MeerKAT-32k commissioning: NGC 1365

25 February 2020
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Observations

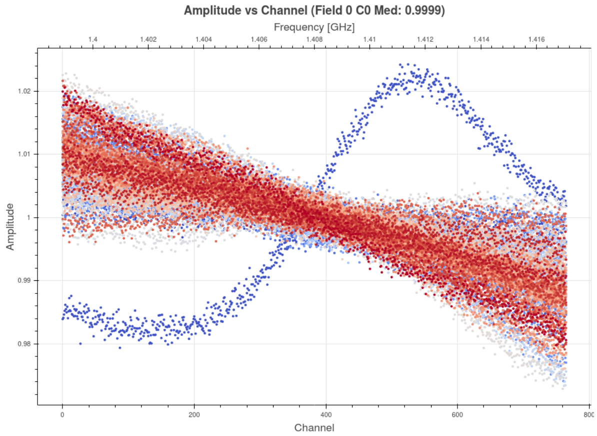
The data were taken on 17 December 2019, project ID 20191217-0024, over the course of ~ 10 h. Sixty MeerKAT antennas were online (the offline antennas were m027, m032, m037, m052). The primary (bandpass and flux) calibrator PKS 1934-638 was observed for 10 min at the start for the observation. The secondary (gain) calibrator J0440-4333 was observed for 2 min every ~ 25 min (total integration ~ 50 min). The target NGC 1365 was observed for a total of 7 h. Polarisation calibrators were also observed but were not used for this first round of data reduction and analysis, which focuses on total intensity continuum and spectral line over a narrow band at 1.4 GHz.

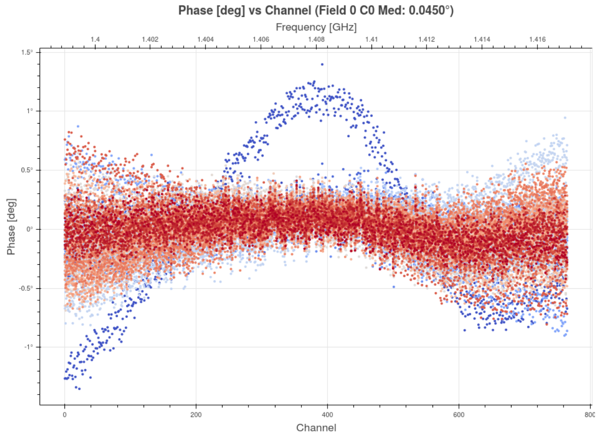
Cross-calibration and flagging

For this first report we processed a 20-MHz-wide band going from 1398 to 1418 MHz (766 channels). This frequency range is virtually free of RFI. We transferred XX and YY visibilities in this frequency range to a local machine at INAF - Cagliari for quick processing. We used the Caracal pipeline (a.k.a. MeerKATHI) jointly developed by INAF and SARAO. We followed standard data reduction steps as detailed below.

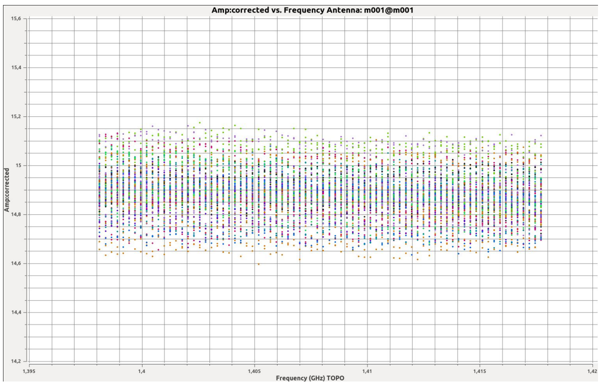
We kept level-0 flags from SARAO. Additionally, we flagged the calibrators based on their Stokes Q visibilities using AOFlagger. We solved for time-independent delays and time-independent normalised complex bandpass using the primary calibrator. We solved for frequency-independent complex gains using the secondary calibrator, bootstrapping the flux calibration from the primary. We calibrated and flagged iteratively. We set the reference antenna to m008. During calibration we ignored baselines shorter than 150 m.

