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Lessons learned from six decades of radio polarimetry

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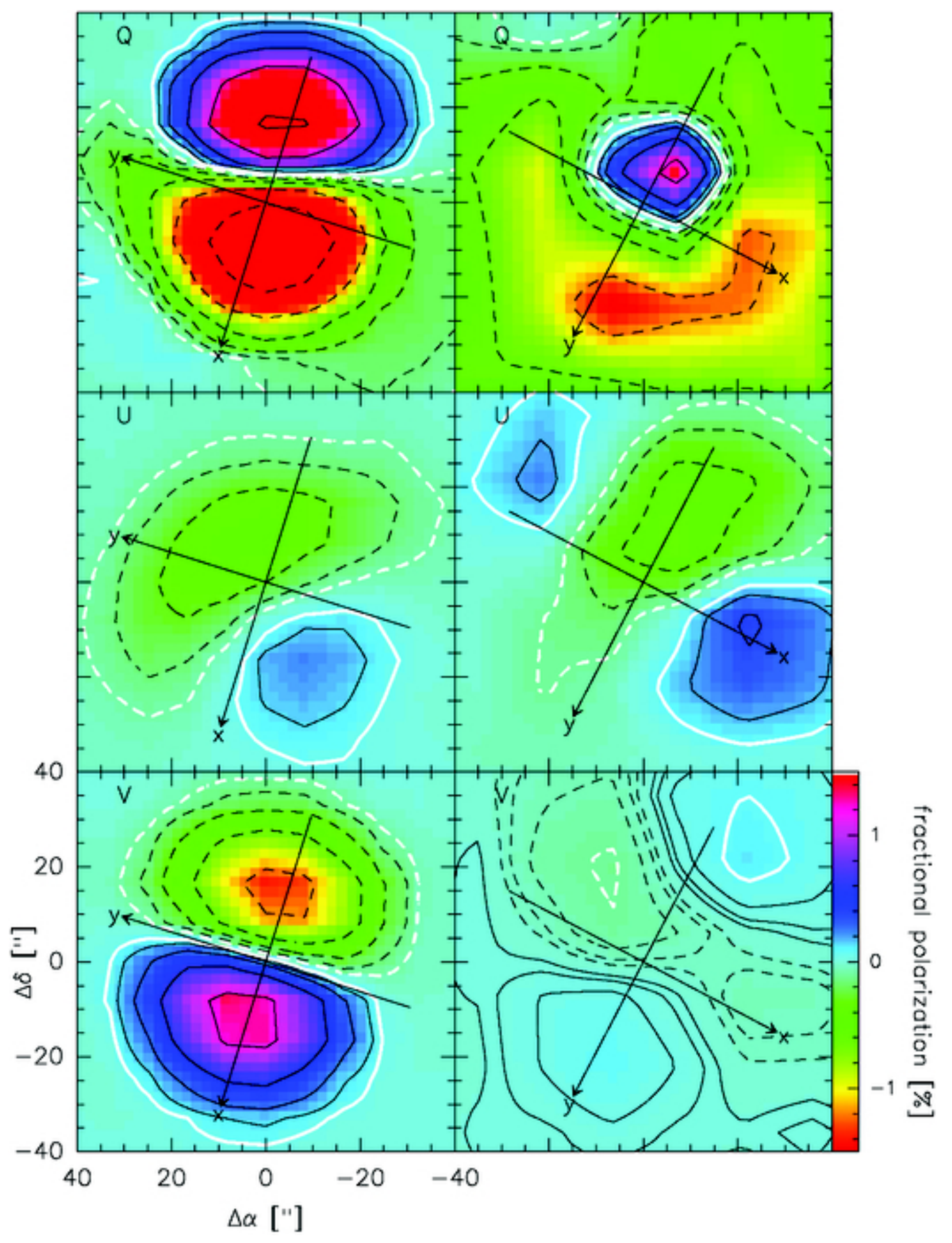
Challenges in wide-field polarimetry: Optimized instrumentation versus post-observing correction

The characterization of polarized emission from continuum radiation and spectral lines across large-scale galactic and extragalactic fields is a typical application of single-dish telescopes, from radio to far-infrared wavelengths. The first radio records date back to the 1950s. Despite the analytical usefulness of polarimetry, it is usually added to the design specifications of telescopes and their instrumentation in notoriously advanced development stages. The instrumental contamination of the Stokes parameters can be corrected by means of dedicated calibrations, which proves difficult for the assessment of historical data [1] and extended fields. In the following we summarize the sources of instrumental polarization and propose a post-observing correction algorithm.



