Contents

List of Figures

List of Tables

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.

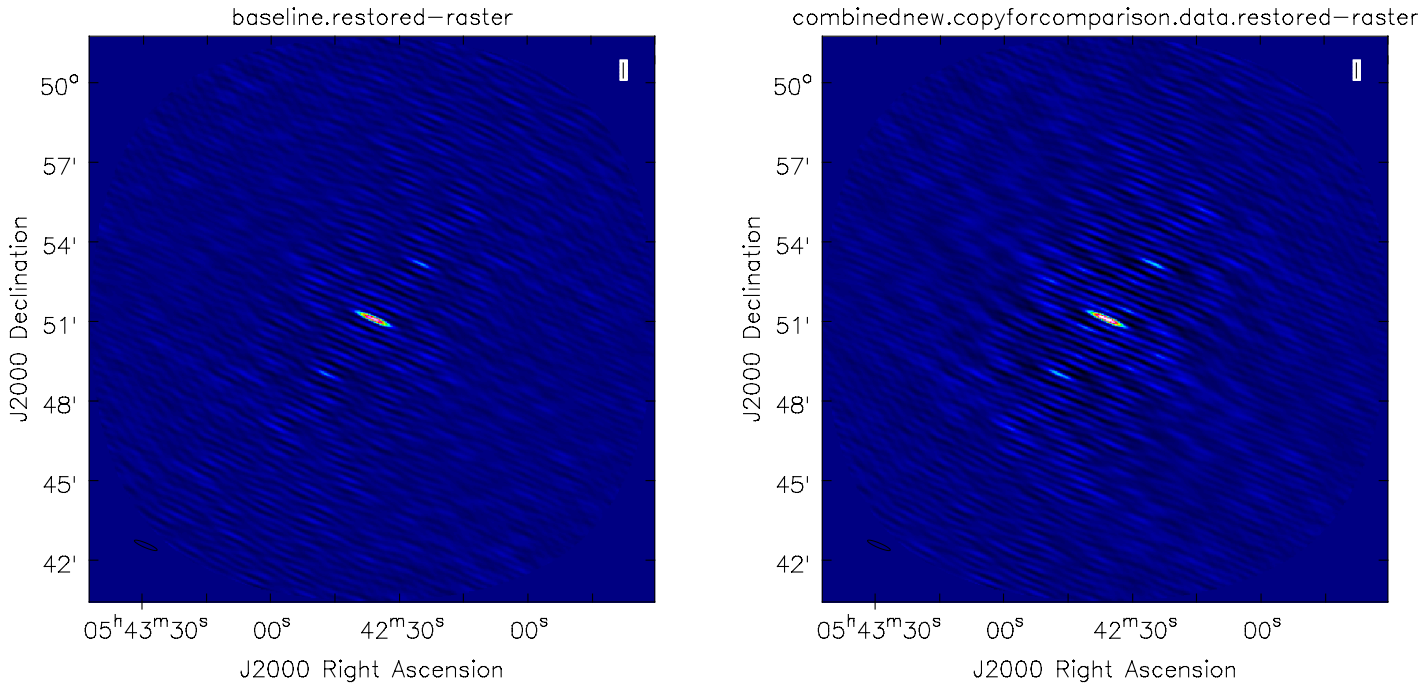

Figure B.1: *Left:* Image of 3C 147 with uncombined core stations. *Right:* Image of 3C 147 with all core stations combined using the NDPPP StationAdder step, and all core stations flagged afterwards. The color scale is the same for both images.

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.

