LBWG memo 7

Use of EHT Imager to generate models for self-calibration

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Motivation. We need to generate a believable model, preferably from the data, in order to start self-calibration. An imager using closure phases and amplitudes exists (`http://adsabs.harvard.edu/abs/2018ApJ...857...23C`) and provides a promising means to

Installation of software. There are three relevant repositories, which can be installed by the user in a non-system wide location if need be. Here are specific instructions:

```
# install nfft
cd /home/lmorabit/software
git clone https://github.com/NFFT/nfft nfft_src
cd nfft_src
./bootstrap.sh
./configure --enable-all --enable-openmp --prefix=/home/lmorabit/software/nfft
make
make install

# install pyNFFT
cd /home/lmorabit/software
git clone https://github.com/ghisvail/pyNFFT/
cd pyNFFT
python setup.py build_ext --inplace -I /home/lmorabit/software/nfft/include \
    -L /home/lmorabit/software/nfft/lib -R /home/lmorabit/software/nfft/lib
python setup.py install --user

# install eht-imaging
cd /home/lmorabit/software
git clone https://github.com/achael/eht-imaging
cd eht-imaging
pip install . --user
```

If you have installed the EHT imager with `conda` and have issues with library versions of `ZLIB`, you may need to update your `LD_LIBRARY_PATH` to point to the anaconda version, within the appropriate library directory of anaconda:

```
setenv LD_LIBRARY_PATH /path/to/anaconda2/pkgs/zlib-1.2.11-ha838bed_2/lib:
                            {$LD_LIBRARY_PATH}
```

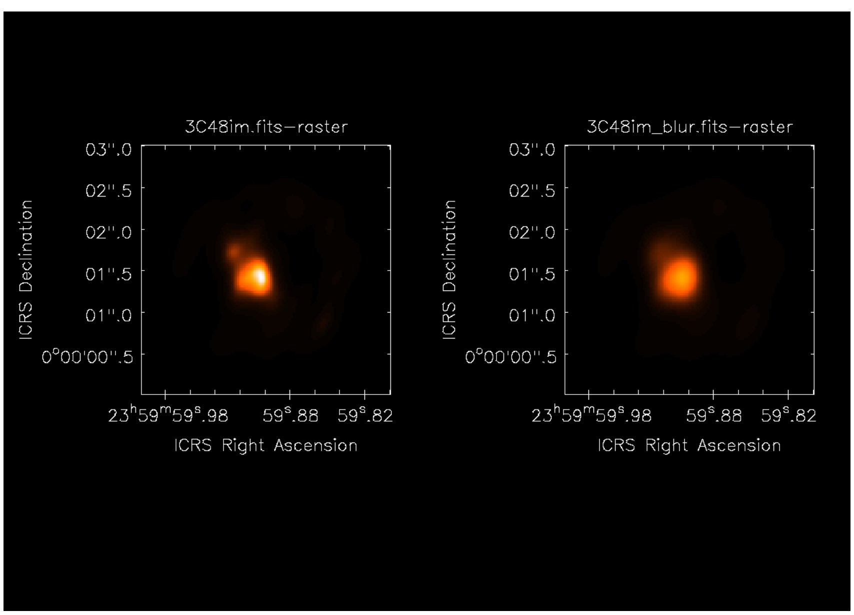
If you are using a MS that has been written out by AIPS and converted to fits (or written as fits by AIPS), the imager will fall over because the telescope names are written in a column called `STATION` instead of `NAME`. You can solve this problem in CASA as follows:

```
tb.open ('my.MS/ANTENNA',nomodify=False)
a = tb.getcol('STATION')
tb.putcol('NAME',a)
tb.close()
```

Testing the EHT imager. I have tested the EHT imager on several types of datasets, with varying levels of success. There is a script on the github[1] which can be used to prepare LOFAR data and start making a model with sensible input parameters. This involves:

