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 corrections. 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 Practical considerations

The following tutorials will make use of a standalone version of the `ASPRO` tool. `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.

`ASPRO` is originally intended to aid in the preparation of interferometric observations, and will be used as such in the second tutorial. However, in the first tutorial, we will use `ASPRO` in an older [3], less user-friendly, but more flexible, way.

Launching `ASPRO` on the school's computers

[1] `http://www.jmmc.fr`

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

[3] You may sometimes experience strange behavior for this version of `ASPRO` such as non-responding buttons or a different response to what you expect. It is a good idea to look to error messages on the terminal. More than often it is a file name problem. Anyway, 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!

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

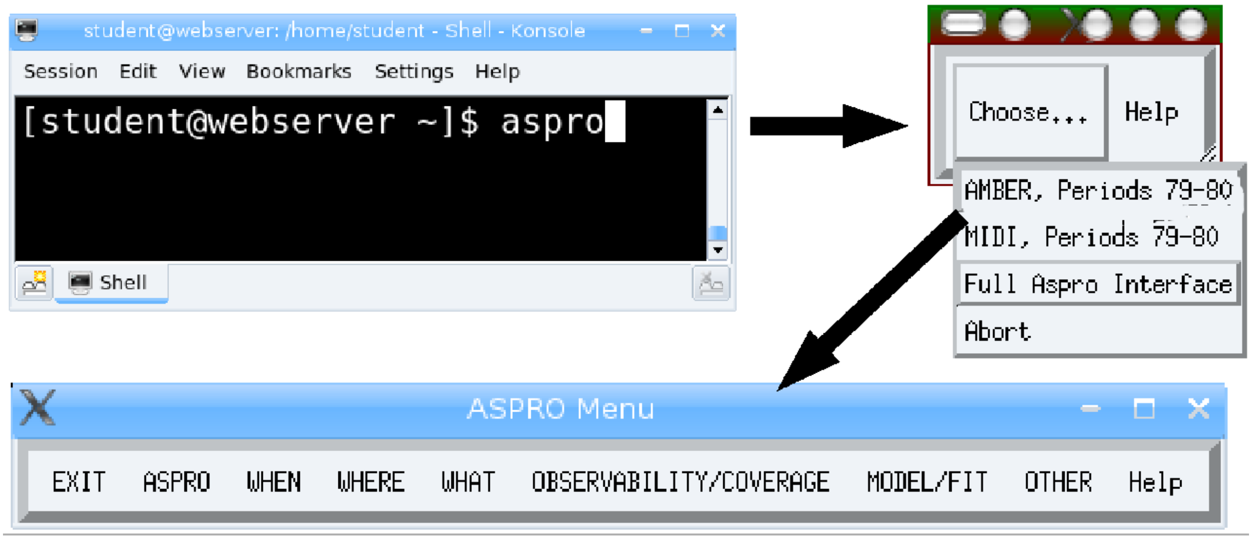

Fig. 1. The steps to launch `ASPRO` on a local computer.

Location of the tutorial data For the tutorial, the data is stored in `$HOME/Tuto_Models/STRIPS` and the others directories at this level.

2 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 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 need to look at the Tables 1 and 2.

Exercise 1: 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 interpretations of the data.

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

Table 2
Description of the parameters of the ASPRO model software module. **Be sure to regard the parameter units.**

name / parameter	1^{st} (")	2^{nd} (")	3^{rd} (no unit)	4^{th} (unit)	5^{th} (unit)	6^{th} (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 !

Plotting a uniform disk visibility curve: Use a well-sampled linear "strip" in UV coverage, such as `/school/tutorial/Tuto1_Models/STRIPS/strip-H-0.uvt` as the "template UV Table" for the `Model Parameters...` panel. **Beware**, the chooser in the panel adds the extension of the file (".uvt"), that the `ASPRO` program **does not expect**, so remove the extensions from all filenames in the panels.

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)`).

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

<u>*Exercise 4:*</u> *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.

Exercise 6: 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[4]).

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