An Introduction to Interferometry

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Interferometry is needed at radio/millimetre/submillimetre wavelengths because of the limitations of building large single dish telescopes.

- Spacing the antennas out provides better angular resolution.
- Adding more antennas provides more collecting area.

(Credit: ESO)

Having said this, single dish telescopes still have some key advantages over interferometers.

- Single dish telescopes can measure the total energy from objects.
- Single dish telescopes can usually map large areas more effectively.

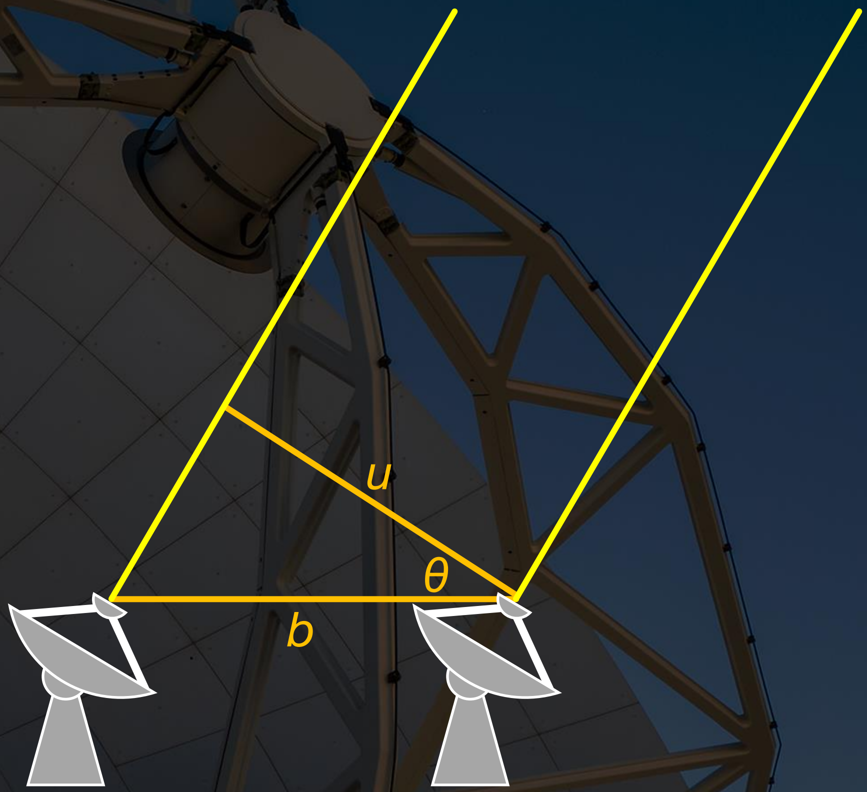
(Credit: Large Millimeter Telescope)

In the classical diagram of two antennas, an electromagnetic wave will travel further to one antenna than the other.

The waves will appear out of sync.

The separation of the antennas is measured by *b*, but their separation as projected onto the sky is *b* cos θ, which is set to *u*.

In two dimensions, *u* and *v* are used to describe the separation of the antennas as projected onto the sky.



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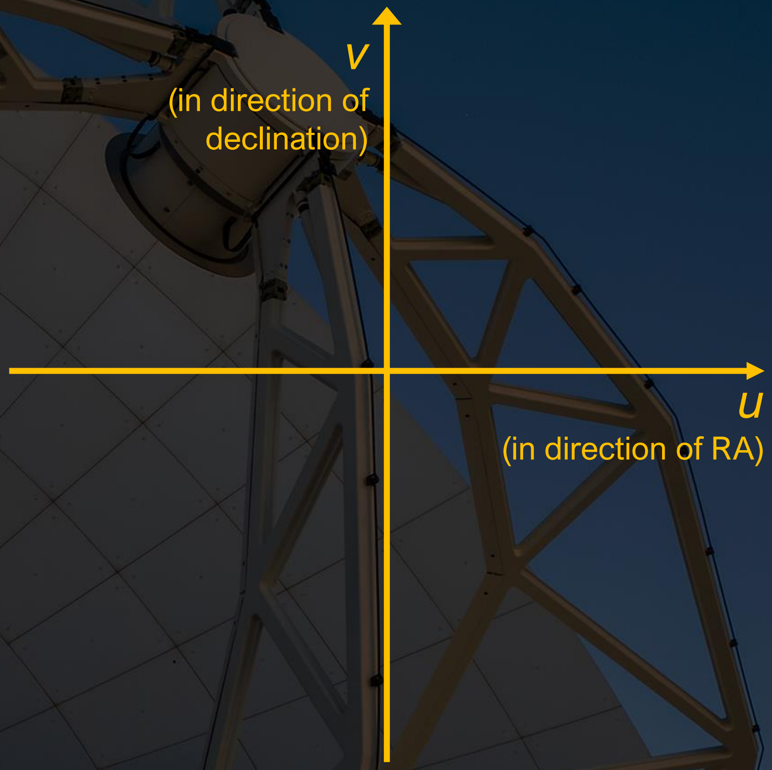
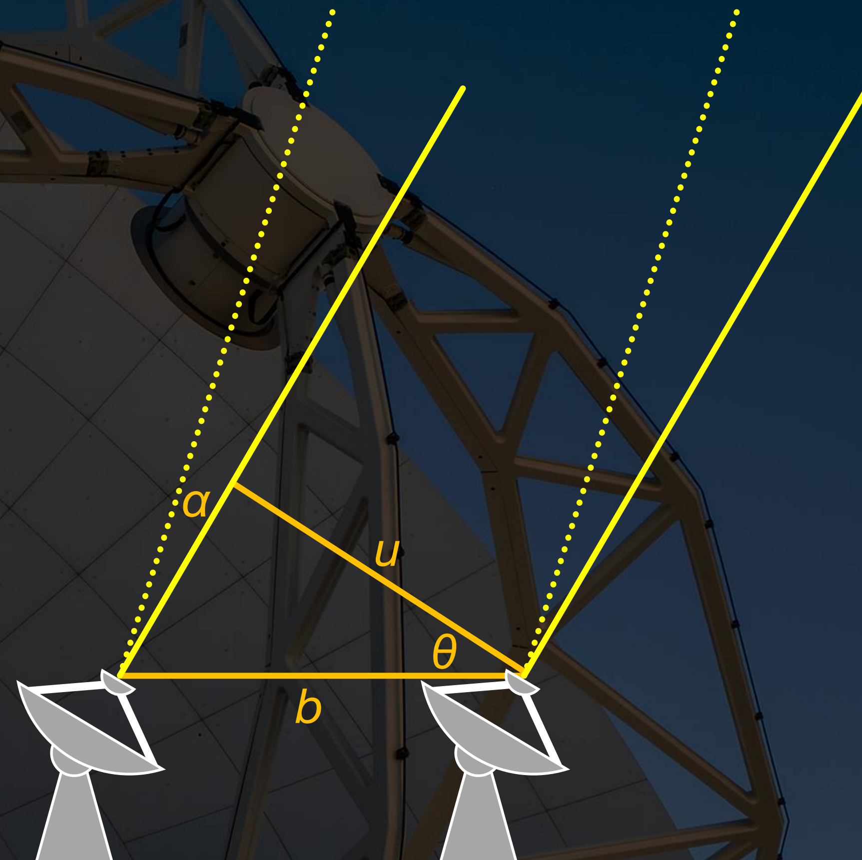


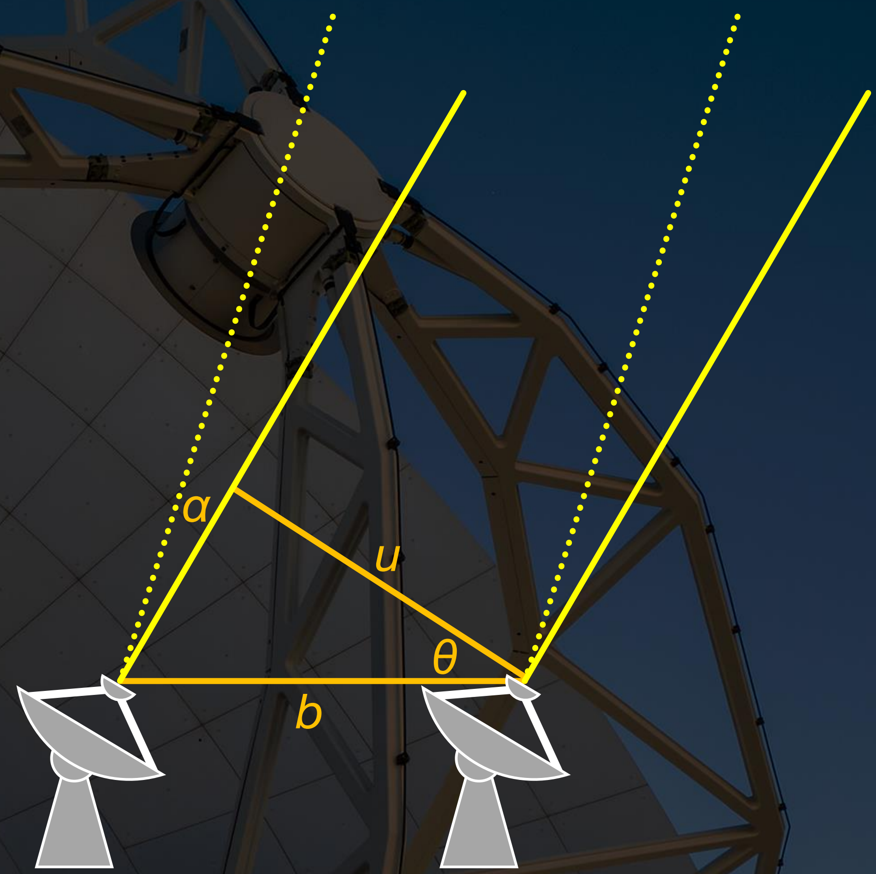
Shifting an object off-axis results in an extra change in the path length that can be written as $u \sin \alpha$ or ul.

The equivalent in the orthogonal dimension is written as vm.



The relations between the signals measured by the two antennas can be written as

$$V_2 = V_1 e^{2\pi i(ul+vm)}$$



Typically, interferometers do not record the measurements from individual antennas but from pairs of antennas.

The signals from pairs of antennas multiplied together and averaged using correlators.

