Ay122b Radio/mm/sub-mm: basic interferometry lab

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For this lab you will be analyzing the output from a quasi-monochromatic interferometer implemented on the DSA antennas. Necessary background reading is in section 3.7 (up to and including 3.7.2) of Essential Radio Astronomy (ERA – `https://www.cv.nrao.edu/~sransom/web/Ch3.html`). By completing the lab you will learn the following:

1. How to predict the data output by an interferometer, and how to use this prediction to perform baseline-dependent calibration.
2. How to measure the position of a radio source with interferometric data.
3. How to determine whether your source is or isn't resolved by the interferometer.

1 Background

It helps with understanding to see the same ideas expressed in multiple ways, and interferometry is a particularly complex idea (pun intended). At every time, t, a single interferometer baseline between antennas a and b measures the complex visibility:

$$V_{ab}(t) = g_{ab} \int_{\mathrm{FoV}} I(\hat{\mathbf{s}}) e^{-i2\pi \mathbf{b_{ab}} \cdot \hat{\mathbf{s}}/\lambda} d\Omega. \tag{1}$$

This is equation 3.186 of that ERA link above. Here, $I(\hat{\mathbf{s}})$ is the intensity distribution on the sky as a function of the direction unit-vector $\hat{\mathbf{s}}$, $\mathbf{b}_{ab}$ is the baseline vector (difference in the positions of antennas a and b), λ is the wavelength, $i = \sqrt{-1}$, and the integral runs over solid angle within the mean field of view (FoV) of the antennas. I have also inserted a gain term g_{ab}, which represents an error associated with measurements on a given baseline.

One might ask: what is actually time-variable on the RHS of this equation? This of course depends on the coordinate system you choose. In this lab, we consider $\mathbf{b}_{ab}$ as fixed, and $\hat{\mathbf{s}}$ as time-variable as the sky drifts overhead. You can also assume that g_{ab} and λ are independent of time, although this is not always the case for 'real' interferometers.

If there is only one bright source within the FoV, with intensity I_0, Equation (1) reduces to

$$V_{ab}(t) = g_{ab} I_0 e^{-i2\pi b'_{ab}(t)/\lambda}, \tag{2}$$

where $b'_{ab}(t)$ is the *projected* baseline length towards the source at time t. In this lab, you will first use observations of the bright quasar 3C 273, which dominates the intensity within the FoV, to solve for g_{ab} on every baseline. Of course, to do this you will need to know the position and flux density of 3C 273 (e.g., you can search on `https://ned.ipac.caltech.edu/`) and the measurement times in order to predict $b'_{ab}(t)$.

For the second part of the lab you will need to solve for the position of a mystery source, given the measurements of g_{ab} you derived from 3C 273. This will need to be done in two parts. A priori you do not know whether or not the source is consistent with a dominant point within the FoV, and so you do not know whether to choose Equations (1) or (2). You will need to demonstrate that the source is indeed point-like by comparing the visibility amplitudes on different baselines. Second, assuming all goes well, you then need to apply Equation (2) to fit for the source position. This is not straightforward, and will require some creativity!

2 Data and deliverables

You will be provided with two data sets: `3C273.npz` and `mystery.npz`. An example python-3 notebook will also be provided to show how to read the files. The files will consist of around 3 min of observations of the two sources with 24 antennas of the DSA. Vectors of times, baseline pairs, antenna positions, and visibility measurements will be included. The antenna positions will be in the tangent plane relative to the fiducial geocentric location of OVRO: 37.2317 deg N, 118.2951 deg W. Recall that the DSA antennas point at fixed locations on the meridian; the pointing elevations will also be provided.

Please submit jupyter notebooks that implement the following:

1. Solve for the projected baseline lengths at each time, given a source position.
2. Calibrate the baseline gains using 3C 273.
3. Fit for the position of the mystery source, using an initial guess based on the antenna pointing.

You will be assessed mainly on whether your derived position for the mystery source is reasonable! Feel free to seek as much help as is needed along the way, by sharing your notebooks with us. The more detail that you provide in the notebooks the better! Please also respond to the following questions:

- Is the mystery source resolved by the array? Why, or why not?

- What are some issues with using baseline-dependent calibrations in practise? How could these issues be circumvented?