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Title: Radio galaxies at low frequencies: high spatial and spectral resolution studies with LOFAR
Issue Date: 2016-09-13

APPENDIX A

Demixing LOFAR Long Baselines

A.1 Introduction

At low radio frequencies there are a few sources that dominate the sky. They are called the ‘A-team’ sources and include Cygnus A and Casseopeia A (and to a lesser extent Taurus A and Virgo A). The A-team sources have flux densities of thousands to tens of thousands of Janskys. Even when these bright sources are off-axis, they can still contribute significantly to the visibilities in an observation and their effects must be removed before the data can be used. This is done using a process called ‘demixing’ that relies on models of the A-team sources to predict their contribution to the visibilities (van der Tol et al., 2007). The demixing process is therefore only as good as the models of the A-team sources, which can be large (up to arcminutes) and have complex morphologies with flux on small scales (arcsec or less).

Ideally the A-team models would include components as compact as the highest resolution achievable with LOFAR, containing the correct fluxes for the LOFAR frequency range. The current A-team models are limited to either high-resolution models made at higher frequencies, or low-resolution models made at the appropriate frequencies. When demixing an LBA data set, I noticed that there was still some contribution from a nearby A-team source on the longest baselines, corresponding to the highest resolutions.

This appendix first describes the data reduction and inspection that led to uncovering this issue. Following that I show simulations which demonstrate that high-resolution models of A-team sources are necessary to properly demix baselines of all lengths.

A.2 Data Reduction and Inspection

The dataset consisted of a 6 hour simultaneous beam LBA observation taken on 15 June, 2013. The target was 3C 368 and the calibrator was Cygnus A. The continuous frequency coverage was 30 – 78 MHz for both target and calibrator. The data was pre-processed by the Radio Observatory (RO), including RFI flagging with the AOFlagger (Offringa, 2010) but not including demixing. I used the RO provided script to fix the beam information[1] and demixed Casseopeia A from the calibrator data set, and both Casseopeia A and Cygnus A from the target data set. The calibrator data were averaged to 1 channel per subband and 2 sec integration time and diagonal gain solutions were found using a model of Cygnus A made from HBA data (John McKean, private communication). The gain solutions were transferred to the target field, and the data were phase-only calibrated against the GSM.PY skymodel (described in the LOFAR Cookbook[2] for the Dutch array. These data were averaged to 1 channel per subband and 2 sec integration time.

Fig. A.1 shows the A-team elevation plotted for one hour of the observation, with the pointing also marked. For this observation, we had determined that Cas A and Cygnus A needed to be demixed. We used the standard ATEAM_LBA.SKYMODEL to demix.

Both the gains from the calibrator and the phase-only gains from the target were transferred to a separate target data set containing information from the international baselines. This data set had higher frequency resolution by a factor of 16. The international station visibility amplitudes were scaled by a factor of 120, thought to be appropriate from the SEFD. All core stations were combined into station TS001 using the Station Adder in the *new default pre-processing pipeline* (NDPPP), then core and remote stations were removed. Ten subbands (1.95 MHz) around the peak sensitivity of LOFAR (about 60 MHz) were converted to circular polarization using SIMPLE2CIRC.PY and combined into one measurement set, which was converted to uvfits format using MS2UVFITS. The data were then read into AIPS and indexed.

I used the AIPS task IBLED to perform baseline-based flagging to remove any lingering bad data in order to help the fringe fitting. I noticed that all baselines involving the superterp and either a DE or UK station clearly had beating and/or strongly time-varying amplitudes, see Fig. A.2. The maximum amplitudes reached are about 100 Jy.

