Reduction of the mosaic of M83 (NGC 5236) in the wide-band fine mode

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List of Abbreviations

CAM	Control and Monitoring
SKA	Square Kilometre Array
CASA	Common Astronomy Software Applications
SoFiA	Source Finding Application
ATCA	Australian Telescope Compact Array
LVHIS	Local Volume HI Survey
VLA	Very Large Array
THINGS	The HI nearby Galaxy Survey
MHONGOOSE	MeerKAT HI Observations of Nearby Galactic Objects : Observing Southern Emitters
LADUMA	Looking At the Distant Universe with the MeerKAT Array
T_{sys}/η	System temperature over aperture efficiency
rms	Root mean square
LSRK	Local Standard of Rest Kinematic

1 Introduction

1.1 Background

M83 (NGC 5236) is a spiral galaxy with active star formation near the centre of a small group of galaxies. The source has an optical extent of 12.9' x 11.5' but the HI extent is around a degree in scale. The galaxy has a HI integrated flux of 1630.3 Jy km/s, a peak flux of 7.710 Jy (Barnes et al. 2001), and a distance of $D_{cepheid} = 4.5 \pm 0.3$ Mpc. This makes the source one of the brightest extragalactic HI sources in the southern sky.

There are multiple HI observations of M83 with comparable baseline distributions: with the Australia Telescope Compact Array (ATCA) as part of "The Local Volume HI Survey" (LVHIS) (Park et al. 2001), and with the Very Large Array (VLA) as part of "The HI nearby Galaxy Survey" (THINGS) (Walter et al. 2008). The galaxy has a recessional velocity of 513 km/s putting it outside of the Galactic HI and associated high velocity clouds of our galaxy. There is also a spectrum from the HIPASS survey (Barnes et al. 2001).

1.2 LVHIS ACTA data

LVHIS presented the 9-point mosaic of M83, done with ATCA in Koribalski (2018). This provides a comparable dataset for us examine the accuracy of our data. The beam in the LVHIS mosaic is 85.8" x 60.8" and was done with natural weighting. A plots of the LVHIS mosaic of M83 as shown in Figure 1 . In the centre plot we have matched the contours to be the same in both the LVHIS images on the top and the MeerKAT images on the bottom.

1.3 Commissioning task and testing

The choice of this field and type of observation for science commissioning was done on the basis that this would provide a stringent test of the 32K correlator mode. 32K will be used initially for the approved Large Survey Projects LADUMA and MALS. This test gives confidence in the correlator for these surveys. In addition to a test of the spectral line correlator modes in imaging neutral hydrogen, we expect to be able to reproduce the THINGS and LVHIS observations on the MeerKAT radio telescope.

2 The Observation

2.1 Observational setup

The observation has 7 pointings of the mosaic centred on M83 with a separation of 0.707 degrees. The centre pointing on M83 is labeled $M83_4$. The complex gain calibrator for the observation was PKS1313-33, which is 5.8 degrees from M83 but only has a flux of 0.72 Jy. Two Flux and Bandpass calibrators were included, PKS0408-65 and PKS1934-638, to ensure that there will always be one up above 20 degrees elevation. The observation was run using a generic script that loops through all the targets and complex gain calibrator, and periodically visits any/all available bandpass/flux calibrators. We chose to observe the bandpass calibrator for 600 seconds every hour during the observation, with the seven mosaic targets observed for 100 seconds each and the complex gain calibrator was observed for 120 seconds. This means that the complex gain calibrator would be observed every ≈ 16 minutes. 17% of observing time was spent slewing between all the calibrators and target. This is not an optimal setup for scientific observations but was chosen to have additional checks on gain and system stability.