(Credit: ALMA (ESO/NAOJ/NRAO), S. Argandoña)

The resulting output signals are called complex visibilities. The visibilities can be written as

$$\mathcal{V}(u,v) \propto \iint V_1(l,m)\, V_2(l,m)\, dl\, dm$$

$$\mathcal{V}(u,v) \propto \iint V_1(l,m)^2\, e^{2\pi i(ul+vm)}\, dl\, dm$$

$$\mathcal{V}(u,v) = \iint \mathcal{I}(l,m)\, e^{2\pi i(ul+vm)}\, dl\, dm$$

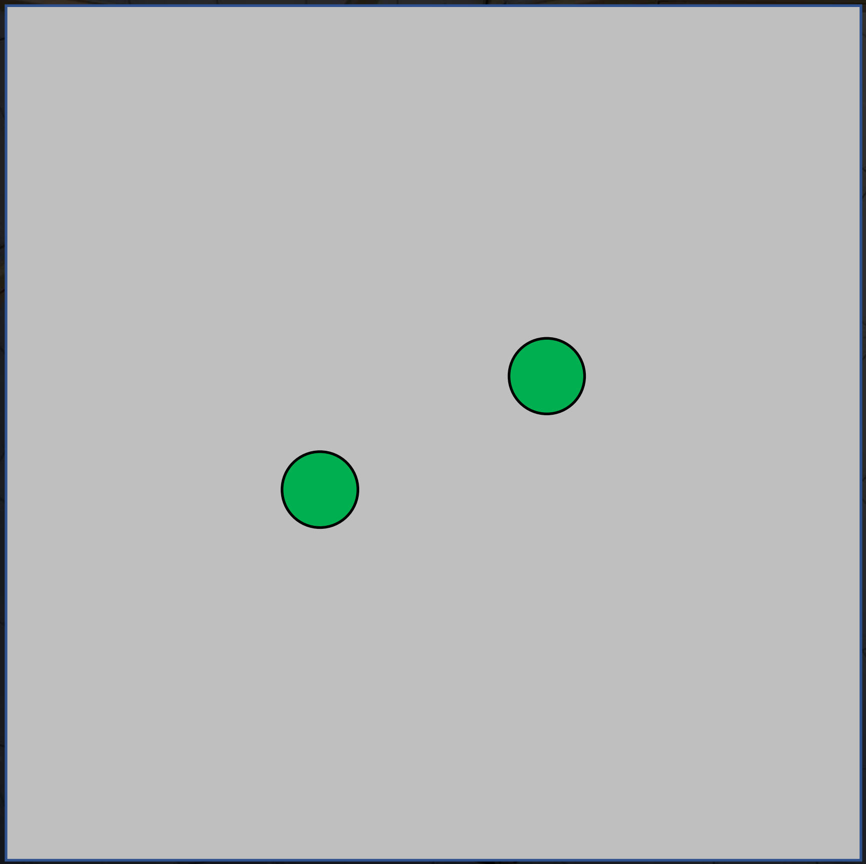
$$\mathcal{V}(u,v) = Aei^{\varphi}$$

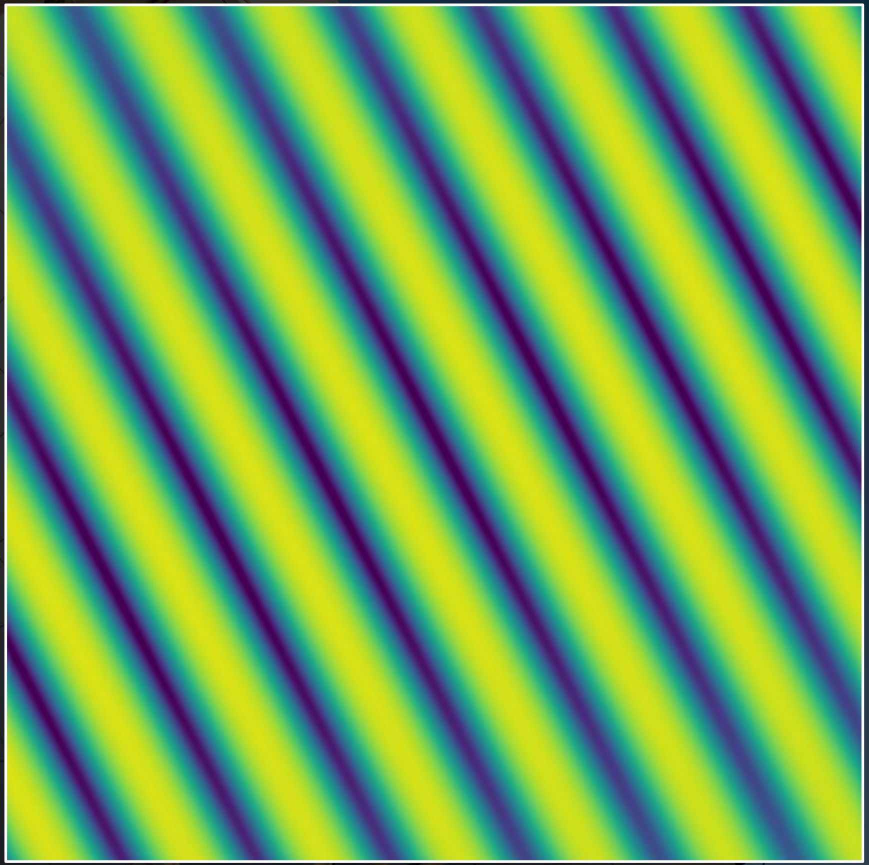
The amplitudes (*A*) from the correlator output describe the total amount of emission measured by the antenna pair (which corresponds to a specific spatial scale as will be described in the next slides).

The phases (φ) from the correlator output describe the position of the emission offset from the centre of the beam of the telescope.

The calibration process involves making corrections to these amplitudes and phases that account for and remove effects related to the atmosphere, the weather, and the instrument.

Each pair of antennas is effectively sensitive to emission on a specific spatial scale. Antennas that are closer together can detect emission on larger scales, while antennas that are further apart can detect emission on smaller scales.





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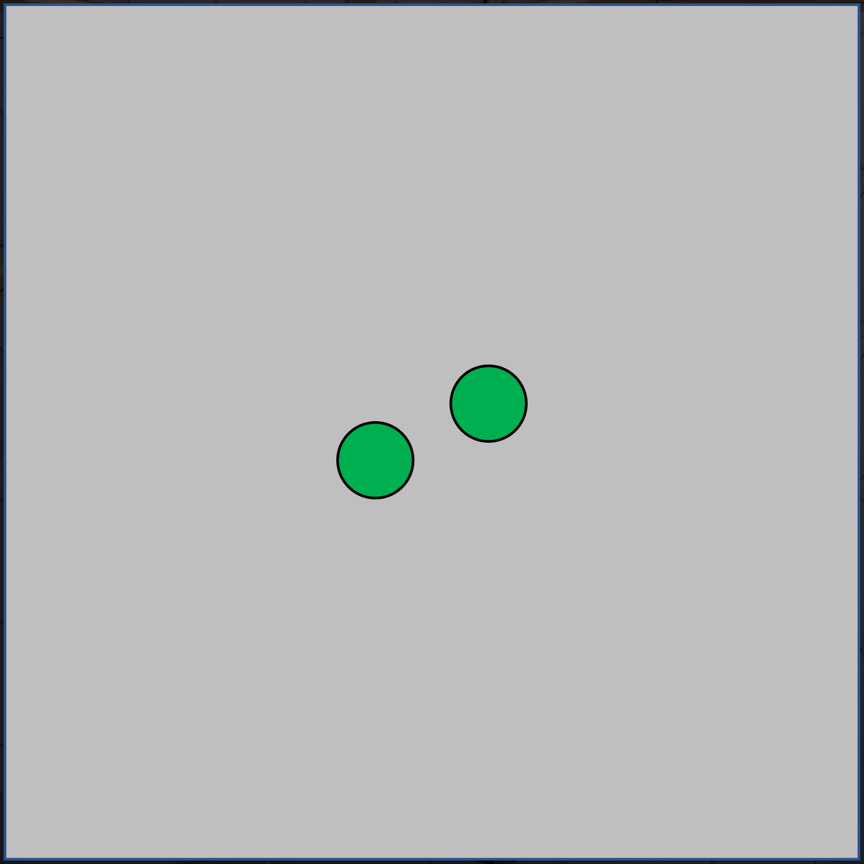

