2015 VLTI school

Cologne, 6–13 September

Practice session : Interferometry basics

The aim of the following series of exercises is to show you that it is actually quite easy to deal with interferometric data and to teach you the basics about interferometric observations.

The first series of exercises presented here aim at 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). Then, at the end of this session we will deal with real interferometers and learn about observability, delay line constraints, and UV coverage.

This pratice session is meant to be carried out with the `ASPRO2` software, developed by the Jean-Marie Mariotti Center.

1 Getting started with `ASPRO2`

`ASPRO2` is a preparation software for real interferometric observations. However, an imaginary interferometer consisting of 17 North-South-aligned telescopes located at the North Pole has been added for this practice session. This allow us to obtain unrealistic yet interesting UV coverage : aligned strip of regularly-spaced baselines ranging from 1 to 100 m. This strip of baselines can be easily rotated by changing the observational hour-angle.

Now it's time to play. First launch `ASPRO2` and load the first example file : *Example1.asprox*. This loads an observation configuration of putative star located at (0^o,$+89^o$) observed with our polar interferometer at the autumn equinox during the meridian passage.

Look at the `ASPRO2` interface. It is divided into two main parts. The top part has four regions:

- **Targets** : to put either the name of your targets resolved by CDS or their coordinates
- **Main Setting** : to select an interferometer and an instrument
- **Configuration** : to select a specific baseline or a set of baselines (depending on the interferometer/instrument possibilities)
- **Constraints** : to select the observation date and also the minimum elevation accessible by the interferometer

The bottom part is divided into four tabs giving access to :

- **Map** : the position of the telescopes of our interferometer, here our North-Pole 17-telescopes interferometer.
- **Observability** : the observability of the targets considering the current selected date and interferometer.
- **UV Coverage** : the UV-coverage of our current configuration. Some instrument parameters such as the observing wavelength or mode can be modified here too.
- **OIFits viewer** : some plots of the simulated dataset, only available if you have previously selected a model for your target.

In this first section we will mainly work with the last tab **OIFits viewer**.

2 Our first model : the uniform disk

It is now time to play with a first model. The one already loaded in the *Example1.asprox* file is a uniform disk. It is the grounding of almost all interferometric-data analysis, and it is very often used, not only to perform stellar diameters fits, but also first-order interpretations of any extended objects.

Question : What is the visibility function of a uniform disk?

Question : Give the expression of the first value for which the visibility becomes zero?

This corresponds to the interferometer spatial (or angular) resolution, i.e. the smallest object that can be fully resolved.

Question : Give the same expression with the stellar diameter and wavelength expressed in mas and μm, respectively.

Now look at the **OIFits viewer** tab. Plot the visibility amplitude and phase (VISAMP and VISPHI) as a function of the baseline length (i.e. RADIUS in the software). To do so click on the three dot (...) button at the bottom-right corner, and then select the good X and Y Axes. Roughly measure on the plot the smallest baseline for which the visibility becomes zero and assume that the observations were made in the B band (i.e., at λ=0.46μm).

Question : What is our object diameter in mas?

Imagine that you obtained a single visibility measurement (i.e. for a single baseline) and assume that the studied object looks like a uniform disk.

Question : In which case(s) can you determine an unambiguous diameter?

Now look at the phase. It is always equal to 0^o or 180^o. The jump between these two values happens when the visibility amplitude is equal to zero.

Question : Explain this phase signal.

Question : Finally, what are the baseline length corresponding to the first zero of visibility and the amplitude of the second-lobe of the visibility function?

3 A few other 1D distributions

Even if the uniform disk model is widely use both to measure stellar diameters and to estimate other objects' extension, it is not the most adapted model for many astrophysical objects.

In this section, we present three commonly used 1D models :

- the **Gaussian disk**, mostly used for circumstellar disk, stellar wind, and other astrophysical object with no sharp edge.
- the **ring**, adapted to measure inner rim of dusty circumstellar disks, dust shells, or spherically symmetric nebulae.
- the **limb darkened disk**, used for accurate stellar diameter measurements.

3.1 Gaussian distribution

Let's see how to modify a target model. First, in the **Edit** menu, click on **Target Editor**. It opens a new window named "Target Editor" that contains two tabs : **Targets** that shows the list of targets and their parameters, and **Models**, that is used to associate a model (intensity distribution) to a target. For this practice session we are only interested by the second tab.