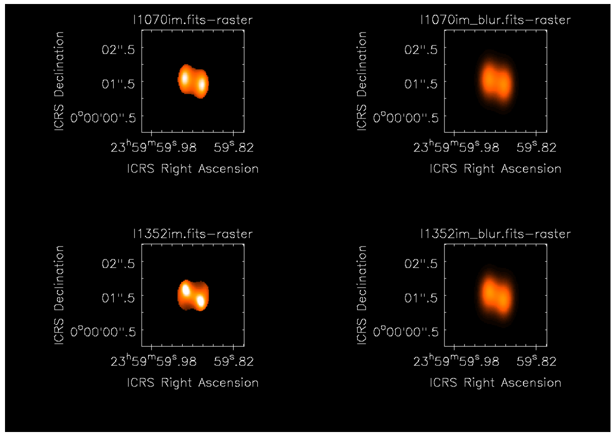
- Using `taql` to make a smaller measurement set with the requested closure antennas (must be at least 4 stations).
- Calculating the 'zero-baseline' flux from the shortest baseline in the data
- Multiplying the weights by a factor so their values are around unity rather than 1e-11
- Converting the measurement set to uvfits and reading this in to the eht imager
- Plots of $u - v$ coverage, amplitude vs. uv-distance
- Fits files of dirty and clean beams, dirty image
- Constructing a Gaussian prior
  - Either from FIRST catalogue if it exists or;
  - A single point source or;
  - User input parameters (not fully functional yet)
- Using the `imager_func` to fit closure phase and amplitude
- Saving final image(s) as fits

High SNR case: 3C 48. In the case of a bright calibrator source, this works quite well.



[1] https://github.com/lmorabit/long_baseline_pipeline/tree/master/eht_imager_scripts

Lower SNR cases: 2 in-field calibrators in XMM-LSS. Both of these sources are about 1-2 Jy.



These sources were a bit more tricky, and I found that flux could quite easily be pushed into the sidelobes, giving horrible results. One of the biggest things that helped was using the `clipfloor` parameter to avoid this.

Testing on J1327+5504. I still have not successfully made a model of this source – I think this is because I have been working on a dataset where the clocks haven't been corrected for the international stations. The pipeline delay calibration (i.e., diagonal solve + clock/TEC separation in LoSoTo) on J1327+5504 seems to have gone wrong in some way; points with huge values of amplitude have been introduced. I'm now trying to track down the problem with this, which I think is related to the remote stations. The RS should already have been corrected and they have the noisiest solutions. Initial delay calibration tests were done (see Memo 6) using only the combined station and international stations, so I'm trying to repeat that.

A list of things to consider.

- This is VERY sensitive to outliers – it will be important to either give it well-flagged data or use the EHT imager built-in flagging to get rid of outliers
- Do not make the FOV less than twice as big as the FWHM of the prior. If you do this, you can end up pushing flux towards the edges
- the EHT imager team finds a clipfloor of about 1-5 percent of the maximum flux works fairly well
- Not particularly sensitive to the initial number of pixels – can get away with something like 64 and then increase to 128 on subsequent iterations
- The software writers recommend using closure phase and amplitude rather than bispectrum. In some cases, bispectrum can help you if you get stuck in a local minimum on the closure phase and amplitude χ^2 surface.

Conclusions + ongoing tests. When the EHT imager is run with human interaction, it can do a pretty decent job. Scripting it is a bit trickier, but I think it can be made to generate sensible models. It will be necessary to test this on as many different objects as possible, which I'm working on.

Some tests on 1327+5504 (added by NJ 2018 Aug 2)

This is an LBCS source which is clearly detected to all stations, and has high closure phase on all stations.

Initial tests showed that closure-phase imaging is quite temperamental and may depend on a number of variables: how many channels of data are used; how many antennas; the mode used (`cphase/camp` or `bs`); and whether the channels are averaged[2].

A matrix of tests was done using the bright delay calibrator source 1327+5504. The data were fringe-fitted in AIPS (in multiple channels to approximately fit the dispersive delay, see memo 2) and written out as FITS. The source 1327+5504 is represented as a single elongated source in FIRST, but actually consists of a 5″ double. Five different channelizations were tested:

1. 432 channels of 48.8 kHz each
2. A subset of 100 channels
3. A subset of 20 channels
4. 432 channels, but averaged into 54
5. 432 channels, but averaged into 8

and six different formats labelled as follows:

- **T:** 3 telescopes (ST001-Ef-Ju) with mode `bs`
- **U:** 3 telescopes as above with mode `cphase`
- **V:** 4 telescopes (ST001-Ef-Ju-Po) with mode `bs`
- **W:** 4 telescopes as above with mode `cphase`, `camp`
- **X:** All international stations (ST001 plus DE601-UK608) with mode `bs`
- **Y:** All international stations with `cphase`, `camp`

[2]In addition, I get a different answer depending on whether I use a fits file directly, or whether I write it to a measurement set and allow the `eht_imager` script to write it back to FITS. Further investigation shows that there are two differences between such files: (1) the conversion to MS and back again has involved a change in the reference frequency and recalculation of u and v; (2) some visibilities (seemingly at random) have been replaced by zeroes (see the appendix). The EHT imager appears to care a lot about a relatively small number of visibilities being replaced in this way. Note the remark above about the `STATION` column in files written by AIPS.

