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Calibrating linear polarization data at 16 cm with ATCA/CABB

Based on the meeting on the 16th of August 2011
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Summary. The goal of this document is to define a strategy for calibrating linear polarization data in the 16 cm band of the ATCA. Summarising, instrumental on-axis polarization levels of P/I $\lesssim$ 0.1% can be achieved with standard calibration techniques, and without splitting the 2 GHz band into smaller sub-bands. Off-axis leakages can be suppressed by mosaicking, basing the pointing distance on the half-power beamwidth at 3.1 GHz.

Throughout this memo it is assumed that the `miriad` software package is used for the calibration.

The problem

Instrumental leakages vary considerably over the 16 cm band of the Compact Array Broadband Back-end (CABB). Our current understanding is that this is the only polarization-specific effect which makes calibrating CABB data more complicated than calibrating pre-CABB data. In this document we analyse the instrumental linear polarization performance of the ATCA in the 16 cm band, both on-axis and off-axis. Because of the large fractional bandwidth at 16 cm, polarization imaging and in particular image deconvolution have become very complicated to handle in `miriad`; for these tasks the user should use `casa` instead.

Mark Wieringa has been working on a version of `miriad` that stores leakages for sub-bands of the data. Currently `miriad` only stores a single leakage table for the entire frequency band; if one wants to calculate leakages for sub-bands of the data the CABB band has to be broken up into these sub-bands on a computer hard drive. Mark found that other `miriad` tasks also need to be updated so that these tasks can use the new gains and leakage tables. He estimates that he can test a first version of his new `miriad` implementation by the end of August[2].

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[2] Solving for frequency-dependent leakages has been implemented since `gpcal` version 1.11, from the 8th of September 2011, with the keyword `nfbin`

On-axis leakage

During green time on the 3rd of November 2011 we observed PKS 1934-638 seven times during a 7.5 h period, each time for about 30 minutes, to estimate the on-axis instrumental polarization level of the ATCA. These observations showed that standard calibration techniques result in measured on-axis P/I of 0.08%. To get to this value, we used rotation measure synthesis, and we measured the strongest polarized intensity in the part of the rotation measure spectrum that is aliasing-free[3]. Seven observations in different times of the night consistently reproduced a polarized flux of about 9 mJy (detected at the 180 – 190 σ level). 5-minute observations of PKS 1934-638 will already detect this polarized flux at the 75 σ level, which means that we can use observations of PKS 1934-638 as flux calibrator from the Australia Telescope Online Archive (ATOA[4]) to monitor leakage variability over time. Only baselines larger than 1 kλ (142 m) were used when measuring fluxes, this effectively removes diffuse emission on large angular scales. Although the values for Stokes Q and U as a function of frequency showed a much larger scatter, rotation measure synthesis averages these fluctuations over the 2 GHz CABB band, which reduces the impact of these fluctuations. On the other hand, a 'classical' fit of polarization angle vs. wavelength squared is sensitive to these fluctuations, which results in an unacceptably large value for the reduced χ^2 of the fit.

Work by Shane, Naomi, Jamie, Julie and Dominic shows that instrumental leakages vary over the CABB band; Figs. 5 and 6 from the L/S commissioning memo shows that the large-scale component of this variation is well sampled when the 2 GHz CABB band is split into 16 sub-bands. Each of these sub-bands is then 128 MHz wide, the same bandwidth as was available with the old (pre-CABB) correlator on the ATCA. Solving for the leakages in the individual sub-bands gives a measured on-axis P/I of 0.05% for our observations of PKS 1934-637 on the 3rd of November. The leakage variation as a function of frequency is furthermore dominated by the real part of the leakages[5].

Ray pointed out that with a circularly polarized source like PKS 1934-638 we are looking at an end-on jet, and such sources tend to show variability in linear polarization. However, Long-Baseline Array observations of PKS 1934-638 showed that this source has two lobes instead of an end-on jet (Tzioumis et al. 2010). Even so, observing PKS 1934-638 over multiple epochs will still be useful, since it will tell us how instrumental leakages vary over time.

A sub-band of 128 MHz is the smallest bandwidth that is currently still practical (before the `nfbin` option became available in `gpcal`). Julie and Shane have tested smaller sub-bands; they ran into scripting difficulties when they were concatenating sub-bands that were completely flagged (using the `miriad` task `uvglue`). This happens for example around 1.5 GHz, where radio-frequency interference dominates the astronomical signal.

