MEERKAT64 WIDEFIELD POLARIMETRY OF DEEP2

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Purpose

1. Perform full polarisation calibration and imaging of DEEP 2 widefield observation.
2. Asses full polarisation performance and sensitivity of the 64 antenna SKARAB correlator in 4k mode.

Observations

Frequency range: 0.859 - 1.705 GHz
centre frequency: 1.284 GHz
Observation details (internal observation request link):

- Observed from 2018-07-27 21:01:07.556 UTC to 2018-07-28 13:08:19.005 UTC
- Number of antennas: 61
- Duration: 14.42 hrs on target, 16 hrs total
- Scan lengths: 900 s on target, 64 s on gaincal, 600 s on bpcal
- Calibrator cadence: gaincal and target scans interleaved, with bpcal scans observed at a 3 hr cadence.

Data: Capture block ID 1532725253
Source list:

ID	Name	RA(J2000)	DEC(J2000)	Tags
0	J1939-6342	19:39:25.03	-63:42:45.6	delaycal bpcal
1	J0252-7104	2:52:46.15	-71:04:35.3	delaycal gaincal
2	DEEP_2	4:13:26.40	-80:00:00.0	target

Data reduction

Reduction scripts used:

- Location to be shared at a later stage.

Software versions: CASA 5.1.2-4, Python 2.7.12, Stimela 1.0.0, WSClean version 2.5

Introduction

This report details the full polarisation calibration, using an unpolarised calibrator, and imaging of a DEEP field pointing, DEEP 2. This portion of sky was chosen for commissioning both KAT 7 and MeerKAT. It was chosen from the SUMMS (Sydney University Molonglo Sky Survey) survey data (Bock et al., 1999; Mauch et al., 2003). The methods followed in this memo are based on an earlier reduction and analysis of nine DEEP field pointings from the MeerKAT AR 1.5 which was made up of 16 antennas (Legodi, 2018). This memo focuses on the calibration strategy whereas the earlier work also included tertiary analysis such as source finding, spectropolarimetry and rotation measure synthesis.

Methodology

Observation

The DEEP2 field (proposal ID SCI-20180426-TM-01, capture block ID 1532725253) was observed with 61 antennas from 27-July-2018/21:01:15.6 to 28-July-2018/13:08:11.0 (UTC). The observation length was 16 hours. The MeerKAT SDP calibration report and progress log output can be found on the MeerKAT archive along with data links. No major issues were reported during the observation save for the following (from (internal) 20180723-20180730 Operations Meeting minutes):

- M062 was reported to be inactive due to AP failure - Jira ticket (closed)
- M028 was marked faulty due to feed cover not removed - Jira ticket (closed)
- Delay Solutions appeared to be out of range for some antennas (M048, M057 and M046) - Jira ticket (closed)

Calibrations

Initial data inspection, editing and calibration steps and some of their results are given below. The following explanations borrow heavily from the online CASA documentation that can be found here: CASA pre-release — CASA Documentation. There also various guides to calibrating different types of radio data here: CASA Guides

Initial data inspection and editing

Prior to calibrating the raw visibilities, a set of steps was followed to edit and perform rough flagging on obviously bad data. Some bad data ranges are known, such as RFI infested frequencies, while others become apparent upon inspection of the data. For the latter, and especially given the large data volume of the raw data (~1.8 TB), visibilities of the calibrator J1939-6342 (PKS 1934-638) were inspected and flagged accordingly. These same edits and flags were then applied to the rest of the data. The steps followed are as follows:

1. Initial flagging of the visibilities in the input measurement set, named “`ms`”, was performed to remove channels with unusable data using the CASA task “`flagdata()`” with the following options:

   ```
   flagdata(vis=ms, mode='manual', spw=badspw).
   ```

   Where “`mode='manual'`” allows for manual selection of data at frequencies/channels specified by the spectral windows “`spw=badspw`” which contain the bad data. These channels were manually identified as they were locations of obvious/known RFI.

2. PKS1934-638 was set as the primary calibrator, used as the flux and bandpass calibrator. It was named “`fluxfield`” and “`bpassfield`” in the reduction scripts (Google drive link).
3. J0252-7104 was set as the secondary calibrator -- named “`secondaryfield, xdelfield, kcorrfield, dpolfield,` and `xpolfield`” in the reduction scripts. The source was used to calibrate cross hand delay, gain, antenna-based delay and polarization leakages.
4. The chosen reference antenna was m034 (“antID 33”), as it was the antenna with the least deviation from the median amplitude and lowest RMS noise level in the visibilities (calculated from all baselines with the antenna). Outlier antennas in the amplitude and RMS distributions can be identified and flagged out using this method.
5. The antenna amplitude median and RMS values for each antenna, “`ant`”, were calculated from the input measurement set “`ms`” using the CASA task for calculating statistics of a measurement set, `visstat()` with the following options:

   ```
   visstat(vis=ms,field= fluxfield,antenna=ant,timeaverage=True,
   
   timebin='500min',timespan='state,scan',reportingaxes='field').
   ```

Where the data is averaged in time with averaging bins of 500 minutes. The time bins are spanned across both scans and states.

6. Prior to further processing, automated flagging was then done on the remaining visibilities to eliminate artefacts that were missed by manual inspection. "`flagdata()`" was used again but with the following inputs:

```
flagdata(vis=ms,mode='tfcrop',spw=myspw,ntime='15min',combinescans=True,a
ction='apply',timecutoff=4.5,timefit='poly',extendflag=False,
freqcutoff=4.5, datacolumn='DATA'),
```

where `mode='tfcrop'` flags outlier visibilities in the frequency-time domain. With "`timefit='poly'`", the task fits a polynomial to the data along the time axis with a 15 minute buffer specified by "`ntime='15min'`". The resulting data which is taken to the next step is at channels specified by "`spw=myspw`" .

Data calibration

1. Time and frequency related variations such as antenna-based delays, time-dependent gains and bandpass variations are calibrated for first (see CASA documentation on gain calibrations here). Following which, polarisation related issues (see CASA documentation on polarisation calibrations here) such as cross-hand delays, polarisation leakage, and x-y phase were calibrated in the standard manner, which in the case of polarisation calibration where antenna based variations are calibrated for first, will be detailed in the steps below. Note that with unpolarised calibrators, such as PKS 1934-638 and J0252-7104 (our polarisation calibrator), we do not know the absolute Stokes Q and U nor do we have a valid xy-phase solution of the source fields so we cannot relate the leakage back to the source frame. A polarised calibrator will, however, determine the absolute leakages. Good parallactic angle coverage, provided by observations over long periods (≥ 12 hours) following radio sources across the sky further improves leakage solutions and minimizes the leakage terms as their vector sum will approach zero (Jagannathan et al., 2017). Our polarisation calibrator was observed over a period of ~14 hours as it was also set as the gain calibrator for the target field. What can be determined from unpolarised calibrators are polarisation leakage terms as these will manifest as a sinusoidal variation with time/parallactic angle. Fractional polarisation values of the calibrators can be determined from the time-dependent gains as the apparent polarisation can be related to the known Stokes I of the calibrators. Calibration steps followed are as follows:

   a. Flux density calibration using the task `setjy()` which sets the primary calibrator flux model:

   ```
   setjy(vis=ms,field = fluxfield, spw = myspw,
   scalebychan=True,standard='Perley-Butler 2010').
   ```

   Where the best suited flux model standard is specified with "`standard='Perley-Butler 2010'`". Others can be found on this link.

   b. Antenna-based delays were calibrated using the task `gaincal()` with m034 as the reference ("`referenceant`"):

   ```
   gaincal(vis=ms,caltable=kcorrfile,field=kcorrfield,spw=myspw,

   refant=referenceant,minblperant=3,solnorm=False,gaintype='K',
   solint = '10min', combine = 'scan',parang = False, append =
   False).
   ```

   The resulting solutions are displayed in Figure 1.

