Calibrating GMRT polarisation data
June 2015

This document gives a data reduction recipe in AIPS for analysing GMRT polarisation data put together by the GMRT Science Operations group. This recipe has successfully worked for GMRT 610 MHz data acquired in May 2014 but, in principle, should work well at the lower GMRT bands. The major difference for the different wavebands are the polarisation calibrators that need to be used. While 3C286 and 3C138 are good polarisation calibrators at 610 MHz, the pulsar B1937+21 should be used for the lower GMRT bands.

Once the data reduction is completed as outlined here, you should have the ionospheric effects and instrumental polarisation calibrated and applied to the data. The data is then imaged for the different Stokes parameters. These can then be used for rotation measure synthesis, if desired.

The document is divided into two parts - observing strategy and data reduction in AIPS.

Queries can be addressed to ngk@ncra.tifr.res.in mentioning 'GMRT Polarisation' in the subject line and we will try our best to help.

1 Recommended Observing strategy

The observing strategy generally followed for regular continuum Stokes I observations is observing an amplitude/bandpass calibrator for 10-15m followed by a loop wherein a few minutes on a phase calibrator and 30-40m on the target source are repeated. The observations generally end by another 10-15m run on the amplitude/bandpass calibrator. For polarisation observations, observe at GMRT in the 'full polar' mode, follow the same strategy as for Stokes I observations but remember to include a couple of scans on a polarisation calibrator - one of 3C286 OR 3c138 at 610 MHz and B1937+21 at lower frequencies. The mode of observing to use is full polar, 32 MHz, 256 channels. While the mode with a larger number of channels is available, we do not recommend that due to it causing buffer loss problems in the correlator.

For polarisation studies, it is important to be able to calibrate the instrumental polarisation due to the feeds. For an alt-azimuth mount like GMRT, a calibrator observed over a large range of parallactic angles can isolate the instrumental polarisation from source polarisation. The phase calibrator is ideal for determining this calibration. Additionally, the phase difference between the R and L polarisations needs to be determined. This requires a known polarised calibrator like 3C286 and 3C138. The expected polarised signal and polarisation angle are noted for VLA frequencies above 1 GHz at https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/pol. We also recommend this document for more information on polarisation calibration. and recommend referring to the technical memo by Jamie Farnes at http://ncralib1.ncra.tifr.res.in:8080/jspui/handle/2301/574 which gives de-

tails of the analysis and scripts which went into the first published polarisation observations with the GMRT (Farnes, Green, Kantharia 2014).

For 610 MHz, it is advisable to observe one of 3C286 or 3C138 during an observing run and preferably both of them if available at 610 MHz to ensure a backup scan. If only one calibrator is available, it might be useful to have at least two runs on it to provide a backup scan.

2 Polarisation calibration in AIPS

In this section, we describe the recipe that can be used for calibrating GMRT polarisation data in AIPS.

