

Interferometry Basics in Practice: Exercises, 2nd part

Florentin Millour^a, Jorg-Uwe Pott^b, Damien Ségransan^c,
Jean-Philippe Berger^d, Gilles Duvert^d & Fabien Malbet^d

^a*Max-Planck-Institut für Radio-astronomie, Auf dem Hügel 69, 53121 Bonn,
Germany*

^b*W. M. Keck Observatory, Kamuela, HI 96743, USA*

^c*Observatoire Astronomique de l'Université de Genève, 51, chemin des Maillettes,
CH-1290 Sauverny, Switzerland*

^d*Laboratoire d'Astrophysique, Observatoire de Grenoble, 414, Rue de la Piscine,
Domaine Universitaire, 38400 Saint-Martin d'Hères*

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 Center¹, but can also be done using other observation preparation software, such as viscalc² 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 <http://www.jmmc.fr>

² <http://www.eso.org/observing/etc/>

1 Observability and *UV* coverage

What you will need for this particular practice session:

You will need to use ASPRO and the catalogs named `sampleSources1.sou` and `sampleSources2.sou` provided with this practice session (you can copy this information into text files, see below). To set up ASPRO, please refer to the 1st part of this practice session about visibilities and model fitting.

```
!-----
! sampleSources1.sou
!-----
ACHERNAR    EQ 2000.000    01:37:42.8466 -57:14:12.327
NGC_1068    EQ 2000.000    02:42:40.8300 -00:00:48.400
BETELGEUSE  EQ 2000.000    05:55:10.3053 +07:24:25.426
HD_68273    EQ 2000.000    08:09:31.9503 -47:20:11.716
HD_81720    EQ 2000.000    09:25:19.2802 -54:27:49.559

!-----
! sampleSources2.sou
!-----
STAR_40     EQ 2000.000    16:00:0.0     40:00:0.0
STAR_30     EQ 2000.000    16:00:0.0     30:00:0.0
STAR_20     EQ 2000.000    16:00:0.0     20:00:0.0
STAR_10     EQ 2000.000    16:00:0.0     10:00:0.0
STAR_0      EQ 2000.000    16:00:0.0      0:00:0.0
STAR_-20    EQ 2000.000    16:00:0.0    -20:00:0.0
STAR_-40    EQ 2000.000    16:00:0.0    -40:00:0.0
STAR_-60    EQ 2000.000    16:00:0.0    -60:00:0.0
STAR_-80    EQ 2000.000    16:00:0.0    -80:00:0.0
```

Exercise 1: Setting up an observation

Set the date: In the *WHEN* menu, *Date & Time Setup*, put the date 28-AUG-2007 and time 14:00:00.

Set the place: In the *WHERE* menu, select *VLT, 2 Telescopes*.

Set the target: In the *WHAT* menu, choose *Use Object catalog* and select the file `sampleSources1.sou`. If you use the web version of ASPRO, you need

to have an account on the JMMC server and to copy your files beforehand using the *File Management* panel.

Check the settings: Check with the *WHAT* menu *View Object catalog* and look at the result in the xterm window. Note: you can do this step only with a local version of ASPRO as the web version has no access to a terminal.

Exercise 2: Observability of sources at different declinations and delay line constraints

First, we will check the observability of the sources with *OBSERVABILITY/COVERAGE, Observability of Source*. Set the minimum elevation to 30° , check the *Plot the twilight zones* button, and use UT1 and UT2. When everything is done, press the *GO* button.

Which stars are observable? Is the chosen date appropriate for observing all stars together?

Delay lines limitation: Now, go to *OBSERVABILITY/COVERAGE, Observability limits due to delay lines*. How does it change the observability? Compare the observability with UT1-UT4 and G1-J6. What do you conclude?

Sampling the UV plane with the VLTI

This goal of this section is to see how the *UV* coverage changes with baseline orientation and source declination.

You should first load the catalog named `sampleSources2.sou`. It contains 7 stars of R.A. 5:00:00 and of different declinations. In this section, you will make intensive use of the *OBSERVABILITY/UV COVERAGE* menu of ASPRO.

Exercise 3: UV tracks for a North-South baseline

We will now study the *UV* coverage of the sources with *OBSERVABILITY/COVERAGE, UV coverage & PSF*.