[1] https://www.astron.nl/radio-observatory/observing-capabilities/depth-technical-information/system-notes/wrong-information-

[2] https://www.astron.nl/radio-observatory/lofar/lofar-imaging-cookbook

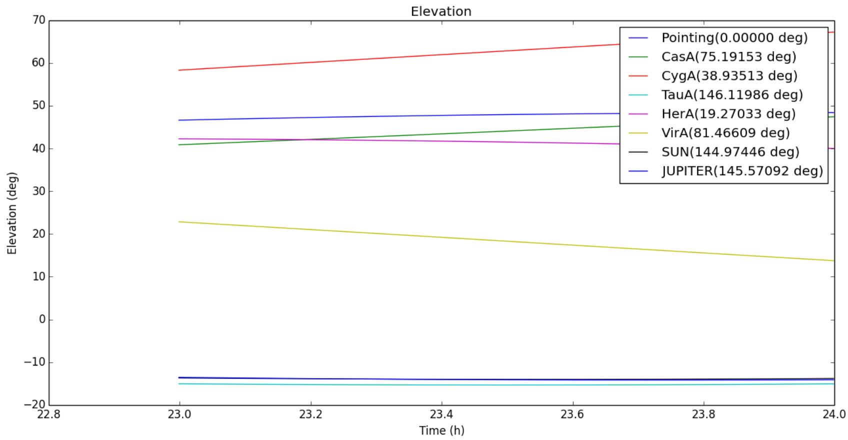

Figure A.1: A-team elevation plotted for the 1hr of observation that was simulated.

An inspection of the amplitude versus uv-distance showed that the first minimum occurs at a scale that corresponds to about 130 arcsec, which is roughly the size of Cygnus A. The beating is not evident on the international-to-international baselines, only on international-to-superterp baselines. In the case of the shortest international-to-international baseline, DE601-DE605, the baseline is only 52 km, and the models have sufficient resolution to demix this baseline. In the case of the other international-to-international baselines, there is either insufficient resolution in the the model, or not enough sensitivity, or a combination of both. I constructed a simulation to investigate this.

A.3 Demixing Simulation Input Models

In order to test whether the resolution of the skymodel used to demix can cause the beating we see on the international baselines, I constructed a simulation with a higher resolution A-team source. I split out an hour of the observation from one subband (corresponding to what is plotted in Fig. A.1). This provided a measurement set with the same date, times, and pointing phase center as the observation. I simulated a single point source at the phase center with a flux of 48 Jy, similar to 3C 368. I then constructed a model of a Cygnus A-like A-team source, i.e., two lobes, each with a compact hotspot. Using the coordinates of the hot spots of Cygnus A, I simulated two lobes, each with one point source and

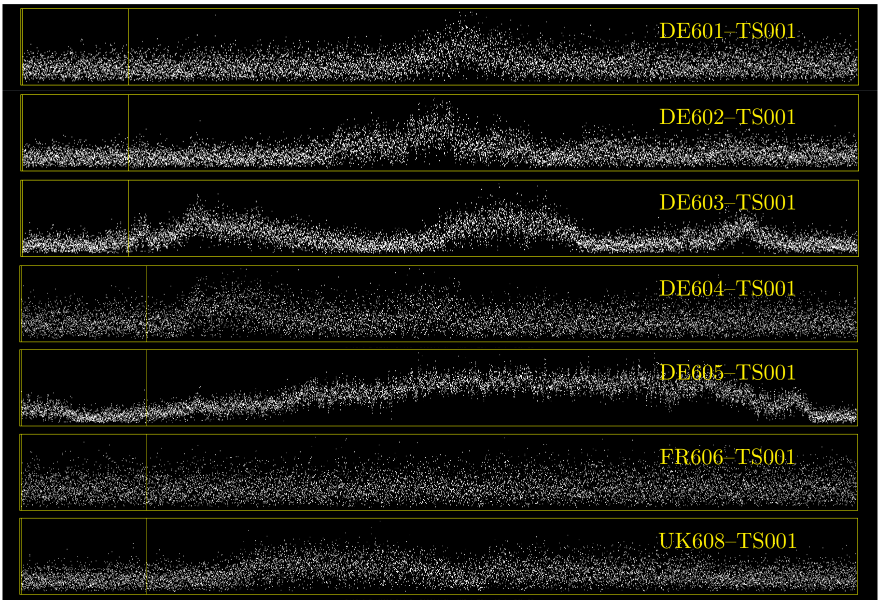

Figure A.2: Amplitude versus time for the entire six hour observation.

one Gaussian. A depiction is given in Fig. A.3 and the associated information is in Table A.1.

