10^{th} VLTI School of Interferometry

Somewhere on the web, June 2021

Practice session II : Oberservation preparation with ASPRO

In the previous practice session you used the `ASPRO2` software to learn the basics of long-baseline interferometry and how visibility and phase measurements can help constrain the size and shape of astronomical objects unresolved by single dish telescopes.

In this second practice session, we will deal with the reality of interferometric observation: observability, UV-coverage, delay line restrictions, flux sensitivity, calibrators...

Now it is time to say good bye to Santa Claus and his North-Pole sixteen-telescopes interferometer and head south, toward the Atacama desert in Chile where the VLTI is located. On our way we'll make a few stops in southern California at the CHARA array.

1 Science Case : Imaging FS CMa environment with MATISSE

In all the upcoming practice sessions (data reduction, model-fitting, image reconstruction and radiative transfer) you will deal with some MATISSE data obtained on an enigmatic star: FS CMa. It was the first star imaged with MATISSE during its commissioning in 2018. It is a natural choice for us to use it also in our example of preparation of a MATISSE observing programme.

FS CMa is a hot star showing the B[e] phenomenon : strong infrared excess due to dust located in a disk-like structure, emission lines of hydrogen produced in a dense gaseous environment, and forbidden emission lines produced in a more diluted environment. As few other B[e] stars, its evolutionary status remains highly debated. The disk might be the remnant of a protostellar disk, in that case FS CMa would be a Herbig Be star, but the material could also have been ejected from the stellar surface because of fast-rotation, radiative pressure, or an interaction with an unseen companion.

One reason to choose it as a test target of MATISSE imaging capability was that it had already been imaged in the H-band with the VLTI/PIONIER instrument. The Figure below presents the PIONIER image from Kluska et al. (2020) that the MATISSE commissioning team used to prepare their observations.

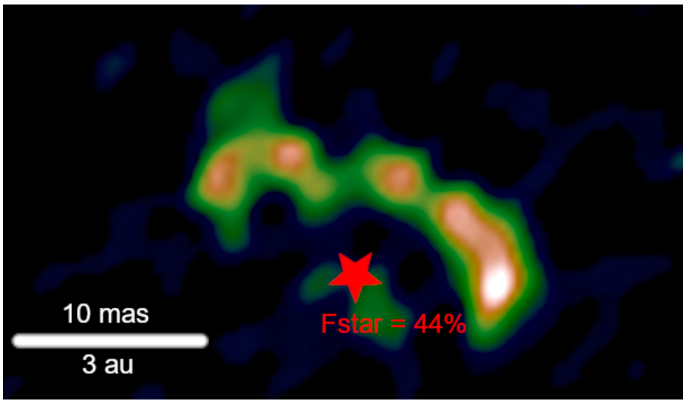

Figure 1: VLTI/PIONIER image of FS CMa. The star position (removed during the image reconstruction) and contribution to the H-band flux are shown in red (adapted from Kluska et al. (2020)

Question : What do we see in the PIONIER image? Why is it asymmetric?

Question : What do you except to see in MATISSE image in the L band? In the N band?

Question : What physical parameters could be constrained from MATISSE observations?

2 Interferometric Observability

The first things to do when preparing observation (or a proposal) is to check :

- if our object of interest is observable with the facility we want to use
- and if it is, when is the most suited period of the year to observe it

Open `ASPRO2` and enter **FS CMa** in the **Targets** input field on the upper left corner of the interface. By pressing **Enter** the object will be resolved by the CDS database and added to the list of targets on the field below the input one.

By hovering the mouse over the name of the target, we can see many information on the object including its coordinates and its magnitude in many bands. The same information are also shown in the **Targets** tab of the **Target Editor** menu.

Question : What are FS CMa right ascension (α) and declination (δ)?

Now go to the **Observability** tab. The star is currently not observable (in June). You can change the date of observation in the **Constraints** box on the upper right of `ASPRO2` interface. Verify also that the **Min. Elevation** is set to 30^o which is a standard value for both VLTI and CHARA. Pointing lower than that is not recommended unless you cannot do otherwise.

