

Aperture Synthesis Labs Using the VSRT Interferometer

If not yet familiar with the use of the VSRTs or of the analysis software VSRTI_Plotter, you should first read the document `IntroductiontoVSRT.pdf`.

A. The VSRT Primary Beam

In general, before making measurements with an interferometer one should be familiar with the important characteristics of the individual antennas. One such characteristic about the VSRT interferometer which you will need to know for the subsequent labs is the width of the beam of each feed. The beam of the individual antennas that make up an interferometer is called the primary beam. Sources in the sky which are located away from the center of the primary beam can still be detected but the detected flux density will be decreased by a factor equal to the primary beam sensitivity at that position. When using an array of antennas to obtain an image of a radio source, the primary beam of the individual antennas essentially provides an upper limit to the field of view of the image, since radio emission coming from directions outside the primary beam will appear fainter, if detected at all.

Observing Procedure:

1. Place the feeds as close to each other as possible and place a single helical CFL (standing on its end) at a distance of about two meters and in line with the midpoint between the feeds, as shown in Figure 1.
2. Check the “pointing” of each feed by altering its pointing direction while watching the signal in the single scan spectrum. Adjust the pointing direction of the feeds one at a time to ensure that you get the maximum signal when the CFL is at the 0° position.
3. Press the “record” button, and give the file a name that contains a pair of single quotes with the number ‘0’ inside the quotes. For example, the file name can be: `Juanita_Beam‘0’_15Sep`. For this file, the ‘0’ means that these data correspond to when the CFL was located at a position angle of 0° . It is very important for reading the data into the VSRTI_Plotter package for the data analysis that your data file



FIG. 1: VSRT set-up for Plot Beam lab. The feeds are placed close together and aimed at a CFL, standing on end, at a distance of 2 m.

contain the single quotes with a number between – the VSRTI_Plotter program will look for the single quotes to read in the value of the angular position of the CFL.

4. While the data is recording, watch the screen and stop the recording after about 50 scans. Take note of the antenna temperature and rms.
5. Keeping the distance of the CFL from the mid-point of the feeds roughly constant, move the CFL along an arc to a different position as depicted in Figure 2. Do *NOT* turn the feeds to keep them facing the CFL. Measure the angular position of the CFL relative to the midplane of the baseline. This is most easily accomplished using a little trigonometry, i.e. by measuring the perpendicular distance of the CFL from the mid-plane line, dividing by the distance of the CFL from the feeds and finding the inverse sine.
6. Click on “Record” and give the same file name as before but with the new value of the angular position of the CFL, *in degrees*, between the single quotes. Record for about 100 scans.
7. Repeat steps 5 and 6 for all angles from -45° to $+45^\circ$ in steps of 5° . Increase the integration times as you get to larger angles - use about 60 scans for angles above 12°

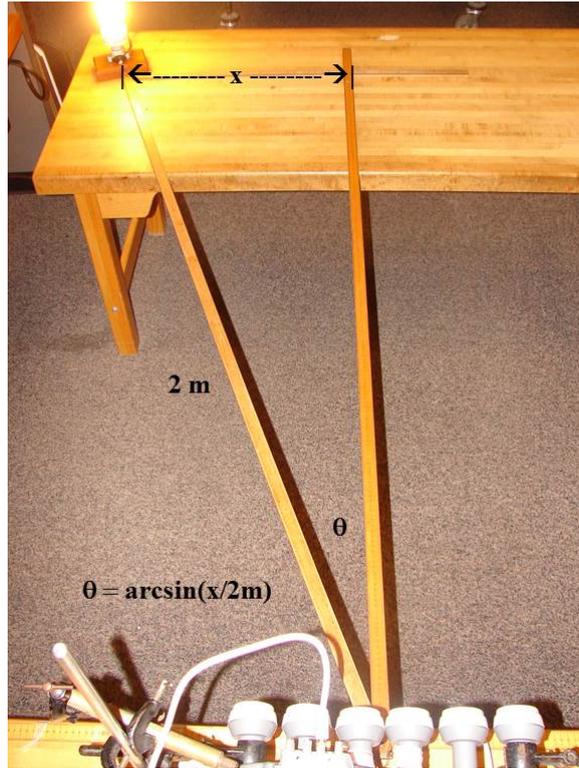


FIG. 2: Keeping the feeds still, move the CFL along an arc, keeping it the same distance from the feeds, and determine the angle by measuring the distance of the CFL from the center line and calculating the arcsin of that distance divided by the distance of the CFL from the feeds.

and about 100 scans for angles above 20° . At the larger angles, the signal will get weaker and so you'll want a smaller uncertainty to increase the signal to noise.