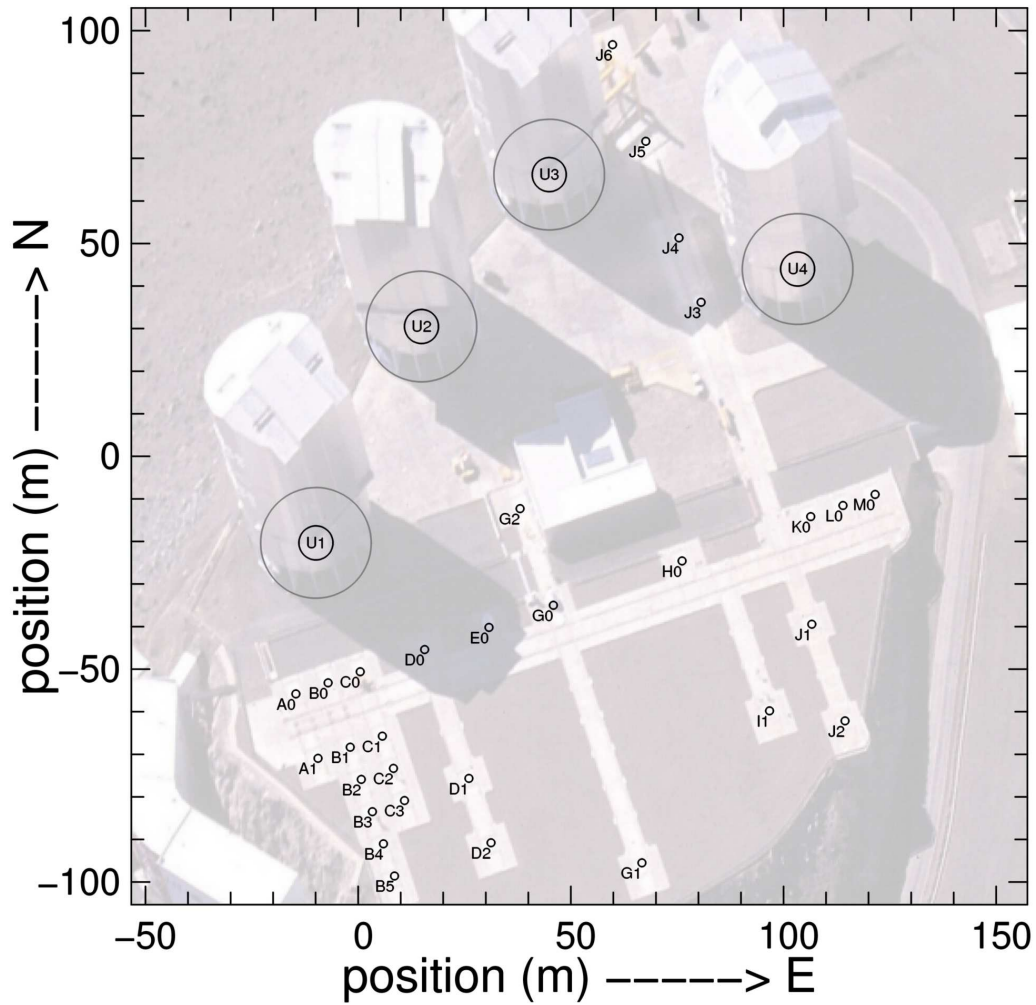


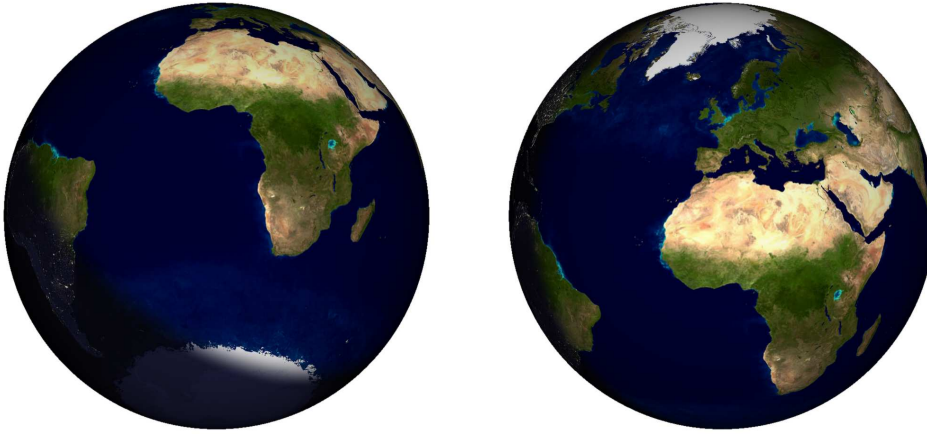
Fig. 1. The VLTI stations. Photo: Gerhard Hüdepohl

- Select the star at declination -20 and set the wavelength to 2 microns. In the *Telescopes & Stations* panel, select a 2-telescope baseline oriented N-S (cf. Fig. 1) and have a look to the shape of *UV* coverage you get.
- Change stars, going from positive to negative declination and see what happens (you can over-plot the graphs by unchecking the *RESET FRAME* button in the *Telescopes & Stations*).

Hint: Look at the orientation of the Earth in Fig.2.

Exercise 4: UV tracks for an East-West baseline

Select a large 2-telescope baseline oriented E-W. Visualize the observability of the targets and check the delay line constraints. Plot the *UV* coverage for several stars.



3

Fig. 2. The Earth, as seen from a -25° declination (left) and a $+25^\circ$ declination (right). These images were generated using the free software xplanet, <http://xplanet.sourceforge.net>.

UV tracks shape: Why are the *UV*-tracks elliptical (you can refer to the interferometry introduction articles)?

UV tracks and target declination: Have a look at the *UV*-tracks of a star above the equator and below the equator. What do you notice?

Hint : Look at the figure of the Earth in Fig.2 again.

Importance of the baseline orientation: Compare the N-S baseline and the E-W baseline in terms of *UV*-coverage and observability (how much *UV*-track do you cover with the same fixed delay?) Play with the star and the end of hour angle range.

