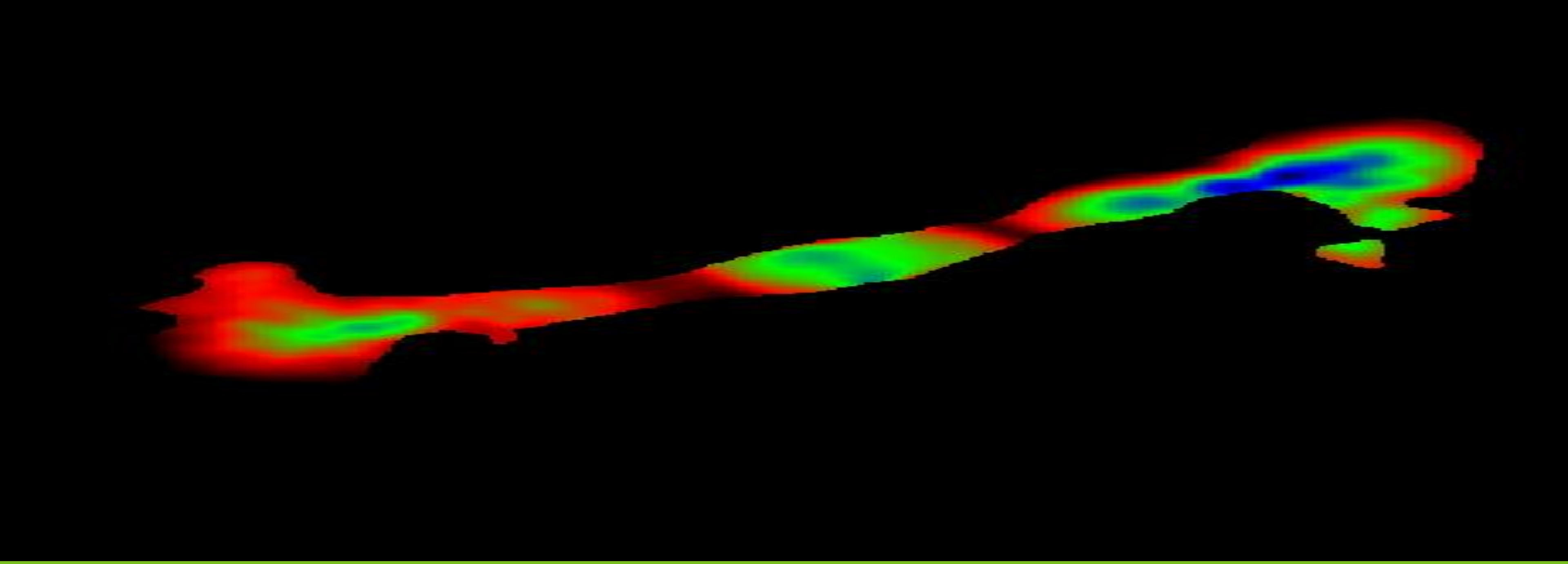

Wideband Imaging and Measurements

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Outline

- Why are wide bandwidths useful?
- How are wide bandwidth images made?
- How do we make accurate measurements from wide bands?
- What problems might we have with wide bandwidths?

Wide Bandwidths

For continuum mapping, the more bandwidth you get, the lower the thermal noise level can be.

$$\sigma = \frac{\sqrt{2}kT_S}{A\epsilon\sqrt{\Delta\nu_{IF}\tau}}$$

In this equation for RMS noise, the bandwidth enters as ${}^{1}/_{\sqrt{\Delta\nu_{IF}}}$, so as the bandwidth gets larger, the noise gets smaller.

Not only advantageous for continuum!

Spectral-line observations can also benefit from an increase in bandwidth.

Although a line is the same width regardless of the receiver bandwidth, having larger bandwidths available allows you to:

- more quickly search frequency-space for line emission at an unknown velocity
- observe more than one line simultaneously
- better estimate the bandpass in the emission-free bandwidth, and thus more accurately measure the line emission

Divide and Conquer

Wide bandwidths cause issues.

Simplest solution: split up your bandwidth, and make several smaller-bandwidth images, do your measurements on each separately, or stack the images together.

This is sometimes the only solution, but often this approach does not let you get everything you can from your data.

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Imaging Wideband Continuum

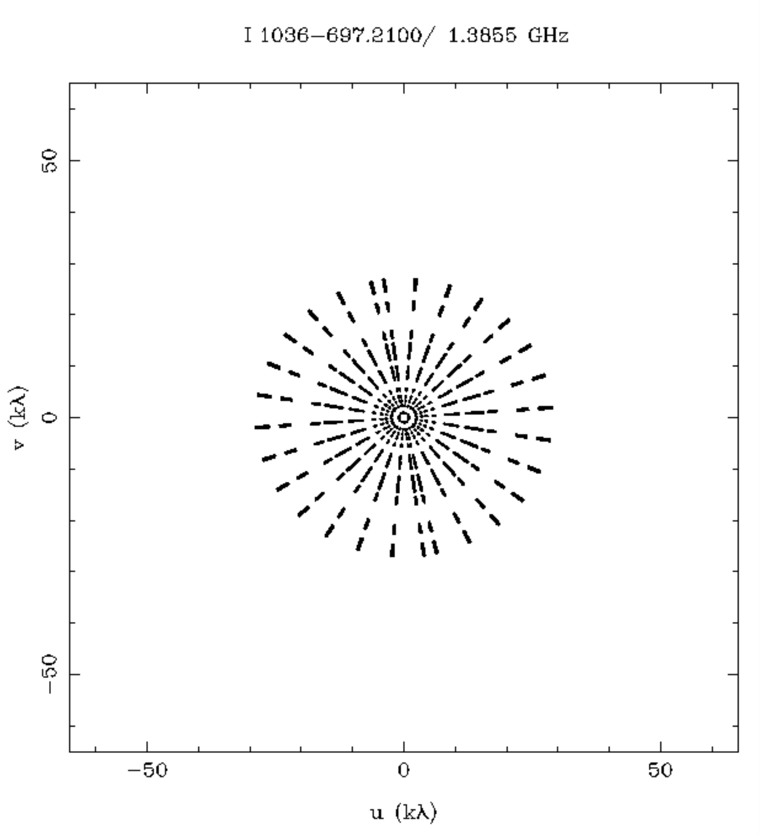
The imaging process for wideband continuum images is call multi-frequency synthesis.

In our most popular CABB mode, the 2048 MHz of bandwidth is split into 2048 channels, each channel being 1 MHz wide. Each channel is individually gridded to make a single image covering the entire band.

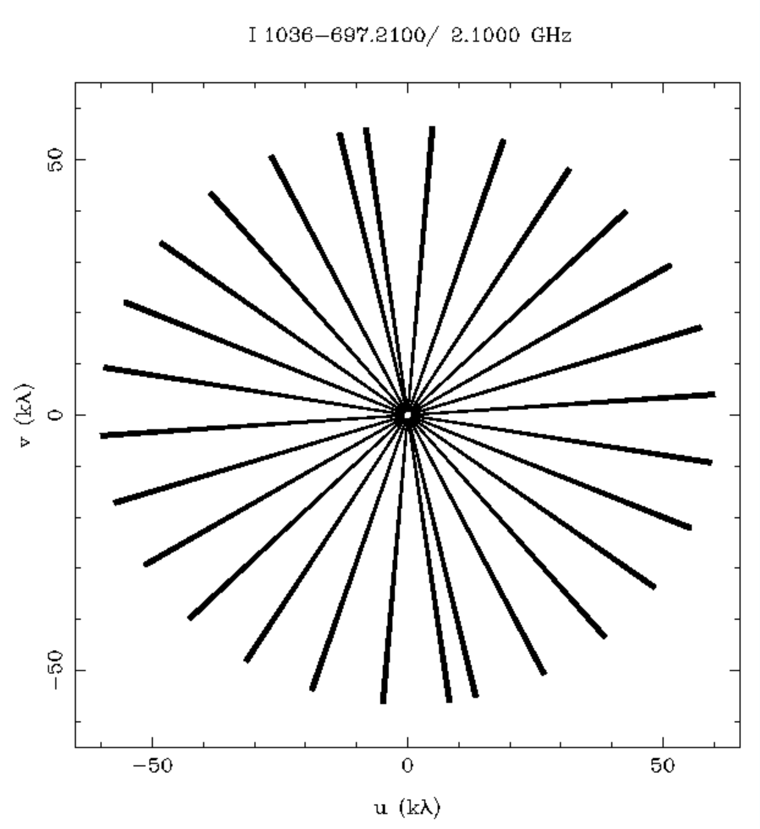
This can have benefits not only for sensitivity but for uv-coverage as well.

uv coverage improvement

6 km array, 128 MHz bandwidth (old ATCA correlator)



6km array, 2048 MHz bandwidth (CABB correlator)



Multi-frequency synthesis

The observing bandwidth is split into channels, and each channel's real and imaginary components are placed on a uv grid, and the entire thing is Fourier transformed to make the image.