As mentioned in the previous section, polarisation calibration consists of two main steps - determining the instrumental polarisation and determining the phase difference between the two orthogonal polarisations. The two main tasks in AIPS for this are PCAL and RLDIF. In the 31DEC10 version of AIPS, these tasks ran only on single channel data. However version 31DEC12 allows the polarisation calibration tasks to run on several channels spanning a bandpass. Since GMRT data is always acquired in the spectral line mode, PCAL and RLDIF are useful in the multi-channel mode of operation.
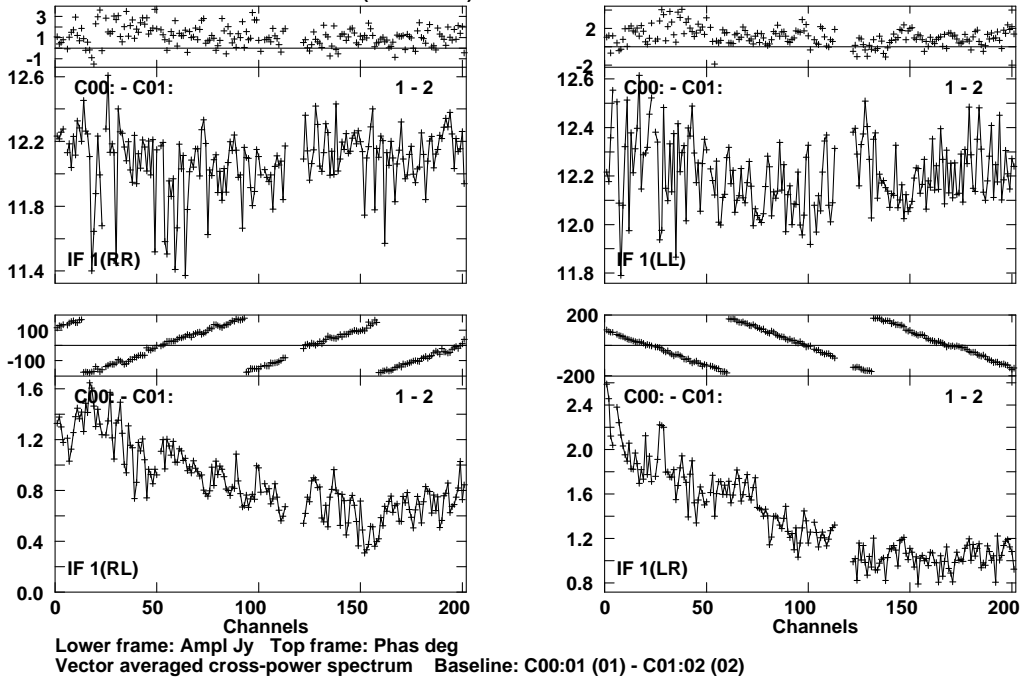
We enumerate the different tasks and the sequence in which they need to be run. Suggested values of the adverbs are given and a short summary of the important inputs/outputs and the reasons for running the task where required are given. For completion, the recipe includes basic details on flagging and gain/bandpass calibration in addition to polarisation calibration. The black belt GMRT user can start from step 7 for polarisation calibration.

1. **CALIB, CLCAL, UVFLG**: To iteratively gain calibrate and edit corrupted data using gain calibration of a single channel data on all the calibrators (unless signal-to-noise on a calibrator is low in which case you will need to average channels after BPASS and do this). For point source approximation, use UVRANGE=2,20 at 610 MHz: 3C48, 3C286, 3C147. This avoids central square baselines. For FLGIT, run SETJY to set all fluxes to zero and gain calibrate. Several runs of CLCAL - once for each calibrator and one run for the target source. Output: CL version 2, FG.

2. **BPASS:** To generate bandpass gains. Run on phase calibrator + bandpass calibrators. Use BPLOT to examine channel data (20 channels at a time) and identify bad channels and remove from all sources. Output: BP

3. **FLGIT, CLIP, UVFLG:** Remove bad data. Run FLGIT with *OP-CODE 'MWFL', DOCAL=1, DOBAND=1, APARM=4,3,1.5,0,0,2.5,9,0,0,1* to remove bad data from calibrators in temporal and spectral domains. These APARMS seem to work for 610 MHz and can be modified if a

large fraction of data is flagged - more than a few percent. The APARM will change for other wavebands. FLGIT has to be run with lower flux density cutoff in APARM for the target source.

4. **TASAV:** Copy all the tables from the UV data to a dummy UV file and delete SN, CL (ver 2), BP from the UV database.

5. **SETJY:** Set flux densities of primary calibrators.

6. **CALIB, GETJY, CLCAL, UVFLG:** To iteratively gain calibrate and edit corrupt data from single channel calibrator data till satisfactory solutions are obtained. Input: CL version 1 Output: CL version 2.

7. **TASAV:** Copy all the tables from the UV data to a dummy UV file as backup and continue.

8. **LISTR:** To list the parallactic angle coverage. A good coverage allows for better calibration of feed/instrumental polarisation. Inputs: *OPTYPE 'gain', INEXT 'cl', DPARM=9,0, SOURCES 'cal1' 'cal2'....*

9. **TECOR:** Calibrate ionospheric Faraday rotation using TEC maps in IONEX format. See explain TECOR in AIPS for details on downloading the TEC maps in IONEX format. Input : CL version 2, SOURCE " and Output: CL version 3.

