# MeerKAT-32k zoom mode commissioning: NGC 1365

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*Daniel Molnar, Paolo Serra*
*(INAF - Osservatorio Astronomico di Cagliari)*

## Observations

We analyse MeerKAT 32k zoom-mode data taken on 1 May 2020 in preparation for the MeerKAT Fornax Survey (observed target: NGC 1365; project ID: SCI-20180516-PS-01, MS name: 1588316462_sdp_l0.ms).

The data were taken over the course of ~ 9 h. Fifty-nine MeerKAT antennas were online (the offline antennas were m005, m023, m025, m037 and m043). We used J0408-6545 as our primary (bandpass and flux) calibrator, which was observed for 10 min every ~2h after the first 2h of the session (total integration ~ 39 min). The bandpass calibrator J1939-6342 was also observed for 10 min at the start for the observation session but we did not use this scan in our analysis. The secondary (gain) calibrator J0440-4333 was observed for 2 min every ~ 21 min (total integration ~ 49 min). The target NGC 1365 was observed for a total of 7.2 h.

## Cross-calibration and flagging

For this report we processed a ~ 42-MHz-wide band going from ~ 1350 to ~ 1392 MHz containing the central 13,000 channels out of the 32,768 channels of the MeerKAT zoom band. This selects the most sensitive part of the band and avoids the bandpass roll off and the non-calibratable discontinuity at the band's edges[1]. For the full MeerKAT Fornax Survey we will use a slightly larger portion of the band: the central 16,384 channels.

We transferred HH and VV visibilities to a local machine at INAF - Cagliari. To speed up data processing and match our scientific goal (i.e. ~ 1 km/s velocity resolution at the redshift of Fornax) we binned channels by a factor of 2 and, thus, worked with 6,500 6.5-kHz-wide channels. Data reduction was done using the CARACal pipeline, version 1.0.3 (https://caracal.readthedocs.io/en/latest/; Jozsa et al. 2020) 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

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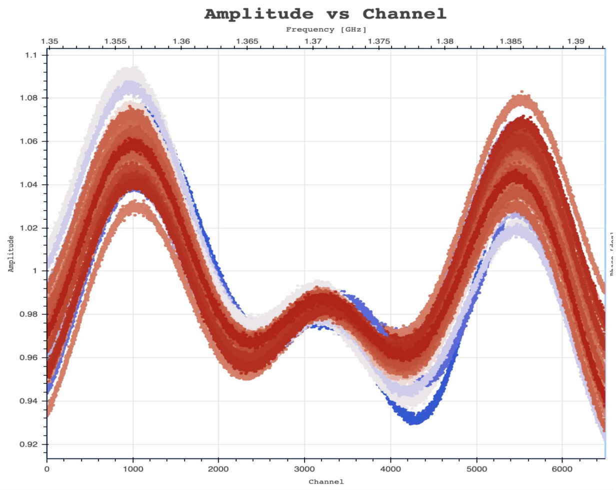
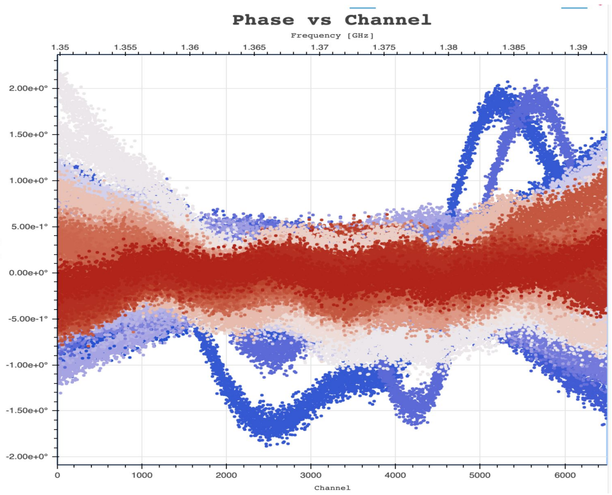
[1] For details on the spectral jump appearing in our bandpass see our earlier report at https://docs.google.com/document/d/1p5yxGcoItNC1Witu9f401Aa5n0xLXFqyBkP5uTPQyks/edit?usp=sharing.

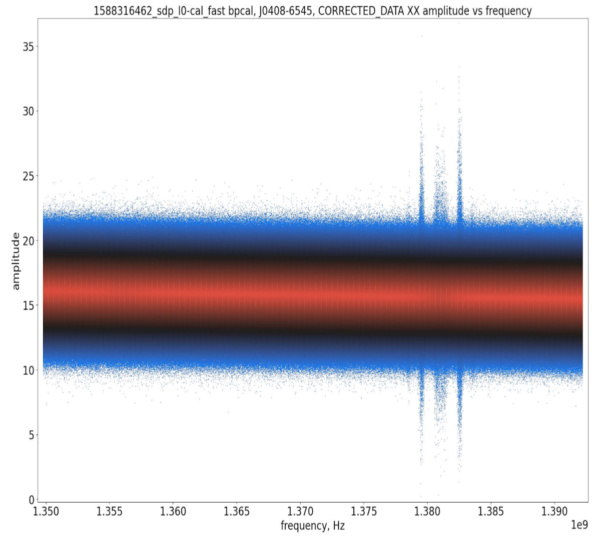
calibration from the primary. We calibrated and flagged iteratively. We set the reference antenna to m021. During calibration we ignored baselines shorter than 150 m.

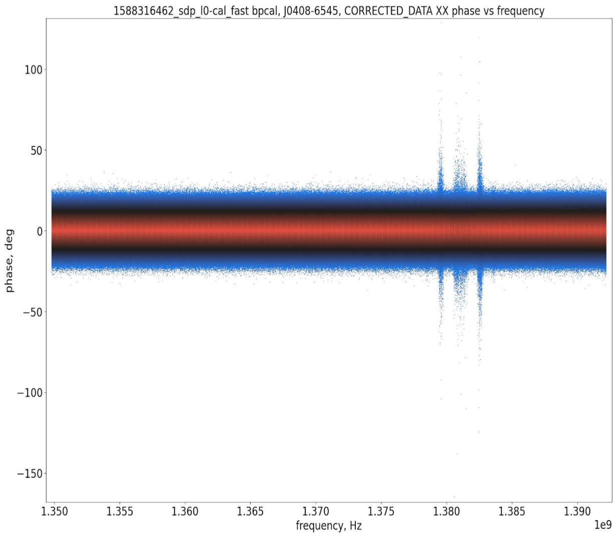
The calibration solutions appear reasonable. Delay corrections are in the range [-0.2, +0.5] ns. The plots below show the bandpass solutions colour-coded by antenna. The antennas with a somewhat anomalous phase bandpass shape are m001 and m006 (blue and light-blue outlier curves in the phase vs channel figure).





The calibrated visibilities of the primary and secondary calibrators appear reasonable. Below we show the time averaged amplitude and phase spectra of the primary. The only obvious – but marginal – problem in these plots is the residual weak RFI at 1380 MHz.