8. Put all your data files into a single folder.

Analysis:

1. Open the VSRTL-Plotter program, and select "Plot Beam." Open the folder with your data files, select all the data files, and drag-and-drop the whole set into the "data files" box on the right side of the VSRTL-Plotter window. A plot of your data should appear instantly on the left.
2. Select "Show Beam Pattern." You'll instantly see a curve representing the theoretical beam pattern for an antenna with the specifications set in the boxes to the right.
3. Try changing the value of the input parameters and then click on "Update." Note how the model curve changes.

4. Note that the bottom of the curves don't match up. This is because of noise in the system...you'll never get a zero signal, even when there is no source to detect. So, adjust the "noise" level until the theoretical and observed curves match at the bottom. You can then adjust "D" some more until the model curve matches the data.
5. When the curves match as best that you can make them, note the value of "D." This is your measured value of the effective diameter of the feeds (in the same units as that used for λ input box, which, in the default setting, is cm). For comparison, use a ruler to measure the physical diameter of each feed. How does this compare with your inferred effective D?
6. Move the mouse to the plot screen and right click to save the plot as a JPEG. Include this plot in your report.
7. Note the full-width-at-half-maximum (FWHM) of the beam pattern. This is the primary beam width of the VSRT feeds.
8. Convert your primary beam width to radians and compare with that given by

$$FWHM = 1.02 \frac{\lambda}{D},$$

where D is the diameter of the antenna and λ is the wavelength (2.5 cm) of the radiation.

9. Try different values of "D" and note how it changes your beam pattern. Specifically, when "D" increases, what happens to the beam pattern. Now adjust λ and note how the beam pattern changes. Note, in particular, how the width of the beam depends on λ and D.

Examination of Beam Pattern without VSRT Equipment:

If you don't have a VSRT Interferometer or any data, you can still use this tool to explore how an antenna's beam depends on the parameters. Click on "Show Beam Pattern," and adjust the values of "D" (the diameter of the antenna) and λ (the wavelength of the radiation) and see how the beam pattern changes. Measure the FWHM of the beam pattern and compare to that given by

$$FWHM = 1.02 \frac{\lambda}{D},$$

To save the plot as a jpg or eps file, move the mouse to the plot screen and right click.

B. Interferometric Observation of a Single Resolved Source

The Visibility Function:

When radio astronomers use an array of antennas to make an image of a radio source, each pair of antennas acts as an interferometer. And, the data used to make the images are the outputs from the interferometers as a function of the “baseline” – a vector defined by the separation distance of the antennas and the direction of their relative orientation. The response of each interferometer also depends on the direction of the radio source in the sky and on the shape and size of the radio source. The dependence on the direction of the radio source is called the fringe function, and is a well known function. The dependence of the detected signal on the source structure, as a function of baseline divided by the wavelength, is the “**visibility function**,” $V(\frac{b}{\lambda})$. Note that the independent variable is not simply baseline, but baseline divided by wavelength.

In professional radio astronomy interferometric observations, the fringe function is removed from the data leaving only the visibility function. In this lab, we place the source in line with the center of the baseline and keep the source at that position. The fringe function, then, does not come into play, and so the response of the interferometer is purely the visibility function. To obtain the visibility function, you will need to make measurements with a range of baselines.

Also, to keep the lab relatively simple and straight-forward, we only measure the visibility function in one dimension. Our visibility function, therefore, is easily displayed in a simple graph, and is shown in the graph window at the left side of the VSRTI_Plotter window.

Observations of a Single Resolved Source

When observing a source with a large angular size, the radio waves enter the antennas over a range of direction angles, and this causes a decrease in the combined signal from the two antennas. This decrease is more pronounced for antennas that are further apart. As a result the total detected power on longer baselines for a large source will be less than that from a smaller source with the same total flux density. And, similarly, interferometers with greater distances between the antennas are more sensitive to the source’s angular size. A shorter-baseline interferometer, therefore, will have less of a decrease in the detected power than will an interferometer with a longer baseline. This effect is commonly described by saying that the longer baselines “resolve out” some of the flux of the source. And, the longer



FIG. 3: A straight-tubed CFL stands on end behind a gap produced by a pair of metal sheets. The metal sheets block the view of the sides of the CFLs.

the baseline, the more of the flux is resolved out.

