An Introduction to Interferometry

George Bendo
UK ALMA Regional Centre Node
Jodrell Bank Centre for Astrophysics
The University of Manchester

Interferometry is needed at submillimetre/millimetre 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.

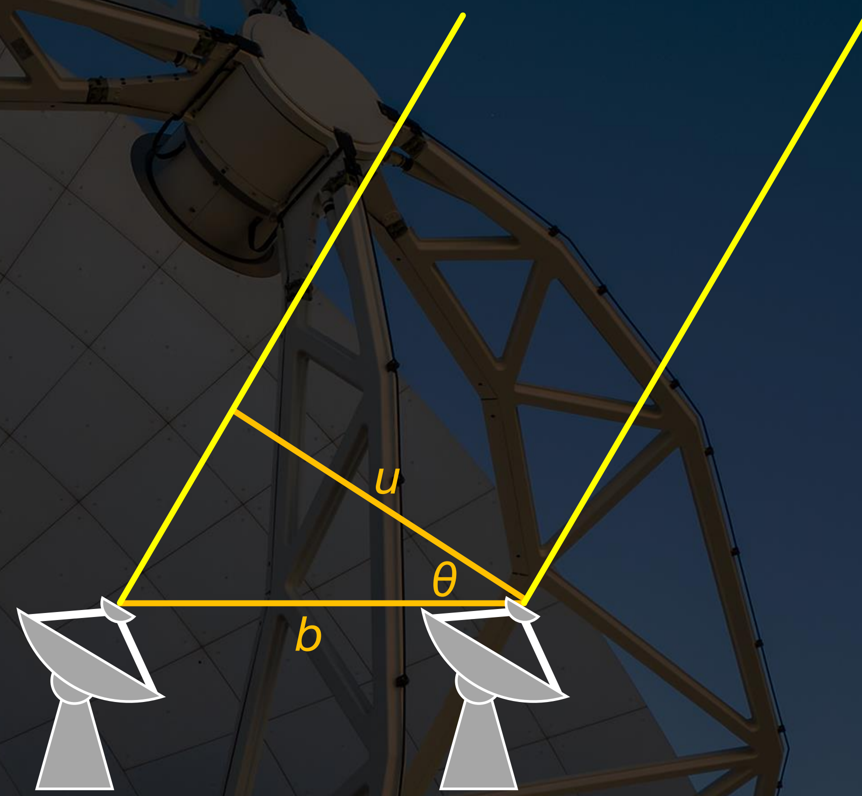

(Credit: Large Millimeter Telescope)

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.

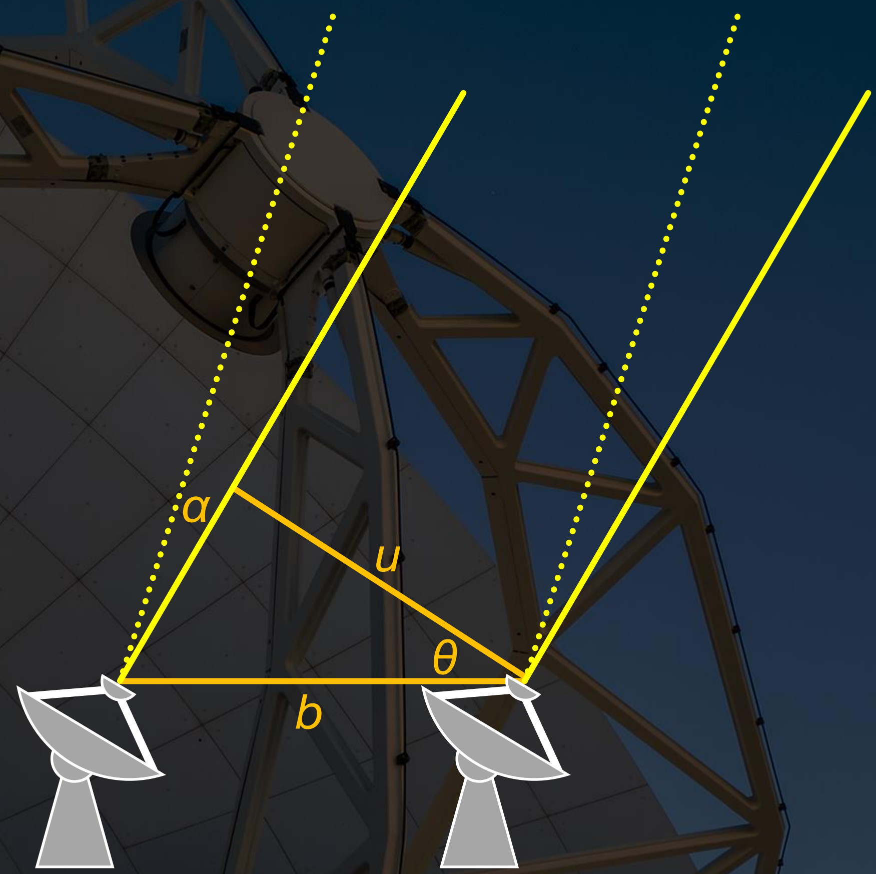
The separation of the antennas is measured by *b*, but their separation as projected onto the sky is *b* cos θ, which is set to *u*.

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



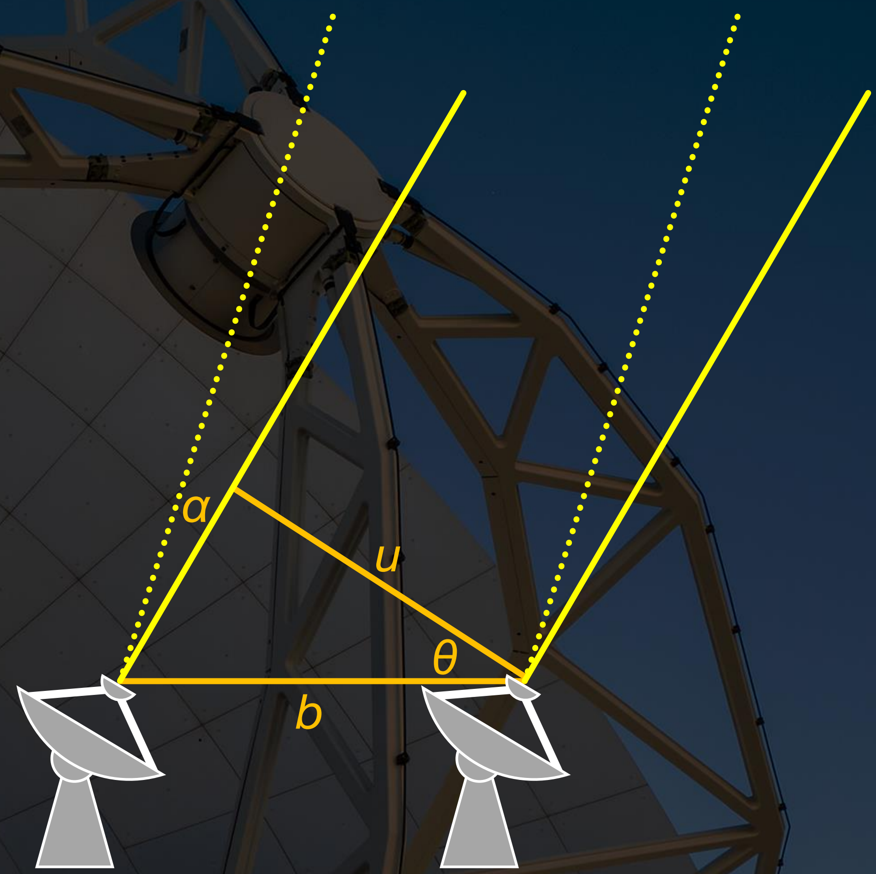
Shifting an object off-axis results in an extra change in the path length that can be written as *u* sin α or *ul*.

The equivalent in the orthogonal dimension is written as *vm*.