Exercise 5: UV tracks for a 3-telescope-array

Observability:

- Select a large 3-telescope array configuration (in the *WHERE* menu).
- Visualize the observability of the targets (including constraints on delay lines). Look at the *OBSERVABILITY/COVERAGE*, *Observability limits due to delay lines* panel to see why the observability range is smaller with 3 telescopes than with 2 telescopes.

UV tracks for different configurations: In the *UV coverage* panel, try to add several 3-telescope configuration. For that you need to un-check the *reset frame* button. As an example, you can select 4 configurations i.e. A0-G1-J6, G2-J1-D2 and A1-B2-C1.

Beam shape: You can then display the “dirty beam” (the same as in radio-astronomy !) by using the *Display PSF* panel.

Exercise 6: Radius measurement of a star (uniform disk)

Here you will play with configurations and “real” observations. You will have a set of stars you want to observe. You must figure out if they are observable and choose the best observing setup to accurately measure the diameters.

In this part, you should load the catalog named `sampleSources1.sou`. Select an instrument and the K band ($2.1\mu\text{m}$). You should also select an observing period and an optimal array configuration to determine the radius of the targets with the highest accessible accuracy. In this section you will make intensive use of the *WHAT & Object Model* menu (or *UV Model/FIT*, *Source modeling* menu) and *OBSERVABILITY/COVERAGE* menu of ASPRO.

Table 1

Star main characteristics of catalog `sampleSources2.sou`

Object	Spectral Type from simbad	Ra	Dec	Diameter [mas]
Betelgeuse	M2Iab	05:55:10.31	+07:24:25.4	44.20
Achernar	B3Ve	01:37:42.85	-57:14:12.3	2.53
HD 81720	K2III	09:25:19.28	-54:27:49.6	0.93
HD 68273	K2III	08:09:31.95	-47:20:11.7	0.5
NGC 1068	AGN	02:42:40.83	-00:00:48.4	3

Use the appropriate uniform disk model to either display the amplitude, the phase of the visibility, or the derivatives with respect to the diameter to visualize which part of the *UV* plane really constrains the model.

Optimizing the observability of a series of sources: Can you find a setup which fits well all the stars together? For that purpose, you must find a night and configuration which fits well all the stars characteristics for observability, visibility level, delay lines constraints, and *UV* tracks.

Radius measurement: Can one determine the radius of these stars?

More details about the object: Can one determine phenomena that occur at higher spatial frequencies, like limb darkening?

Knowing the limitations: What accuracy do you need to fulfill your objectives?

1.1 Exercise 7: Binary parameter determination

In fact a “mistake” was introduced in the previous list: the star HD 68273 is a binary star (real name γ^2 Velorum). First load/re-load the catalog named `sampleSources1.sou` and then select star HD 68273. Let us consider it as a binary system with the properties summarized in Table 2.

Table 2
Binary system characteristics

Ra	Dec	ρ [mas]	P.A. [°.]	Δ mag
08:09:31.9503	-47:20:11.716	3.65	75	0

- Select the baseline G2-G1
- Visualize the UV coverage and the amplitude. Does this baseline constrain the parameters of the binary? Plot the visibility as a function of time.
- Select the baselines A0-M0. Visualize the amplitude, the phase, and their derivatives.
- Does this baseline constrain the parameters of the binary?
- Plot the visibility as a function of time.
- What do you notice about the baseline orientation / the binary system position angle?

2 Observability and UV coverage (Solution)

The same procedure as before was used to produce these corrections: ASPRO was used for getting the figures and GIMP to over-plot the graphs together for illustration. **As in the previous section, please try the exercises first before reading these corrections.**

Exercise 1: Setting up an observation

After having set the date, time, place, and target (Fig. 3), you can start using ASPRO and its many features to check and prepare observations. Fig. 4 is what you should get in your shell when setting *View Object Catalog* correctly.