By plotting the visibilities (for a source located at $\theta = 0$) for a range of baseline distances one can, then, infer the angle over which the flux density of an extended source (i.e. not a point source) is distributed.

In this lab, you will obtain and plot the visibilities vs. baseline and discover the baseline-dependence of the detected power, revealing that the CFLs are not really point sources.

Observing Procedure:

1. Place a straight-tube CFL, standing on its end (so that it has a rectangular shape as viewed from feeds) and at the mid-plane position ($\theta = 0$).
2. Place two metal sheets slightly in front of the CFL by a few cm, but with a gap, equal in width to the CFLs (about 4.5 cm), for the radiation to pass through, as shown in Figure 3. The metal sheets should be tall enough to reach the top of the CFL; paper clipping two pieces of scrap aluminum to metal book ends works well. (The metal sheets are used to solve the problem posed by the three-dimensionality of the CFLs. See the Appendix, at end, for more discussion.) The gap between the edges of the metal sheets should be 2 meters from the feeds.
3. Start by placing the feeds one above the other (so that their horizontal distance is zero), as shown in Figure 4.

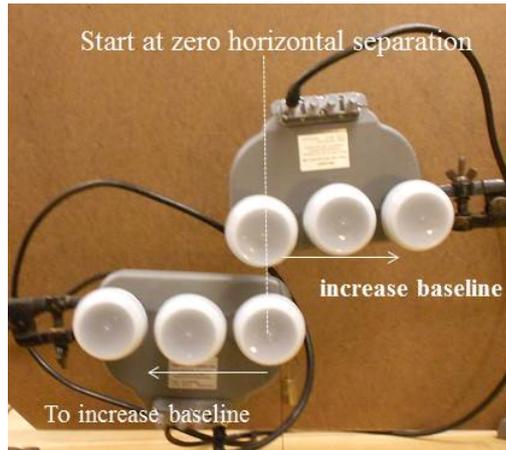


FIG. 4: Feeds are aligned vertically to produce a zero horizontal separation distance. (Note, this should only be done for rectangular sources (or real point sources)).

4. Click “record,” and in the file name type ‘0’ between single quotes, to represent a baseline distance of 0. Record until $n \approx 50$.
5. Move the feeds to a horizontal separation distance of 2 cm by moving each of them 1 cm in opposite directions. Click “record,” and put the value of the baseline distance (in cm) between the single quotes.
6. Increase the separation distance of the feeds by another 2 cm. Keep the distance of the feeds from the gap constant by moving them along an arc centered on the gap. Also, turn the feeds as you move them so that they are always facing the gap. Take care to ensure that the feeds are exactly the same distance from the gap. Click “record,” use the same file name but with the new value of the baseline distance, *in cm*, between the single quotes.
7. Repeat the last step, always increasing the separation distance of the feeds by 2 cm, up to a separation distance of 60 cm. (See Appendix for a discussion of the maximum baseline you can use.) When the detected power gets below 15 K, increase the integration time to 100 scans.
8. Replace the straight-tubed CFL with a larger helical CFL and widen the gap to match its width (about 7.5 cm). Repeat the above experiment. Save the data into files with a different name (and store in a different folder).

Analysis:

1. Open VSRTL_Plotter and select “Plot Visibilities.” Drag-and-drop the data files for the set-up with the smaller gap into the data files box. You should see a graph of detected power vs. $\text{baseline}/\lambda$ that decreases with increasing b/λ .
2. Click on “Display Model Visibility”, set $T2 = 0$ and for “shape1” select “rectangular.” Adjust the values of $T1$ and $\Phi1$ until the curve fits the data. (The equation of the model is given in the Appendix, at the end.) The value of $\Phi1$ is the apparent angular size of the CFL in radians according to the data. This implies a linear size, l , of the CFL given by

$$l = \Phi d$$

where d is the distance of the CFL. (Recall that a body’s apparent angular size in radians is approximately equal to its linear size divided by its distance.) If you followed the instructions here your distance, d , is equal to 2 meters. Compare your inferred value of l to the linear distance across the gap between the metal plates. These values should agree, within experimental error.