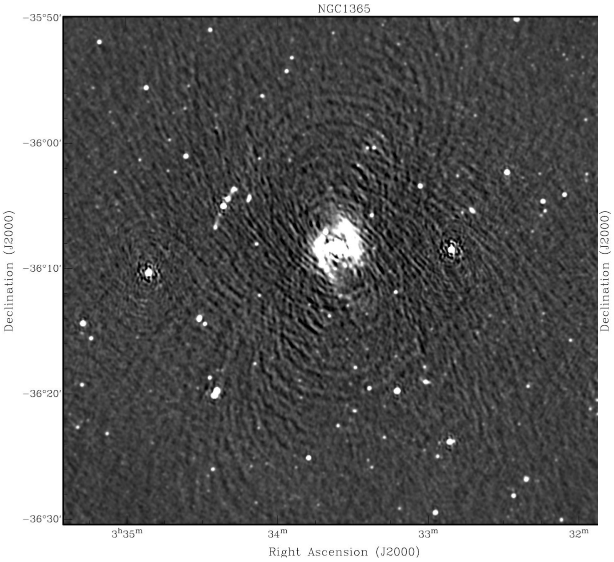


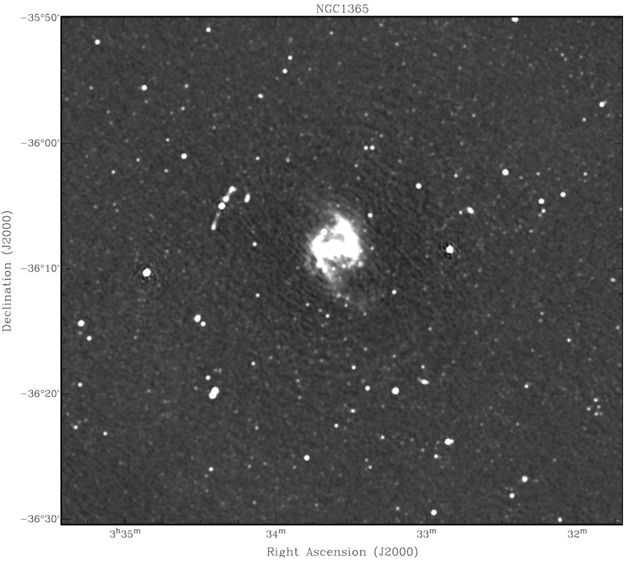


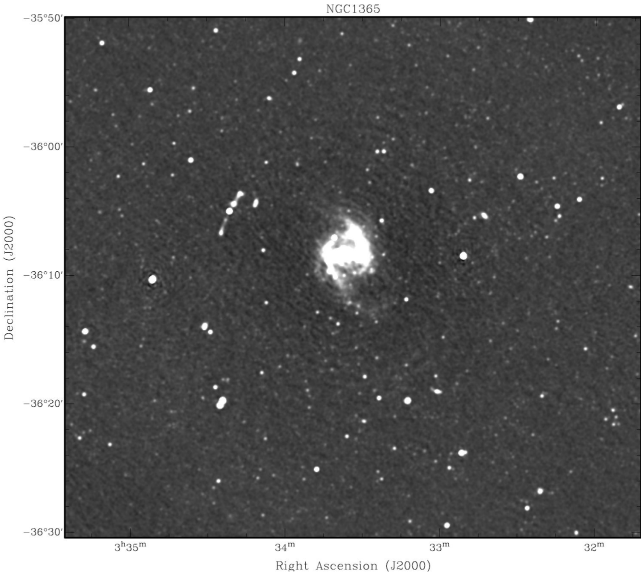
With the exception of the known GPS L3 RFI at 1380 MHz, the frequency range analysed for this report is virtually free of RFI (~ 3 % flagged fraction, raising to ~ 18% at 1380 MHz).

## Continuum imaging and self-calibration

For the purpose of continuum imaging we averaged the cross-calibrated, flagged target visibilities down to ~ 1-MHz-wide channels, flagged all channels with bright spectral line HI emission, and imaged using WSclean with Briggs' *robust* = – 0.5, 12 arcsec tapering, pixel size = 4 arcsec, field size = 3 deg. We imaged the 42-MHz-wide band in four ~ 10-MHz-wide channels, fitting a second-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 2 times, with a final (3rd) image made after the last round of self-calibration. We self-calibrated with Cubical solving for frequency-independent gains (phase-only) with a solution interval of 2 min.



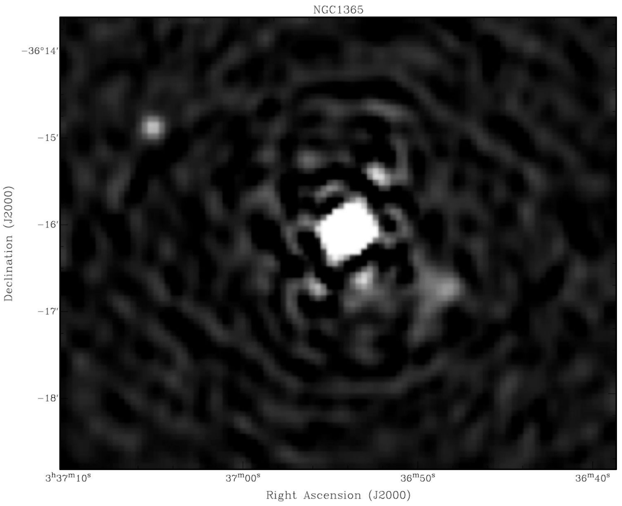




Above we show the improvement of the continuum image during the imaging and self-calibration loop (left to right, top to bottom). The final image is on the bottom-left and is nearly identical to the second image (top-right). The main improvements come from the first run of self-calibration. The main goal of our final imaging step was to build a reliable sky model inclusive of all brightest continuum sources, which will then be transferred to the high-spectral-resolution .MS and subtracted before making a line cube.

We highlight the good quality of the image in the central region, where 0.54 Jy of continuum emission from NGC 1365 dominate. This measurement is in excellent agreement 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 a few percent. As a further example, for a point source 15 arcmin east of NGC 1365 we measure a flux density of 58 mJy. Once primary-beam corrected by a factor 1/0.86 using the Mauch et al. (2020) primary beam model at 1370 MHz, this value agrees with the NVSS catalogue value of 67 mJy.

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 ~ 3000 (example below).