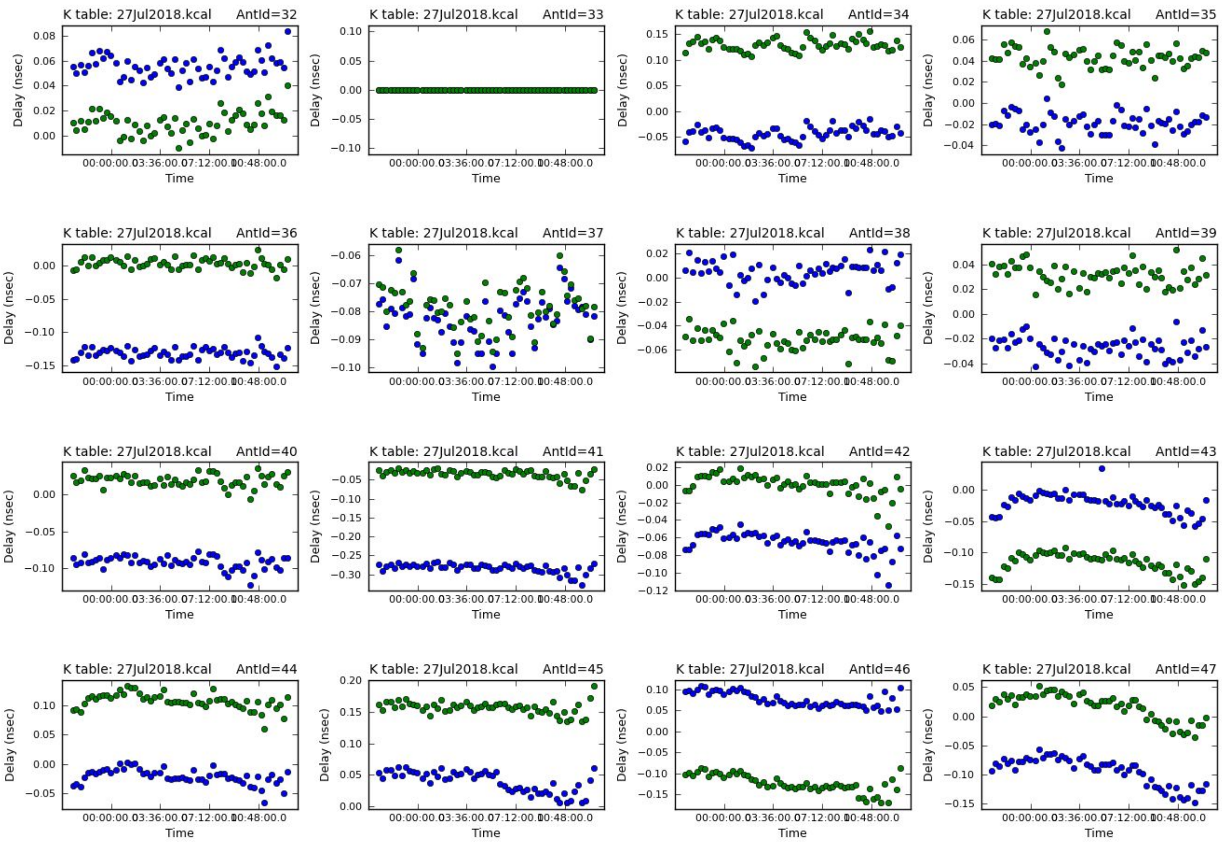


Figure 1. Antenna-based delays.

c. Bandpass variations were calibrated using the task `bandpass()`:

```
bandpass(vis=ms,caltable=bpassfile,field=bpassfield,spw=myspw,
refant=referenceant,minblperant=3,solnorm=True,solint='inf',
combine='scan',bandtype='B',fillgaps=8,gaintable=kcorrfile,
gainfield=kcorrfield,parang=False,append = False).
```

[Figure 2](#) displays the solutions.

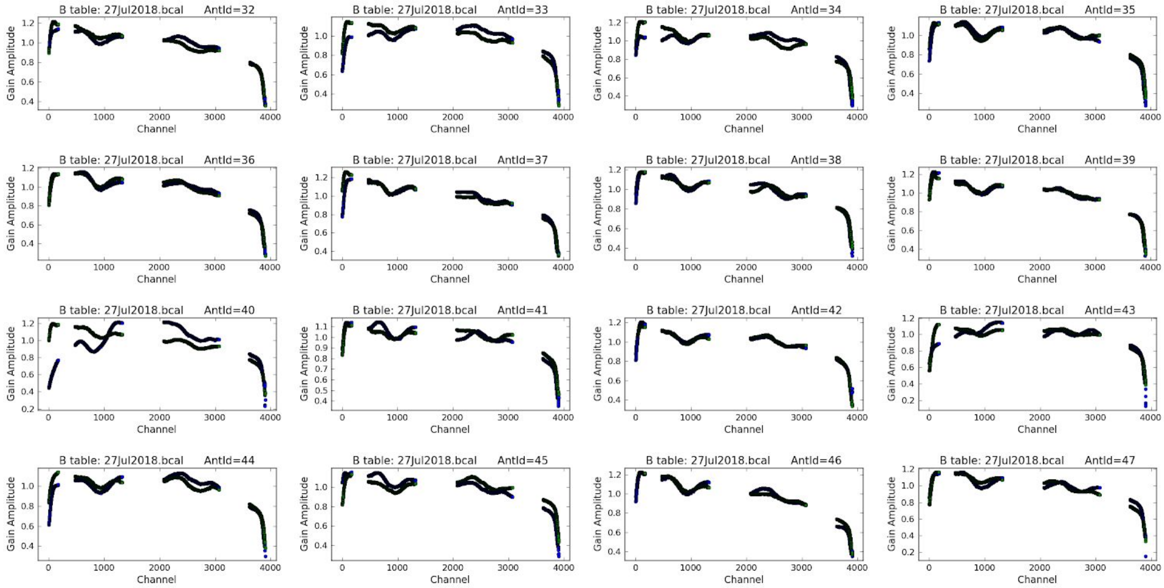


Figure 2. Bandpass solutions

d. The next step is to solve for cross-hand delays that are due to the residual delay difference between the X and Y on the reference antenna. Cross-hand delays were calibrated in the following manner, using `gaincal()` with `gaintype = 'KCROSS'` and assuming non-zero linear polarisation in our calibrator as we assume non-zero polarisation signatures in the cross-hands. This is because, in linear polarisation cases, both source and instrumental polarisation effects manifest in all four correlations at zeroth or first order. Time dependent gains will be affected by this and thus an iterative solution strategy will be needed to calibrate out the polarisation effects. A calibrator with high polarised signal to noise and which has been observed over a large parallactic angle is most optimal as opposed to an unpolarised calibrator. Also, since parallactic angle coverage is required, a single scan of a strongly polarised calibrator will not be sufficient as the time variable instrumental response cannot be isolated (e.g Jagannathan et al., 2017; Jagannathan, 2018). The input flux model is specified with "`smodel=[1.,0.,1.,0.]`", polarisation of 100% in Stokes U, and does not need to have accurate fractional polarisation values as only delays are determined while absolute polarisation fractions or angles are not:

```
gaincal(vis=ms,caltable=xdelfile,field=xdelfield,refant=referencea
nt,spw=myspw,gaintype='KCROSS',smodel=[1.,0.,1.,0.],solint='inf',c
ombine='scan',minblperant=minbaselines,minsnr=0,gaintable=[kcorrfi
le,bpassfile],gainfield = [kcorrfield, bpassfield]).
```