The simulations were performed with both beam and gain enabled. I then performed two separate demixing trials:

- **Trial 1:** Demixing the high-resolution model of the A-team source that I originally predicted.
- **Trial 2:** Demixing a low-resolution model that consists of the Gaussian components of the lobes only, but with total flux of Gaussian+point source

Table A.1: Model parameters

	Comp.	Major axis	Minor axis	flux
Lobe A	Gauss.	20″	20″	2,000 Jy
Lobe A	Point	–	–	8,000 Jy
Lobe B	Gauss.	10″	10″	1,000 Jy
Lobe B	Point	–	–	7,000 Jy

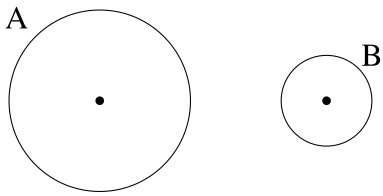

Figure A.3: Model of Cygnus A-like A-team source. The filled black circles are each one point in the model, and the open circles represent Gaussians. The model parameters are listed in Table 1.

(per lobe).

The two trials have the same total amount of flux, but allow for a comparison of the results of demixing with high- and low- resolution models.

A.4 Results

Fig. A.4 shows the results for a selection of core-to-international baselines. It is clear that the low-resolution model does not demix the flux of the A-team source, while the high-resolution model does. Demixing with the high-resolution model does leave some residuals, for example as seen on Baseline CS001LBA-DE602LBA just before time=500. I suspect that these residuals are a result of imperfect beam models.

A.5 Conclusions

The simulations show clearly that a low-resolution model cannot be used to demix baselines for which the resolution is better than the model. There are some residuals left over even after demixing the high-resolution model, which could be caused by imperfect beam models.

To enable proper demixing of long baselines for LOFAR, high-resolution models of the A-team sources will be necessary. Observations of the A-team sources with all LOFAR stations with both high band antenna (HBA) and LBA frequency ranges is the only way currently available to provide models with appropriate resolution for demixing all LOFAR baselines.