In each case a 15″ FOV was used with a 7″ Gaussian prior, apart from series T where 10″ was used (this did not make much difference), and `clipfloor=0.0001`[3]. Each run had a first pass using the Gaussian prior, followed by a blur step and a second pass, with a final blur step producing the output image.

All runs proceeded well (in the sense of a chi-square which decreased throughout and where the iterations did not obviously end prematurely) apart from the following:

- T2 and T3 stopped after a few iterations, and required the stopping criterion resetting to `stop=1.0E-12`.
- T4 crashed with `Abnormal termination in LNSRCH` and a message to the effect that `J: NaN`
- T5 stopped after a few iterations in the first pass, but was OK in the second.
- Y1 crashed in the same way as T4.

Results are shown in Fig. 1. Conclusions:

- Mode `bs` provides good solutions in all cases for 3 or 4 telescopes.
- Using the closure quantities explicitly works for 4 telescopes in cases where all of the channels are present, but not when fewer channels are present. It does not work properly for 3 telescopes when only closure phases can be used.
- No procedure produces good solutions when all of the international stations are included. This is probably because many low-S:N baselines, where the closure signal is well below the thermal noise, are present.
- The parameters used to drive the EHT imager will have to be chosen carefully, and some sanity checking will be necessary.
- There will probably have to be a loop to catch crashes due to `clipfloor`, with the value being decreased if necessary.

Tests on 1334+5501

This source was observed by LBCS, but is listed as undetected on all stations (however, with a quality flag). It has significant closure signal to DE601 and DE605, but not to longer baselines.

1334+5501 is a large double source close to the centre of the survey field, but close enough to 1327+5504 that the same delay solution should be applicable.

[3]Higher values such as 0.001, the default, crashed as all the prior was removed.

The first test below shows the result of an `eht_imager` run using 4 telescopes (ExEfJuPo), closure phase and amplitude optimization, `clipfloor`=0.001, and a model from FIRST.

Five initial runs were done and the results are partially encouraging (the first two are, the last three aren't). The first run used the delay-corrected data (with 432×48-kHz channels), and little change is seen from the prior to the results. The second test used the same FIRST prior but with the data replaced with random noise, in order to test whether the optimization is governed by the prior or not (Fig. 2). In this case, where the data have been made to disagree with the prior, the prior is correctly optimized away.

In the other cases, where a deliberately incorrect prior is used, the imager is unable to recover. Test 3 used an axis orthogonal to the correct one, test 4 used a large Gaussian, and test 5 (not shown in the figure) used two components with the correct orientation, but 80% of the correct separation. In each case something very similar to the prior is returned as the final answer.

The tests were repeated using the bispectrum instead of closure phase and amplitude. **In this case, none of the tests works properly!** The failure mode in each case is that the prior gets optimized away to zero.

Some tests on 1327+5430

I'm not reporting these in detail since these are very similar results to 1334+5501. Basically: a wrong prior is not corrected, and is spat back out as the result; but if the data are randomized, the prior is optimized away. The one difference is that the prior in this case is only optimized away if the bispectrum is used; it is not optimized away if the closure phase and amplitudes are used.

This is probably not surprising given the closure statistics on this source (really significant only to DE605) and its detection only to DE605 in LBCS.

Some conclusions to date

- The imager seems to work be st for closure phase and amplitude optimisation, with a wide bandwidth (20MHz, 432 48-kHz channels) and with a reasonable prior.
- Performance is significantly degraded with fewer channels, or if data is included that is significantly noisy.
- For data which contains no correlated signal, closure optimisation seems usually to be robust (in the sense that a prior is optimized away).
- The ability of the algorithm to converge if the prior is not good is not reliable.

