Preparation of VLTI observations

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Abstract

This chapter provides a step-by-step overview of the most important issues that should be addressed by astronomers planning a VLTI proposal or observing run. Each problem is first presented in general terms, along with guidelines on how to address them. In addition, the entire procedure is illustrated for the case of a realistic observing scenario. Illustrations for this tutorial are largely based on the JMMC-distributed ASPRO-VLTI software, which provides the user with quantitative and graphical information that can be helpful in preparing VLTI proposals and/or observations.

Key words: VLTI, AMBER, MIDI, JMMC, ASPRO-VLTI

1 Introduction

The purpose of this tutorial is to guide the reader through the various steps (s)he should take during the preparation of VLTI proposals and/or observations. More specifically, we will tackle a sequence of questions that should be addressed prior to writing proposals and being at the telescope:

– Is VLTI appropriate for the observations of my target (Sect. 3)?
– Is my target observable with VLTI (Sect. 4)?
– What is the appropriate VLTI instrument for this project and can it be used with the adequate set-up (Sect. 3 and 5)?
– What set of baselines is most appropriate for this project (Sect. 6)?
– Can I find a good interferometric calibrator (Sect. 7)?
– How accurately will the observation constrain the geometry of the target (Sect. 8)?

It is important that potential VLTI users go through each of these steps, in order to assess both the feasibility and usefulness of the proposed observations.

Each section of this tutorial will start with a general approach of a certain topic and will be followed by a short example.

As an illustration of the preparation of VLTI observations, we will assume that the user plans to observe a spectroscopic binary system (that consists of two unresolved point sources), HD 147889, whose projected orbit runs along position angle 100° (East from North). At apastron, its projected separation reaches about 0.6 mas but, if observed at a random time along its orbit, the projected separation is only 0.2 mas (statistical average). Furthermore, the flux ratio of the binary is about 0.25 mag throughout the near- and mid-infrared wavelength regime with an uncertain amount of variability around that value. In this example, the user's goal is to determine whether VLTI observations can resolve the binary, quantitatively retrieve its physical parameters (separation and flux ratio), and what the most appropriate array and instrument configuration is to reach this goal. In particular, we will want to use the highest possible spectral resolution, in search for potential differences between the continuum and some spectral features. In addition, the user will want to decide whether (s)he would be able to detect a potential third component of the system if it were located 4 mas away.

2 Tools to prepare VLTI observations

Preparing VLTI observations is a similar process to all other types of astronomical observations, with the important caveat that, because interferometry is a complex observing mode, dedicated tools must be used in the preparation. In particular, because interferometric observations only sample a few points in the (u, v) plane, it is not sufficient to run a back-of-the-envelope calculation to show that a baseline of a certain length will resolve an object's structure. While this may indeed be true, it is also quite possible that such observations do not provide any useful constraint on the object geometry. The user must thoroughly simulate his/her observations beforehand to assess the relevance of interferometric observations to his/her scientific goals.

Dedicated, documented and supported software for VLTI observations with AMBER and MIDI are available from both the Jean-Marie Mariotti Center [1] and ESO [2]. While they offer similar features for all geometrical aspects, ASPRO-VLTI goes a bit further with its model-fitting capabilities. It is nonetheless recommended to use both types of software to double-check one's results. In this chapter, we will mostly use the JMMC instrument- and array-specific software ASPRO-VLTI when simulating observations and pro-

[1] `http://www.mariotti.fr/aspro_page.htm`
[2] `http://www.eso.org/observing/etc/`

ducing graphical ouputs. This software is updated every semester to match the most recent ESO-provided specifications of VLTI stations and instruments. At the time of writing, the P79-specific (April–September 2007) version is available online on the JMMC webpage. This is the version used here. Keep in mind, however, that some illustrations presented here may no longer be up-to-date starting from and beyond P80 (October 2007 – March 2008) due to improvements in VLTI capabilities and characteristics. Alternatively, one can use ESO's software VisCalc ("observation simulator") and CalVin ("calibrator finder"), which are also updated every semester.

3 Selecting the instrument

The first decision to make is the instrument that will be used. VLTI currently offers two instruments that focus on different wavelength ranges. AMBER is a **near-infrared 3-telescope** combiner whereas MIDI is a **mid-infrared 2-telescope** combiner. Specific scientific goals may imply that using one of these instruments is useless: this is for instance the case for observations in a particular spectral feature, for objects which are not detected in one of the two wavelength regimes, or in cases where 3 simultaneous baselines are required (e.g., closure phase measurements). Nonetheless, it is important to check whether the required instrument is observationally relevant. The astronomer should also wonder whether the instrument (s)he plans on using offers a spectral resolution that is adequate to reach his/her goals. Observing structures that emit as blackbodies can be performed with the lowest spectral resolution of the instruments, but analysis of particular atomic/molecular features may require a much higher resolution. If no instrument stands out scientifically, one must be selected on the basis of it providing the most useful constraints.

To decide which instrument should be used, it is important to compare the resolution of the interferometer at a certain wavelength with the expected angular size of the target. The first null of the interferometric beam (the "resolution") occurs at a spatial scale of λ/B, where B is the projected baseline. If the object is much smaller than this scale, it will be only marginally resolved by the interferometer, usually yielding only a weak constraint. On the other hand, if the object is much larger than this resolution, then it will be completely over-resolved, implying low-accuracy results and/or ambiguity on the object size. For instance, to accurately constrain a binary system, the spatial resolution should be similar to the binary separation or only slightly larger. There are exceptions to this rule of thumb, but this is a reasonable starting point.