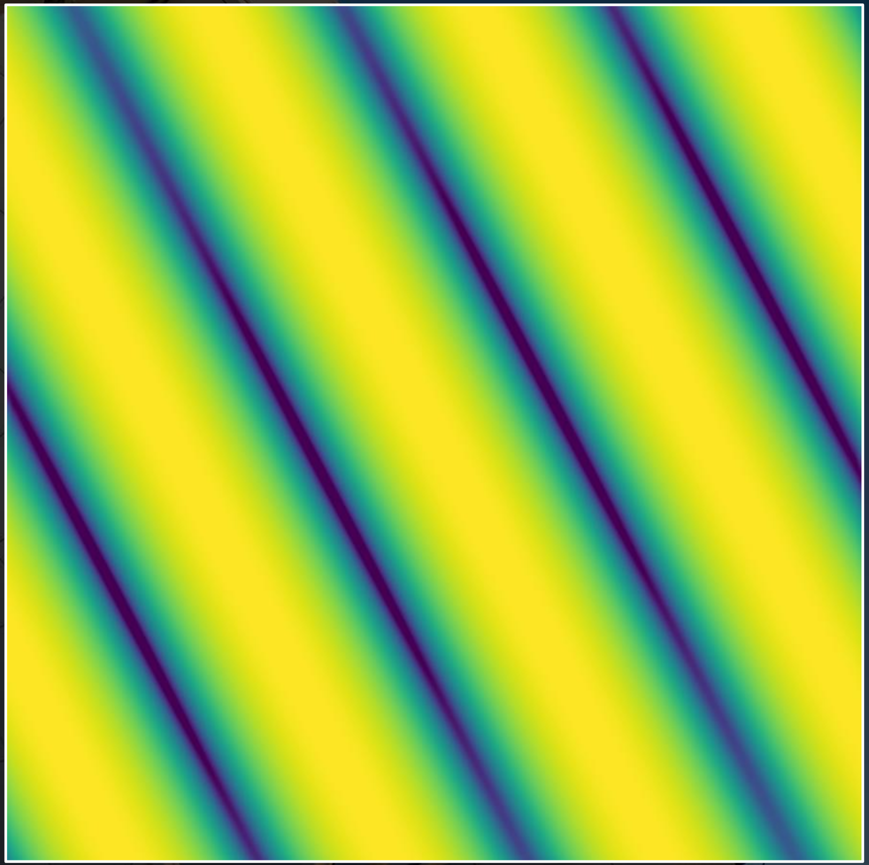

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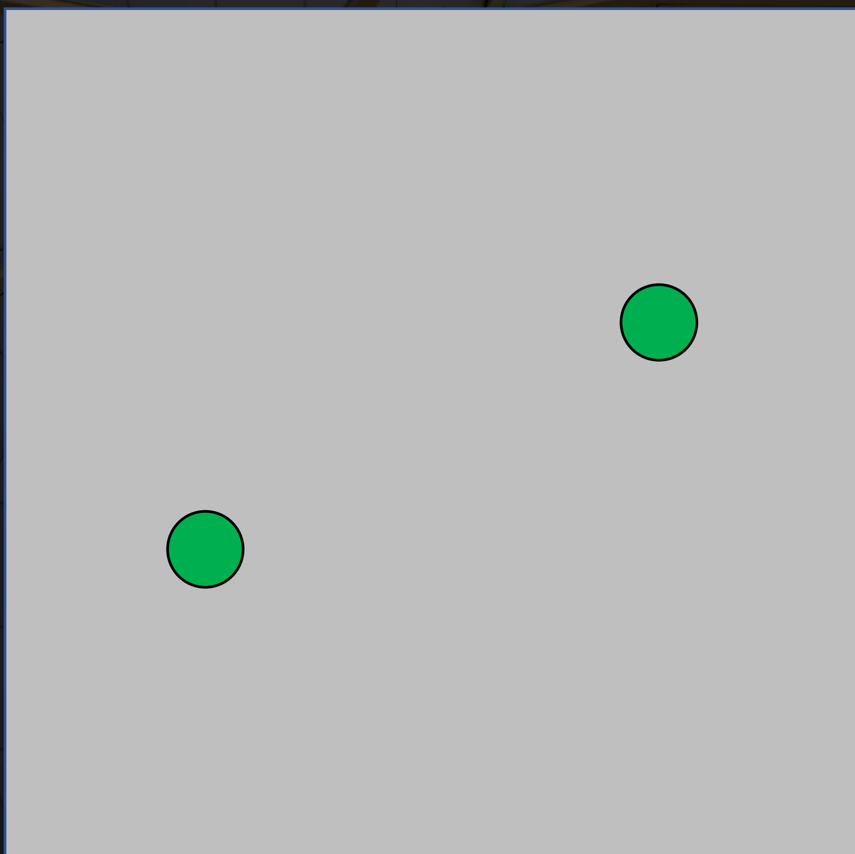
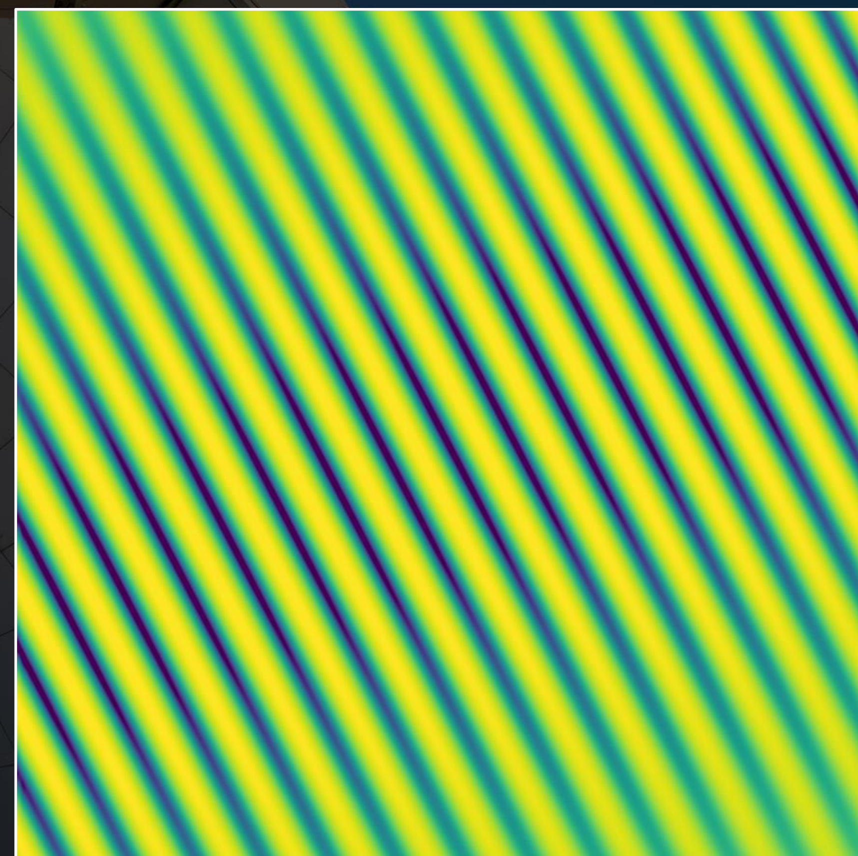
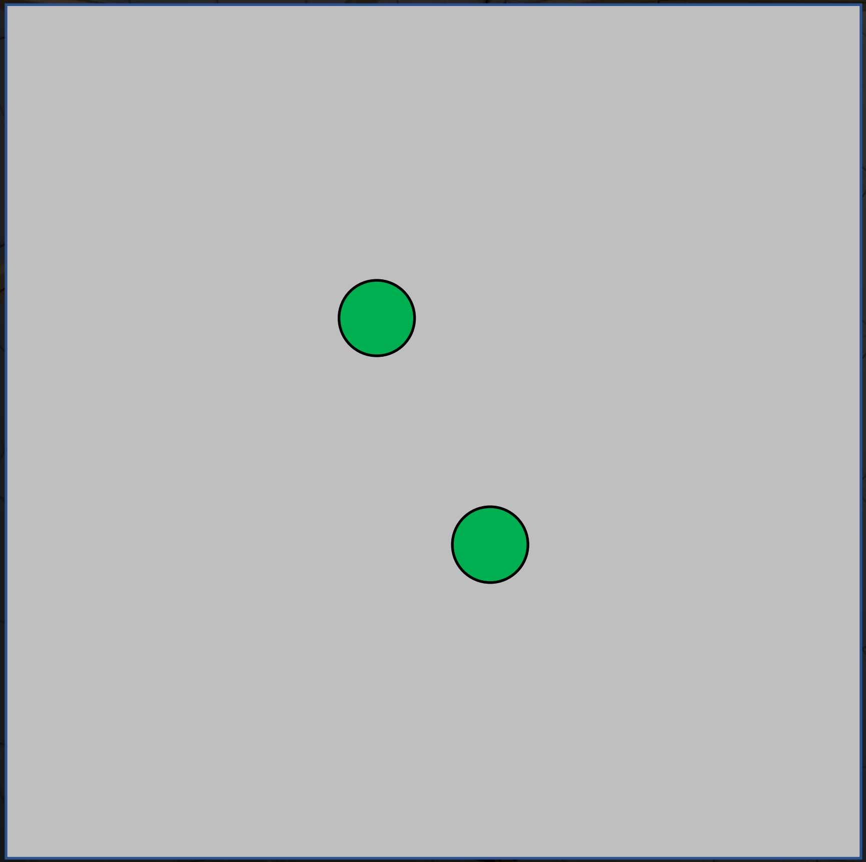
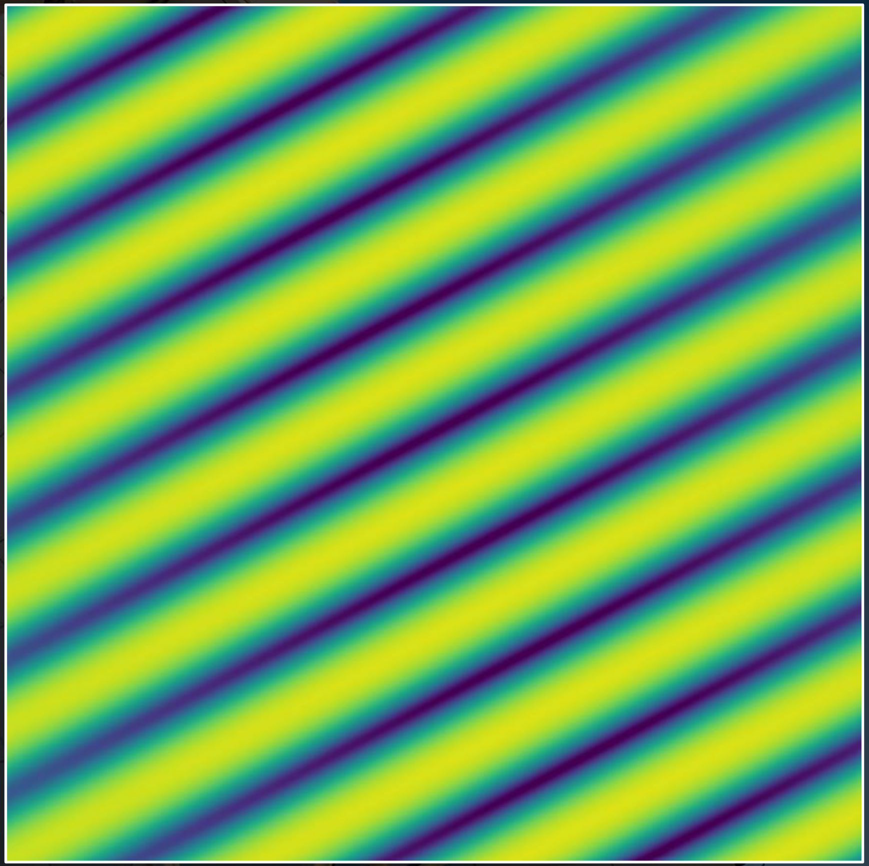


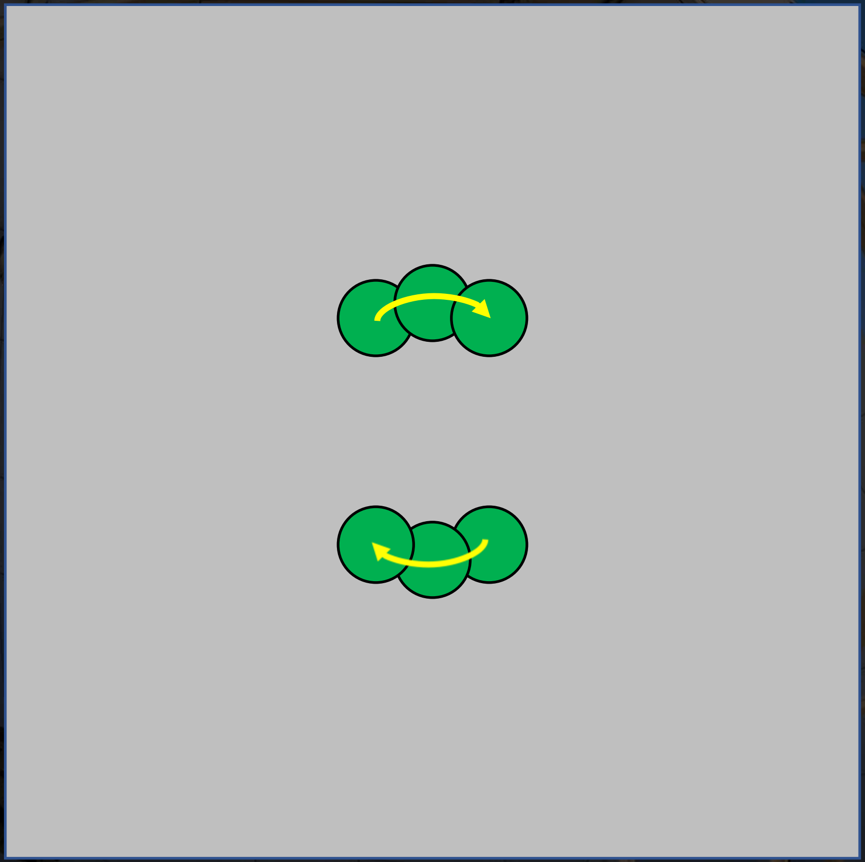


The relative orientation of the antennas is also important. To measure emission in two different dimensions, it is important to have two pairs of antennas with orthogonal orientations.