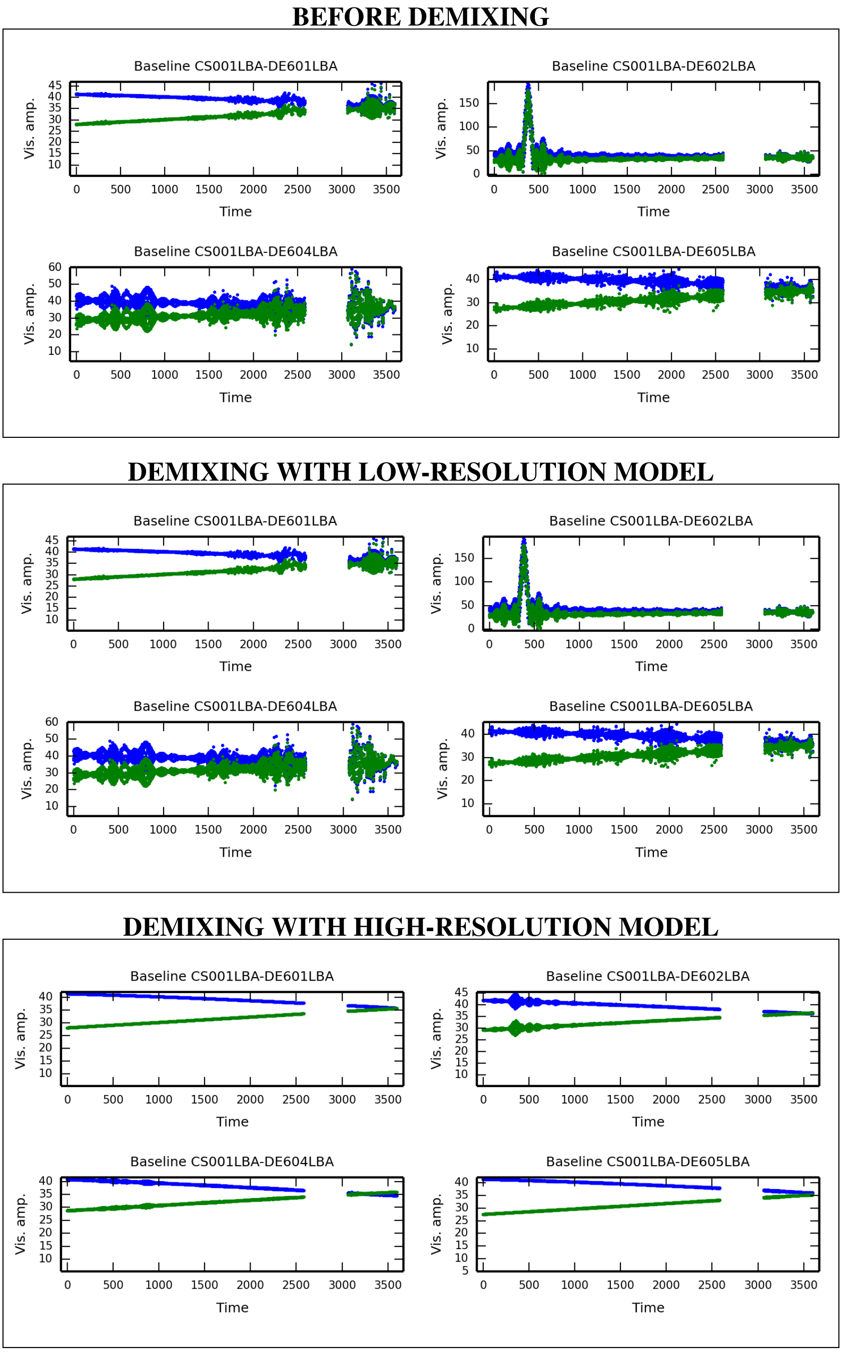

Figure A.4: Visibility amplitude versus time for a selection of baselines from the simulations.

APPENDIX B

The LOFAR Station Adder

B.1 Introduction

The 'StationAdder' step in the *new default pre-processing pipeline* (NDPPP) combines stations together by adding together visibilities from all baselines to a particular station. This is primarily used to increase the signal to noise ratio for baselines containing international stations by combining all of the core stations into a single 'Super' station. However, the long baseline working group has found that the StationAdder has provided images and/or calibration solutions that are noisier than expected. I have determined that this is at least partly due to the fact that while the documentation for NDPPP advertises that the weighted sum of visibilities is calculated for the output combined visibility, only the sum of visibilities is actually calculated.

This appendix outlines the steps taken to determine the problem, and shows the improvement when using the weighted sum of visibilities rather than the sum. A further improvement of ~ 1 per cent in image noise was found when using the weighted sum of the u, v, w coordinates.

B.2 Diagnosing the Problem

A single subband of a 15 minute LBA observation of 3C 147 that includes all international stations was used for this test. The data were first calibrated using the Black-Board Selfcal software (BBS; Pandey et al., 2009). Images were made before and after using the StationAdder to combine all core stations, and Fig. B.1 shows the difference in image quality. For the imaging, all of the shortest (core – core) baselines were flagged, and a uv-maximum of $15\,\mathrm{k}\lambda$ was used (i.e., no international stations). Only 10 iterations were used to make all images.

The image made with the uncombined stations has a noise level of $1.15\,\mathrm{Jy\,bm^{-1}}$. The image made with the StationAdder 'Super' station has a noise level of $1.58\,\mathrm{Jy\,bm^{-1}}$, almost 30% higher than before the stations were combined.

