Wide Bandwidth Imaging: Challenges and prospects for the EVLA and beyond

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Outline

- EVLA requirements for wide-band imaging
- Description of existing wide-band imaging algorithms
- Simulation of a wide bandwidth data set (1GHz at Lband)
- Comparison of imaging results using various algorithms.
- Summary of what is currently achievable with existing algorithms, and what needs to be targeted for future work.

Multi Frequency Synthesis (MFS)

Goal: Produce a high dynamic range wideband continuum image with minimal deconvolution errors due to spectral variation of source flux and the primary beam.

EVLA specifications (L Band):

- Imaging dynamic range $> 10^6$
- Continuum point source sensitivity (12hr) $< 1\mu Jy$.
- Total bandwidth at L Band : 1.2 GHz -> 2 GHz
- Total usable bandwidth at L Band : 500MHz.
- Fast, high fidelity imaging of extended low brightness sources with μK brightness sensitivity.

Existing MFS algorithms [Conway,Cornwell,Wilkinson,1990] have been designed mainly to obtain enhanced UV coverage from sparse arrays, and are reported to achieve dynamic ranges of few 1000:1 and with spectral deconvolution errors below the rms limit, up to bandwidths of 25%.

Algorithms

Single channel imaging: Deconvolve each channel separately and combine the images appropriately.

- ✗ Imaging sensitivity is limited to the single channel rms.
- ✗ Imaging resolution varies across frequency.
- ✗ Does not take advantage of the added uv coverage of the wide band information.
- ✓ Independent of the shape of the spectrum.

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MFS: Grid visibilities at different frequencies separately to avoid bandwidth smearing.
Augment the deconvolution process to account for spectral effects due to source flux variation and the changing primary beam across frequency.

- ✓ Full imaging sensitivity can be reached by using all the data during imaging.
- ✓ Full imaging resolution can be obtained.
- ✓ Benefits from additional uv coverage.
- × Current algorithms are dependent on spectrum models.

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Hybrids: Combine single channel techniques which are independent of spectral models, with bandwidth synthesis techniques to obtain full resolution and sensitivity.

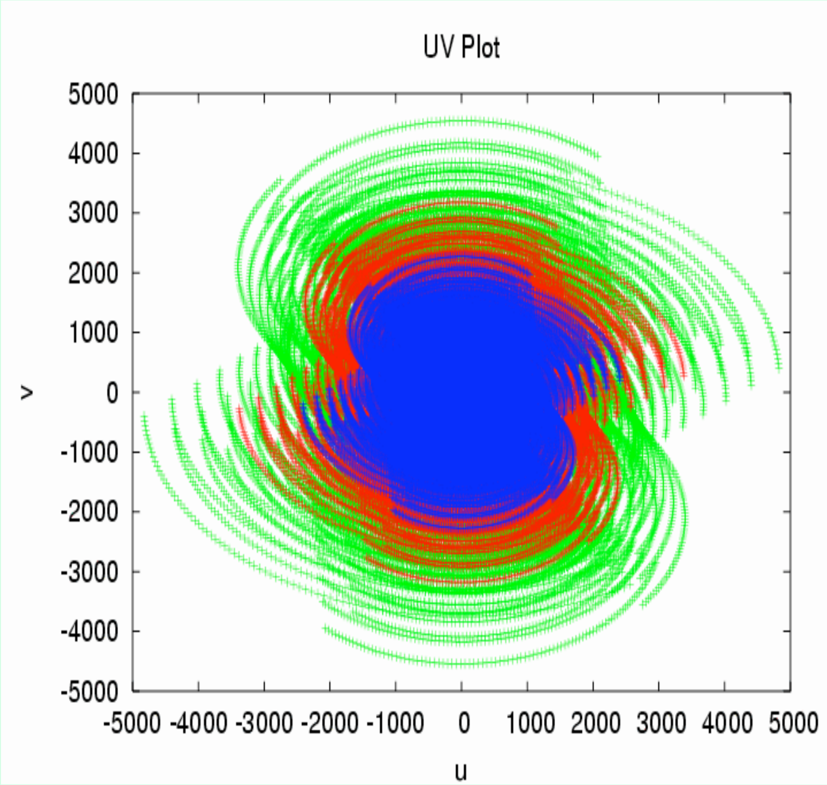
Multi Frequency synthesis

Step 1

Grid visibilities from each channel separately on to the uv plane.