In the **Models** tab, there is only one target, i.e. our hypothetical (0^o,$+89^o$) star, and one model associated to this target, i.e., *disk1*. The model is briefly described in **Model Description**, and the list of model parameters and their values are given in **Model Parameters**. You can check that the diameter you found in the previous section is close to the one given in this window.

Note that all models have three additional parameters, i.e. *flux_weight*, which is useful only for multi-components models, and the *x* and *y* positions, to allow adding off-center components. For our one component models, the flux weight will always be 1 and the position (0,0).

Now, remove the disk model by selecting it in the left field and clicking on the **Remove** button, select "Gaussian" in **model type**, and click on **Add**. Look at the new set of parameters shown in the bottom part of the window. This model has also four parameters, i.e. *flux_weight1*, *x1*, *y1*, like for all models, and *fwhm1*, the full width at half maximum of the Gaussian distribution. Let's set this value to 4 mas and then click on **Ok** to close the window.

Question : What is the Fourier transform of a Gaussian distribution?

Question : Compare the phase signal to that of the uniform disk.

Question : What is the baseline length corresponding to a visibility of 0?

3.2 Ring

Open the **Target editor** again, **Remove** the Gaussian model and **Add** a Ring model instead. This time the model has 5 parameters : *flux_weight1*, *x1*, *y1*, a diameter like the uniform disk, and also a width. Let's consider the case of a 4 mas infinitely-thin ring : *diameter1*= 4, and *width1* = 0.

Question : What are the baseline length corresponding to the first zero of visibility and the amplitude of the second lobe?

3.3 Limb darkened disk

This time choose a limb-darkened disk model in the **Target editor**. Don't forget to remove the previous model. Read the explanations on the model parameters. Reasonable values for limb darkening in the visible are a_1=0.9 and a_2=-0.2. Keep a 4 mas diameter.

Question : Note the baseline length corresponding to the first zero of visibility and the second-lobe amplitude.

Note that you will learn more about limb darkened model in next week...

3.4 Comparison of these models

In the previous sections you have build four models (uniform disk, Gaussian distribution, ring, and limb darkened disk) with a characteristic size of 4 mas. Their main difference is the smoothness/shrapness of the intensity distribution.

Question : First, classify the models in term of sharpness/smoothness

Question : What is the relation between the distribution sharpness and the second-lobe amplitude ?

Question : What about the position of the first zero of the visibility?

3.5 Model confusion

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

Question : Compare the visibility obtained with a 20 m baseline for a 2 mas uniform disk and a 1.2 mas Gaussian distribution.

Question : How can we discriminate between these two models?

3.6 Point source and flat field

There is two additional intensity distributions that are widely used for modelling :

- the **point source** used to model a source too small to be resolved whatever by the interferometer
- the **flat field** used to represent the exact opposite, a fully resolved object.

Note that these models are useless on their own and are only used to build multi-component models.

Question : What are the point source and flat field visibility functions?

In `ASPRO2` point sources are modeled using the *punct* function. Flat field are not included yet, but can be modelled using a very extended uniform disk, for example with $D = 10^6$ mas.

4 Going 2D with flattened models

In the previous sections you learned about 1D functions to model interferometric measurements. Now it is time to take a look at two-dimensional intensity distributions.

4.1 Elliptical distributions

Elliptical distributions are among the most simple, yet useful, 2D intensity distributions. They are defined by the same parameters as their circular counterparts, but with two addtionnal parameters:

- the elongation (*elong_ratio*) defined by the ratio of the major axis over the minor axis.
- the major-axis position angle (*major_axis_pos_angle*)

Ellipse (*elong_disk*), elliptical Gaussian (*elong_gaussian*), and elliptical ring (*elong_ring*) are currently included in `ASPRO2`.

Choose a North-South *elong_disk* model with a 2 mas minor-axis and an elongation ratio of 2.

Question : Compare its visibility function to the one obtained for the 4 mas uniform disk.

Now modify the model so that the major-axis is oriented East-West.

Question : Where is the first zero of the visibility function?

Question : What uniform disk diameter does this correspond to?

Put the disk major-axis at 45^o. Remember we use a North-South projected baseline.

Question : Can you conclude on the extension measured by an interferometer?

Now, let's use a new set of baselines. Load the configuration file *Example2.asprox*. Look at the UV plan in the **UV coverage** tab. The baselines in the new set all have the same length, i.e. 42m, but they have different position angles, and cover all directions.