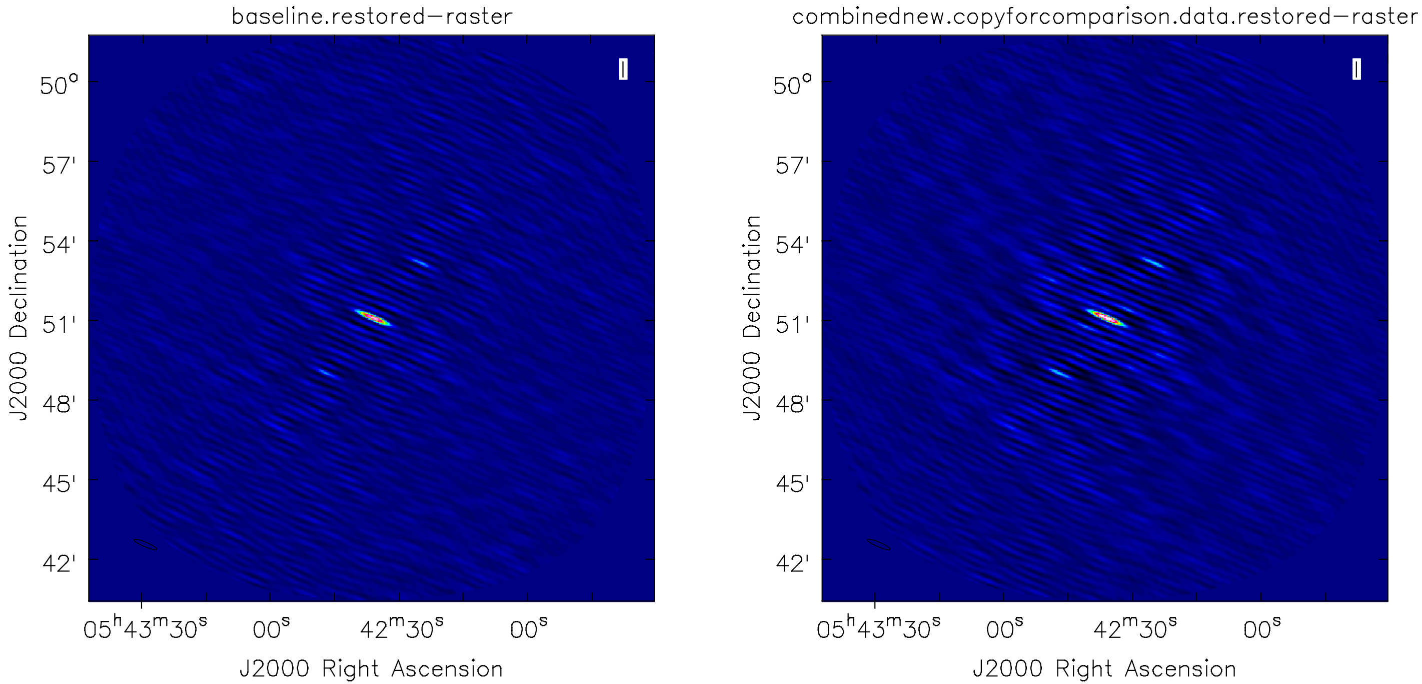

Figure B.1: *Left:* Image of 3C 147 with uncombined core stations. *Right:* Image of 3C 147 with all core stations combined using the NDPPP StationAdder step, and all core stations flagged afterwards. The color scale is the same for both images.

Comparison of individual visibilities using PLOTMS from the Common Astronomy Software Applications (CASA; McMullin et al., 2007) software package led me to believe that the new, combined visibility was merely the sum of the combined visibilities, rather than the weighted sum. To demonstrate this, I wrote a script[1] to read a measurement set containing both the uncombined and combined stations to find their corresponding visibility data. From the uncombined visibility data, both the sum and the weighted sum of the visibilities to be combined were calculated, and compared with the actual combined visibility values. The combined visibility weights are the straightforward sum of the weights of the uncombined visibilities, as expected. However, there is zero difference between the combined visibility value and the unweighted sum of the visibilities that were combined to create the new combined visibility. The difference between the calculated weighted sum of the visibilities to be combined and the combined visibility as calculated by the StationAdder is shown in an Argand diagram in Fig. B.2.

B.3 Fixing the Problem

To fix this problem, I wrote scripts[2] to calculate the correct weighted sum of visibilities, and additionally the weighted geometric center of the u, v, w coordinates of the visibilities being combined. This is different from the default method used by NDPPP to calculate the u, v, w coordinates. NDPPP first calculates the geographical position of the 'Super' station based on the longitude and latitude of the combined stations, and then re-calculates the u, v, w coordinates based on the station positions.

Figure B.3 shows a comparison of the uncombined, StationAdder combined, StationAdder combined + weighted sum corrected, and StationAdder combined + weighted sum corrected + weighted u, v, w coordinates calculated. The same imaging parameters were used for all images, and they are all set to the same color scale. For images using the combined 'Super' station, the core stations were flagged prior to imaging.