10. **RLDLY:** To estimate the delay differences between R and L polarisations. If the phase on a cross-polar bandpass (check on a polarised calibrator) in POSSM (APARM(1)=1) shows a ramp (see Figure 1) then this task needs to be run. Use a polarised calibrator like 3C286 or 3C138 and a good reference antenna. Inputs: *DOCAL=1, DOBAND=1, SOLINT=16.9s (change if required), CALSOUR '3C138', REFANT=n* Input is CL table 3, output is CL table 4. Use POSSM to confirm corrections as shown in Figure 1.

11. **SPLAT:** To apply the flagging on the data and exclude edge channels. Inputs: e.g.*BCHAN=20, ECHAN=220, DOCAL=-1, DOBAND=-1, FLAGVER=0* Output: New UV database containing a subset of channels with flagging applied to the data. These are the channels to be used for polarisation calibration and this database is to be used in subsequent steps.

12. **PCAL:** Estimate instrumental leakage terms and source polarisation for continunum. The simpler linear approximation for point sources (APPR) has been used here. Inputs: *SOLTYPE 'APPR', UVRANGE=0,20, SPECTRAL=0, CPARM(2)=1, REFANT=n, ICHANSEL=c1,c2,1,0, SOURCE 'cal1' 'cal2'...* Outputs: Estimates source polarisation (Q,U,V) which are included in the SU table and the antenna leakage terms are updated in the AN table.

C00: - C01:   1 - 2

IF 1(RR)

C00: - C01:   1 - 2

IF 1(LL)

C00: - C01:   1 - 2

IF 1(RL)

C00: - C01:   1 - 2

IF 1(LR)

Channels

Lower frame: Ampl Jy   Top frame: Phas deg
Vector averaged cross-power spectrum   Baseline: C00:01 (01) - C01:02 (02)

C00: - C01:   1 - 2

IF 1(RR)

C00: - C01:   1 - 2

IF 1(LL)

C00: - C01:   1 - 2

IF 1(RL)

C00: - C01:   1 - 2

IF 1(LR)

Channels

Lower frame: Ampl Jy   Top frame: Phas deg
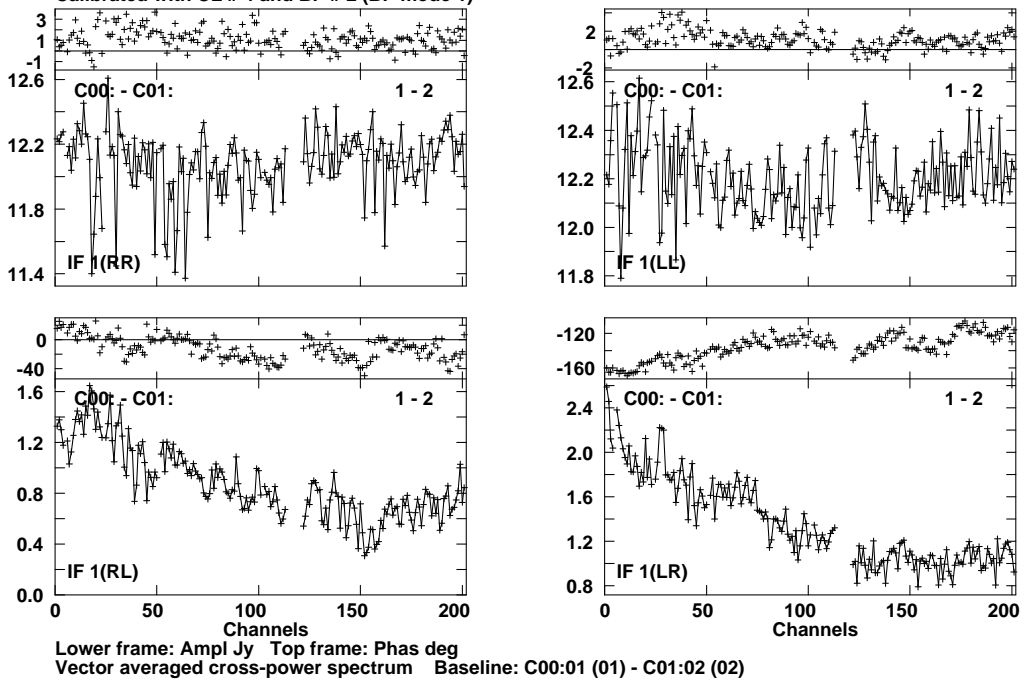Vector averaged cross-power spectrum   Baseline: C00:01 (01) - C01:02 (02)