Very easy in principle! But in reality we have a couple of complicating factors.

Fractional Bandwidth

The information contained in a single channel is the average of all the frequencies that channel covers.

Larger channels and bandwidths make the observation more sensitive, but we also have to be aware of the "fractional bandwidth" that each channel represents.

$$fractional\ bandwidth = \frac{\Delta\nu}{\nu_0}$$

where $\Delta\nu$ is the bandwidth (either of the channel or band),

and ν_0 is the observing centre frequency

Fractional Bandwidth

For the ATCA with CABB, we have a bandwidth of 2048 MHz.

In the 16cm band, which is centred at 2100 MHz, the fractional bandwidth we can observe is ≈ 1. The lowest frequency we routinely observe is 1076 MHz.

Using 1 MHz channels, the fractional channel bandwidth at the lowest frequency is 0.09%. Using 64 MHz, it is 6%.

Such a large fractional channel bandwidth can cause “bandwidth smearing”.

Bandwidth Smearing

The response to a point source that has coordinates (l, m) on the sky will be radially elongated towards the phase centre by:

$$\sqrt{l^2 + m^2}\frac{\Delta\nu}{\nu_0}$$

Consider a 6km array at 2100 MHz; it has a resolution of 2.5 arcseconds.

A 64 MHz channel would smear twice that amount at $\sqrt{l^2 + m^2}$ = 164 arcseconds. That's only halfway to the half-power point of the primary beam!

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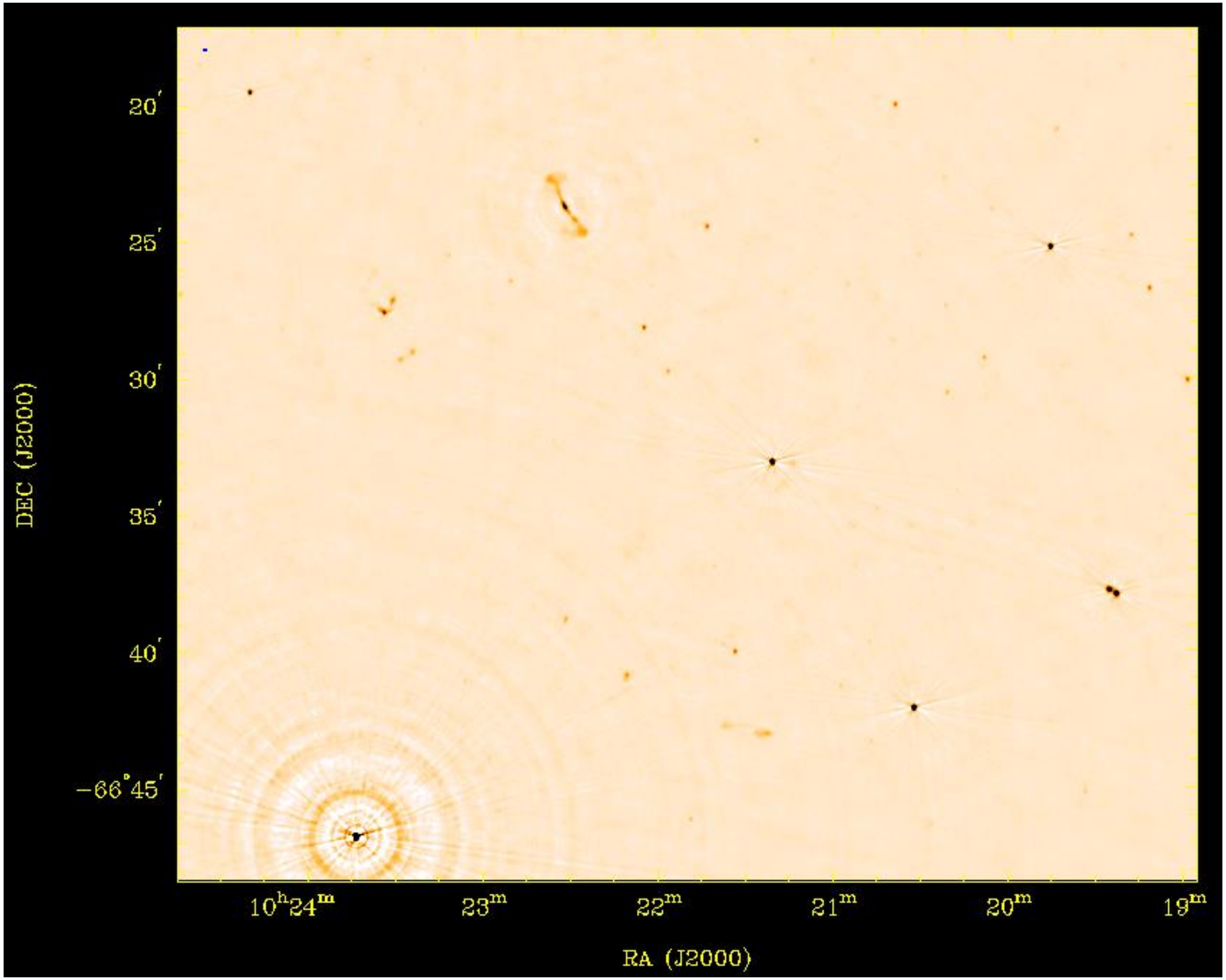
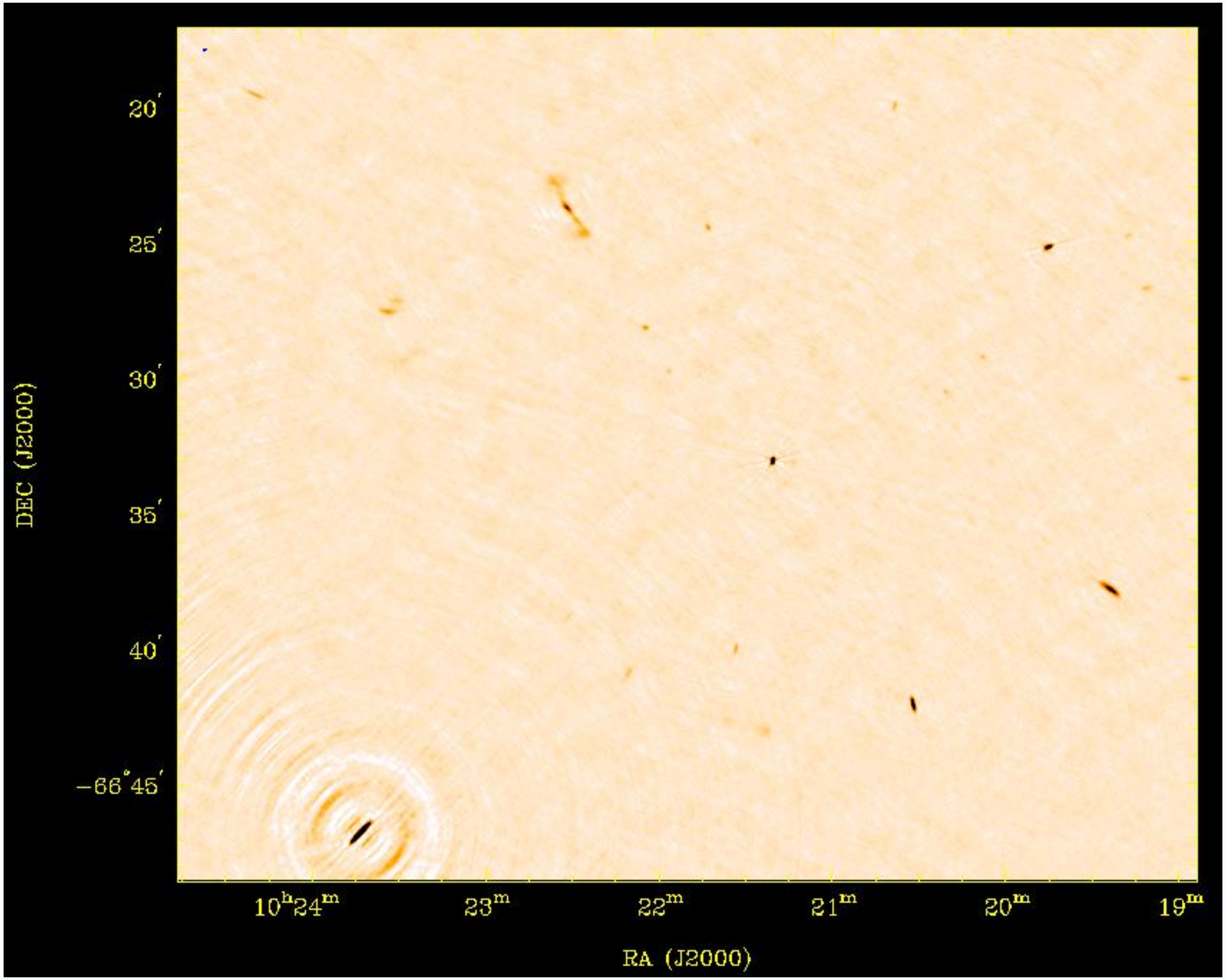
Bandwidth Smearing