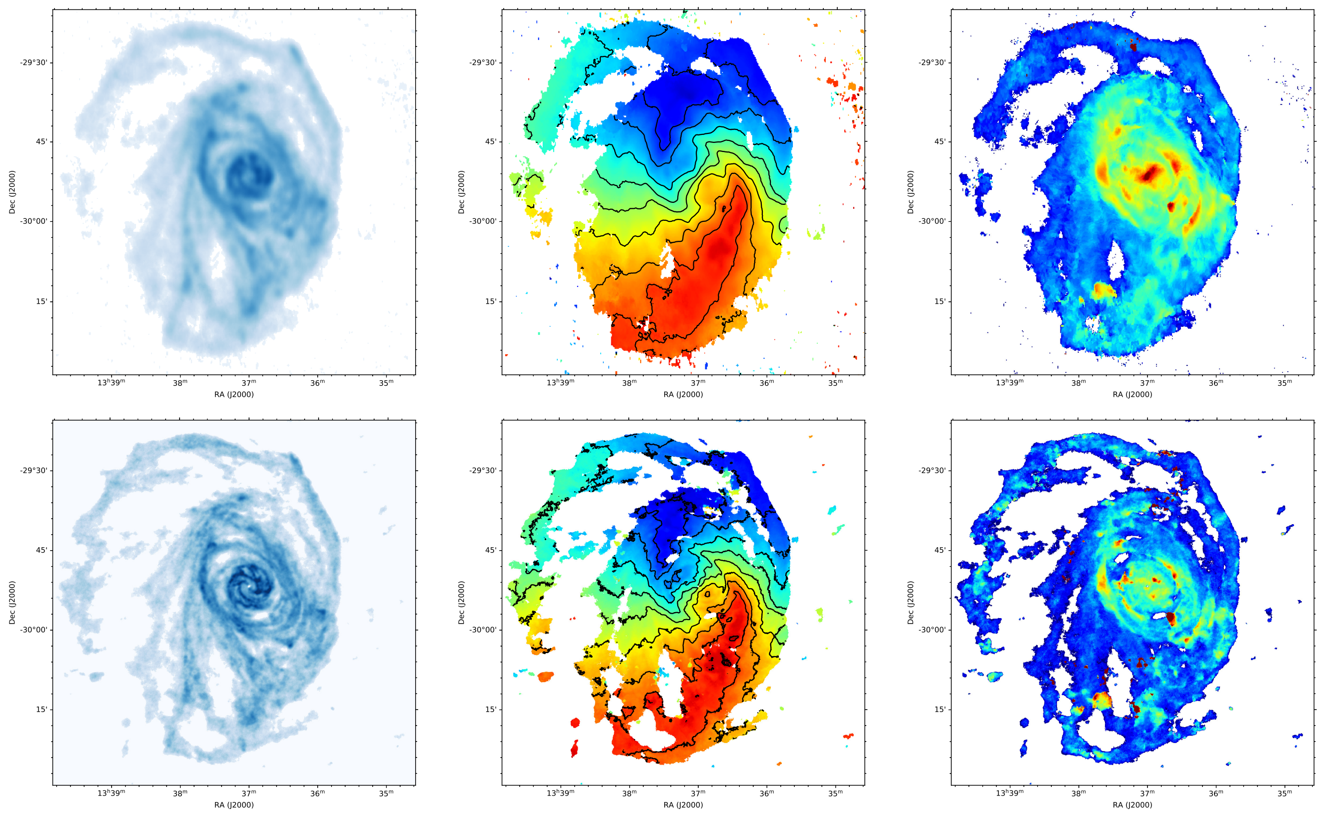

Figure 1: Images of M83 from the Local Volume *HI* Survey (LVHIS) Koribalski (2018) (top) and the MeerKAT observation on the 8th of December 2019 (bottom) with the same colour scales. The graphs left to right are the integrated value of the spectrum, the intensity weighted coordinate, and the intensity weighted dispersion of the coordinate. The contours levels in the middle plot are: 649, 617.5, 586, 554.6, 523.1, 491.7, 460.2, 428.7, 397.3, 365.8 $km.s^{-1}$

2.2 Observation data

The observation was performed in the early morning of the 8th of December 2019 at 01:31 UTC through to 12:30 UTC with the capture block ID of 1575768670 and in schedule block 20191206-0003. This was observed as part of the proposal COM-20191119-SP-01 which was used for 32k Testing with the M83 Field. The observation was performed with the "wide band fine" 32k correlator mode. This correlator mode has 32768 channels over the 856 MHz of bandwidth. This gives a channel width of 26.1 kHz (5 km/s). An accumulation length of 8 (7.997) seconds was used for this observation The observation contains 4944 dumps of 7.997 seconds with 32768 channels and 7320 correlation products resulting in a size of 9487 GB. This is summarised in the Table 1 .

