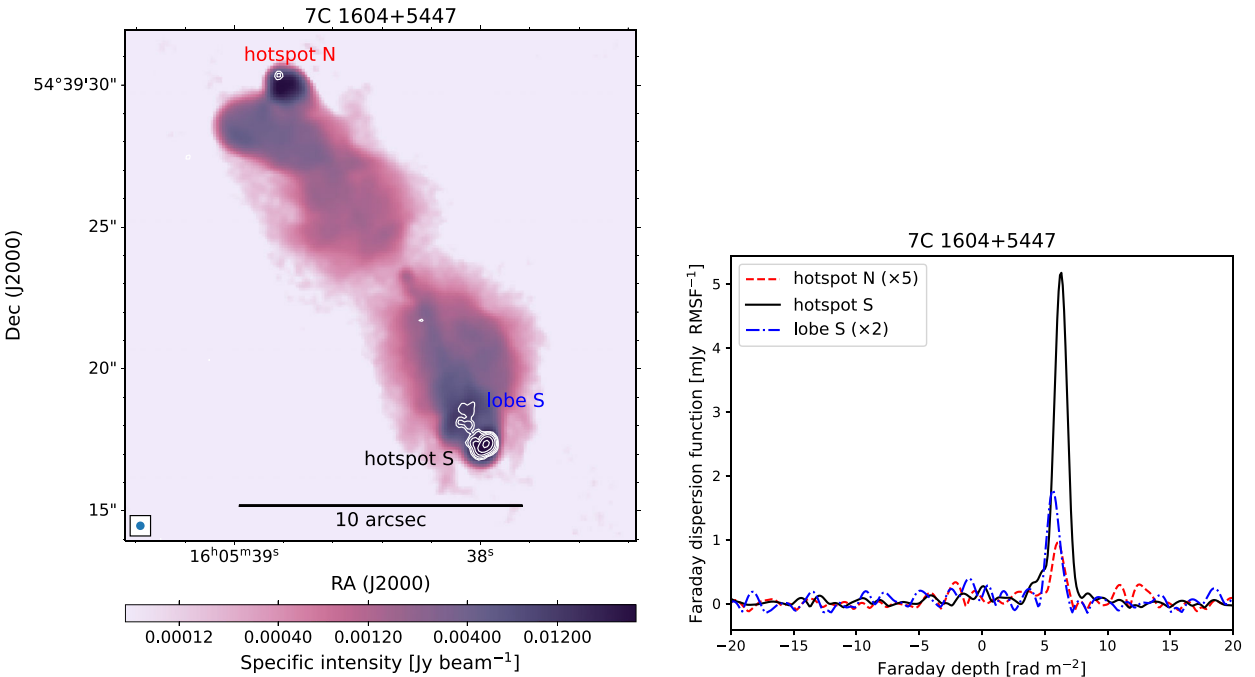


Figure 5. Left panel: Stokes *I* image of 7C 1604+5447 at a resolution of 0.3 arcsec. Linearly polarized intensity contours are overlaid at levels of $6 \times \sigma_{\text{rms},P}$ [1, 2, 4, 8, ...], with $\sigma_{\text{rms},P} = 8 \mu\text{Jy beam}^{-1}$ the noise level in the polarized intensity image. Right panel: Faraday dispersion function for various regions across the source. To improve visibility, the spectra corresponding to the fainter northern hotspot and ‘lobe S’ are scaled by factors of 5 and 2, respectively. The uncleaned (dirty) Faraday spectra are shown in Figs B1, B2, and B3.

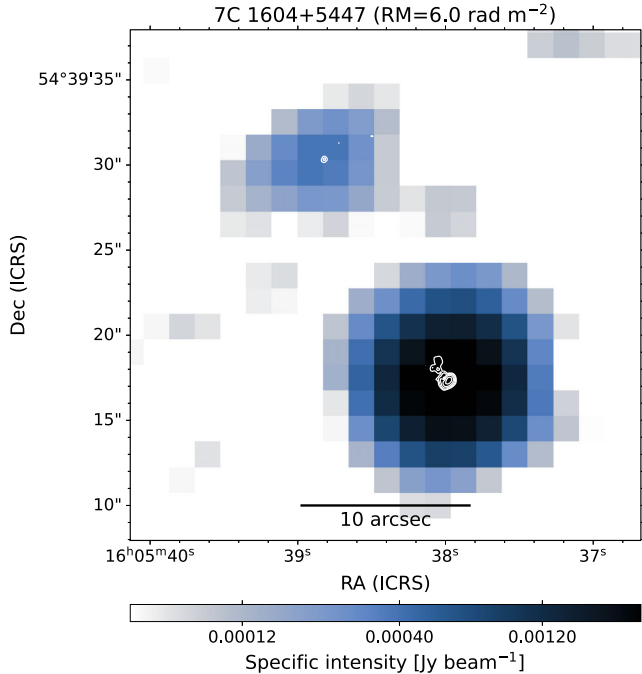


Figure 6. Comparison of polarized intensity images extracted from the Faraday cube at a Faraday depth of $RM = 6 \text{ rad m}^{-2}$, shown at angular resolutions of 6 arcsec (colour scale) and 0.3 arcsec (contours). Contours are drawn at levels of 5, $\sigma_{\text{rms},P}$, [1, 2, 4, 8, ...], where $\sigma_{\text{rms},P}$ denotes the rms noise in polarized intensity. The 6 arcsec image was obtained by excluding the international stations prior to imaging.

polarized emission from the southern lobe is shown in Fig. A1 in Appendix A.

Given the high signal-to-noise detection of the southern hotspot, we can further characterize its polarization properties as a function of wavelength, including the polarization fraction. These results are shown in Fig. 7 (left panel). S. Piras et al. (2024) reported a polarization fraction of 1.75 per cent for the peak pixel in polarized intensity at 6 arcsec resolution, while N. Herrera Ruiz et al. (2021) reported a lower value of 0.41 per cent at 20 arcsec resolution. In our high-resolution data, we measure a polarization fraction of ~ 0.6 per cent at the longest wavelengths, increasing to ~ 4 per cent at the shortest wavelengths, clearly indicating wavelength-dependent depolarization. We thus fitted these data with an external Faraday rotation depolarization model of the form

$$P(\lambda^2) = p_0 \exp(-2\Sigma_{\text{RM}}^2 \lambda^4) \exp\left[2i\left(\chi_{\lambda_0^2} + \text{RM}(\lambda^2 - \lambda_0^2)\right)\right], \quad (11)$$

where p_0 is the intrinsic polarization fraction and Σ_{RM} is the Faraday dispersion within the integration area. This model has the same form as equations (4) and (5), but includes an exponential depolarization term. From this fit we obtain a Faraday dispersion of $\Sigma_{\text{RM}} = 0.172 \pm 0.086 \text{ rad m}^{-2}$.

A hint of a faint jet-like feature appears to extend southwards from the nucleus (Fig. 5), while no jet emission is detected to the north. This asymmetry suggests that the southern jet is relativistically beamed and oriented closer to our line of sight. The band-averaged polarization fractions of the northern and southern hotspots, 2.12 ± 0.01 per cent and 0.55 ± 0.06 per cent, respectively, may therefore provide evidence for the Laing–Garrington effect (S. T. Garrington et al. 1988; R. A. Laing 1988). In this

scenario, the approaching jet is Doppler boosted, placing its associated lobe closer to the observer, such that the radiation traverses a smaller column of the host galaxy’s Faraday-rotating plasma and is consequently less depolarized.

4.3 4C +55.32

4C +55.32 is an FR II radio source (B.-Q. Lao et al. 2024). The source has an optical counterpart (M. J. Hardcastle et al. 2023) at a spectroscopic redshift of $z = 0.22795$ (S. Alam et al. 2015). The integrated flux density at 144 MHz is 3.23 Jy (ILTJ161212.30+552303.7; T. W. Shimwell et al. 2022). polarized emission from 4C +55.32 has previously been detected at 1.4 GHz (J. J. Condon et al. 1998; A. R. Taylor et al. 2009; J. K. Grant et al. 2010; J. S. Farnes et al. 2014), but the source was not detected in earlier LOFAR polarization studies.