3. Save an image of your graph by right clicking on the plot window.
4. Click “Delete data” and then drag-and-drop the files for the data with the wider gap. How does this change the plot on the left? Don’t worry about the absolute value of the measured power between the two plots, since they involved different lamps. Focus, primarily, on the difference in the shape.
5. Find the best fit value of $\Phi1$ and again calculate the inferred value of l and compare with the setting you used (~ 7.5 cm).
6. Note that in this experiment, the CFL never moved relative to the midpoint of the baseline. In this experiment, therefore, the change in the measured power is not due to the same concept demonstrated in the “Plot Beam” lab. In this lab, the source was stationary, but the feeds were moved to different baselines. You measured the interferometer response as a function of *baseline distance*. This is called the “visibility function.” Discuss the shape of the visibility function for an observation of a *resolved* source and how this shape changes as the size of source is decreased.

7. By extrapolation, try to infer what the shape of the visibility function is for a point source. Test your answer by viewing model curve (“Display Model Visibilities”) when the value of Φ_1 is set to 0 (remember to click “Update”). When the visibility function is such a shape, then no angular size of the source can be inferred and so this indicates when a source is *unresolved*.
8. Discuss why real interferometric observations of radio sources involve more than one pair of antennas. Consider the fact that with three antennas, for example, there are three pairs of antennas, and each pair can involve a different baseline distance. How does observing with a large number of antennas, such as with the VLA, provide the information needed for radio astronomers to obtain images of resolved radio sources? (Hint: consider the graph you created to reveal the visibility function and how quickly the data for this graph could be obtained if you had more than two feeds.)
9. Consider, and discuss, the *resolution* of an array of antennas as it relates to the linear size of the array. Is an array which includes large baselines more or less capable than a smaller array of inferring the structure of a compact source. For an array with a range of baselines, which baselines determine the resolution – the longest or shortest? Write a mathematical relation to determine the resolution angle of an array of antennas.
10. Consider if you observed a large source with a large array which involved only very long baselines (such as VLBI). Explain why this situation might result in a null detection. It is, therefore, not a good idea to observe a radio source with an array with too good resolution. When planning an observation of a known source, you should pick the instrument whose resolution best matches your source.

C. VSRT Observation of a Pair of Sources

Observing a pair of sources, separated by an angle large relative to the resolution of the interferometer, is, essentially, combining the interferometer responses to sources at two different positions. As mentioned in the previous lab the interferometer response has a dependence on source position. In the same way that light passing through two slits produces a striped pattern with the distance between the stripes depending inversely on the distance between the slits, the visibility function of a pair of sources has a sinusoidal dependence on b/λ with a wavelength (or “spatial period”) that is inversely proportional to the angular separation of the sources. By plotting the visibilities for a range of baseline distances one can, then, identify a binary source and determine the separation angle of the sources.

In this lab, you will use two CFLs to reveal the sinusoidal shape of the visibility function for two sources and show the relation between the angular separation of the CFLs and periodicity in the visibility function.

Observing Procedure:

1. Start by placing the feeds one above the other (so that their horizontal distance is zero).
2. Place a pair of helical CFLs, both standing on end, at a distance of 2 meters from the feeds, and separated by 40 cm in the perpendicular direction. Aim the feeds at the midpoint between the CFLs. A picture of the set-up is shown in Figure 5.
3. Click “record,” and put a ‘0’ between the single quotes in the file name (to represent a baseline distance of 0). Record until $n \approx 50$.
4. Move the feeds to a horizontal separation distance of 2 cm by moving each of them 1 cm in opposite directions. Click “record” and put the value of the baseline distance (in cm) between the single quotes.
5. Repeat step 4, always increasing the separation distance of the feeds by 2 cm, up to a separation distance of 60 cm. Turn the feeds as you move the CFLs so that they are always facing the midpoint between the two CFLs. (See the Appendix for a discussion