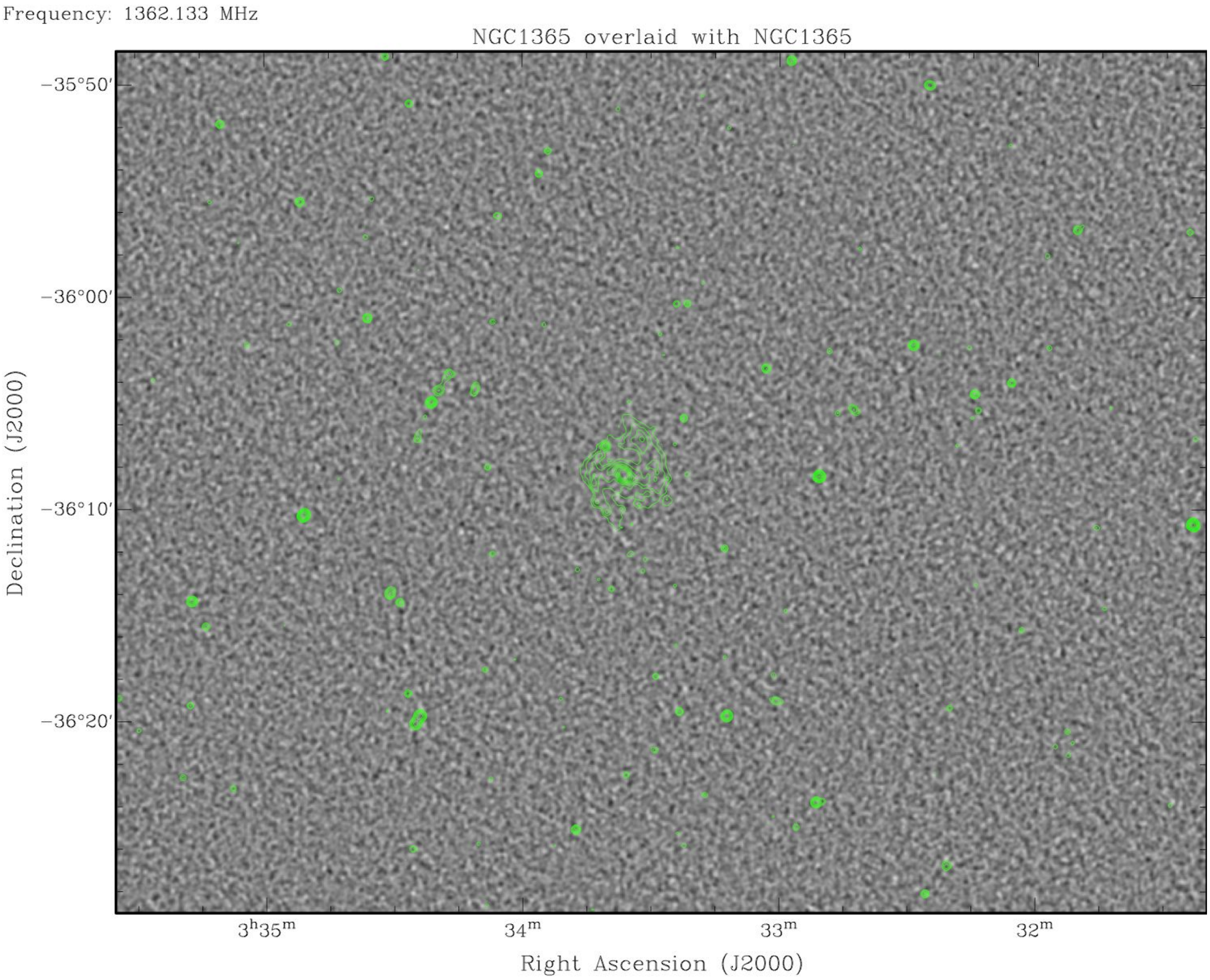
The image noise is 9.5 microJy/beam in the far field. This is consistent with the noise level expected for 59 antennas, 7.2 h on target, Tsys/efficiency = 22 K, and Briggs *robust* = –0.5 (for which we assume a factor of 1.8 compared to the expected noise with natural weighting).

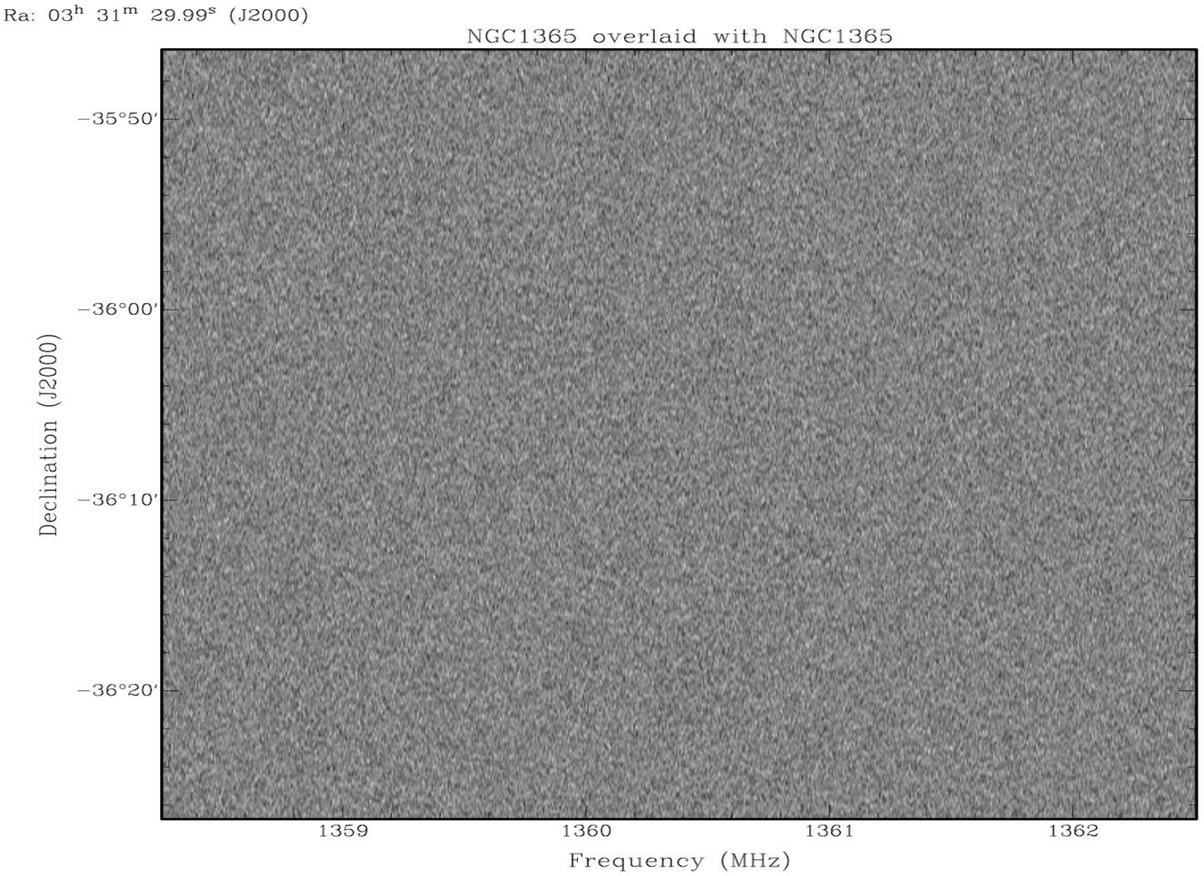
## Spectral line imaging

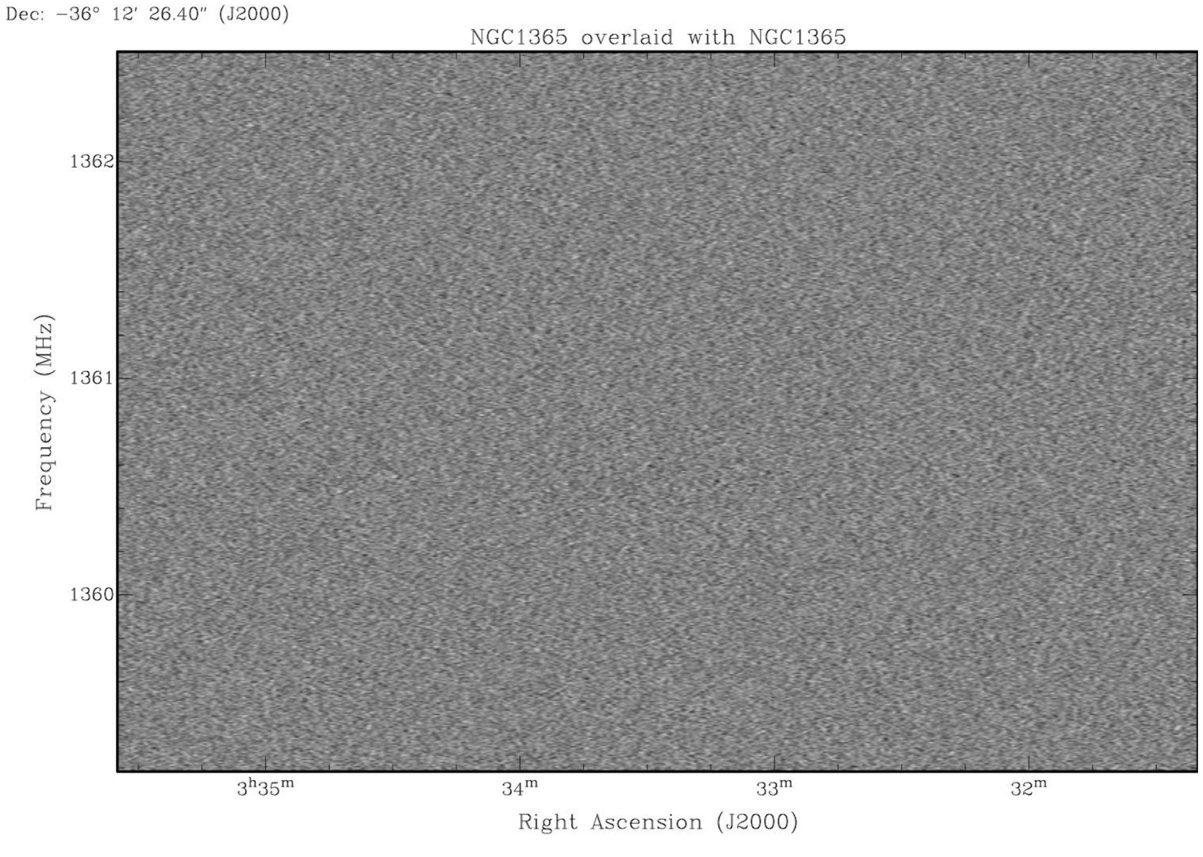
This step of the data reduction was done serially on smaller chunks of the 42-MHz-wide band to speed up the analysis of the line cube. We split the 6,500-channel .MS into 10 .MS files of 650 channels each (about 4-MHz-wide each). We transferred the final self-calibration solutions to these 650-channel .MS files individually. As mentioned above, we also transferred the sky model from our final self-calibrated continuum image to subtract the bright continuum. The latter step, which requires interpolation in frequency, is the most time-consuming step of the data reduction. Any remaining continuum emission was removed with UVLIN by fitting and subtracting a first order polynomial to all real and imaginary visibility spectra for each 650-channel .MS independently.