Figure 1: (Top)Before running RLDLY. Note the phase ramps in the lower two plots showing RL and LR correlations. (Bottom) After running RLDLY. Note the phase ramps in the lower two panels have been corrected.

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13. **RLDIF:** Determines the R-L phase of the polarisation cailbrator by using the known polarisation angle to be $0.5\tan^{-1}(U/Q)$. Run twice - first to determine R-L phase and identify and flag outliers: Inputs: *DOAPPLY=-1, DOPOL 1 SPECTRAL=0 Source '3c138', UVRANGE=0,20*

    Second run of RLDIF: Inputs: *DOAPPLY=1, DOPOL=1, SOURCE '3c138', SPECTRAL=0, UVRANGE=0,20, CL table 4* Outputs: CL table 5 with appropriate corrections.

14. **PCAL:** Estimate instrumental leakage and source polarisation across the band. The simpler linear approximation for point sources (APPR) has been used here. Inputs: *SPECTRAL=1; CPARM(3) 0, SOLTYPE 'APPR', UVRANGE=0,20, CPARM(2)=1, REFANT=n, ICHANSEL=0* Outputs: PD table – polarisation leakage D terms, CP table – calibrator polarisation

15. **RLDIF:** Determine and examine the R-L phase angle of polarised calibrator (3C286 or 3C138 at 610 MHz) across the band. Inputs: *DOPOL=1, SOURCE '3C138', SPECTRAL=1, DOAPPLY=-1, OUTPRINT 'RLDIF-PHASE.DAT'* Outputs: generates a text file with the R-L corrections. If problem values are found, then edit data and rerun.

    Second run of RLDIF: Apply R-L angle corrections. Inputs: *DOPOL=1 SOURCE '3C138', SPECTRAL=1, DOAPPLY=1, OUTPRINT 'RLDIF-PHASE.DAT'* Outputs: Task updates the BP, PD, CP tables and makes a new version ie version 2.

    Third run of RLDIF: Check R-L angle corrections. Inputs: *DOPOL=1, SOURCE '3C138', SPECTRAL=1, DOAPPLY=-1, OUTPRINT 'RLDIF-PHASE.DAT'*

16. **POSSM/BPLOT:** Check PD and CP tables (Figure 2). CP table: *APARM(8)=6* and PD table: *APARM(8)=7 or 8.*

17. **UVFLG:** If high leakage antennas/channels are found or phase is ramping, flag these, delete the PD, CP tables and BPVER=2 and repeat from PCAL (step 13). If all is well then you have generated the required polarisation calibration tables!

18. **SPLIT:** Make single source files - gain, bandpass and polarisation calibrated output files for calibrators and only gain and bandpass calibrated for target source. Inputs for calibrators: *DOCAL=1, DOBAND=1, DOPOL=1, APARM=0.* Inputs for target sources:*DOBAND=1, DO-CAL=1, DOPOL=-1, APARM=0.* Retain all channels output from SPLAT if rotation measure synthesis is desired else run SPLAT and average.

