Interferometry Basics in Practice: Exercises

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Abstract

The following exercises aim to learn the link between the object intensity distribution and the corresponding visibility curves of a long-baseline optical interferometer. They are also intended to show the additional constraints on observability that an interferometer has.

This practical session is meant to be carried out with the `ASPRO` software, from the Jean-Marie Mariotti Center [1], but can also be done using other observation preparation software, such as viscalc [2] from ESO.

There are two main parts with series of exercises and the exercises solutions. The first one aims at understanding the visibility and its properties by practicing with simple examples, and the second one is about *UV* coverage.

Key words: Optical long baseline interferometry, visibility, phase, *UV* coverage, VLTI, `ASPRO`

1 From model to visibility (exercises)

This first series of exercises is made for training your practical comprehension of the link between the image space (where you usually work) and the Fourier space (where an interferometer produces its measurements). Optical

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[1] `http://www.jmmc.fr`
[2] `http://www.eso.org/observing/etc/`

long-baseline interferometry experts constantly switch between Fourier and image space. This training will help to get used to this continuous switching.

What you will need for this particular practice session

All exercises of this practice session will be done assuming a simple yet unrealistic *UV* coverage. Synthetic *UV* Tables simulating such *UV* coverages are provided for use:
`strip-[J,H,K,N]-[000,..,170].uvt`, where the number `xxx` is the projected baseline angle in degrees.

`ASPRO` is able to do many things, but this session will focus on the *MODEL/FIT - UV plots and source modeling* part.

You will probably also need Tables 1 and 2.

Table 1
   All integrated `ASPRO` models one can use during this practice session and their useful parameters.

`ASPRO` name	Source shape	useful parameters
POINT	Unresolved (Point source)	None
C_GAUSS	Circular Gaussian	FWHM Axis
E_GAUSS	Elliptic Gaussian	FWHM Axis (Major and Minor), Pos Ang
C_DISK	Circular Disk	Diameter
E_DISK	Elliptical Disk	Axis (Major and Minor), Pos Ang
RING	Thick Ring	Inner Ring Diameter, Outer ring diam
U_RING	Thin Ring	Diameter (1 value: unresolved!)
EXPO	Exponential brightness	FWHM Axis
POWER-2	$B = 1/r^2$	FWHM Axis
POWER-3	$B = 1/r^3$	FWHM Axis
LD_DISK	Limb-Darkened Disk	Diameter, 'cu' and 'cv'
BINARY	Binary	Flux ratio, rho, theta

<u>*Exercise 1:*</u> *The diameter of a star.*

The aim of this exercise is to have first contact with uniform disks, which are very often used to perform photospheric diameters fits or first-order interpre-

Table 2

Description of the parameters of the ASPRO model software module. **Be sure to regard the parameter units.**

name / parameter	1st (")	2nd (")	3rd (no unit)	4th (unit)	5th (unit)	6th (unit)
POINT	R.A.	Dec	Flux	0	0	0
C_GAUSS	R.A.	Dec	Flux	Diameter (")	0	0
E_GAUSS	R.A.	Dec	Flux	Maj. diam. (")	Min. diam. (")	Pos. Ang. (°)
C_DISK	R.A.	Dec	Flux	Diameter (")	0	0
E_DISK	R.A.	Dec	Flux	Maj. diam. (")	Min. diam. (")	Pos. Ang. (°)
RING	R.A.	Dec	Flux	In diam. (")	Out diam. (")	0
U_RING	R.A.	Dec	Flux	Diameter (")	0	0
EXPO	R.A.	Dec	Flux	Diameter (")	0	0
POWER-2	R.A.	Dec	Flux	Diameter (")	0	0
POWER-3	R.A.	Dec	Flux	Diameter (")	0	0
LD_DISK	R.A.	Dec	Flux	Diameter (")	cu	cv
BINARY	R.A.	Dec	Flux	Flux Ratio	Rho (")	Theta (°)

Notes: - for the binary model, the **Flux Ratio** is $F_{secondary}$ / $F_{primary}$, and **Rho** & **Theta** are the angular separation (") and position angle (degrees) of the binary.

- **R.A.** and **Dec** are usually set to zero while **Flux** is set to one.

- "0" means you have to fill the parameter value a with zero. Be careful to put a 0 instead of leaving it blank, otherwise the software will crash !

tations of the data.

Plotting a uniform disk visibility curve: Given a star with a 2 milli-arc-second (mas) photospheric radius, use the model function to plot the visibility versus the projected baseline length (baseline **radius**). For this purpose, you can use the *MODEL/FIT.UV Plots & Source Modeling* menu.

Zero visibility: At what baseline does the visibility become equal to zero (you can refer to Berger & Segransan, 2007, for example)? Use this number to evaluate the disk diameter.

Diameter uniqueness: Can you measure a unique diameter if your visibility is non-zero but you know the star looks like a uniform disk? If yes, how?

Exercise 2: Binary star.

When the amount of data you get is a low number of visibilities, the object's complexity for your interpretation cannot be too high. Therefore, binary models are often used to understand the data when asymmetries happen to be proved by means of interferometry (by a non-zero closure phase) or by indirect clues (a polarization of the target, for example). Therefore, one has to understand the behavior of such a model.

Plotting a binary star visibility curve: Display the visibility and phase as a function of projected baseline (using the file `strip-K-60`) of a binary with unresolved components with 4 mas separation, a flux ratio of 1, and a position angle of 30 degrees. Do the same thing with different separations. Comment on the result.

Varying the flux ratio: Using the previous model, now vary the flux ratio from 1 to 1e-6. Comment on how the dynamic range requirement to detect the companion translates into visibility and phase constraints?