2048 x 1 MHz channels



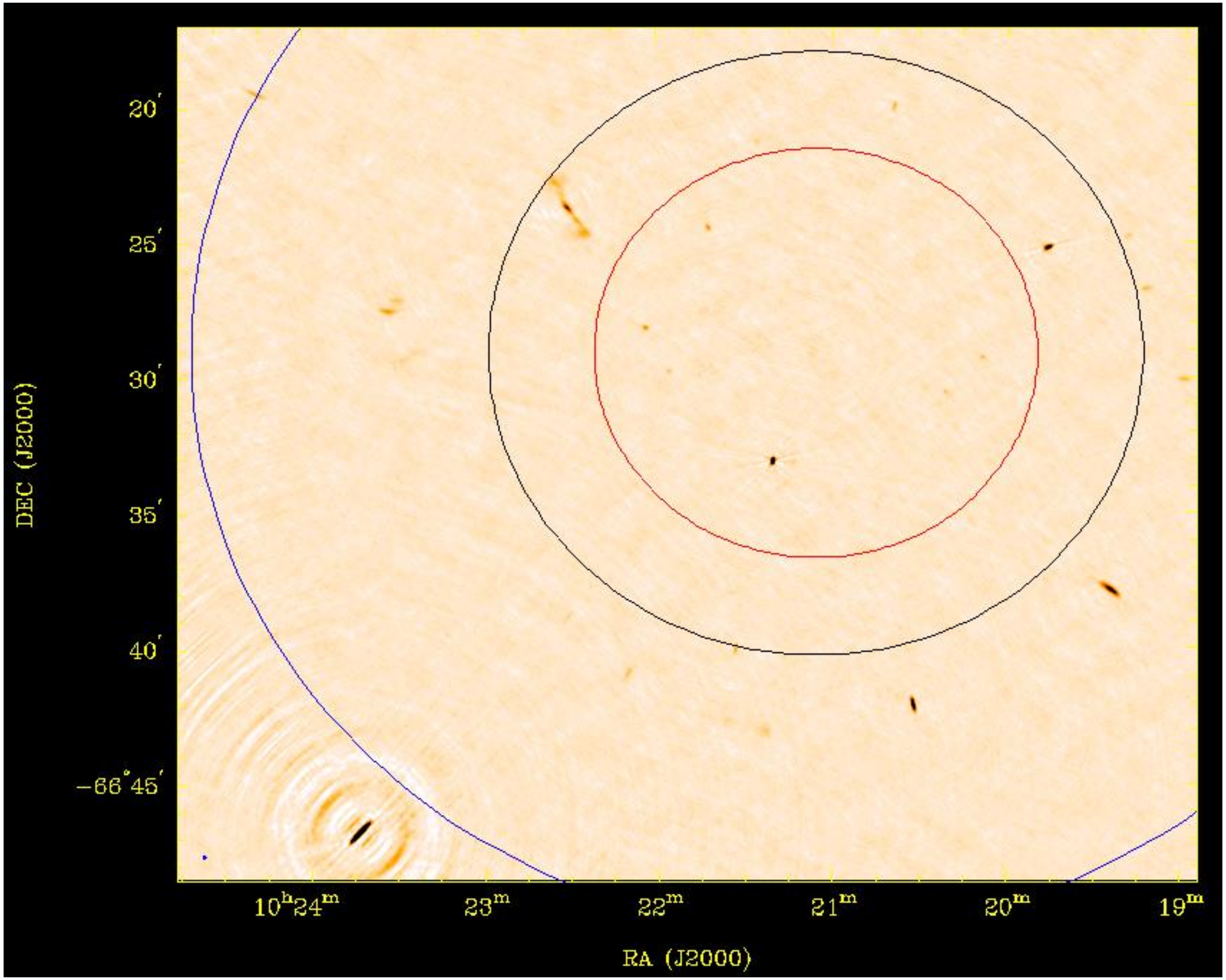
Bandwidth Smearing

32 x 64 MHz channels



Bandwidth Smearing

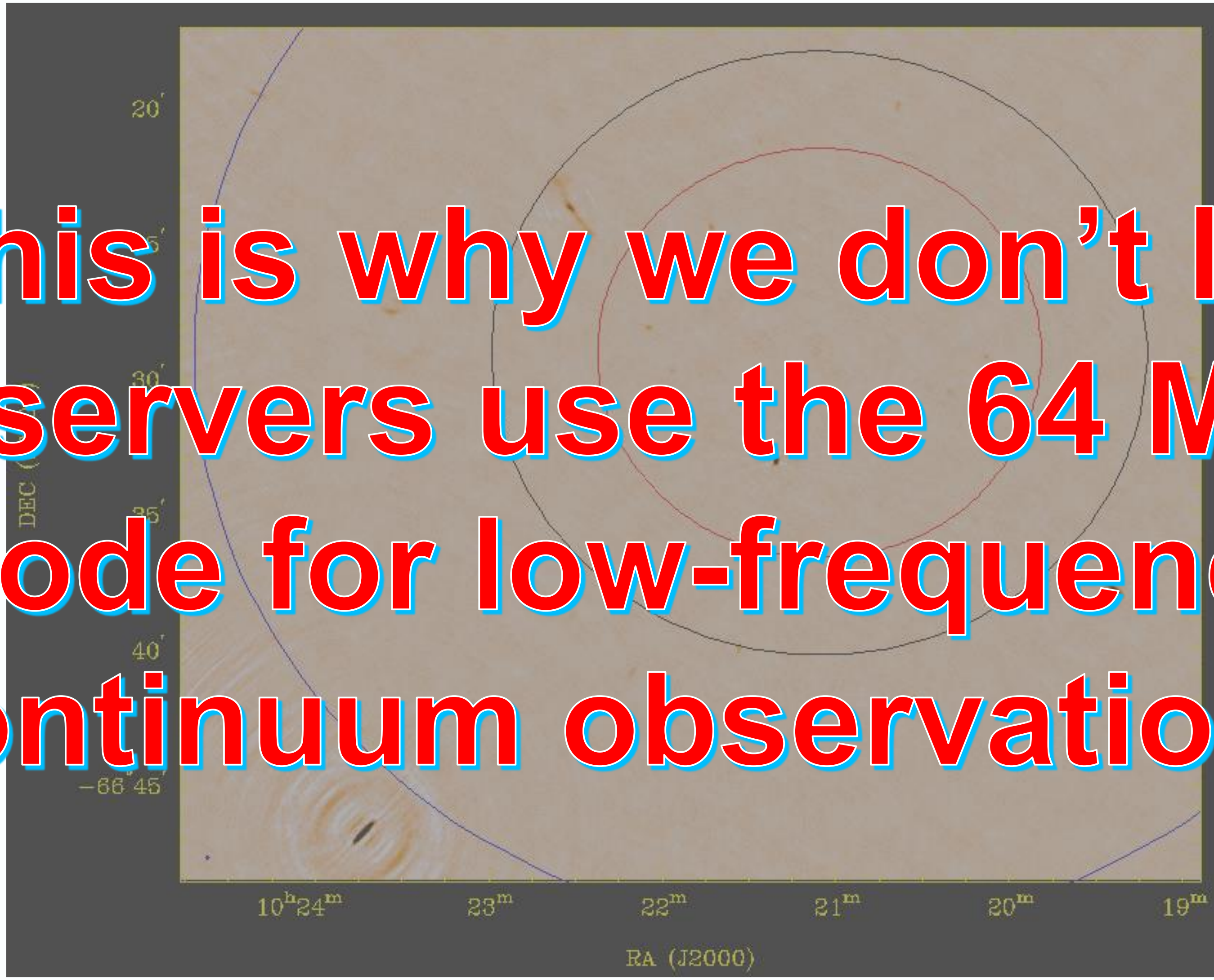
32 x 64 MHz channels



Primary Beams

3.1 GHz
2.1 GHz
1.1 GHz

Bandwidth Smearing



This is why we don't let observers use the 64 MHz mode for low-frequency continuum observations