19. **IMAGR:** Make Q, U, I images of calibrators to check that your analysis has worked. Polarised emission should be detected from 3C138 and 3C286 as shown in Figure 3.
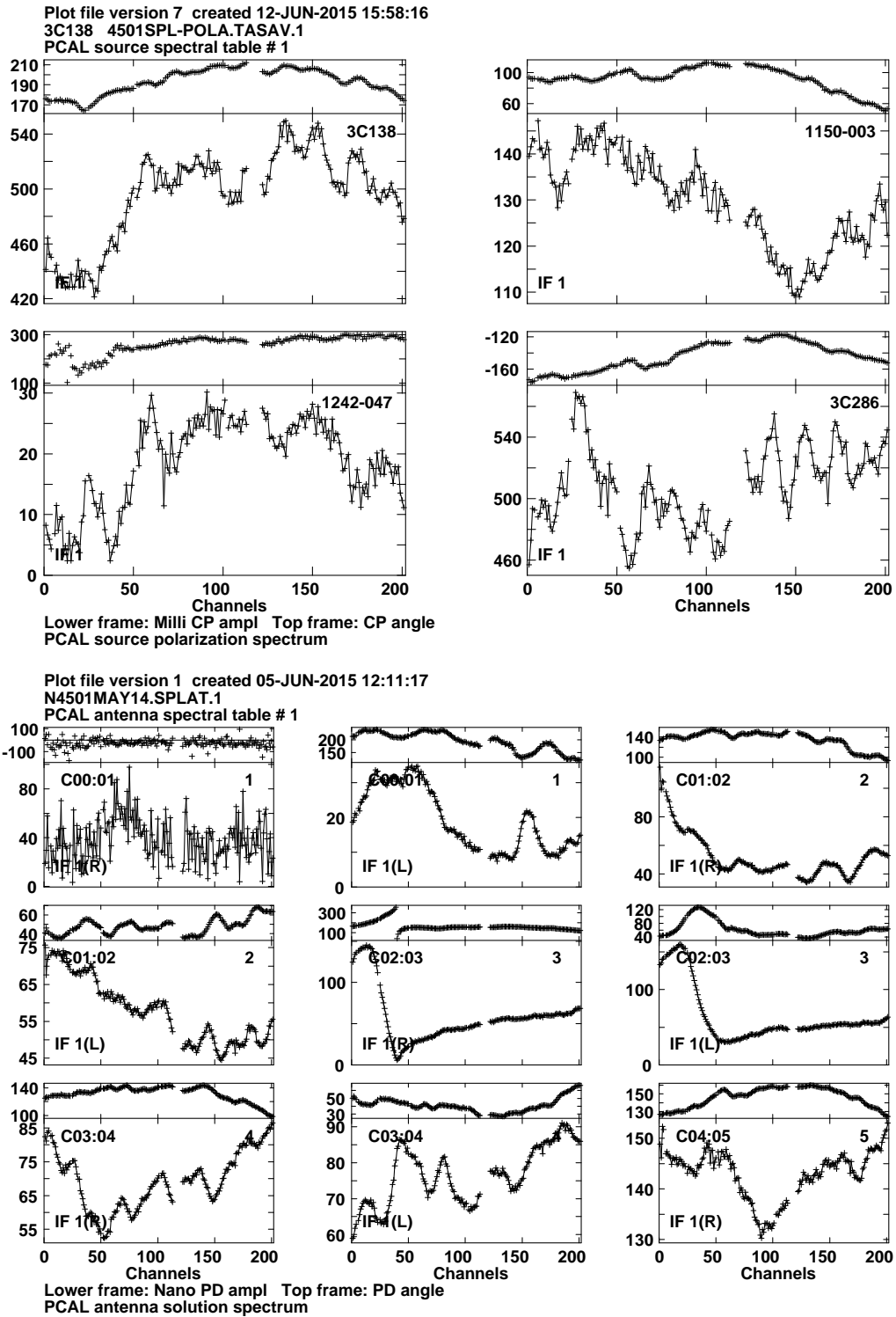
Plot file version 7 created 12-JUN-2015 15:58:16
3C138   4501SPL-POLA.TASAV.1
PCAL source spectral table # 1

Lower frame: Milli CP ampl   Top frame: CP angle
PCAL source polarization spectrum

Plot file version 1 created 05-JUN-2015 12:11:17
N4501MAY14.SPLAT.1
PCAL antenna spectral table # 1