The difference in images can be seen by eye in Figure B.3, but the noise provides a quantitative measurement. Table B.1 lists the noise for each image, as calculated by the CASA task IMFIT.

While the final image with the correct weighted sum combined visibilities and weighted center of mass u, v, w coordinates only improves the noise by

[1] *show_weightedsum.py*, available upon request.

[2] *fix_weightedsum.py* and *fix_weightedsum_uvw.py*, available upon request.

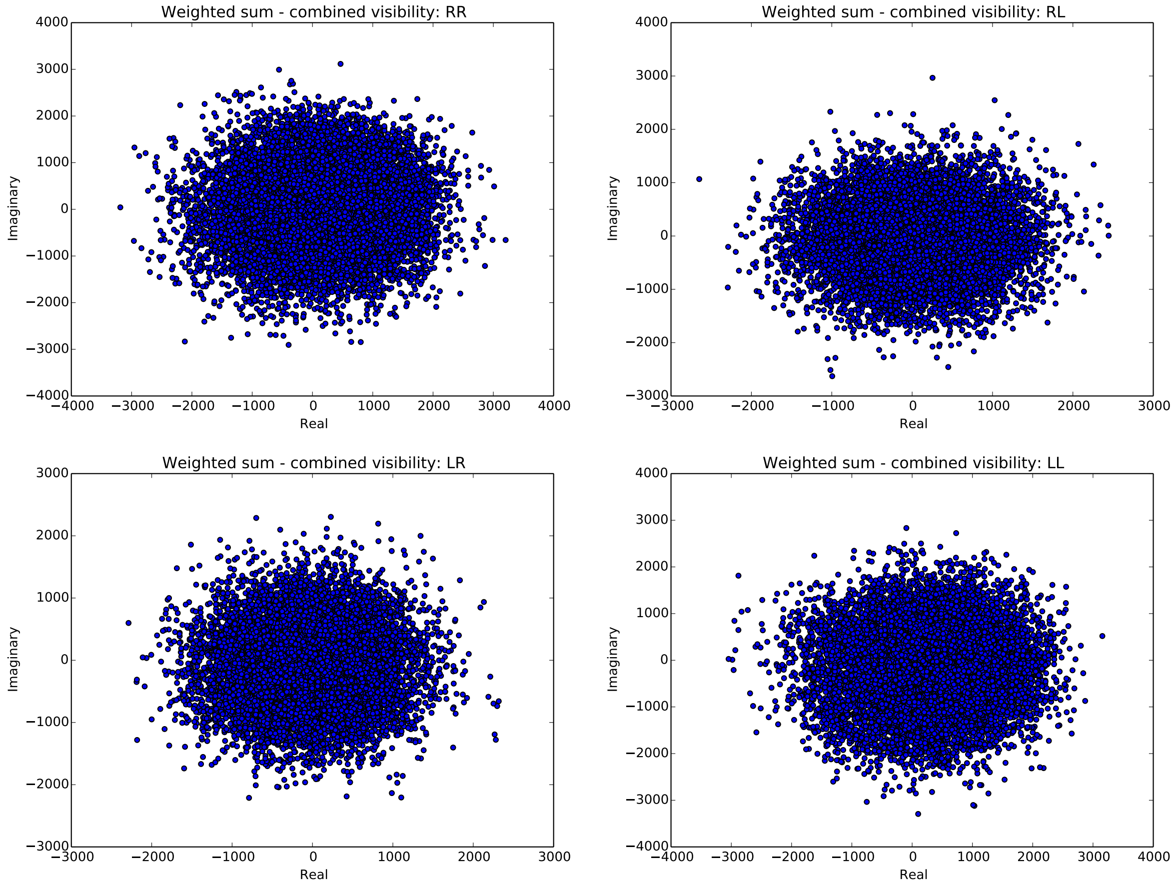

Figure B.2: The value of the weighted sum minus the value of the NDPPP StationAdder computed visibility, for the four different correlation products.