Spectral Index

The flux density of a source is not generally the same at all frequencies. It will usually vary smoothly however, and can in most cases be described by:

$$I(\nu) = I(\nu_0)\left(\frac{\nu}{\nu_0}\right)^{\alpha}$$

α is the spectral index. In this lecture, our convention is that if the spectral index is negative, the flux density of the source decreases with increasing frequency. Commonly, ν is in GHz, and:

Steep spectrum = $\alpha < -0.5$

Inverted spectrum = $\alpha > 0.5$

Flat spectrum = $-0.5 < \alpha < 0.5$

Calibration of Spectral Index

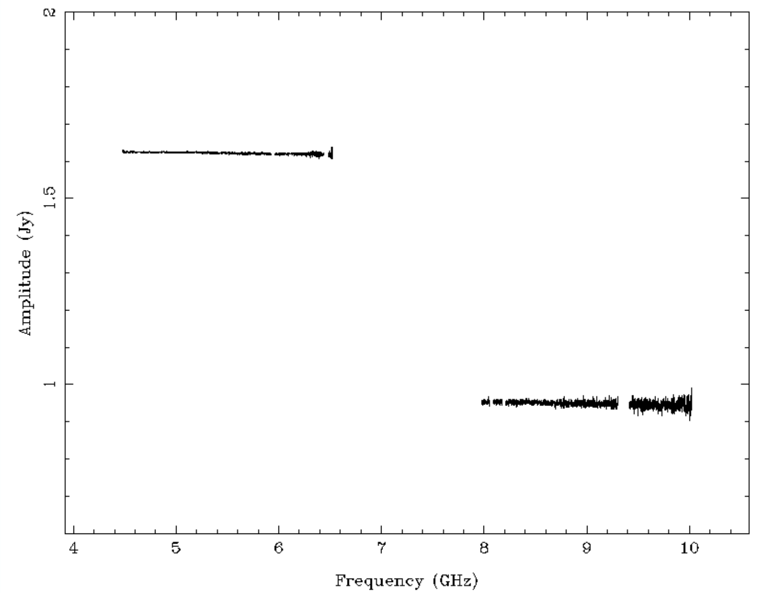
It is very important to ensure that you account for spectral index during calibration.

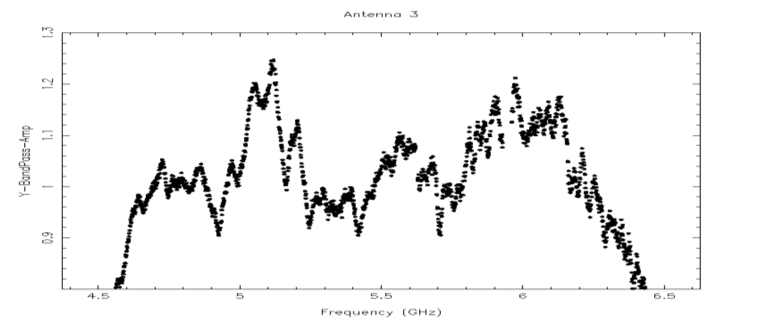
Ideally, the bandpass calibration can be performed with a source that has a known flux density model, such as 1934-638. This is not always possible though, since many very strong sources are quite variable.

Correction of the bandpass response function can be done later if required though, as it is usually just a slope adjustment.