Choose a maximum single channel width so as to restrict the extent of image domain bandwidth smearing to a scale smaller than the resolution element.

$$\Delta\nu < \nu_0 (D/b_{max})$$



For data with very high spectral resolution, visibilities from all channels within $\Delta\nu$ when gridded, will fall onto the same uv grid point. The total data volume can therefore be reduced (while preserving sensitivity) by averaging channels up to this resolution.

Multi Frequency synthesis

Step 2

During deconvolution, take into account source flux variation across frequency.

$$I(\nu) = I(\nu_0)(\nu/\nu_0)^{-\alpha}$$

Expanding $I(\nu)$ in terms of $\ln(\nu_0/\nu)$ gives $I^D = (I^M \ast B_0) + (I^M\alpha \ast B_1) + (I^M\alpha^2 \ast B_2) + \ldots$

where $B_n = \Sigma[\ln(\nu_0/\nu)]^n S(\nu)$ are the logarithmic spectral dirty beams over which a joint deconvolution is performed.

[Conway,Cornwell,Wilkinson, 1990]

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Error analysis:

The on source contribution from B_1 is negligible, and is $O(I\alpha^2/200)$ for B_2.

Maximum sidelobe levels for the first three beams can be estimated to be $I/10$ for B_0, $I\alpha/200$ for B_1, and $I\alpha^2/2000$ for B_2.

[Conway,Cornwell,Wilkinson, 1990]

Simulation parameters

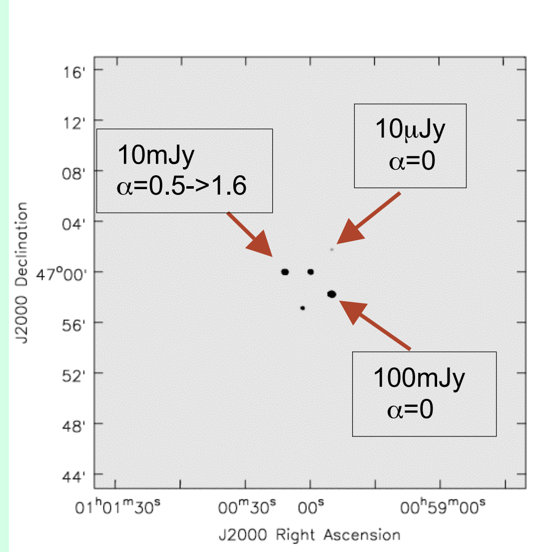
- Telescope : VLA C array
- Frequency : L Band (1420 MHz)
- 32 10MHz wide channels, 40MHz apart
- Total Bandwidth : 320MHz (spread over 1280MHz)
- 8 hour observation with 300s integrations.

- Noise per visibility : 1mJy
- Single channel rms noise : 4μJy
- Continuum point source rms : 0.7μJy
- Expected dynamic range : 10^5

- Point sources (100mJy, 10mJy, 1mJy, 100μJy, 10μJy)
  The 10mJy source has a spectral index varying linearly between 0.5 and 1.6.

- Extended sources (core-jet profile)

- Primary beam effects have been ignored in this analysis.