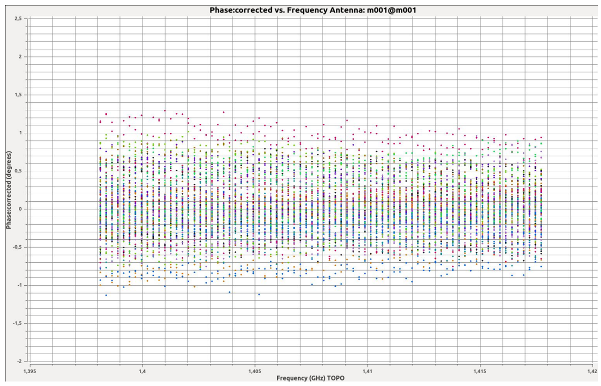
The calibration solutions appear reasonable. Delay corrections are in the range [-0.4, +0.3] ns. The plots below show the bandpass solutions colour-coded by antenna. The only antenna with an anomalous bandpass shape is m001 (clearly visible in blue).



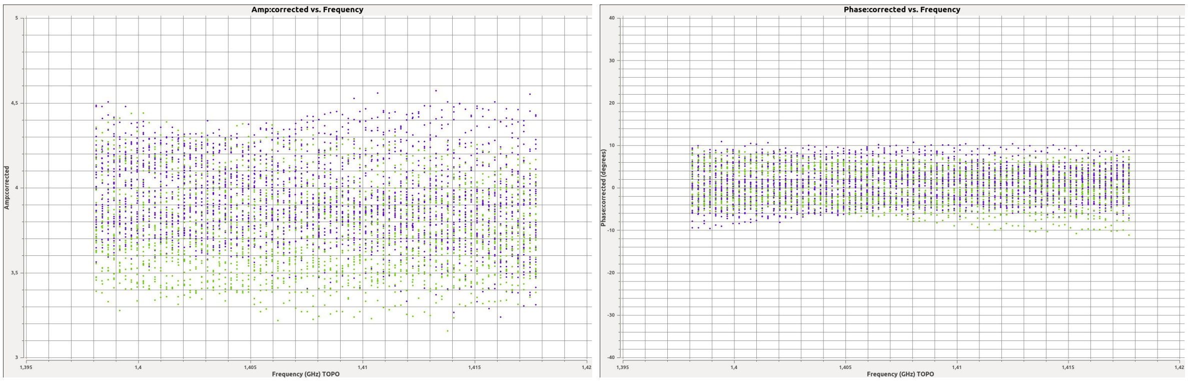


Despite the anomalous bandpass solution obtained for m001, the time-averaged visibility spectra of the primary calibrator for baselines with this antenna are good. This is shown by the amplitude (left) and phase (right) spectra below, colour-coded by baseline with m001 and binned by a factor of 10 in frequency. This suggests that the anomalous bandpass shape of m001 is stable in time at least during the 10 min scan of PKS 1934-638.