Phase versus visibility: Would the phase alone be sufficient to constrain the binary parameters?

Exercise 3: Circumstellar disk.

The last model we will see in this practice session is a Gaussian disk that can, in a first approximation, simulate a circumstellar disk, or an optically thick stellar wind. The idea here is to understand how visibilities change with source elongation.

Plotting a Gaussian disk visibility curve: Display the visibility curve of a disk which is assumed to have an elliptical Gaussian shape (model `E_GAUSS`). Use the minor and major axes (parameters 4 & 5) to simulate an inclination. The display should be done for several PAs (`strip-*-(0,30,45,60,90)`).

4

Aspherity and visibility variations: Comment on how the aspherity induced by the inclination changes the visibility function at a given projected angle.

Exercise 4: Model confusion and accuracy.

If the baseline you have chosen is too long or too small relative to the typical size of your source, this may cause problems when you try to interpret your data. Here you will see why.

Plotting several model visibilities: Use the model function to compute the visibility of a star with a uniform disk brightness distribution (2 mas radius), circular Gaussian disk (1.2 mas radius), and binary (flux ratio 1, 1 mas separation, 45° PA) with the baseline stripe `strip-K-60`. No superposition of the plot is possible, so use the *show plot in browser* option, save it as a postscript file, and compare the different files afterwards. Compare their visibilities at 100 m in the K band.

Model confusion at small baselines: How can we distinguish between these various models? What about measurements at 200 m? What do you conclude?

The role of measurement accuracy: Does the measurement accuracy play a role in such model discrimination?

Which baseline for which purpose: Construct a 2-component model in which a central, unresolved star (`POINT`) is surrounded by an inclined, extended structure. You can use an elliptical Gaussian distribution (`E_GAUSS`) for this purpose (minor and major axes in the range 0.5 to 15 mas).

Try two scenarios:

- an extended source easily resolvable but with a flux contribution much smaller than the star;
- a smaller extended source but with a larger flux contribution.

What are the best baseline lengths for estimating the size and relative flux contributions with an interferometer?

<u>*Exercise 5:*</u> *Choosing the right baselines.*

Given a specific object's shape, one can determine how a baseline constrains a given model parameter. We will see this aspect here. In order to determine the parts of the *UV* plane which constrain the model most, one can make use of the first derivative of the visibility with respect to a given parameter (e.g. derivative of visibility versus diameter).

Uniform disk: Choose a uniform disk model. What is the most constraining part in the *UV* plane?

For this exercise, in the `UV EXPLORE` panel, you will need the "U versus V" plot. Check the `under-plot model image` option, and choose the appropriate derivative in the `plot what...` line.

Gaussian disk: Do the same exercise using a Gaussian disk.

<u>*Exercise 6:*</u> *An unknown astrophysical object.*

The wavelength at which an object is observed is also important. This exercise attempts to illustrate this point.

Loading and displaying a home-made model: Load the fits Table `fudisk-N.fits` corresponding to the simulation of a certain type of astrophysical object (here, a disk around an FU Orionis object) using *OTHER/Display a GDF or FITS image* menu. If the color scale is not appropriate, check the *Optional parameters* button and select another color scale. Notice what the contrast of the object (angular units in radians) is.

Computing the visibilities of a home-made model: Compute the visibility of the model in the N-Band with *MODEL/ FIT.UV Plots & Source Modeling/USE HOMEMADE MODEL*. To do so, select the appropriate grid `strip-N-60` in the *Input Information* menu. Use `UV EXPLORE` to plot the visibility amplitude versus the spatial frequency radius.

Comparing visibilities for different wavelengths: Repeat these operations in the K band, then the H and J ones. Compare the visibility profiles. Conclude on the optimal wavelength to observe the object with the VLTI (maximum baseline is 130 m today).

Exercise 7: Play with spectral variations, closure phases, etc.

Bonus exercise: Try to guess what this model shows just by looking at the visibilities (please do not cheat!).

Plotting visibilities and closure phase versus wavelength: Using a given model of a binary star (γ^2 Vel, file gammaVelModelForAspro.fits), try to plot visibility and closure phases as a function of wavelength (see the *OTHER ... Export UV table as OI fits* and *OTHER ... OI fits file explorer* menus).

Qualitative understanding: Compare the obtained visibilities with what you would get with an `ASPRO` model of one Gaussian and one uniform disk of diameters 0.5 mas, a separation of 3.65 mas, and an angle of 75 degrees. What do you conclude?

Looking at the solution: After your conclusions, you can look at the model by opening it with a fits viewer (for example, fv [3]).

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[3] `http://heasarc.gsfc.nasa.gov/lheasoft/ftools/fv/`

2   From model to visibility (Solutions)

The author of this paper carried out the previous exercises using `ASPRO` (and an image processing software for superposition of the graphs: `GIMP`) to give an idea of what one should get with `ASPRO` when following the previous exercises. **Please try to do the exercises yourself before reading these solutions**.

Exercise 1: The diameter of a star.