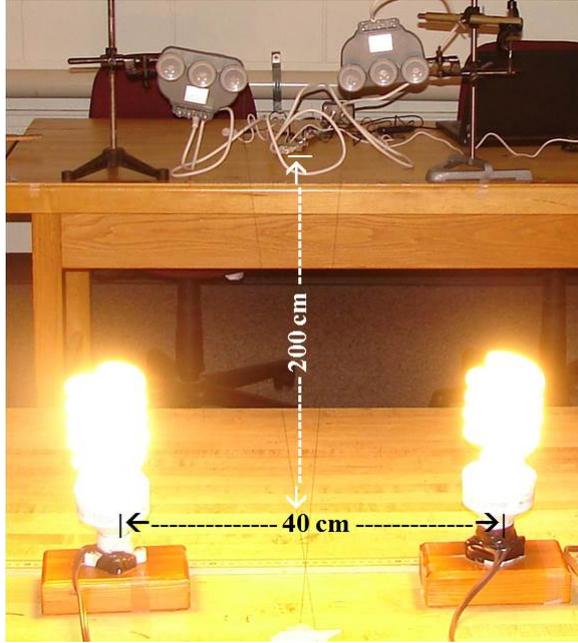


FIG. 5: Two helical CFLs separated by 40 cm at a distance of 2 m from the feeds. The picture was taken when data was being recorded with the feeds separated by about 20 cm

of the maximum baseline you can use.) When the antenna temperature is below 30 K integrate for 60 scans and when it is below 15 K integrate for 100 scans.

6. Rearrange the CFLs so that they are separated by 30 cm and repeat the above procedure but make sure that the file names are different, and/or place them into a different folder. Obtain a third data set for CFLs separated by 20 cm.

Analysis:

1. Open VSRTL_Plotter and select “Plot Visibilities.” Drag-and-drop the data files for the 40-cm separation distance. You should see a quasi-sinusoidal function appear, whose amplitude decreases with baseline distance. The decreasing amplitude is due to the resolving of the individual CFLs, as you demonstrated in the observations of a single source lab. The oscillations, though, indicate that there is a second source, away from $\theta = 0$.
2. Measure the distance between peaks, in terms of b/λ , in the sinusoidal function. Call this Θ . Calculate the angular separation of the CFLs in radians from $\theta(\text{radians}) = x/d$, where x is the linear separation distance between CFLs.

3. Click “Delete Data” and then drag-and-drop the data set for CFLs separated by 30 cm, and measure the distance between peaks and calculate θ from x/d . Do the same with the data set for CFLs separated by 20 cm.
4. In a separate plotting program (such as Excel), plot Θ vs. θ (in radians). What is the relation between these two parameters? Do your data fit the relation $\Theta = 1/\theta$?
5. Drag-and-drop each data set into the data files box again. This time click on “Display Model Visibility” and set “shape1” and “shape2” to “rectangular”. (Note: if you placed the CFLs on their sides, with the ends aimed at the feeds, then you should select “uniform disk” for the shapes.) Adjust the five input parameters (Φ_1 and Φ_2 are the angular sizes of the CFLs in radians, T1 and T2 are the powers, in Kelvin, of each lamp, and θ is the angular position, in radians, of the second lamp relative to the first, as seen from the center of the feeds baseline) until the data best fit the curve. (The equation of the model is given in the Appendix, at the end). For your best fit models, write the values of θ and calculate the inferred linear separation distances of the CFLs using

$$x = \theta d.$$

Compare with the actual values of x in the set-ups.

6. As in the “Observations of a Single Resolved Source” lab, the CFLs did not move relative to the midpoint of the baseline and so your plot again shows the visibility function. Discuss the shape of the visibility function for an observation of a double source and how this shape changes when the angular separation between the two pieces change.
7. Imagine planning an observation at a wavelength of 6 cm of a double radio source in which the sources are separated by 30 arcseconds. If planning an observation of this source, what ranges of baselines would be needed to map this double source?

D. VSRT Observations of a Mystery Source

[Note to instructors: If you wish to assign this lab and would like advice about how to set up a mystery source that is solvable, feel free to e-mail me (marrj@union.edu).]

Your instructor will have some number of CFLs inside a cardboard box. Your goal, now, is to use the feeds, at a range of baselines, repeating the procedure of the previous lab but with the CFLs hidden in the box, obtain a visibility function, analyze it, and make a model of what you think the “structure” of the mystery source is (how many CFL’s and in what positions?).