In Fig. 8, the 0.3 arcsec resolution Stokes I image shows two main lobes, with the northern lobe being more extended than the southern one. In addition, extended emission is visible between the two radio lobes. Both lobes exhibit a double-hotspot structure. In the linearly polarized intensity image, we detect polarized emission from this source at low radio frequencies for the first time. The polarized emission originates from the double-hotspot region at the outer edge of the southern lobe. The Faraday dispersion function peaks at $RM = -1.25 \pm 0.01 \text{ rad m}^{-2}$ for the emission. The detailed polarization properties of 4C +55.32 as a function of wavelength are shown in Fig. 7 (right panel). We find a polarization fraction of ~ 0.4 per cent at the longest wavelengths, increasing to ~ 2 per cent at the shortest wavelengths. Fitting the external depolarisation model from equation (11), we obtain a Faraday dispersion of $\Sigma_{\text{RM}} = 0.164 \pm 0.082 \text{ rad m}^{-2}$.

The source was likely missed in previous LOFAR searches for polarized emission because its polarized signal peaks at a Faraday depth close to the region affected by contamination around zero RM (right panel Fig. 8). The leakage signal (i.e. instrumental polarization) is intrinsically centred at 0 rad m^{-2} . This leakage signal is broadened by the ionospheric RM correction and the RMSF, which has a typical magnitude of $\mathcal{O}(1 \text{ rad m}^{-2})$. A comparison with the RM spectrum extracted from the northern double hotspot region, which has a similar total intensity, shows that the polarized signal from the southern lobe is not dominated by instrumental leakage. The level of contamination, estimated from the northern hotspot region, is approximately an order of magnitude lower. Moreover, the polarized emission from the southern lobe is clearly offset in Faraday depth from the peak associated with leakage.

Assuming that all observed polarized emission from the northern double-hotspot region is due to instrumental leakage, as it peaks at zero Faraday depth, we use this signal to estimate the fractional leakage from Stokes I into linear polarization in our data. We do so by dividing the maximum detected linearly polarized intensity at the northern hotspot by the corresponding Stokes I flux density, yielding a leakage level of 0.11 per cent. Using the same method, we compute the Stokes I to Stokes V leakage, finding a value of 0.021 per cent.

In the LoTSS survey, the typical instrumental polarization leakage is approximately 0.2 per cent from Stokes I into Stokes Q/U , and 0.056 per cent from Stokes I into Stokes V (T. W. Shimwell et al. 2022). A caveat of our analysis is that this estimate is based on a single measurement; the leakage level is expected to vary with angular separation from the polarization leakage calibrator

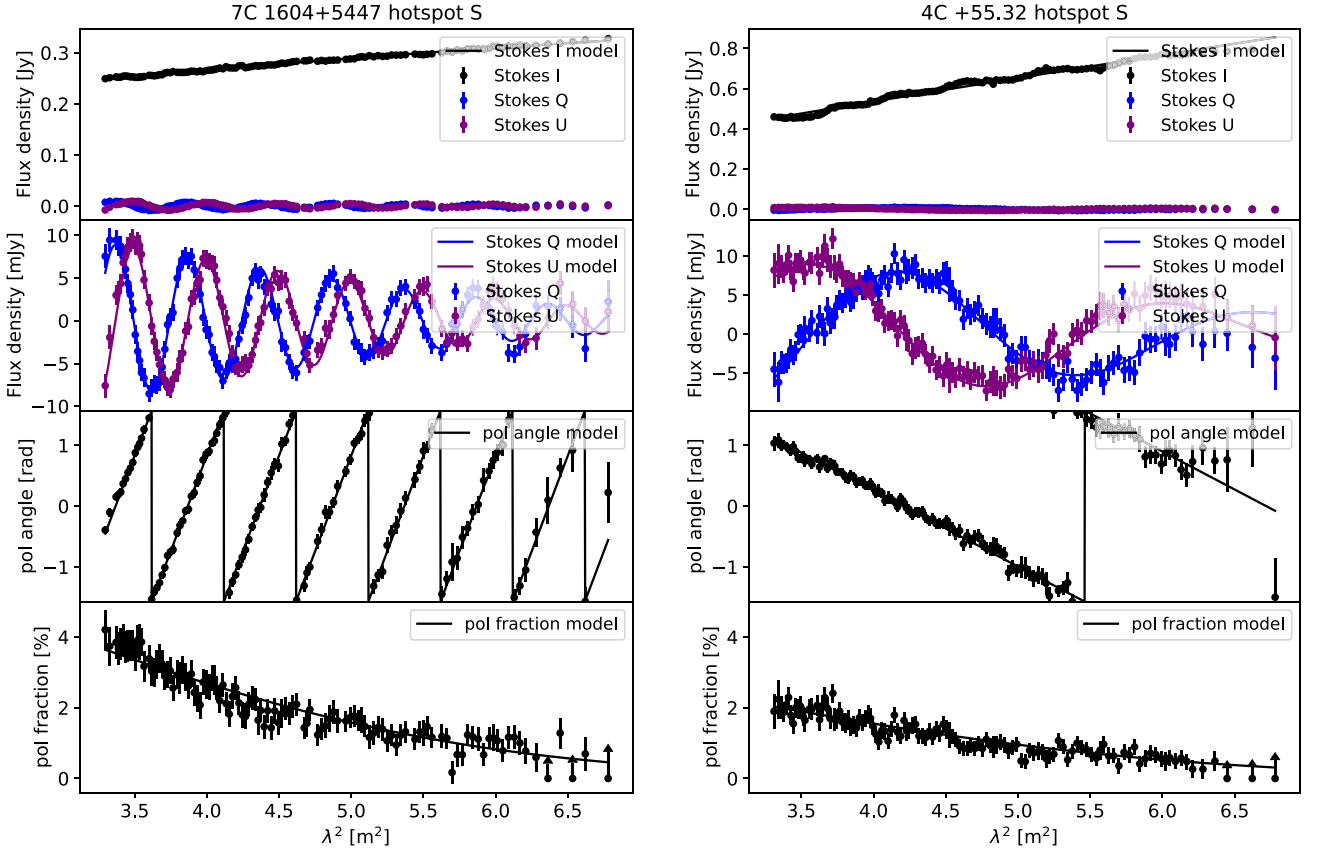


Figure 7. Left panels: Polarization properties of 7C 1604+5447 as a function of λ^2 . From top to bottom, the panels show the Stokes I , Q , and U flux densities; a zoom-in of the Q and U flux densities; the polarization angle; and the polarization fraction, defined as $\sqrt{Q^2 + U^2}/I$. A corresponding model fit (equation (11)) to these quantities is shown with solid lines. Arrows indicate lower limits on the polarization fraction. The total linearly polarized flux density, $\sqrt{Q^2 + U^2}$, was corrected for Ricean bias (J. F. C. Wardle & P. P. Kronberg 1974). Right panels: The same quantities, shown for the source 4C +55.32. The subtle step-like pattern imprinted on the Stokes I spectrum of 4C +55.32 is a by-product of the Stokes I amplitude self-calibration, combined with the WSCLEAN wideband imaging setting `-channels-out 6`, which discretizes the self-calibration model. This effect is also present in other sources, but becomes apparent only for the brightest ones with sufficiently high signal-to-noise ratios.

due to small deviations in the LOFAR station beam compared to the theoretical beam model.

4.4 7C 1607+5402

7C 1607+5402 has been identified as a quasar (QSO) at a redshift of $z = 0.99270$ (S. Alam et al. 2015; B. W. Lyke et al. 2020). The source is also detected at X-ray wavelengths (W. Voges et al. 2000; T. Boller et al. 2016; S. Wang et al. 2016). 7C 1607+5402 is an example of a giant radio galaxy hosted by a quasar, with two radio lobes spanning a projected linear size of ~ 1 Mpc (A. Kuźmierz & M. Jamroz 2021; M. Mahato et al. 2022; R. I. J. Mostert et al. 2024; M. Simonte et al. 2024). The integrated flux density of the source at 144 MHz is 532.7 mJy (M. J. Hardcastle et al. 2023).