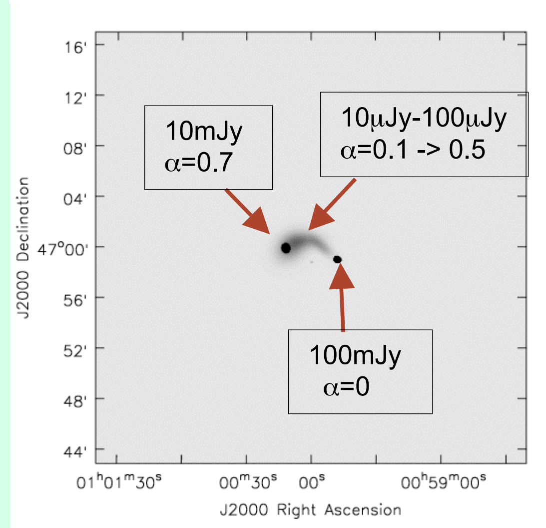


Image Statistics

- RMS : achieved noise level away from the true source
- Peak residual : flux of the weakest believable feature
- Dynamic range w.r.to off source rms : $\max(I^{restored})$/(off source rms)
- Dynamic range w.r.to peak residual : $\max(I^{restored})$/(peak residual)
- Median Image fidelity : median [$I^{restored}/(I^{restored}-I^{true})$]
- Normalized χ^2 (on-source) : $D = I^{restored}-I^{true}$

  Normalized $\chi^2 = \mathrm{var}(D)/\sigma^2$

  $\mathrm{Var}(D) = (\Sigma D^2)/(n-1)$

Normalized χ^2 is equivalent to the F statistic used to compare two distributions.

+ Since var(D) is related to total power, normalized χ^2 is sensitive to differences between the variance of D and that of the thermal noise σ^2.
+ Since a zero mean is assumed in the calculation of var(D), any non-zero mean component in D will be accounted for, as it contributes to the total power.
+ The ideal case of pure thermal noise in D results in Normalized $\chi^2 = 1.0 \pm \varepsilon$
+ sqrt(χ^2) : total deviation in units of thermal noise ($n\sigma$).

Single Channel Imaging

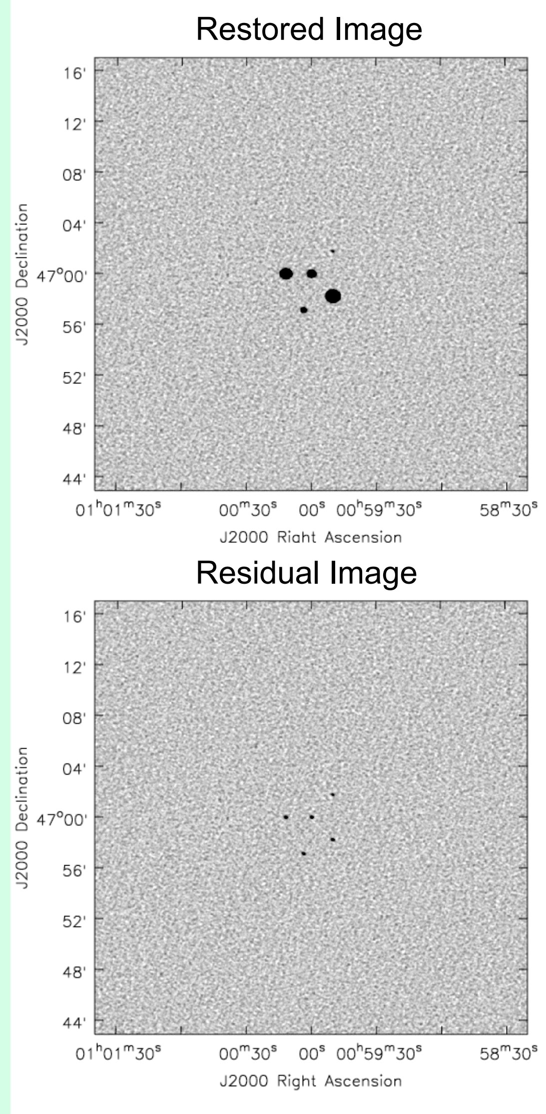
(1) Deconvolve each channel separately
(2) Average all the images together.