3 Data inspection

3.1 Flagging data

A subset of data from 1378.46 MHz to 1430.70 MHz (channels 20000 to 22000) was exported to measurement set format and the flagging was done as detailed below. There was no data flagged for antenna shadowing. Galactic HI was flagged from the flux calibrator PKS1934-638 in channels 1420.10 to 1420.41

Table 1: Observation and Correlator values used in this report.

Parameter	Value
Correlator mode	32k wideband c856M32k
Correlator version	s_c856m32k_2019-11-29_1623.fpg
Experiment ID	20191206-0003
Observation Started	2019-12-08 01:31:18 UTC
Observation ended	2019-12-08 12:30:14 UTC
Dump period	7.997s
Total Dumps in observation	4944
Number of channels	32768
Number of correlation products	7320
Number of Antennas	60
Size of Observation	9487.012 GB
Channel Width	26123 Hz
Centre Frequency	1284 MHz
Bandwidth	856 MHz

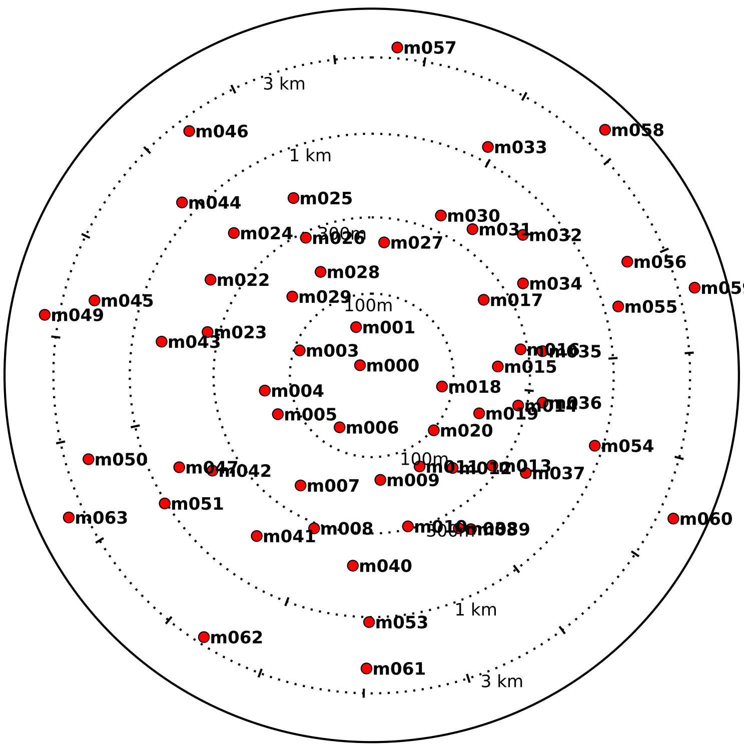

Figure 2: A log radial plot of 60 antennas that were used in the observation. The MeerKAT antenna distribution consists of two co-centric Gaussian distributions one that has a spread to $1Km$ and other out to $4Km$.