Question : When is the star observable at VLTI?

Question : Optimise the observing date to have the longest Observability

Question : Does this date depends on α? What about δ?

In the **Main settings** box you can change the Interferometer, Period of observation (this mainly change the instruments available at each facility), and the instrument. In the **Configuration** box, we can select between the available telescopes configurations. In the case of VLTI, you can choose between:

- the UTs configuration : UT1 UT2 UT3 UT4
- SMALL ATs configuration : A0 B2 D0 C1
- MEDIUM ATs configuration : K0 G2 D0 J3
- LARGE ATs configuration : A0 G1 J2 J3
- ASTROMETRIC ATs configuration (only for GRAVITY) : A0 G1 J2 K0

A0, B2 D0, C1, G1, K0, J2, J3 are stations on the VLTI platform where the movable auxiliary telescopes (ATs) can be set. You can check their positions on the platform on the **Map** tab.

Question : What is the point of moving telescopes between observations?

Let's go back to our observability problem and to the **Observability** tab. Change the selected VLTI instrument to MATISSE, GRAVITY and then PIONIER and check the observability for each of them.

Question : Does the observability depends on the selected instrument?

Now try to change the telescope configuration.

Question : Does this affect the observability?

Question : Which configuration offers the longest observability? the shortest?

Question : Is the shortening of observability symmetric in time?

Go back to the **Map** tab and for all configurations look at :

- the position of the telescopes on the platform
- the length of the baselines (given on the right part of the interferace).

Imagine the star moving from East (right) to West (left) during the night.

Question : Find the two main reasons for the shortening of the observability

Now, let's check if the star is observable with CHARA? We might want to perform some observations later in another band with this Northern facility.

Question : Is the star observable at CHARA?

Question : Is the observability longer or shorter than at the VLTI? Why?

Beyond our programme on FS CMa we would like to observe other Herbig or B[e] stars shown in the table below.

Name	Right Ascension	Declination
HD 50138	06 51 33.34	-06 57 59.9
HD 62623	07 43 48.43	-28 57 17.7
HD 85567	09 50 28.54	-60 58 02.9
MWC 297	18 27 39.5	-03 49 52.0
HD 200775	21 01 36.92	+68 09 47.7

Table 1: Some Herbig and B[e] stars

Question : Without using `ASPRO2` determine where and when can we observe these targets[1]?

3 UV-Coverage

The UV Coverage is defined by the (U,V) coordinates (in meters or in unit of B/λ) of all measurements made on a specific target. The more measurements you made (with different UV coordinates) the better sampling of the Fourier space (or UV plan) you get, and consequently, the more constraints you can put the target intensity distribution.

But interferometry is a time consuming technique, a calibrated measurement takes between 30min on PIONIER to 1h for MATISSE or GRAVITY. The consequence is to optimise the number of observations depending on the goal of your project and the complexity of the object: a survey of stellar diameters requires only one or two measurements per target, whereas imaging programmes require, at least, a few tens of uv points on a single object.

It is now time to switch to the **UV coverage** tab and select **VLTI** and **MATISSE_LM** in the **Interferometer** and **instrument** ones, respectively.

In the central plot we can see the "UV tracks" of each of the 6 baselines of the selected configuration. You can select multiple configuration simultaneously. Select all ATs configurations. This is what we want to use for our imaging programme.

Question : What is the origin of these tracks and why are the baselines length and orientation changing during the night?

The shape of the tracks are elliptic. Add two fake stars to your target list :

- a star at the equator: **06:00:00 00:00:00**
- a star close to the south pole : **06:00:00 -80:00:00**

Question : Why didn't we choose a star at the real pole (δ=-90:00:00)?

Question : Are the tracks similar for these two objects and FS CMa?

Remove these two objects before continuing to the next section.