Go to the **OIFits viewer** tab and plot the Visibility (VISAMP and VISPHI) as a function of the position angle (POS_ANGLE).

Question : Without looking at the target model can you determine the major-axis position angle?

Question : Assuming that the object is an elliptical Gaussian what are the major-axis and minor-axis FWHMs?

4.2 Application to geometrically thin disk

Elliptical intensity distributions are widely used to model geometrically-thin circumstellar disks. In this case the flattening is due to the projection of the disk on the sky-plane, i.e., perpendicular to the observer line of sight.

Question : Assuming a disk seen under an inclination angle i, what will be the flattening of its projection on the sky-plane?

Question : Conclude on the inclination angle of our object.

5 Composed models

Many astrophysical objects are not simple enough to be modelled by a single component. For instance, to model some circumstellar environment, you often need two components : some elliptical one for the environment itself, and a uniform disk or point source, for the star if its contribution to the total flux is not negligible.

Imagine that your model is a weighted sum of N components :

$$I_{tot}(x,y) = \sum_{i=1}^{N} f_i\, I_i(x,y) \tag{1}$$

where $I_i(x,y)$ is the intensity distribution of the ith component and f_i its relative flux with Σf_i=1.

Question : What is the visibility function (i.e. normalized Fourier Transform) for this model?

5.1 Star + circumstellar disk model

Let's look at a simple star + circumstellar disk example. First, load a new observation file : *Example3.asprox*. Go to the UV coverage and look at it. It is composed two perpendicular strips of baselines : one North-South and one East-West. It will allow us to probe our object along these two perpendicular orientations.

Now, open the **Target Editor** and create a two components model composed of a 0.5 uniform disk (for the star) and an elliptical Gaussian distribution (for the circumstellar disk), with a 8 mas major-axis oriented North-South and a 4 mas minor-axis. Put the flux contribution of each component to 50%.

Plot the visibility amplitude and phase as a function of the baselines lengths.

Question : Describe the visibility function.

Change the flux ratio between the two components and look at the visibility function.

Question : What has been modified? Can you explain why?

Now imagine that you want to constrain the circumstellar environment extension and flattening.

Question : What baseline lengths and orientations will you choose?

Question : Will these set of baselines give information on the stellar surface?

5.2 Binaries

A second kind of very useful two components model is the binary model. We will use a single strip of North-South aligned baselines to exlpore this model. So, load the *Example1.asprox* file.

Then, open the **Target Editor** and create a model consisting of two point sources. Set their flux to 0.2 and 0.8. Look at the second component, the *x2* and *y2* parameters have been replaced by *rho2* and *theta2*, i.e. polar coordinates. Choose *rho2*=5 and *theta2*=90. This simulates two unresolved stars separated by 5 mas in the North-South orientation, i.e. aligned with our baselines.

Question : Describe and explain the visibility function.

Write down the amplitude of the sinusoidal modulation. Set the flux ratio to 0.1/0.9 and then to 0.5/0.5.

Question : What is the link between the flux ratio and the amplitude of the binary modulation?

Write down the modulation period in meter, and express it in B/λ units (cycles/rad). Then set the binary separation, i.e. *rho2*, to 10 mas. and do this again.

Question : Give the relation between the binary separation (in rad) and the modulation period (in cycles/rad).

Now change *theta2* to 0^o : binary in the East-West orientation.

Question : Describe and explain the visibility function.

Do the same but with *theta2* equal to 30^o, 45^o, and 60^o.

Question : How does this affect the visibility function? Why?

Finally replace the components by uniform disks and try various diameters between 0 and 2 mas, for each component, separately.

Question : What is the effect of resolving one component on the visibility function?

5.3 Home-made models

Up to now we've been working with simple geometric models. But one might want to use home-made models such as outputs from radiative transfer codes. For that purpose `ASPRO2` allow us to upload images in fits format and computes the visibility corresponding to this model and the selected interferometer and instrument configuration.

In this session, we will use a N band image of a dusty disk surrounding a massive hot star generated with the radiative transfer code MC3D developed by Sebastian Wolf.

First, load the *Example3.asprox* file to have two strips of perpendicular baselines.

Then, open the **Target Editor**. In the **Model** tab, choose **User Model** and then click on the **Open** button. Go to the models sub-directory and choose the HD62623.fits file. After selecting the file you should see the image in the **Target Editor** window.