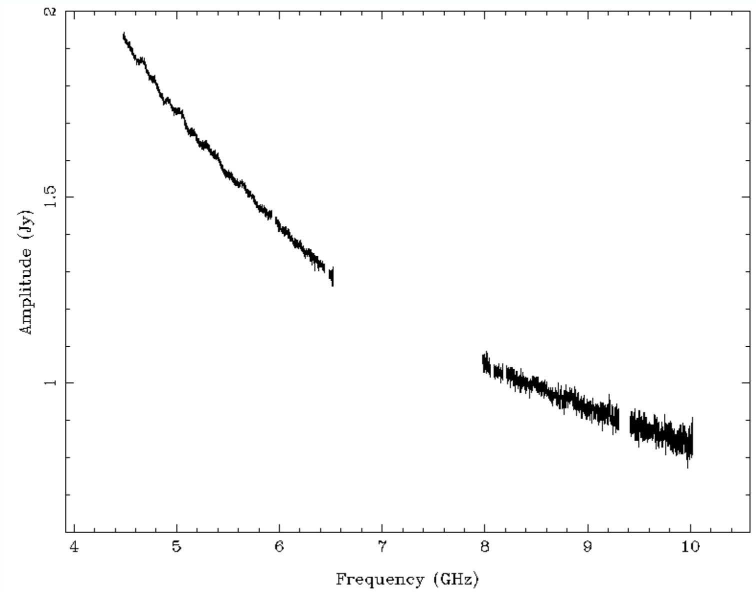
Bandpass Correction

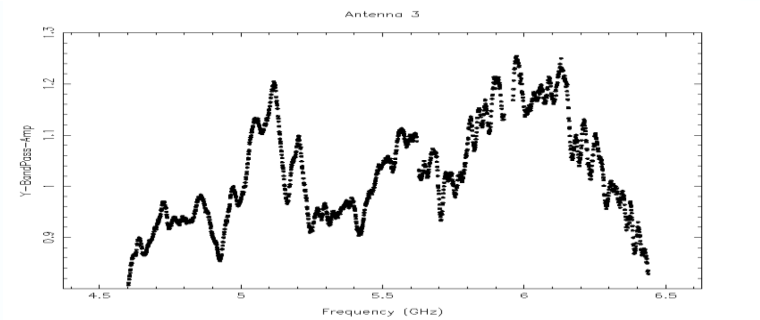
Incorrect Bandpass



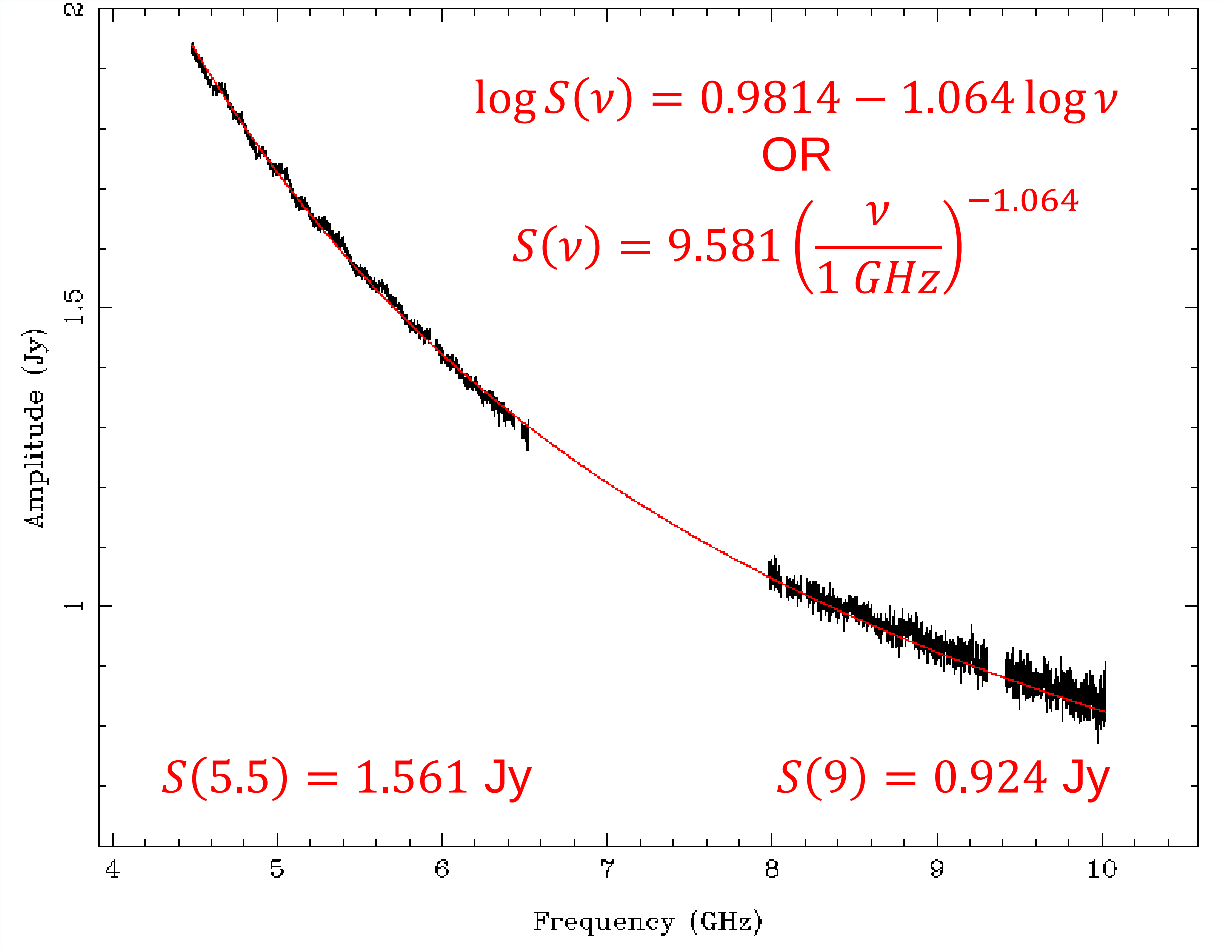


Correct Bandpass





Measuring Flux Density



For a bright source at the phase centre, it is easy to do a linear fit for flux density as a function of frequency.

This is how all flux density measurements are made in the ATCA Calibrator Database.

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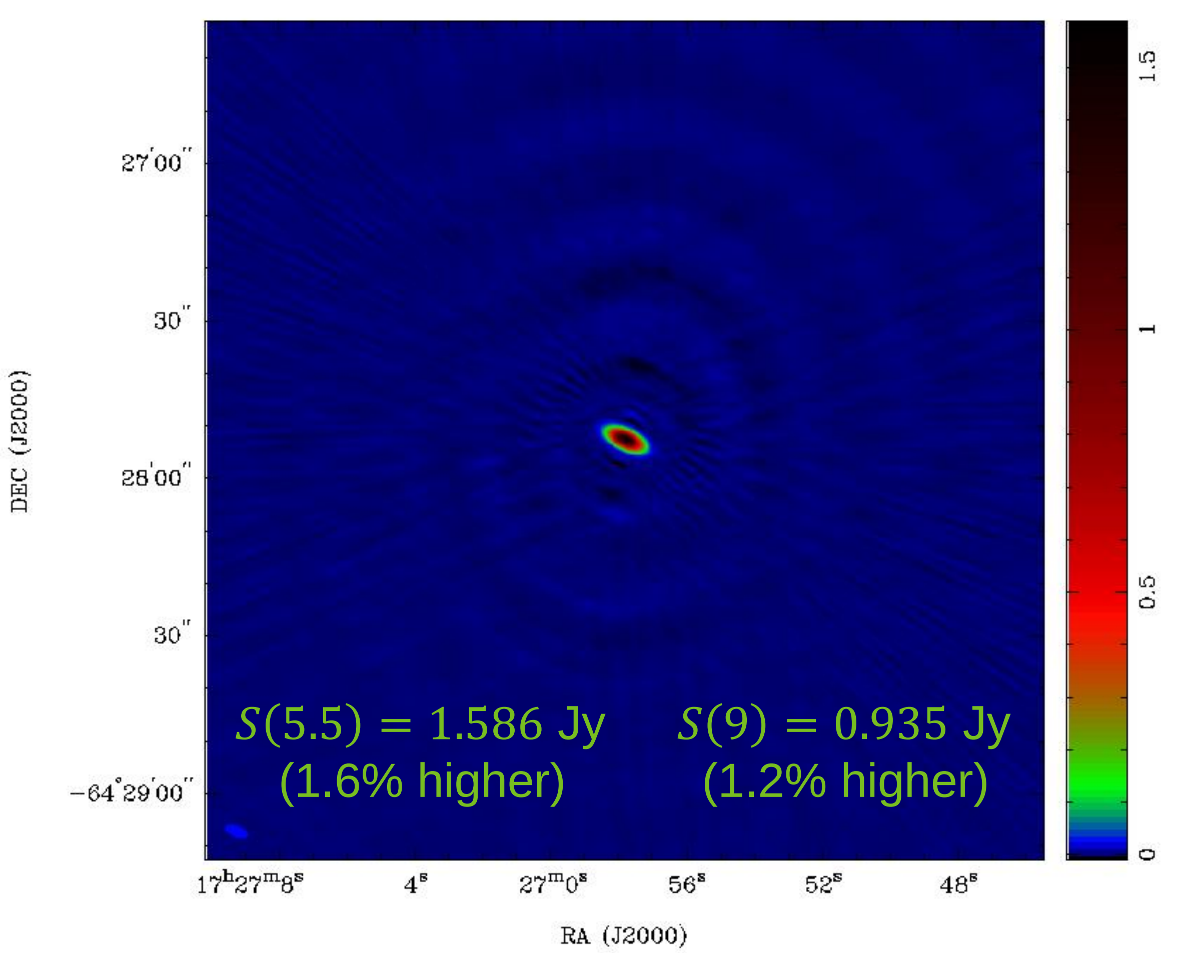
Measuring Flux Density



If you need to image the field to get the flux density, you might get a different answer though.

The same calibrator that we just measured via spectral fit has an image-measured flux density that is higher.

This is because the spectral index hasn't been taken into account.

Correcting Image Flux Density

The band-averaged flux density of a source could be considered as the weighted mean of all the channels going in to the image.

$$S_{avg} = \frac{\sum_{i=1}^{N_{chan}} w_i S(\nu_i)}{\sum_{i=1}^{N_{chan}} w_i}$$

But we know that

$$S(\nu_i) = S(\nu_0)\left(\frac{\nu_i}{\nu_0}\right)^{\alpha}$$

So, substituting, rearranging and simplifying to equal weights:

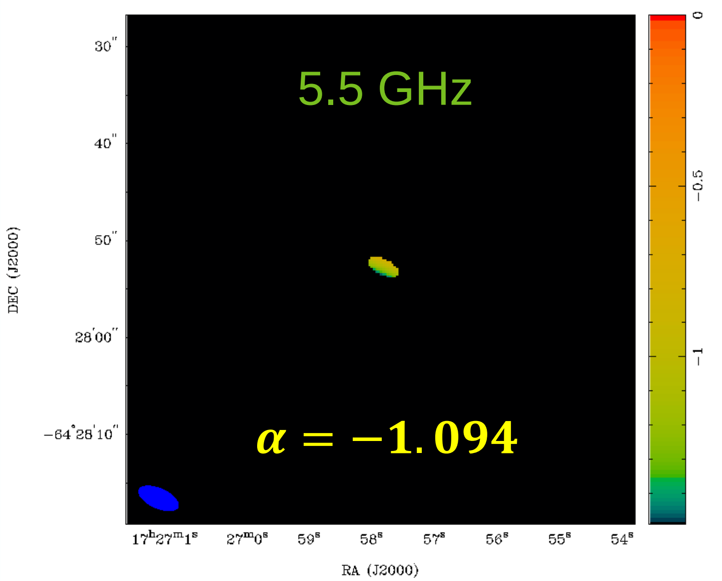
$$S_{avg} = \frac{S(\nu_0)\sum_{i=1}^{N_{chan}} \nu_i^{\alpha}}{\nu_0^{\alpha} N_{chan}}$$

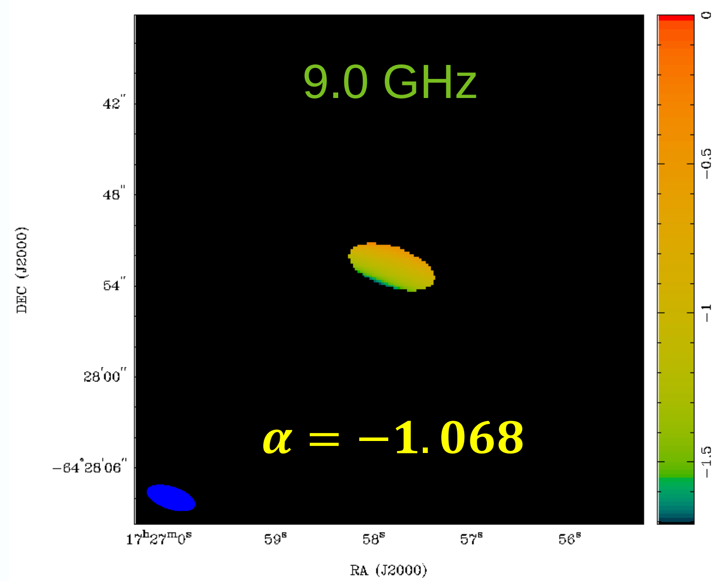
Correcting Image Flux Density

We can further rearrange to recover the flux density at the reference frequency:

$$S(\nu_0) = \frac{S_{avg}\, \nu_0^{\alpha}\, N_{chan}}{\sum_{i=1}^{N_{chan}} \nu_i^{\alpha}}$$

Measure the spectral indices from the images:





Correcting Image Flux Density

Frequency	Spectral f.d.	Image f.d.	Corrected Image f.d.
5.5 GHz	1.561 Jy	1.586 Jy (+1.6%)	1.564 Jy (+0.2%)
9.0 GHz	0.924 Jy	0.935 Jy (+1.2%)	0.930 Jy (+0.7%)

A substantial improvement in accuracy is achieved in this way.