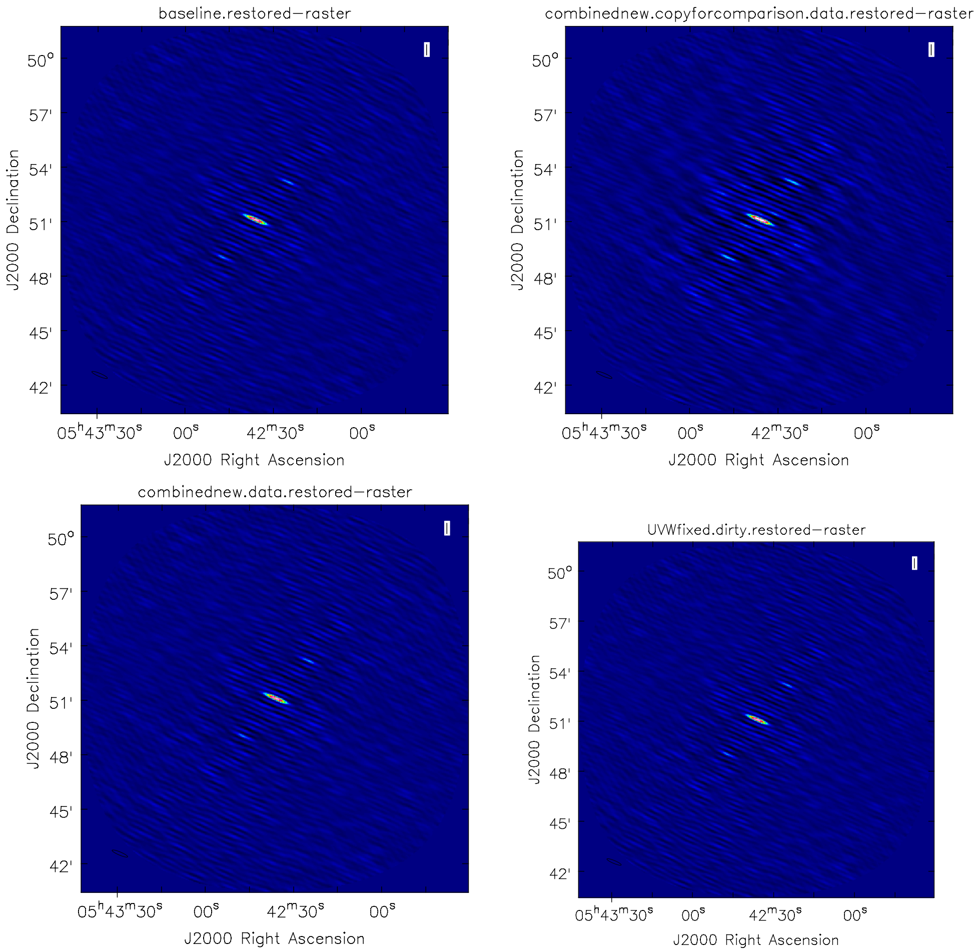

Figure B.3: *Top Left:* Uncombined core stations. *Top Right:* StationAdder combined 'Super' station. *Bottom Left:* StationAdder combined 'Super' station with the corrected weighted sum of visibilities. *Bottom Right:* Same as bottom left, but also with the corrected weighted center of mass of the u, v, w coordinates.

Table B.1: IMFIT calculated noise, $\mathrm{Jy\,bm^{-1}}$

Image	Image noise	Residual image noise
Uncombined	1.37797	1.14927
StationAdder	1.82356	1.57675
Weighted sum	1.37666	1.14932
Weighted sum, weighted uvw	1.36766	1.14101

$\sim 1\%$ when compared to the uncombined image, there is an almost 30% improvement over the image made using the NDPPP StationAdder step.

B.4 Conclusions

This appendix detailed a discrepancy in the NDPPP software and documentation: namely, that when combining stations using the StationAdder step, the weighted sum of the visibilities should be used, but NDPPP instead calculates the unweighted sum. This results in an increase in image noise of about 30%. A script was provided to fix this issue in measurement sets where the uncombined station visibilities still exist. Additionally, it was noticed that the new u, v, w coordinates of the new StationAdder combined visibilities were the unweighted geometric center of mass of the combining visibilities. A script was provided to fix this in addition to the visibility values themselves, and provides another $\sim 1\%$ improvement in image noise. The fixes have since been implemented in NDPPP (Software release 2.12.0).

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