Plotting a uniform disk visibility curve: The figure produced by `ASPRO` should look like Fig. 1, left.
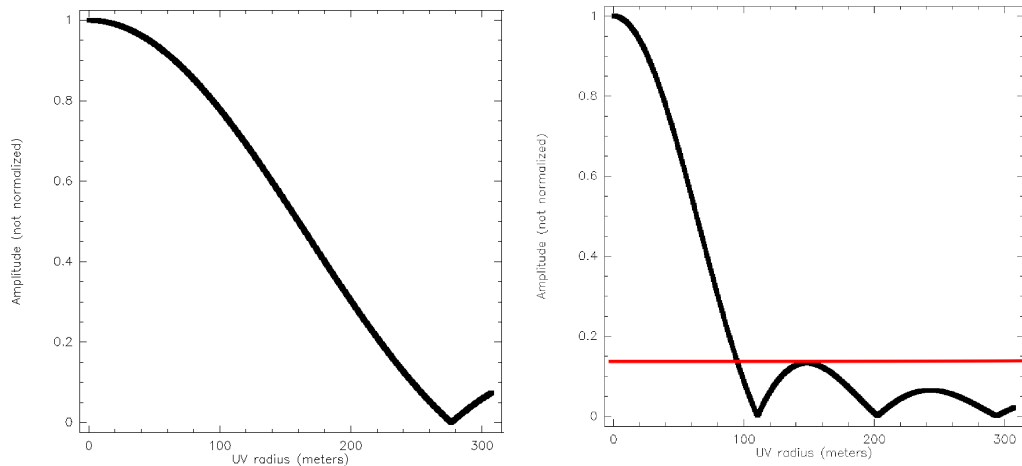
Fig. 1.   **Left:** The uniform disk visibility function cut from exercise 1. **Right:** The place where one can infer a unique diameter from a single visibility measurement for a uniform disk is where the measured contrast is above 0.15. Indeed, below 0.15, several diameters can be inferred from this single visibility measurement (as shown by the red line).

Zero visibility: The visibility for a uniform disk of diameter a is given by the following expression:

$$V(\rho) = 2\frac{J_1(\pi a \rho)}{\pi a \rho} \tag{1}$$

$\rho = B/\lambda$ (B and λ in meters) being the spatial frequency, a being the star diameter (in radians), and J_1 the 1st order Bessel function. Therefore, the value for which the visibility becomes zero is $B = 1.22\lambda/a$.

9

Here, the visibility zeroes around the 280 m baseline. This gives an approximately 1.89 mas diameter for the star, close to the 2 mas input.

Diameter uniqueness: The right plot in Fig. 1 gives a hint of the answer: There are parts of the visibility function which are monotonic (above the red line). In these parts, one visibility gives a unique solution to the diameter of the star. In the parts below the red line, a given visibility corresponds to many different solutions (as the line crosses several points of the curve). Therefore, there is a lower limit on the visibility value ($V \gtrsim 0.15$) where one can infer a unique diameter from a unique measurement.

Exercise 2: Binary.

Plotting a binary star visibility curve: The visibility and phase functions of a binary star are periodic since the image is made of Dirac functions. One can see what can be expected for a 4 mas-separation binary star in Fig. 2. One can see that the visibility does not have a cosine shape, but has sharp changes at visibility 0 for a 1 to 1 binary (black line).

Varying the flux ratio : For other flux ratios (0.8 in red, 0.5 in blue, and 0.1 in green), both the phase and visibility get smoother, and the contrast of the variations gets dimmer. Please note that these are visibility plots made with "AMP" and not "AMP$\hat{2}$" in `ASPRO`.
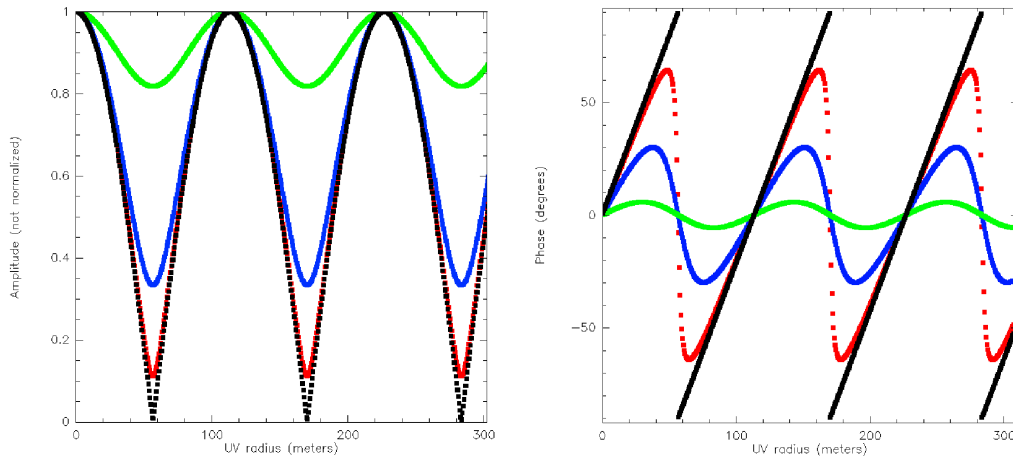