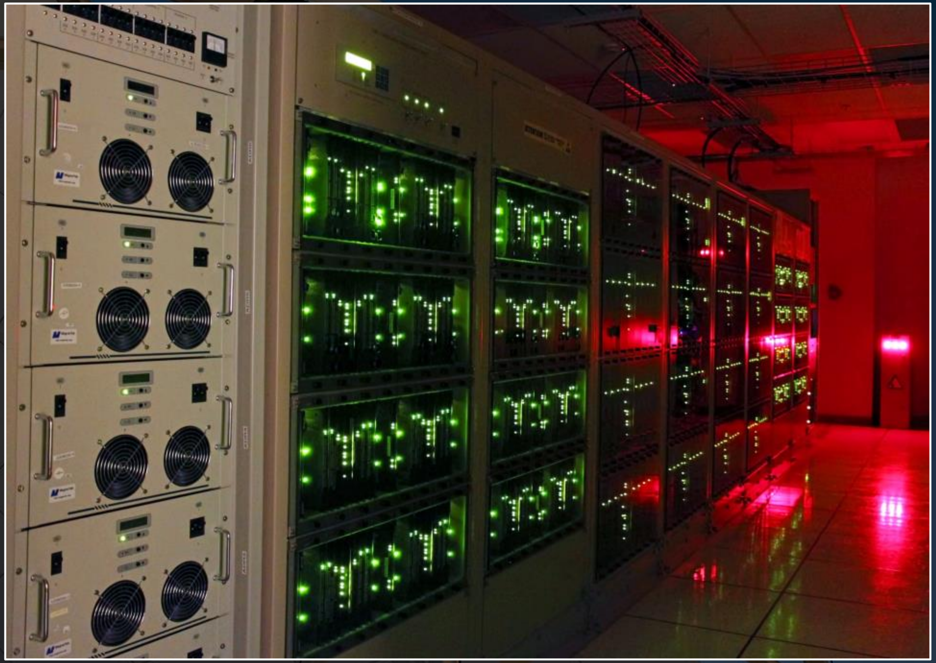
The relations between the signals measured by the two antennas can be written as

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



Typically, interferometers like ALMA 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

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

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

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

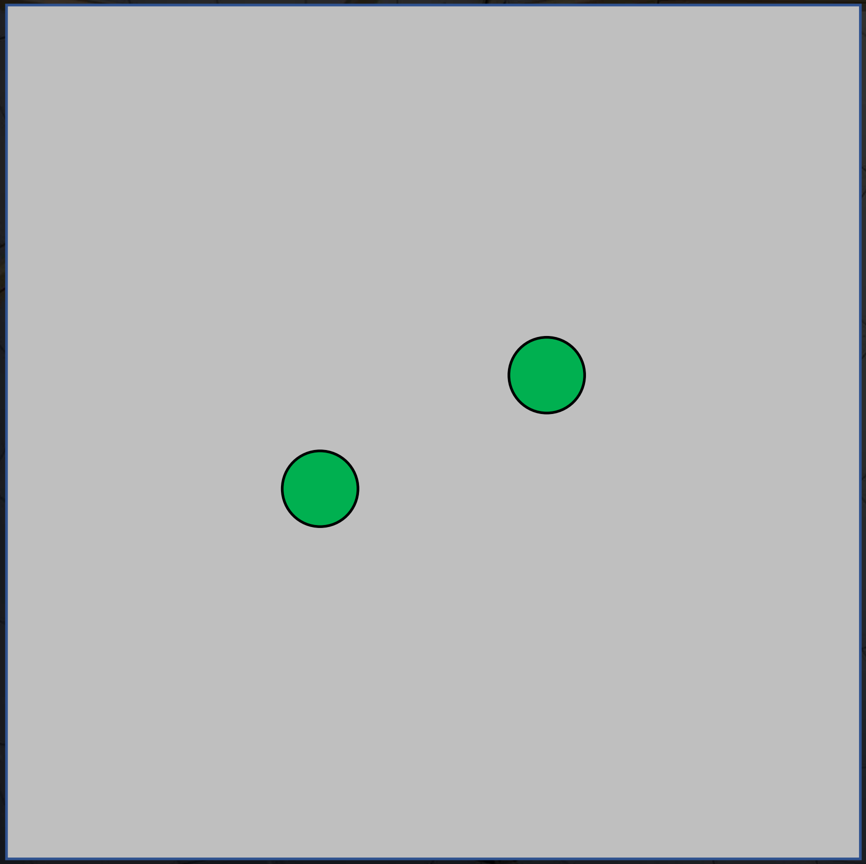
$$\mathcal{V}(u,v) = A e^{i\varphi}$$

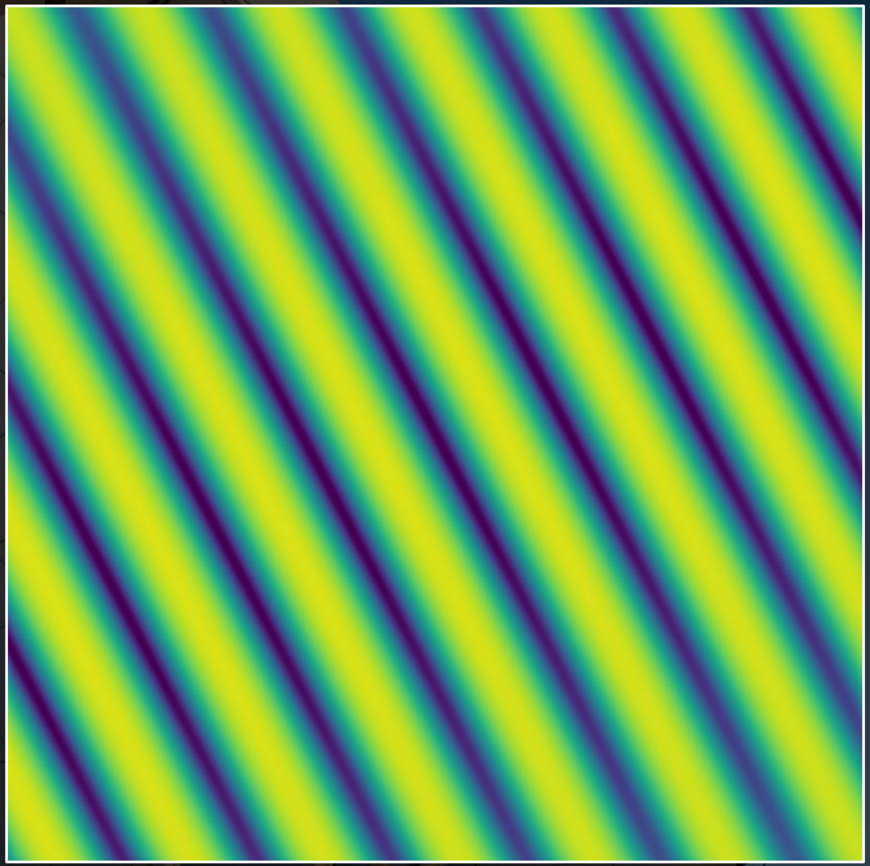
The amplitudes (*A*) from the correlator output describe the total amount of emission measured by the antenna pair (which corresponds to a specific spatial scale as will be described in the next slides).

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

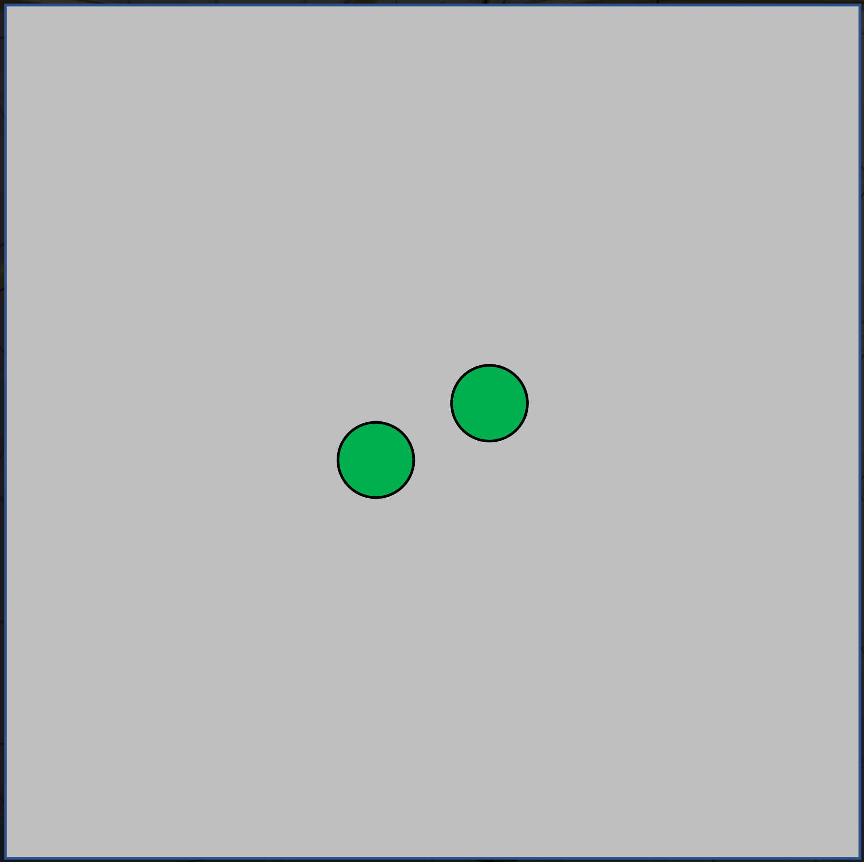
The calibration process involves making adjustments to these amplitudes and phases.