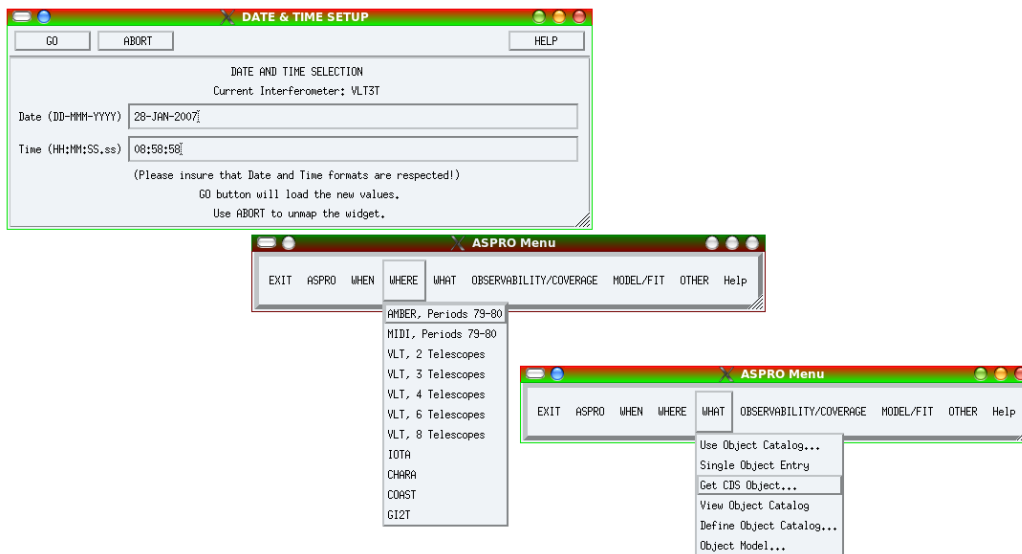


Fig. 3. How to set the date, place, and object. Top: the date setup window appearing when pressing the *WHEN* menu. After changing the date and time, just press *GO*. Middle: the *WHERE* menu, where one can choose between all the supported interferometers. Bottom: the *WHAT* menu. The *Get CDS Object...* is very convenient for quickly finding a target.

Exercise 2: Observability of sources at different declinations and delay line constraints

Which stars are observable? Fig. 5 shows the observability for the second catalog of sources (`sampleSources2.sou`). The gray area corresponds to the night, and the black lines correspond to the observability of sources by their height above the horizon (here 30°). First, you can see that a source at


```

Aspro>
!-----
! sampleSources1.sou
!-----
ACHERNAR    EQ 2000.000    01:37:42.8466  -57:14:12.327
NGC_1068    EQ 2000.000    02:42:40.8300  -00:00:48.400
BETELGEUSE  EQ 2000.000    05:55:10.3053  +07:24:25.426
HD_68273    EQ 2000.000    08:09:31.9503  -47:20:11.716
HD_81720    EQ 2000.000    09:25:19.2802  -54:27:49.559

```

Fig. 4. Display of the catalog in the terminal window.

declination +40 is not observable at all, due to the latitude of Paranal: about 30°.

Delay lines limitation: The additional constraints coming from the interferometer are displayed in red just above the usual observability plot: the left graph is for stations UT1-UT4 and the right one is for G1-J6. You can see the difference for 2 extreme cases: a (roughly) East-West baseline (UT1-UT4) and a North-South baseline (G1-J6). The North-South baseline restricts the access to northern sources, whereas the East-West baseline restricts the observability during the night.

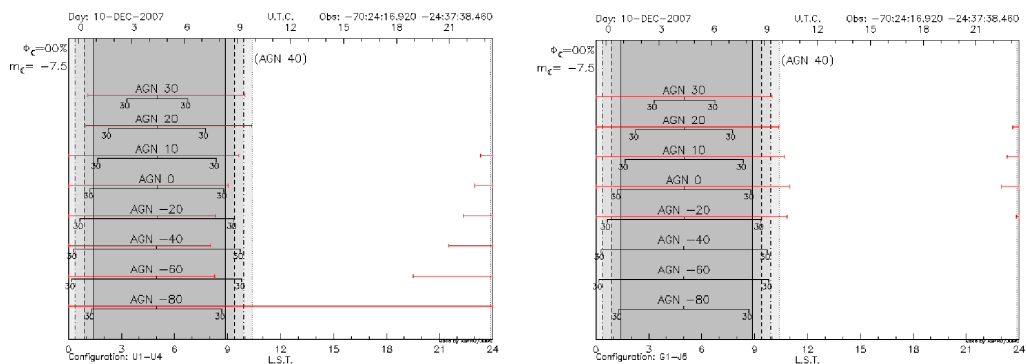


Fig. 5. **Left:** Observability of sources at different declinations for the UT1-UT4 baseline (roughly East-West baseline). **Right:** Observability of sources for the G1-J6 baseline (North-South).

Exercise 3: UV tracks for a North-South baseline

The UV tracks for the targets of the 2nd catalog (`sampleSources2.sou`) are shown in Fig. 6. The North-South baseline gives roughly North-South UV tracks, but the limitations due to the delay line limits are quite severe here since a very long baseline (G1-J6) was used. This can be seen in the very short

accessible UV tracks for the 20 and 30° declination targets. One can see here that the 0° declination target gives a line in the UV plane.

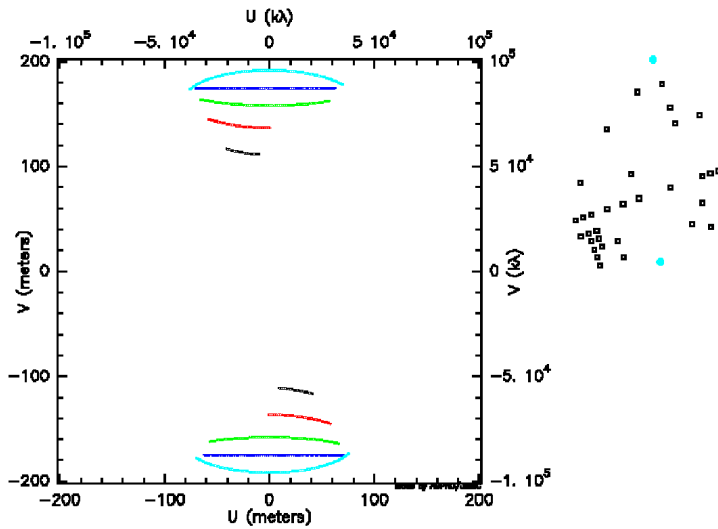


Fig. 6. UV plane tracks due to the Earth rotation for a N-S baseline (G1-J6) and for different declinations: cyan for -20° , blue for 0° , green for 10° , red for 20° and black for 30° .