Dominic has reported alternative calibration strategies where leakages are determined on a channel-by-channel basis using PKS 1934-638 (these are outlined in Fig. 1). He used

[3] This is the range from -RM_max to +RM_max, where RM_max = $1.9/\delta\lambda^2 \approx 14{\times}10^3$ rad/m^2 for our observations, where $\delta\lambda^2$ is the average width of the frequency channels expressed in units of wavelength squared

[4] http://atoa.atnf.csiro.au/

[5] Hamaker et al. (1996) describe in their Appendix D that to first order the real and imaginary parts of the leakages reflect the relative orientation and the ellipticity of the receiver dipoles.

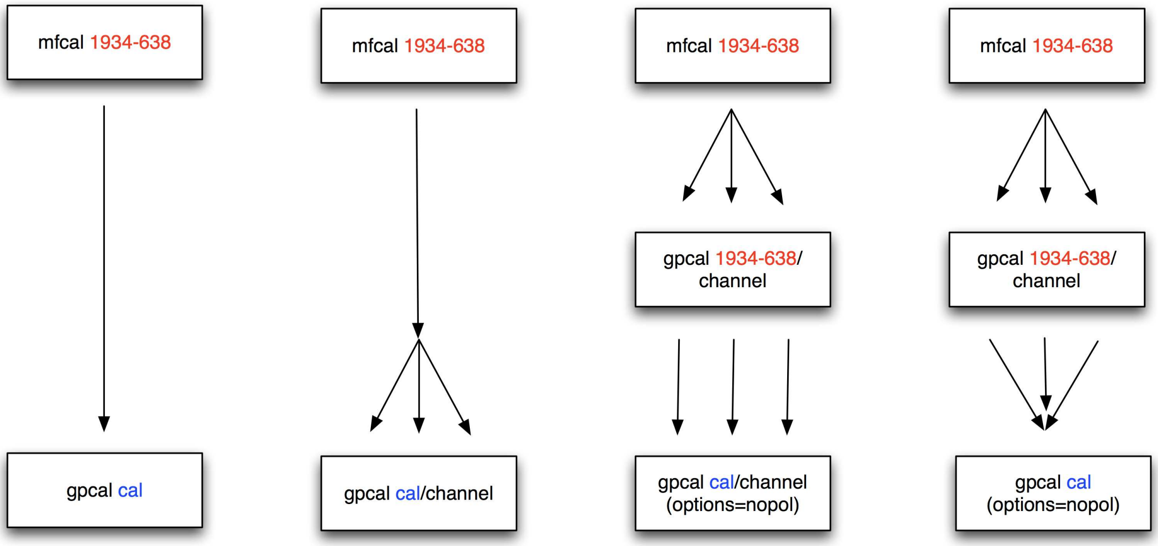

Figure 1: Overview of the four calibration strategies that Dominic tested; "cal" refers to the phase calibrator. Leftmost: the canonical strategy, where PKS 1934-638 is used for the bandpass solution, and `gpcal` is run on the phase calibrator to determine the complex gains and leakages. The other three strategies solve for leakages on a per-channel basis (the diverging arrows symbolise splitting the full frequency band): recipe 2 uses the phase calibrator to calculate leakages, and recipes 3 and 4 use PKS 1934-638. "options=nopol" means that `gpcal` is only used to determine gains, and not leakages as well. Recipes 2 and 3 calculate gains for the phase calibrator on a per-channel basis, while recipes 1 and 4 calculate gains for the entire band. Julie used a strategy similar to recipe 4, but she calculated leakages for 128 MHz sub-bands of the data using the phase calibrator instead of PKS 1934-638. Shane split up the band into 128 MHz sub-bands before running `mfcal` on PKS 1934-638, and ran `gpcal` on these sub-bands from PKS 1934-638 and the phase calibrator.

pre-CABB data, which means that his channels were 8 MHz wide. Solving for the complex gains in the phase calibrator on a per-channel basis often leads to convergence problems in the `miriad` task `gpcal`, also in the case of bright phase calibrators. For sources brighter than about 1 Jy he recommends a recipe where leakages are calculated for individual frequency channels in an observation of PKS 1934-638, then transferred to the phase calibrator and target source, after which the channels are re-combined and `gpcal` is used on the full frequency band of the phase calibrator (recipe 4 in Fig. 1). He will investigate if this alternative strategy also improves the polarized intensities and rotation measures of phase calibrators fainter than 1 Jy, or whether the older, simpler calibration strategy gives results of comparable quality (this is described in more detail in Schnitzeler et al. 2012)

Off-axis leakage

Naomi and Jamie used 4 hours of green time to map off-axis leakages over the full CABB band in one quarter of the primary beam, using a Cartesian pointing grid (*See Fig. 3 from the L/S commissioning report*). Their work shows that off-axis leakages at the half-power point of each frequency rise from $\sim$ 1% at 1.1 GHz to 6% at 3 GHz (with a scatter of 1–2%), with a peak of 13% at 2.5 GHz (*See Fig. 4 from the L/S commissioning report*).