[1]The latitudes of VLTI and CHARA are -25^o and +34^o, respectively

4 Setting-up a model for our object

As we have seen in the previous practice session there are to way to model our object with ASPRO2:

- using a **combination of analytical models**: uniform disk, ellipse, Gaussian distribution, ring...
- loading a **fits image or image-cube** (as the ones available on the AMHRA website)

We already have an idea of the object geometry thanks to the PIONIER image. In the H-band (see Fig 1) the object is composed of a star and a relatively thin flattened ring with a relative contribution to the total flux of 44% and 56%, respectively.

According to the JSDC catalogue, the stellar diameter is 0.16 ± 0.01 mas.

Question : How would you model the star for our MATISSE observation?

For the ring, in the H-band, we will consider the following parameters:

- Minor-axis diameter: 10 mas
- Elongation ratio: 1.5
- Width: 4 mas
- Orientation of the major-axis: 70^o

Create a model with these two components and parameters values in the **Target Editor** menu.

Question : Which of these parameters are excepted to be constant between the H-band and the N-band and which will depends on the wavelength? How?

Now go to the **OIFits Viewer** tab and plot the **VIS2DATA** & **T3PHI** (i.e. Closure phase) as a function of the **SPATIAL_FREQ**. Note that it is the default view, so normally you don't have to change it. Select the three ATs configurations simultaneously and choose **Station configuration** in the **Color by** scrolling menu (bottom right of the interface). You can also select the **Draw Lines** option in the lower right corner.

In the plot we see the visibility decreasing and then oscillating around a plateau.

Question : What is the cause of the oscillation?

Question : What determine the level of the plateau?

Question : Conclude on the expected visibility curve for the L, M, and N bands

Question : Do you expect the real closure phase to be different to a one of our very simple model? Why?

5 About the instrumental sensitivity

ASPRO2 is able to estimate noise on the simulated data using a consistent noise model for each instrument. However, as you can see in the visibility plot there is no noise on our data.

This is due to the fact that the L, M and N band photometry is missing (see the message in red above the plotting window). When adding a target ASPRO2 resolve it with the CDS and use the *Simbad database* that does not contain L, M and N band flux measurements as a default.

For MATISSE, we usually use flux measurements from the *Mid-infrared stellar Diameters and Fluxes compilation Catalogue* (MDFC) accessible via the CDS Vizier service. For FS CMa, the fluxes are $F_L = 39.7$ Jy, $F_M = 52.4$ Jy, and $F_N = 115.2$ Jy.

Open the **Target Editor**, go to the **Targets** tab and enter these values manually in their corresponding fields. Check that the **jy** option is selected for the **flux unit**.

Question : With such noise on the data, are the observation still useful?

You can change the **Atmosphere quality** value in the **UV Coverage** tab. When hovering a value, the definition in term of seeing and coherence time (t_0) is given. For instance, the **AVERAGE** atmosphere correspond to a seeing of 1" and t_0=3.2ms.

Question : Is there a significant gain in term of data quality for observation under GOOD atmosphere quality? What about EXCELLENT?

Question : Is the data always useful even under AWFUL quality?

Question : Do the same with MATISSE_N instrument

Finally, let's assume a much dimmer target, for instance with a L_band flux of 1 Jy. Change the Flux in the **Target Editor** menu. Don't forget to switch back to MATISSE_LM.

Question : Under which atmospheric quality will the data be useless?

Before continuing, put back the 39.7Jy flux for the L band and a GOOD atmosphere quality.

6 Finding Calibrators for our observations with `SearchCal`

As you have learned in the *Introduction to interferometry* lecture, one need to calibrate interferometric data by observing normal stars of small angular size and known diameter. `SearchCal` is a tool developed by the JMMC to help you find such good interferometric calibrators.

Without closing `ASPRO2` launch `SearchCal`. The two software can communicate together. Let's send our science object to `SearchCal`. In `ASPRO2`, click on the **Interop/Search Calibrators/SearchCal** menu. This will send FS CMa coordinates, and information on the longest baseline used (137m), the observing band (L), and the object magnitude in that band (Lmag = 2.15 ⇔ F_L = 39.7Jy).