Off source rms : 1.007 μJy
Peak residual : 21.6 μJy

Dynamic Range w.r.to rms : $9.9\text{x}10^4$
Dynamic Range w.r.to peak residual : $4.6\text{x}10^3$

Normalized χ^2 (on source) : $2.81\text{x}10^7$

Note :
- On source flux has errors at the 1mJy level (on 100mJy).
- Imaging sensitivity is limited by single channel noise.
- imaging resolution is limited to that of the lowest frequency.
- No noticeable large scale deconvolution errors due to incorrect spectrum estimation in the residual image.



Bandwidth Synthesis (flat spectrum model)

(1) Grid visibilities from each channel separately.

(2) Assume a flat spectrum and do a joint deconvolution.

Off source rms : 1.85 μJy

Peak residual : 10.3 μJy

Dynamic Range w.r.to rms : 5.4×10^4

Dynamic Range w.r.to peak residual : 9.6×10^3

Normalized χ^2 (on source): 9.66×10^3

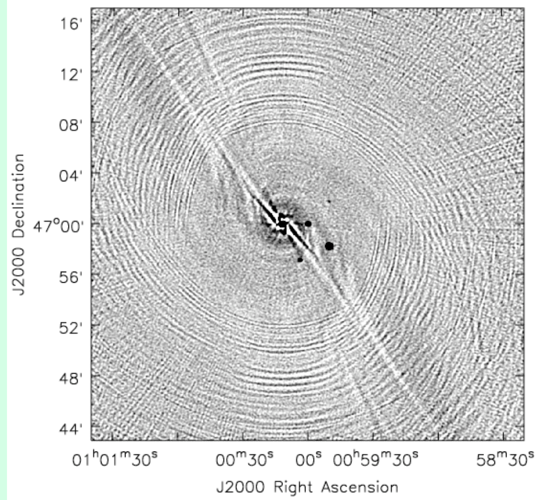
Note :

- The assumption of a flat spectrum leads to large scale deconvolution errors at the 10 μJy level around the 10mJy source with spectral index 0.7.

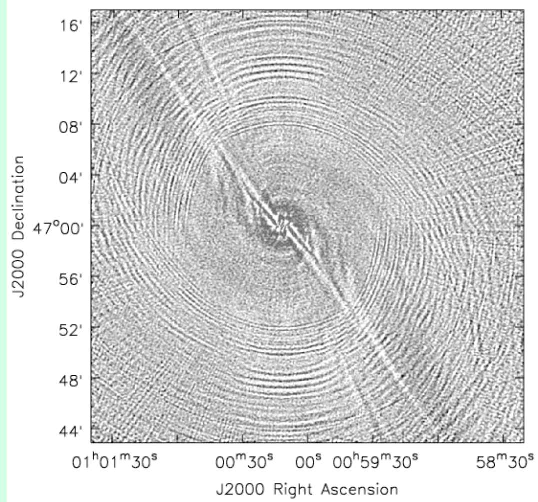
Predicted errors arising from ignoring B1 and B2

- On source $I\alpha^2/200$: 4.9μJy
- Near-in sidelobes : $I\alpha/200 + I\alpha^2/2000$ = 7μJy + 0.49μJy

Restored Image



Residual Image



MFS (power law spectrum model)

Miriad 'mfclean' implementing the Conway/Sault algorithm.

Off source rms : 1.03 μJy
Peak residual :9.6 μJy

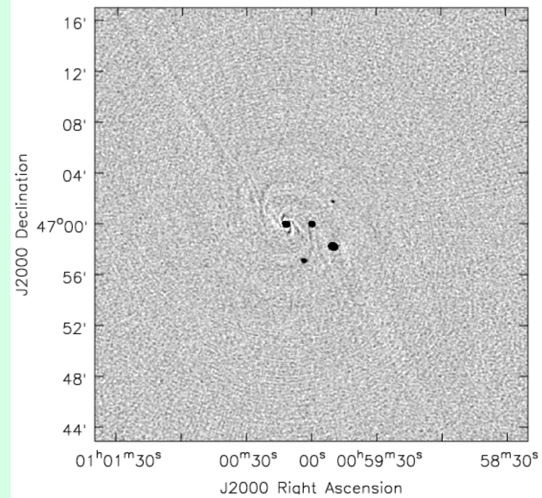
Dynamic Range w.r.to rms : 9.6×10^4
Dynamic Range w.r.to peak residual : 1.04×10^4