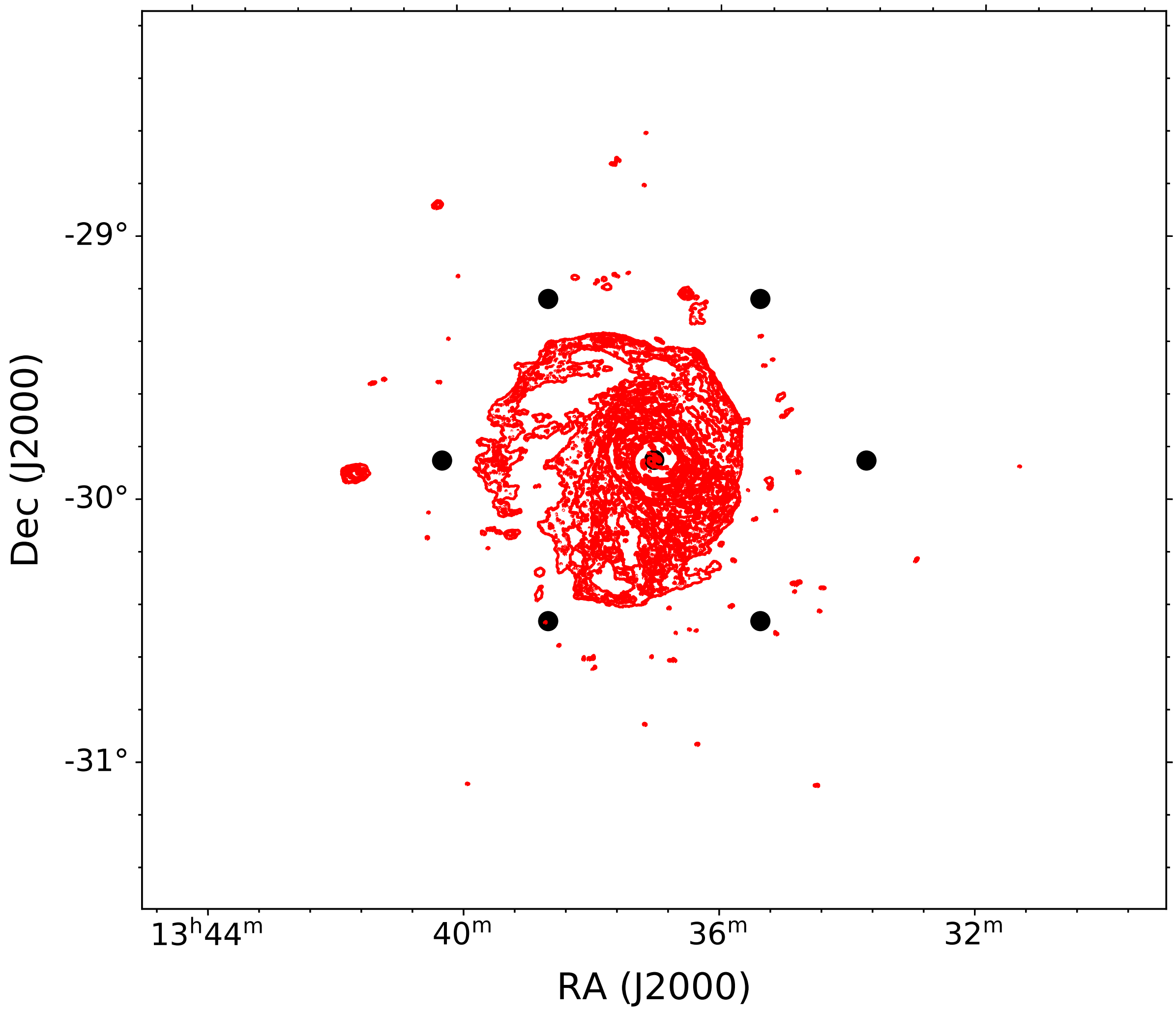

Figure 3: The HI contours (red) and pointing centre of each of the fields in the mosaic have been overlaid in grey. Each pointing was separated by $1/\sqrt{2}$ degrees to ensure uniform response of the telescope over the imaged area (assuming the telescope has a 1 degree FWHM beam).

Table 2: The theoretical noise per channel, calculated per field based on the number of un-flagged visibilities. The mean system temperature across the frequency range w$T_{sys}/\eta = 19.73$K.

Source	Time on source (minutes)	Theoretical RMS $T_{sys} = 19.73$K
J0408-6545	19.7	0.8294 mJy
PKS1313-333	67.0	0.4499 mJy
J1311-2216	32.5	0.646 mJy
J1939-6342	29.9	0.678 mJy
$M83_0$	55.0	0.5006 mJy
$M83_1$	54.8	0.5018 mJy
$M83_2$	54.1	0.5051 mJy
$M83_3$	53.4	0.5082 mJy
$M83_4$	53.6	0.5076 mJy
$M83_5$	53.8	0.5063 mJy
$M83_6$	53.6	0.5076 mJy
J1331+3030	19.9	0.8266 mJy

MHz and from PKS1313-333 in the range 1420.46 to 1420.597 MHz . Antenna M003 was flagged due to a pointing problem which can be seen in the calibration report.