`SearchCal` has found tens of possible calibrators. By default calibrators are order by distance to the science target. The three important characteristics to select good calibrators are the following:

- magnitude : the brighter the better
- expected visibility with longer baseline : the less-resolved, the better
- distance to the science object: the closer, the better

It is not always possible to find a good calibrator that satisfy this three characteristics, but in our case we have plenty of them...

Question : Find a good calibrator for MATISSE L&M bands (the best one might not be the first in the list)

You can send the selected calibrator (right click on it first) back to `ASPRO2` using the `SearchCal` **Interop** menu.

Question : Is this calibrator a good calibrator for MATISSE N band observation? (Check in the OIFits viewer tab. Why?)

Let's now find a N-band calibrator. Select **MATISSE_N** in `ASPRO2` **Instrument** scrolling menu, verify that FS CMa is still selected in the **Targets** list and send it again to `SearchCal`

Question : What has change in the SearchCal interface?

Question : Find a good calibrator for that band and send it back to `ASPRO2`

Now you have two calibrators, one for the L&M bands, and one for the N-band. You can plot their excepted visibility curve in `ASPRO2` **OIFits Viewer** tab.

Question : Is the N-band calibrator a good calibrator for MATISSE L band observation? Why?

7 Exporting data from ASPRO2

7.1 Exporting OIFits file(s)

The OI-FITS format is commonly used to store data provided by optical interferometers. The reduced data of all current instruments at VLTI and CHARA use this format. Although highly standardised[2] the format is flexible enough to allow multiple data types (absolute square visibility, closure phase, differential visible and phase, correlated flux, total flux...) from multiple instruments to be stored in the same file.

By exporting to an OIFITS file all the observables simulated by ASPRO2 we will be able to import them in most model-fitting and image reconstruction tools developed for optical/IR interferometry. For example, we could try to use our simulated data with the model-fitting tool `LITpro` or with MATISSE reconstruction software `IRBIS`. Note that both sotware will be presented during this school in other practice sessions.

As the simulated data from `ASPRO2` contains realistic noise figures, this can help determine if you can get the expected astrophysical result accuracy on the model parameters (for instance the diameter and width of our ring model, or the flux ratio between the central star and the ring), using the selected UV plan coverage and atmospheric condition.

But for our example, let's just try to export our simulated data for FS CMa and check if this worked by loading them in `OIFitsExplorer`, an OIFits vizualisation tool developed by the JMMC. Select the three ATs configurations, and click on **Export to OIFits file** in the **File** menu.

Now launch `OIFitsExplorer` and click on **add OIFits file** in the **File** menu. The simulated data from ASPRO as been loaded. As you can see the interface is very similar to that of `ASPRO2`.

We will talk more about OIFits files and `OIFitsExplorer` in the next practice session : *MATISSE Data Reduction*.

7.2 Exporting Observing Blocks for ESO p2

When preparing observations for ESO you are require to upload observing Blocks (OBs) to the ESO preparation tool `p2`. The OBs contains information on the target (coordinates, magnitudes) and the instrumental setup (with instrument, with spectral mode, integration times...). These OBs are needed by Paranal astronomers and operators to perform your observations.

In order to facilitate the process of creating OBs you can export them from `ASPRO2` into `p2`. For that purpose you have to launch a small python program called `a2p2`[3]. This tools connect to on `p2` your ESO account (for this practice session you will connect to the p2 tutorial account).

Connect to the `p2` tutorial account : **https://www.eso.org/p2demo/home**. Create a directory with your name in the **60.A-9003(M) MATISSE** folder. Then launch `a2p2`. It should connect directly to the tutorial account. Once connected you should find your directory in the tree structure. Select it. Finally, in `ASPRO2` select FS CMa and click on the **Send Obs. blocks(s) to A2p2** in the **Interop** menu. The OBs have been sent to `a2p2` and then to `p2`. Check that they have been imported into your directory on the `p2` website.