The cross-hand delay across all antenas is found to be 0.563703 nanoseconds.

e. Time-dependent gains (FIgures 3 to Figure 4): As mentioned above, an iterative solution strategy for the time-dependent gains is required to disentangle the effects of instrumental polarisation in the cross-hands. The gain and bandpass calibrators are assumed to be unpolarised and thus we set `smodel=[1.,0.,0.,0.]` and solve for the gains on the calibrators with `gaintype='G'`:

```
gaincal(vis=ms, caltable = gain1file, field = fluxfield, spw =
gainspw,refant = referenceant, solint = 'int',uvrange =
'150~10000m',minblperant = 3, solnorm = False, gaintype =
```

```
'G',gaintable = [kcorrfile,bpassfile,xdelfile],gainfield =
[kcorrfield,bpassfield,xdelfield],append = False, parang = True),
```

```
gaincal(vis=ms, caltable = gain1file, field = secondaryfield, spw
= gainspw,refant = referenceant, solint = 'int', minblperant = 3,
solnorm = False,gaintype = 'G', smodel=[1,0,0,0],gaintable =
[kcorrfile,bpassfile,xdelfile],gainfield =
[kcorrfield,bpassfield,xdelfield],append = True, parang = True).
```

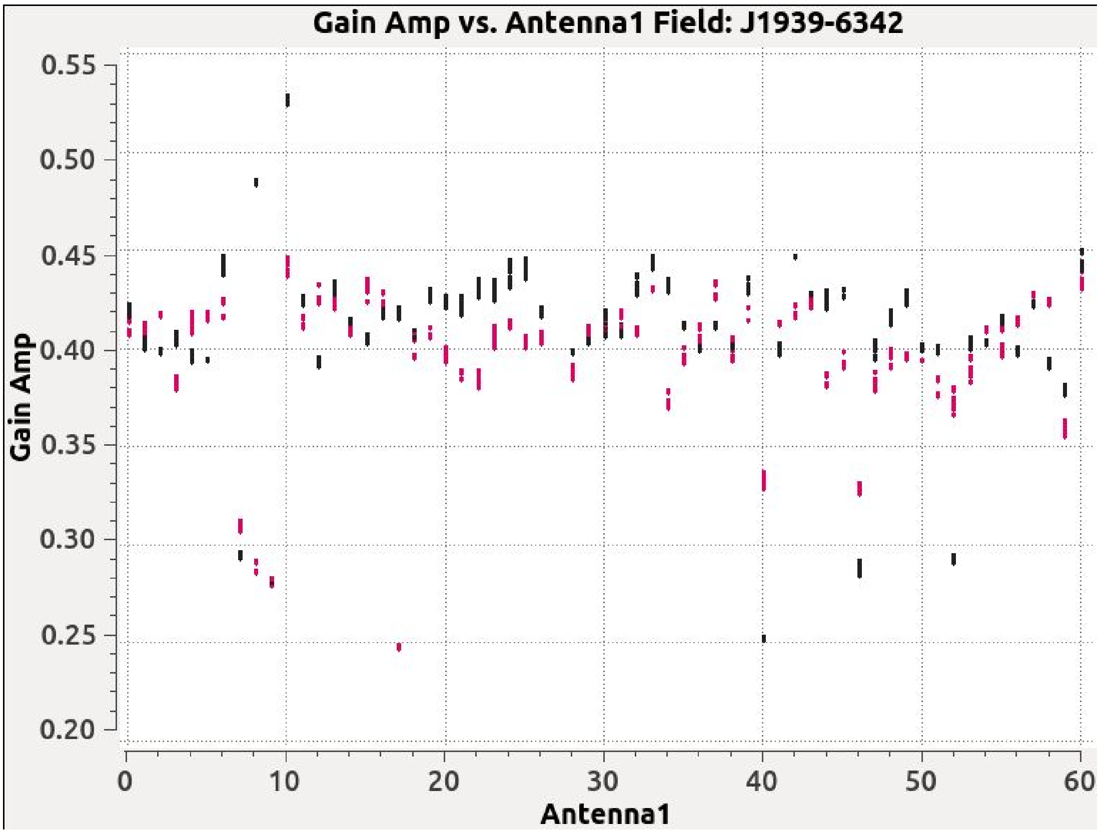
The apparent Q and U can then be determined from the gains with the task "`qufromgain()`" from the CASA helper tasks script "`almapolhelpers.py`"[1]:

```
GainQU = qufromgain(gain1file).
```

The output is the mean values across the bandwidth as fractions of Stokes I:

```
QU from gain = {0: (-0.004998958419194999, 0.003583252825119869),
1: (-0.0007425753742893442, 0.003038634978469989)}.
```

This reports a measured linear polarisation in PKS 1934-638 (field ID = 0) of ~0.62% and ~0.31% in J0252-7104 (field ID = 1). Note that the assumption is made that Q and U do not vary with frequency (the rotation measure is not considered), which is seldom the case.



[1] Developed for the ALMA telescope with its linear polarisation feeds. The tasks are also applicable to MeerKAT and KAT 7.

Figure 3a. Time-dependent gain amplitude ratios as functions of antenna for the primary calibrator, PKS 1934-638. The colours encode correlations.