Naomi pointed out during our meeting that the off-axis leakages at 2.4 GHz were also high with the old S-band system, which we should keep in mind when assessing the quality of off-axis leakages (I'm paraphrasing Naomi here). Currently the best practical solution to suppress off-axis leakages is to use a mosaic with a fine sampling grid, the separation between antenna pointings being dictated by the half-power beamwidth at 3.1 GHz. As Dave suggested, observing over a long period of time further averages out leakage effects since the sky rotates with respect to the primary beam of the antennas. Chris is working on an algorithm which calculates for any sightline what the instrumental polarization level is from each of the contributing primary beams; such an algorithm can be used to make a map of instrumental polarization levels throughout the mosaic.

* open points *

• Chris cautioned that the `miriad` task `invert` creates channel maps out to the distance where the primary beam response of the centre frequency has dropped to 3%. Because the diameter of the primary beam changes so much over the CABB band, a sightline that lies far from the field centre will have unacceptably high instrumental polarization levels at the high-frequency end of the CABB band. These frequency channels should therefore not be used for these sightlines (this leads to the idea of a frequency-dependent usable surface area, which is included as the final bullet point in the memo that describes progress since our meeting on 16/8/2011). Furthermore, a large fraction of the primary beam at the low-frequency end of the CABB band is usable, but not mapped with `invert`: at the point where the primary beam response at 2.1 GHz (the centre frequency of the 16 cm band) has dropped to 3%, the primary beam response at 1.3 GHz is still about 40% (using model atca.2 in the `miriad` task `pbplot`). The outer part of the primary beam at 1.3 GHz can therefore still be used for science, albeit at poorer sensitivity since only a small fraction of the 2 GHz CABB band is usable this far from the pointing centre. The observer is recommended to split up the band, and image the sub-bands separately.
• Update: On the 10th and the 16th of September, and on the 3rd of November 2011, Jamie and Dominic observed PKS 1934-638 in different parts of the primary beam of the ATCA. These observations cover all 4 quadrants of the primary beam of the ATCA with a much finer, polar grid, instead of the Cartesian grid that Naomi and Jamie used. We will use these new observations to map the primary beam in both total and polarized intensity.
• Reid et al. (2008) compared mapping off-axis leakages and subtracting these from the data to doing a holographic mapping of the antennas, and using these holographic maps to remove off-axis leakages. Their Fig. 2c/d shows that doing holography instead of mapping off-axis leakages can be a big improvement. However, holographic mapping requires a large effort, and mapping off-axis leakages can be carried out on a short timescale.

– Related issues –

• Mike Kesteven has holography data for the ATCA (measured a long time ago)
• Tim Cornwell has characterised the primary beam around 1.4 GHz (but not the off-axis leakages) of the ATCA based on beam scans and a model for the illumination pattern. The model is available as a FITS image, `glish` script, in `ASKAPsoft`, and in `casa`. He reckons that although the data were obtained with the pre-CABB system, the beam pattern is

still accurate around 1.4 GHz in the CABB system.

- Running the `miriad` task `mfboot` with mode=scalar solves the problem with wiggles in the Stokes I spectrum of phase calibrators, which Shane had reported previously.
- Placing zoom bands in regions that are heavily affected by radio frequency interference (RFI) in the 16 cm band allows removing narrow-band RFI without losing too many usable channels. This would add data points with comparatively large values of wavelength squared for observations that depend on RM synthesis, at the cost of a more complicated rotation measure spread function.
- Fig. 2 in the L/S commissioning report shows that the side-lobes of the primary beam are rather high, this could be taken up with the engineers. However, the primary beam response that is shown in Figs. 2 and 7 of the L/S commissioning report is almost identical to measurements of the primary beam response from the early 90s (Staveley-Smith et al. 1991, Wieringa & Kesteven 1992). Since it wasn't necessary to fix this over the last 20 years we don't need to invest time to fix this on the short/medium term.
- Julie has offered to write down her notes on mosaicking in `casa`.

References

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