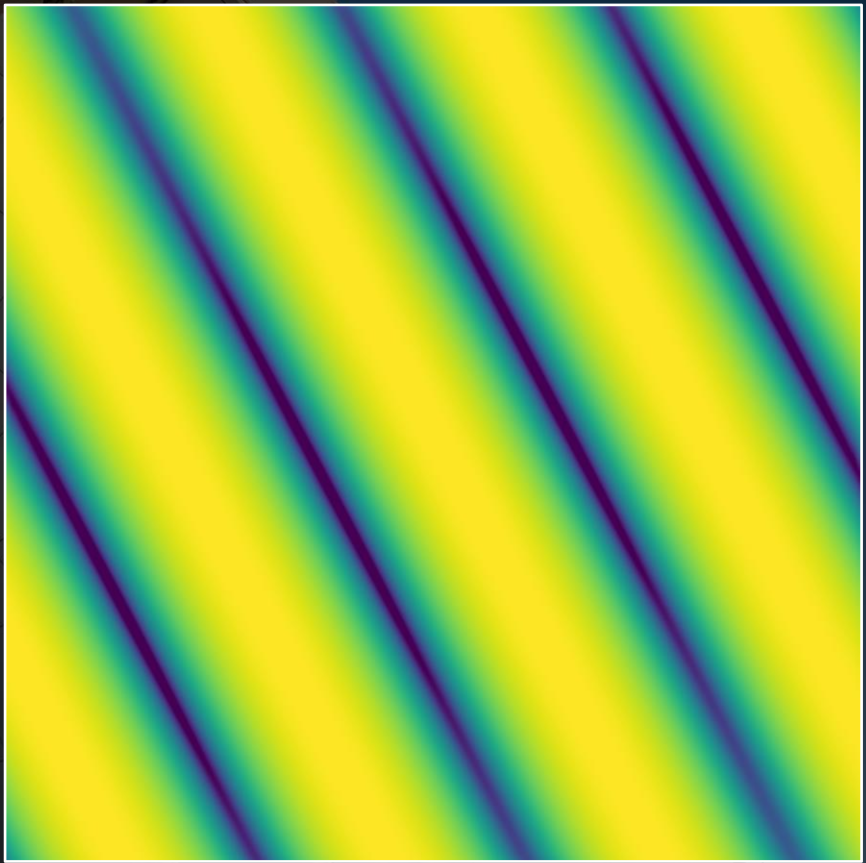
Each pair of antennas is effectively sensitive to emission on a specific spatial scale. Antennas that are closer together can detect emission on larger scales, while antennas that are further apart can detect emission on smaller scales.



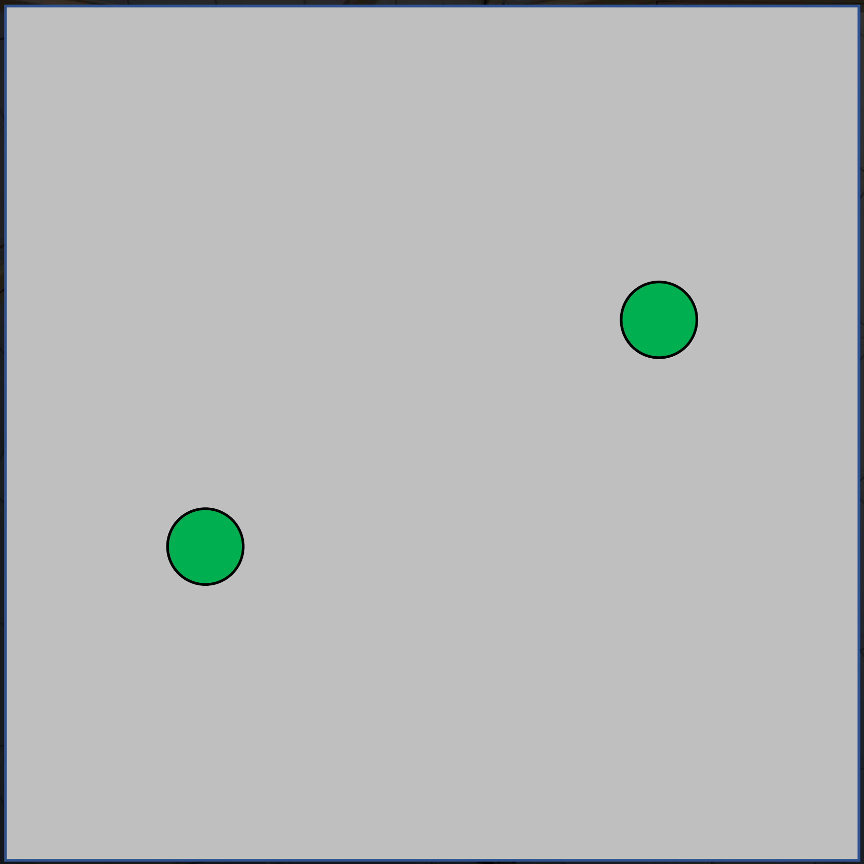


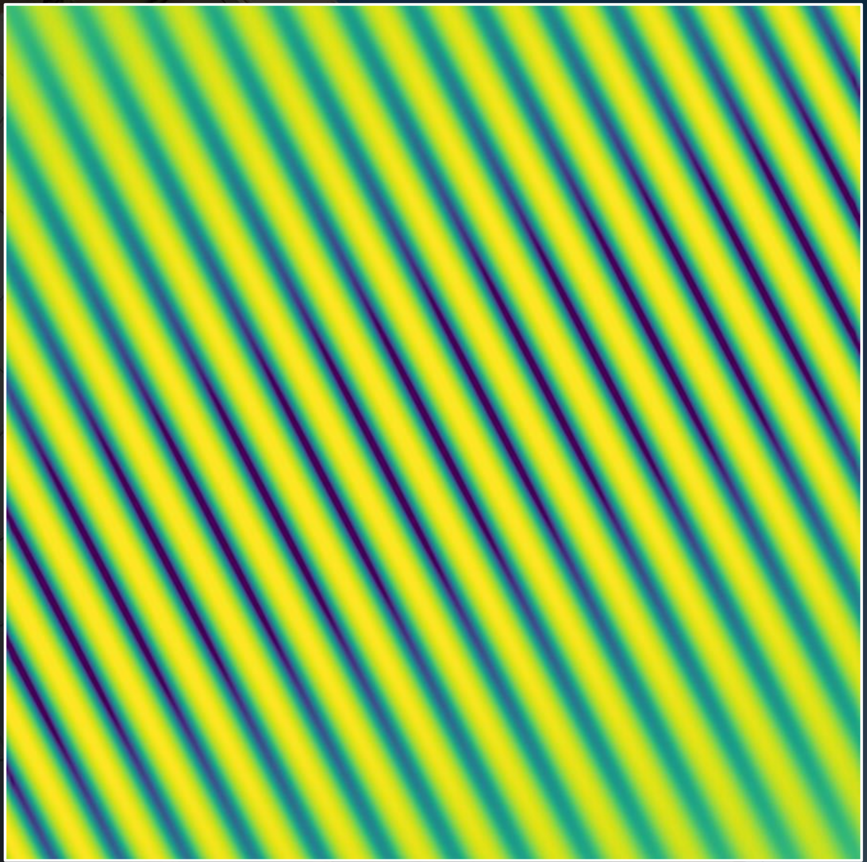
Each pair of antennas is effectively sensitive to emission on a specific spatial scale. Antennas that are closer together can detect emission on larger scales, while antennas that are further apart can detect emission on smaller scales.