Question : Can you explain the shape of the intensity distribution?

Close the **Target Editor** window, and go to the **UV Coverage** tab to select the N band. Look at the 2D Fourier transform of the image overplotted on the UV Coverage plot.

Finally, go back to the **OiFits viewer** tab to see North-South and East-West cuts of the 2D-visibility function.

Question : Is the visibility function closer to that of a Gaussian distribution or uniform disk?

Question : What are the values of the visibility in the two orientations for a 20 m baseline?

Question : Using these values estimate the objects extension in the North-South and East-West orientations.

Question : Assuming that the disk is geometrically thin what is the object inclination angle?

Now look closer at the phase signal. It is non zero for large baselines and for one baseline alignment.

Question : Try to explain the phase signal? (You can look back at the image in the Target editor

6 Effect of the observed wavelength

6.1 Achromatic objects observed at various wavelengths

The spatial resolution of an inteferometer strongly depends on the observing wavelength. Imagine that our North-Pole interferometer is able to observe in any photometric band between 0.46μm (B) and 12μm (N).

Question : Which band will give the highest resolution?

To change the observing wavelength go to the **UV Coverage** tab. You can select a photometric band between B and N in the **Instrument mode** list.

Question : Give the ratio between the resolutions in N and B bands

Let's assume a 0.05 uncertainty on our visibility measurement and three baselines of 50, 70 and 100 m.

Question : In which band should we observe a 1 mas star?

Question : Should we observe a 5 mas star with the same configuration?

Now, let's do a multi-wavelength observation. First load the *Example4.asprox* file. It contains a 3 telescopes (S0-S5-S16) configuration of baselines. Unlike for the other exercices the observing wavelength is not fixed to one band but ranges between 0.1μm to $10_m\mu$m.

Note that for this observation we use a 1 mas uniform disk model.

First plot the visibility and phase as a function of the baseline length to see the visibility of the three baselines.

Question : Explain why we obtain a large range of values for the visibility of each baseline.

Now plot the visibility as a function of the spatial frequency B/λ (SPATIAL_FREQ). The different colors correspond to different wavelengths from purple for the smallest one (0.5μm) to red for the largest one (10μm).

Question : For this achromatic model case, conclude on the effect of observing at multiple wavelengths.

6.2 Examples of chromatic objects

Unfortunately, most astrophysical objects are in fact wavelength dependent. For instance, the size of a circumstellar environment usually grows with the wavelength, as larger wavelengths probe colder medium, thus further from the central star.

Question : Assuming that a star and its circumstellar environment emit as black-bodies, can you conclude on their flux ratio dependence on the wavelength? Which component will dominate the visible flux? What about the mid-infrared?

We will look at such a chromatic model contained in the *chroma_model.fits* file. After loading it, you will see the first image in the model corresponding to the first wavelength, i.e. 0.5μm. You can change the intensity dynamic for **LINEAR** to **LOGARITHMIC**. Doing that, you clearly see the two components of the model, i.e. a uniform disk (star) and an elongated Gaussian distribution (disk).

Now click on the **Animate** button to see the model dependence with the observing wavelength from 0.5μm to 10μm.

Question : How does the model depend on the wavelength?

Close the **Target Editor** and go to the **OiFits Viewer** tab. Plot the visibility as a function of the spatial frequency.

Question : Explain the visibility variation as a function of the wavelength.

Don't worry if this section is too short. You will learn more about chromatic models next week!

7 The art of interferometric observations

In this second part of the practice session, we will deal with the reality of interferometric observation: observability problems, delay line restrictions, and UV-coverage limitations.

Now it's time to say good bye to Santa Claus and his North-Pole imaginary interferometer as we will use two real arrays : CHARA located close to Los Angeles and the VLTI in Chile.

7.1 Interferometric observability

7.1.1 Basic astronomical observability

Load the observation file *Observability1.asprox*. It contains a list of hypothetical stars with α=0^o and -89^o < δ <+89^o.

Question : What are the limits in declination that can be achieved with the CHARA and VLTI interferometers?

For this configuration we defined the elevation limit to be 30^o above the horizon. Any object below this limit will be considered as non-observable.

Question : From these observability plots can you determine the VLTI and CHARA latitudes?