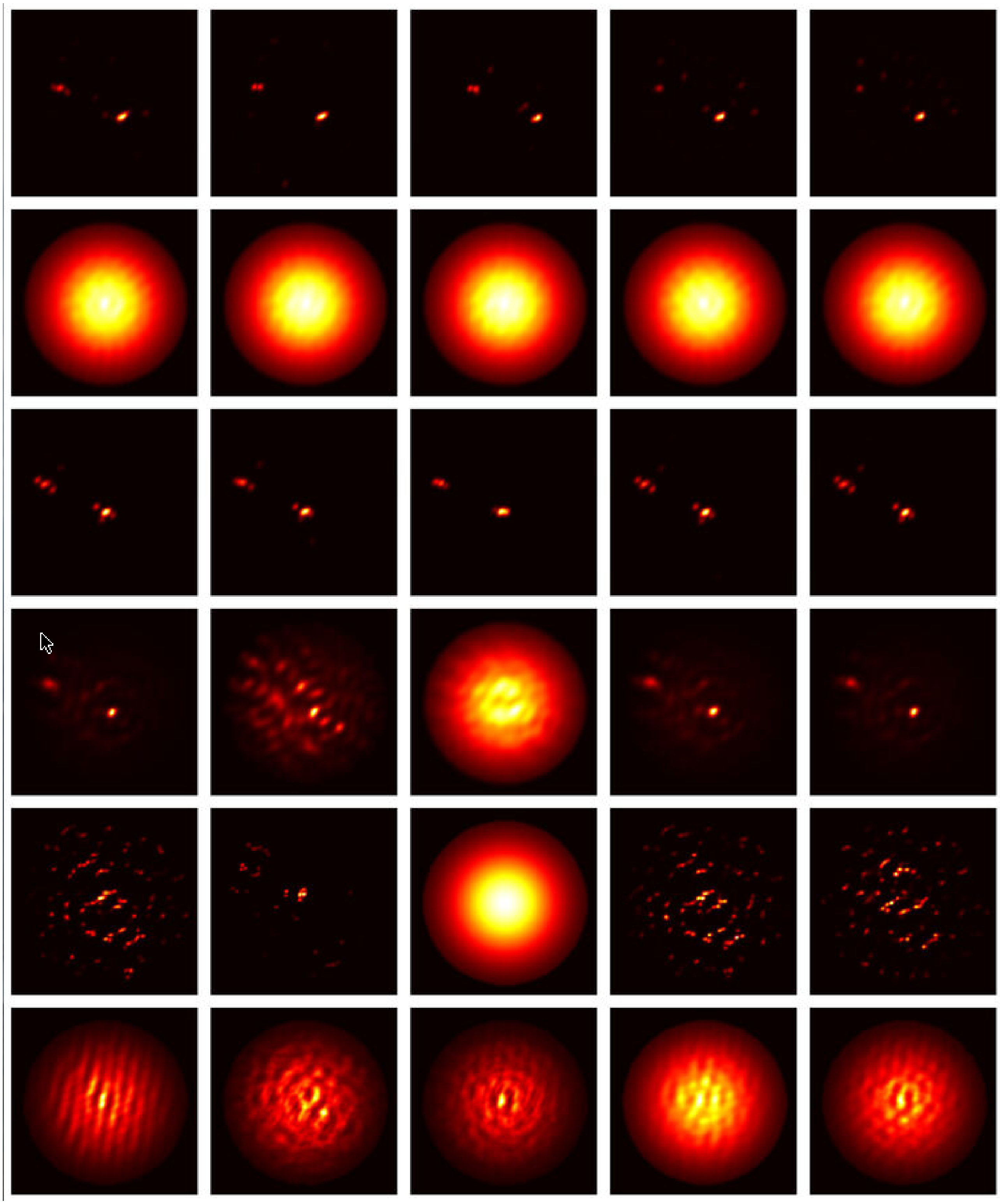


Figure 1: EHT imager tests on 1327+5504. Columns represent channel configurations 1-5 and rows are data formats T, U, V, W, X, Y respectively (see text).