Fig. 9 (top panel) shows a Stokes I image at 1.2 arcsec resolution, revealing an FR II morphology with a pronounced asymmetry in lobe brightness. A higher-resolution 0.4 arcsec image (middle panel of Fig. 9) reveals a compact feature in the western lobe (labelled ‘spot’). The nature of this feature is unclear; it may correspond to a jet instability or deflection, or alternatively represent a hotspot. polarized emission from 7C 1607+5402 at 1.4 GHz was previously reported by J. K. Grant et al. (2010). At LOFAR HBA frequencies, polarized emission was detected by N.

Herrera Ruiz et al. (2021); S. Piras et al. (2024) using images at 20 and 6 arcsec resolution, with the polarized signal originating from the western lobe.

In our 0.4 arcsec resolution LOFAR image, we detect polarized emission associated with the compact ‘spot’ feature. However, the 6 arcsec resolution study of S. Piras et al. (2024) indicates that most of the polarized emission arises from the north-western part of the lobe. This component is not detected at 0.4 arcsec resolution, implying that it is resolved out. To recover this emission, we re-imaged the LOFAR data, producing Q and U cubes at a resolution of 1.2 arcsec by applying a uv -taper and combining the LOFAR core stations into a virtual super-station, thereby reducing contamination from nearby sources. In the resulting 1.2 arcsec linearly polarized intensity image, shown as contours in the top and middle panels of Fig. 9, we detect the extended polarized emission, while polarized emission from the ‘spot’ feature is also recovered.

From the Faraday spectrum (bottom panel Fig. 9), we measure an RM of 7.30 ± 0.08 rad m^{-2} for the ‘spot’, and 7.26 ± 0.05 rad m^{-2} for the north-western lobe. These values can be compared to those reported by N. Herrera Ruiz et al. (2021); S. Piras et al. (2024), who measured 7.30 ± 0.02 and 7.17 ± 0.02 rad m^{-2} , respectively.

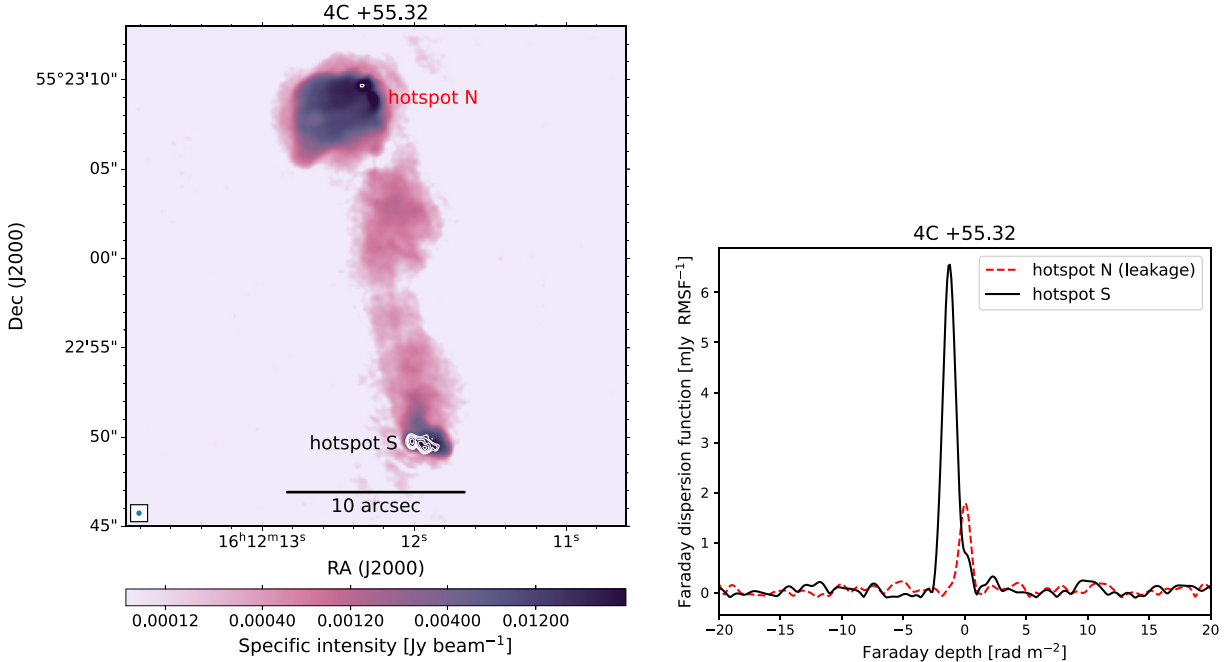


Figure 8. Left panel: Stokes I image of 4C +55.32 at a resolution of 0.3 arcsec. White contours show the linearly polarized intensity at levels of $15 \times \sigma_{\text{rms},P}$ [1, 2, 4, 8, ...], where $\sigma_{\text{rms},P} = 10 \mu\text{Jy beam}^{-1}$ is the rms noise in the polarized intensity image. Right panel: Faraday dispersion functions extracted from the northern (red) and southern (black) hotspot regions. The spectrum from the northern hotspot peaks close to 0 rad m^{-2} , indicating that the detected signal is likely dominated by instrumental polarization leakage near zero Faraday depth. This interpretation is supported by the very low measured polarization fraction of 0.11 per cent. Despite having a similar Stokes I intensity, the southern hotspot shows a significantly stronger polarized signal. Although a weaker asymmetric wing consistent with the leakage pattern seen in the northern hotspot is present, the majority of the signal arises from intrinsic polarized emission associated with the source. The uncleaned (dirty) Faraday spectrum is shown in Fig. B4.

4.5 CR Draconis in Stokes V

J. R. Callingham et al. (2021a, b) detected at 146 MHz highly circularly polarized Stokes V radio emission from the binary M-dwarf system CR Draconis (BD+55 1823; GJ 9552) in the ELAIS-N1 deep field. This was the first radio detection of the source, following non-detections in earlier surveys at 325 MHz (S. K. Sirothia et al. 2009), 610 MHz (T. Garn et al. 2008), and 1.4 GHz (A. R. Taylor et al. 2007). J. R. Callingham et al. (2021b) argue that this emission originates from coherent radio bursts, powered by the electron-cyclotron maser instability (ECMI; C. S. Wu & L. C. Lee 1979; R. A. Treumann 2006), which is caused by binary interaction.

The flare star of CR Draconis exhibits a B-band ($\sim 450 \text{ nm}$) flare rate of approximately one every $\sim 10 \text{ h}$ (G. Vander Haagen 2018), implying that a flare is likely to occur during most of our 8 hour LOFAR observations. We measure in our Stokes I images a total intensity that spans from $0.64 \pm 0.13 \text{ mJy}$ in observation L798074 to $2.07 \pm 0.41 \text{ mJy}$ in observation L686962. The corresponding Stokes V images give us total intensities ranging from $0.44 \pm 0.09 \text{ mJy}$ in observation L816272 to $1.99 \pm 0.40 \text{ mJy}$ in observation L686962. The inferred circular polarization fraction reaches a maximum of 96 ± 21 per cent in observation L686962, while the minimum value of 51 ± 21 per cent is measured for observation L816272. Although our observations were taken several years after those presented by J. R. Callingham et al. (2021b), the measured flux density variations and circular polarization fractions are consistent with their reported values.

Gaia DR3 measured a proper motion for CR Draconis of $0.440 \pm 0.001 \text{ arcsec yr}^{-1}$ (Gaia Collaboration 2022). With our

high-resolution observations spanning 2.5 yr, we are able to resolve this motion in Stokes V . Since the source lies $\sim 0.9^\circ$ from the pointing centre, time-smearing effects on the longest baselines are significant in two of the observing epochs. To mitigate this, we image all four observations at a resolution of $0.57'' \times 0.55''$, where time smearing is substantially reduced (Fig. 10). The proper motion corresponding to Fig. 10 ranges from $0.44 \pm 0.11'' \text{ yr}^{-1}$ to $0.33 \pm 0.11'' \text{ yr}^{-1}$, where the latter corresponds to the proper motion between the two most time-smeared observations. Our proper motion measurements agree with those from Gaia DR3, underscoring the high precision of our astrometry.