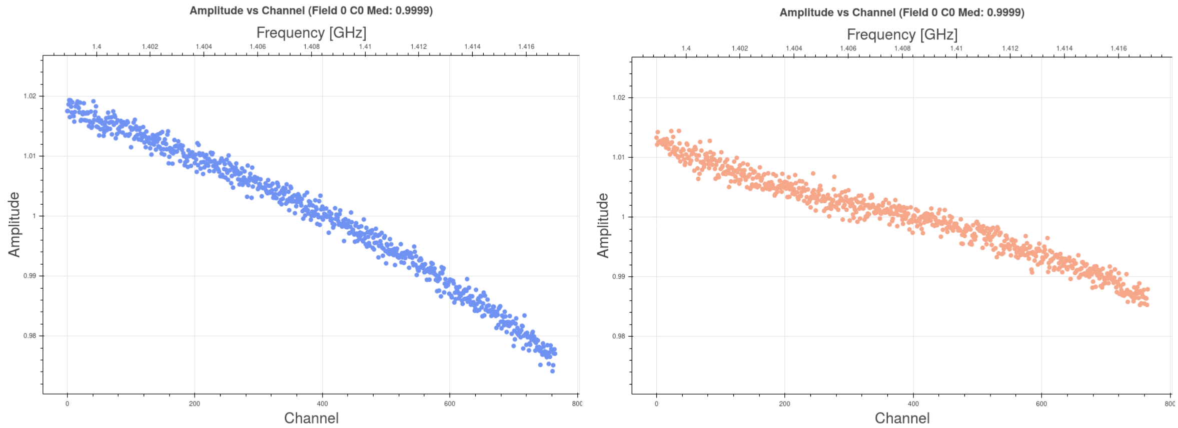




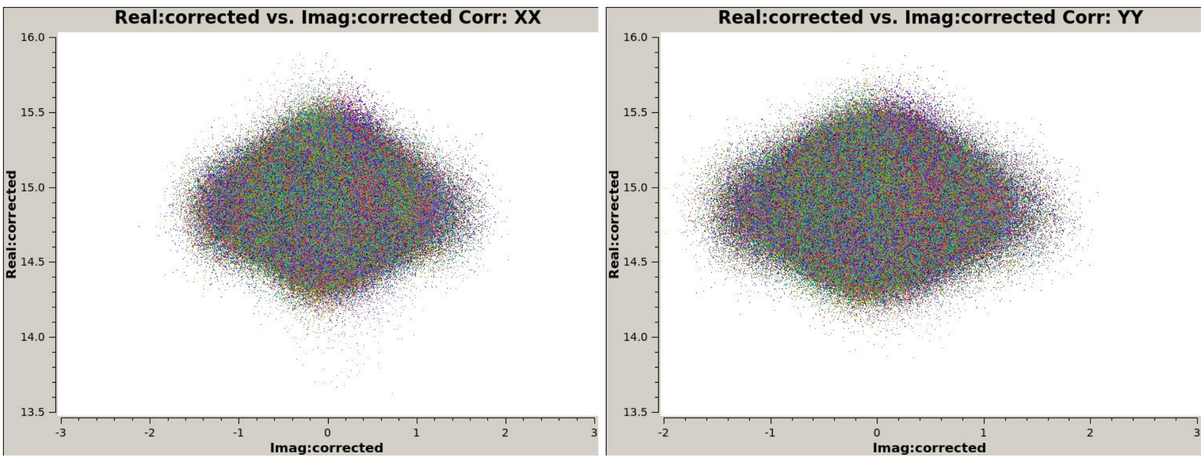
To check whether the m001 bandpass is also stable over a longer time interval we have inspected the time variation of the visibility spectra of the secondary calibrator calibrated with the above time-independent bandpass. We find that baselines with antenna m001 do not behave differently than other baselines. For example, we show below all single-scan XX spectra of baselines m001&m040 (purple) and m003&m039 (green), again binned by a factor of 10 in frequency. Spectra with antenna m001 do not exhibit a significantly larger spread of amplitude (left) or phase (right) than spectra with other antennas. We conclude that, although characterised by a peculiar bandpass shape, m001 appears to be delivering good data.



We also searched for any periodic, single-channel dips/spikes in the visibility spectra. The bandpass solution is obtained per channel, with no smoothing along the frequency axis. Yet, it does not show any periodic single-channel dips/spikes down to a < 1% level (see bandpass solutions above and, for clarity, two single-antenna examples below).