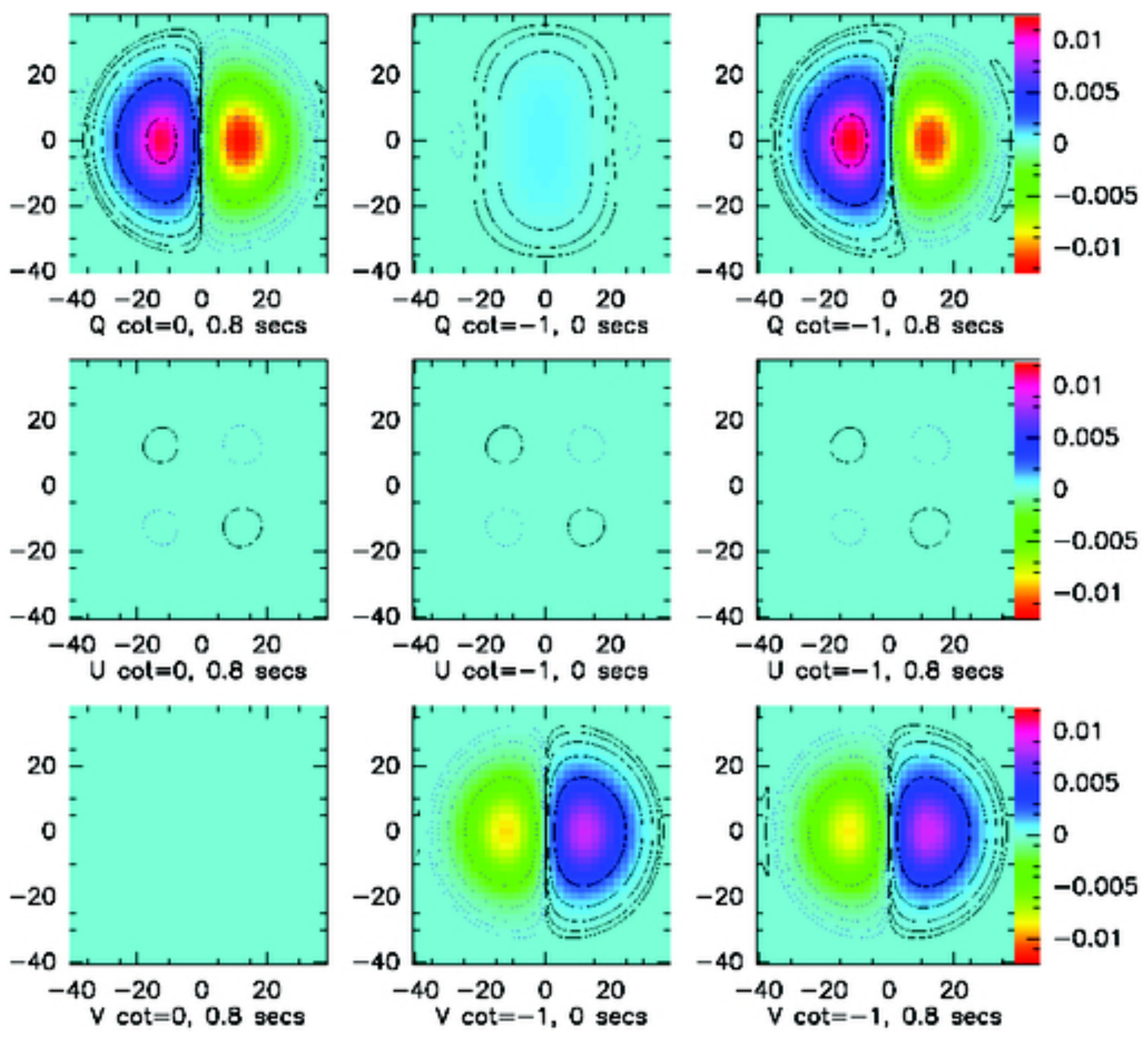


Fig. 2: *Simulations of far-field cross-polarization [7], in Stokes Q, U and V (dual polarization feeds & beam splitting grid). Left column: 0.8 arc sec co-alignment, grid in optimum orientation. Center: Perfect co-alignment, grid in non-optimum orientation. Right: Co-alignment 0.8 arc sec, non-optimum orientation.*