Normalized χ^2 (on source): 4.4×10^6

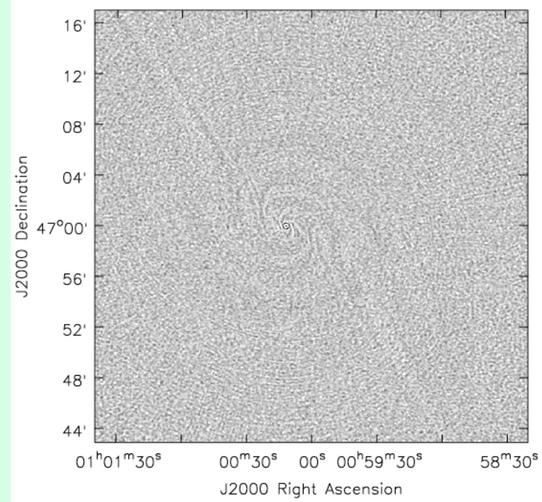
Note :
- Low level large scale deconvolution errors persist due to the varying spectral index across the band.
- Minimum peak residual, minimum off source rms, but mJy level on-source errors persist.

[For a source with a pure power law spectrum, the obtained rms noise is 0.93 μJy with a peak at 4.5 μJy.]

Restored Image



Residual Image



Hybrids

(1) Divide the data into chunks of channels, over which the spectrum varies at most as a power law. Use the MFS algorithm on each chunk. Sensitivity is limited to that given by the chunk size.

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(2) Estimate the frequency dependence from single channel maps, subtract out the corresponding model visibilities, and perform an MFS on the combined residuals.

So far, this has been the most promising algorithm (for EVLA specifications).

The first pass of single channel imaging estimates and removes flux up to the single channel sensitivity limit - irrespective of the spectrum.

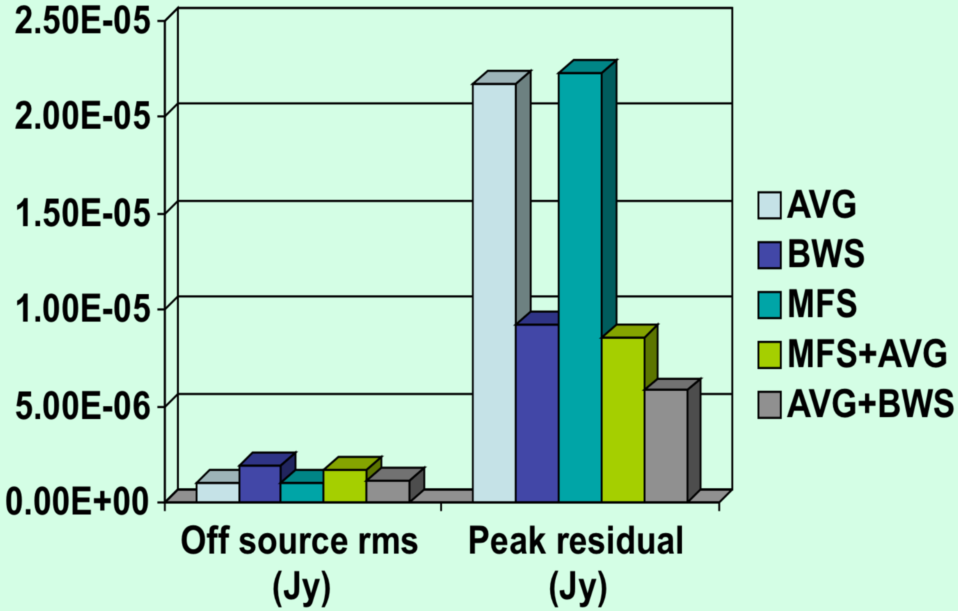
The maximum residual flux is now at the single channel sensitivity limit, and a flat spectrum (or power law) assumption would usually suffice.