3.2 Theoretical sensitivity

After removing slews and and flagging detailed in sections above we calculate the accumulated time on target detailed in the Table 2 and using the system temperature $T_{sys}/\eta = 19.73$K we can calculate the theoretical sensitivity.

4 Reducing the data

The reduction process and tasks were performed using the CASA python system. The parameters for the observation and reduction were chosen to ensure that any array or antenna problems would not be unintentionally calibrated out or obscured.

PKS1934-638 was used as the flux, bandpass and delay calibrator in this observation. Delay calibration was done on each of the scans on PKS1934-638 and the delays were found to only have a scatter of ± 0.3 nanoseconds; following this all the combined scans from PKS1934-638 were used to generate a single delay calibration for the observation.

An initial complex gain calibration was done on PKS1934-638 and was used to produce a bandpass and flux calibration from all the combined PKS1934-638 scans.

The complex gain table was then discarded and recalculated using PKS1313-333 together with the delay and bandpass calibration. The flux scaling for the complex gain was calculated and applied to the seven mosaic fields and the seven fields were then split out. Continuum emission was fitted over 1411.11 MHz to 1415.55 MHz and 1419.74 MHz to 1425.48 MHz with a 3^{rd} order polynomial and then subtracted from the uv data.

To calculate the cleaning threshold a dirty image was generated with an image size 4096 by 4096 pixels with a robust weighting of 1 and a cell size of 3 arc seconds of an emission free channel at 1416.08 MHz. 128

w-projection planes were used. The observation used the 60 antennas and the resulting beam size 22.14 by 20.34 arc seconds. The rms noise found for the dirty image in a non-emission channel was 0.5469 mJy.

The noise for a single outlining field, $M83_6$, the naturally weighted noise was 0.5797 mJy. This is about 14% higher than the theoretical rms noise that is expected for $T_{sys}/\eta = 19.3$K or about 3% higher that the older measured value for the array of $T_{sys}/\eta = 22$K. A total theoretical noise of 0.508 mJy was assumed for the mosaic image.

The final image, a mosaic of the 7 fields centred on $M83_4$, was then deconvolved down to a threshold of 3 times the rms of the dirty image. 160 channels were imaged from 1415.55 to 1419.73 MHz which covered the HI emission of M83. CASA's task tclean was used with a Briggs weighting of 1 and a MeerKAT primary beam model of a projected cosine, listed in Section 8, to do a joint deconvolution of the seven fields of the mosaic and correction for the primary beams sensitivity. The produced a cube of 160 channels and a resolution of 24.9 by 23.6 arc seconds with 4096 by 4096 pixels.

This was then passed through the source finding application SoFiA, to extract the neutral Hydrogen and produce the smaller cubes with only the HI emission for each of the detected sources and other diagnostic plots.

