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Monte Carlo Studies of Transverse Faraday Rotation Profiles

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1. Introduction

Faraday Rotation of the observed polarization angle occurs when an EM wave propagates through a magnetized plasma. In the simplest case, this rotation is proportional to the wavelength squared and the Rotation Measure RM, which, in turn, depends linearly on the integral electron density and line-of-sight magnetic (B) field component.

Faraday Rotation measurements are an important tool for investigating the B fields associated with the relativistic jets of Active Galactic Nuclei (AGN); for example, a toroidal or helical B field component should give rise to a systematic gradient in the observed RM across the jet. However, real observed radio images have finite resolution. Typical beam sizes for cm-wavelength VLBI observations are often comparable to the observed jet widths, raising questions about whether these jets are well enough resolved to reliably detect transverse Faraday-rotation structure (e.g. Taylor & Zavala 2010, ApJ, 722, L183).

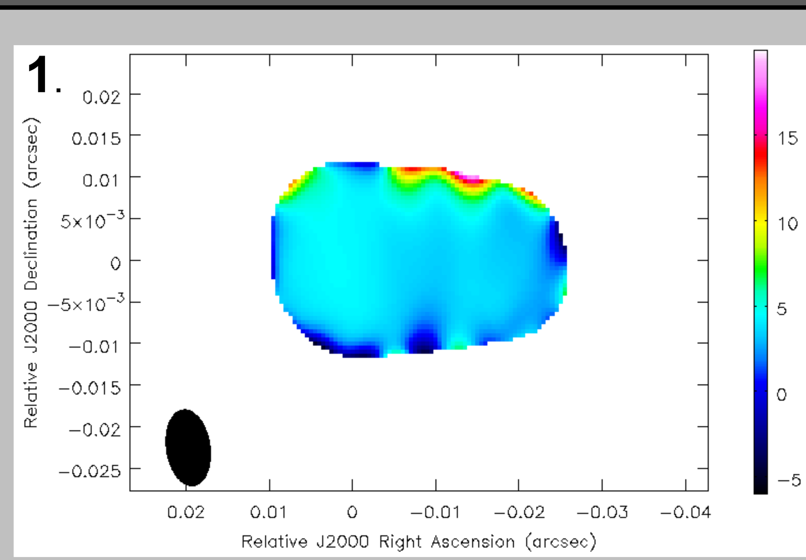
This question has been investigated by Hovatta et al. (2012) [AJ, 144, 105] and Algaba (2013) [MNRAS, 429, 3551], who used Monte Carlo simulations to consider the occurrence of RM gradients due to noise and limited baseline coverage for various observed jet widths. We have instead considered the properties of observed RM gradients for various intrinsic jet widths relative to the beam width. Our new Monte Carlo simulations clearly demonstrate the possibility of detecting transverse Faraday-rotation structures even when the intrinsic jet widths are considerably smaller than the beam width.

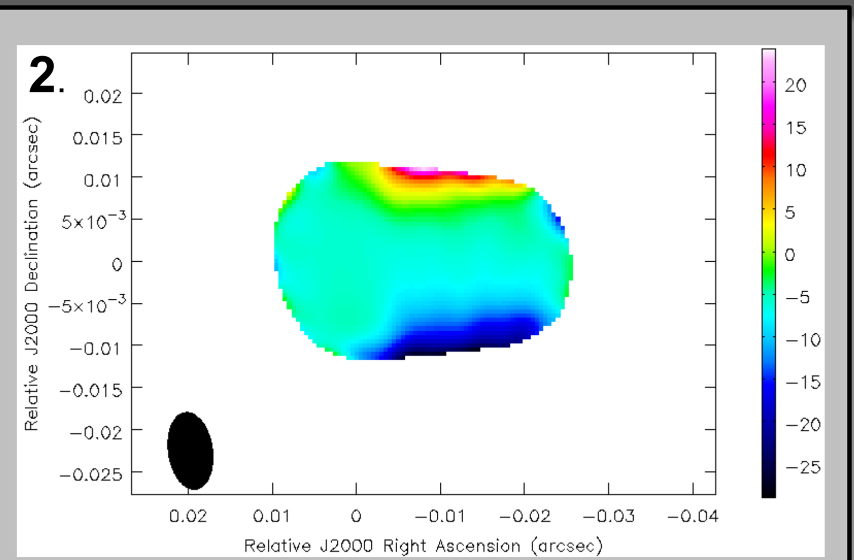
2. Monte Carlo Analysis Method

1. Calculate model Stokes Q and U maps containing transverse RM gradients.
2. Obtain corresponding model visibility data for baseline (UV) distributions from "snapshot" observations with the Very Long Baseline Array (VLBA)
3. Add random noise and polarization-angle uncertainties of up to 3°
4. Obtain I, Q, U, polarization angle and RM maps using AIPS or CASA.
5. Repeat steps 3 and 4 many times for the same model visibilities to obtain Monte Carlo statistics.