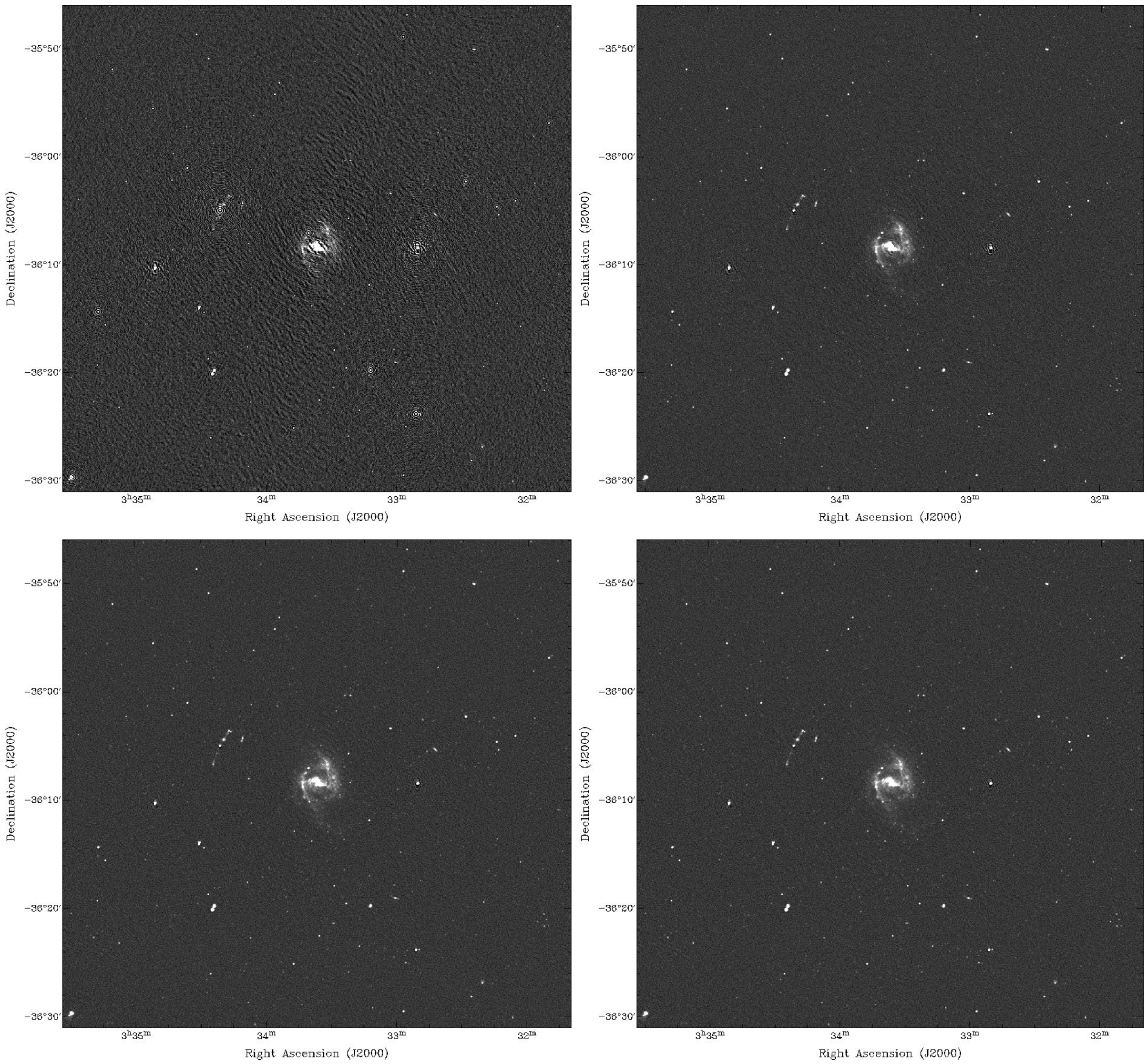
The calibrated visibilities of the calibrators exhibit the expected distribution of amplitudes and phases on most baselines -- see plot below for the bandpass calibrator, which shows all data with some time and frequency binning. The distributions are not perfectly circular, so some small deviations from pure observational scatter exist.



The cross-calibrated target visibilities were flagged with AOFlagger based on Stokes Q using a shallow flagging threshold. Overall, 1.1% of the target visibilities were flagged in this narrow band (excluding auto-correlations).

Continuum imaging and self-calibration

For the purpose of continuum imaging we averaged the cross-calibrated, flagged target visibilities down to ~ 500-kHz-wide channels, flagged all channels with bright spectral line HI emission, and imaged using WSclean with Briggs' *robust* = –1, pixel size = 2 arcsec, field size = 3 deg. We imaged the 20-MHz-wide band in two 10-MHz-wide channels, fitting a first-order polynomial along the spectral axis for each clean component. We cleaned down to 0.5 σ within progressively more complete clean masks created using the SoFiA source finder. We imaged and self-calibrated the data iteratively 3 times, with a final (4th) image made after the last round of calibration. We self-calibrated with Cubical solving for frequency-independent gains (phase-only) with a solution interval of 2 min.