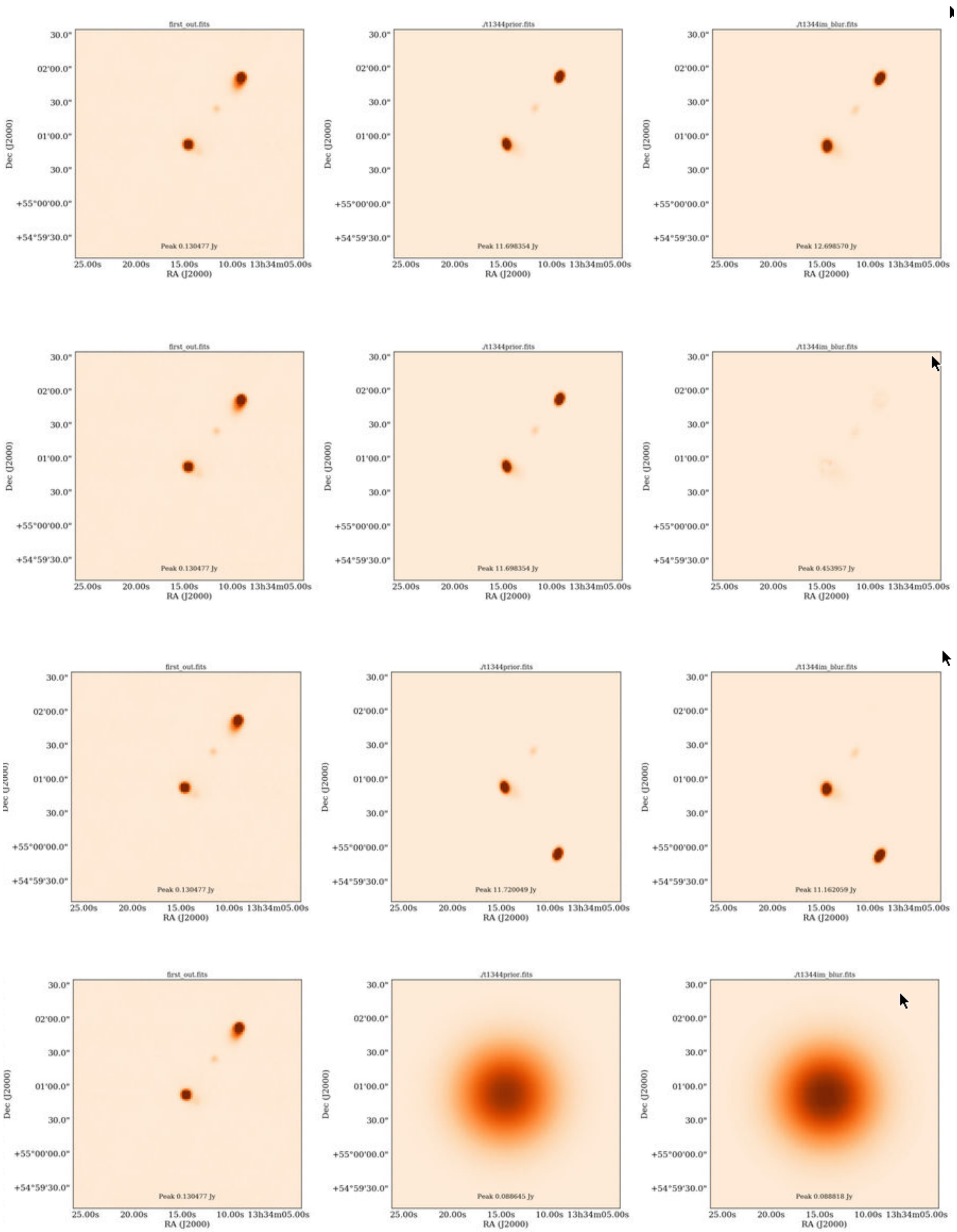


Figure 2: EHT imager tests on 1334+5501 using a FIRST prior. Columns are the FIRST image; the Gaussian-derived prior fed to the imager; and the output from the imager. The second row uses randomised data, and the other rows use the actual data.