For our analysis we used intrinsic jet widths from 0.05 to 0.40 beam widths, polarized fluxes from 5% to 25% and RM ranges from ±8 to ±30 rad m^{-2}.

Figures for Section 2

1.


2.


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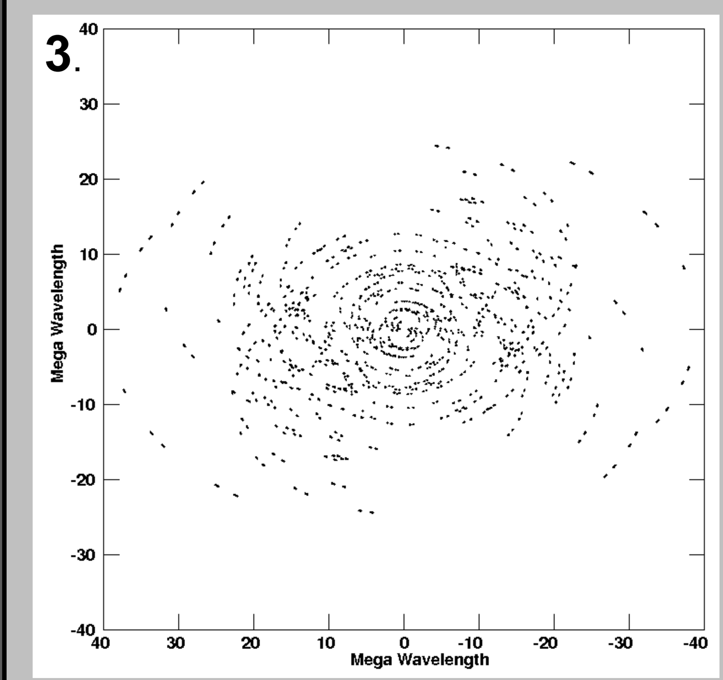
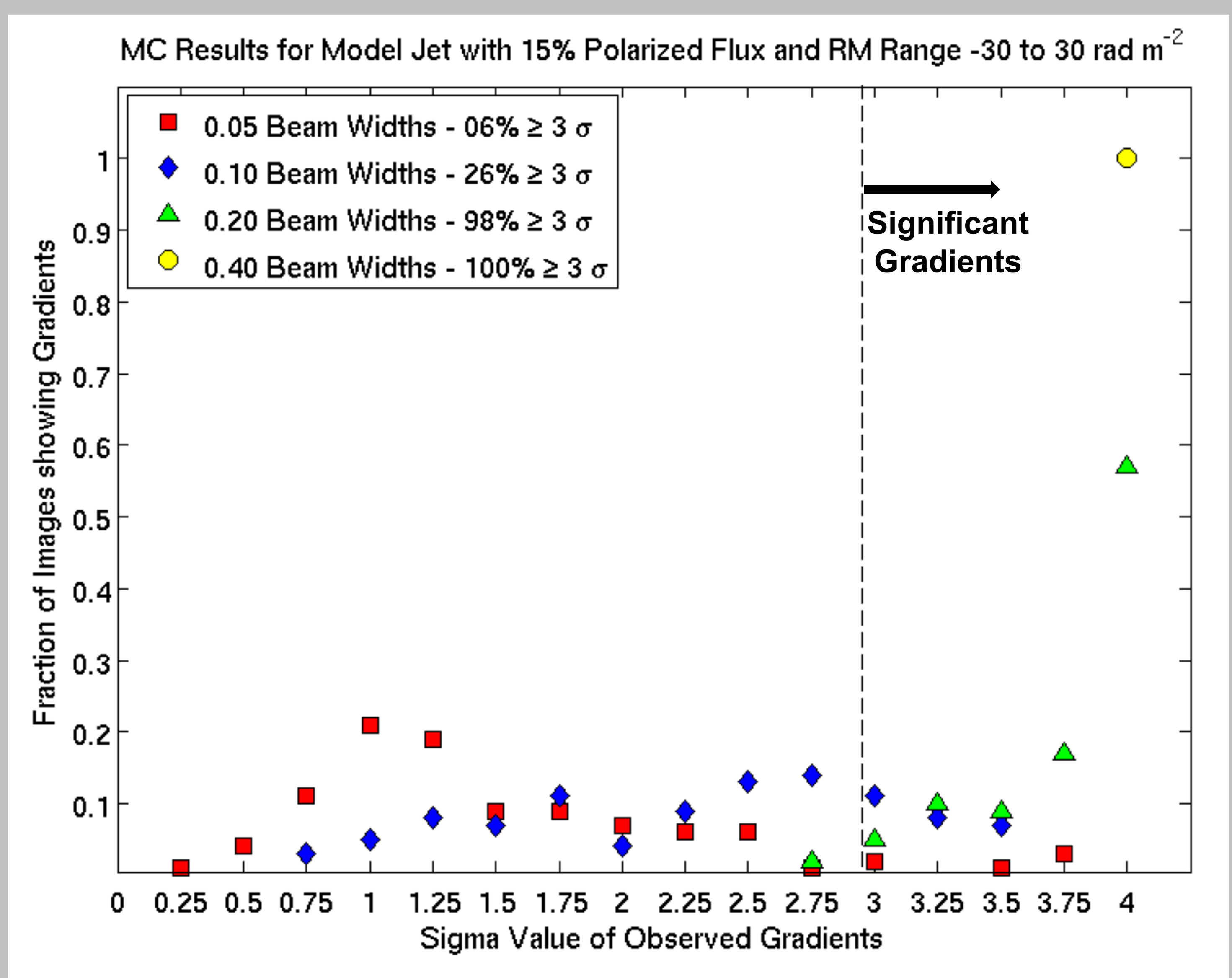