Since our selected frequency range does not in fact probe the Fornax volume, but the cosmic void behind Fornax, we do not expect many, if any at all, HI detections. Therefore, after continuum subtraction, we did not clean the cubes but only produced dirty cubes with WSClean using the same imaging parameters as for the continuum image (*robust* = –0.5, 12 arscec tapering, etc.). Our main goal is to investigate the noise properties of the cubes.

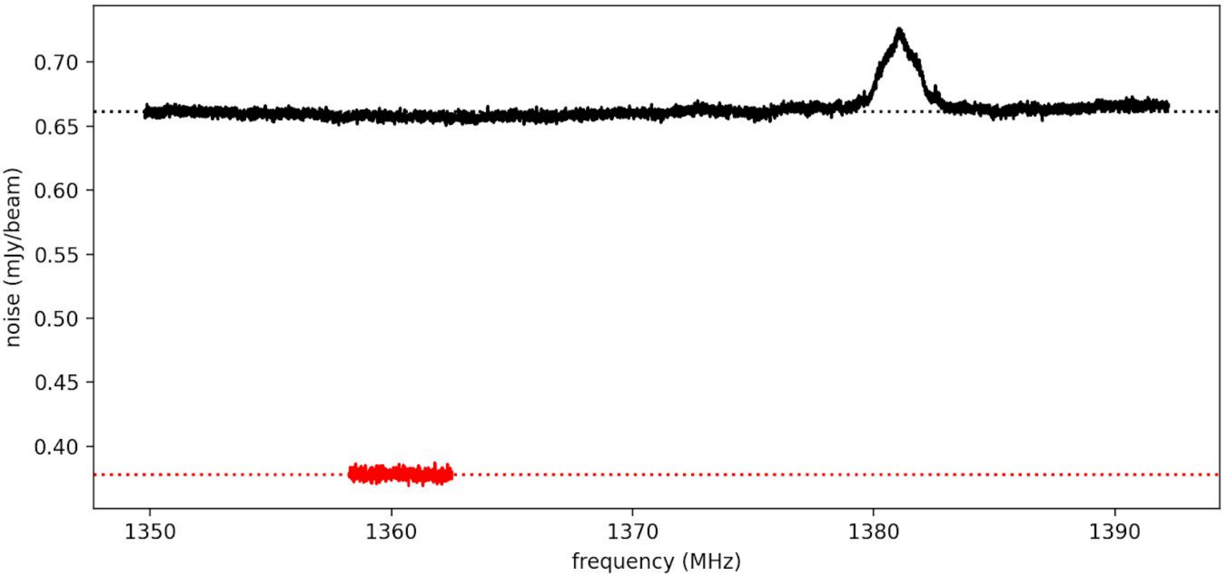
Below we show sample slices through the resulting cubes. In the RA-Dec slice we show the bright continuum sources with green contours. Overall, all 10 sub-band cubes look extremely clean, with no artefacts and a Gaussian distribution of pixel values.




Ra: 03h 31m 29.99s (J2000)
NGC1365 overlaid with NGC1365
Declination (J2000)
−35°50′
−36°00′
−36°10′
−36°20′
1359
1360
1361
1362
Frequency (MHz)


Dec: −36° 12′ 26.40″ (J2000)
NGC1365 overlaid with NGC1365
Frequency (MHz)
1362
1361
1360
3h35m
34m
33m
32m
Right Ascension (J2000)

Considering all sub-bands together, we measure a median RMS noise of 0.66 mJy/beam per 6.5 kHz channel, with little variation from channel to channel (see black line below; the rms increase at 1380 MHz is consistent with the 18% fraction of flagged data due to the GPS L3 signal; the dotted line represent the 0.66 mJy/beam median value). This noise level is slightly lower than the expected value of 0.72 mJy/beam obtained for 59 antennas, Tsys/efficiency 22 K, 7.2 h on target, and scaling the 0.40 mJy/beam expected natural noise level by a factor of ~1.8 to account for our *robust* = –0.5 weighting (tapering by 12 arcsec should not change the noise level significantly).



To remove the complication of having to scale the noise according to the adopted robust weights we also made a single 650-channel cube with natural weights and measured a median rms of 0.38 mJy/beam. Again, this noise level is essentially independent of frequency (red line above) and slightly better than the expected value of 0.40 mJy/beam assuming Tsys/efficiency = 22 K. In fact, our result is consistent with Tsys/efficiency = 20.5 K at these frequencies, which is the value included in the recent MeerKAT call for proposals.

In order to check the consistency of noise properties, assess the quality of our continuum model subtraction (both using the clean components of the self-calibrated continuum image and UVLIN) and look for spectral dips and spikes (see our previous 32k broad-band commissioning report[2]) we extracted single pixel spectra towards 13 continuum sources spanning ~2 orders of magnitude in continuum flux density, as well as 15 emission-free sightlines at various distances from the phase centre (within 1 degree = primary beam half power). The image below shows on- and off-continuum-source slightlines in red and blue, respectively, overlaid on the continuum image.