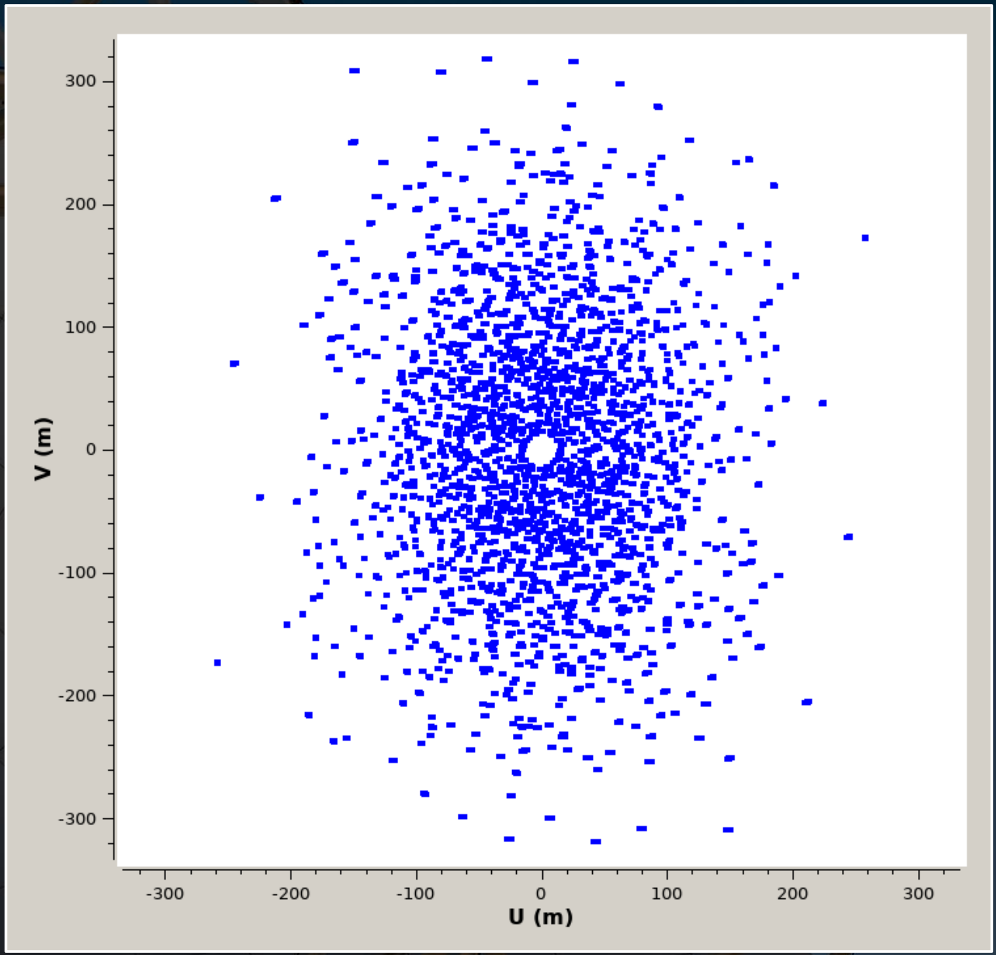




Also, the relative orientation of a pair of antennas as projected on the sky will change as the Earth rotates. This can be useful for measuring structures in the sky on different angles.



The projection of the baselines of all of the antennas on the sky is referred to as the uv coverage of the interferometer.

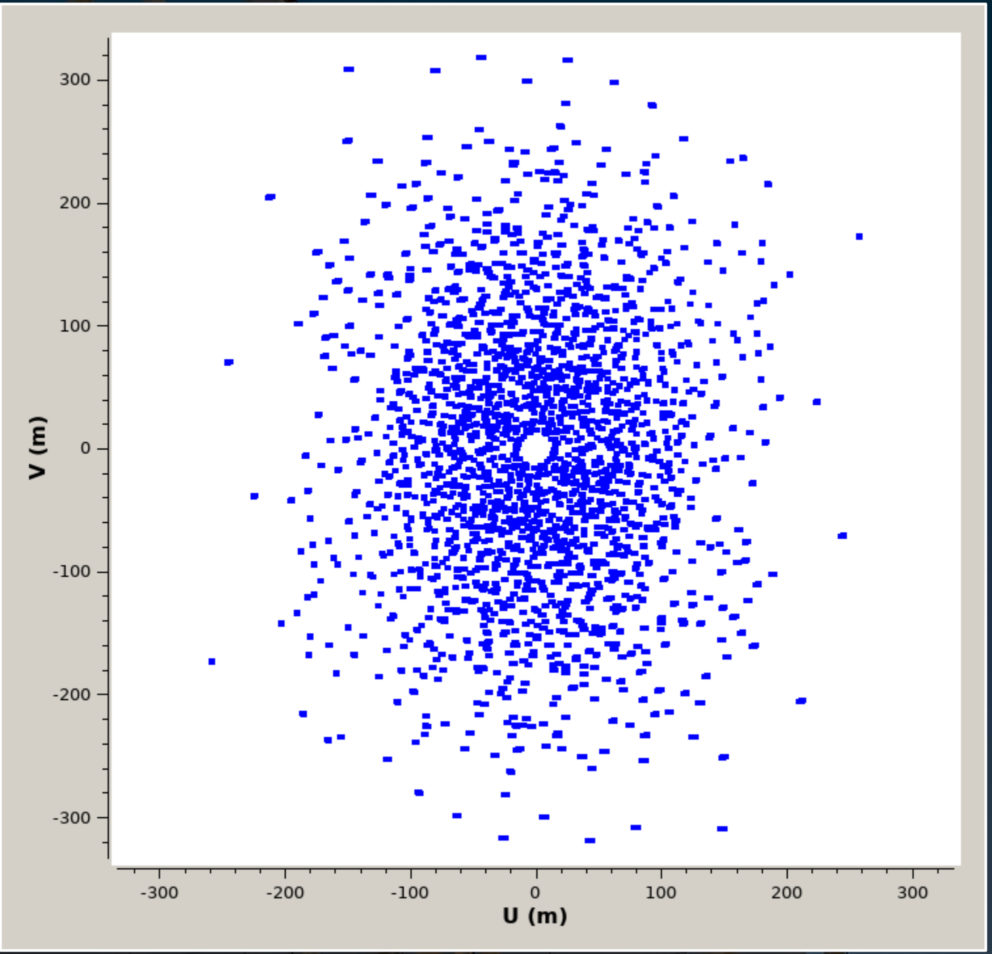


The visibilities are related to the emission from the sky through a Fourier transform.

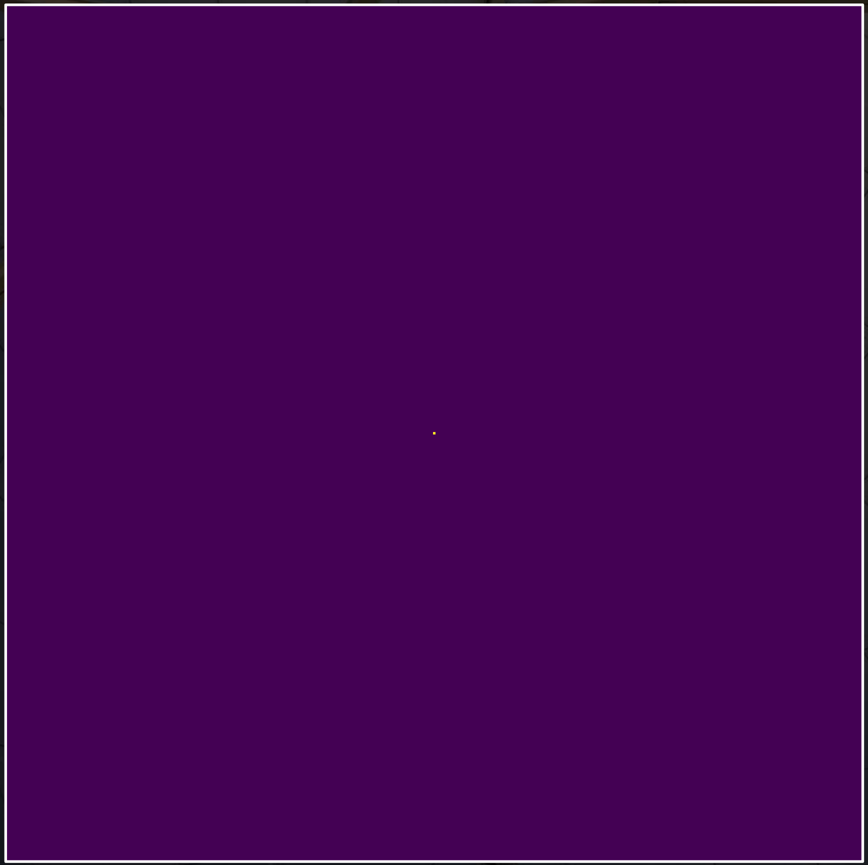
$$\mathcal{I}(l,m)= \iint \mathcal{V}(u,v)\, e^{-2\pi i(ul+vm)}\, du\, dv$$

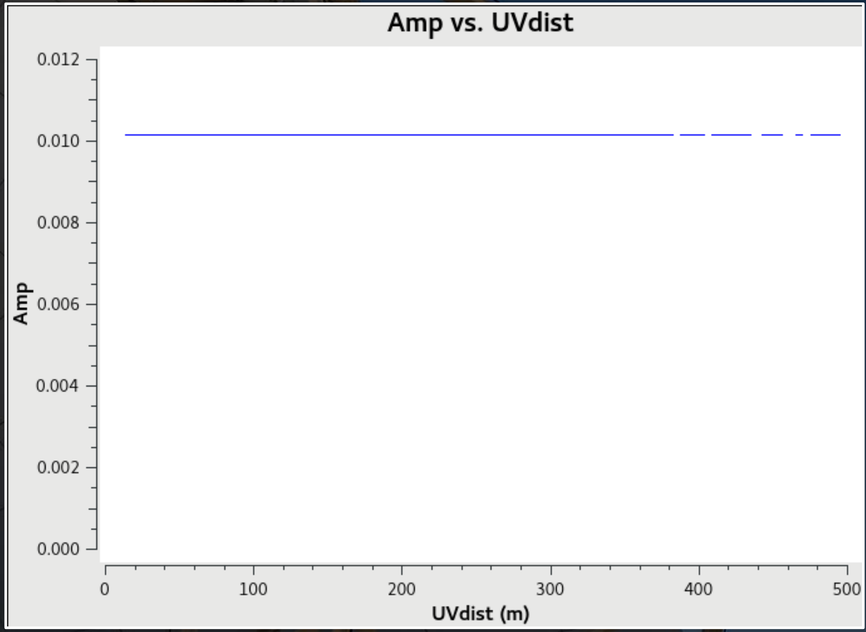
The uv coverage is therefore directly related to the Fourier transform of the spatial scales that are measured in the sky.