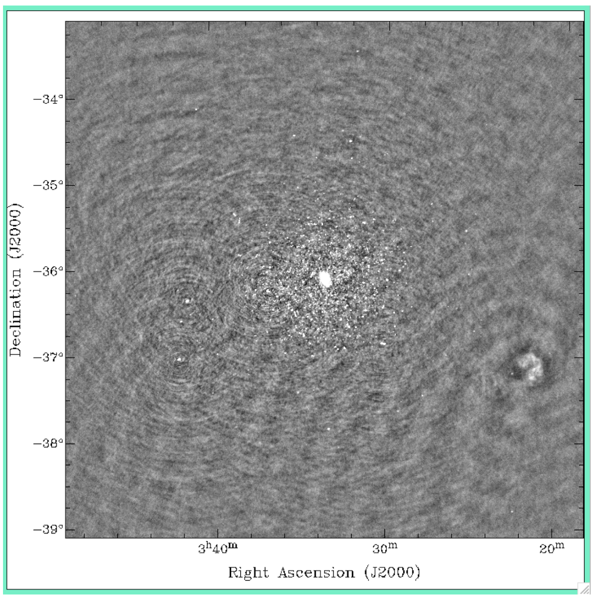


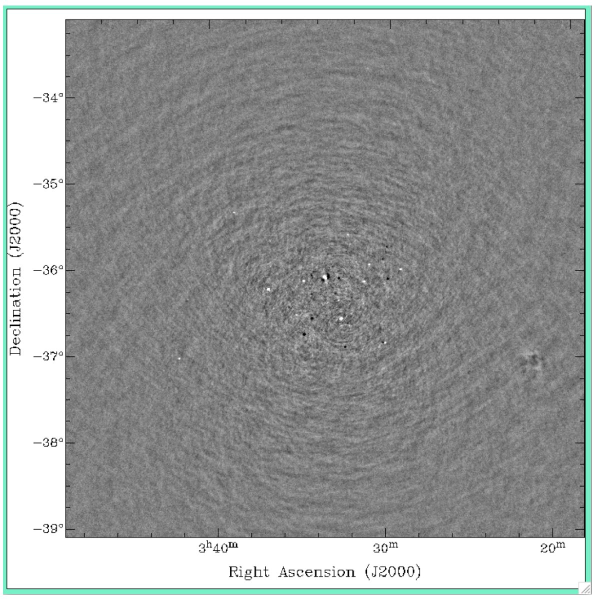
Above we show the improvement of the continuum image during the imaging and self-calibration loop (left to right, top to bottom). The final image is on the bottom-right and is nearly identical to the third image (bottom-left). The main improvements come from the first and second runs of self-calibration. We highlight the good quality of the image in the central region, where 0.58 Jy of continuum emission from NGC 1365 dominate. This measurement agrees with previous measurements at 1.4 GHz (e.g., 0.53 Jy according to the VLA observations presented in https://ui.adsabs.harvard.edu/abs/1996ApJS..103...81C/abstract). This suggests that the flux calibration is correct within ~ 10%. As a further example, the point source 8 arcmin west of NGC 1365 has a flux density of 66 mJy in our image after primary beam correction (using a 1-deg-FWHM Gaussian), 14% higher than its 58 mJy in NVSS.

At about half power (not shown in the images above) the brightest sources show residual artefacts. These might be due to (possibly direction dependent) gain amplitude errors not calibrated for. The dynamic range in small boxes around these sources is ~ 2000.

The image noise is 21 microJy/beam in the far field. This is 40% higher than the noise level expected for 60 antennas, 7 h on target, Tsys/efficiency = 22 K, and Briggs *robust* = –1. Given that the absolute flux calibration appears correct within ~ 10% (see above), and that the noise of the HI cube is consistent with the expectations (see below) it is unclear what is causing this apparent noise increase in the continuum image. This result is independent of whether we make the final image from visibilities at 25-kHz or 500-kHz spectral resolution.

We further investigated the noise increase by making a 6x6 deg^2 image with natural weighting in both Stokes I and Q. We cleaned the Stokes I image with the same clean mask used for the last continuum image of the self-calibration loop (see above), while we did not clean the Stokes Q image. Both images are shown below. We measured the rms noise level in the four ~20x20 arcmin^2 far corners to minimise sidelobes and artefacts from sources in the centre of the image. In Stokes I we found (10.0, 10.4, 10.9, 11.2) microJy/beam, 40% to 58% larger than the expected natural noise of 7.1 microJy/beam. In Stokes Q we found (8.8, 8.8, 8.9, 9.0) microJy/beam, 24% to 27% higher than expected.