1. Sample RM map for model jet of width 0.05 beam widths, 15% polarized flux and RM range ±30 rad m^{-2}.
2. Sample RM map for model jet of width 0.40 beam widths, 15% polarized flux and RM range ±30 rad m^{-2}.
3. Sample VLBA UV Distribution (declination +42° observed at 22cm) used during this analysis.

3. Ability to Detect RM Gradients

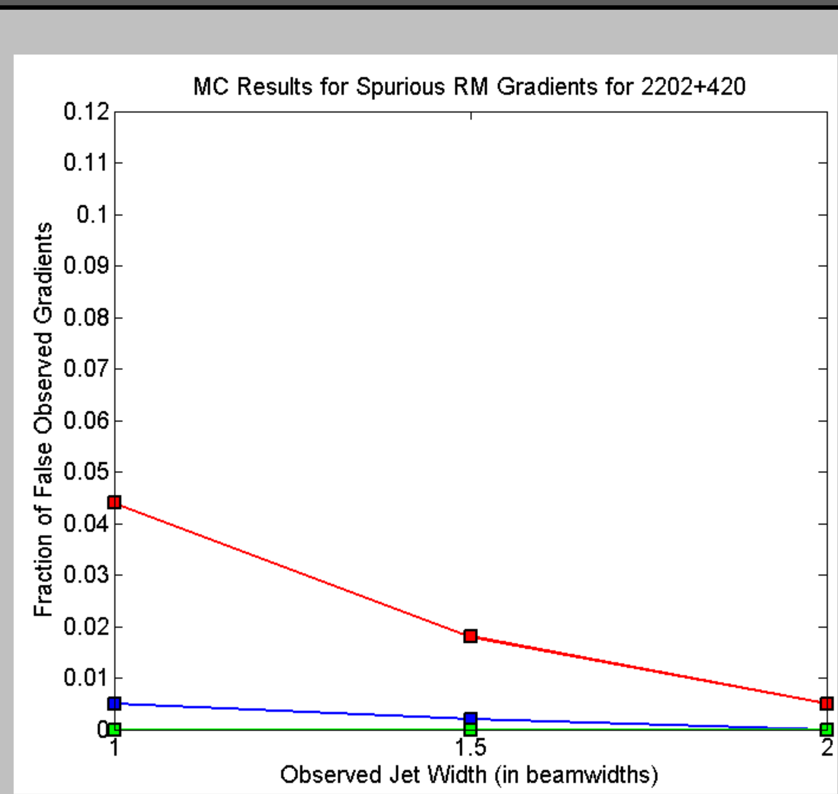
The results presented here were obtained for a source at +42° declination observed at 18, 20, 21 and 22cm. The procedure outlined in Section 2 was repeated 100 times for each parameter set and multiple transverse slices were taken across each RM map. The RM difference across each slice and its associated error were calculated.