Now load the *Observability2.asprox* file. It contains another list of hypothetical stars with δ=0^o and 0h< α <18h.

Question : When should we observe a star with α=0h, 6h, 12h, and 18h?

Question : Does it depend on the interferometer?

7.1.2 Delay lines constraints

In stellar interferometry delay lines are needed to compensate the optical path between multiple telescopes in order to make the different beams interfere. consequently, in addition to the previously defined observability constraints, an interferometer has additional constraints due to the finite size of its delay lines.

Open the *Observability1.asprox* file again. Look at the observability for all available VLTI baselines (use the MIDI instrument). The change of observability between these baselines in only due to delay line restrictions.

Question : Are the restrictions larger for small or long baselines? Can you explain why?

Now look in particular at UT1-UT4 and A1-K0, two roughly East-West baselines, and G1-J3 and H0-G1, two North-South baselines.

Question : Are the effect of delay line on observability different for these two kind of baselines?

Finally, look at the observability with all UT baselines and then switch to the AMBER instrument instead of MIDI. AMBER is a three-beam combiner as you probably already know. Look at the observability of all UT triplet of baselines.

Question : Is the observability better with AMBER or with MIDI? Explain why.

You can do the same with PIONIER the new VLTI four beams combiner. It has only one possible quadruplet with UTs.

Question : Can you draw some conclusion on the delay line constraints as a function of the number of baselines?

7.2 UV Coverage

An UV Coverage is defined by the (U,V) coordinates of all measurements made on a specific target. To constrain an object intensity distribution you need to probe it's Fourier plan, and thus fill at maximum its UV plan.

7.2.1 Supersynthesis effect due to earth rotation

The (U,V) coordinate of a baseline is not equivalent to the physical separation of the two telescopes compositing it, but to it's projection on the sky plane.

Thus, during a night, as a target moves in the sky, the projected baseline changed. This effect, that allow one to probe several spatial frequencies of an object with a single physical baseline, is often called supersynthesis effect.

Question : For which position in the sky the physical and projected baselines are always equal?

7.2.2 UV tracks for North-South baselines

Let's see what is the supersynthesis effect for different kinds of baselines and objects. First choose a large North-South baseline with the VLTI (MIDI instrument again). Then open the **UV Coverage** tab.

Question : Describe the UV-tracks obtained with this baseline for stars of different declination.

Question : Can you obtain an East-West projected baseline?

7.2.3 UV tracks for East-West baselines

Now, choose a large East-West baseline.

Question : Describe the UV-tracks obtained with this baseline for stars of different declination.

Question : Can you obtain a North-South projected baseline?

7.2.4 UV-tracks with more telescopes.

Look at the UV-Tracks for three (AMBER) and four (PIONIER) telescopes.

Question : Give the number of simultaneous baselines for these instruments.

Question : What is the formula giving the number of baselines as a function of the number of telescopes?

Question : Finally, verify this formula on the CHARA/MIRC_6T instrument.

Question : What is the main problem of this six telescopes combiner?

7.3 Bonus... if you're faster than Flash : Optimize your observations

Here is a list of targets with a small description of what you want to measure for each of them :

- HD 196740 : Measure the diameter. The stellar diameter is of the order of 0.3 mas.
- Vega : Measure the diameter. The stellar diameter is of the order of 2.9 mas.
- Betelgeuse : Measure the diameter. The stellar diameter is of the order of 44 mas.
- Achernar : Measure the extension and flattening of this fast rotating star. Its polar diameter is of the order of 2 mas and the flattening ratio is 1.5.
- γ Cas : Measure the stellar diameter (about 0.5 mas) and its circumstellar environment (about 5-10 D$_\star$) of this Be star. The star has an intermediate inclination angle, i.e. 45^o.
- MWC 297 : Measure the disk extension of this young star. The extension goes from a few mas in the visible to several tens of mas in the mid-infrared.
- δ Cen : This is a newly discovered binary star. The first time it was observed, a separation of 63 mas.

Question : Try to determine which date, interferometer (between VLTI and CHARA), instrument (AMBER or MIDI for the VLTI and VEGA or CLIMB for CHARA), and configuration are optimized to constrain the geometry of these targets.

For some of these targets there might be many good solutions : just choose one!

First, click on **Files** and **New Observation**. Then, to add a real star in `ASPRO2`, just type its name in the **Targets** field, it will search for its coordinates in the SIMBAD database.