Exercise 4: UV tracks for an East-West baseline

UV tracks shape: For the answer to this question, please refer to Millour (2008). The UV tracks correspond to the projection of a circle (due to the Earth rotation) on an inclined plane (the plane of sky) and are therefore arcs of ellipses.

UV tracks and target declination: Fig. 7 now shows the East-West baseline. As one can see, East-West baselines will never give a North-South UV projection on the sky. Also, the total range of UV plane projected angles is maximum for high declination targets (either positive or negative). As for the previous case, a 0° target gives a straight line in the UV plane and, therefore, provides less coverage than a high declination target.

Exercise 5: UV tracks for a 3-telescope-array

Observability: First, one needs to check the observability when taking a big triangle (B5-J6-M0, Fig. 8, left panel). As one can see, the observability constraints are much more stringent than before, using a lower number of telescopes. The *Observability limits due to delay lines* panel (right side) now

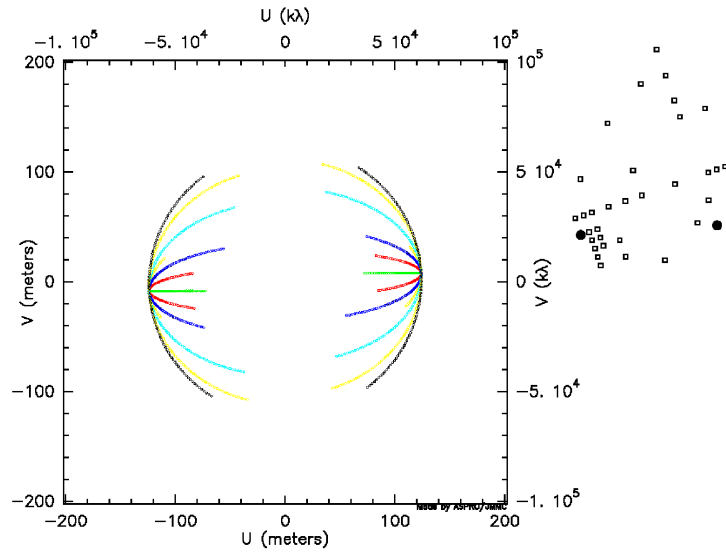


Fig. 7. UV plane tracks due to the Earth rotation for an E-W baseline (A1-J2). The color-coding for the different declinations is the following: black for -80° , cyan for -40° , blue for -20° , green for 0° , red for 20° and yellow for 40° .

gives meaningful information; i.e., splitting the constraint by delay line. Here, one can see that the most constraining baselines are the B5-J6 and M0-B5, and the M0-J6 baseline does not too much constrain the observability.

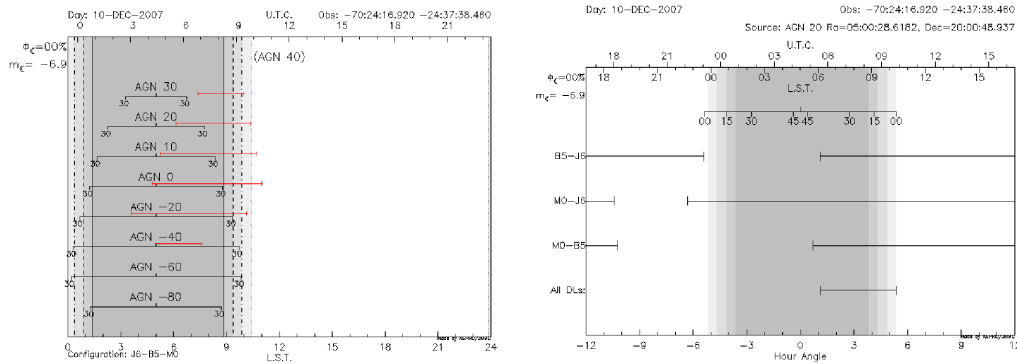


Fig. 8. **Left:** Observability of sources for a big triangle of baselines (B5-J6-M0). The constraints due to the delay lines (red lines) are now larger than for 2 telescopes. **Right:** Detail of the delay line constraints: the B5-J6 and M0-B5 are the most constraining baselines.

UV tracks for different configurations: In Fig. 9, the UV tracks for the different triangles and different object declinations (0° , -20° and -40° from top to bottom) are shown. One can see that many aspects will affect the UV coverage:

- declination - which affects the quantity of different position angles.

- delay lines constraints - which prevent one from observing with large baselines (bottom graph).
- available baselines - which limits the available stations due to the interferometer possibilities.

Beam shape: One can see that the many aspects raised before will affect the UV coverage and, therefore, the quality of the PSF (plotted using the *show dirty beam* option):

- declination affects the quality of different position angles and gives irregular secondary lobes to the PSF.
- The delay line constraints prevent one from observing with large baselines (bottom graph) and widen the PSF (loss of angular resolution).
- The available baselines give an elongated PSF in the E-W direction for the VLTI, since the longest baseline is in the N-S direction.