Note that this only applies to linear spectral index with no curvature, and that the correction has to be done manually (Wolfram Alpha is your friend).

It is left as an exercise for the reader to deal with higher order α terms:

$$\alpha \rightarrow \alpha_0 + \log\left(\frac{\nu}{\nu_0}\right)\left[\alpha_1 + \log\left(\frac{\nu}{\nu_0}\right)\alpha_2\right]$$

Miriad cannot make images with higher order spectral index terms, but CASA can.

Average Frequency Calculation

Our correction equation is actually calculating the frequency that we are measuring at.

$$S(\nu_0) = \frac{S_{avg}\ \nu_0^{\alpha}\ N_{chan}}{\sum_{i=1}^{N_{chan}} \nu_i^{\alpha}}$$

Obviously, S_{avg} is actually $\mathrm{S}(\nu_{avg})$. Now compare with:

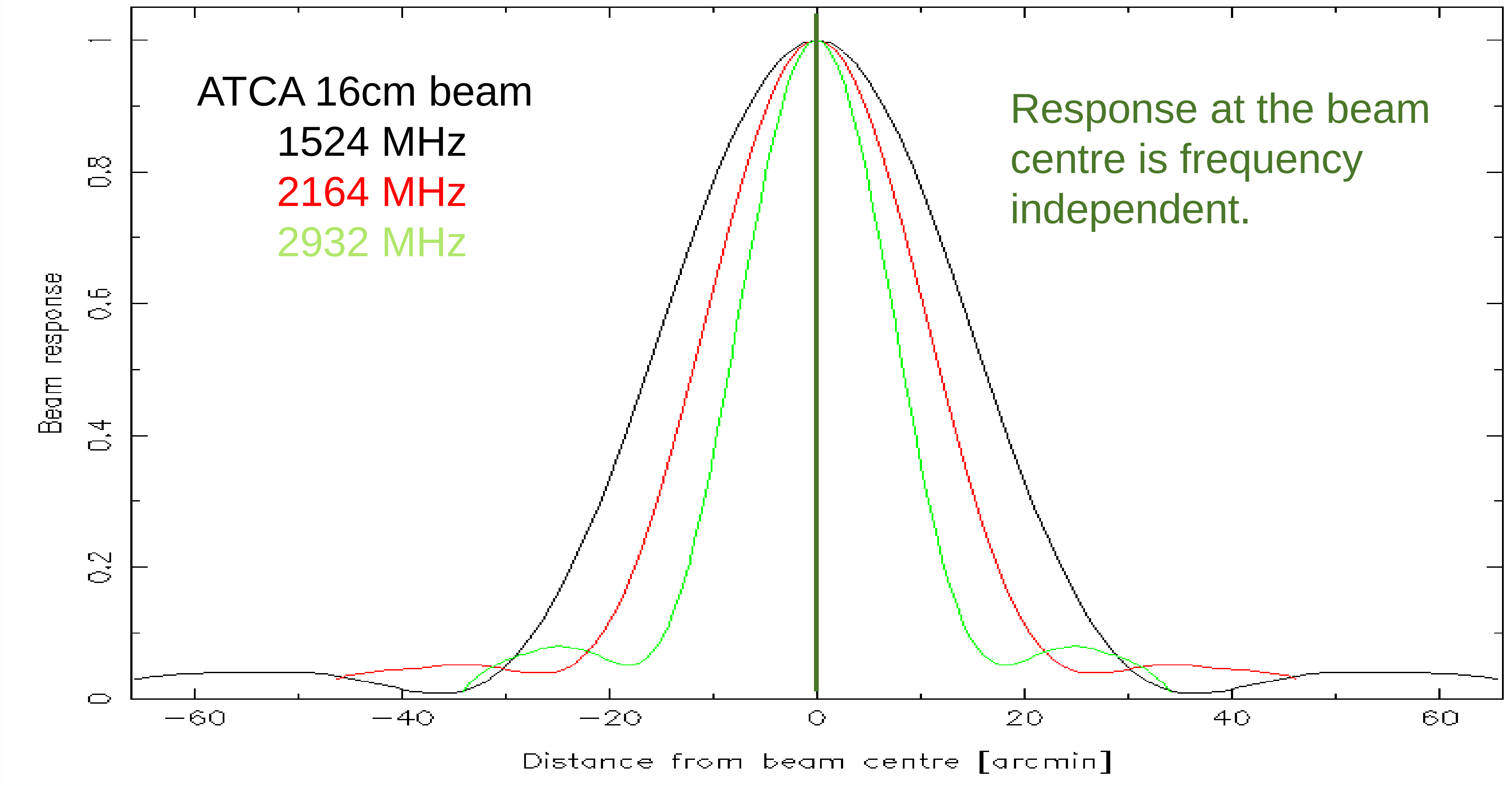
$$S(\nu_i) = S(\nu_0)\left(\frac{\nu_i}{\nu_0}\right)^{\alpha}$$

Identifying the correspondence and rearranging gives us the average frequency as:

$$\nu_{avg} = \left(\frac{N_{chan}}{\sum_{i=1}^{N_{chan}} \nu_i^{\alpha}}\right)^{\left(\frac{1}{-\alpha}\right)}$$

Correcting Spectral Index

Spectral index is dependent on the distance from the beam centre.