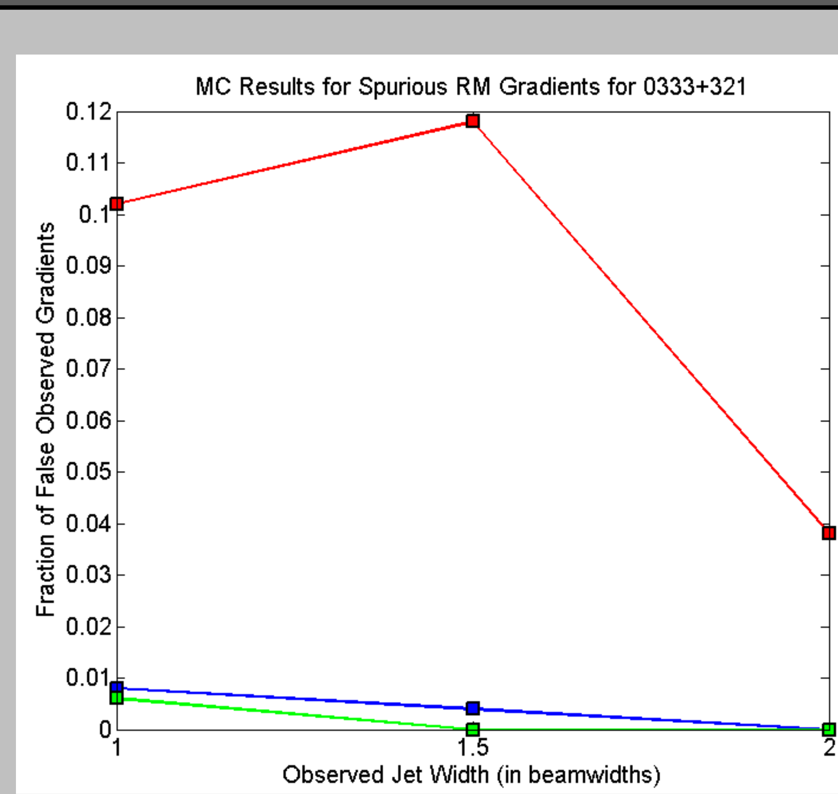


The above figure shows that the number of significant gradients (≥ 3σ) increases with the intrinsic jet width, but some 3σ+ gradients are observed even for the narrowest jet widths considered.

The number of 2σ RM gradients is also higher than expected for purely spurious gradients (see Section 5). An intrinsic width of 0.4 beam widths corresponds to an observed width of about 1.5 beam widths.

4. Appearance of Spurious Gradients





The Monte Carlo simulations were also carried out for model jets without RM gradients. The results presented here were obtained for a source at +42° declination observed at 18, 20, 21 and 22cm and a source at +32° declination observed at 1.9, 2.5, 3.5 and 3.7 cm.

The above figures show the fraction of spurious gradients observed (2σ, 3σ and 4σ). 3σ or greater spurious gradients were observed in fewer than 1% of cases, even for the narrowest model jets considered. The observed UV distribution and wavelength range have much more significant effects on the probability of observing spurious gradients than the jet width.

5. Conclusions

Taylor and Zavala (2010) proposed that an observed jet width of at least 3 beam widths is required in order for an observed transverse RM gradient to be reliable.

We have demonstrated that this criteria is far too severe: it may be possible to detect transverse RM gradients even when the intrinsic jet width is only 0.10 - 0.05 of the beam width (observed jet width approximately 1 beam width), depending on the wavelength range used. The reliability of observed RM gradients should instead be estimated from the RM difference across the jet (> 3σ), the extent of the RM gradient along the jet, the quality of the RM fits and the possibility of distortion by optical depth effects.

Spurious RM gradients at the 4σ level occurred in less than 1% of our simulations using model data without RM gradients, even in the case of very narrow jets (down to 0.01 of the beam width for the 18-22cm simulations!). Thus, in the absence of other grounds for doubt (e.g. poor RM fits), transverse RM gradients spanning RM differences of 4σ or more can certainly be considered reliable, even if the transverse distance spanned is comparable to the beam width.