5 DISCUSSION

5.1 Low-frequency polarized emission at sub-arcsecond resolution

Our observations provide a first view of polarized emission from three radio galaxies at sub-arcsecond resolution at a central frequency of approximately 140 MHz. At these frequencies, but at much lower angular resolution ($\sim 20 \text{ arcsec}$), FR II radio galaxies constitute the largest class of polarized sources, accounting for about 40 per cent of the polarized population and occurring roughly twice as frequently as FR I sources (S. P. O'Sullivan et al. 2023). This contrasts with observations at 1.4 GHz, where FR I and FR II sources are found in comparable numbers (e.g. J. K. Banfield et al. 2011; S. P. O'Sullivan et al. 2015).

Given that radio hotspots in FR II sources are intrinsically compact and are high S/N, it is likely that FR II sources constitute an even larger fraction of the low-frequency polarized

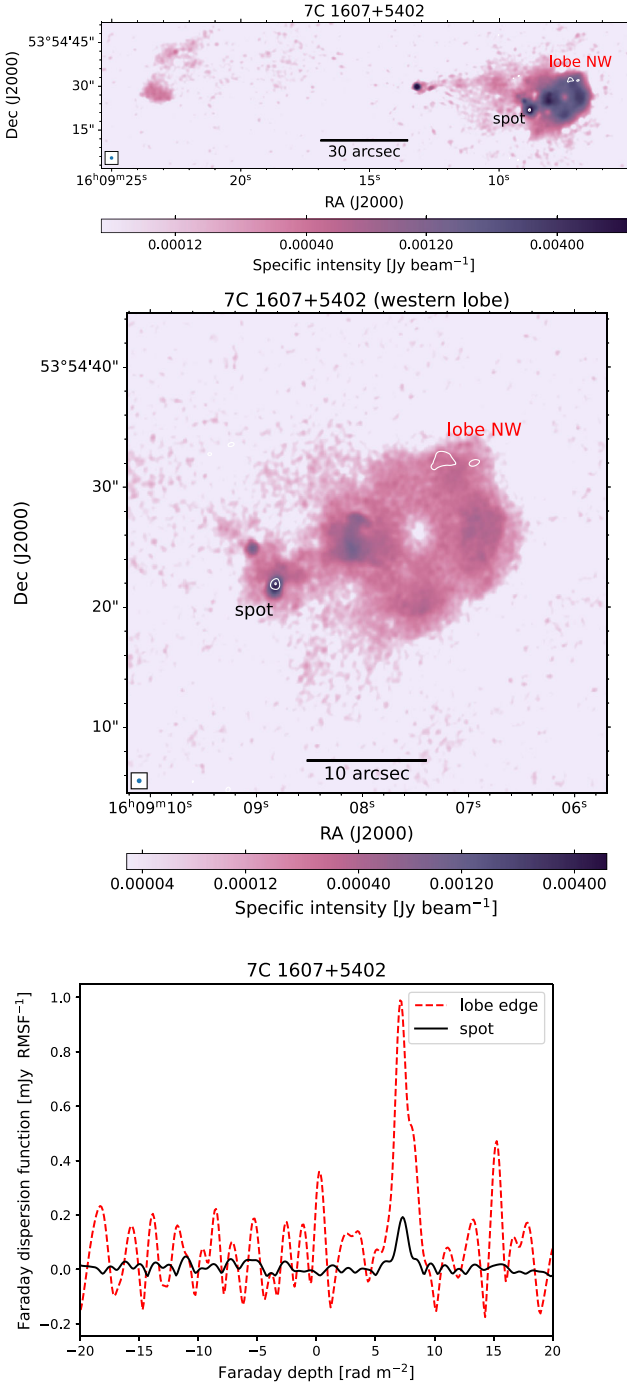


Figure 9. Top panel: Stokes I image of 7C 1607+5402 at a resolution of 1.2 arcsec. White contours indicate the linearly polarized intensity at levels of $6 \times \sigma_{\text{rms}, P}$ [1, 2, 4, 8, ...], where $\sigma_{\text{rms}, P} = 12 \mu\text{Jy beam}^{-1}$ is the rms noise in the polarized intensity image. Middle: Stokes I image of 7C 1607+5402 at a resolution of 0.4 arcsec. White contours show the linearly polarized intensity from the 1.2 arcsec-resolution polarized intensity image, plotted at the same contour levels as in the top panel. Bottom panel: Faraday dispersion functions for the ‘spot’ (black) and ‘NW lobe’ (red) regions, extracted from the polarized intensity cubes at resolutions of 0.4 and 1.2 arcsec, respectively. The uncleaned (dirty) Faraday spectra are shown in Figs B5 and B6.

source population when observed with baselines. Indeed, for two of the sources in our sample, the polarized emission detected at 0.3 arcsec resolution originates from the hotspots. For the third source, the polarized emission arises from a compact region that may represent a hotspot or another compact feature within the radio jet. In this case, we also detect polarized emission near the edge of the radio lobe; however, this component is extended and only becomes visible at the lower angular resolution of 1.2 arcsec. We caution, however, that drawing firm conclusions about the low-frequency polarized source population at sub-arcsecond resolution requires a more thorough analysis and a systematic search for polarized emission across the full data set.

5.2 Availability of an unpolarized in-field calibrator

In this work, we have shown that the polarization calibration scheme described can successfully be applied to 32 h of observations with the full international LOFAR array, revealing for the first time low-frequency polarized emission at sub-arcsecond resolution in both linear and circular polarization. Below, we discuss the applicability of this approach to other LOFAR observations.

As demonstrated by LoTSS studies of linear and circular polarization (J. R. Callingham et al. 2023; S. P. O’Sullivan et al. 2023), accurate polarization calibration can be applied to the large majority of LOFAR observations with the Dutch part of the array. The main complication arises in fields that contain very strong, compact polarized emission. In these cases, the underlying DDF-pipeline assumption that the field-averaged polarized signal is approximately zero may break down (C. Tasse et al. 2021). As shown by S. P. O’Sullivan et al. (2023), this occurs in $\lesssim 10$ per cent of LoTSS fields and results in an artificial polarization signature being imprinted on all sources in the field. Additional steps would be required for such fields to be processed for polarization with the international baselines, as otherwise the polarization calibration of the Dutch LOFAR stations would be too heavily compromised (for possible approaches to address this see section 2.3.4 in S. P. O’Sullivan et al. 2023).

For international baseline calibration, any source that can serve as a successful in-field calibrator can, in principle, also be used as a leakage calibrator, provided it is unpolarized in the HBA band. The signal-to-noise ratio is generally sufficient because the in-field calibrator is also required to solve for the much more rapidly varying ionospheric total electron content (TEC) effects on time-scales of $\lesssim 1$ min. This implies that there should be sufficient S/N to solve for leakage terms on the longer time-scales of $\gtrsim 30$ min. The amount of linear polarization of in-field calibrators can be verified by consulting the LoTSS polarization catalogues (i.e. S. P. O’Sullivan et al. 2023). For sources that remain compact, the polarization properties are expected to remain unchanged. However, for significantly resolved sources, linearly polarized emission may be present on long baselines while remaining undetected at LoTSS resolution due to beam depolarization. For this reason, it is preferable to select a compact calibrator source. Fortunately, the vast majority of radio sources are unpolarized at metre wavelengths. This assumption is even safer for circular polarization, as the number of in-field calibrators that are circularly polarized is expected to be extremely small. Based on the Stokes V catalogue of J. R. Callingham et al. (2023), covering 5634 deg^2 , only one detected circularly polarized source has an integrated Stokes I flux density above 100 mJy (121.7 mJy), whereas in-field calibrators are typically required to have integrated flux densities