It is important to fill in the uv coverage as much as possible to measure emission on all spatial scales.

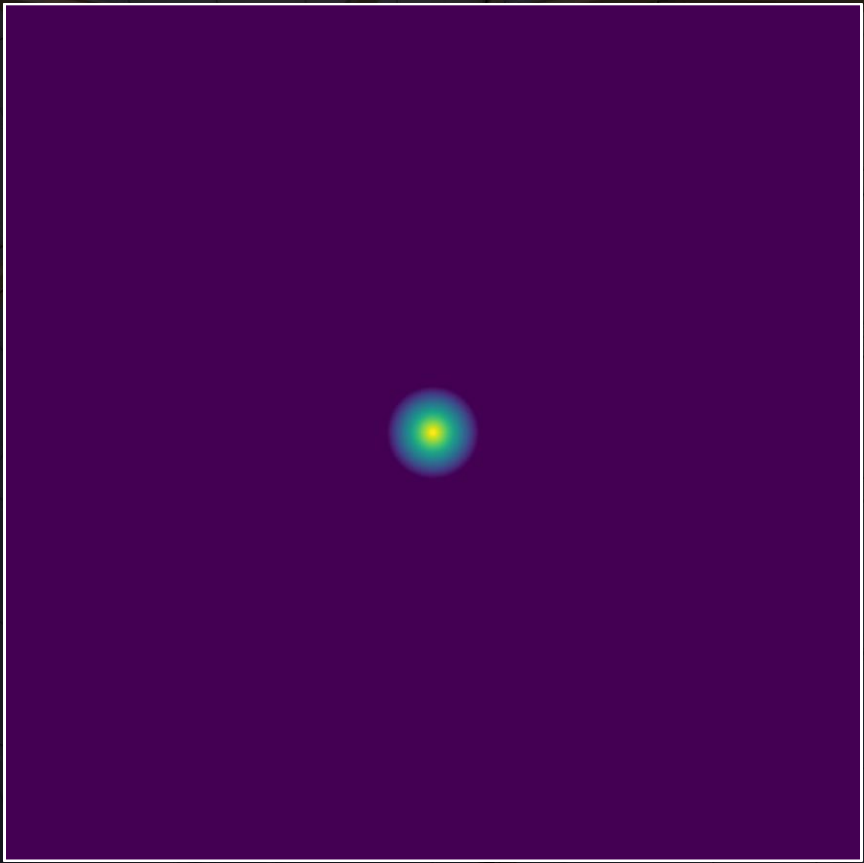


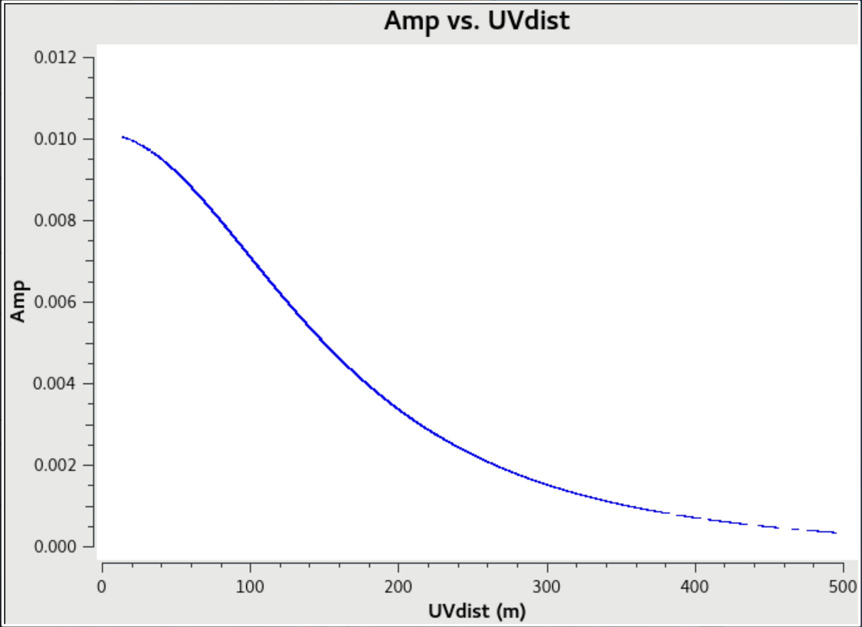
Plots of the amplitudes versus uv distance are effectively similar to what the objects look like after undergoing Fourier transforms. Different objects will appear differently in these plots. Point sources (or unresolved sources) will appear as flat lines.





The amplitudes for exponential disks (or other extended objects) will decrease as a function of uv distance. The size of the object in uv space is inversely related to the size of the object as it appears on the sky.





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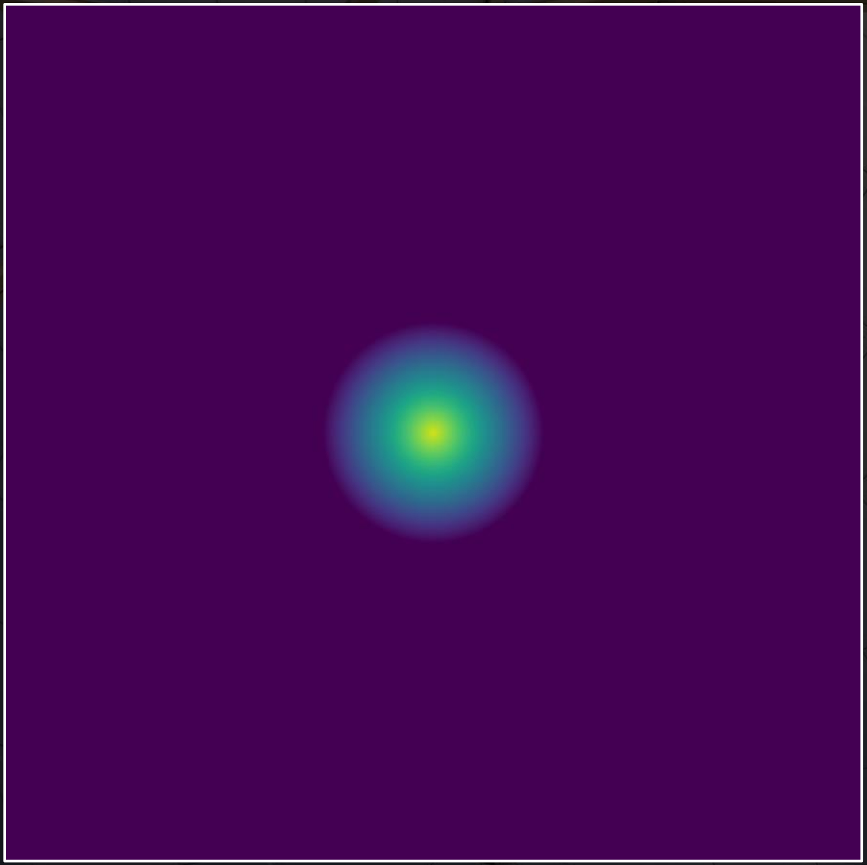
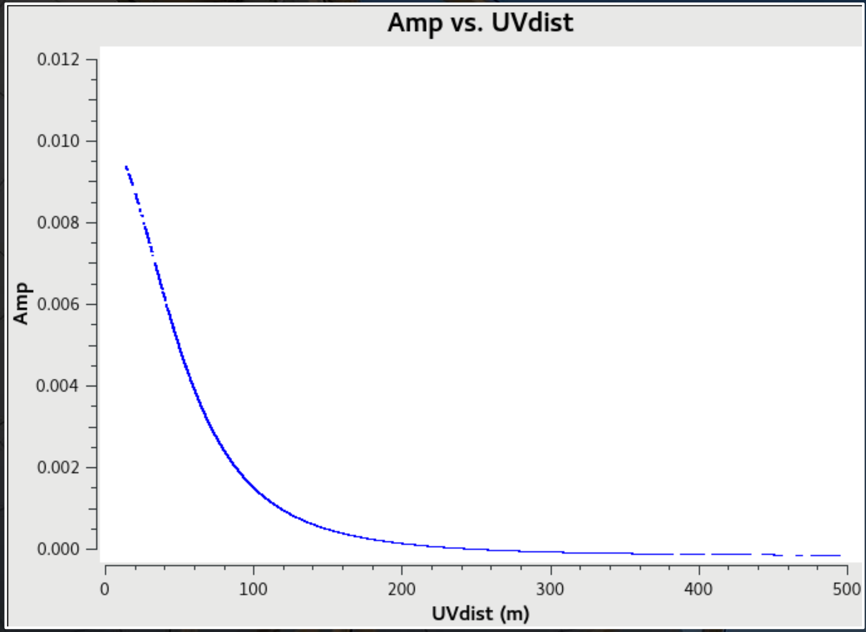
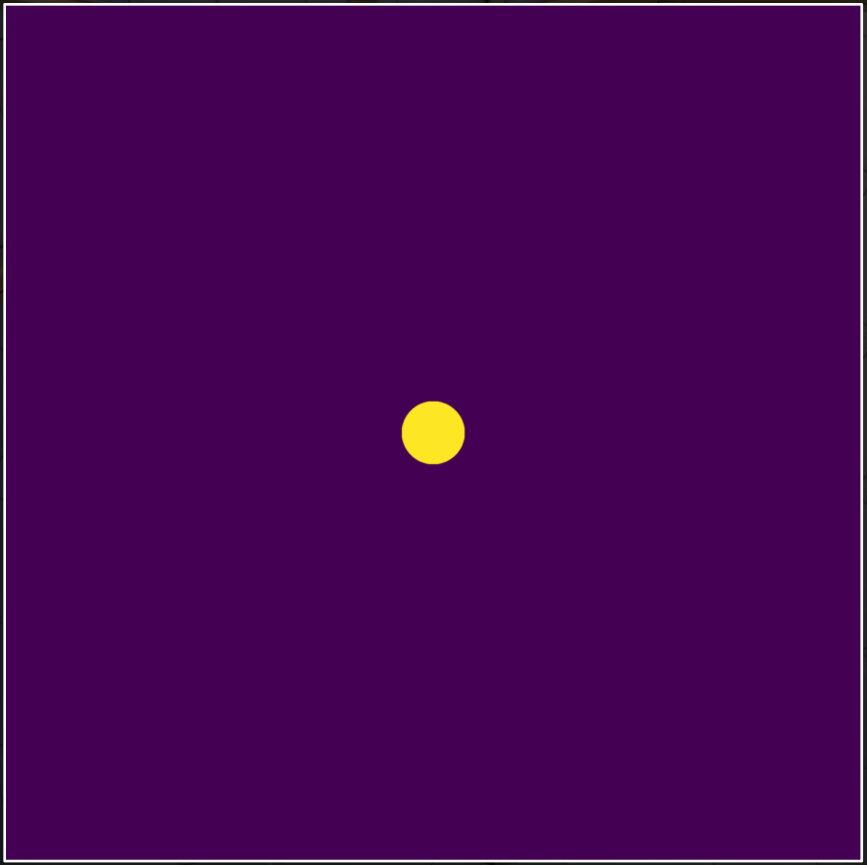
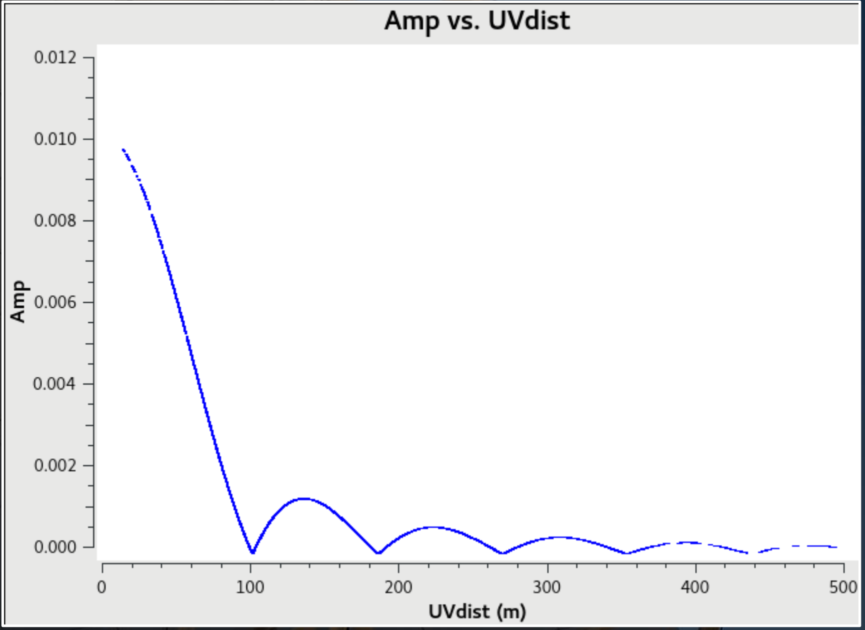




