Facets of Instrumental Polarization - Lessons learned from Single-Dish Polarimetry

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- Fundamental algorithms to describe polarimetry in radio astronomy
- Facets of instrumental polarization: instrumental polarization of unpolarized sources, Stokes conversion of polarized ones
- Examples from single-dish correlation polarimetry

Polarimetry has rarely been included in the baseline design of either telescopes or instruments, at least for night-time astronomy.
J.H. Hough, Astronomical Polarimetry (2004)

Fundamental Algorithms

- Müller matrix: ideal to describe mixed polarization states, but phase shifts (interferometry !) can only be described by finding their effect on the Stokes parameters.
- Complex Jones vectors: full phase information, but without any add-on to the theory they cannot describe mixed polarization.
- Way out: complex coherency matrix formulation (Born & Wolf, 1956, Ko, 1967).
- Hamaker et al. (1996) use the coherency vector instead.
- Physically more transparent: stay within the coherency matrix formulation. There are two probabilities: one for a photon to be in a given polarization state, and second one for the presence of this polarization state in an ensemble of photons.

Calculation of interferometer response (I,Q,U,V are complex Stokes visibilities)

- Coherency matrix: $$\rho = 0.5 \begin{pmatrix} I+Q & U-iV \\ U+iV & I-Q \end{pmatrix}$$
- Effect of receiving elements (here: cross correlation):

$$H\overline{V} = \begin{pmatrix} g_1 \\ 0 \end{pmatrix} \otimes \left(0, \ \overline{g_2}\right) = \begin{pmatrix} 0 & g_1\overline{g_2} \\ 0 & 0 \end{pmatrix}$$

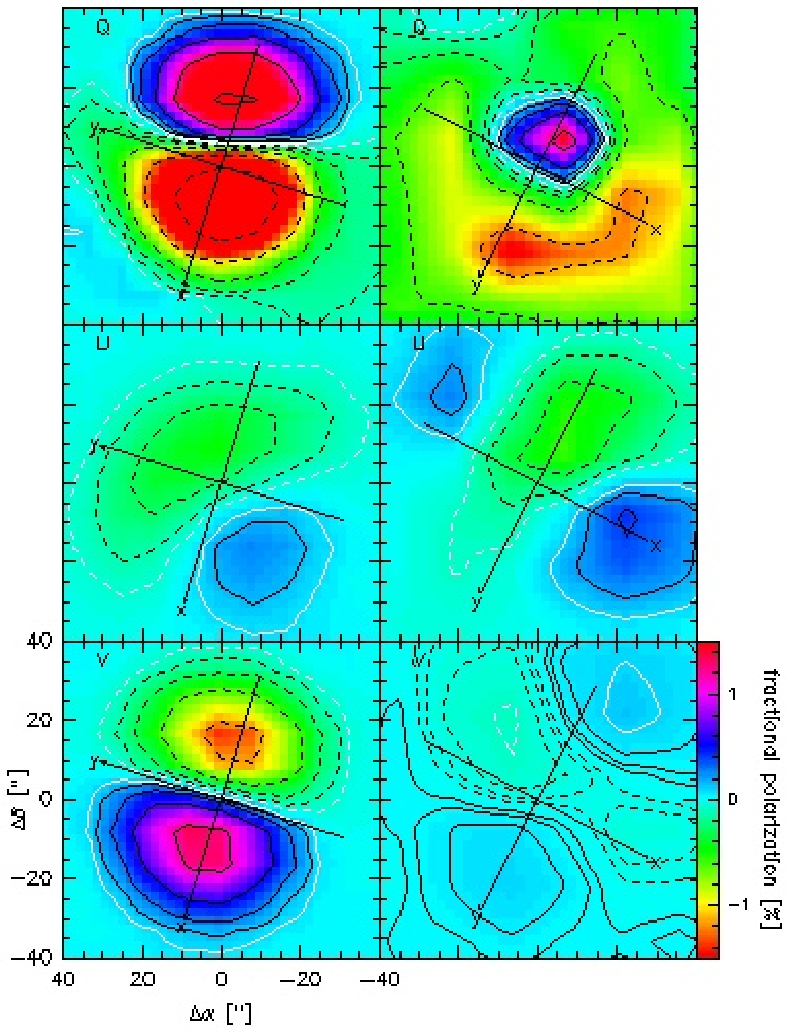
$$V\overline{H} = \begin{pmatrix} 0 \\ g_2 \end{pmatrix} \otimes \left(\overline{g_1}, \ 0\right) = \begin{pmatrix} 0 & 0 \\ \overline{g_1}g_2 & 0 \end{pmatrix}$$

- Output signal: $$S_1 = tr\left(\rho H\overline{V}\right) = 0.5(U+iV)g_1\overline{g_2}$$ $$S_2 = tr\left(\rho V\overline{H}\right) = 0.5(U-iV)g_2\overline{g_1}$$

- If gains phase calibrated: U = S_1+S_2 and V = i(S_2-S_1)
- Yields “blackbox formula” of Morris et al. (1964), Weiler (1973).
- Instrumental polarization calculated by linear and similarity transformations of the complex matrices $H\overline{V}$ and $V\overline{H}$.