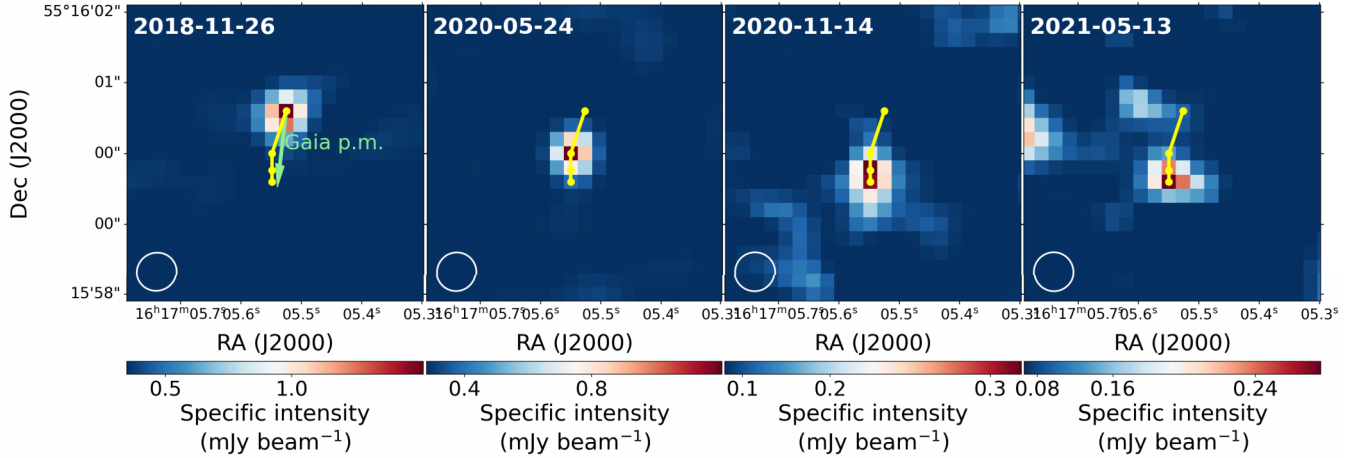


Figure 10. Proper motion of CR Draconis across the four ELAIS-N1 observations at $0.57 \text{ arcsec} \times 0.55 \text{ arcsec}$ resolution, imaged in Stokes V . The yellow line indicates the four positions of the sources from the four observations, fitted with PYBDSF (N. Mohan & D. Rafferty 2015). The light green vector indicates the proper motion over 2.5 yr ($87.97 \text{ mas yr}^{-1}$, $-430.963 \text{ mas yr}^{-1}$) from *Gaia* (Gaia Collaboration 2022). The beam shape is indicated in the bottom left corner.

of $\gtrsim 200\text{--}300 \text{ mJy}$. Consequently, at most one or two potential in-field calibrators are expected to violate the Stokes $V = 0$ assumption for a full northern sky survey.

If the chosen in-field calibrator turns out to be polarized, an alternative bright source within the field can be used instead. Moreover, if an incorrect assumption about the calibrator’s polarization state is made, this will result in artificial polarization being introduced into all other sources in the field, providing a clear diagnostic of the issue.

5.3 Availability of an in-field polarized calibrator

To align two or more observations in Faraday depth, or to perform such an alignment on shorter time intervals within a single observation if needed, the detection of linearly polarized emission is required. Misalignments in polarization angles arise primarily due to ionospheric Faraday rotation, which introduces an ionospheric contribution to the rotation measure, RM_{ion} . The bulk of this effect (typically a few rad m^{-2}) is removed using satellite-based ionospheric models using RMEXTRACT at the start of the data processing, leaving residual offsets of approximately $0.1\text{--}0.3 \text{ rad m}^{-2}$ after correction (C. Sotomayor-Beltran et al. 2013).

From the four observations listed in Table 1, we find that our measured values are in approximate agreement with this level of precision, with a standard deviation of 0.2 rad m^{-2} . To obtain better statistics, we also consider the study by S. Piras et al. (2024), which provides RM measurements for 19 observing runs (their table 4). From these values, we derive a standard deviation of 0.06 rad m^{-2} , which lies at the lower end of the expected residual range and indicates a high accuracy of the satellite-based ionospheric correction for these observations. We note, however, that the accuracy of these corrections depends on the ionospheric conditions sampled. In Section 5.4, we investigate possible RM variations on shorter time-scales within single observing epochs.

At 20 arcsec resolution in LoTSS-DR2 (8 h per pointing), an average surface density of linearly polarized sources of 0.43 deg^{-2} was reported by S. P. O’Sullivan et al. (2023). Given the typical field of view of the international LOFAR stations of $\sim 6.5 \text{ deg}^2$, this implies that, on average, slightly fewer than three polarized sources are expected within a single pointing. In the ELAIS-N1

field, we aligned the observations in Faraday depth using the source 7C 1604+5447, which is detected at high S/N in 8 h of observations. The source 4C +55.32 would also provide a suitable alternative for this purpose. In contrast, 7C 1607+5402 represents a more challenging case, as its polarized flux density is approximately a factor of 10–20 lower than that of 7C 1604+5447. We note that a full search for polarized emission using our LOFAR international baseline data for this field has not yet been performed, and additional suitable polarized sources may be present, as suggested by the larger sample reported by S. Piras et al. (2024).

As a practical strategy for efficient pipeline processing of LOFAR data including all international stations (L. K. Morabito et al. 2022), we suggest first checking for the presence of an in-field polarized calibrator using catalogues of polarized sources detected by LoTSS (S. P. O’Sullivan et al. 2023), or, if none are available, sources known to be polarized at higher frequencies (e.g. from NVSS; J. J. Condon et al. 1998; A. R. Taylor et al. 2009; J. S. Farnes et al. 2014). This is important because, aside from LoTSS, there are currently no low-frequency polarization surveys covering most of the northern sky. If no suitable polarized calibrator is found, the next step is to inspect all facet calibrator sources (24 to 30 for this field J. M. G. H. J. Jong et al. 2024, 2025a), which are already processed by the pipeline and are typically among the brightest sources in the field, thus increasing the likelihood of detectable polarized emission. This approach is computationally inexpensive, as it only requires additional imaging and RM-synthesis steps on small data sets with limited image sizes (since LOFAR core stations are phased-up into a single virtual superstation).

The polarization angle alignment itself is a global correction, consisting of a single RM and a polarization angle offset that is common to all antennas. In principle, this correction can also be derived through alternative methods. For example, E. Lenc et al. (2016, 2017) and I. Šnidarić et al. (2023) demonstrated that the polarized Galactic foreground can be used for this purpose. Alternatively, one could exploit the larger field of view of the Dutch LOFAR stations, which covers approximately four times more sky area per pointing (T. W. Shimwell et al. 2022), thereby increasing the probability of finding a suitable polarized calibrator. Given these considerations, the global polarization angle