Exercise 6: Radius measurement of a star (uniform disk)

Optimizing the observability of a series of sources: The first step is to set up an observation date in order to be able to observe all targets together in one night. The optimal date of observation would be the 15th of December, but the moon is full on the 20th. However, one can choose this date (Fig. 10) since interferometry is insensitive to the moon phase. I also chose the UT1-UT3-UT4 triplet since there is a faint target in my sample (NGC 1068) and checked that it does not put too many additional constraints on the observability of the source due to delay lines.

Radius measurement: First of all, you need to look at the standard accuracy of the instrument you will use to be able to know what you can expect from your observations. The ESO *Call for Proposal*⁴ gives you information about AMBER and MIDI (the two offered instruments) accuracy you can expect. For AMBER in P81, the accuracy is 3% for an uncalibrated visibility point; i.e., about 5% for a calibrated one. If you look at the different targets here (I have taken a diameter of 3 mas for NGC 1068, see Fig. A.2), you can see that with this accuracy, both the star Betelgeuse and HD 68273 (γ^2 Vel) are unreachable for diameter measurement. The star HD 81720 will be measurable but with a poor accuracy on the diameter. Therefore the targets you will really be able to observe using these baselines are Achernar, NGC 1068, and partially HD 81720. For the two other stars (HD 68273 and Betelgeuse),

⁴ <http://www.eso.org/sci/observing/proposals/>

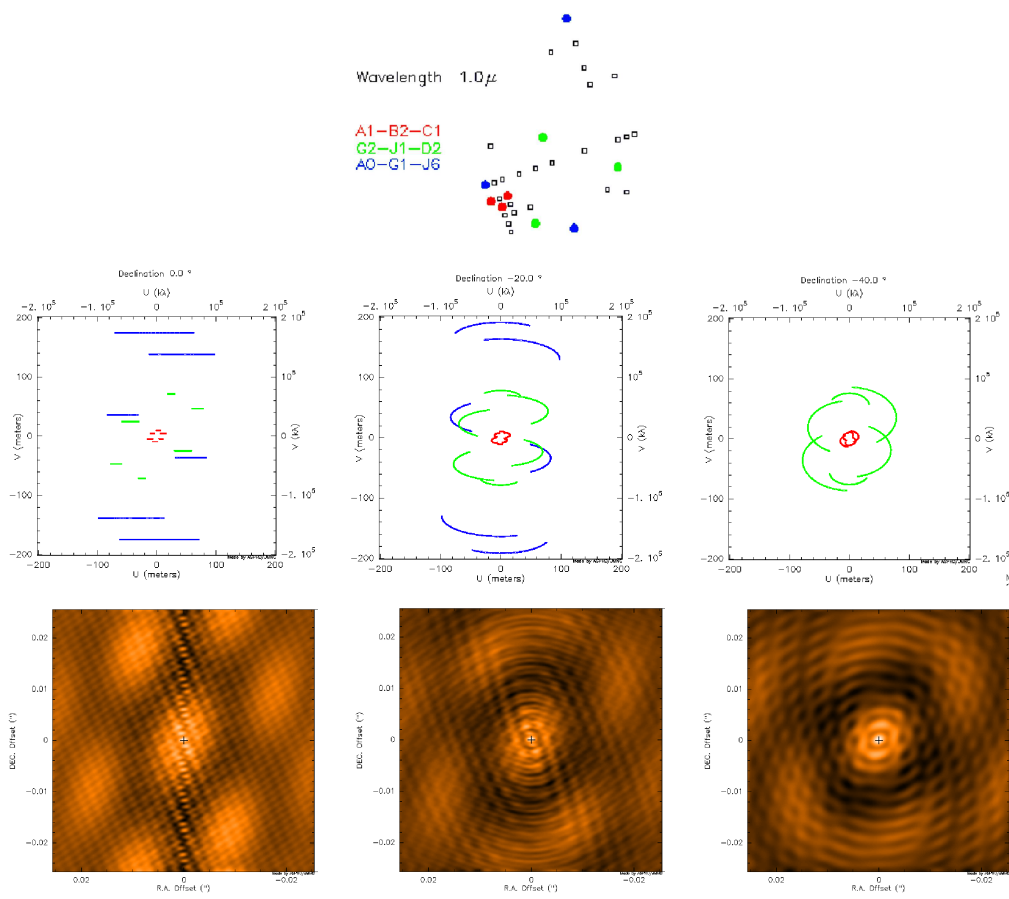


Fig. 9. **Top:** Sketch of the stations used in this example. **Middle-Left:** UV tracks for a 3-telescope observation on a 0° declination object and several telescopes configurations: A1-B2-C1, A0-G1-J6 and G2-J1-D2, corresponding roughly to 3 observing nights using AMBER and with complete freedom in the stations selection. **Bottom-Left:** The corresponding “dirty beam”, or what would look like the PSF if one would observe a point-source with a telescope having an aperture similar to the previous UV track. **Middle:** Same as 1^{st} plot, but for a -20° declination target. **Bottom-Middle:** The corresponding dirty beam. **Middle-Right:** Same as before but for a -40° declination target. Note that the biggest triangle does not appear in this plot, as the constraints due to the delay lines prevents from observing with these telescopes. **Bottom-Right:** The corresponding dirty beam.

you will need other configurations (a short baseline triplet for Betelgeuse and the longest available baselines for HD 68273) to reach your goal of measuring a diameter.