Fig. 2. **Left:** The visibility amplitude for a separation of 4 mas and different flux ratios (from the lower to the upper curves: 1 to 1 in black, 0.8 to 1 in red, 0.5 to 1 in blue, and 0.1 to 1 in green). **Right:** The visibility phase for the same separation and flux ratios.
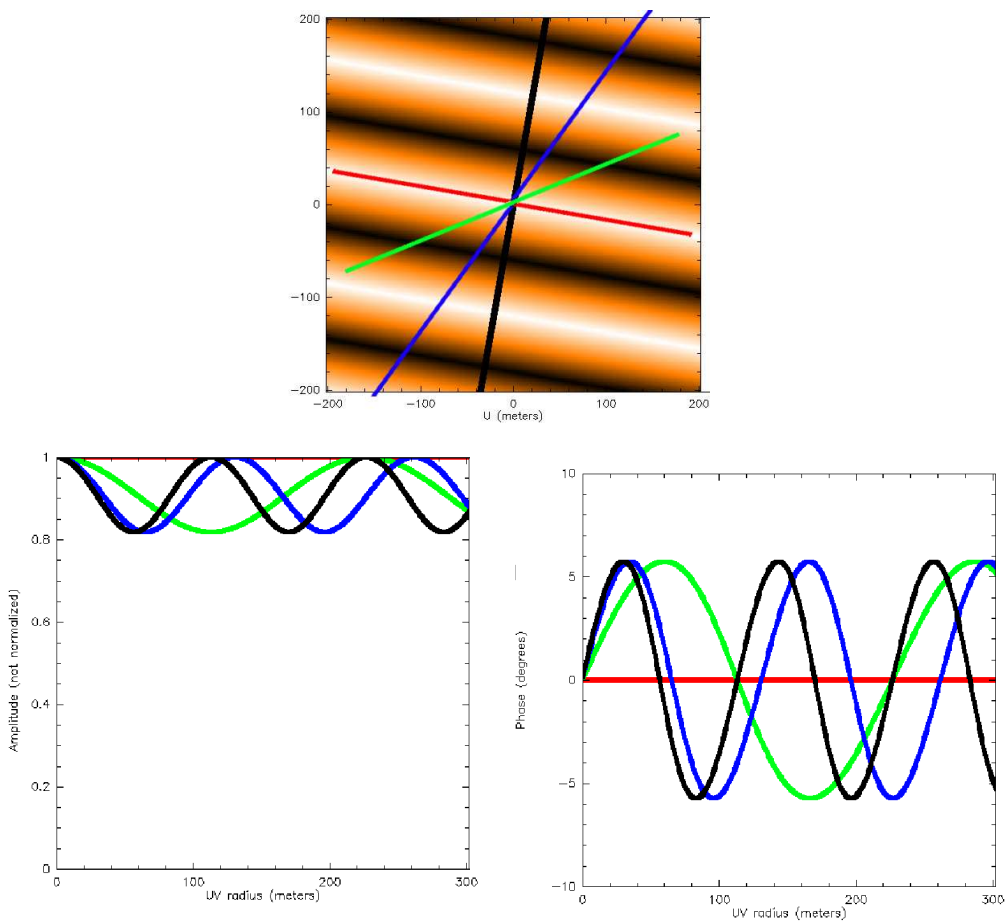
Fig. 3. **Top:** *UV* map showing the previous binary star visibility modulus. This visibility shows characteristic modulation stripes perpendicular to the binary orientation. **Bottom-Left:** Visibility modulus as a function of base length for the different projected stripes, in different colors (the number of sine arches increases with the different orientations): red is 90° relative to the binary orientation, green is 60°, blue is 30° and black is 0°. **Bottom-right:** Visibility phase as a function of base length for the same stripes as before.

Phase versus visibility: To see how visibility or phase can constrain a binary star model, one can just try to change the baseline orientation and see how visibility and phase vary. In Fig. 3, bottom-right, one can see the result of such exercise. One has seen that the phase is sensitive to the contrast of the binary (Fig. 2), as is the visibility, but it is also sensitive to the position angle (both of the binary star and of the baseline) and the binary separation. Therefore, the phase can be used instead of the visibility to constrain the binary parameters!
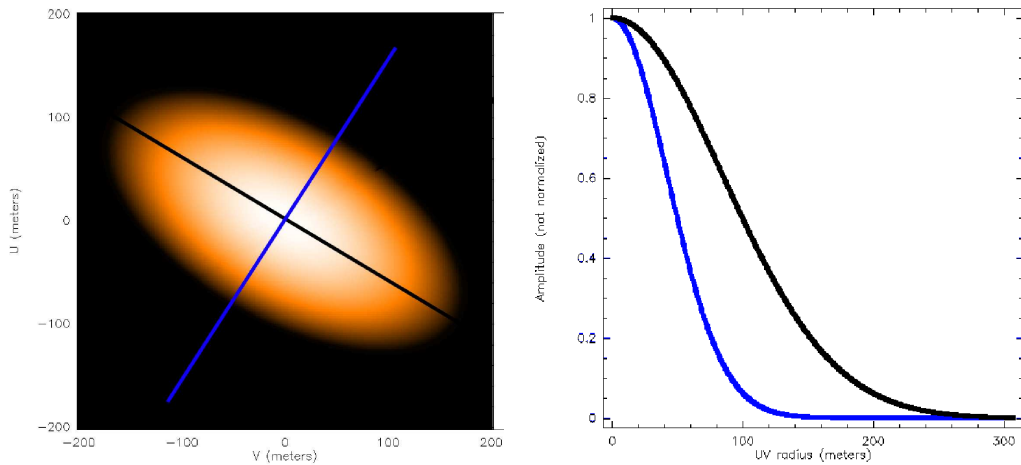
11

Fig. 4. **Left:** *UV* map showing the visibility amplitude for a 2x4 mas elongated Gaussian disk. The black and blue lines correspond to the right part of the figure. **Right:** Visibility versus base length for the minor (black, upper curve) and major (blue, lower curve) axes of the Gaussian disk. Please note that the visibility is lower in the direction of the major axis and greater in the minor axis direction.

Exercise 3: Circumstellar disk.

Plotting a Gaussian disk visibility curve: The example of this exercise is a disk of 2x4 mas and a position angle of 60 degrees. The resulting *UV* map and cuts in the *UV* plane are shown in Fig. 4.

Aspherity and visibility variations: As one can see, for a given baseline and a varying position angle, the visibility goes up and down, the minimum corresponding to the major axis and the maximum corresponding to the minor axis. One has to note (and can check) that the phase function for such a model is zero.

Exercise 4: Model confusion and accuracy.