The amplitudes for planets will look like $sinc^2$ functions. Planets are often used for flux calibration. However, because the signal drops to 0 at large uv distances, only the data from short uv distances (corresponding to short baselines) can be used for deriving the flux calibration.





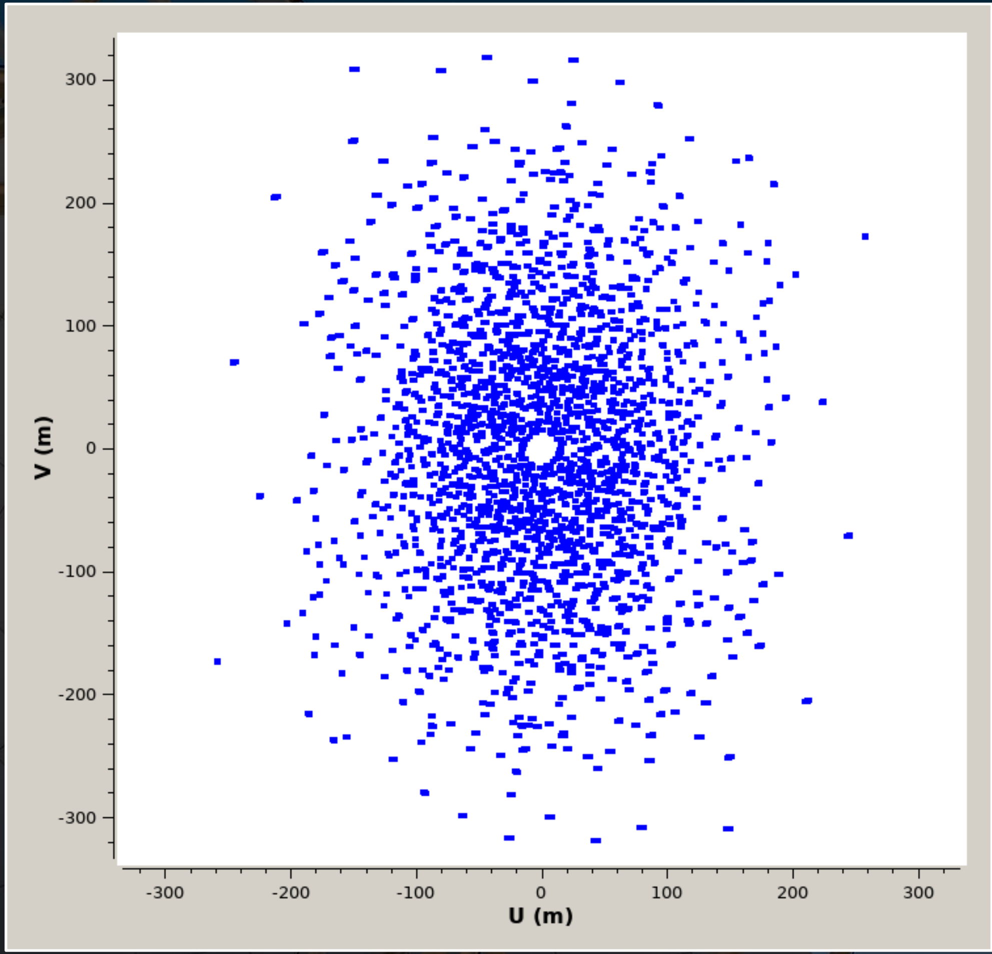
The angular resolution of an interferometer is given by

$$\theta_{beam} = 1.22\,\lambda\,/\,L_{max}$$

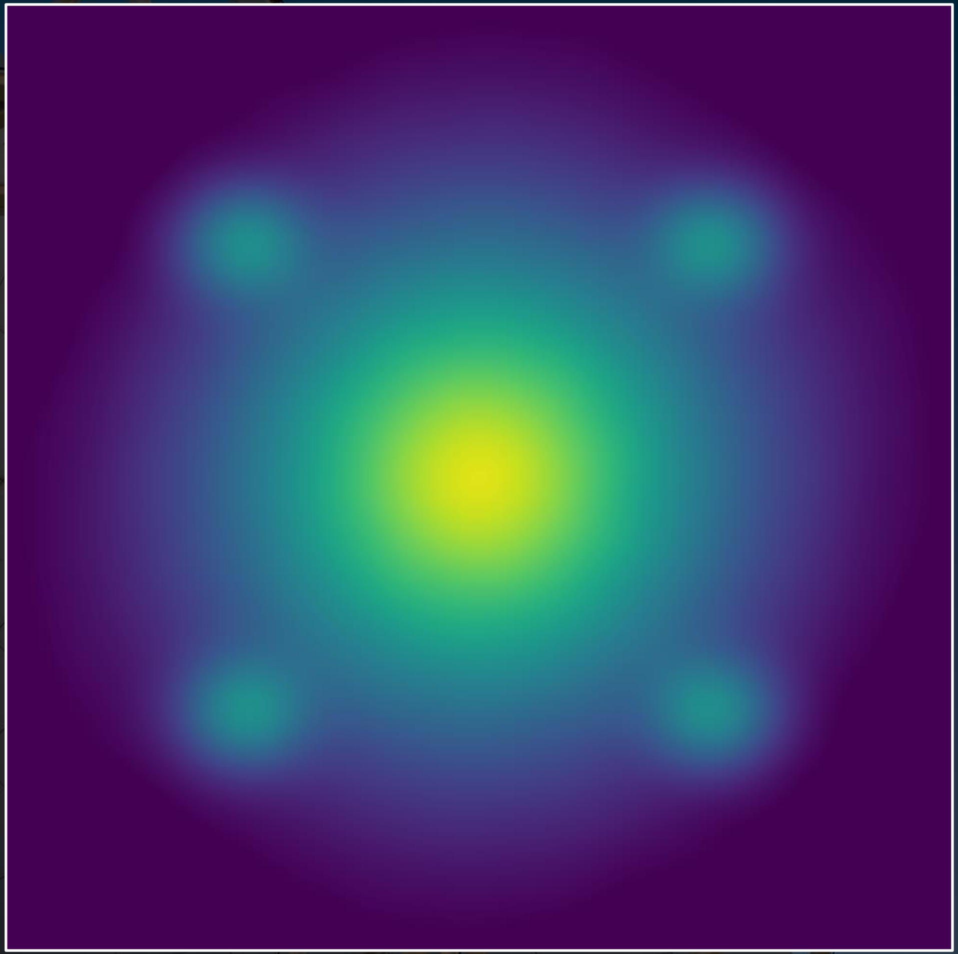
which is a classic angular resolution equation.