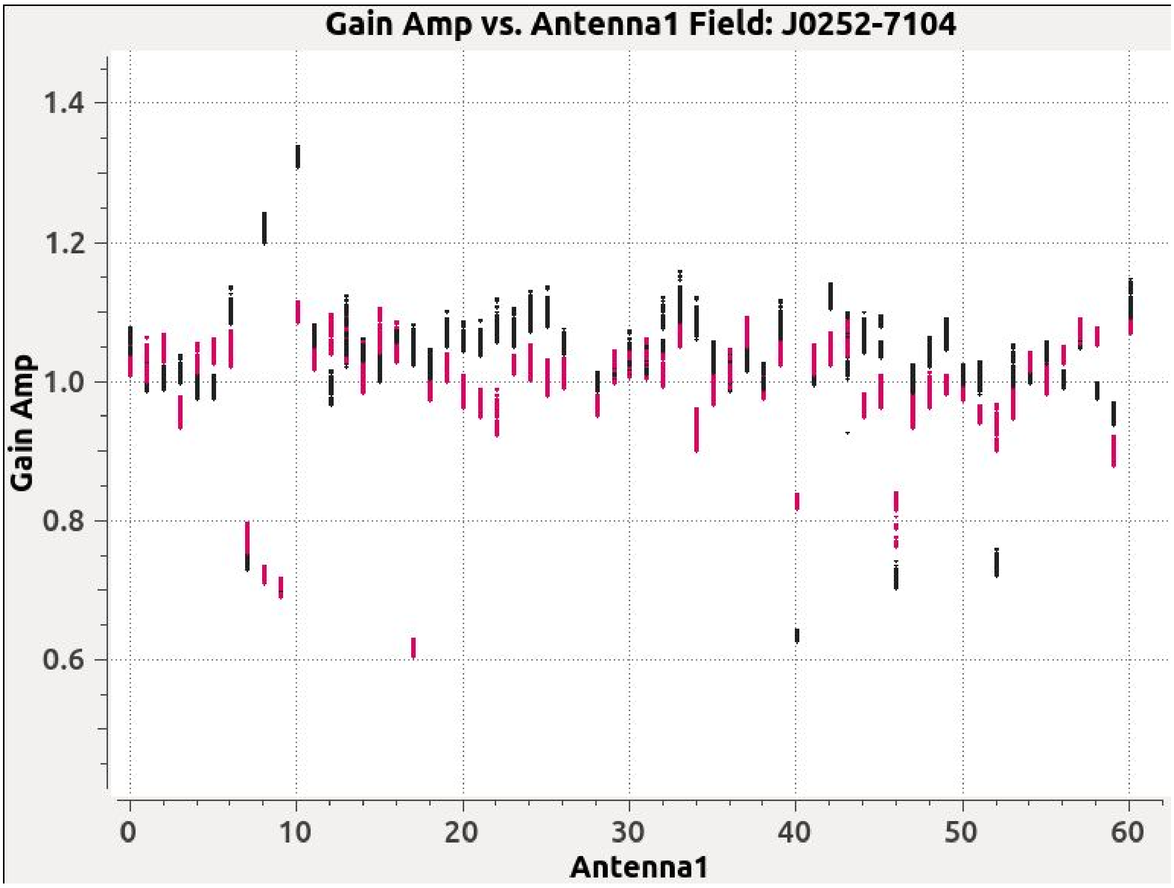


Figure 3b. Time-dependent gain amplitude ratios as functions of antenna for the secondary calibrator, J0252-704.

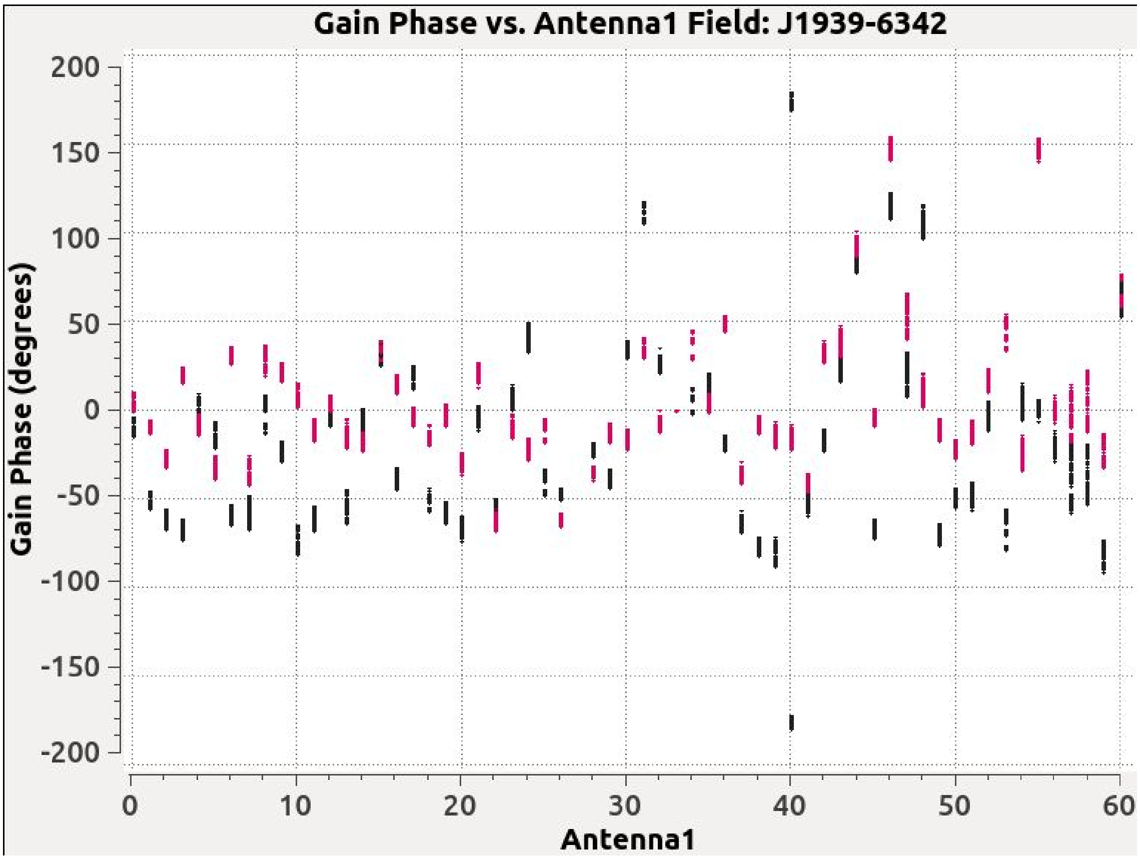


Figure 4a. TIme-dependent gain phases as functions of antenna for the primary calibrator.

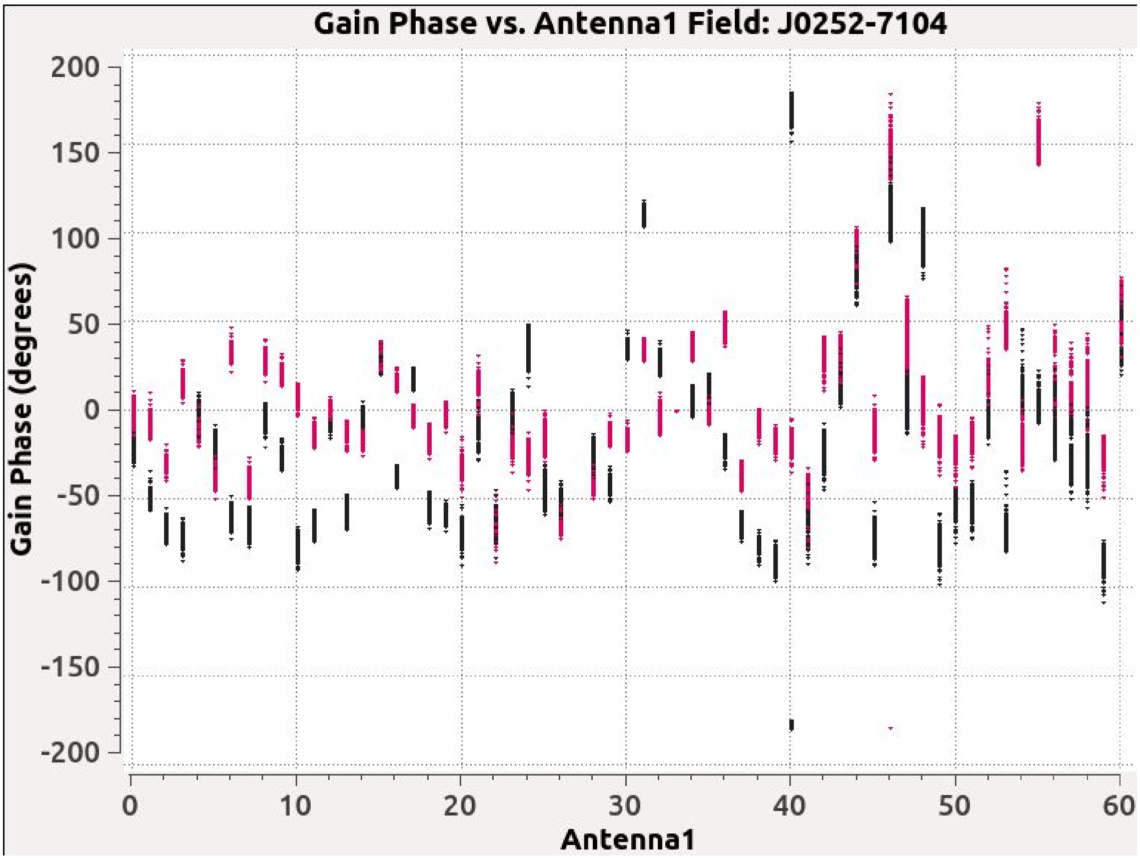


Figure 4b. TIme-dependent gain phases as functions of antenna for the secondary calibrator.