Plotting several model visibilities: In Fig. 5 different plots are superimposed using the GIMP software. The uniform disk is in black, the Gaussian in blue, and the binary in red.

Model confusion at small baselines: Two green lines represent the 100 m and 200 m baselines. One can see the importance of multi-measurements at different baselines to be able to disentangle the different objects' shapes. With only one visibility measurement, one will never be able to distinguish between
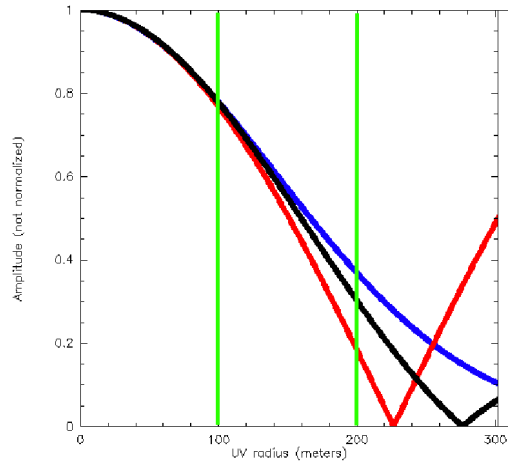
Fig. 5. Illustration of model confusion for different baselines and models: blue (top curve) is a Gaussian disk, red (bottom curve) is a binary star, and black (middle curve) is a uniform disk. The first green vertical line represents a 100 m baseline. If the accuracy is not better than about 0.01, then no distinction can be made between the different models. For the 200 m baseline (second green vertical line), an accuracy of 0.1 or better is sufficient to discriminate between the different models. Note, however, that one needs more than 1 point to be able to really distinguish between the models.

these different models. With the two visibility measurements, one can see that it will be possible to disentangle the different models if both very different baselines AND a sufficient accuracy can be reached.

The role of measurement accuracy: Here, if one has visibility error bars of 0.05, one can distinguish between the sources using the 100 and 200 m baselines, but not with an accuracy of 0.3. This importance of accuracy in model confusion is illustrated by Fig. 6. The 1st plot (on the left) is a central point with 90% of the total flux contribution and a large (15mas) Gaussian disk around, accounting for 10% of the flux. Errors bars of 0.1 would prevent one from finding the Gaussian component, and the measured visibility (0.9 ± 0.1) would be compatible with a completely unresolved star. The right graph shows the same but with the flux ratio inverted (90% of the flux to the disk and 10% to the central star). In this case, the visibilities would be compatible with a fully resolved, extended component, given an accuracy of 0.1 on the visibility, and the point source (the central star) would not be detected. So, not only the number of baselines but also the accuracy of the measurement is of high importance to distinguish between different models.

Which baseline for which purpose: Here, one can see that since there is an unresolved source in the object image (a central source), measuring the

visibility at long baseline directly provides the unresolved$_{\text{flux}}$/resolved$_{\text{flux}}$ flux ratio.

If one wants to get information on the disk itself (size, shape, etc.), the shorter baselines are more appropriate, since the visibility will vary according to the source shape.
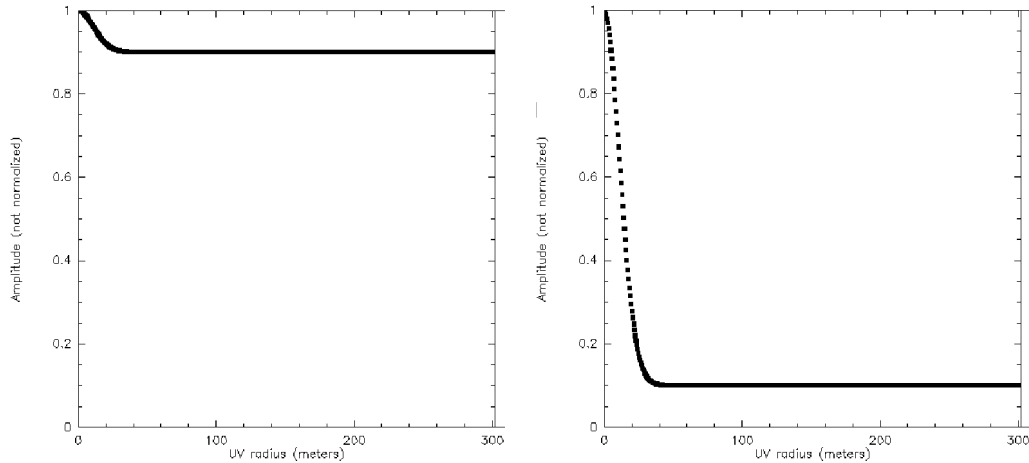

Fig. 6.   **Left:** Visibility cut for a point star accounting for 90% of the total flux and a 15 mas Gaussian disk accounting for 10% of the flux. **Right:** Visibility cut for a point star accounting for 10% of the total flux and a 15 mas Gaussian disk accounting for 90% of the flux.

Exercise 5: Choosing the right baselines.

The idea here is to use the nice feature of `ASPRO` that is able to plot the derivatives of visibility versus the different parameters of the input model. To do so, one has to go to the *UV explore* panel, select U as X data and V as Y data, and finally select $d(AMP)/d(4)$ in the *Plot what...* part. This will plot the derivative of the visibility amplitude versus the 4th parameter (radius, as shown in Table 2).

Fig. 7 shows the model visibility and its derivative, relative to the model size, for a Gaussian disk and a uniform disk.

Uniform disk: The size used is 2 mas. The derivative peaks where the visibility slope versus baseline is the largest. This means that for a small baseline change, a large visibility change will be observed; i.e., the biggest constraint will be applied to the corresponding model in the model fitting process.