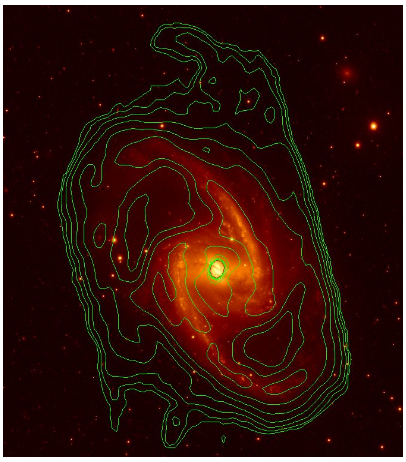


Spectral line imaging

We transferred the final self-calibration solutions to the full-spectral-resolution target visibilities. We subtracted the continuum emission as in UVLIN. I.e., rather than subtracting the continuum clean components (which is very time consuming in our pipeline and is work in progress) we fit and subtract a 4th order polynomial to all real and imaginary visibility spectra independently. We do not Doppler-correct the visibility spectra because we do not want to modify any unwanted, single-channel spectral features in the data, which might be of interest for commissioning (see below).

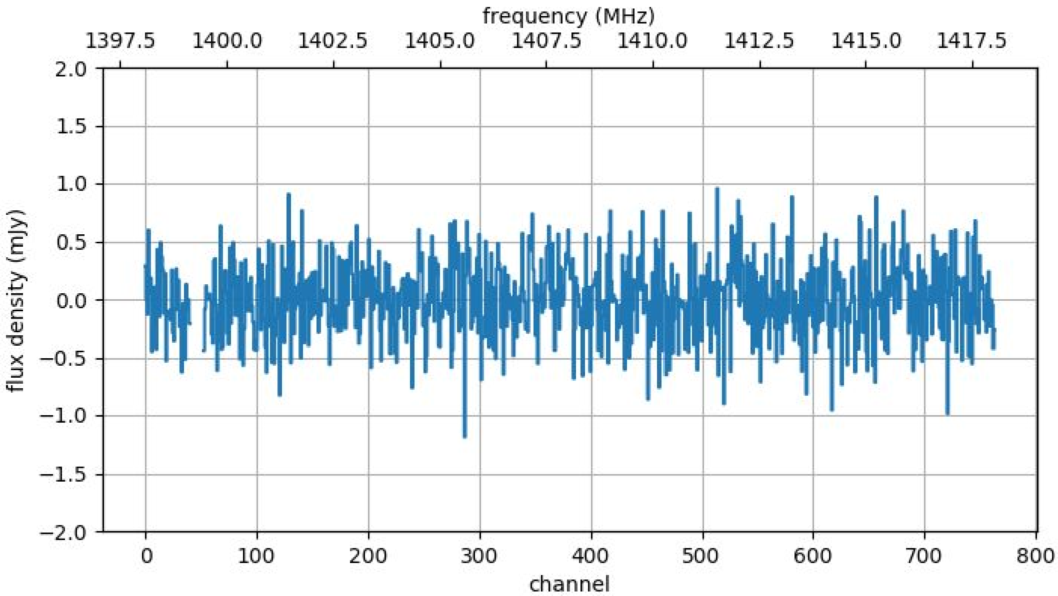
We imaged the HI spectral line with WSclean within our pipeline. We set Briggs *robust* = –0.5 to get a Gaussian dirty PSF central lobe, and tapered by 30 arcsec FWHM to increase surface-brightness sensitivity. We cleaned by setting WSclean auto-mask to 6 and auto-threshold to 0.5. The rms noise level in the cube is 0.37 mJy/beam per 26-kHz-wide channel, which is consistent with the expectations (0.20 mJy/beam natural noise, to be multiplied by a factor of ~1.9 when using *robust* = –0.5; tapering by 30 arcsec should not change the noise level significantly).