Lower frame: Nano PD ampl   Top frame: PD angle
PCAL antenna solution spectrum

Figure 2: (upper) CP table showing calibrator polarisation spectrum; (lower) PD table showing leakage spectrum for different GMRT antennas. Notice that some antennas show a large value e.g. C04 and C02 shows large variation across the band.
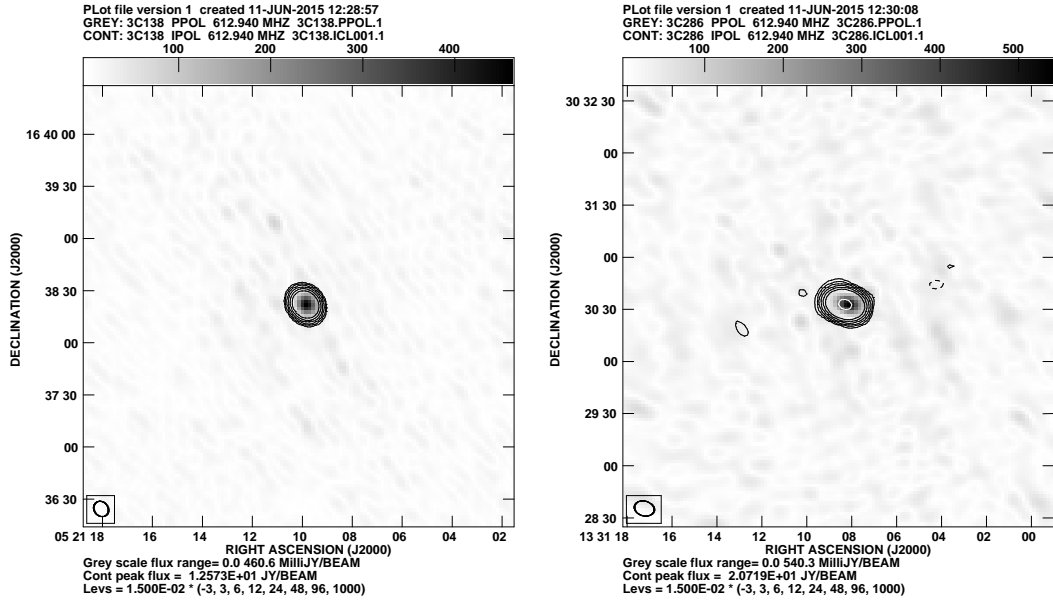
Figure 3: Stokes I in contours and polarised emission in grey scale at 610 MHz. Left panel shows 3C138 and right panel shows 3C286.

20. **IMAGR and CALIB:** Self-calibrate the target source data.

21. **SPLIT:** Apply polarisation calibration to target source after self-calibration. Copy PD table to the relevant database and then SPLIT.

22. **IMAGR:** Make Stokes I, Q, U polarisation images of target source. A continuum image can be made or channel images can be made.

23. **COMB:** Give Q and U images as inputs to generate the polarised emission image as shown for a field in Figure 4. Inputs: *OPCODE 'POLC' or 'POLI'*.

The above should result in images of polarised emission from sources in your target field. If you generate Q and U cubes from the calibrated UV data then these can be used for rotation measure synthesis. Rotation Measure Synthesis has been successfully implemented on GMRT 610 MHz data and details can be found in the techinical memo by Jamie Farnes at http://ncralib1.ncra.tifr.res.in:8080/jspui/hand and in the research paper reporting these by Farnes, Green, Kantharia (2014, MNRAS, 437, 3236).

3   Cautionary words

- Best used for objects near the pointing centre.