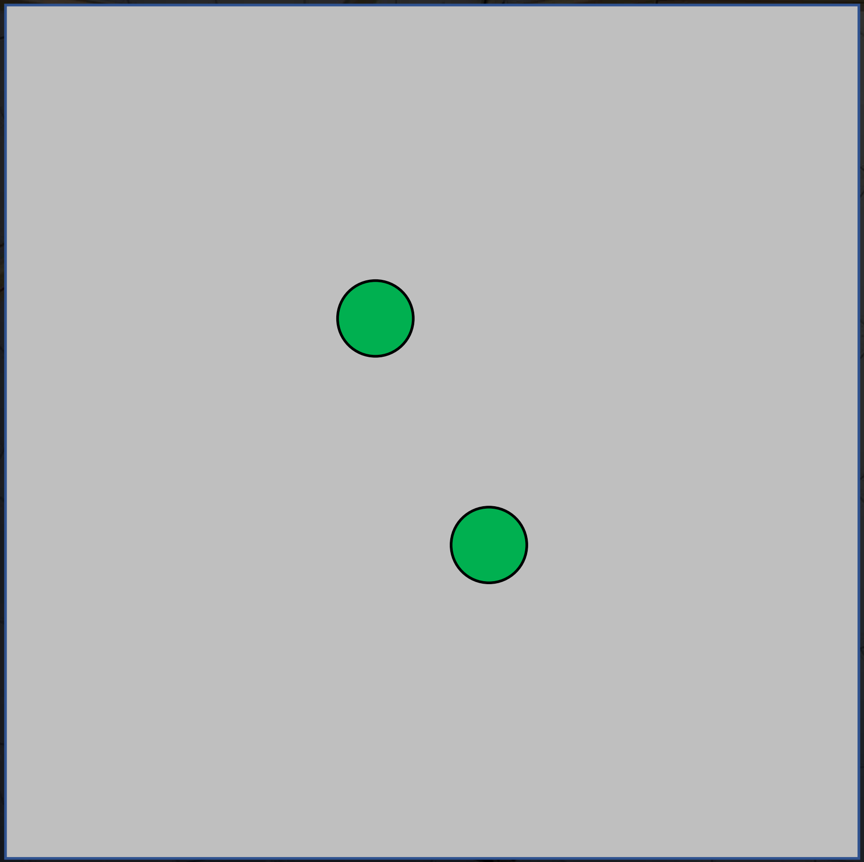


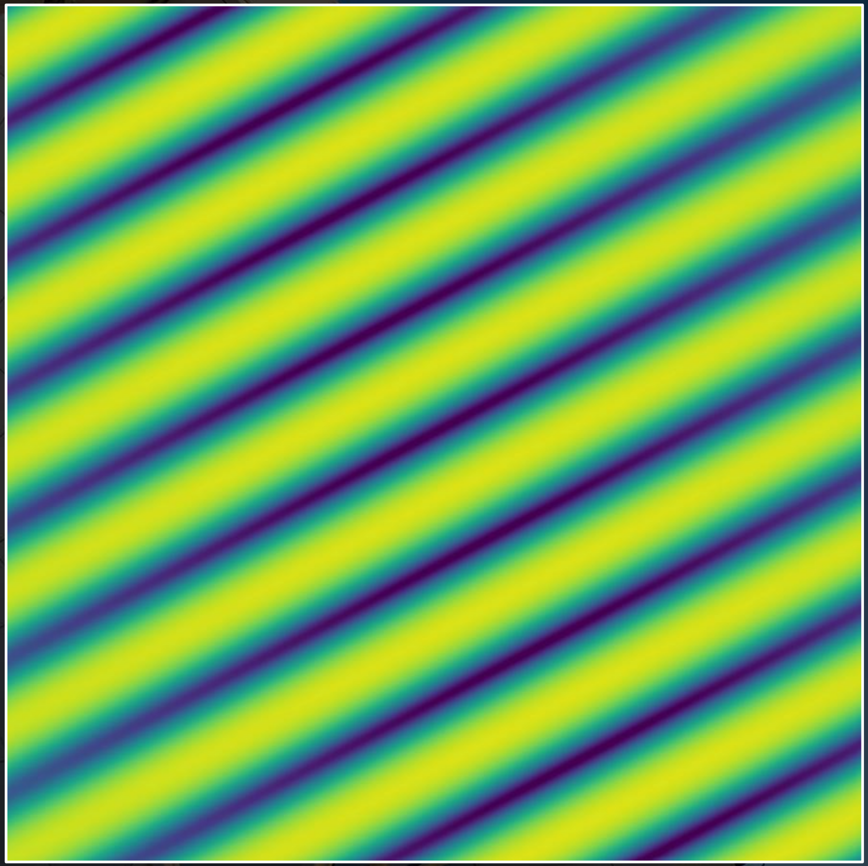
Each pair of antennas is effectively sensitive to emission on a specific spatial scale. Antennas that are closer together can detect emission on larger scales, while antennas that are further apart can detect emission on smaller scales.



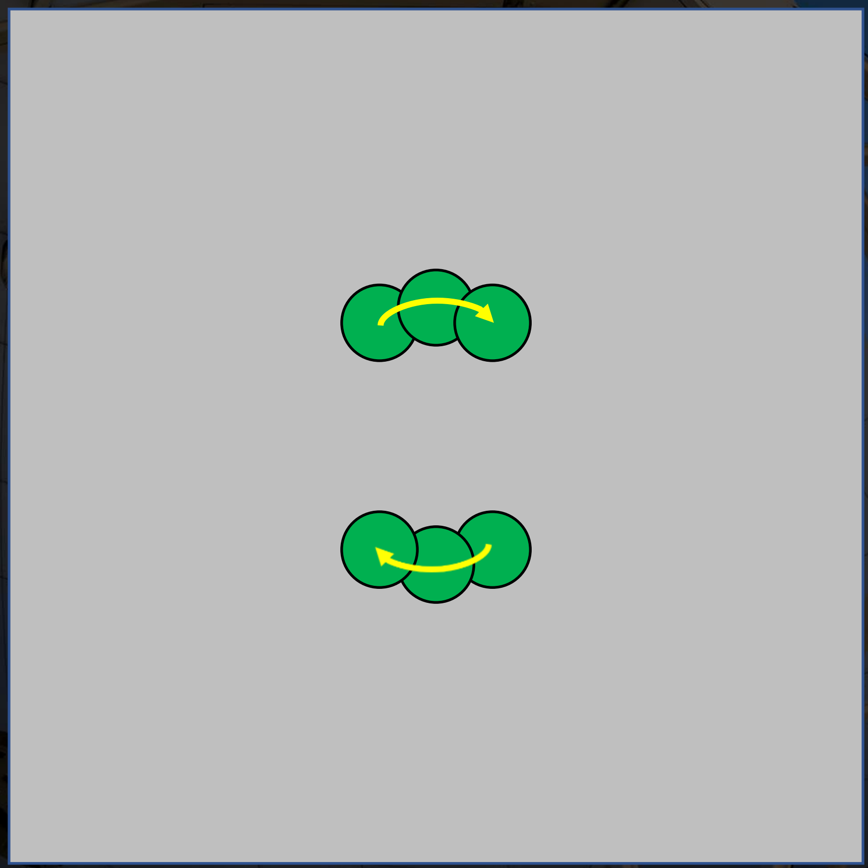


The relative orientation of the antennas is also important. To measure emission in two different dimensions, it is important to have two pairs of antennas with orthogonal orientations.

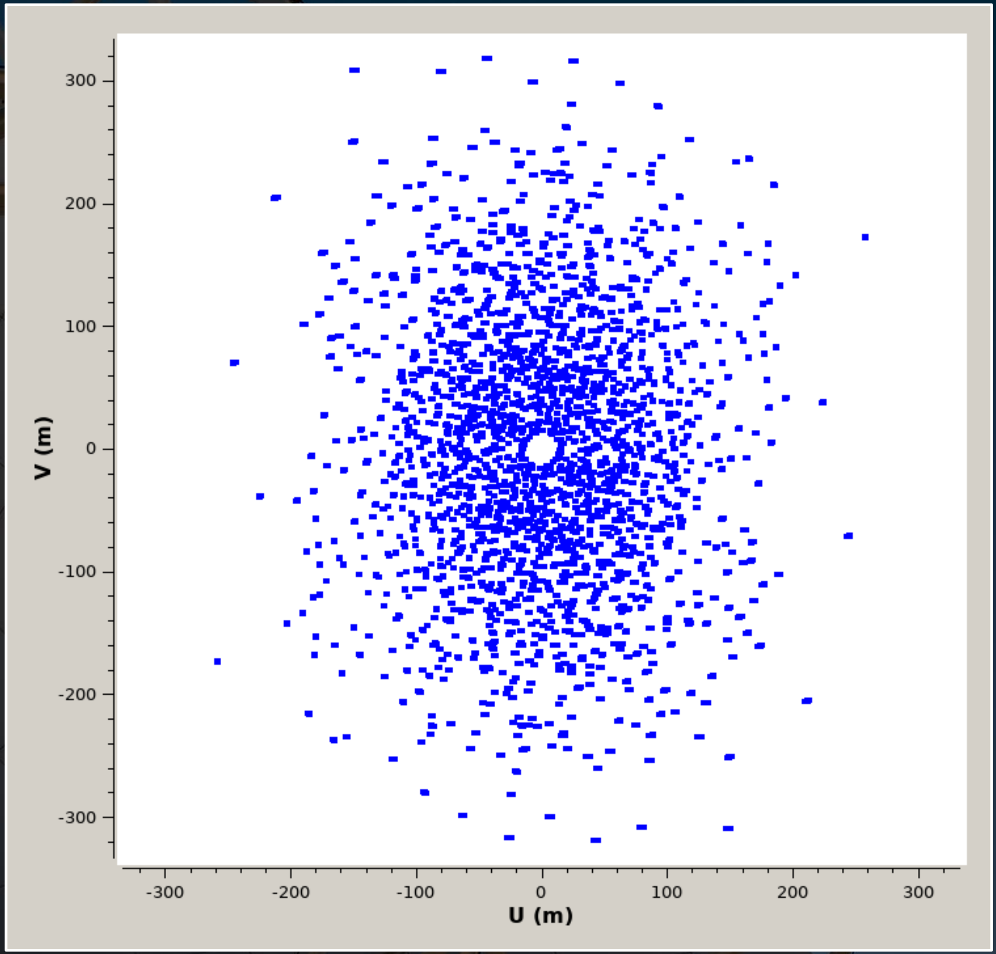




Also, the relative orientation of a pair of antennas as projected on the sky will change as the Earth rotates.