f. Following the solutions above, the X-Y phase offset (Figure 4c) and calibrator polarisation fractions can be determined from the cross-hands. The above estimation of fractional polarisation assumes stability in the gain amplitude polarisation ratio, which may not be so. These estimates from the gains do however resolve the nπ ambiguity (there is an nπ ambiguity in the X-Y phase - see e.g Farnsworth et. al 2011; Ma et al. 2017) in the polarisation fractions. `gaincal()` with `gaintype='XYf+QU'` is used:

```
gaincal(vis=ms, caltable = xy0ambpfile, field = dpolfield,spw =
myspw,refant = referenceant, solint = 'inf', combine = 'scan', gaintype =
'XYf+QU',minblperant = minbaselines, smodel = [1.,0.,1.,0.], preavg =
200.0,gaintable = [kcorrfile,bpassfile, gain1file, xdelfile],gainfield =
[kcorrfield, bpassfield, secondaryfield, xdelfield],append = False).
```

A polarised source model is imposed as some polarisation from the cross-hands is expected. The resulting polarisation fractions for J0252-7104 are corrected for the nπ ambiguity with:

```
xyamb(xytab=xy0ambpfile, qu=GainQU[int(dpolfield)], xyout = xy0pfile).
```

The new source model:

```
S = [1.0, -0.0007425753742893442, 0.003038634978469989, 0.0]
```

```
Fractional linear Polarisation = 0.003128.
```

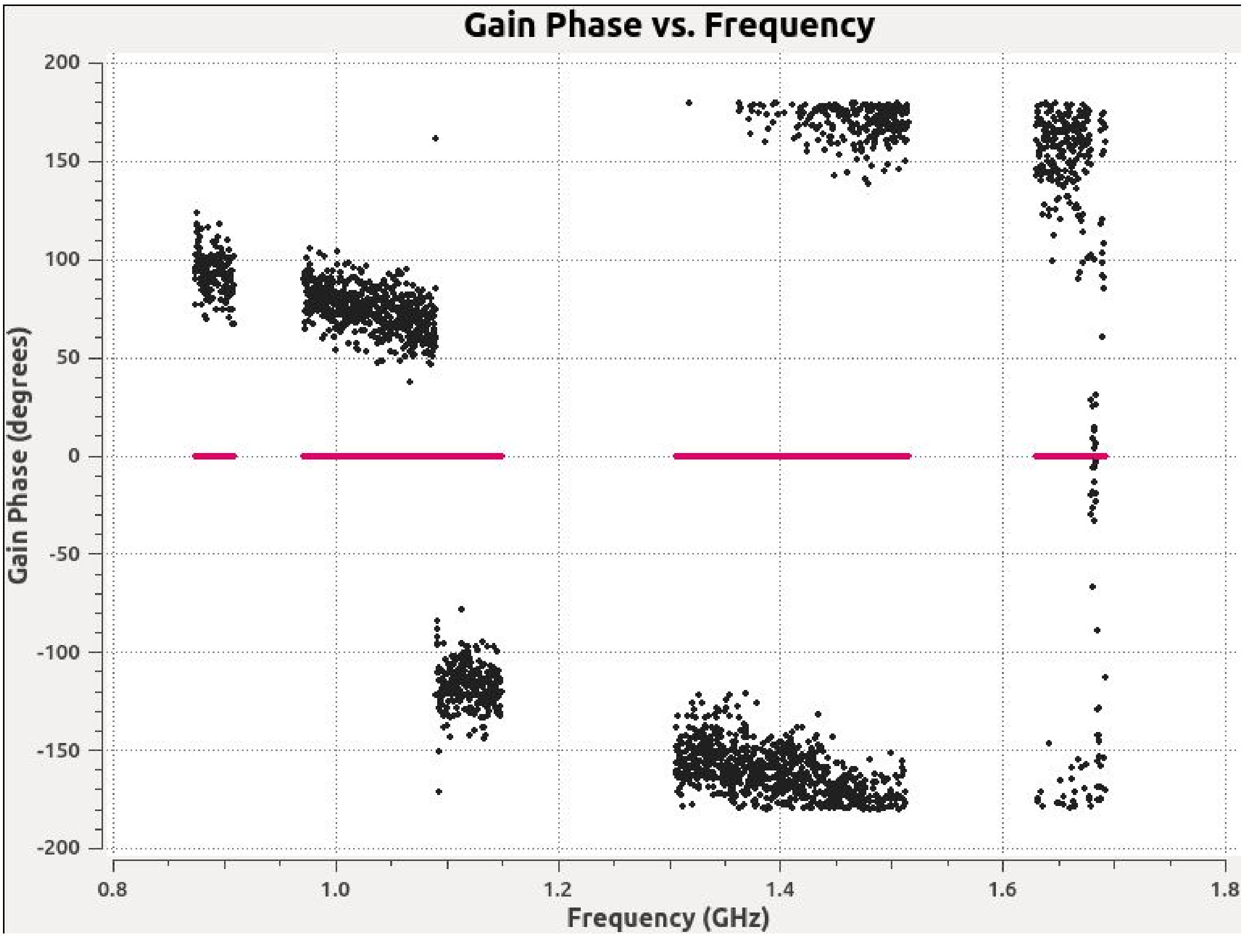


Figure 4c. Cross-hand phases showing jumps of ~180 degrees for some of the band. Colours indicate different correlations.

g. Gain solutions are then redone with the new calibrator source polarisation:

```
gaincal(vis=ms, caltable = gainfile, field = fluxfield, spw =
myspw,refant = referenceant, solint = 'int', solnorm = False,  gaintype =
'G',minblperant = minbaselines, minsnr = 0, calmode = 'ap',gaintable =
[kcorrfile,bpassfile,xdelfile],gainfield =
[kcorrfield,bpassfield,xdelfield],parang = True, append = False)
```

```
gaincal(vis=ms, caltable = gainfile, field = secondaryfield, spw =
myspw,refant = referenceant, solint = 'int', solnorm = False,  gaintype =
'G',minblperant = minbaselines,combine = '', smodel = S, minsnr =
0,gaintable = [kcorrfile,bpassfile,xdelfile],gainfield =
[kcorrfield,bpassfield,xdelfield],append = True, parang = True)
```

The updated solutions are placed in a different calibration table via: `caltable = gainfile.`

h. Instrumental polarisation solutions, leakages, are obtained with the task `polcal()` :

```
polcal(vis=ms,caltable=dtempfile,field=dpolfield,spw=myspw,refant='',
solint='inf',combine='scan',poltype='Dflls',smodel=S,preavg=200.0,
gaintable=[kcorrfile,bpassfile,gainfile,xdelfile,xy0pfile], gainfield =
```

```
[kcorrfield, bpassfield, secondaryfield, xdelfield, dpolfield],append =
False)
```