Instrumental Polarization

- generation of polarization in unpolarized signals (polarization sensitive gain differences, polarizing elements in optics, misalignment when total power differences are measured)
- spurious conversion of Stokes parameters (phase calibration errors, leakage, beamsplitters in diverging beams). Below: Venus (30m MRT/XPOL, Thum et al., 2008). Right: Simulations.



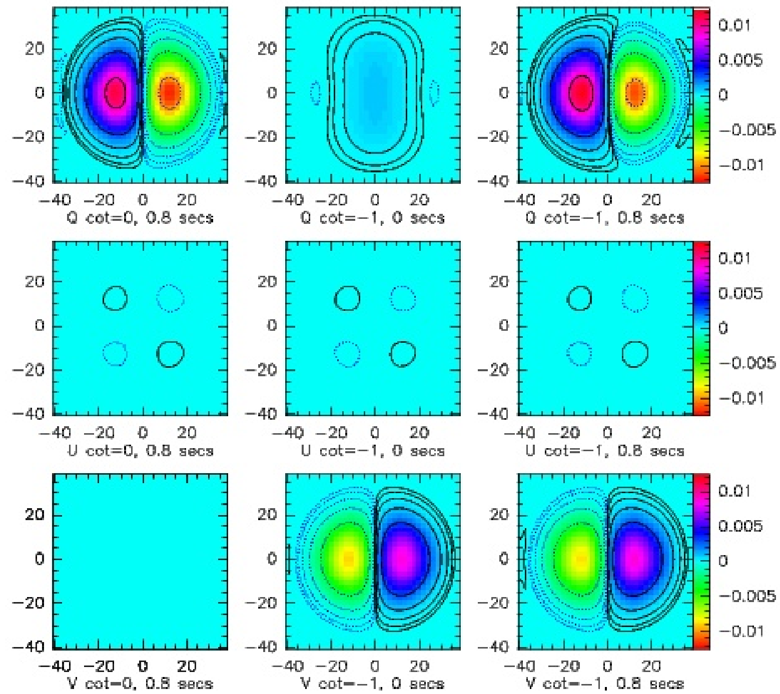


Fig. 7.— Simulation results for the far field cross–polarized sidelobes. The effects of changing the orientation of the polarization grid (*cot*) and the pointing offsets (arc seconds) between the 2 receivers are shown in the 3 columns. Left column - offset 0.8 arc seconds, optimum orientation, middle column, - no offset, non-optimum orientation, right column - offset 0.8 arc seconds, non-optimum orientation. From top row to bottom row are displayed the Muller matrix elements M_{IQ}, M_{IU}, M_{IV}. The contours are at power levels relative to I of ±0.01, ±0.0036, ±0.001, ±0.00036, ±0.0001, ±0.000036.