Correcting Spectral Index

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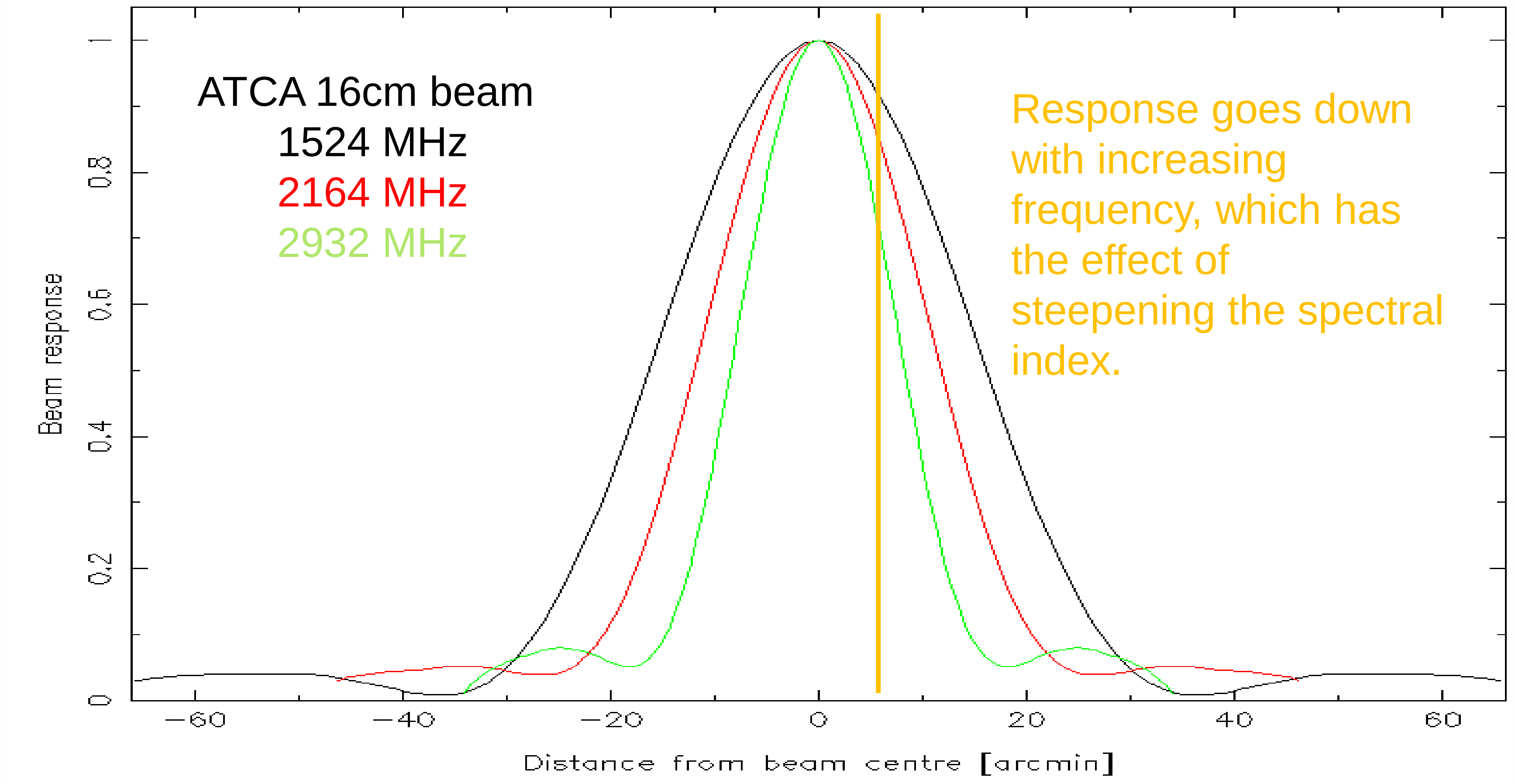
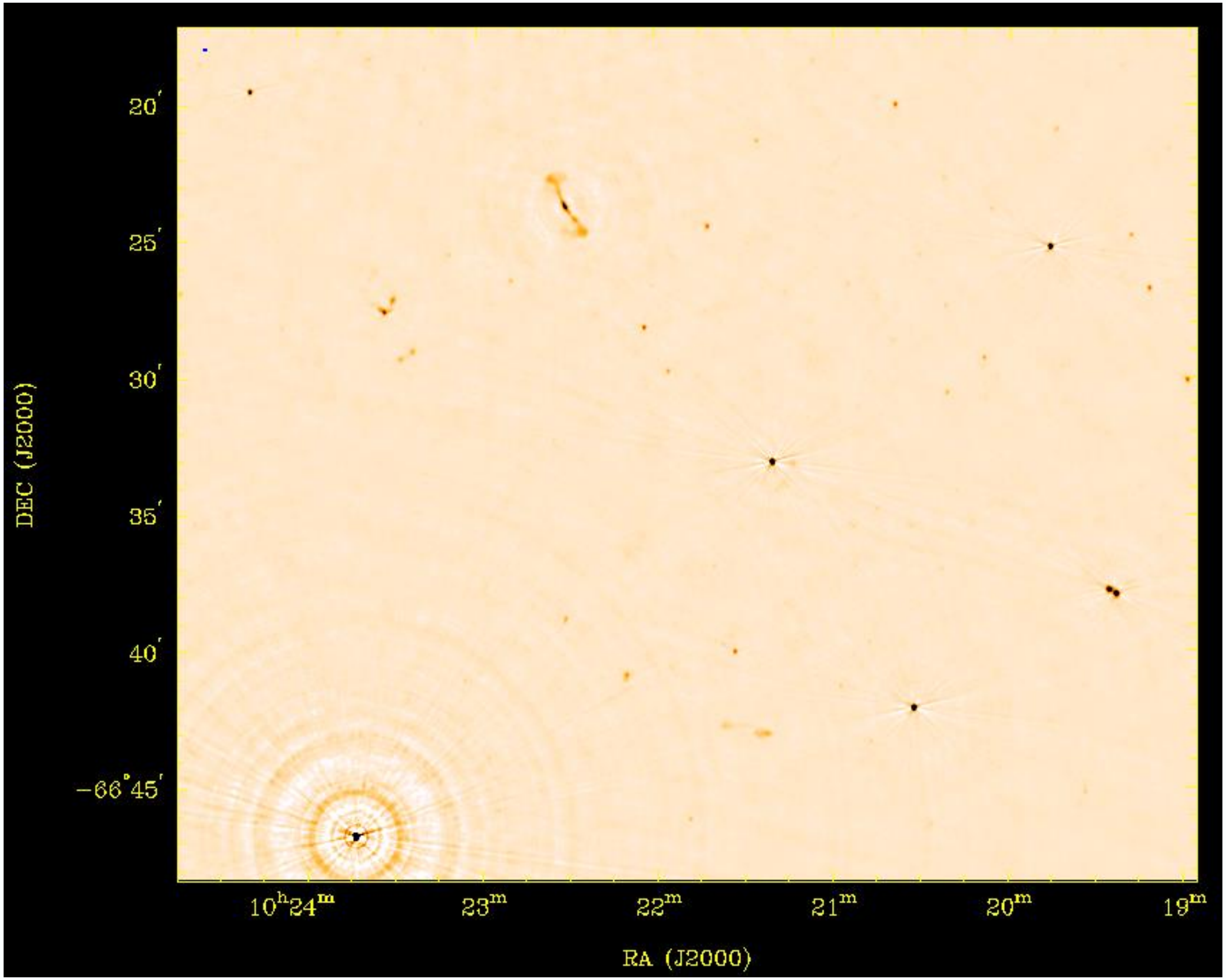
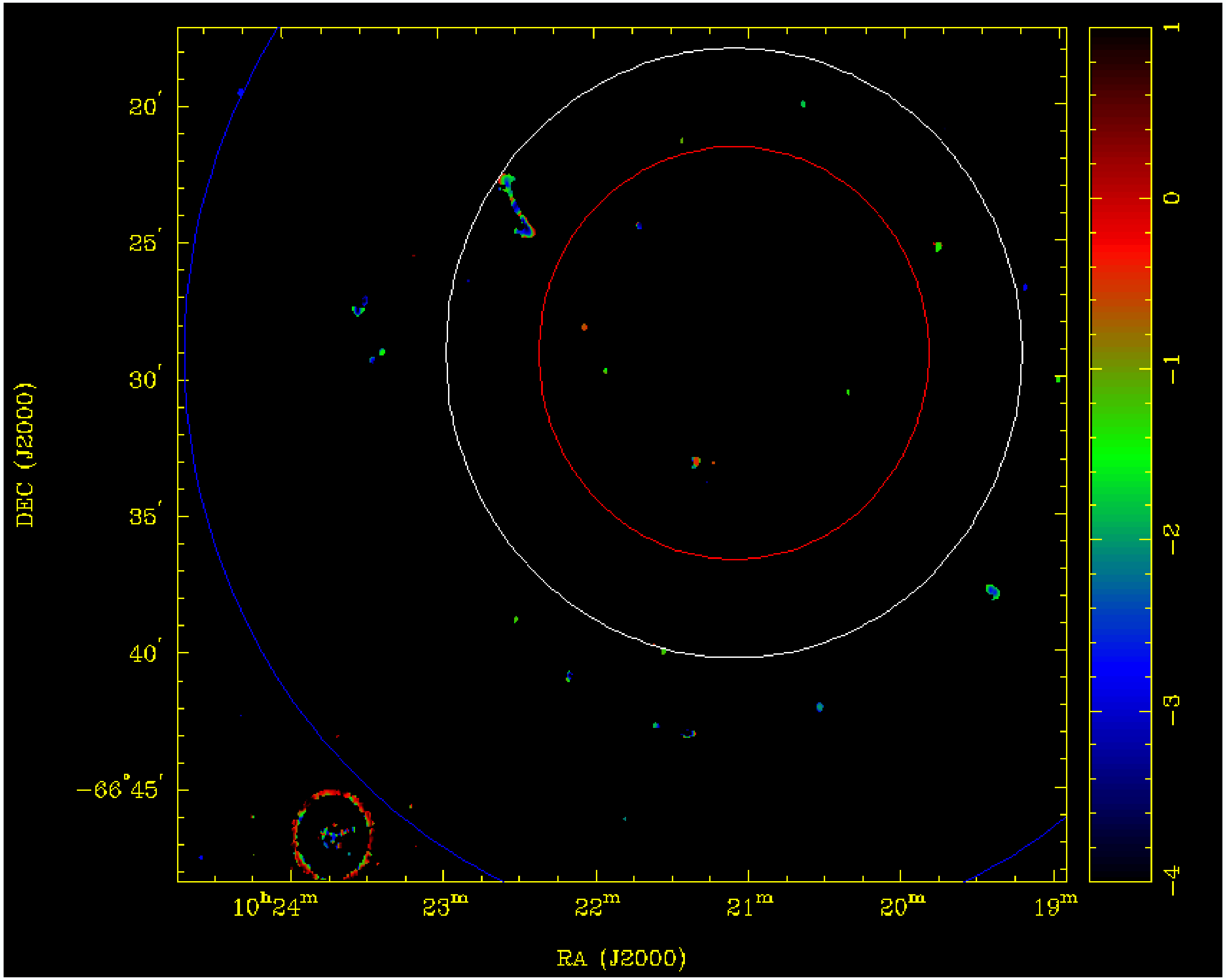