Remember to keep in mind the main principles that were demonstrated in the previous two labs. How does the visibility function appear with a resolved source? How does the visibility function appear for a single pair of sources separated by a given angular distance? Extrapolation of these principles should help you to, now, infer a slightly more complex structure. You cannot use the “Show Visibilities” button to help you in this lab, since the model to match the mystery source has not been put in.

Here are some principles from the previous two labs which we give here as hints for you

1. As demonstrated in the single-resolved-source lab, the longer baselines resolve out more of the structure of an extended source. This means that the zero-baseline visibility should contain the flux from the entire source.
2. *Each* pair of sources produces a periodic visibility function with period given by $\Theta = 1/\theta$. Considering the principle stated in no. 1, each periodicity must have a maximum at the zero baseline...so to identify periodicities, start at $b/\lambda=0$ and look for the next peak after that.

E. The Fourier Transform Relation Between Image Brightness Distribution and Visibility Function

Go to <http://minerva.union.edu/marrj/radioastro/labfiles.html>, download TIFT.zip, and extract all the files. Go into the TIFT folder and make a shortcut of TIFT_Chooser.jar on your desktop. Open TIFT_Chooser and then open TIFTLab.pdf and follow the instructions.

Appendix: Additional Notes:

1. Model Equation

The model used in Plot Visibilities is given by

$$T = \sqrt{T_A^2 + T_B^2 + 2T_A T_B \cos\left(\frac{2\pi b \sin(\theta)}{\lambda}\right)},$$

where the power of each individual CFL, as a function of baseline, b , for a rectangular source, is

$$T_A = T_1 \left(\frac{\lambda}{2\pi b \Phi_1}\right) \sqrt{2\left(1 - \cos\left(\frac{2\pi b \Phi_1}{\lambda}\right)\right)}$$

and

$$T_B = T_2 \left(\frac{\lambda}{2\pi b \Phi_2}\right) \sqrt{2\left(1 - \cos\left(\frac{2\pi b \Phi_2}{\lambda}\right)\right)},$$

and for a “uniform disk,”

$$T_A = T_1 \frac{(J_1(\pi \Phi_1 b / \lambda))}{(\pi \Phi_1 b / \lambda)}$$

where J_1 is the first order Bessel function of the first kind.

2. Maximum Baselines

The interferometric equations for the amplitude of the visibility assume that the rays approach the feeds in parallel rays, which is clearly true for a source that is infinitely far away. For these labs, however, the CFLs are only about 2 meters away while the feeds get up to tens of centimeters apart. The assumption of parallel rays, therefore, can break down if the feeds are put too far apart. The assumption of parallel rays is used in the derivation of the equation to assign the path-length difference, which causes the phase difference in the two feeds. For the results of these labs to not be significantly altered by an error in the assumed phase difference, the difference between the model and true path length difference needs to be within 1/8th of λ , so that the model and true phase differences stay within $\frac{\pi}{4}$. This constraint is satisfied if

$$\frac{bx}{d} \left(1 - \frac{1}{\sqrt{1 + (b/2d)^2}}\right) < 0.003$$

where b is the baseline distance, x is the largest linear distance between points of radio emission (i.e. the diameter of the CFL for the Single-Resolved Source lab, and the distance between CFLs in the Double-Source lab), and d is the distance along the mid-plane from the CFL plane to the feeds plane (following the instructions of the labs here, $d = 200$ cm).

For the Single-Resolved Source lab, in which $x=5$ cm, one should keep the baseline shorter than 160 cm.

For the Double-Source lab, where the largest $x = 40$ cm, the baselines should be kept under 80 cm.

3. Apparent Angular Size of CFL's

When conducting the “Single Resolved Source” lab, if the metal screens are not used to set the width, the apparent size of the CFL will be larger than the CFL itself. This occurs because of the 3-dimensionality of the situation. The feeds detect radio emission from the back of the CFL as well as the front. As the feeds are moved to larger baselines, their view of the CFLs include the sides of the CFL. The effect is that the CFLs appear like larger sources. The inferred diameter of the CFL without the metal shields in the single-resolved-source lab is about 7.5 cm, while the physical diameter of the CFL is, in reality, about 4 to 5 cm. For this reason, we recommend that the single resolved source lab be conducted with a pair of metal shields in front of the CFL to, effectively, make a slit with adjustable width. The shields block the radiation from the sides when the feeds move to larger baselines.