Instrumental Conversion of Stokes Parameters

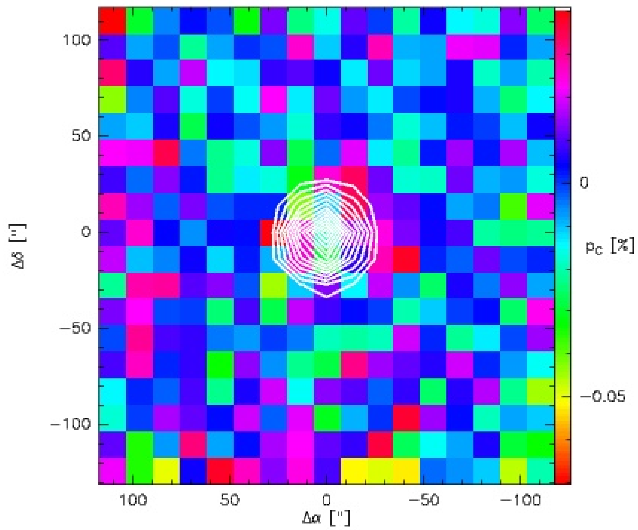
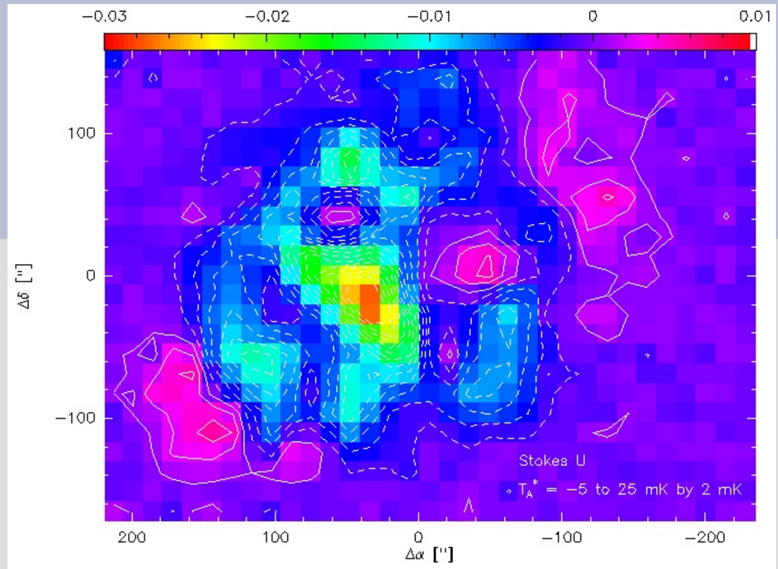


Figure 5: Fractional circular polarization towards Mars (false-colour plot). The Stokes I map (after destriping using the plait algorithm) is shown as white countours (level spacing: 0.6 K, equivalent to $10\sigma_{rms}$).



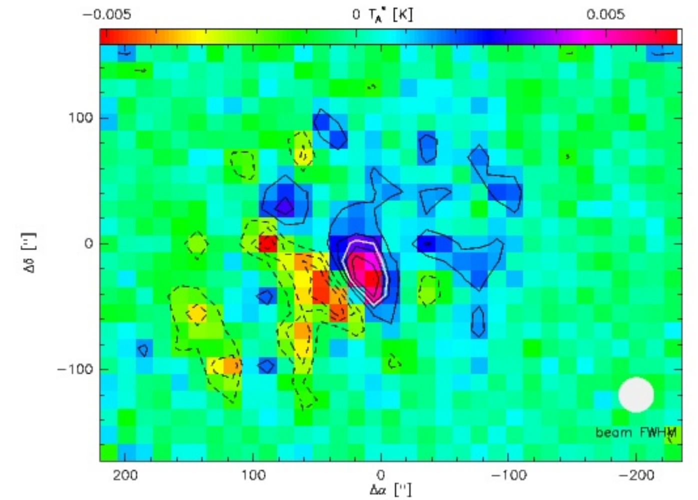


Figure 4: Stokes V map of Tau A, scaled in antenna temperature. Black contours: levels at −3.9 to −1.3 mK (dashed), then +1.3 to 6.5 mK, by 1.3 mK. The level spacing corresponds to the $3\sigma_{rms}$ noise level. The white contour indicates the half-power contour, the beam size (FWHM) is indicated in the lower right.

Top left: Mars, white contours: Stokes I pattern (30m MRT/XPOL, λ = 3mm). False colours: Stokes V (instrumental).
Top right: Stokes U (intrinsic).
Bottom: Conversion from Stokes U to V due to a residual phase error < 1° (no significant intrinsic Stokes V).

Conclusions and Recommendations

Polarization is a basic property of photons, just like frequency. It is often almost as densely coded with information.

R. Antonucci (2000)

- Timescale of phase variation by 1° for a point source at 10'' E from phase reference center for EW baseline of 180 m @ 100 GHz: 10 min.
- Phase shift due to a 1% circular polarization in presence of a 28% linear polarization in Stokes U: $\Delta\varphi = 2°$
- Phase calibration needs to be better than 0.5° rms for a 4σ detection of this signal.
- Probably need to separate phase calibration of IF bandpass (higher order polynomials, noise source injection) from RF bandbass (smoother) if no sufficiently strong polarized calibrators available.
- Problem with usual calibration of leakage terms using unpolarized point sources: do not account for polarized sidelobes.
- Measurements (single-dish correlation polarimetry mode) and modeling of polarized sidelobes is needed to assess fidelity for polarimetry of extended sources (e.g. synchrotron emission from supernova remnants, dust in molecular cloud cores). Need to model ALMA's instrumental polarization, allow for time variability of instrumental response (e.g. parallactic rotation of Stokes beam pattern, mainly fixed in the Cassegrain focus).
  Way out: time-dependent convolution of visibilities with FT of Stokes response.