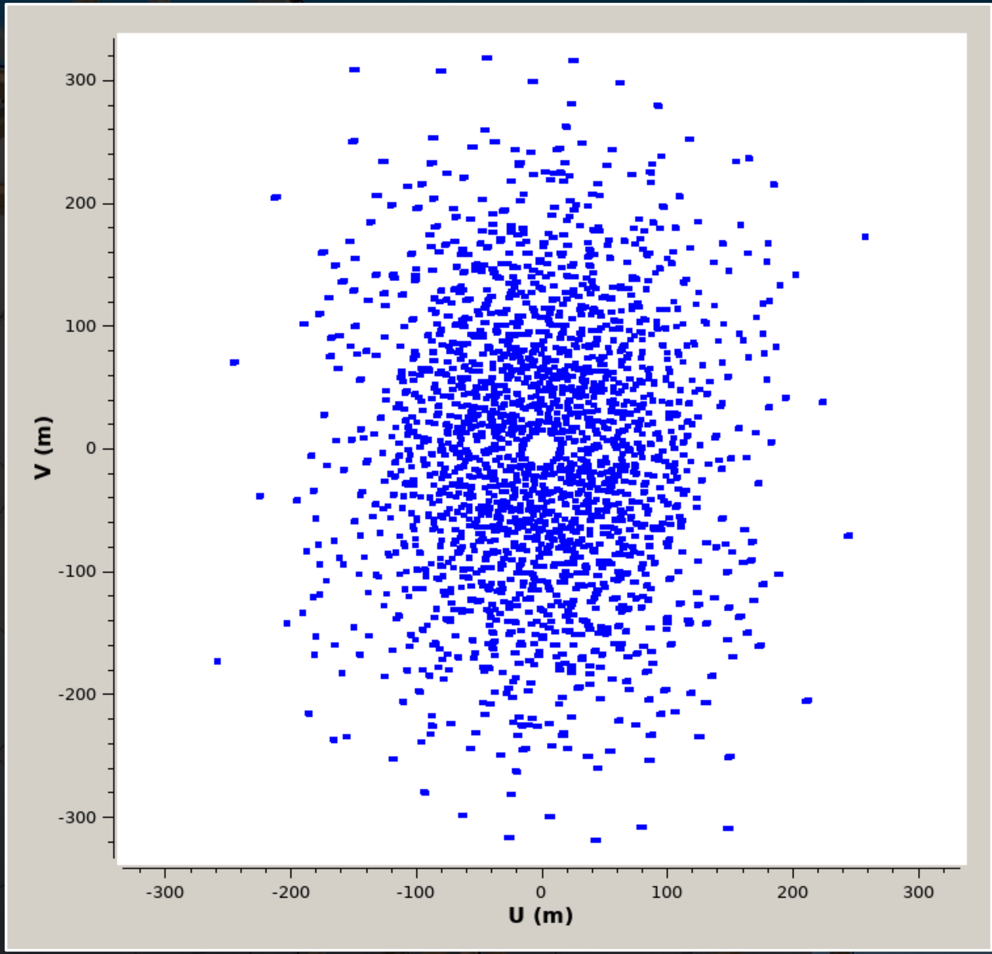


The projection of the baselines of all of the antennas on the sky is referred to as the uv coverage of the interferometer.



The uv coverage is 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.



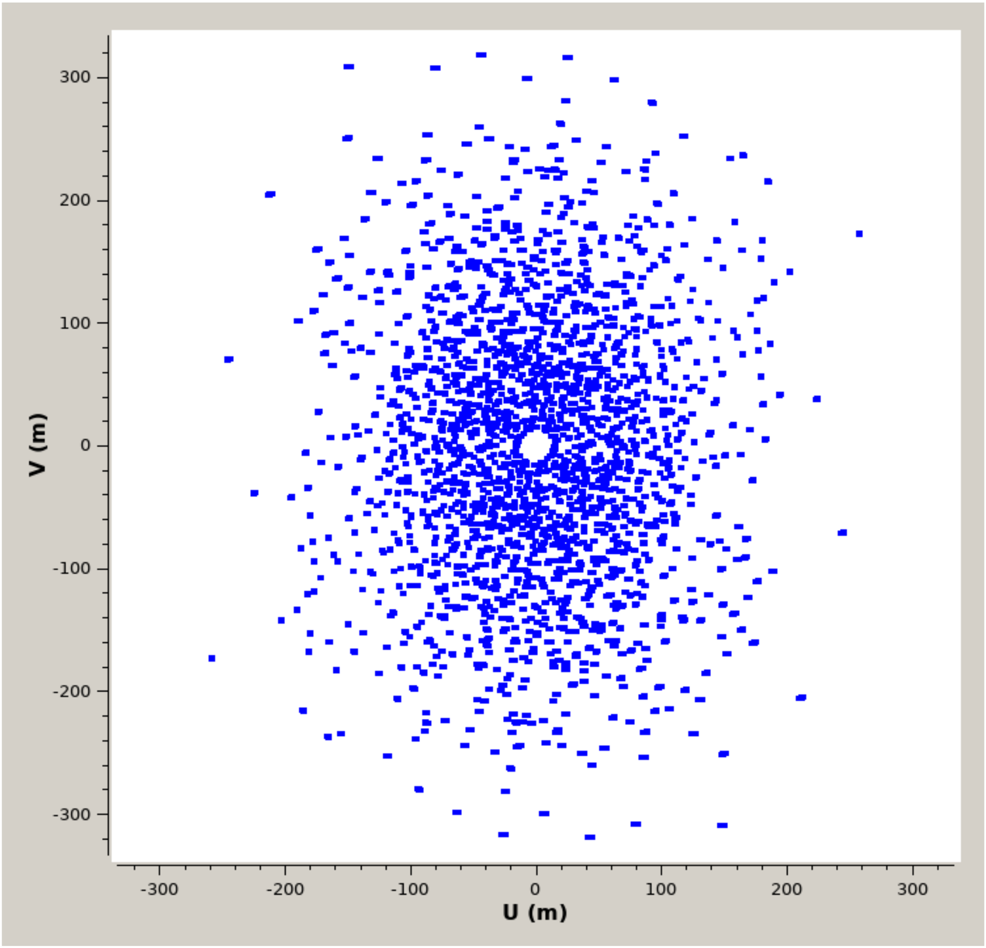
The angular resolution of an interferometer is given by