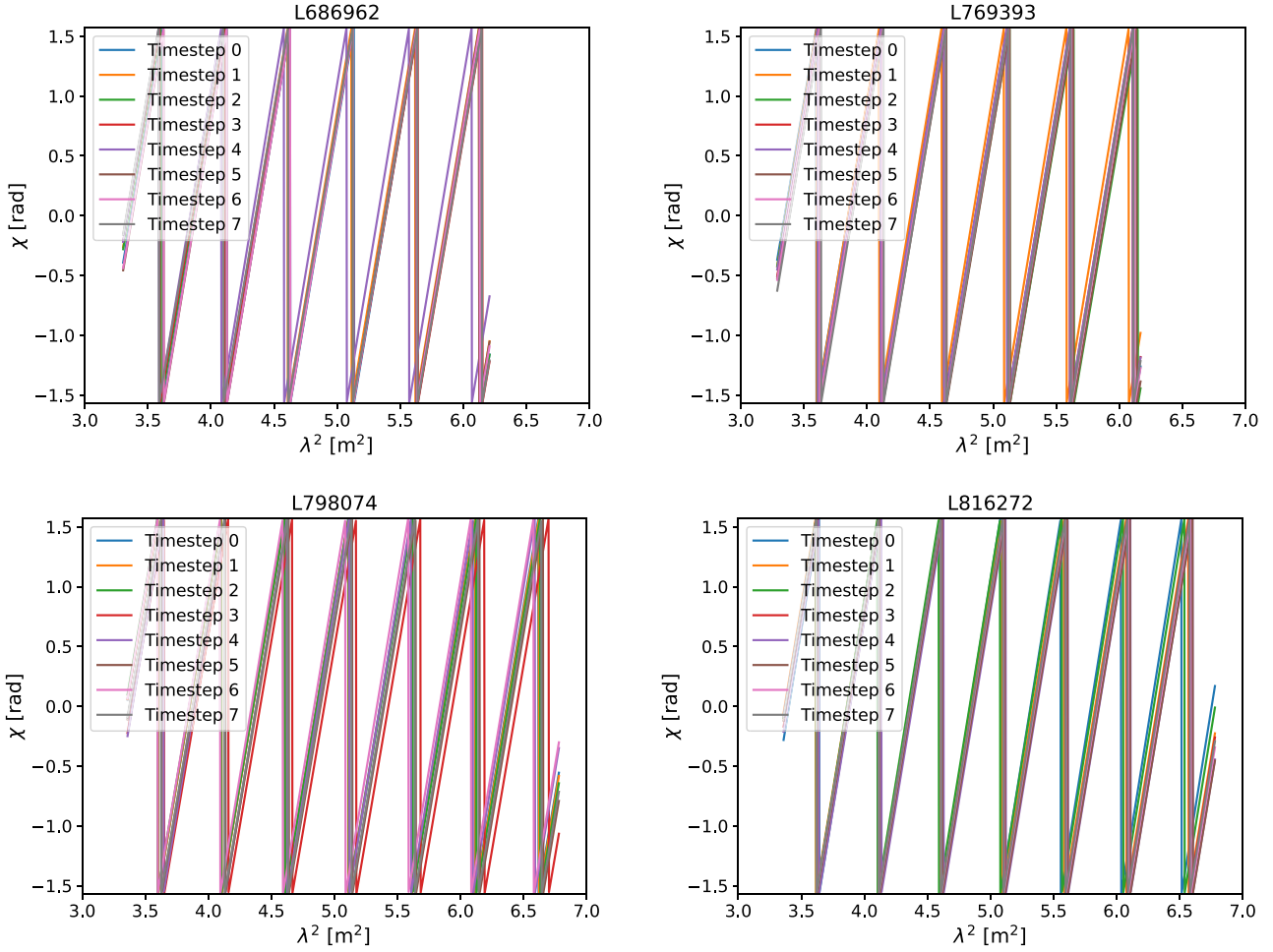


Figure 11. Polarization angles obtained from fits to the peaks of the RM spectra for eight 1 h subsets of the four observations.

alignment could also be performed prior to any international baseline processing, avoiding the need to apply this correction at the international baseline processing stage.

5.4 Intra-observation polarization angle alignment

In Section 3.2, we described how the four observing epochs were aligned in Faraday depth and the resultant polarization angle. Here, we investigate whether an additional correction is required on shorter time-scales than the ionospheric corrections applied with RMEXTRACT at the start of the data processing. To this end, we constructed polarization cubes by dividing each observation into 1 h time intervals. For each interval, we fitted the peak of the Faraday spectrum using RM-TOOLS. The resulting best-fit models, expressed in terms of polarization angle as a function of λ^2 , are shown in Fig. 11.

The fitted curves are similar across all time intervals, with deviations of less than 1 rad over the full λ^2 range. The largest differences occur at the lowest observing frequencies (highest λ^2), where the deviations reach approximately 0.5 rad for L798074. To assess whether these differences are significant or instead driven by measurement uncertainties, we estimated the uncertainties using a Monte Carlo approach.

For a representative example (L798074, time interval 2), we generated ten synthetic data sets by randomly drawing Stokes Q and U flux densities from normal distributions defined by the measured values and their uncertainties. We then refitted the RM peak in Faraday depth space for each realization. The resulting fits are shown as orange lines in Fig. 12. Based on this analysis, which was also performed for other time intervals and observing epochs, we find no evidence for significant variations in the polarization angles within individual observations, as the observed temporal variations are comparable to the uncertainties from the fitting.

Further investigations using a larger number of observations, sampling a wider range of ionospheric conditions, and/or employing a polarized calibrator with higher signal-to-noise would be valuable to quantify whether intra-observation polarization angle corrections are ever required. For our four observations, however, such corrections do not appear to be necessary, suggesting that they are likely not required for the majority of LOFAR observations.

The alignment in Faraday depth and the resulting polarization angle corrections described in this section and in Section 3.2 were performed using Stokes Q and U polarization image cubes. An alternative approach would be to obtain these corrections directly in the visibility domain. This could be achieved by

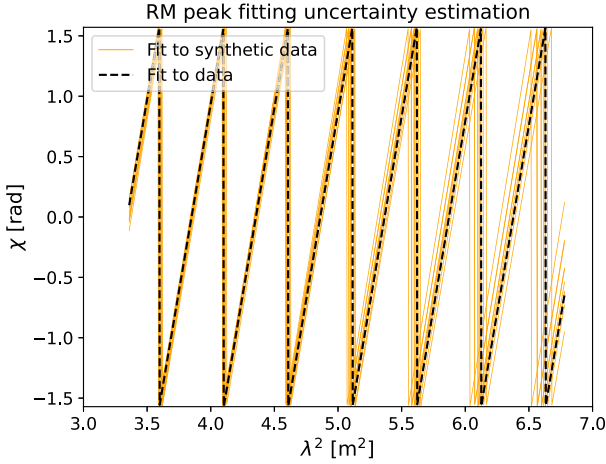


Figure 12. Polarization angles obtained from a fit to the peak of the RM spectrum for a 1 h subset of the L798074 data (time-step 2, covering the period 2–3 h from the start of the observation). The orange lines show fits to models generated from ten synthetic data sets, created by randomly drawing Stokes Q and U channel flux densities from normal distributions defined by the observed values and their uncertainties. These fits illustrate the uncertainty associated with the RM peak fitting.

predicting a polarized sky model from a reference observation into the `MODEL_DATA` column of the measurement set and subsequently solving for the RM and intercept, or by solving for a frequency-dependent rotation angle. In both cases, the derived corrections should be global, that is, identical for all antennas. Future investigations into carrying out such approaches using DP3 (G. Diepen, T. J. Dijkema & A. Offringa 2018; T. J. Dijkema et al. 2023) would be valuable, particularly for data sets with many repeated observations, as this would allow one to bypass the creation of Stokes Q and U cubes and the associated fitting procedures or RM-synthesis.

5.5 Outlook

In this work, we obtained our results using 32 h of ELAIS-N1 data. Recent work by T. W. Shimwell et al. (2025) has imaged ELAIS-N1 using 505 h of LOFAR observations with only the Dutch LOFAR stations. From this dataset, J. M. G. H. J. de Jong et al. (in preparation) have selected 200 h of data that were taken with the international LOFAR stations and processed them with the recently improved calibration strategy (J. M. G. H. J. Jong et al. 2025a), combined with the polarization calibration discussed in this paper. With a central Stokes I RMS sensitivity of $5.6 \mu\text{Jy beam}^{-1}$, these data are 2.5 deeper compared to this work and therefore enable a search for previously undetected polarized sources in ELAIS-N1.

Combining this with the recent work by V. Gustafsson et al. (2025), which implements a three-dimensional (3D) transformation from spatial and frequency domains into sky–Faraday depth space, including a 3D deconvolution scheme, could further improve deconvolution depth and the reconstruction of the polarized signal. Furthermore, the use of Sidereal Visibility Averaging (SVA; J. M. G. H. J. Jong et al. 2025b)⁷ makes deep imaging with more than 100 frequency channels and hundreds of hours

of LOFAR observations computationally feasible, whereas such processing would otherwise be prohibitively expensive.