Appendix: conversion problem

```
BEAM_1      Freq=  0.124778744    Sort= TB     70 XX          70 YY          70 XY          70 YX
  Vis #     IAT      Ant  U(klam) V(klam)   Amp  Phas Wt   Amp  Phas Wt   Amp  Phas Wt   Amp  Phas Wt

   2929  0/10:55:05 15-18     177      74   6.251  -5 11   4.690  85 11  14.172-162 11  30.209-120 11
   2930  0/10:55:05 15-23      11     107   2.425 139 92   3.931  16 92   0.355  63 92   0.471 -24 92
   2931  0/10:55:05 18-23    -166      33   1.162  28 95   1.381 -57 95   2.729 119 95   1.186 -62 95
   2932  0/10:55:13 15-18     177      74   4.225-127 11  39.508 -17 11  20.556 -39 11   2.302 -25 11
   2933  0/10:55:13 15-23      11     107   5.745 -17 92   1.472  -2 92   2.656 -85 92   2.084-175 92
   2934  0/10:55:13 18-23    -166      33   3.256 -76 95   6.473 -96 95   2.549  29 95   4.816   4 95
   2935  0/10:55:21 15-18     177      74  42.505 102 11  39.800  62 11  34.189 -24 11  30.819 150 11
   2936  0/10:55:21 15-23      11     107   1.605 -77 91   3.288 -24 91   1.932  68 91   5.781 166 91
   2937  0/10:55:21 18-23    -166      33   3.900 -69 95   5.153   5 95   2.356  -8 95   4.813-106 95
   2938  0/10:55:29 15-18     177      74   4.597 -36 11  15.247 -24 11  17.481  48 11  48.004 161 11
   2939  0/10:55:29 15-23      11     107   1.665-128 92   0.383 -67 92   1.615 163 92   1.338 105 92
   2940  0/10:55:29 18-23    -166      33   4.422  40 96   2.938  -9 96   2.191   5 96   2.003 117 96
AIPS 1: Resumes
>getn 51
AIPS 1: Got(1)   disk= 1  user= 340   type=UV   T2.RANDOM.1
>go prtuv
 lof020    PRTUV(31DEC16)    340     10-AUG-2018  09:08:13    Page    1
File = T2          .RANDOM.   1   Vol = 1    Userid =  340     Channels =   70 to    70
Source= BEAM_1     RA   =  13 27 37.20   DEC  =  55 04  6.2 IF =  1
Freq=  0.124778744 GHz   Ncor=  4   No. vis=      9993   Sort order= TB
NOTE: U,V and W are in wavelengths at the reference frequency
Weights have been multiplied by  1.0E+01

BEAM_1      Freq=  0.124778744    Sort= TB     70 XX          70 YY          70 XY          70 YX
  Vis #     IAT      Ant  U(klam) V(klam)   Amp  Phas Wt   Amp  Phas Wt   Amp  Phas Wt   Amp  Phas Wt

   2929  0/10:55:05 15-18     193      81   0.000   0  0   0.000   0  0   0.000   0  0   0.000   0  0
   2930  0/10:55:05 15-23      12     116   0.000   0  0   0.000   0  0   0.000   0  0   0.000   0  0
   2931  0/10:55:05 18-23    -181      36   1.162  28 84   1.381 -57 84   2.729 119 84   1.186 -62 84
   2932  0/10:55:13 15-18     193      81   0.000   0  0   0.000   0  0   0.000   0  0   0.000   0  0
   2933  0/10:55:13 15-23      12     116   0.000   0  0   0.000   0  0   0.000   0  0   0.000   0  0
   2934  0/10:55:13 18-23    -181      36   3.256 -76 82   6.473 -96 82   2.549  29 82   4.816   4 82
   2935  0/10:55:21 15-18     193      81   0.000   0  0   0.000   0  0   0.000   0  0   0.000   0  0
   2936  0/10:55:21 15-23      12     116   0.000   0  0   0.000   0  0   0.000   0  0   0.000   0  0
   2937  0/10:55:21 18-23    -181      36   3.900 -69 82   5.153   5 82   2.356  -8 82   4.813-106 82
   2938  0/10:55:29 15-18     193      81   0.000   0  0   0.000   0  0   0.000   0  0   0.000   0  0
   2939  0/10:55:29 15-23      12     116   0.000   0  0   0.000   0  0   0.000   0  0   0.000   0  0
   2940  0/10:55:29 18-23    -181      35   4.422  40 83   2.938  -9 83   2.191   5 83   2.003 117 83
AIPS 1: Resumes
```

Figure 3: Printout of a small amount of data from a file (top) written in FITS by AIPS and (bottom) converted to a MS and then written out in FITS again by `msuvfits` for presentation to the imager. A relatively small amount of data is affected by this problem, but it is enough to change the behaviour of the imager.