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

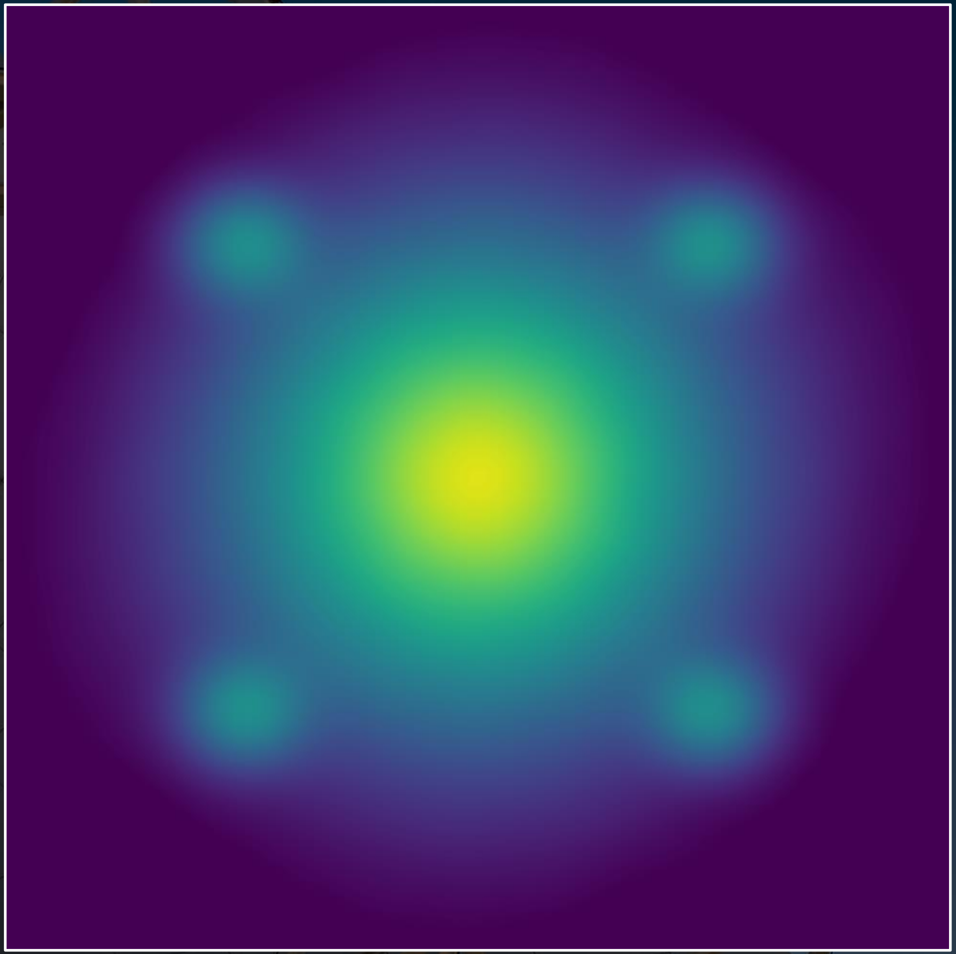
which is a classic angular resolution equation.

However, interferometers cannot measure emission on spatial scales smaller than

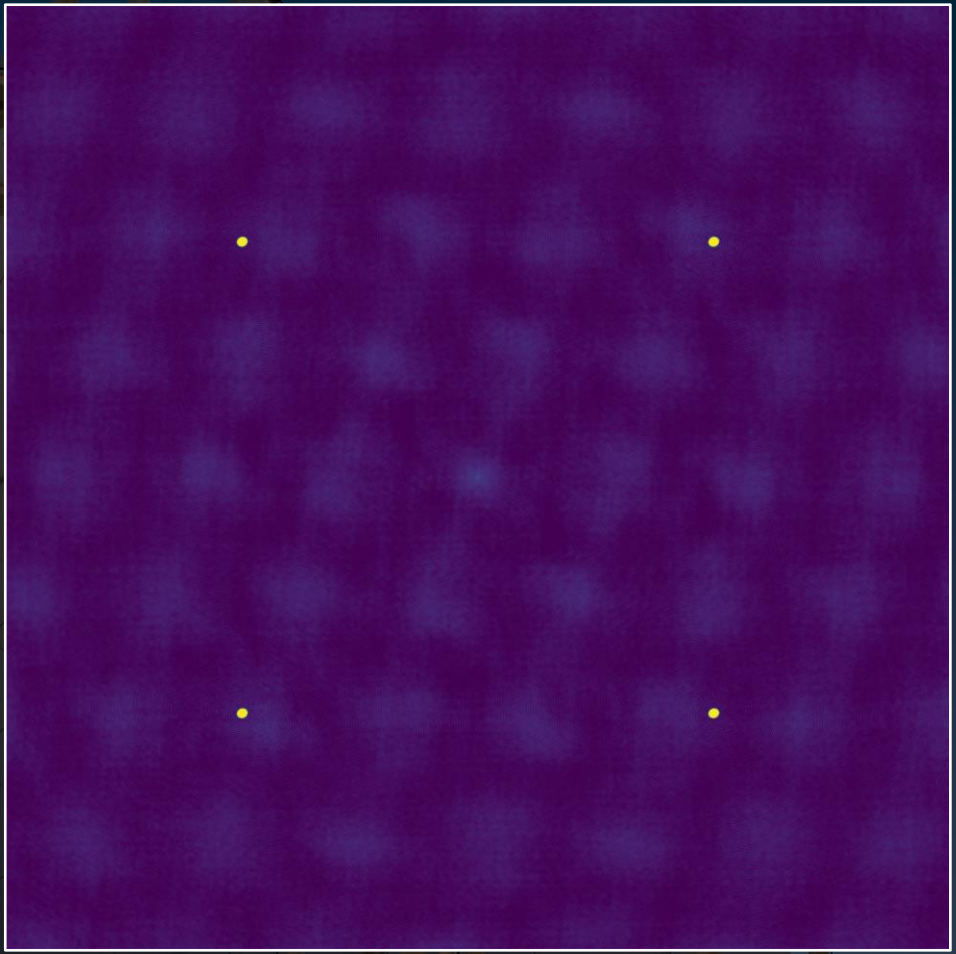
$$\theta_{MRS} = 0.6\,\lambda\,/\,L_{min}$$



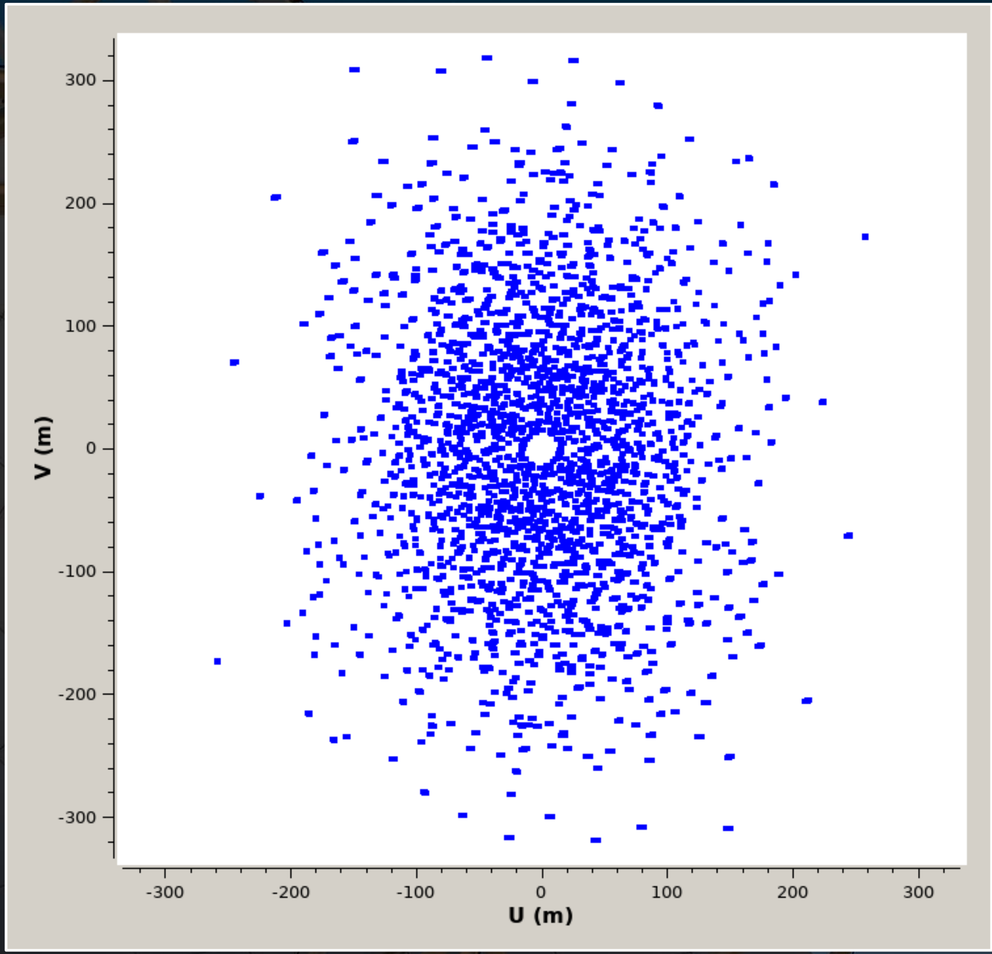
Imaging a field with a compact interferometry array will reproduce more extended structures but will also have a larger beam.