However, interferometers cannot measure emission on spatial scales smaller than

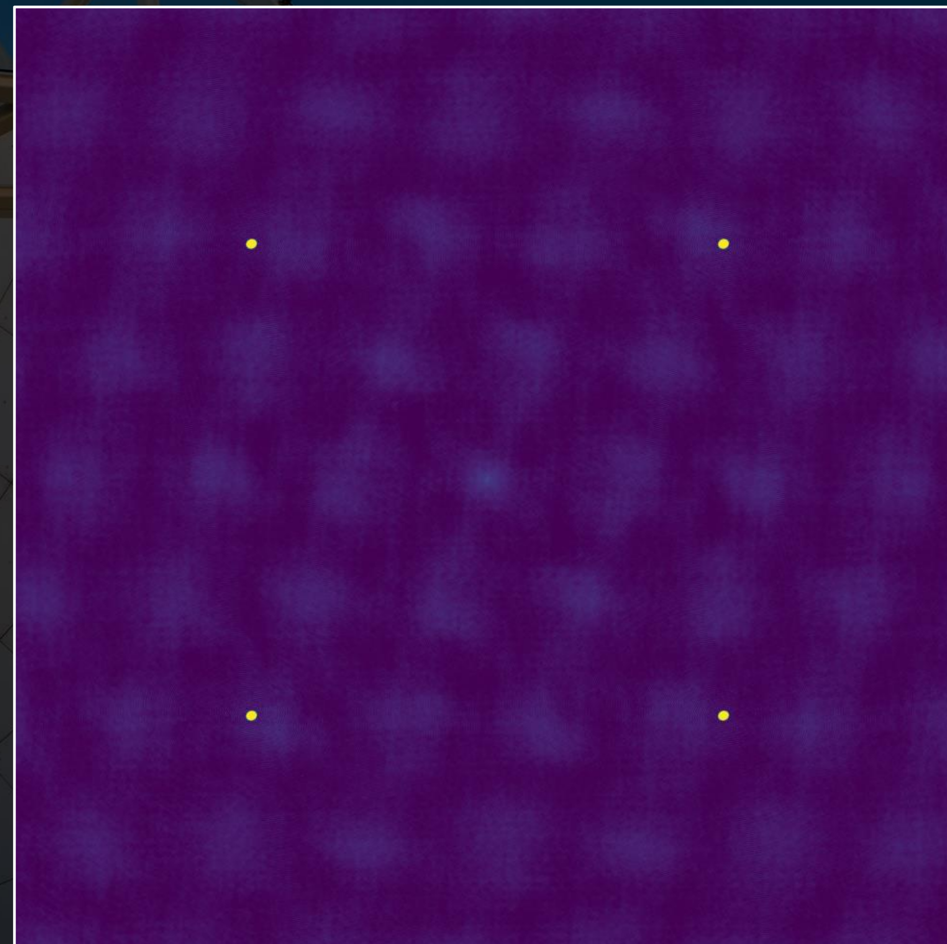
$$\theta_{MRS} = 0.6\,\lambda\,/\,L_{min}$$



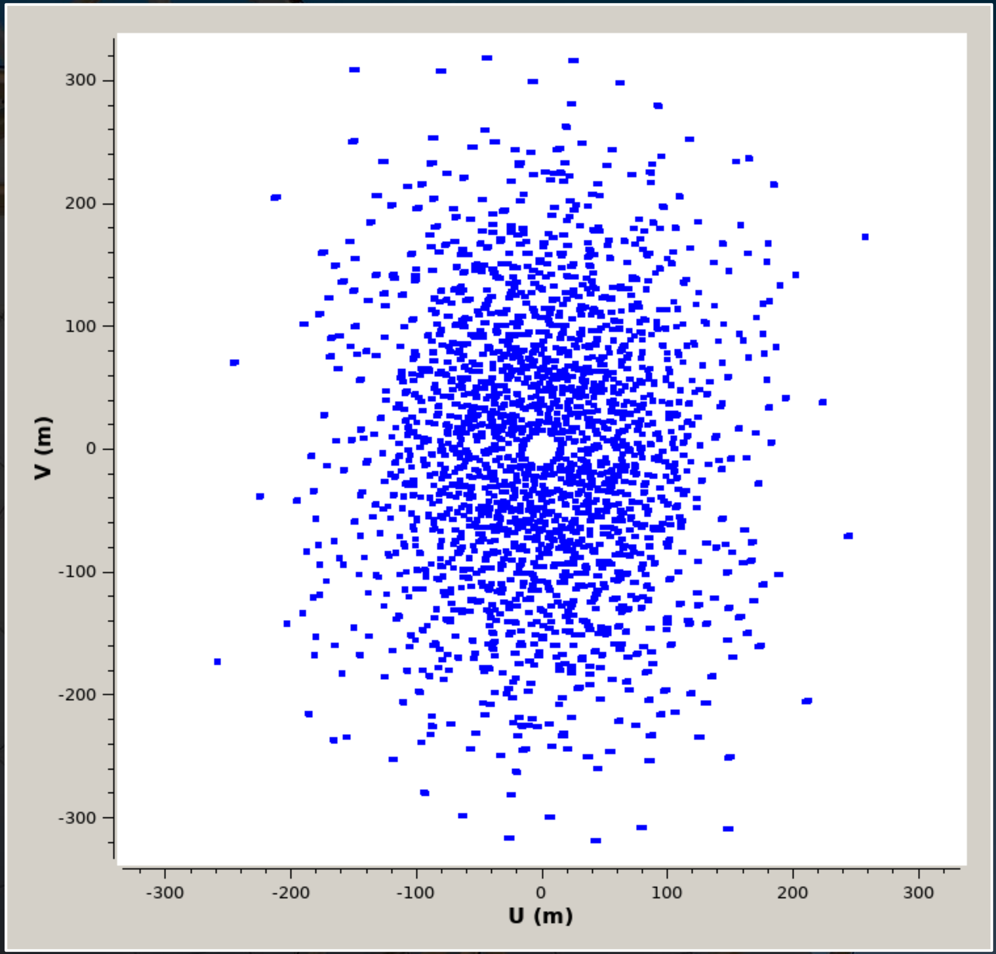
Imaging a field with a compact interferometry array will reproduce more extended structures but will also have a larger beam.



Imaging a field with an extended interferometry array will produce images with smaller beams but potentially with extended emission missing from the image.

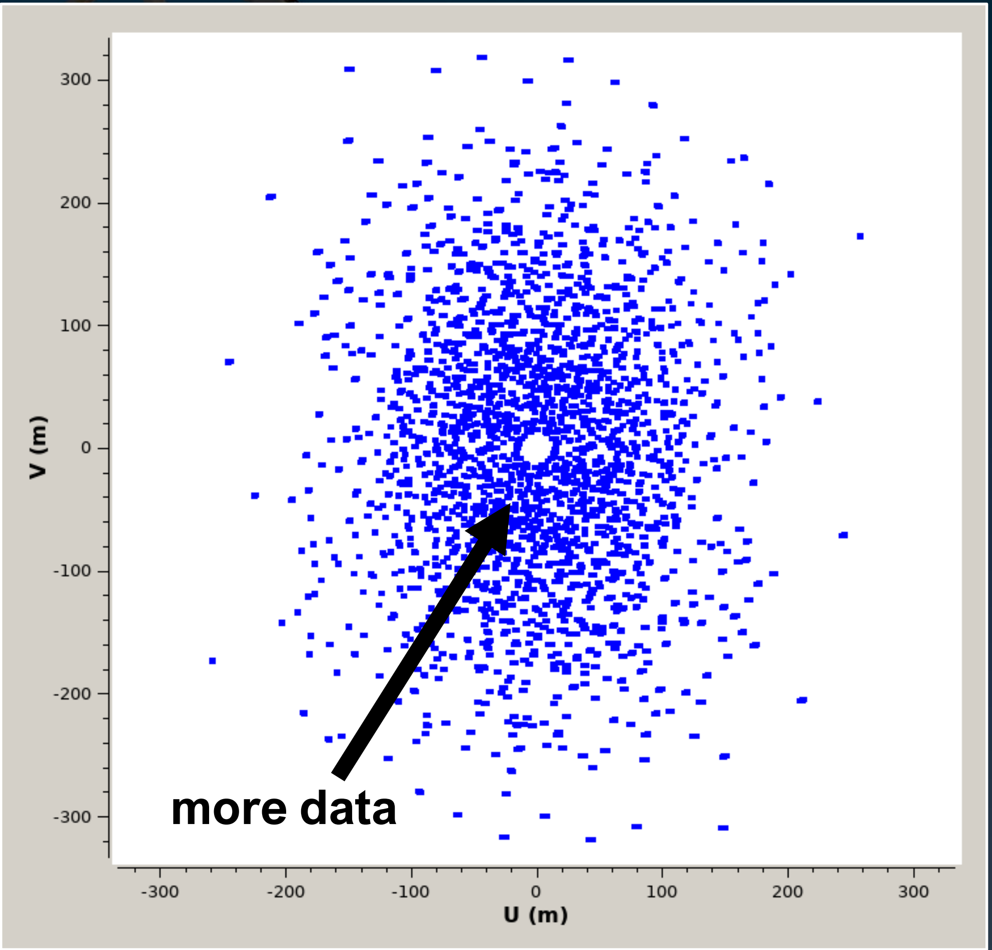


When imaging data, people will often talk about different ways to weight the data in the uv plane. Three different schemes are used.



Natural weighting: Each data point is given equal weighting.

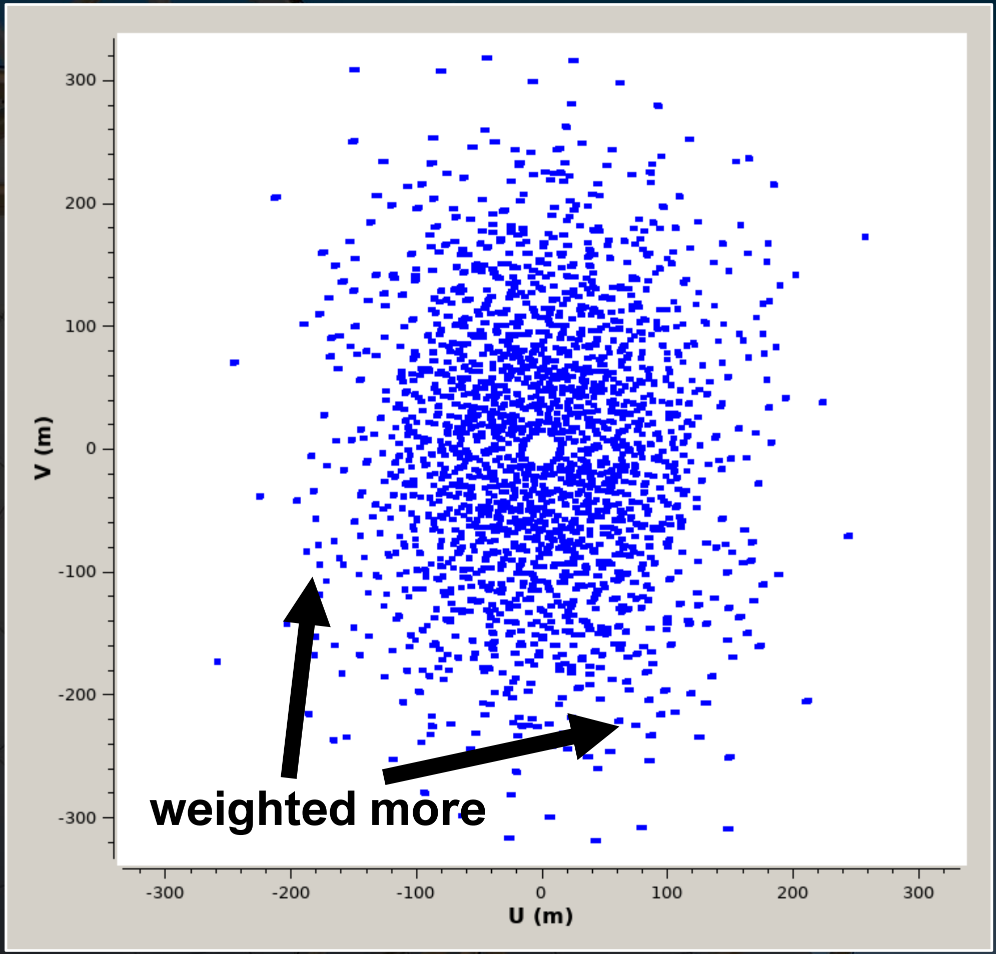
Because the inner regions of the uv plane have more data points, the final images tend to contain more emission from large scale structure and have slightly larger beams.