Fig. 1: *IRAM 30m, beam maps [7] of the Stokes parameters Q, U, and V (from top to bottom) at 86 GHz in 1999 (left) and 2005 (right, for improved co-alignment and optimal beam-splitting grid orientation). All flux scales are in fractional polarizations (indicated on the lower right), contours are at 0.2%, 0.4%, 0.8%, 1.6%, and 3.2%, negative contours are dashed, thick white contours are at ±0.1%. The rotated coordinate crosses show the x- and y-axes of the Nasmyth coordinate system.*

Sources of cross-polarization

The cross-polarization of an axisymmetric telescope is negligible (for a Huygens source [2] shown by [3], [4], including diffraction by [5], [6]). This ideal case is never realized in practice, for various reasons [7]:

- An elevation-dependent deformation of the telescope aperture (from circular to slightly elliptical) introduces a polarization-dependent aperture efficiency.
- Imperfections in the feed horns contribute a few % to the cross-polarization (CP). They are suppressed by a combination of a beam-splitting grid with a mono-mode waveguide, leaving a residual on-axis CP of typically ~1% [8] (also present in ortho-mode transducers [9]).
- Offsets in the co-alignment of feeds with orthogonal linear or opposite circular polarizations cause extended polarized sidelobes in the far field ("beam squint", Fig. 1).
- A de-focus causes a phase error across the aperture plane which is axisymmetric only for a displacement along the optical axis, [10]. With sub-optimal co-alignment this leads to CP [11].
- Polarization-sensitive equipment (e.g., a beam-splitting grid) in a divergent beam induces CP for wires in the plane of incidence [12]. If a beam squint is present, this produces a spurious conversion from Stokes I to Stokes V in the far field.

Some imperfections are suppressed by design optimization and accurate adjustments (Figs. 1,2), others remain and show in observations of weakly polarized sources.

Post-observation removal of cross-polarization

The brightness distribution received from an unpolarized calibrator (Venus, Uranus, Mars if unresolved), fully mapped in all Stokes parameters, allows for the following correction scheme [13]:

B = brightness distribution (intensity), S = flux density, P = point source response.
First index: 0 = Stokes I, j = 1,2,3: Q, U, V, second index: obj: Object, P: Planet.

$$\begin{array}{ll}
\textit{For} \quad j=1,2,3: & \\
\textit{Aim: corrected Stokes maps} & S_{j,obj}=B_{j,obj}*P_0 \\
\textit{Observations yield} & S_{j,obj}=B_{j,obj}*P_0+B_{0,obj}*P_j \\
\textit{Model} & M_j=S_{0,obj}*B_{j,P}=B_{0,obj}*P_0*B_{0,P}*P_j \\
\textit{Correction:} & S_{j,obj}*G-M_j \quad \textit{with} \quad G=P_0*B_{0,P} \\
\multicolumn{2}{l}{\textit{Apply correction, deconvolve with planetary disk profile.}}
\end{array}$$

A demonstration is shown in Fig. 3. While the method preserves the original spatial resolution (Θ_{mb}, the FWHM of the main beam in Stokes I), polarization sidelobes are only corrected on spatial scales ≥ $1.4\Theta_{mb}$, unless a Stokes I map of the target is available with a beam of FWHM $\ll \Theta_{mb}$.