One can see that the optimal baseline is 100 m for the uniform disk. One should know that the optimal baseline to constrain a given model corresponds

to a visibility of about 50%. Very important to know: baselines that are too short or too long will not reveal much information about the source size or shape.

Gaussian disk: The size used is the same as before: 2 mas. The optimal baseline is about 50 m for the Gaussian disk. Therefore, using different baselines, one will be able to both disentangle the model shape (Sharp - UD - or smooth - Gauss - edges?) and constrain the typical size (as seen before).
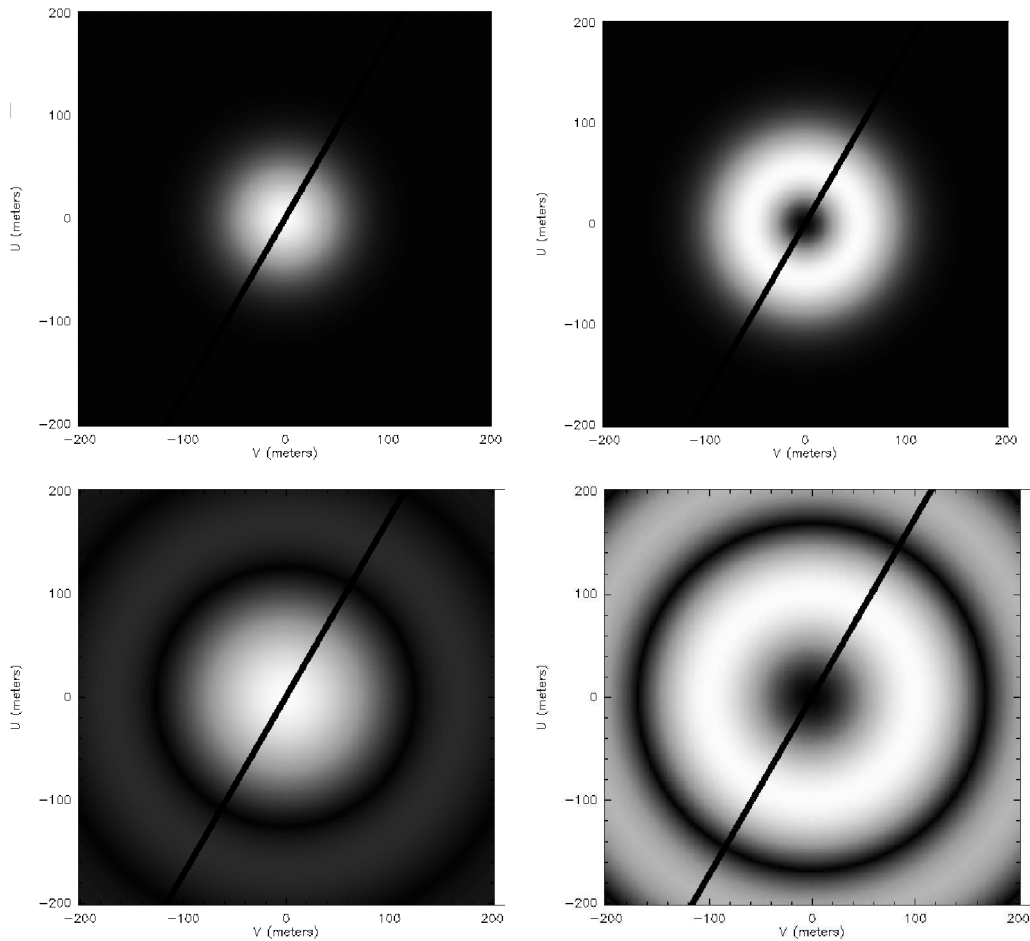

Fig. 7. **Top-left:** Gaussian disk visibility map, as a function of UV coordinates. **Top-right:** Visibility derivative versus the model size (FWHM), showing where the visibility varies more with UV coordinates. **Bottom-left:** Visibility map, but using a uniform disk. **Bottom-right:** Visibility derivative versus model size (FWHM) for a uniform disk model.

Exercise 6: An unknown astrophysical object.

Loading and displaying a home-made model: Fig. 8 (top) shows the model of a young stellar disk produced by F. Malbet. The star-to-disk contrast here is 1 to 10.

Please note that, as for the previous disk model (Exercise 3), the disk is elongated, and therefore, the large visibilities will correspond to the minor axis of the model, whereas the low visibilities will correspond to the major axis.

Computing the visibilities of a home-made model: The lower-left part of Fig. 8 displays a UV map of the model shown in the upper part. This map is very similar to the one shown in Fig. 4, which indicates that the disk mostly looks like a Gaussian disk.

Comparing visibilities for different wavelengths: The lower-right part of Fig. 8 shows the visibility for the minor axis with different wavelengths: J (black, lower curve), K (blue, middle curve), and N (red, upper curve). This shows which wavelength to use to observe the object: the K-band allows both high visibilities for the extended component and low visibilities for the detailed structure of the disk, in the range of the VLTI offered baselines (16-130 m).

Exercise 7: Play with spectral variations, closure phases, etc.

This is a bonus exercise. To manage it, one will need the newest local version of `ASPRO` to cope with closure phases (at the time of writing this solution, the web version of `ASPRO` did not have all functionalities necessary to do this exercise). Therefore, one is not obliged to reach this point.

Plotting visibilities and closure phase versus wavelength: In Fig. 9, one can see the visibilities for a given observational setup (A0-D0-H0) and the closure phase. The author has used, on purpose, an array with aligned baselines to illustrate this exercise.