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

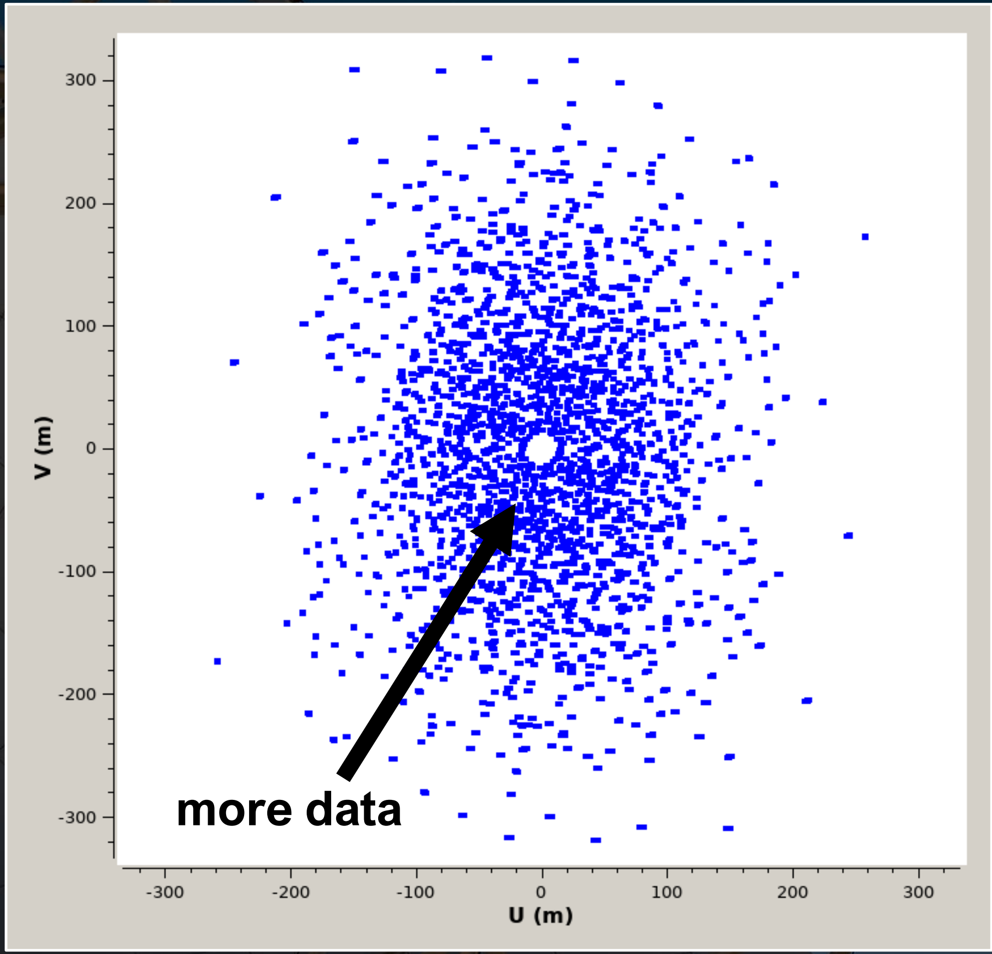


When imaging data, people will often talk about different ways to weight the data in the uv plane. Three different schemes are used.



Natural weighting: Each data point is given equal weighting.

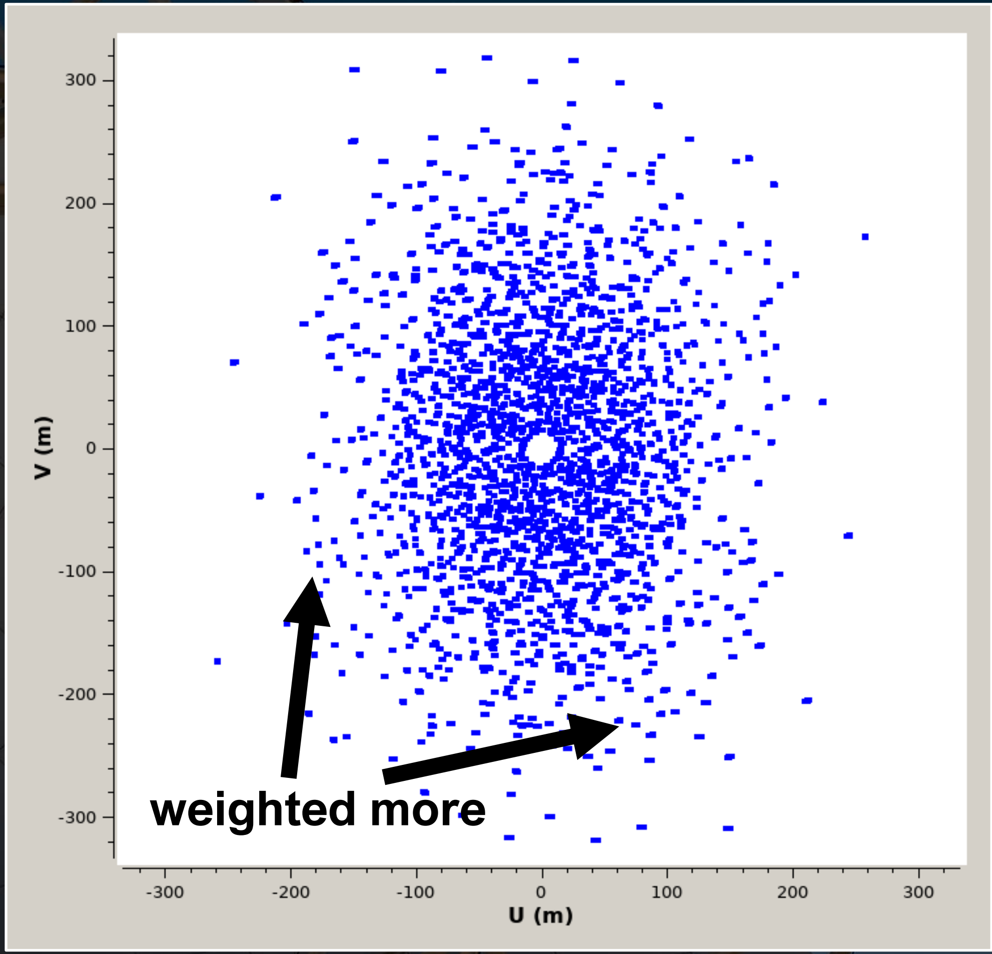
Because the inner regions of the uv plane have more data points, the final images tend to contain more emission from large scale structure and have slightly larger beams.



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 (especially for ALMA).

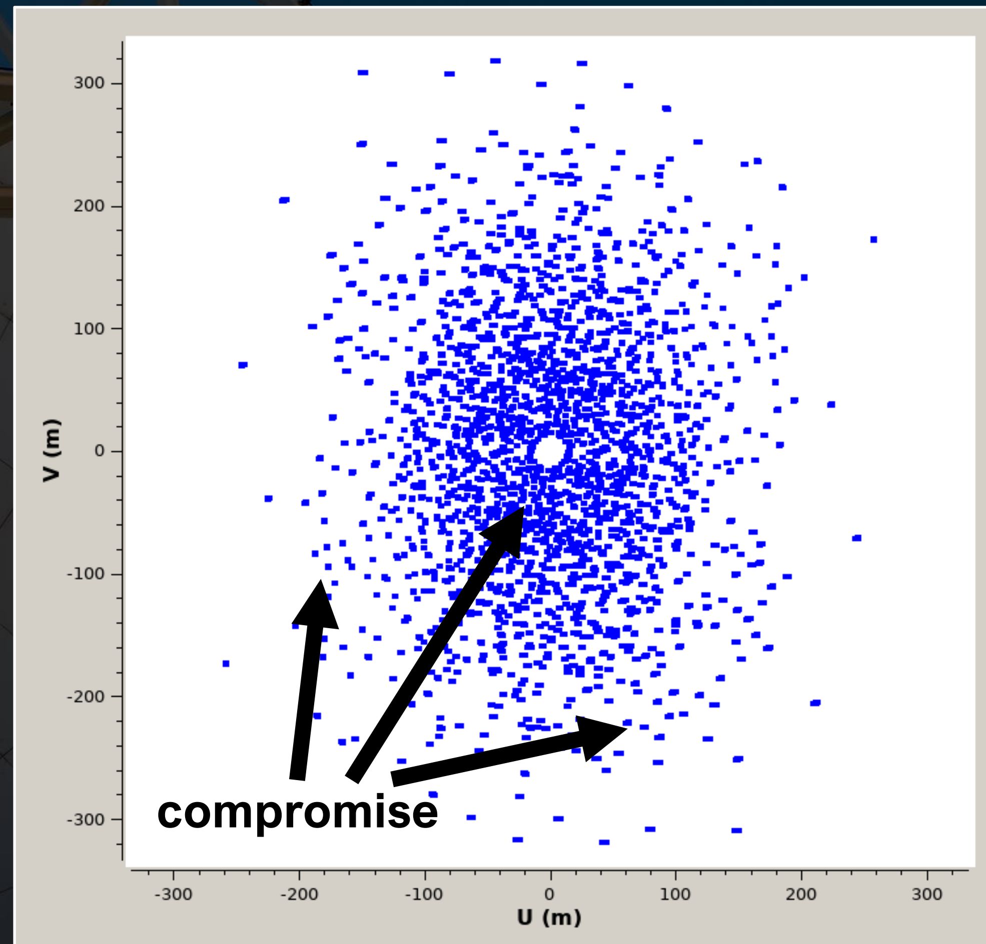


Briggs weighting: This uses a **robust** parameter to adjust between natural and uniform weighting.