Maximum B1 sidelobe level ($I\alpha/200$) < continuum thermal noise limit.

$$4\mu Jy * 0.7/200 < 0.7\mu Jy$$

An advantage is that deconvolution errors in the single channel flux estimation can be reduced as a result of the MFS pass.

Comparison of the algorithms (point source data)



AVG : Channel averaging

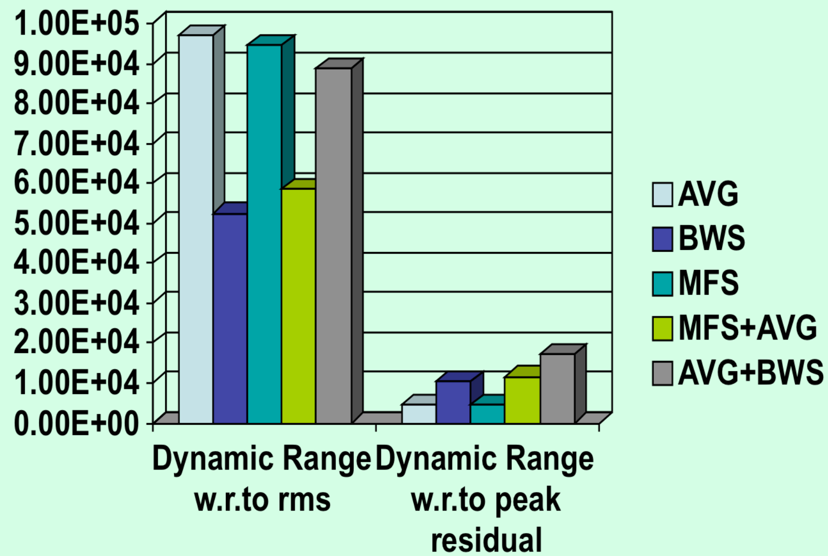
BWS : Multi frequency synthesis with a flat spectrum model

MFS : Multi frequency synthesis with a power law model

MFS+AVG : MFS on channel chunks

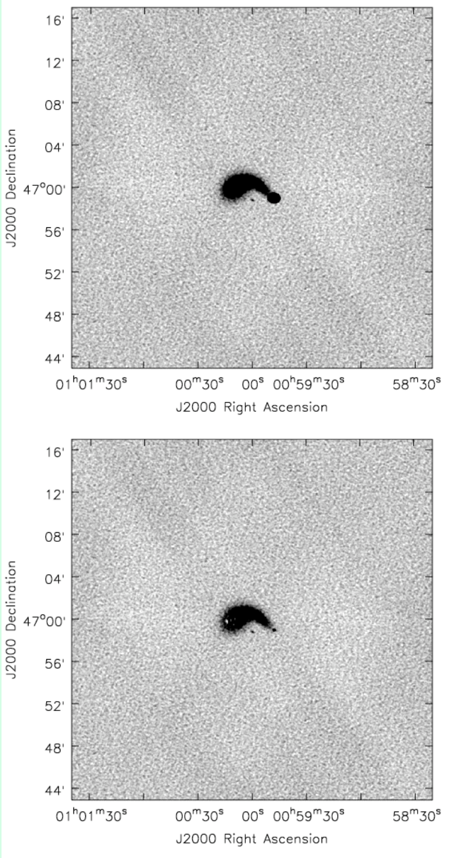
AVG+BWS : Single channel models and BWS on the residuals.

The AVG+BWS hybrid resulted in the Minimum off source RMS and maximum dynamic range.