Qualitative understanding: There are a number of indicative clues to qualitatively understand the shape of the observed object:
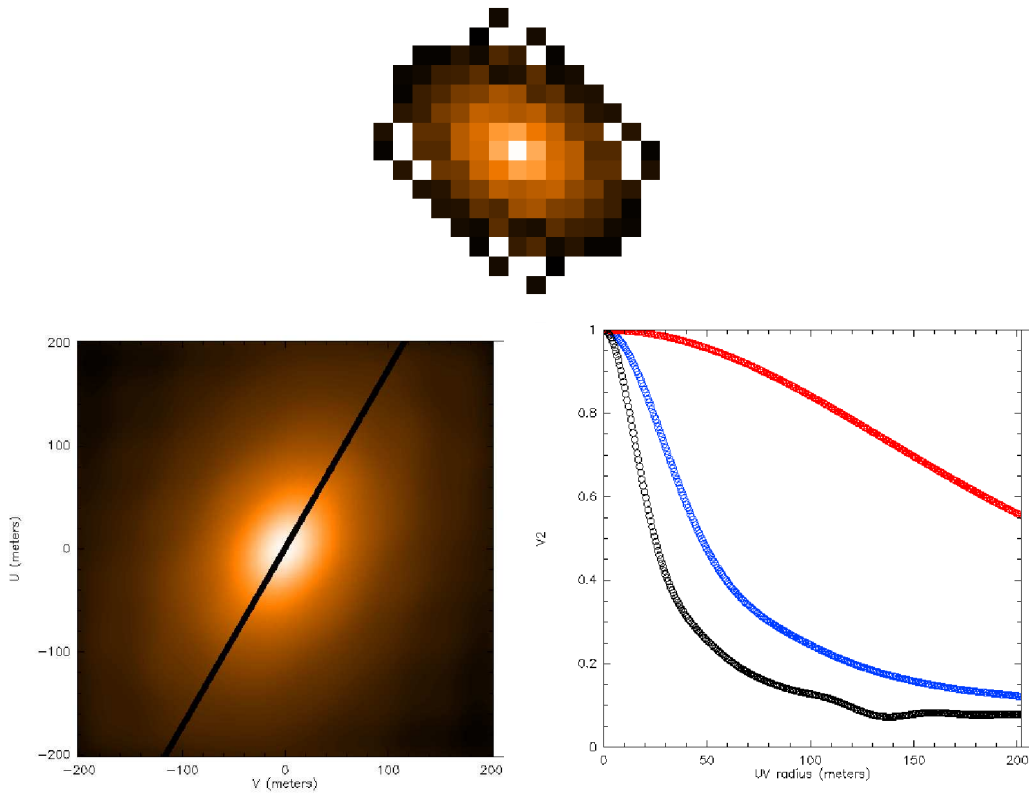
Fig. 8. **Top:** Image of the disk model used in exercise 6 (shown using the fv tool)
Bottom-Left: Visibility map showing the main elongation of the disk, perpendicular to the main elongation of the visibility function. **Bottom-Right:** Visibility of the disk for different wavelength regimes: red (top curve) is N-band, blue (middle curve) is K-band, and black (bottom curve) is J-band.
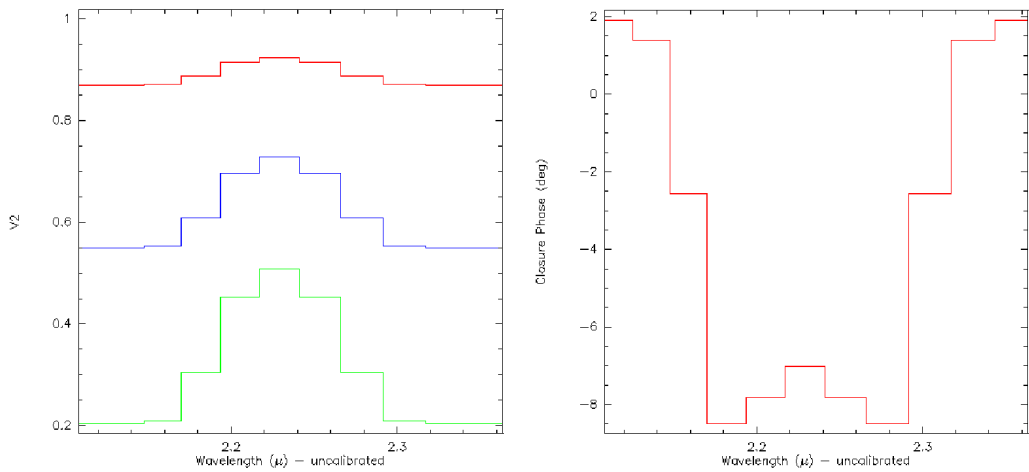

Fig. 9. **Left:** Visibility plot as a function of wavelength for different baselines (in red, green and blue). The global geometry of the model does not change, only the flux ratios between the 3 components. **Right:** Closure phase plot as a function of wavelength.

17

- The different visibilities are decreasing with baseline. Therefore, the object is barely resolved by the interferometer. One cannot qualitatively distinguish between a uniform disk, a Gaussian disk, or a binary star, but one can say the object is resolved at the largest baseline (≈130m) and therefore has a size of about 2mas.
- The non-zero closure phase gives information about the asymmetry of the object. Here, one has a non-zero but very small closure phase. The only simple model known from this practice session which gives a non-zero closure phase is a binary star model. The fact that the closure phase is not 180 degrees gives the additional information that the flux ratio is not 1/1.

Therefore, only qualitatively looking at these data one can say:

- The object is likely to be a binary star,
- the separation is about 2mas,
- the flux ratio is not 1/1,
- so far, one cannot say if each component has been resolved or if there is a third component.