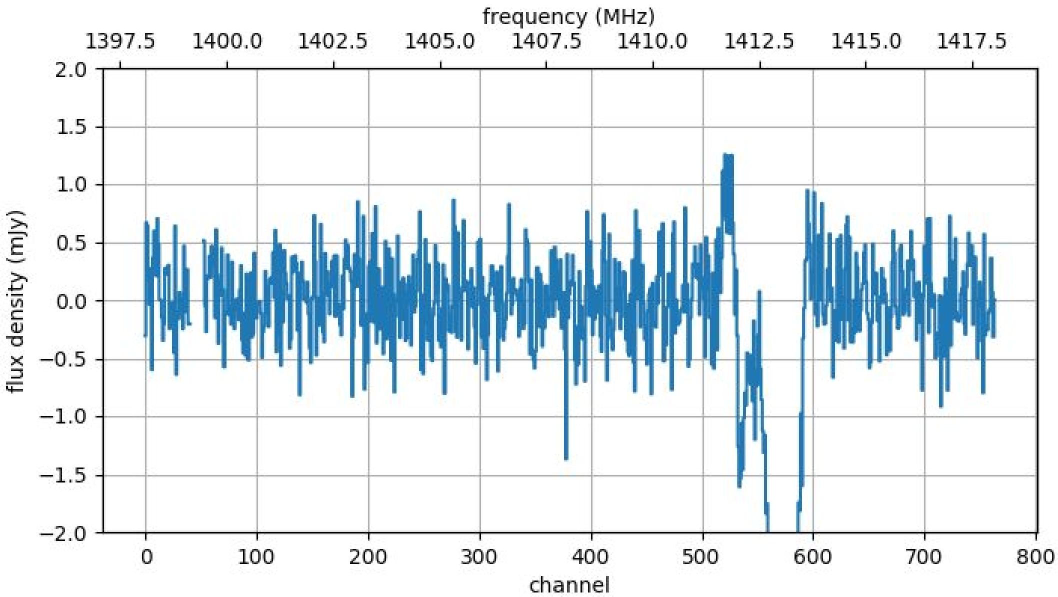
Following a source-finding run with SoFiA we obtained the preliminary HI image shown below (HI contours overlaid on an optical image). The image agrees with previous images of this galaxy (see https://ui.adsabs.harvard.edu/abs/1995AJ....110.2037J/abstract), but it reaches a comparable surface brightness sensitivity at a much better angular resolution. A few, new, faint HI detections are also visible in the data (not shown in the image below).