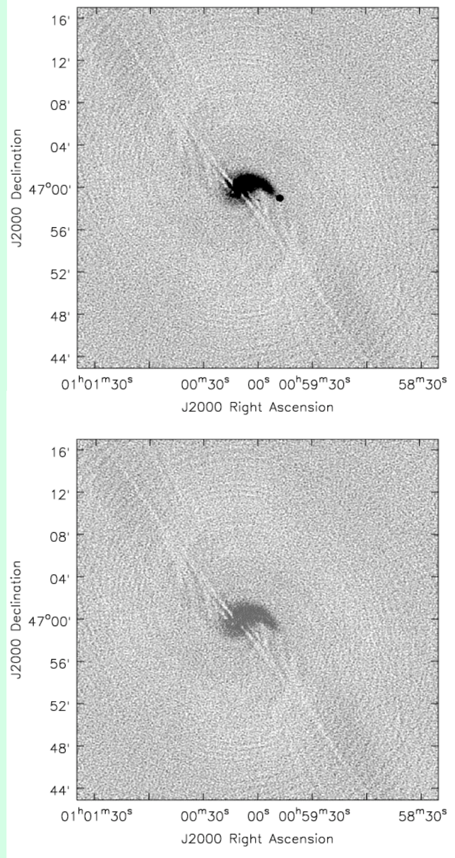
Extended Sources

Channel Average



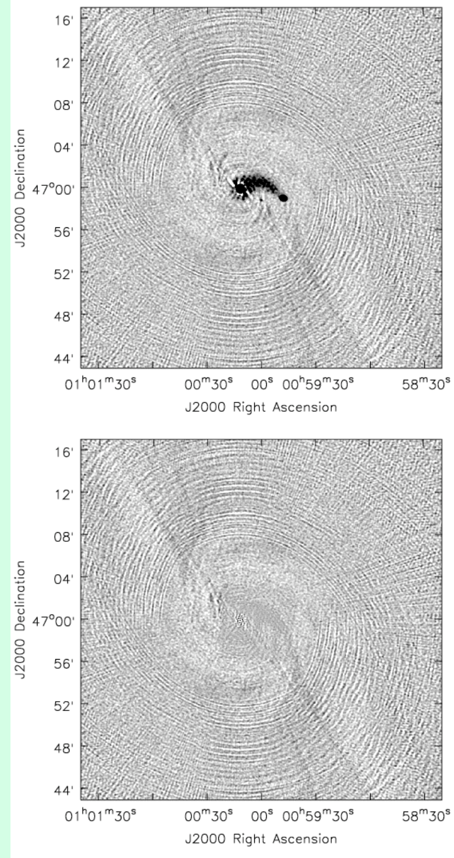
Rms = 1.3 μJy
Peak Residual = 21.7 μJy
Dynamic Range = 4.6×10^3
(w.r.to peak residual)

Bandwidth synthesis



Rms = 1.2 μJy
Peak Residual = 6.1 μJy
Dynamic Range = 1.6×10^4
(w.r.to peak residual)

MFS(miriad mfclean)



Rms = 1.5 μJy
Peak Residual = 12.1 μJy
Dynamic Range = 8.2×10^3
(w.r.to peak residual)

Summary

For the EVLA (L Band)

- Single channel imaging is by itself inadequate due to the single channel sensitivity limit, but can be used in hybrid methods to get to 10μJy sensitivity for point sources.

- Bandwidth synthesis with power law spectral flux variation estimation achieves EVLA specifications for sources with a pure power law spectra. For non-power-law spectra, 10μJy level errors persist on a 10mJy source. Better spectrum models are required.

- Hybrid algorithms that combine the spectral flexibility of single channel techniques, along with the high sensitivity of multi frequency techniques show some promise. These techniques may also turn out to be the most practical, in terms of data processing and computing requirements (parallelization).

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… and beyond.

- Accurate deconvolution of extended emission requires multiscale techniques(msclean,ASP, bayesian), along with techniques to handle arbitrary spectra across the region.
- Primary beam effects : Up to the half power point, the gain variation across frequency can be modeled by a pseudo spectral index [Sault,Wieringa, 1994]

  Full primary beam imaging techniques (via gridding convolution functions per frequency)