Spectral Index Correction



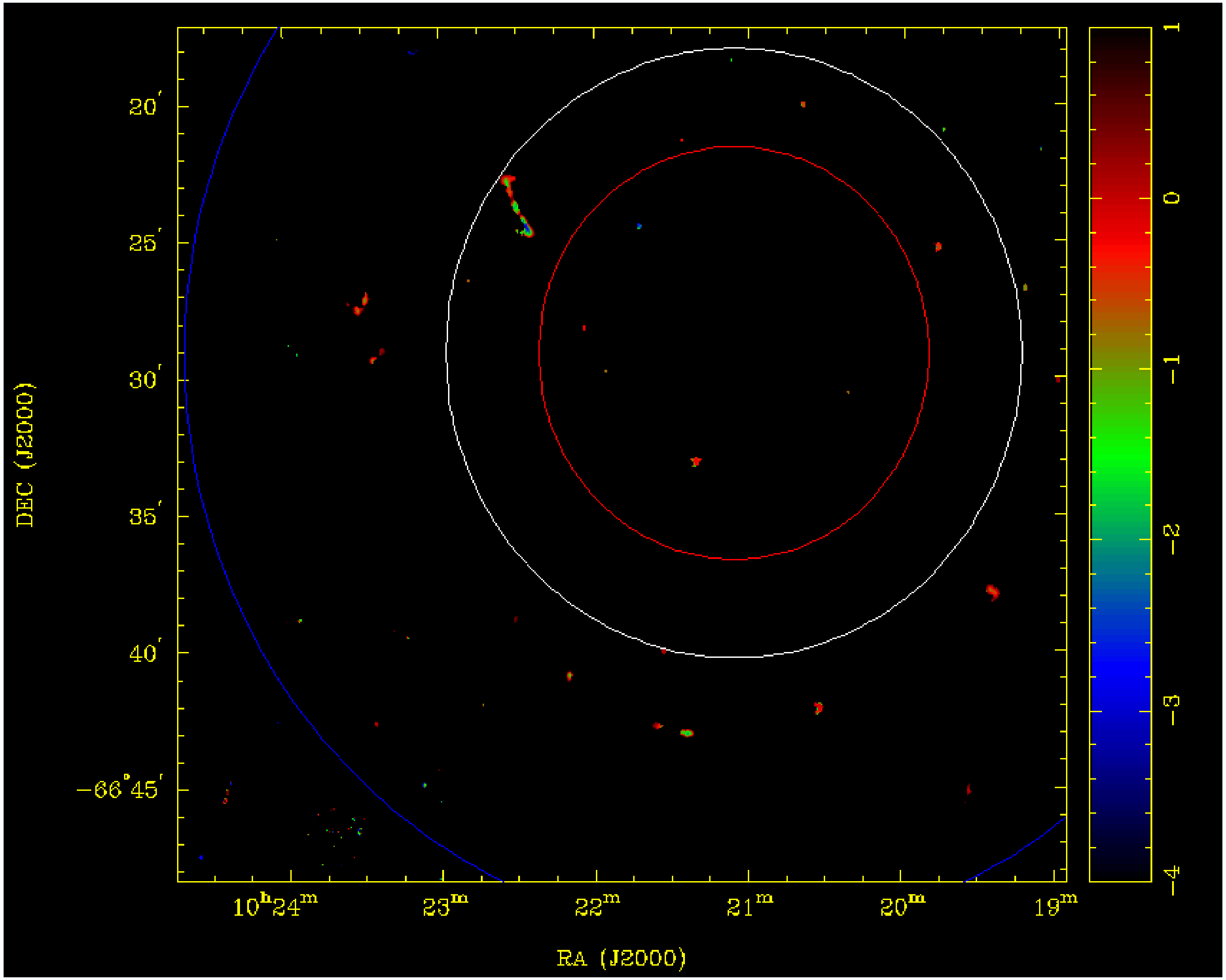
Spectral Index Correction

Not PB corrected

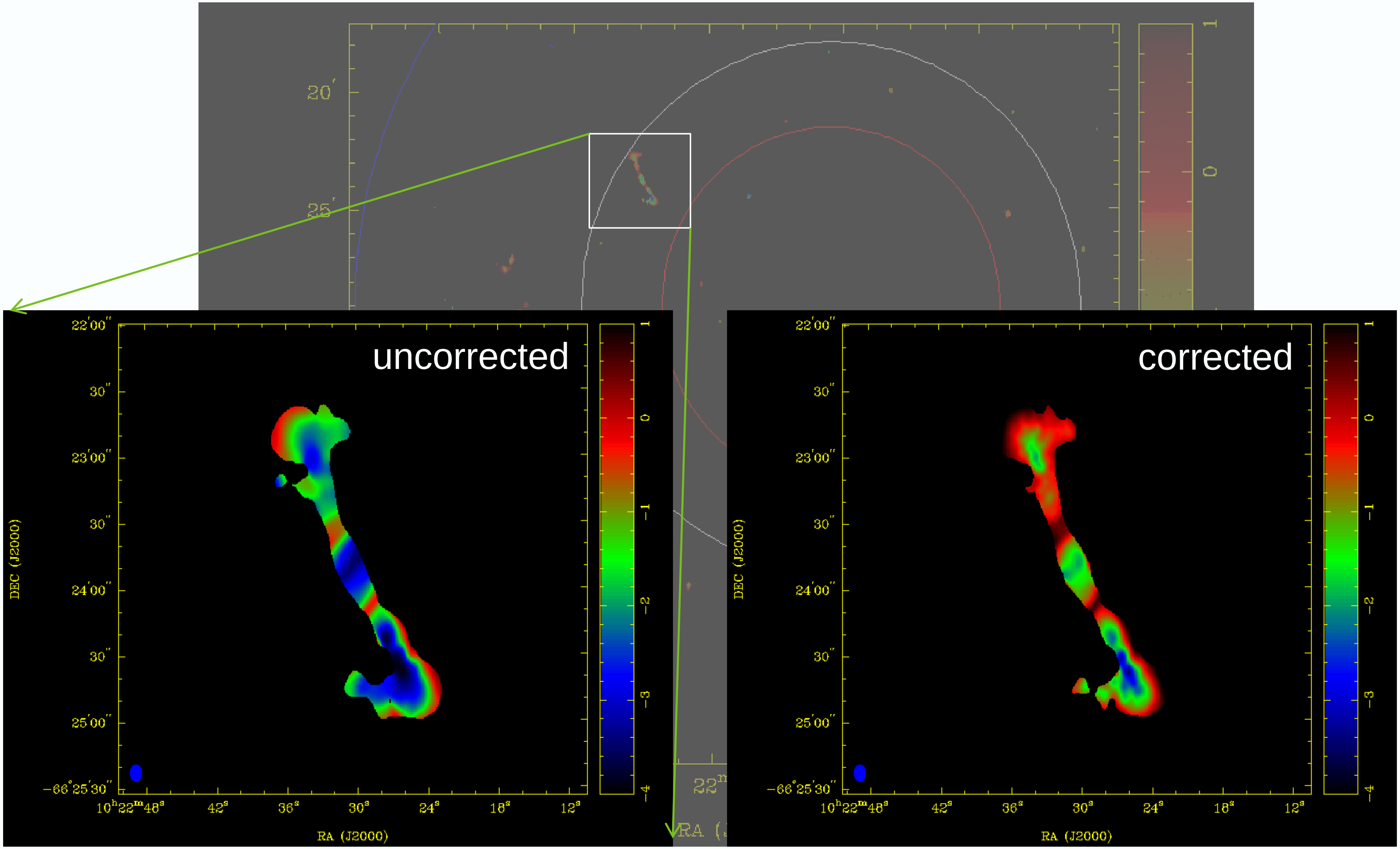


Spectral Index Correction

PB corrected



Spectral Index Correction



Summary

When imaging with wide bandwidths

DON'T	average over too much fractional bandwidth
DO	calibrate using the spectral index of the calibrators
DO	Correct for beam response changes with frequency when calculating spectral index
DO	Use the measured spectral index to correct any measured flux densities

Thank you

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