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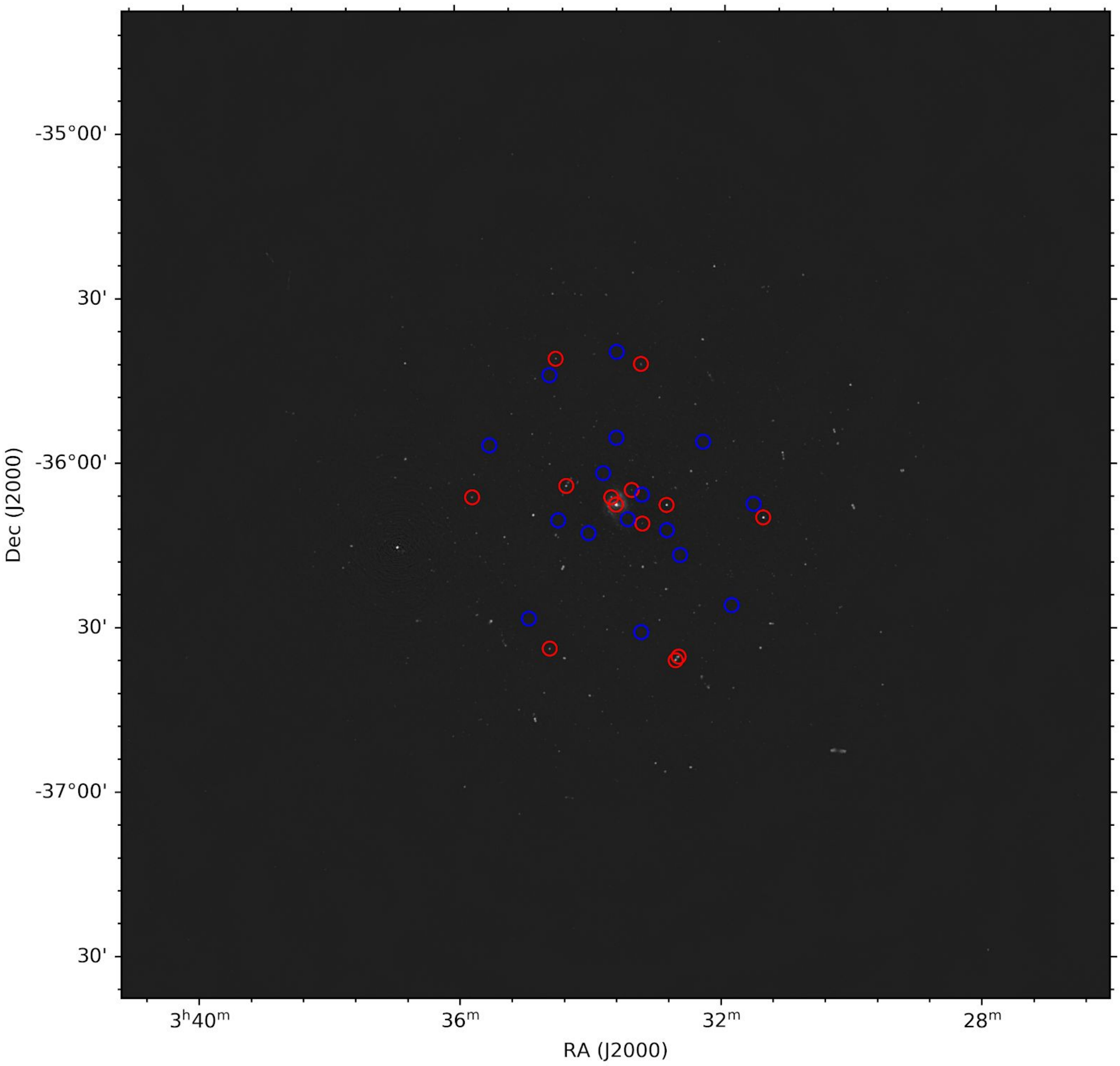
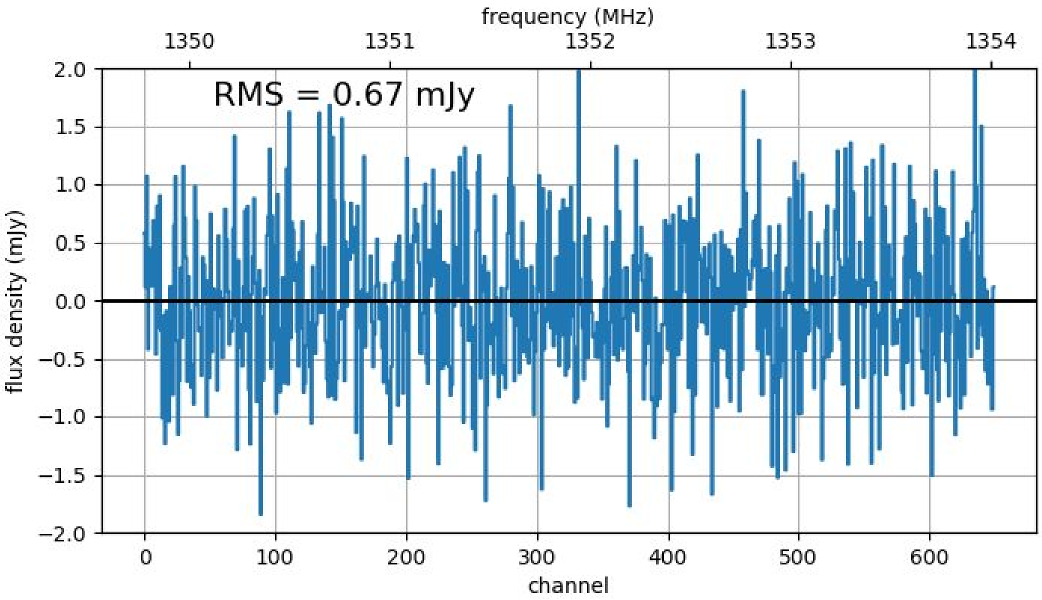
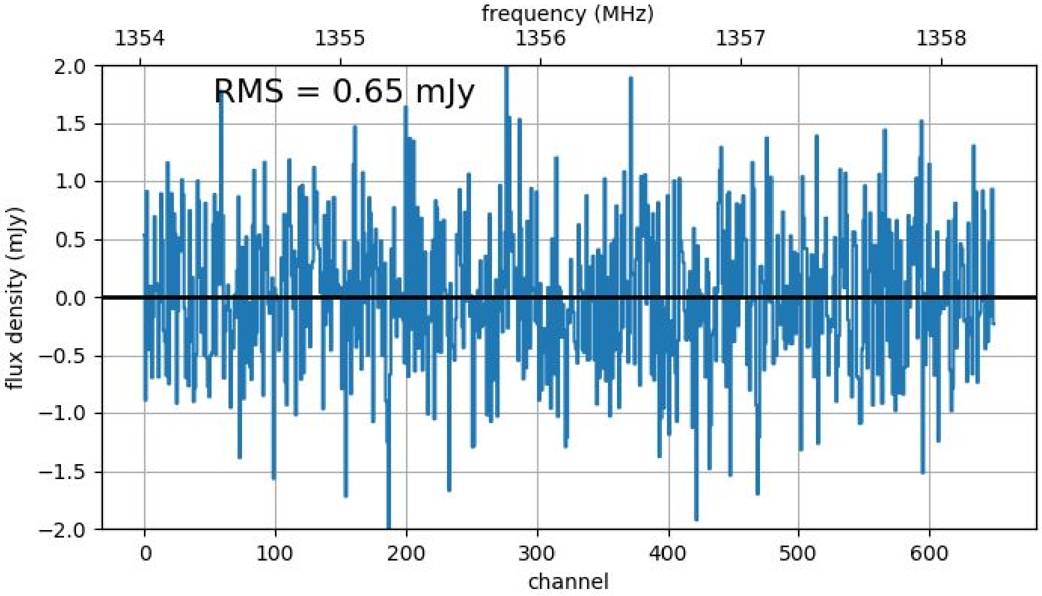
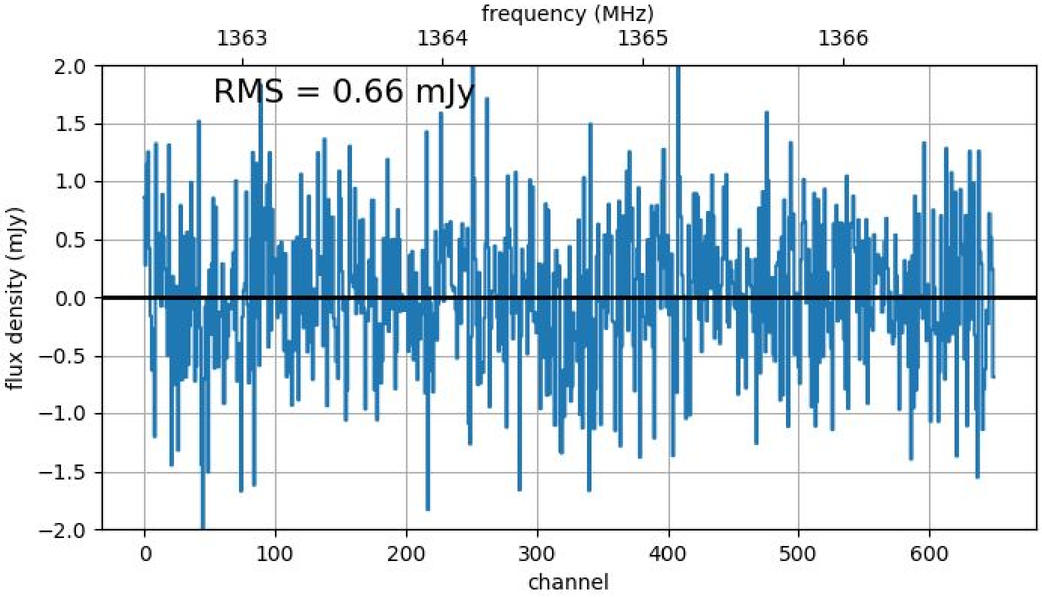
[2] https://docs.google.com/document/d/1utIfZJWRD0qgfLpP03jPNIEpEIIHfnP-saGXynbG-E8/edit?usp=sharing