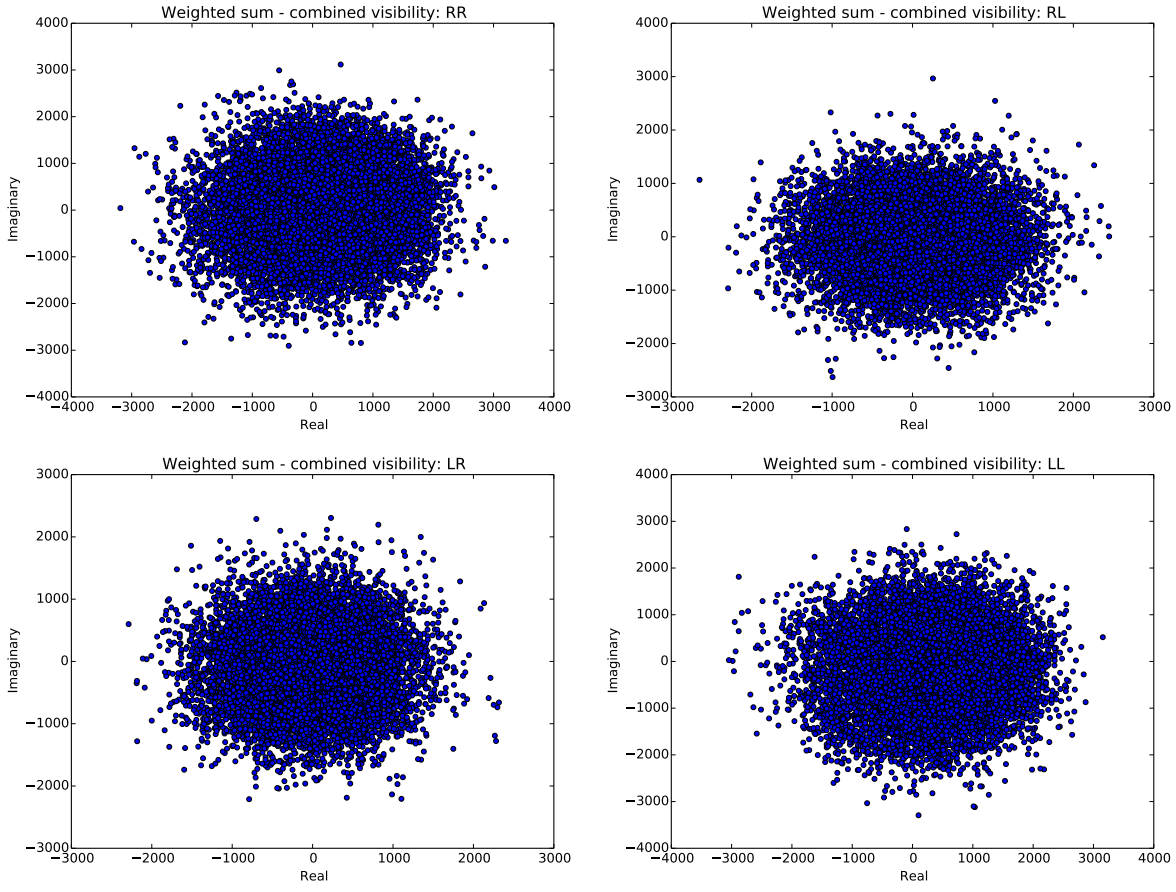

Figure B.2: The value of the weighted sum minus the value of the NDPPP StationAdder computed visibility, for the four different correlation products.

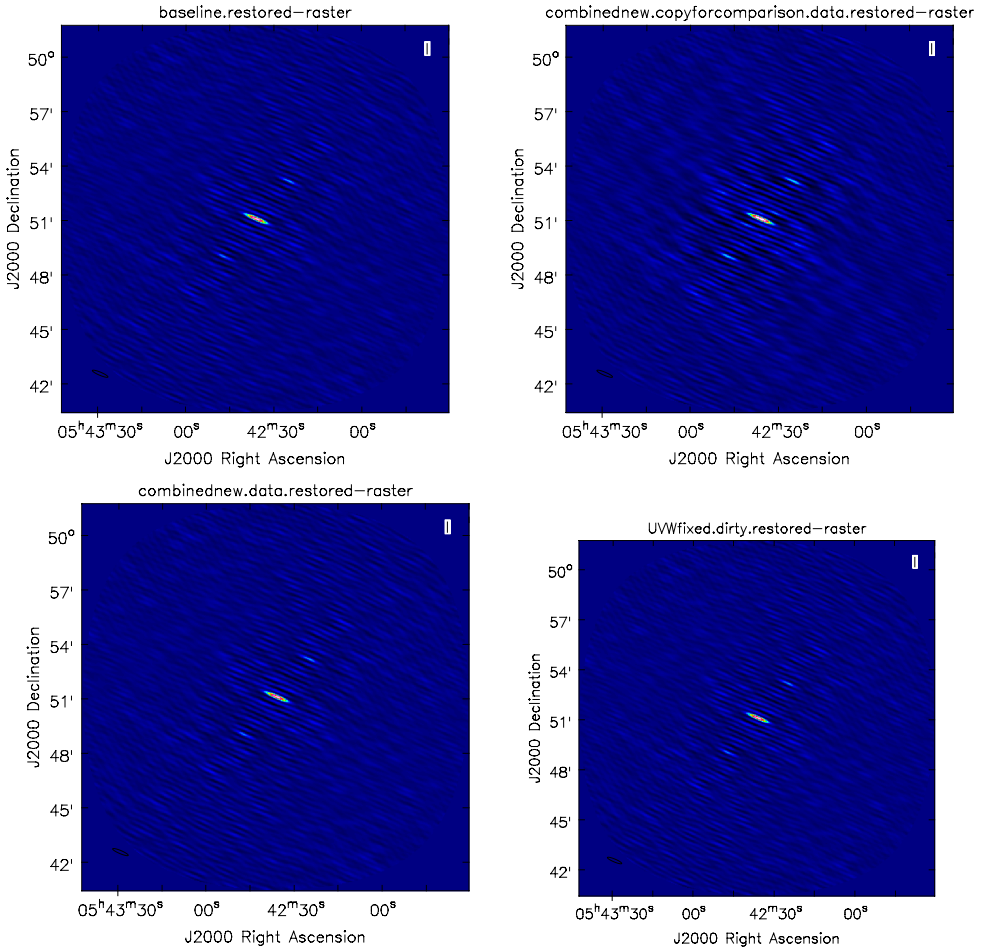

Figure B.3: *Top Left:* Uncombined core stations. *Top Right:* StationAdder combined 'Super' station. *Bottom Left:* StationAdder combined 'Super' station with the corrected weighted sum of visibilities. *Bottom Right:* Same as bottom left, but also with the corrected weighted center of mass of the u,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

Bibliography

McMullin J. P., Waters B., Schiebel D., Young W., Golap K., 2007, in Shaw R. A., Hill F., Bell D. J., eds, Astronomical Society of the Pacific Conference Series Vol. 376, Astronomical Data Analysis Software and Systems XVI. p. 127

Pandey V. N., van Zwieten J. E., de Bruyn A. G., Nijboer R., 2009, in Saikia D. J., Green D. A., Gupta Y., Venturi T., eds, Astronomical Society of the Pacific Conference Series Vol. 407, The Low-Frequency Radio Universe. p. 384