More details about the object: You should also notice that limb-darkening measurements, which need at least one point in the second lobe of visibility, are not achievable, except for Betelgeuse. Finally, one baseline setup is not sufficient to measure all the star diameters: you will need at least a 3-baseline setup to reach your proposal goal (one short baseline setup for Betelgeuse and

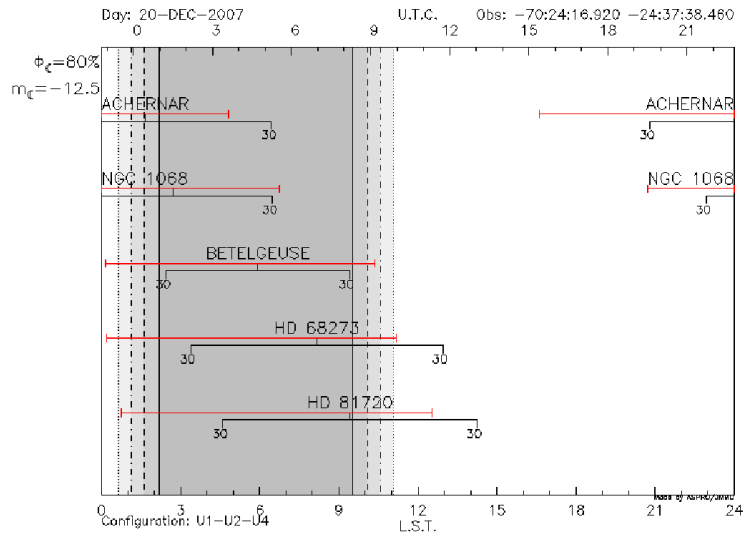


Fig. 10. Observability of the 1st catalog.

one very long baselines needed for HD 68273 and HD 81720 to reach a better accuracy).

Knowing the limitations: By browsing the ESO call for proposals⁵, you can find that the current AMBER accuracy is 0.03 on the raw visibilities. This means 0.05 on calibrated measurements. Therefore, as seen in Fig. A.2, only Achernar and NGC1068 will allow one to “easily” measure a non-zero or non-1 visibility. HD68273 and Betelgeuse will make the measurement very difficult, as the expected visibility is very close to 0 or 1. Then, HD81720, whose visibility at maximum baseline is 0.85, will be marginally resolved and only an upper limit to the diameter will be measurable.

Exercise 7: Binary parameter determination

If the reader has reached this point carried out all of the exercises without any problems, he is now an expert in long-baseline stellar interferometry and can do this exercise without any difficulty ;-)