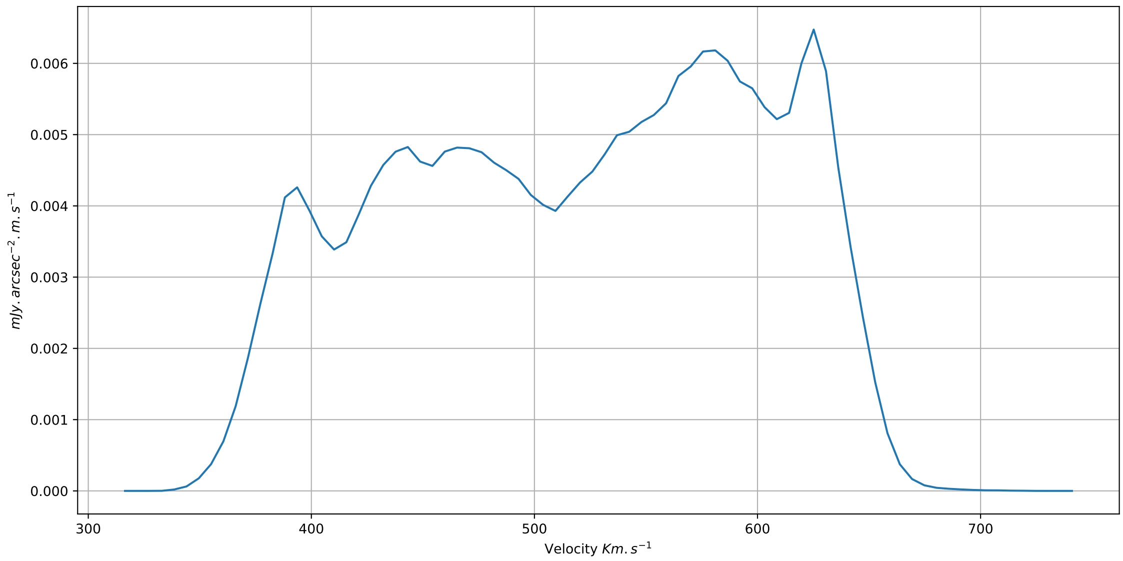

Figure 4: The spectrum of M83 sub-cube generated from the source extraction. The LSRK velocity compares well with other wavelengths and data.

5 Reduction Software and Noise Levels

Previous work on the 32K wide-band correlator for the 16 Antenna ROACH system in 2017 found that the noise level in emission free channels was 30-40% higher that was to be expected from theoretical calculations. After an investigation, it was found that this problem only affected the 32K system while the 4K wide-band correlator did not show this noise increase. I was decided to recheck this problem again when the new SKARAB correlator architecture was commissioned. This was done in 2019 and it was found that this