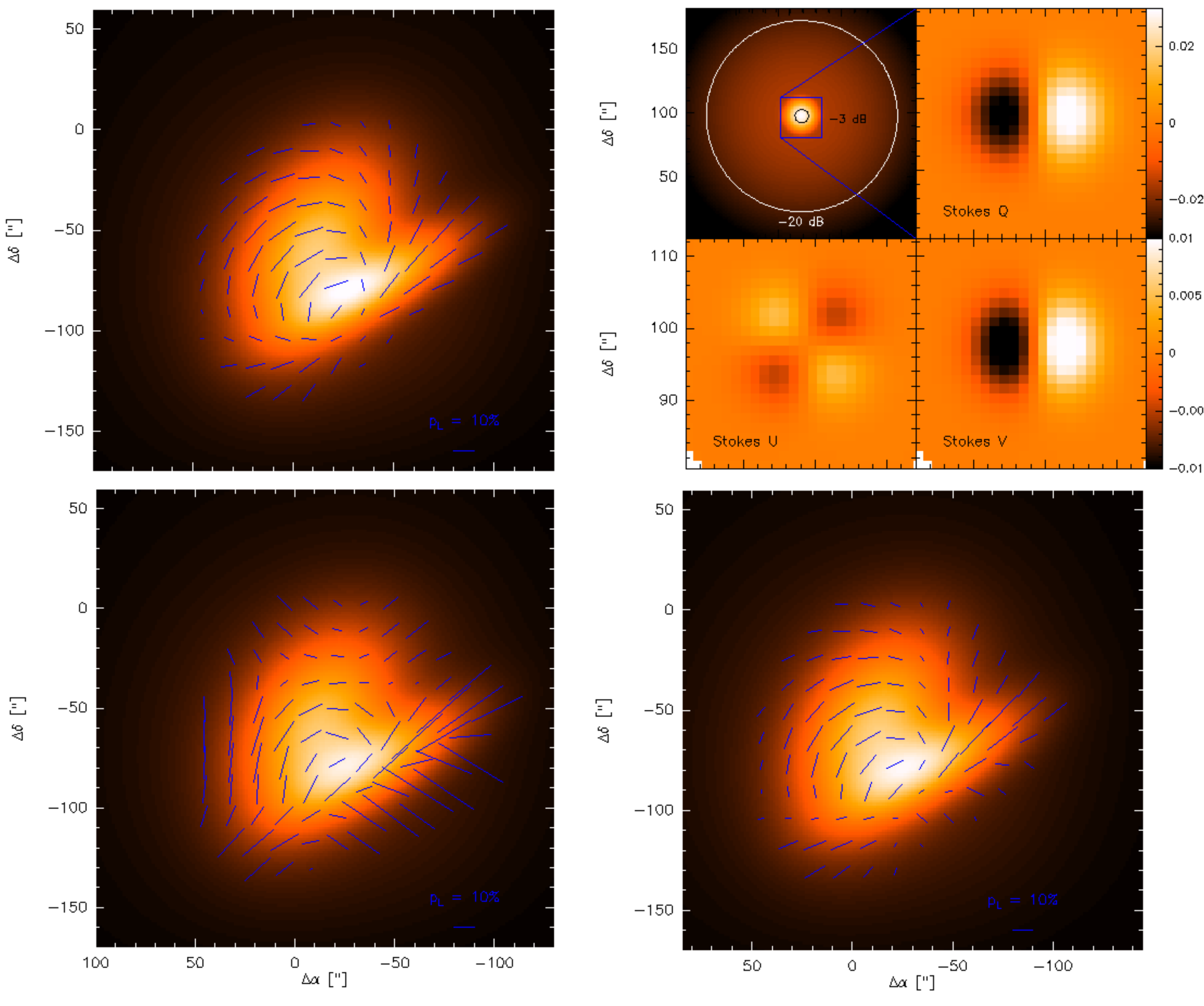


Fig. 3: *Simulation of the deconvolution of a sky-plane projected magnetic dipole field (top left) from the instrumental leakage of Stokes I into Stokes Q, U and V (top right). The bottom panels show the observed (left) and the restored, intrinsic polarization (right).*

Conclusions

Provided that the instrumental cross polarization is sufficiently well known even under various observing conditions, the intrinsic, polarized brightness distribution of the target can be restored with a dedicated algorithm [13]. This correction is particularly useful for wide-field observations, but requires additional calibration measurements which, depending on the instrumentation, may prove substantial and involved. Including high-fidelity polarimetry in the design specifications for radio telescopes and their instrumentation is therefore desirable. Under a more general perspective this may also improve sensitivity and observing efficiency.

References: *[1] Robishaw T. 2008, PhD thesis. [2] Koffman I. 1966, ITAP 14, 37. [3] Hanfling J. 1970, ITAP 18, 392. [4] Safak M. ea. 1976, IEEE Trans. AP-24, 497. [5] Minnett H.C. ea 1968, Proc.IEE 115, 1419. [6] Thomas B. 1976, Elec..Let. 12, 218. [7] Thum C. ea. 2008, PASP 120, 777. [8] Agudo, I. ea 2018, MNRAS in press. [9] Sievers A. ea. 2015, IRAM Report. [10] Baars, J.W.M. 2007, Springer ASSL 348. [11] Wiesemeyer H. ea. 2011, A&A 528, A11. [12] Chu T.S. ea. 1975, BellSys Tech..Journ. 54, 1665. [13] Wiesemeyer H. ea. PASP 126, 1027.*