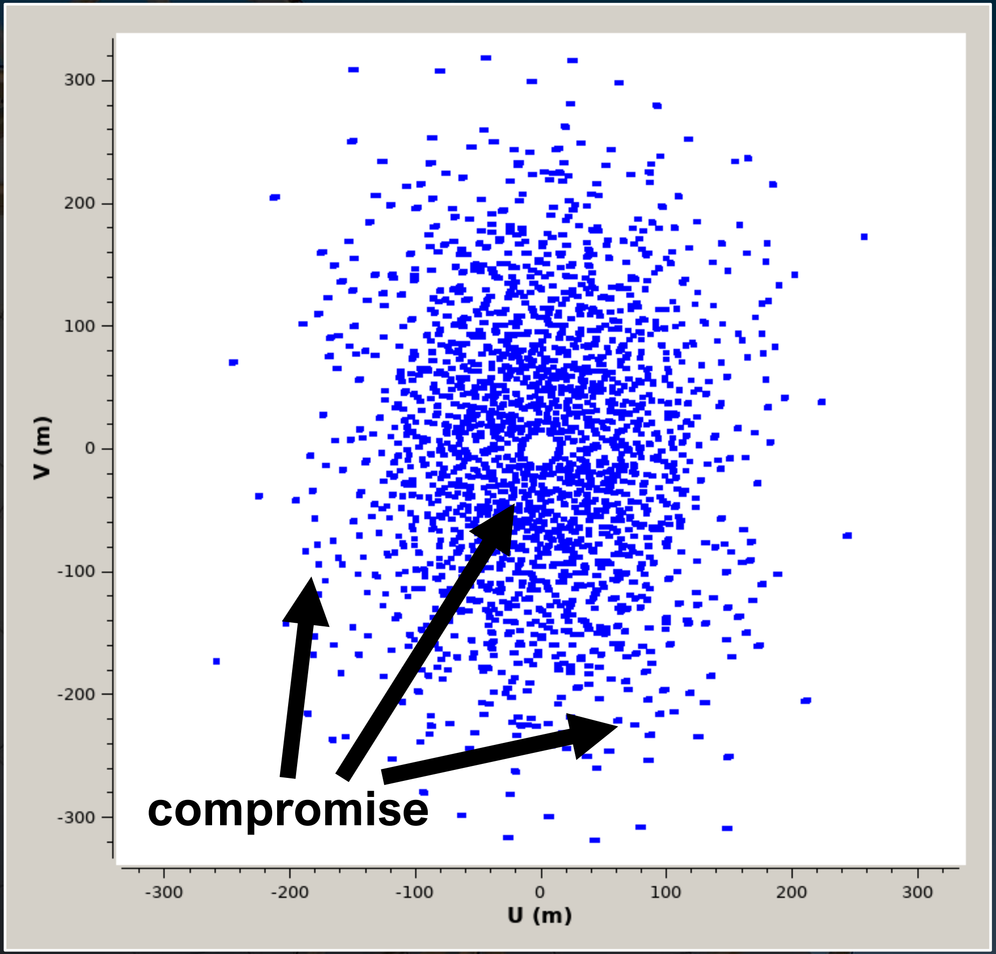
Setting **robust=2** is equivalent to natural weighting.

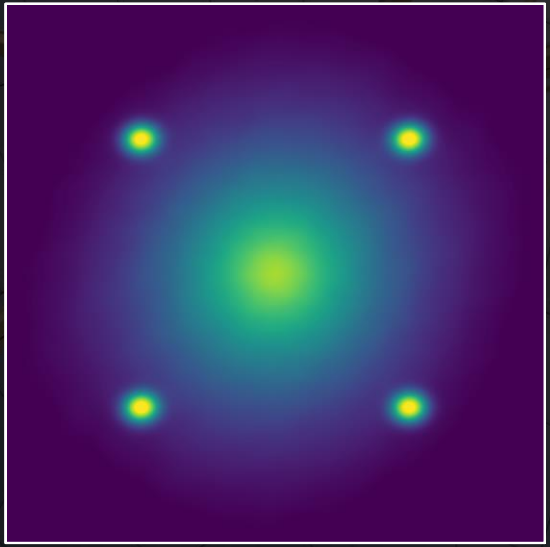
Setting **robust=-2** is equivalent to uniform weighting.

For ALMA, **robust=0.5** is very commonly used.

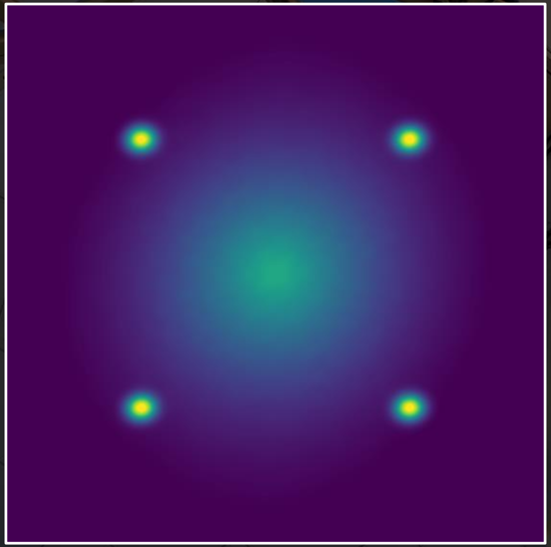


Briggsbwtaper weighting: This is like Briggs weighting, but it includes an additional adjustment to account for the fact that the beam sizes are slightly different for slightly different frequencies.

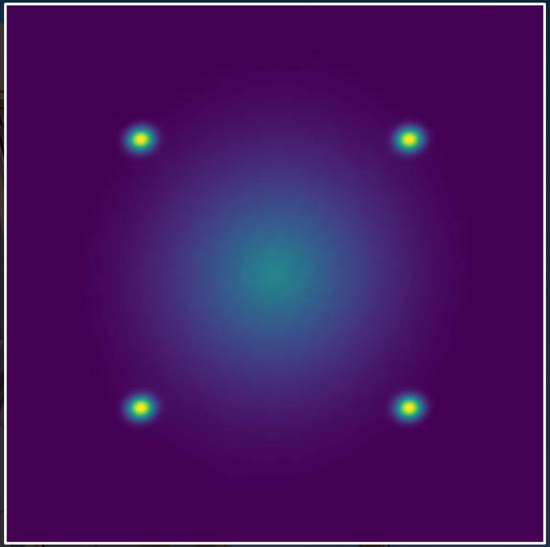




natural



robust=0.5



uniform

The data processing for ALMA consists of three parts:

1. A priori calibration
2. Calibration with the bandpass, amplitude, and phase calibrators
3. Imaging

In the a priori calibration, the following data processing steps are applied to the data:

1. Corrections to the amplitudes are applied based on measurements of the system temperature.
2. Corrections to the phases are applied based on measurements of water vapour along the line of sight.
3. The antenna positions are adjusted.

In the second half of the calibration, the following data processing steps are applied to the data:

1. The phases and amplitudes of the data are corrected as a function of frequency using measurements of a bright, point-like source with a featureless spectrum (the **bandpass calibrator**).
2. The amplitudes are rescaled based on the measurement of a source with a known flux density (the **flux calibrator**).
3. The phases are adjusted as a function of time based on the phase measurements of a point-like source near the science target with a well-known position (the **phase calibrator**).

The **bandpass calibrator** is usually a bright quasar.

In early ALMA observations, the **flux calibrator** was usually a Solar System object, but in observations from the past several years, it is usually a bright quasar that has been cross-calibrated against a Solar System object. (A quasar used as the flux calibrator is usually also the bandpass calibrator.)

The **phase calibrator** is usually a fainter quasar that is close to the science target (although sometimes the bandpass calibrator could be used if it is close enough to the science field).

The final data processing step is the imaging, where the visibility data is Fourier transformed into a sky image.

The beam (or point spread function) from interferometry observations usually has a lot of extended or ring-like structures when directly imaged, so astronomers use a technique called cleaning to re-image the data. Cleaning involves using Fourier analysis to replace the more complicated beam with a Gaussian function.

After this, the data are ready for analysis.