To further standardize and automate the calibration process described in this paper, we are implementing automated polarization calibration within Pipeline for the International LOFAR Telescope (PILOT; van der Wild et al., *subm.*)⁸. This data processing pipeline will be used for future surveys, such as the planned International LoTSS (ILoTSS) survey, which aims to image most of the northern sky at sub-arcsecond resolution. Additional extensions to this pipeline and `facetselfcal`, as part of the OSCARS project⁹ (R. David et al. 2025; J. Jong 2026), will further improve the findability, accessibility, interoperability, and reproducibility of the data products and software, bringing them in line with FAIR principles (e.g. M. D. Wilkinson et al. 2016; S. O’Toole & J. Tocknell 2022).

6 CONCLUSIONS

In this work, we have presented a strategy to calibrate the polarization of International LOFAR Telescope (ILT) observations. This strategy exploits an unpolarized in-field calibrator to correct for slowly varying, time- and frequency-dependent instrumental leakage terms. In addition, by using a linearly polarized in-field reference source, multiple observations from different epochs can be aligned in Faraday depth, and the resulting corrections can be applied directly to the visibility data. This enables deeper imaging and more effective deconvolution than previous approaches for LOFAR, which typically relied on stacking images from different epochs.

We applied this calibration strategy to four 8 h LOFAR observations of the ELAIS-N1 field previously presented in J. M. G. H. J. Jong et al. (2024), including the international stations with baselines up to 1980 km, resulting in a total of 32 hr of data at 115–166 MHz. Using these observations, we successfully imaged and detected three radio sources in linear polarization at sub-arcsecond resolution. Two of these sources were previously detected with LOFAR in linear polarization, while one represents a new polarized detection. Our sub-arcsecond-resolution images allow us to precisely localize the polarized emission, which in all cases arises from compact hotspot regions or compact features in the jets of FR II radio galaxies. In addition, we detect circularly polarized (Stokes V) emission from the binary M-dwarf system CR Draconis and, thanks to the high angular resolution, measure its proper motion across the observing epochs.

Finally, we estimate the instrumental leakage from Stokes I into linear polarization and Stokes V to be 0.11 per cent and 0.021 per cent, respectively, approximately a factor of two lower than the typical leakage levels reported for LoTSS (T. W. Shimwell et al. 2022).

Given the availability of suitable in-field calibrators and the prospect of implementing this approach in a pipeline, this work opens up new opportunities to study the metre-wavelength sky in full polarization at sub-arcsecond resolution over large areas. This can be achieved by exploiting the international baseline data already recorded as part of LoTSS. In addition, this strategy enables ultra-deep polarimetric imaging of well-studied deep fields.

⁷https://github.com/jurjen93/sidereal_visibility_avg

⁸<https://github.com/LOFAR-VLBI/pilot>

⁹<https://oscars-project.eu/>

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The Scientific colour maps (F. Crameri 2023) are used in this study to prevent visual distortion of the data and exclusion of

readers with colour-vision deficiencies (F. Crameri, G. E. Shephard & P. J. Heron 2020).

Artificial Intelligence tool ChatGPT 5.3 was utilized for copy editing and linguistic refinement to ensure clarity. The final manuscript was reviewed and approved by the human authors.

DATA AVAILABILITY

The raw data used in this work are publicly available from the LOFAR Long Term Archive (<https://lta.lofar.eu>). The radio images in FITS format are available from the corresponding author upon reasonable request.

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APPENDIX A: ROTATION MEASURE MAP OF THE SOUTHERN LOBE OF 7C 1604+5447

We used the `rmtools_peakfitcube` function from the `RM-tools` package to create an RM map of the southern lobe of 7C 1604+5447 by fitting the peak of the Faraday spectrum in each pixel of the cleaned Faraday dispersion cube. The results are shown in Fig. A1 (left panel), with the corresponding uncertainty map (σ_{RM}) shown in the right panel. Pixels with $\sigma_{\text{RM}} > 0.08 \text{ rad m}^{-2}$ were blanked. The RM map shows a somewhat bimodal distribution of RM values, centred around 6.3 rad m^{-2} for the brightest part of the lobe and around 5.7 rad m^{-2} for most of the emission to the northeast.

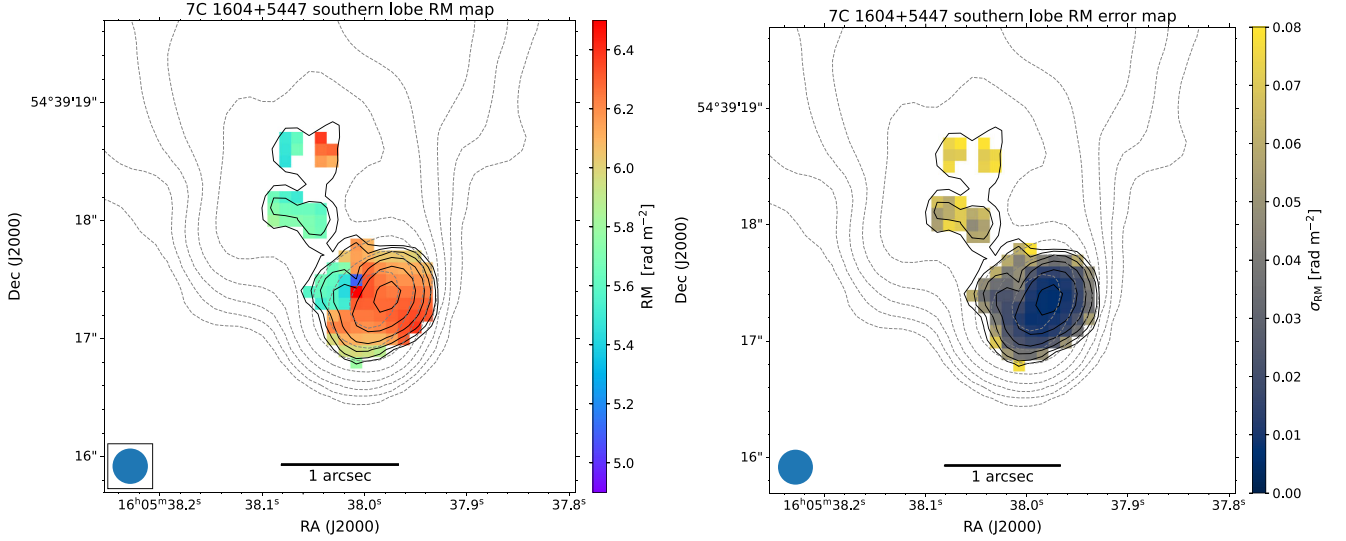


Figure A1. Left panel: RM map of the southern lobe of 7C 1604+5447. The beam size is indicated in the bottom-left corner. Solid contours are the same as in the left panel of Fig. 5, taken from the linearly polarized intensity image and drawn at the same levels. The dashed grey contours are from the Stokes I image and are drawn at levels of $20 \times \sigma_{\text{rms}} [1, 2, 4, 8, \dots]$, where $\sigma_{\text{rms}} = 20.8 \mu\text{Jy beam}^{-1}$ is the rms noise in the Stokes I image. Right panel: The RM uncertainty map corresponding to the left panel.

APPENDIX B: FARADAY DISPERSION FUNCTIONS

In Figs B1–B6, we present the dirty and RM-CLEANed Faraday dispersion functions, including the clean components, for

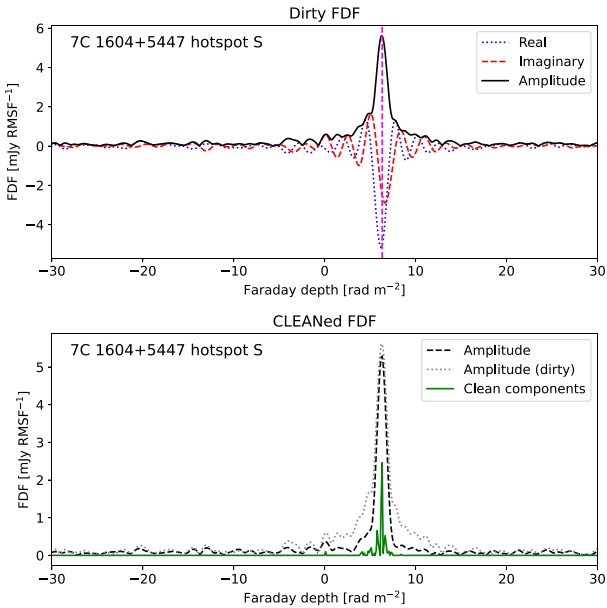


Figure B1. Top panel: Dirty Faraday dispersion function of the southern hotspot of 7C 1604+5447. The real, imaginary, and amplitude components are shown in blue, red, and black, respectively. The dashed vertical magenta line indicates the peak of the Faraday dispersion function. Bottom panel: RM-CLEANed Faraday spectrum corresponding to the top panel. The cleaned amplitude, dirty amplitude, and the amplitude of the clean components are shown in black, grey, and green, respectively.