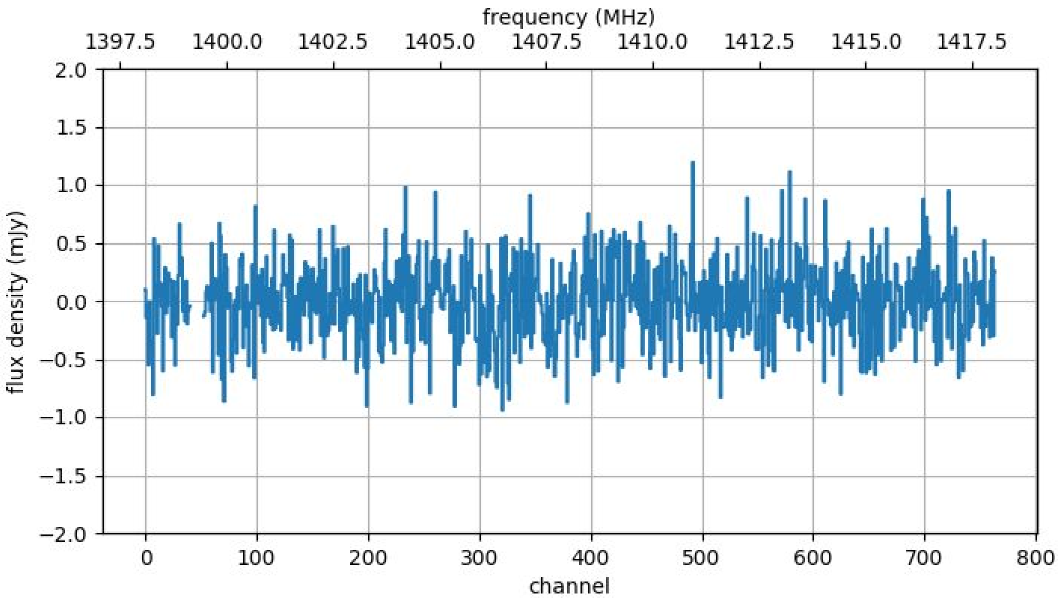


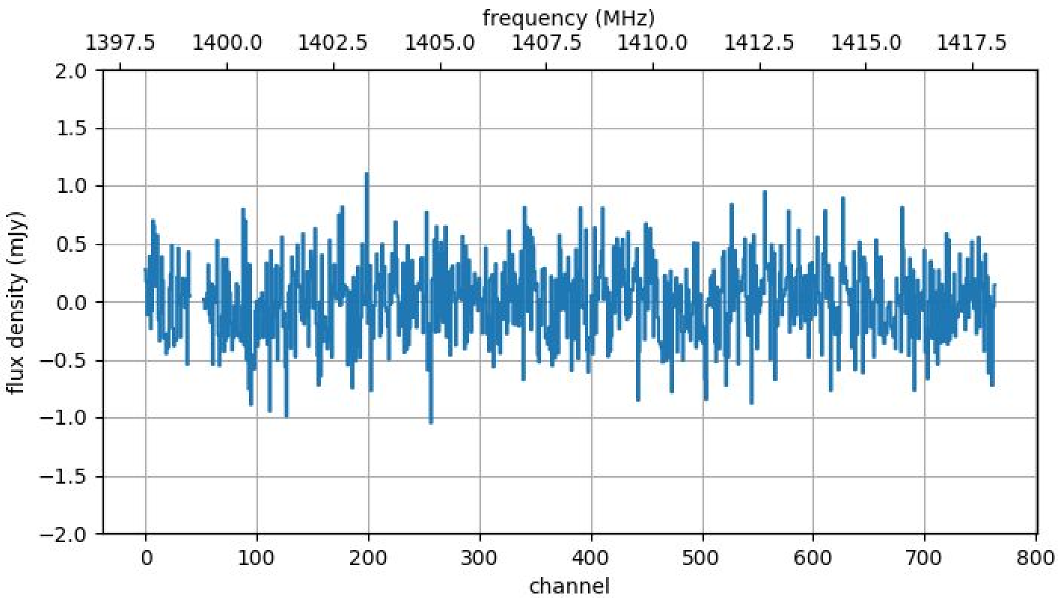
Again, we look for any indications of periodic single-channel dips/spikes in the visibilities by examining the continuum-subtracted spectra from the HI cubes at the location of bright continuum sources. In previous datasets (e.g., Fornax A commissioning observations with MeerKAT/SKARAB-4k) this proved to be an efficient way of finding such dips/spikes because their amplitude is proportional to the continuum flux at that position. Below we show four such spectra extracted at the location of sources brighter than 20 mJy within 20 arcmin of the phase centre. Note that the spectra are shown at the full (26 kHz) spectral resolution.

We do not find any obvious signs of periodic single-channel features down to a few percent of the continuum flux.









Summary and next steps

In summary, we have successfully processed in total intensity a narrow band (20 MHz centred at 1408 MHz) of the recent NGC 1365 MeerKAT/SKARAB-32k commissioning observation. Our main conclusions are the following:

- Cross-calibration solutions appear reasonable with the only possible exception of antenna m001, which exhibits an anomalous bandpass shape but nevertheless seems to be delivering good data.
- In the narrow band processed for this report RFI is nearly absent.
- Following self-calibration, the continuum image of the field is of good quality near the phase centre, showing no apparent artefacts. Some artefacts are visible around

bright sources in the proximity of the primary beam half-power. The dynamic range near these sources is ~2000.

- The noise level in the continuum image is 40% higher than expected. We do not know the cause of this. The flux calibration appears to be correct within 10%.
- The HI cube is of good quality and agrees with previous, published HI results (HI flux, morphology). The noise level of the HI cube is consistent with the expectations (unlike that of the continuum image).
- Based on both the bandpass solutions and the continuum-subtracted spectra at the position of sources brighter than 20 mJy and within 20 arcmin from the phase centre, no periodic single-channel dips/spikes seem to be present in these data.

We are currently improving the continuum subtraction by transferring (and then subtracting) the continuum clean components to the full-spectral-resolution self-calibrated .MS. This will allow us to inspect the continuum-subtracted spectra of continuum sources farther from the phase centre than the ones shown in this report because their continuum emission will have been subtracted better. This step of model transfer is currently very time consuming in our pipeline. We will present those results in a separate report.

Data processing of a wider band (~ 100 MHz) is also ongoing and we will report on that when we have results. This will initially be a simple extension of the work and analysis presented here, i.e., focussed on total intensity continuum and spectral line. Following that, we will start processing the data in full polarisation.