Looking at the solution: Fig. 10 shows the image of the model used in this exercise. As one can see, the components are somewhat resolved, but probably not enough to be detected, and a third component is present. Therefore, the qualitative analysis is not enough, and one has to perform a quantitative analysis to characterize all of these components.
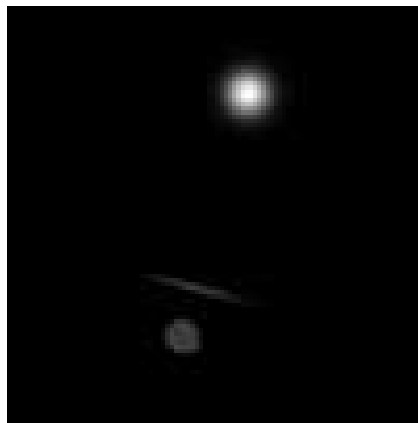

Fig. 10.   Image of the binary+wind-wind collision zone model used in this exercise.

APPENDIX

A Practical considerations

A.1 ***ASPRO*** *rules of thumb*

`ASPRO` is an optical long-baseline stellar interferometry tool intended to help the observations preparation. One can find it on the website `http://www.jmmc.fr`. Note that all exercises can be done at home with an internet connection, given that `ASPRO` can be launched via a java web interface.

Launching `ASPRO` on the web: The `ASPRO` launch is set up in five simple steps:

(1) go to `http://www.jmmc.fr`
(2) Select *ASPRO applet.* A pop-up window should appear (if not, please allow pop-up windows from `http://www.jmmc.fr` in your web browser).
(3) If you have a user account on the JMMC website, then just log in; otherwise, uncheck the *start application using my account information* and proceed to the next step.
(4) in the *Start...* menu, select *ASPRO.* 2 new windows should appear.
(5) The last step is to select the `ASPRO` version you want to use in the menu *Choose....* Here we will use the *Full ASPRO interface* version.
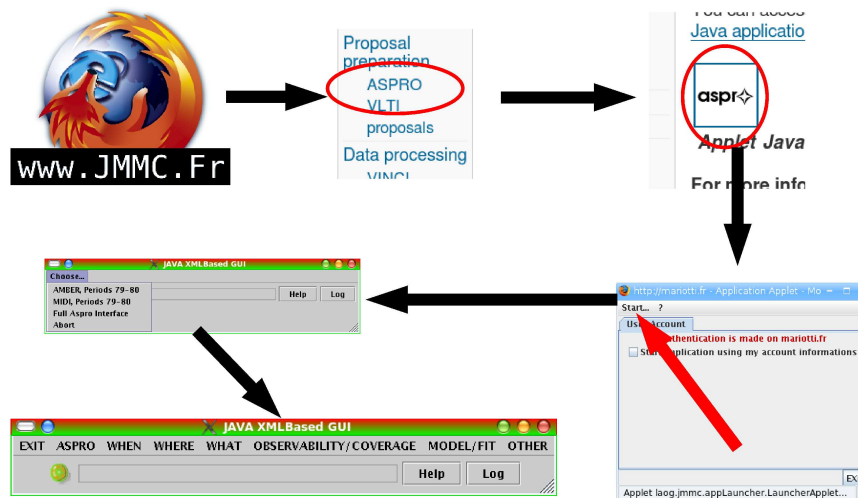

Fig. A.1.   The different steps to launch the web version of `ASPRO`. One only needs an internet connexion and a java-enabled web browser.

19

Launching `ASPRO` on a local computer: If your computer is one of the rare ones to have `ASPRO` locally installed, then the launch is even simpler:

(1) In a command line, type `aspro @oipt`
(2) In the menu *Choose...*, select the `ASPRO` version you want to use. Here, we will use the *Full ASPRO interface* version.
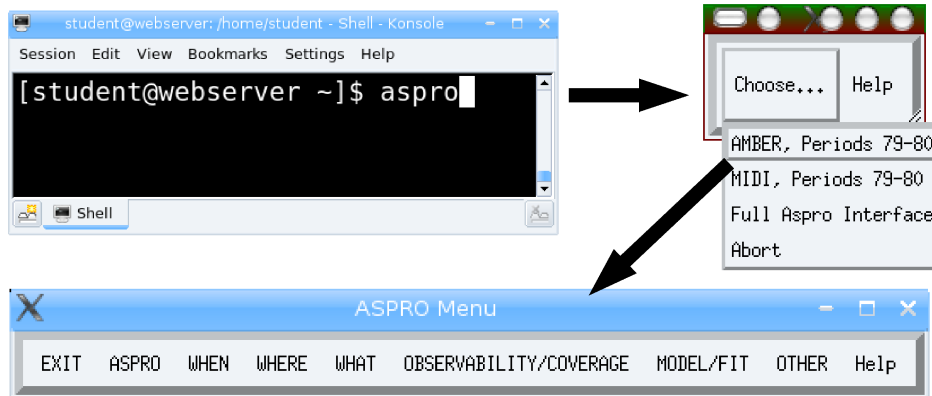

Fig. A.2. The steps to launch `ASPRO` on a local computer: even simpler, but one needs a local version of the software installed!

When `ASPRO` gets stuck: You will sometimes experience strange behavior such as non-responding buttons or a different response to what you expect. If you are in doubt, do not hesitate to quit `ASPRO` by clicking the *EXIT* button. If this button does not work either, you can still write `exit` in the command line, which will kill the Gildas session (and the `ASPRO` one at the same time).

Do not worry, restarting `ASPRO` and entering the different parameters again does not take very long!

References

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