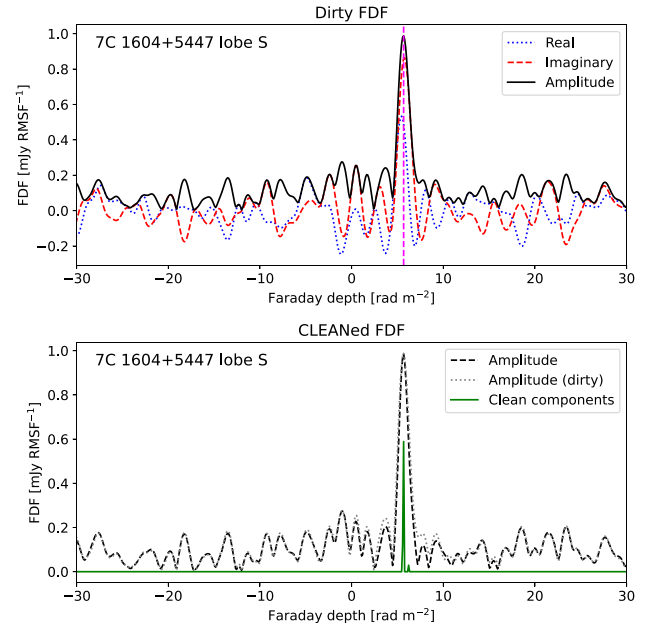
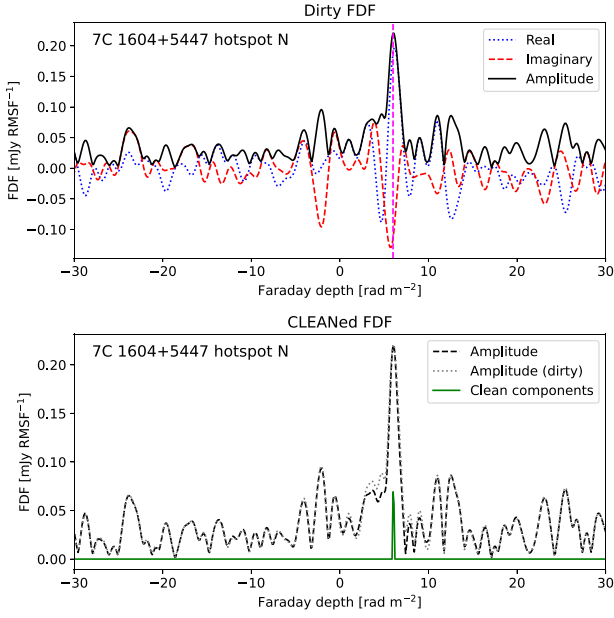
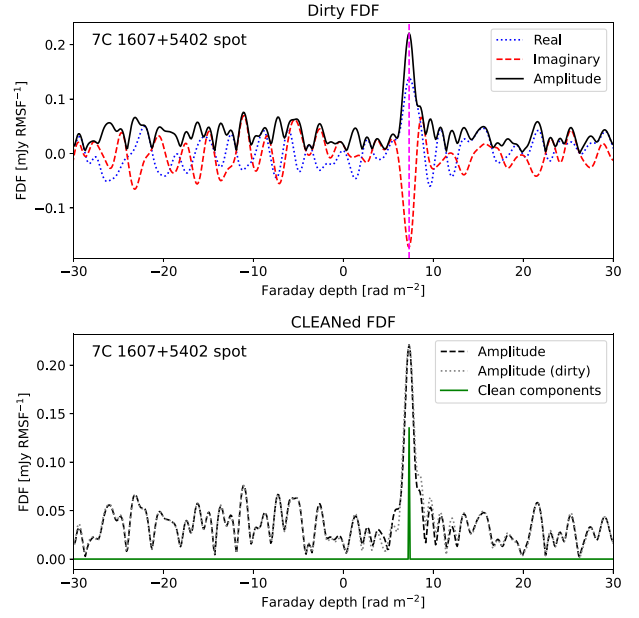
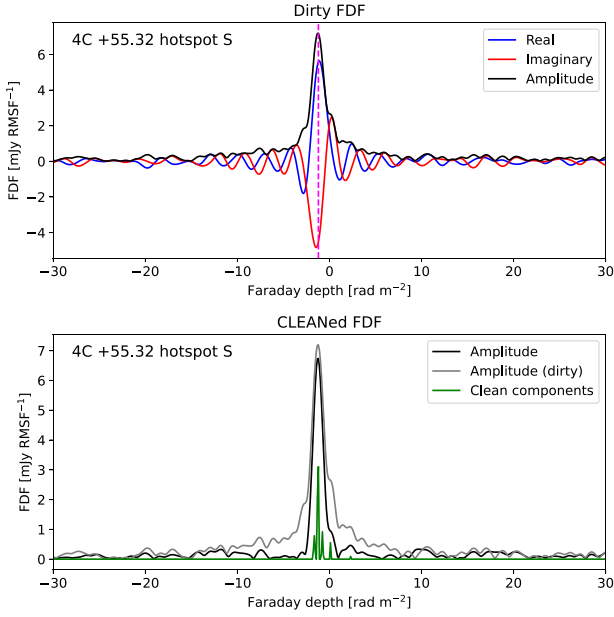
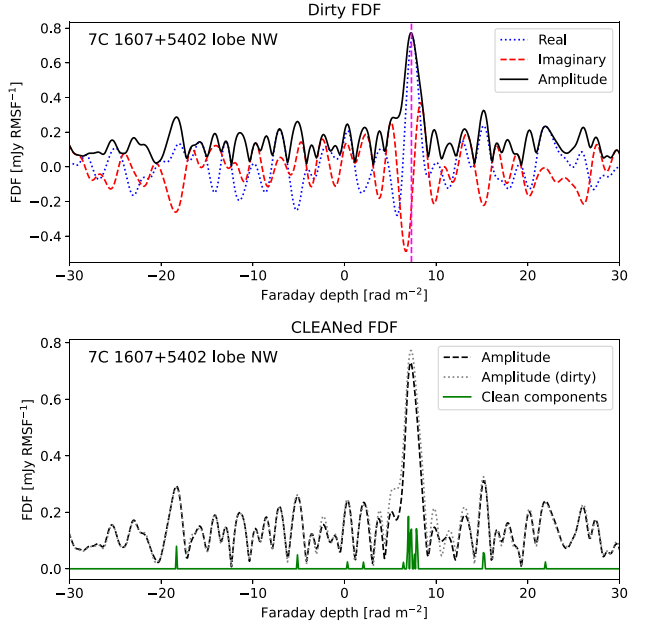


Figure B2. The same as for Fig. B1 but for lobe S of 7C 1604+5447.

the detected polarized source components in 7C 1604+5447, 4C +55.32, and 7C 1607+5402. The locations and names of these components within each source are shown in Figs 5, 8, and 9, respectively.

**Figure B3.** The same as for Fig. B1 but for hotspot N of 7C 1604+5447.**Figure B5.** The same as for Fig. B1 but for the spot of 7C 1607+5402.**Figure B4.** The same as for Fig. B1 but for hotspot S of 4C +55.32.**Figure B6.** The same as for Fig. B1 but for the NW lobe of 7C 1607+5402.

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