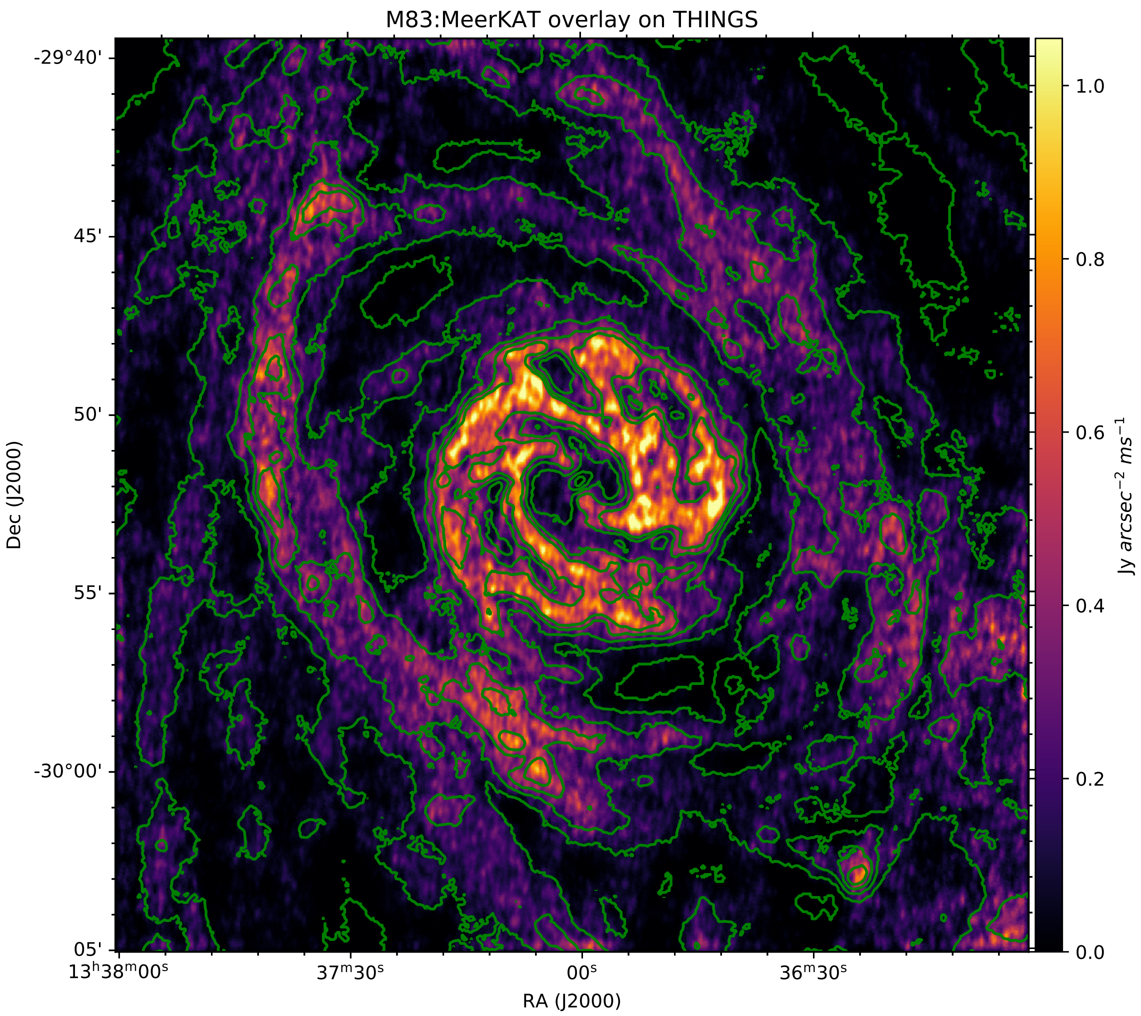

Figure 5: An overlay of the MeerKAT data (contours with levels) and the THINGS observation, The contours are the reduced MeerKAT data with contour levels of [0. 0.25 0.5 0.75 1.] Jy/arcsec$^2 m.s^{-1}$ and has a beam size of 24.88 by 23.56 arc-seconds. The colour map represents THINGS data for this source.