“`poltype = 'Dflls'`” specifies the use of a frequency dependent linear least squares solver for the D-terms. The D-terms are solved for, assuming Q and U do not vary with frequency. These are displayed in Figure 5a. If there was at least one scan of a polarised calibrator, the polarisation angle would then be calibrated following this step. To that end, one would use `polcal()` with “`poltype = Xf`, this determines a frequency dependent polarisation angle solution. The polarisation model of the polarisation calibrator will need to be determined prior to running `polcal() - setjy(..,field=”<polcalfield>”,..)` should be used for this. The apparent Stokes Q and U for all sources can then be used along with the polarisation position angle, to determine the absolute polarisation of all sources. With an unpolarised calibrator, polarisation angle solutions are referenced to the reference antenna feeds, with an inherent unknown offset.

i. And finally the flux scale is set with `fluxscale(`:

```
fluxscale(vis=ms, caltable = gainfile, reference = fluxfield,
transfer = [secondaryfield], fluxtable = fluxfile,
listfile = outdir+'fluxscale-v2.txt',append = False),
```

which outputs:

```
Flux density for J0252-7104 in SpW=0 (freq=1.26143e+09 Hz) is: 6.43998
+/- 0.00740578 (SNR = 869.589, N = 120)
```

j. The calibration solutions are applied to all sources and a post calibration automated flagging is done on the measurement set. The bandpass, time-dependent gains and D-terms can also be recalibrated before applying the solutions to the sources, but that is not done in this memo. Full polarisation calibration is encouraged even when the science goal is not dependent on polarimetry as the measured total intensity may still be coupled to residual polarisation signals.

Residual leakages, see Figure 5a, of more than ~0.15 near 1.03 and 1.09 GHz are found. The mean leakage is found to be ~ 0.05. D-term solutions in the worst portions of the band, following minimal manual flagging, in the AR 1.5 DEEP 2 data were found to be of order 100. See Figure 5b. More aggressive manual reflagging was done on the AR 1.5 data resulting in Dterm amplitudes of order 1 (Figure 5c).

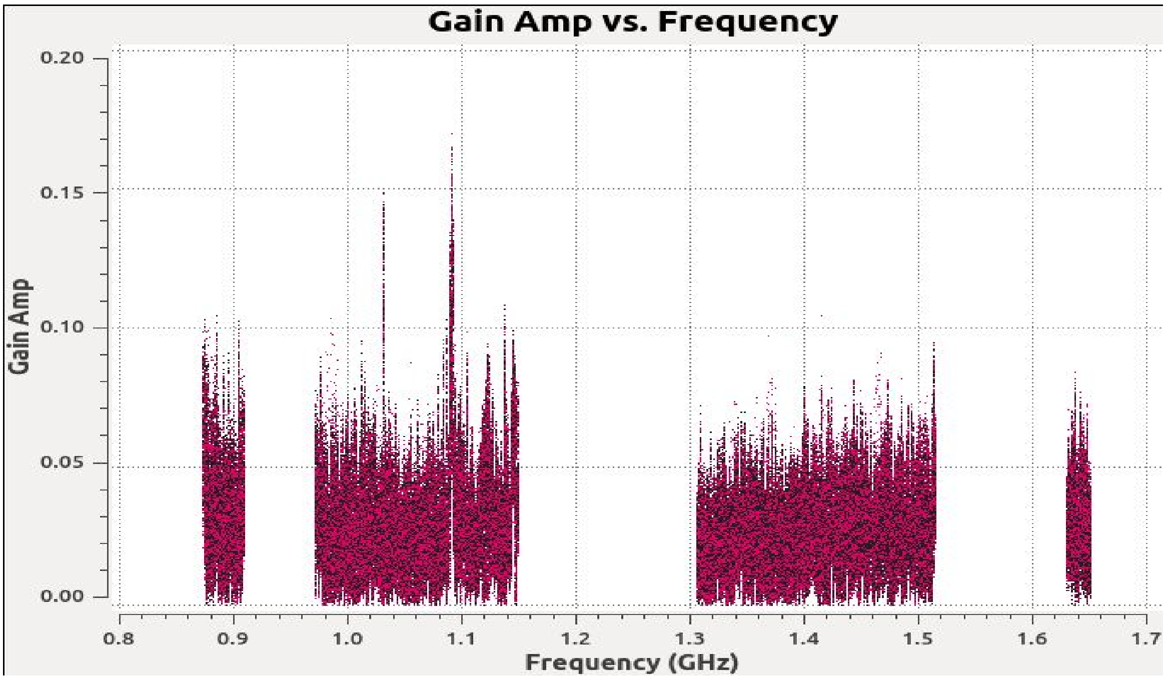


Figure 5a. D-term amplitudes. Notable leakages near 1.02 Ghz and 1.09 GHz.

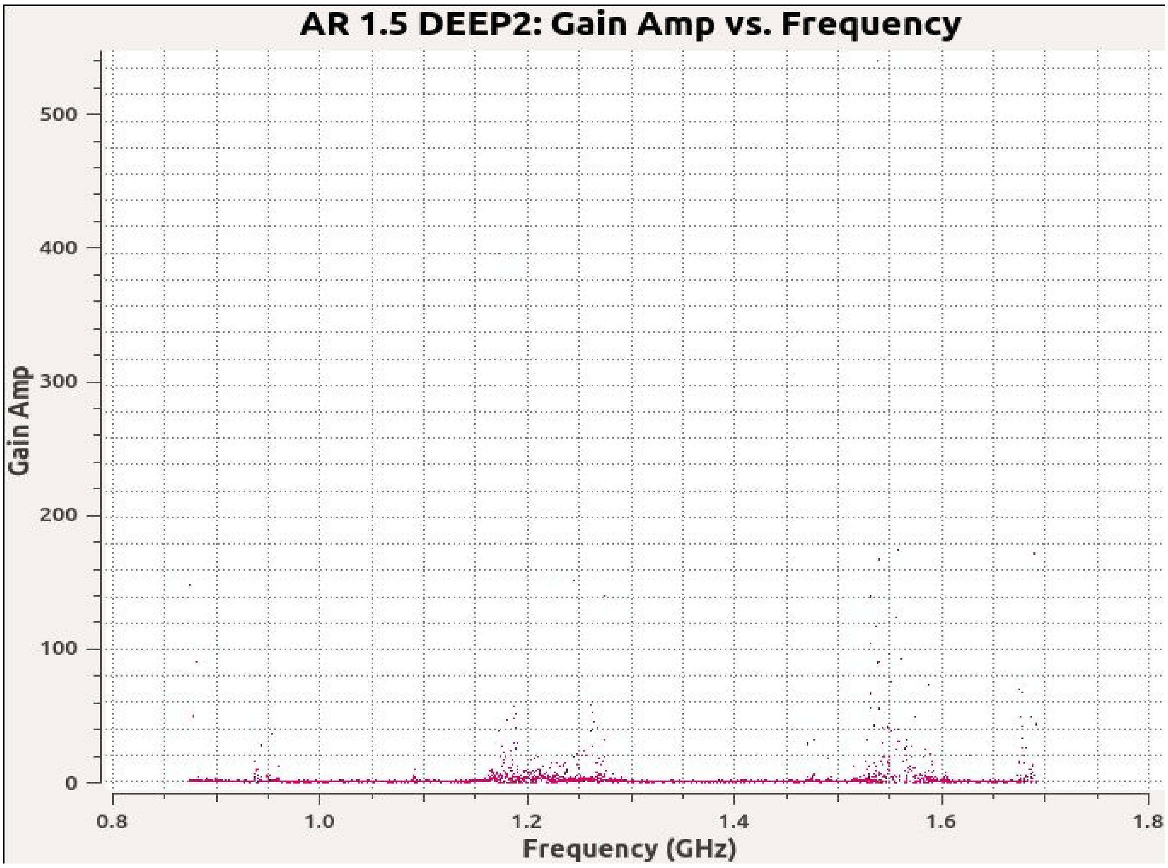


Figure 5b. D-term amplitudes. Notable leakages near 0.94, 1.15-1.3, 1.55 GHz and 1.68 GHz.