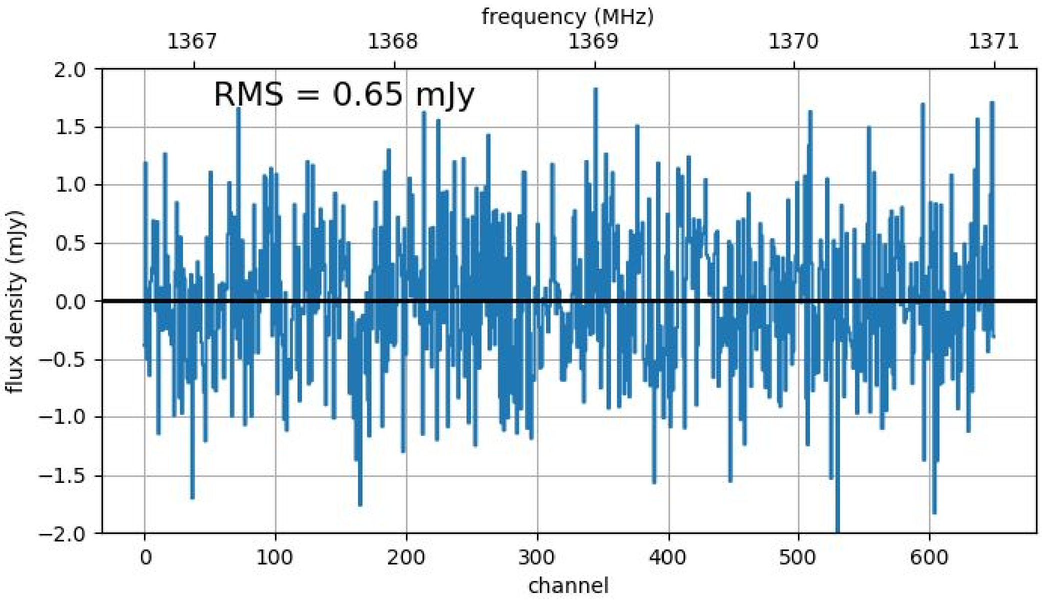


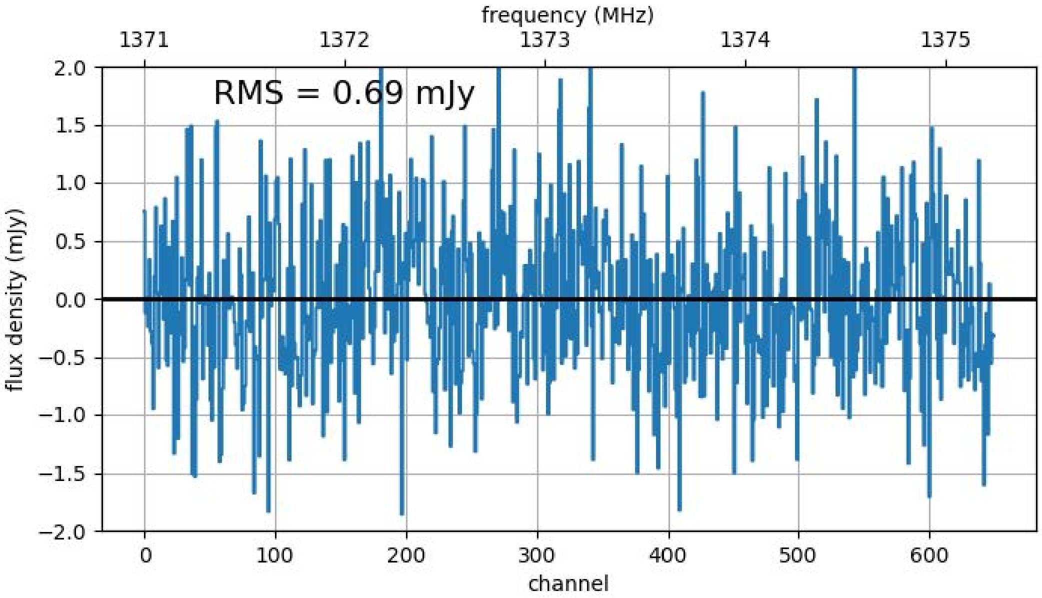
All the extracted spectra appear flat with no exceptions, including those of off-centre bright sources (near half-power), and all have highly consistent RMS values. In the next few pages we show 6 of the spectra extracted at the position of continuum sources in the field, and further down 6 spectra extracted at “empty” positions of the continuum image.

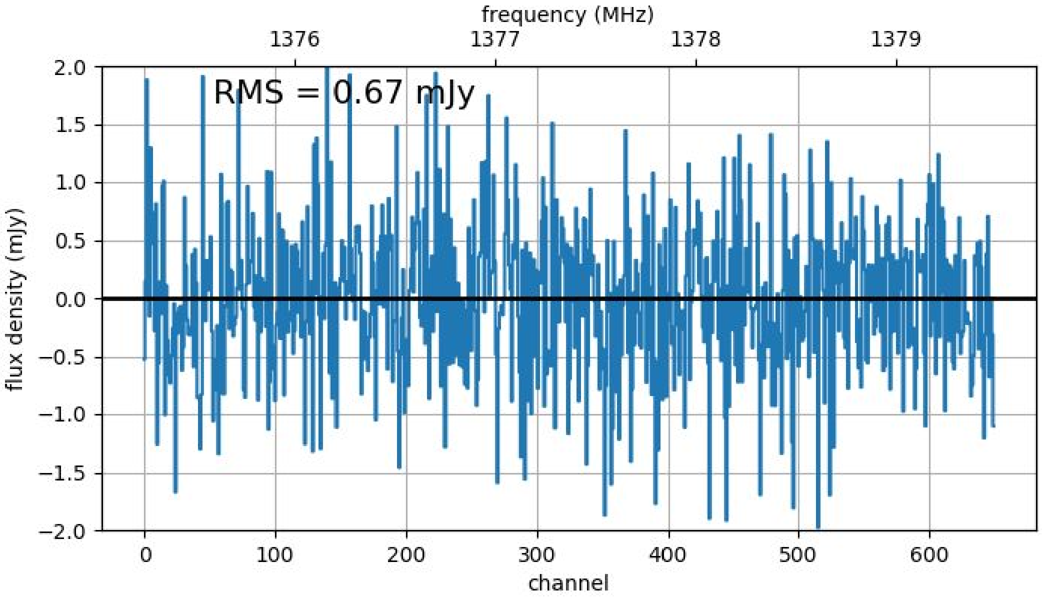

frequency (MHz)
1350
1351
1352
1353
1354
RMS = 0.67 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel

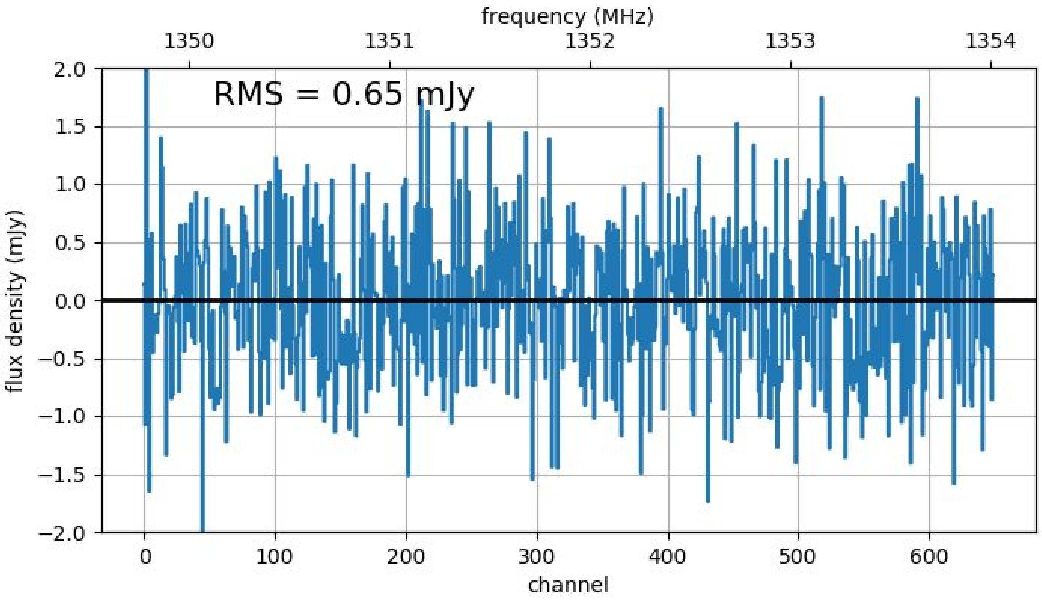

frequency (MHz)
1354
1355
1356
1357
1358
RMS = 0.65 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel

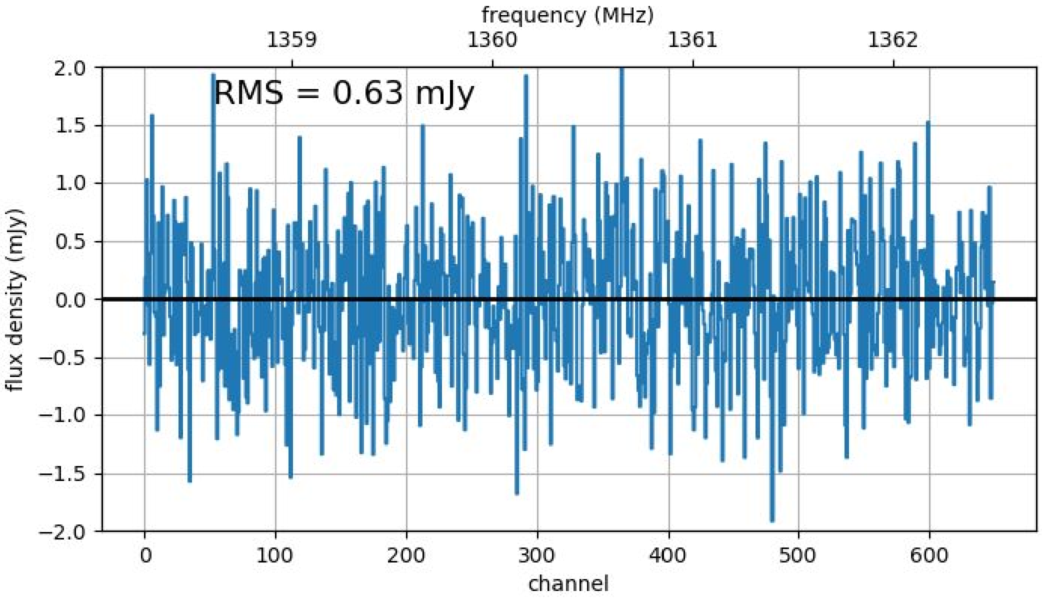

frequency (MHz)
1363
1364
1365
1366
RMS = 0.66 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel

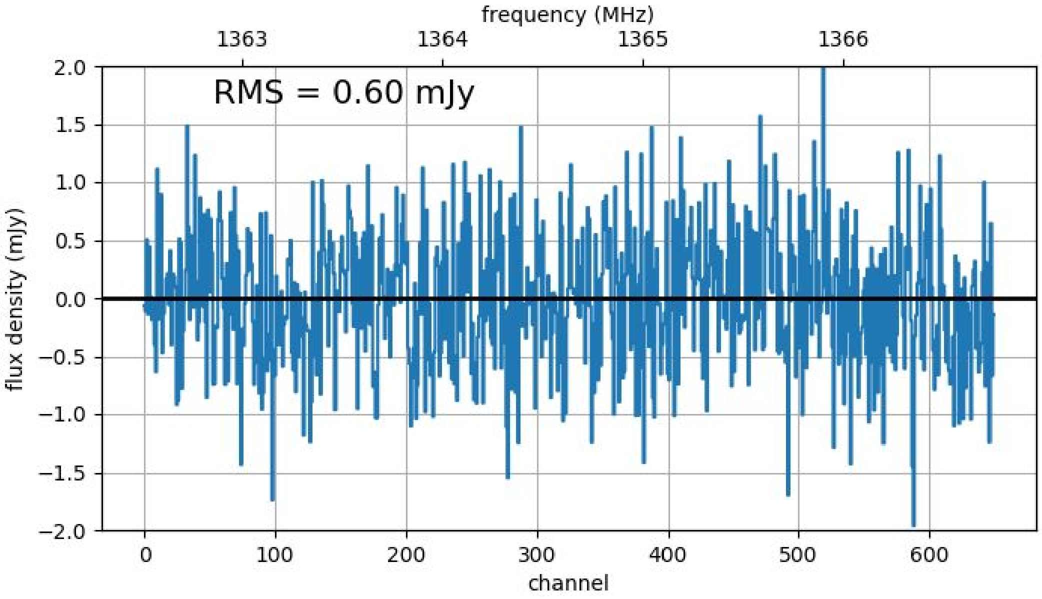

frequency (MHz)
1367
1368
1369
1370
1371
RMS = 0.65 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel

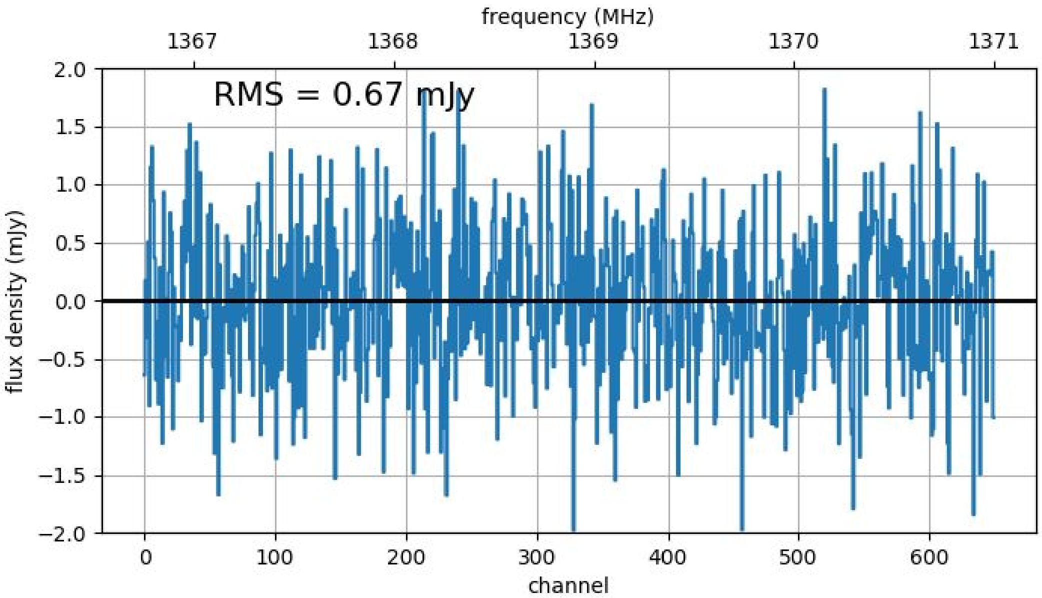

frequency (MHz)
1371
1372
1373
1374
1375
RMS = 0.69 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel

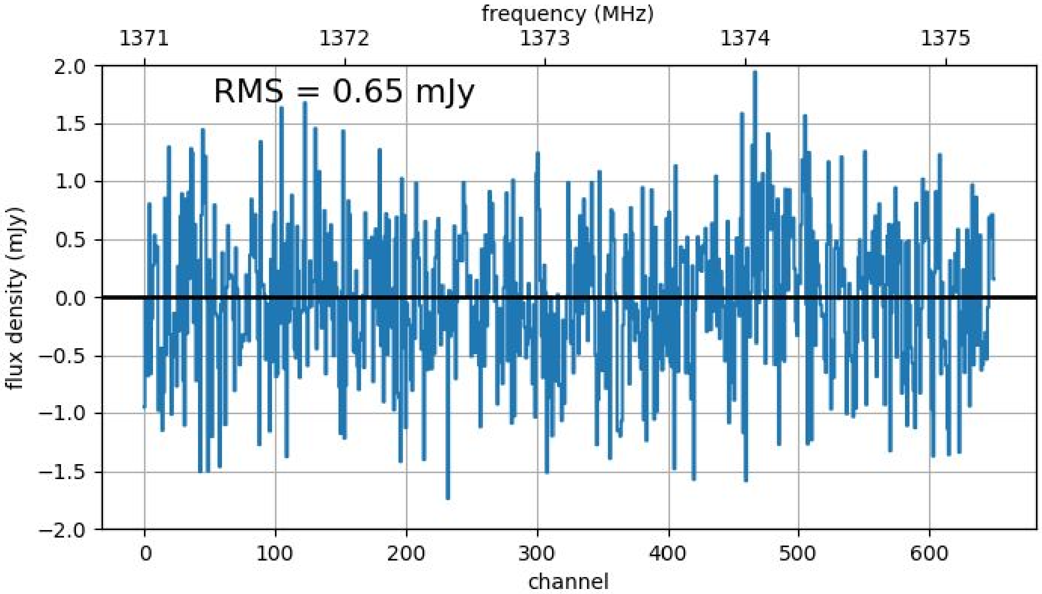

frequency (MHz)
1376
1377
1378
1379
RMS = 0.67 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel

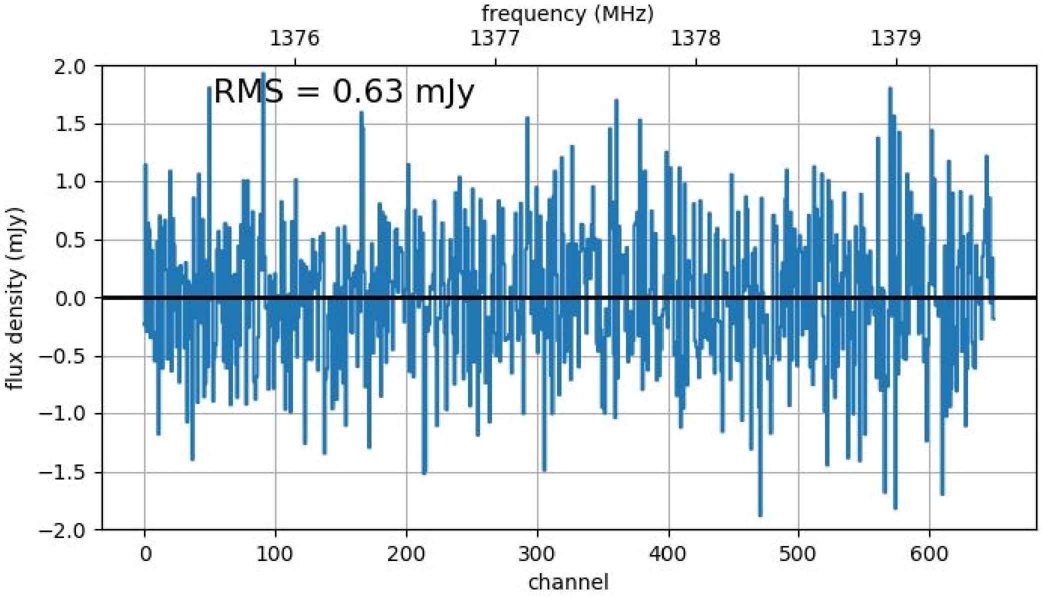

frequency (MHz)
1350
1351
1352
1353
1354
RMS = 0.65 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel


frequency (MHz)
1359
1360
1361
1362
RMS = 0.63 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel


frequency (MHz)
1363
1364
1365
1366
RMS = 0.60 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel


frequency (MHz)
1367
1368
1369
1370
1371
RMS = 0.67 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel


frequency (MHz)
1371
1372
1373
1374
1375
RMS = 0.65 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel


frequency (MHz)
1376
1377
1378
1379
RMS = 0.63 mJy
flux density (mJy)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
100
200
300
400
500
600
channel

## Summary

In conclusion, we have successfully processed the central 42 MHz wide band (centred on 1371 MHz) of a NGC 1365 MeerKAT 32k zoom-mode commissioning observation. Our main results are:

- Cross-calibration solutions appear reasonable with the possible exceptions of antenna m001 and m006, which exhibit an anomalous phase bandpass shape. Both these antennas, however, seem to be properly calibrated.
- In the narrow band processed for this report RFI is nearly absent with the exception of the known GPS L3 RFI at 1380 MHz.
- 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 ~ 3000.
- The noise level in the continuum image is close to the expected value. The flux calibration appears to be correct within a few percent.
- The HI cubes with *robust* = – 0.5 and with natural weighting (the latter over a limited 4-MHz-wide band) are of good quality. The noise level is slightly better than expected assuming Tsys/efficiency = 22 K, and consistent with the expected value assuming Tsys/efficiency = 20.5 K as in the recent MeerKAT call for proposals. This shows that MeerKAT with SKARAB's zoom mode is performing on spec.