You can now check that the value for the Target coordinates and fluxes, and the instrument setting are correct.

[2] OIFITS2 format is described here : https://arxiv.org/abs/1510.04556
[3] available here : https://github.com/JMMC-OpenDev/a2p2

8 Bonus : Beyond our MATISSE Observation

Our MATISSE imaging programme has been a success and we now have very useful images of FS CMa in the L and N bands. The actual images obtained in December 2018 are shown in Fig 2.

There is a lot of information on the dusty disk around FS CMa in these images. Using our data we will be able to probe the disk structure in density, temperature, and chemistry. We even have some information on the central source, i.e. it is not dominated by the star emission but by some hot circumstellar gas.

However, despite all these information from our MATISSE programmes (and the previous PIONIER image) we lack constraints on the stellar surface and the structure of the gaseous environment.

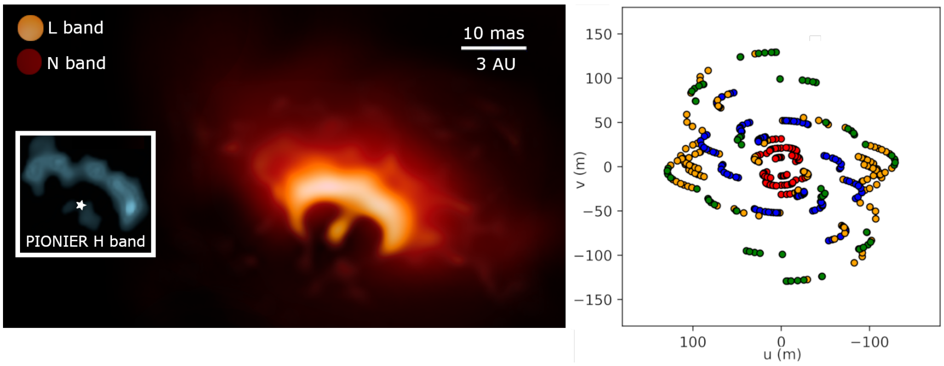

Figure 2: Left : FS CMa image reconstructed from MATISSE observations using MATISSE DRS image reconstruction software IRBIS. Right: corresponding uv-plan coverage.

8.1 Resolving the stellar surface

Question : Is it possible to constrain the stellar diameter using the VLTI? What are the two advantages of using CHARA for that purpose?

Switch to the CHARA array in the **Interferometer** scrolling menu. In the **Period**, choose **CHARA Future** and finally, in **Instrument** choose **SPICA_6T**.

Question : Can we constrain the stellar diameter with CHARA/SPICA? What about the limb darkening or a putative stellar surface flattening?

8.2 Studying the circumstellar gas geometry and kinematics

Interferometric observations with a high-enough spectral resolution (R>500) allows to separate circumstellar gas and dust by looking at narrow spectral features such as emission lines of hydrogen. It also enables the study of the gas kinematics.

Question : Which VLTI and CHARA instrument(s) offer(s) a high-enough spectral resolution to resolve emission lines?

Question : How is it possible to constrain kinematics using spectro-interferometry? What resolution is needed to measure velocities of the order of 100km/s?

Load the model **model_FSCMa_HIGH_BrAlpha.fits**. It contains a model of a star surrounded by rotating gaseous disk and the inner rim of a dusty disk. It is computed in 201 narrow spectral channels centred on the Brα (4.055μm) emission line.

Select **MATISSE_LM**, and **SI_PHOT_LM_MEDIUM** instrument mode (in the UV Coverage tab). Uncheck **Add error noise to data** and finally look at the VIS2DATA and T3PHI plots.

Question : Do you see the effects of the emission line on the visibility and closure phase? Explain them (Use the zoom on the plot). Change the resolution to HIGH and VERY_HIGH...