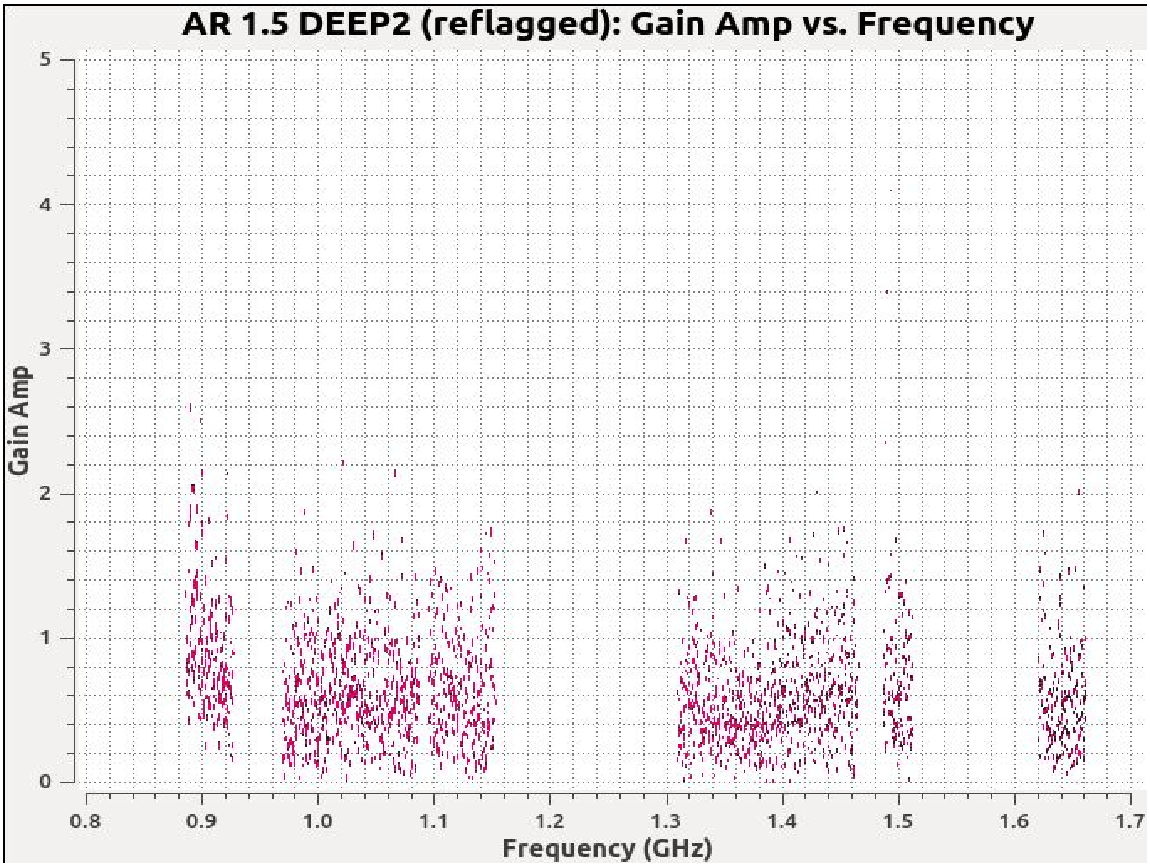


Figure 5c. Same as in Figure 5b but with more aggressive manual flagging.

Results

Imaging

Three types of images were made following standard full polarisation calibrations. These were: self-calibrated images in Stokes I (2 cycles of phase-only self-cal), a full polarisation Stokes IQUV “cube”, and average (along the frequency axis) images of each of the four Stokes planes. Source finding using PYBDSF was done on the self-cal images. This results in a catalogue of radio sources with positions and fluxes that identify each radio source. Stokes IQUV spectra are then extracted, from the cube, at the positions of the PYBDF identified sources. A basic rotation measure synthesis (Burn, 1966; Brentjens and de Bruyn, 2005; Heald, 2008) analysis was then performed on the resulting spectra - rotation measure synthesis results are not presented here.

Flux of Primary calibrator

- Extracted Stokes I, Q, U and V from the brightest pixels in the Stokes IQU cube image of primary calibrator J1939-6342. A simple power law fit to Stokes I data was produced and compared to the Reynolds (1994) polynomial model (see Figure 7).
- Derived Stokes I lower in amplitude than Reynolds (1994) polynomial model.

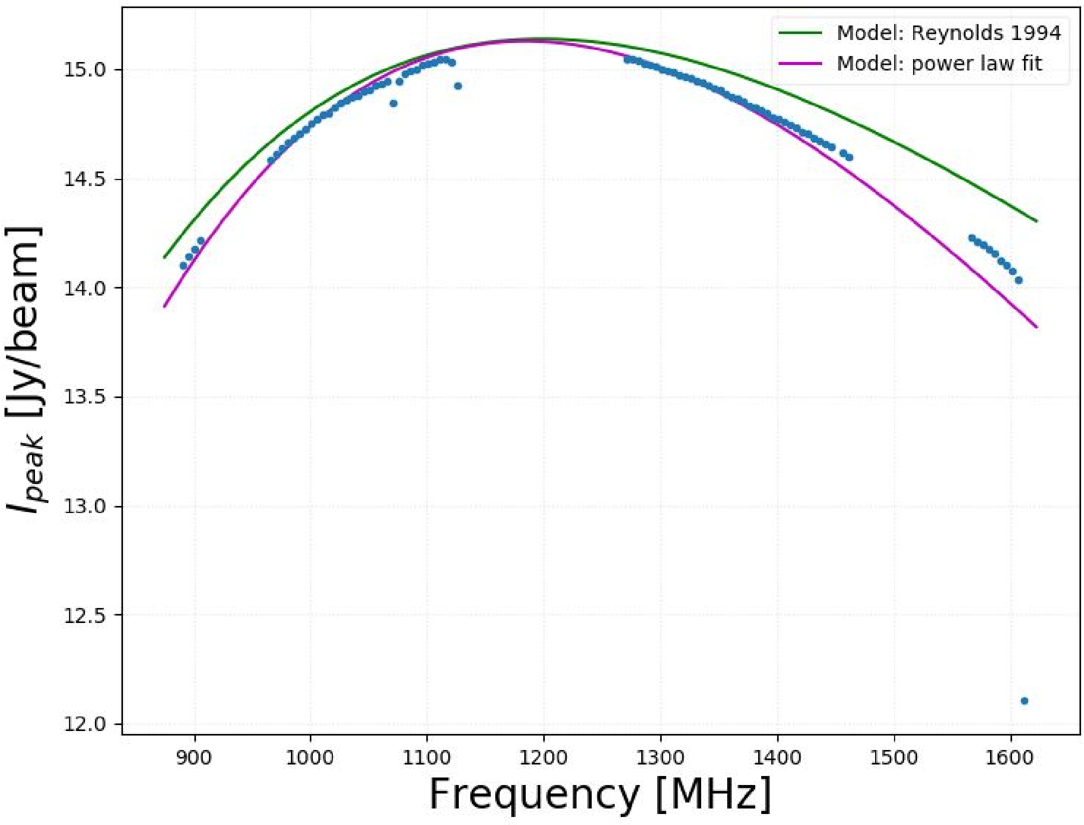


Figure 7. J1939-6342 Stokes I 64 antenna data (points) along with fitted models (curves).