⁵ <http://www.eso.org/sci/observing/proposals/>

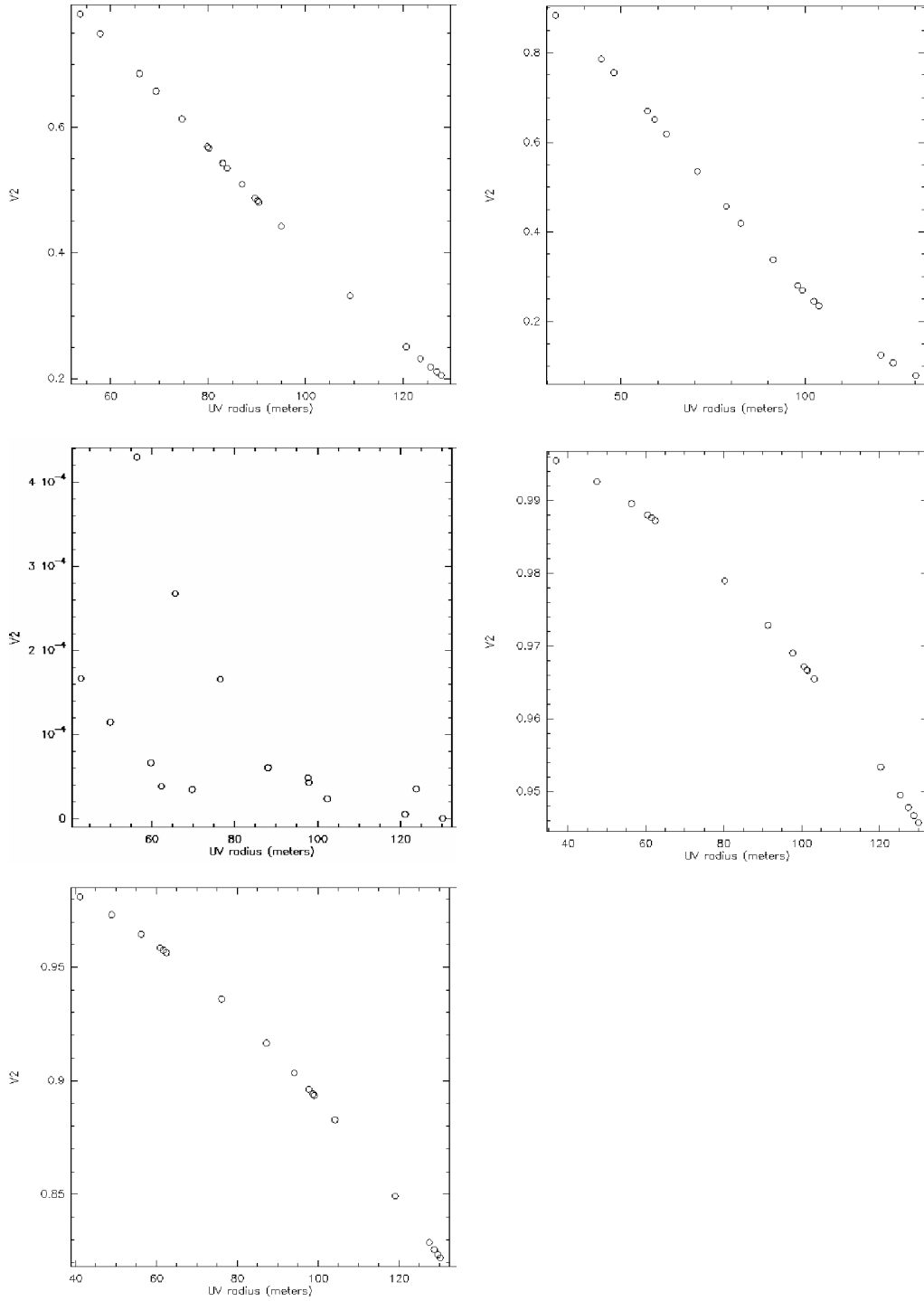


Fig. 11. **Top-Left:** Achernar visibilities for the largest baselines, given a radius of 2.53 mas. **Top-Right:** Same for NGC 1068 and a diameter 3 mas. **Middle-Left:** Same for Betelgeuse, diameter of 44 mas. **Middle-Right:** Same for HD68273, diameter of 0.5 mas. **Bottom-Left:** same for HD81720, diameter of 0.93 mas.

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.

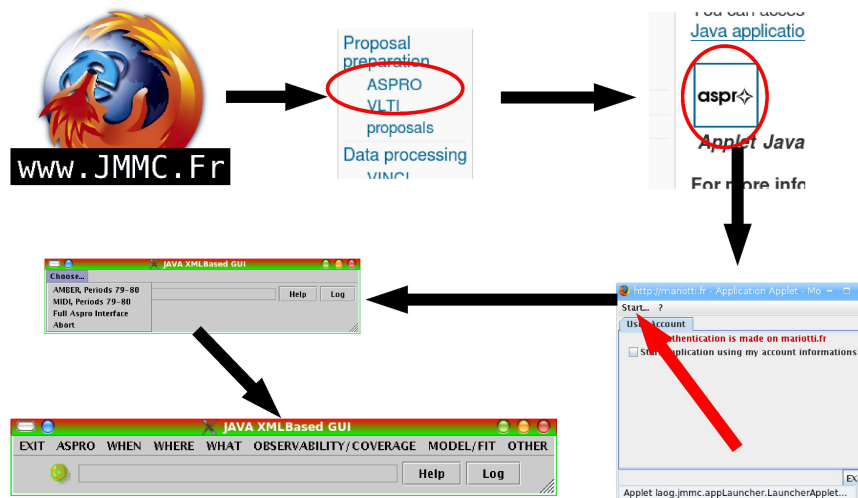


Fig. A.1. The different steps to launch the web version of ASPRO. One only needs an internet connexion and a java-enabled web browser.

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.

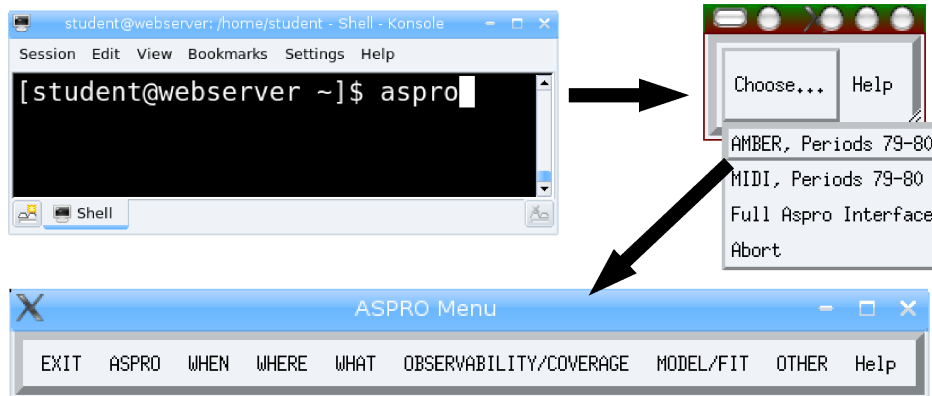


Fig. A.2. The steps to launch ASPRO on a local computer: even simpler, but one needs a local version of the software installed!

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

- Berger, J. P. & Segransan, D. An introduction to visibility modeling, *New Astronomy Review*, 2007, 51, 576-582
- Millour, F., All you ever wanted to know about optical long baseline stellar interferometry, but were too shy to ask your adviser, *New Astronomy Review*, this issue.