Radboud University Nijmegen

RADBOUD UNIVERSITY NIJMEGEN
DEPARTMENT OF ASTRONOMY

Masterclass VWO
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In this practical exercise you will perform some operations on data that was measured with the radio interferometer on the roof of the Huygens building, which you will also visit. Because the afternoon session is only short, we will concentrate on determining some of the system parameters for the interferometer by lookin at the data is has generated.

For this exercise we will use some data files that were recorded with our interferometer. These files can be found on the wiki page of the department (http://www.astro.ru.nl/wiki/), follow the link pointing to 'masterclass VWO'. These data files can be loaded into Excel for processing. The first file, 'singleantenna-23may-2012.xlsx', contains measurements made by one of the antennas of the interferometer and will be used for the first exercise. The second file, '2antennas-24may-2012.xlsx', contains measurements made using both antennas as an interferometer. This file will be used for the second exercise.

1 Measuring radio waves

Radio telescopes measure electronagnetic waves, just like optical telescopes do. Both types of telescope work by collecting incoming electromagnetic waves over a large area, focusing those waves, and recording them. Optical telescopes typically use a CCD (Charge Coupled Device) for recording: this is a sensor type that is typically also used (in a slightly different form, but that's a technical distinction) in digital cameras and mobile phones. A CCD is an array of individual sensors, each of which can register how much radiation it receives because incoming photons kick electrons from one side of the detector to the other, buiding up a small charge that can later be measured. A CCD forms an image: different sensors in the CCD sample different areas of the image plane so we can make a map of what the telescope sees. All this works very similar to the human eye. Radio telescopes on the other hand generally do not make images, because all the focused radiation is measured by one single detector. This detector is effectively a small antenna that directly measures voltages induced by the incoming electric field oscillations of the electromagnetic waves. So, a radio telescope only really has a single 'pixel', whereas an optical telescope's CCD normally has many megapixels. We can make images using radio telescopes by scanning the telescope across a part of the sky and recording the signal we get from its detector.

Scanning a single telescope across a part of the sky is exactly what we did with the radio interferometer on the roof of the Huygens building, resulting in the data file called 'singleantenna-23may-2012.xlsx'. We pointed the telescope towards one side of the sun and scanned across the sun to its other side, recording the signal while doing so.

Exercise 1.1 Use Excel to plot the flux (called 'signal' in the data file) as a function of the angular position on the sky (called 'degrees from meridian' in the data file, where 'meridian' is the southern direction). What do you see?

As you heard in the lecture this morning, there is a simple relation between the angular resolution a telescope can reach, the wavelength of the EM radiation observed and the diameter of the receiver dish. To refresh your memory, here it is again:

$$\theta = 1.22 \cdot \frac{\lambda}{D} \tag{1}$$

In this expression, θ is the smallest angle at which objects can still be discerned from eachother, λ is the wavelength of the radiation that is being observed, and D is the diameter of the telescope dish. Basically, this relation means that any telescope of a certain size can only achieve a limited 'sharpness' of image: the larger the telescope diameter, the smaller θ gets and the finer the resolution of the telescope gets. If we consider a point source (such as how a star in the night sky appears for us with the naked eye, like a tiny dot) and we point an optical telescope at it, the image we get will be a bit blurred - to really see it as a point source, our telescope would need to be infinitely large. The same happens when we scan across a point source with a radio telescope: we don't get a sharp spike exactly when we pass the source, but the signal is 'smeared out', leading to a smooth variation of signal with angle. The θ in the equation above is defined as the angle from the peak of the smeared-out image to the closest minimum.

Exercise 1.2 If you know that the wavelength of the incoming radiation is 21 cm, what is the diameter of the telescope dish? Why would the result you get from this calculation be slightly different from the actual diameter?

Exercise 1.3 The pupil of an average human eye is about 4 mm wide in daylight conditions. Using the (averaged) wavelength of visible light, what is the sharpness with which the human eye can see? How large would a radio telescope have to be to get the same resolution at an observing frequency of 1.4 GHz?

2 Using multiple antennas

One single radio telescope can't produce very sharp images, as we saw in the previous exercise. But who says we need to be limited to a single telescope? We can combine multiple radio telescopes to get much higher resolutions. How this works you learned this morning in the lecture: we can compare the phases of two signals received by different telescopes. This allows us to reach the resolution of a single telescope that is as wide as the distance between the two separate telescopes we actually used. This way, working with telescopes spaced 8000 km apart and observing wavelengths of around 1 mm, we can reach a resolution of around 30 microarcseconds (about 1/120,000,000th of a degree), equivalent to being able to see a tennis ball on the moon from here. That is the sharpest we have ever been able to see using any instrument - even optical telescopes come nowhere near that resolution. This is being done at the moment (the project is called the 'Event Horizon Telescope' project), and its aim is to make the first image of the region directly around a supermassive black hole.

In the data file we will use for this second exercise (the file is called '2antennas-24may-2012.xlsx'), we have the data from tracking the sun across the sky (keeping both telescopes pointed at the sun the whole time) for a few hours. In the data file, we can see the signal we get from combining the signals from the two individual telescopes in the column called 'Sum'. This signal is really the product of the two separate signals: when they are in phase the product is positive (because we multiply two positive numbers or two negative numbers with eachother), and when they are out of phase the product is negative (because we are multiplying one negative number with one positive number).

Exercise 2.1 Plot the 'Sum' signal as a function of time. What do you see? Why does the signal look like that? What functions do you know that have a resemblance to it?

Because we have been following the sun across the sky for a few hours, its position in the sky as seen by the telescopes has changed significantly.

Exercise 2.2 Which consequences does this change of position have for the 'sum' signal we get? To investigate this, try to find out how the period (the time between two consecutive maxima) of the 'sum' signal changes with time. When was the sun's position exactly towards the south? Warning: because the time is split up into 3 components (hours, minutes, seconds) you will need to combine those three into a single number in order to use it in a graph.

Exercise 2.3 Calculate the angle the sun has traversed between a maximum of the 'sum' signal and the next minimum. How does this angle compare to the beam opening angle you calculated in the first section?

Exercise 2.4 Suppose that we only know at a specific moment that the signals of the two antennas are in phase. Does this allow us to find the sun's exact position? Why (not)? What other information would we need to pinpoint the sun accurately?

3 Further information

Of course, there are many more aspects to interferometry which we can't treat in a single afternoon. To understand how an image can be made by combining signals from multiple telescopes, it is good to understand the Fourier transform. Many pages on the internet explain all about the Fourier transform - basically, it tells us how we can construct a function out of many sine waves with different amplitudes, phases and frequencies. In radio interferometry, we use the 2D version of the Fourier transform to reconstruct an image out of all the measurements made with pairs of telescopes. The more telescopes we have in our array, the more pairs we can combine and the better our image will be.

Of course, Wikipedia has an article on interferometry as it is used in astronomy:
http://en.wikipedia.org/wiki/Astronomical_interferometer

You can experiment with the 2D Fourier transform here:
http://www.brainflux.org/java/classes/FFT2DApplet.html
(The website brainflux.org also has more material on the subject)

You can experiment with different telescope setups, simulate a measurement, and find out what the reconstructed image of an object looks like using this webpage:
http://www.jb.man.ac.uk/vri/