- Extensive editing of data is required. For this example field, we started with 26 antennas and finally could use 22 antennas.
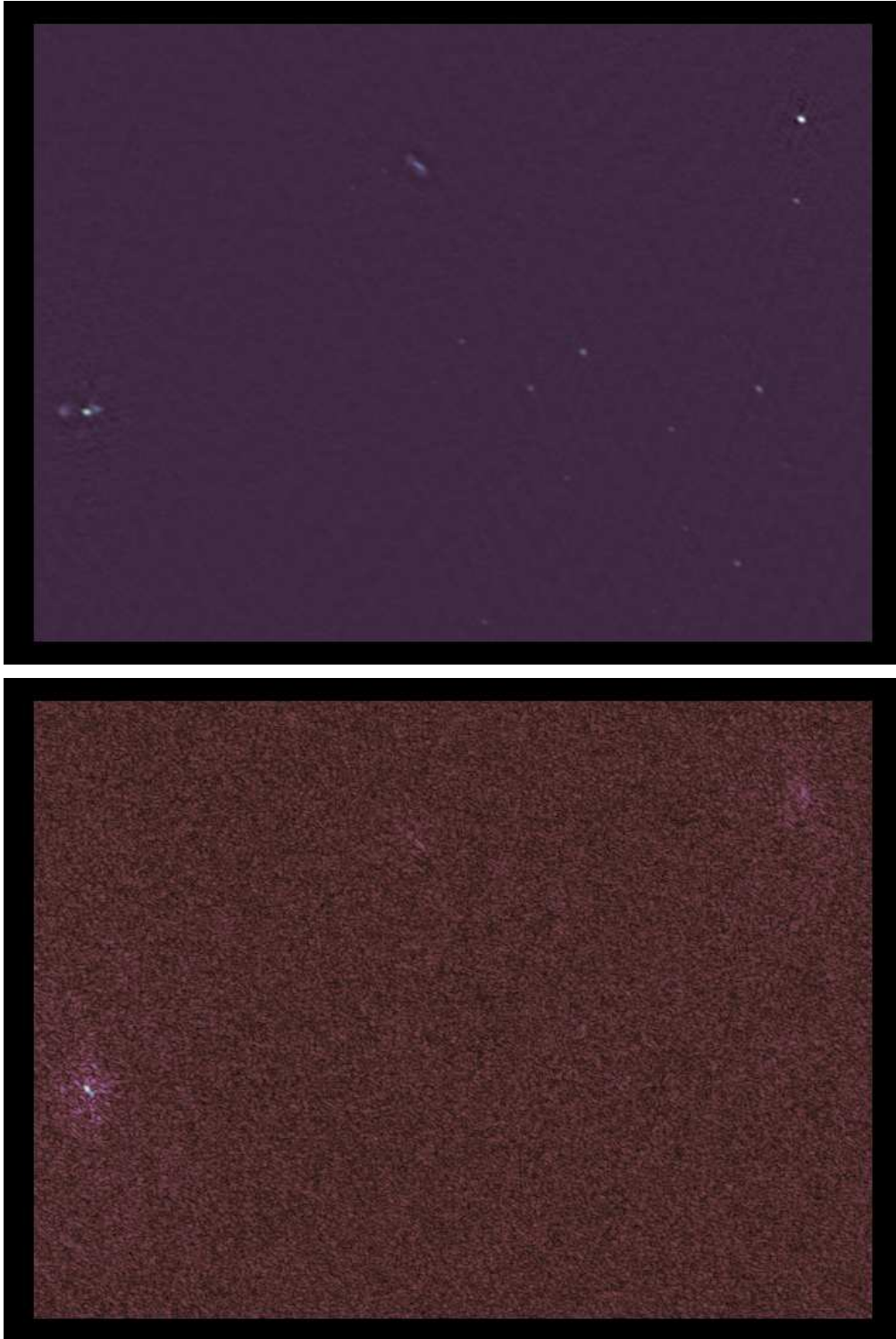
Figure 4: Stokes I (top) and polarised emission (bottom)images at 610 MHz for part of the primary beam close to the pointing centre. Self calibration (both phase and amplitude calibration) has been applied. (Top) The rms noise on the image is 70μJy/beam. (Bottom) The rms noise on the image is 30μJy/beam. No primary beam correction has been applied.

- It is labourious and takes a lot of time! But on the positive side, its great when out pops polarised emission from your favourite target which is well-worth the time spent.

This recipe in AIPS is presented hoping more users will be able to use the GMRT polarisation data at 610 MHz and lower. If you have any queries, comments, criticisms, mistakes-reporting, please write to ngk@ncra.tifr.res.in mentioning 'GMRT Polarisation' in the subject line. Hopefully, a detailed recipe on implementing rotation measure synthesis on GMRT data will be released.
While the recipe ran successfully on GMRT 610 MHz full polar data, it could crash under some situations. If it does for you, do send an email. We thank the NRAO for continuing to support and upgrade AIPS and maintain the AIPS Cookbook both of which have made this analysis easier.