- 64-antenna data is significantly less noisy as compared to earlier 16-antenna (AR 1.5) data, see Figure 8 where earlier data is represented by grey "+" signs while the newer data is represented by red points.

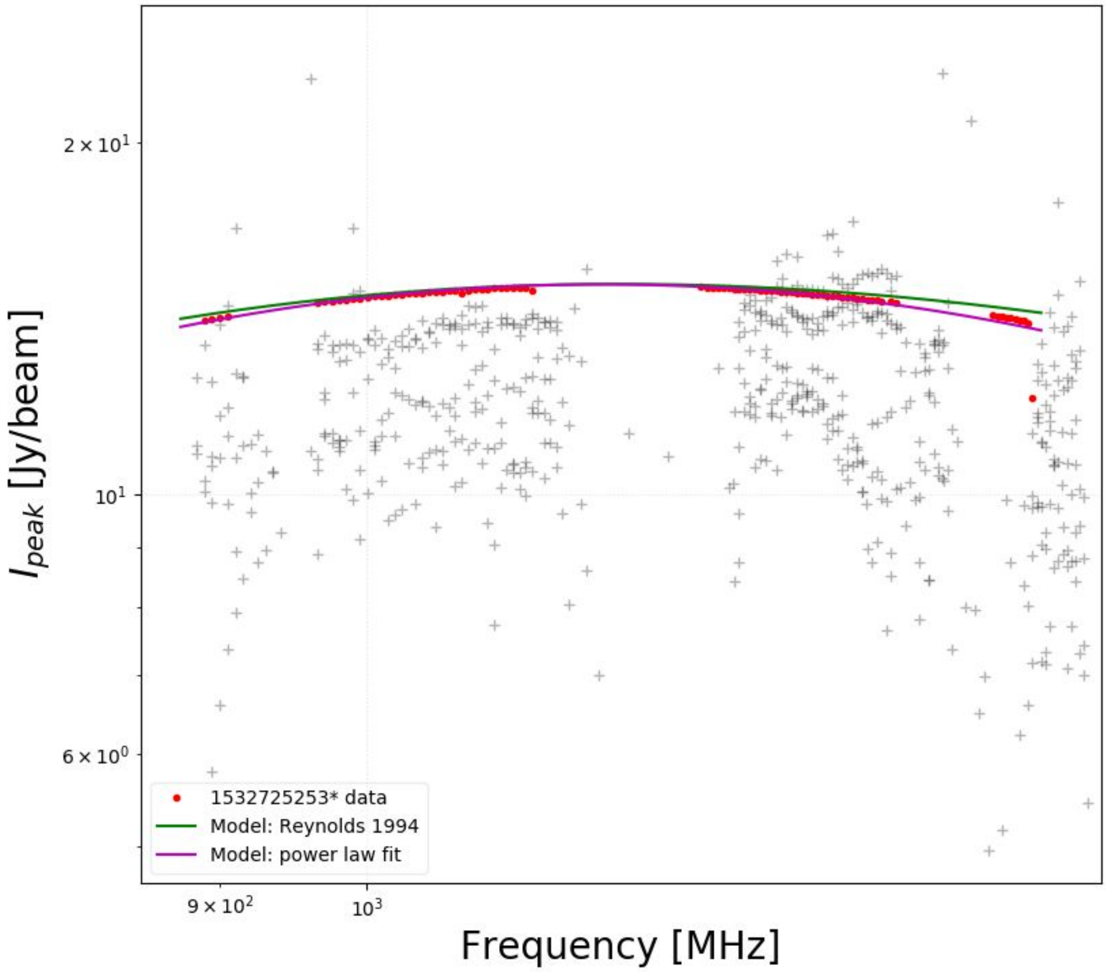


Figure 8. Same as in Figure 7 save for the addition of AR 1.5 data (grey "+").

Measured Sensitivity

Measured Stokes QU sensitivities achieved with standard full polarisation calibration are improved by a factor of ~20 as compared to the AR 1.5 data in which the median Stokes QU rms was 72.0 microJy/beam (Taylor & Legodi 2018). An average (and also median) QU rms of 3.68 microJy/beam with a standard deviation of 0.043 microJy/beam is achieved with the new dataset. An earlier memo by Mauch et al. (2018) gives a naturally weighted theoretical thermal noise of 1.03 microJy/beam for this dataset -- where the data used is from 59 antennas with 32% of the data flagged resulting in a bandwidth of 796 MHz. In our case 39.3% of the data was flagged, data from 61 antennas was used and the imaged bandwidth was a total of 518.5 MHz with the data weighted according to the Briggs strategy with a robustness factor of -1 (Briggs 1995). The rms in Stokes I is found to be 5.0 microJy/beam (averaged I and self-calibrated images show similar rms), while the best sensitivity in the AR 1.5 data was achieved through self-calibration (two cycles of phase-only self-cal) which produced an average rms of 7.4 +/- 1.0 microJy/beam in Stokes I (an average calculated from seven DEEP field pointing images covering most of the DEEP field - Taylor & Legodi 2018). A self-cal, single DEEP2 pointing image from AR 1.5 was found to have an rms of 14.2 microJy/beam. A similar self-cal image of the new DEEP 2 data was found to have an rms of 4.8 microJy/beam.

The DEEP 2 image from the newer data, after self-cal, reaches a noise level of -36.8 dB at 1.28 GHz in Stokes I, falling short of the required -63 dB (at 1.40 GHz) - see Peens-Hough, 2011. The average linear polarisation image has an rms of 0.024 % while the same for Stokes V is 0.016 % with a mean of 0.086 % in the fractional Stokes V image. In the case of the unpolarised calibrator J1939-6342, the self-cal image has noise levels of -39.5 dB at 1.28 GHz in Stokes I. The average linear polarisation image, channel averaged, has rms of 0.0005 % with a polarisation level of 0.0232 %. The mean Stokes V, also channel averaged, polarisation level is measured to be 0.0150 % with an rms of 0.0023 %. The measured polarisation levels in the J1939-6342 image do agree with that measured in Stokes V of the DEEP 2 image (assumed to be zero), indicating that the level of on-axis instrumental leakage present in the new data is approximately 0.02 %, which is a -37 dB noise level. The measured stokes V flux from the secondary calibrator, J0252-7104 (also unpolarised), places an upper limit of 0.032% on the on-axis leakage.

Conclusion

- leakage solutions improved in the full MeerKAT observation relative to the AR 1.5 analysis by 3 orders of magnitude, from ~100 to ~0.1. There was less an initial aggressive flagging in the AR 1.5 data which resulted in much higher D-term amplitudes in RFI infested areas. Manual flagging results in amplitudes of order 1 (Figure 5c).
- Measured Stokes QU rms achieved with standard full polarisation calibration, using unpolarised calibrators, is improved by a factor of ~20 as compared to the AR 1.5 data.
- The average rms in Stokes I is found to be 5.05 microJy/beam. The best sensitivity in the AR 1.5 data, achieved through the same 2 cycle phase-only self-cal, produced an rms of 7.4 +/- 1.0 microJy/beam in Stokes I.
- On-axis instrumental leakage present in the new data is approximately 0.02% with an upper limit of ~0.03% approximated from polarisation levels measured for the unpolarised calibrators PKS 1934-638 and J0252-7104. An improvement from the initial level of ~0.06% from the 16 antenna AR 1.5 observations (e.g. Hugo et al. 2018).

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