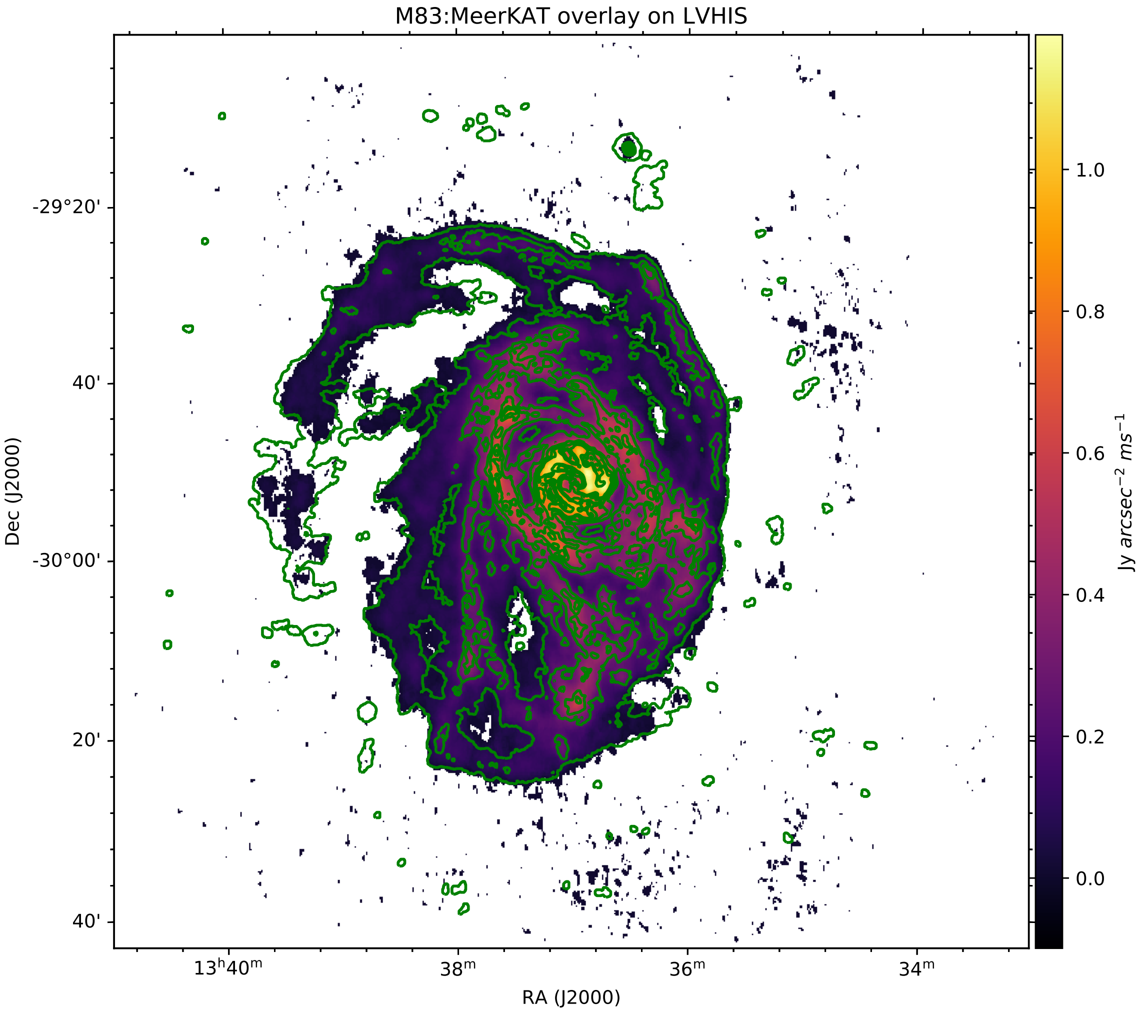

Figure 6: An overlay of the MeerKAT data contours with levels) and the LIVIS 9-point mosaic of M83, done with ATCA,(beam = 85.8" x 60.8", natural weighting), observed 1998/9 Koribalski et al. (2018).The contours are the reduced MeerKAT data with contour levels of [0. 0.25 0.5 0.75 1.] Jy/arcsec$^2 m.s^{-1}$ and has a beam size of 24.88 by 23.56 arc-seconds.

problem had gone away. Investigations into this are detailed in the document Investigating the 30-40% noise increase reported in ROACH2 32k imaging data with included SKARAB 32k imaging data.

During this analysis it was found that the version of reduction software had a large impact on the resulting image noise statistics. It was found that CASA version 4.6 produced images that had $\approx 40\%$ higher noise levels than the CASA versions ≈5.1 and above. The original 2017 tests were done using CASA version 4.6. CASA versions 5.6.2, 5.1.2 and 4.6 were tested.

It has also been found that there were imaging artefacts at the centre of each pointing in the mosaic when using *CLEAN* in CASA versions 5.1 and 5.6.2. However *CLEAN* in these version has been deprecated. The replacement task *TCLEAN* does not have these artefacts.

6 Future plans

In the future we plan to redo this analysis using the spectral imaging pipeline products.

7 List of references

Barnes et al. 2001, Monthly Notices of the Royal Astronomy Society, 322, 486-498
Heald et al. 2016, Monthly Notices of the Royal Astronomy Society, 462, 1238-1255
Koribalski 2018, Monthly Notices of the Royal Astronomy Society, 478, 1611 Park et al. 2001, Astronomical Society of the Pacific Conference Series, 230, 109-110
Walter et al. 2008, The Astrophysical Journal, 136,2563-2647

8 Supplementary Code

The beam model described below is accurate to about $\approx 5\%$ across the array and over the L-band bandwidth. There is the chance that CASA would replace the primary beam model with an incorrect model.

```
def beam(offsetx, offsety, freq):
    """freq in MHz
    offsetx, offsety in degrees"""
    FWHM = np.sqrt(89.5*86.2)/60.*(1e3/freq)
    theta = np.sqrt(offsetx**2+offsety**2)
    a = (np.cos(1.189*np.pi*(theta/FWHM))/(1-4*(1.189*(theta/FWHM))**2))**2
    return a

MEERKAT_PB = vp.setpbnumeric(
    telescope='OTHER',
    othertelescope='MeerKAT',
    dopb=True,
    vect=beam(np.linspace(0,3.0,1000),0,1400.0),
    maxrad='3.0deg',
    reffreq='1.4GHz',
    isthispb='PB',
    dosquint=False)

vp.saveastable('MEERKAT_PB.tab')
```

M83_mosaic_in_wideband_fine

Final Audit Report 2020-06-25

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