Uniform weighting: Data points in more poorly sampled parts of the uv plane are given more weight to counterbalance the higher sampling in other parts of the uv plane.

This produces images with smaller beams but does not reproduce large scale emission as well.

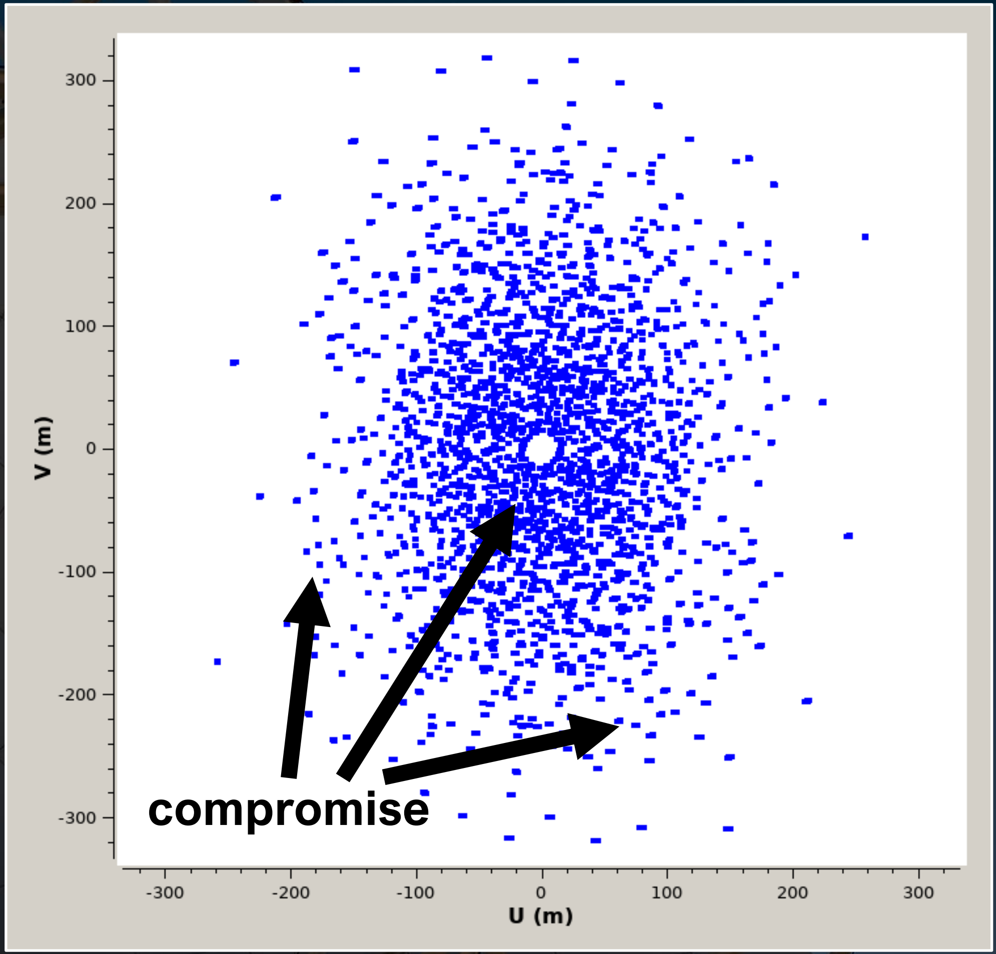
The resulting maps are also noisier.



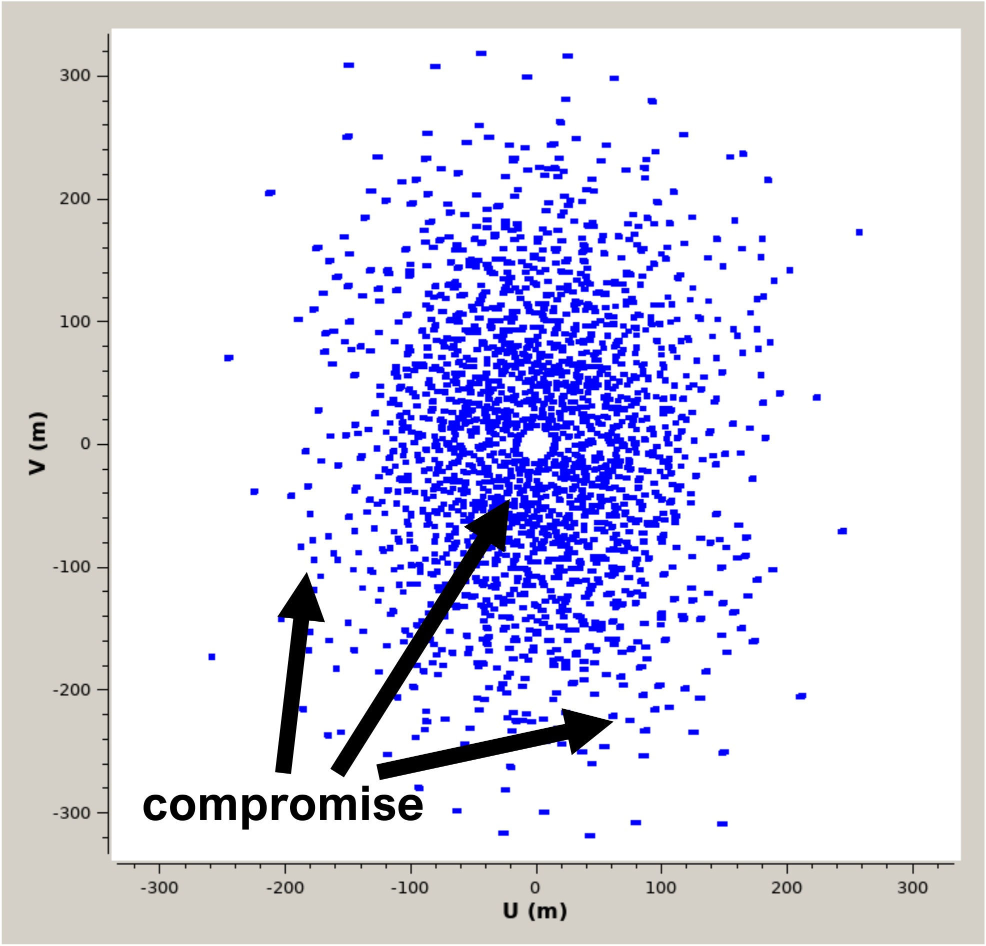
Briggs weighting: This uses a **robust** parameter to adjust between natural and uniform weighting.

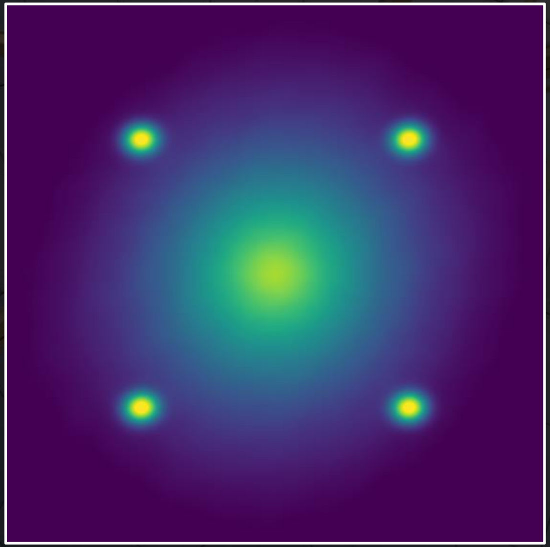
Setting **robust=2** is equivalent to natural weighting.

Setting **robust=-2** is equivalent to uniform weighting.

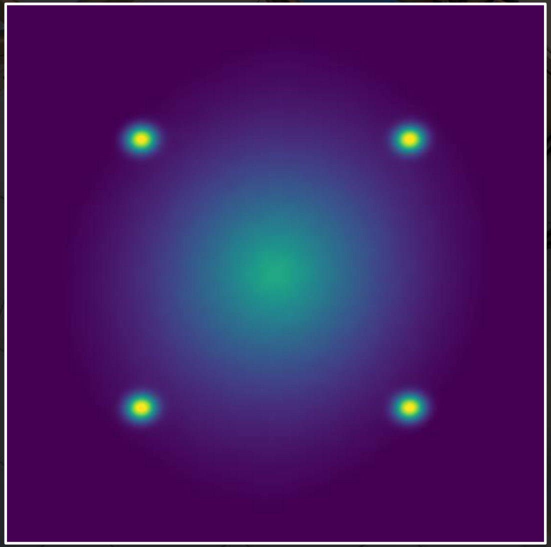


Briggsbwtaper weighting:
This is like Briggs weighting, but it includes an additional adjustment to account for the fact that the beam sizes are slightly different for slightly different frequencies.

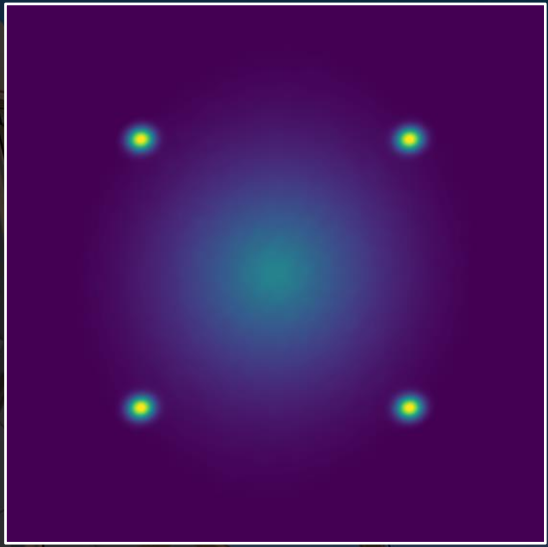




natural



robust=0.5



uniform

As a final note, keep in mind that it is possible to create several moderately different versions of an image from the same radio interferometry data.

This is very different from data processing in other bands, where the data processing steps should always yield very similar if not identical results.

Therefore, when creating images from radio interferometric data keep in mind how different parameter settings will affect the final images.