The first method to decide which wavelength range is better consists in obtaining diffraction-limited observations of the object with a single Unit Telescope or with another telescope of similar size (with adaptive optics images in the near-infrared or direct images in the mid-infrared). If the object does not present a diffraction-limited core in single-dish observations, interferometric observations are unlikely to be the best choice as they will over-resolved the target. If its core is unresolved, on the other hand, interferometry will probe even smaller scale, providing an opportunity to resolve the target. Note that only the unresolved core will contribute to the correlated flux received by the interferometer, and only the brightness of this core, and not the integrated flux of the object, should be considered when checking the observability of the target.

A second, more quantitative method consists in considering the actual resolution of VLTI: at 2μm, a baseline of 100 m is equivalent to a resolution of 4 mas; at 10μm, the resolution is 20 mas. If the object's intrinsic size is much larger than $\approx$10 mas, AMBER observations would probably not be very useful. On the other hand, an object whose size is $\lesssim$1 mas will not be resolved enough with MIDI, independently of the selected baseline. Remember, however, that the projected baselines afforded by VLTI range from 16 m to 200 m, and that both instruments offer a relatively wide range of observing wavelengths. These two key elements allow to adjust the interferometer resolution to an object size.

In practice, these order of magnitude calculations should only be used to clarify the situation, and cannot be the only basis for an interferometric observation, anyway. But failing these tests is a good indication that VLTI is probably not the best way to tackle a certain astrophysical problem.

In our example, the separation of the binary system never exceed 0.6 mas, so we can readily conclude that MIDI observations are not relevant here. On the other hand, the resolution of AMBER, particularly for baselines $\gtrsim$100 m and a wavelength of 1.65μm (H-band), should resolve at least partially the binary. This suggests that AMBER observations may well be useful for this scientific project, but it remains to be determined whether they can constrain the binary parameters sufficiently. This is the purposes of the following sections.

4 Observability of the target

As for any other observation, interferometric observations require that the target be up in the sky! With VLTI, the requirement is that the object be at least 30^o above horizon. Note that, because each observations takes between 60 and 90 minutes, this condition must be fulfilled for at least that much time.

In principle, the VLTI delay lines allow observation of a target anywhere in the sky above this limit. However, there are exceptions for the longest baselines, depending on the treatment of the available delay lines; every semester, the affected baselines are listed in ESO's VLTI webpages [3]. Also, a few of the AT stations suffer from shadowing by the large UT domes when observing at low elevation. This may limit, for some projects, the usefulness of some baselines. The ESO software VisCalc includes up-to-date limitations due to delay line limits and shadowing, allowing the user to determine which baselines are inappropriate. It is therefore important to test proposed observations on this software to check that they will not be affected by these effects.

Besides the brightness of the target itself in the observing band (see below), it is also important to check that the target, or a nearby star (within $60''$), is bright enough to allow telescope guiding: the feeding adaptive optics (MACAO on UTs) and tip-tilt units (STRAP on ATs) both require a minimum flux in the visible to work properly ($V < 17\,\mathrm{mag}$ and $V < 13.5\,\mathrm{mag}$, respectively). In other words, observing extremely red objects in the middle of heavy extinction patches with no foreground or background source is almost hopeless. If such a situation occurs, it is strongly recommended to double-check with the instrument manual and with ESO whether this is feasible.

In our example, the declination of HD 147889 is roughly -24^o*, so it passes almost at zenith from Paranal, and it is bright in the visible (*$V \approx 8\,mag$*), allowing good telescope guiding with both the UTs and ATs. It is therefore feasible to observe this target with VLTI. We now have to decide whether this is at all useful.*

5 Finding an appropriate instrument configuration

Both VLTI instruments offer a set of configurations, and the user must identify the most appropriate to his/her goals. For instance, as with any astronomical instrument, there is a trade-off between spectral resolution and object brightness. The specialness of interferometry, however, is that one cannot always compensate for the faintness of a source by integrating longer: to obtain interference fringes with a good signal-to-noise ratio, a minimum amount of flux is necessary per integration. Until the FINITO fringe-tracking system is operational on VLTI, observations are limited to very short individual integrations and consequently to relatively bright objects. Even when FINITO is available, it may be difficult to obtain very long integrations, and the user may have to compromise with spectral resolution, anyway. Brightness limits for all instrumental configurations are listed in ESO's Call for Proposal, which the user

[3] `http://www.eso.org/paranal/insnews/vlti_overview.html`

should read carefully to determine whether his/her target is bright enough for the desired configuration. Both ASPRO-VLTI and VisCalc actually test if the object brightness allows the requested instrumental configuration.

In our example, the K-band brightness of HD 147889 is $K = 4.6$ *mag, allowing observations during P79 only in the "low resolution" mode, with the UTs or the ATs (using an individual integration time of 100 ms in the latter case). If observations at higher spectral resolution were necessary to reach the scientific goals, the user could only wait until future Calls for Proposals, when fainter sources can be observed. For this particular project, even the "low resolution" mode is satisfying, so we can move on to the next item, i.e. the selection of baselines (array configuration).*

6 Finding an appropriate array configuration

The next step in preparing VLTI observations is probably the one that deserves the most attention. The goal is to decide which array configuration(s) (telescope stations) should be selected. To make this decision, it is necessary to compare the (u, v) coverage of the possible arrays with the Fourier representation of the target's model. The longest baselines may not be the most appropriate, depending on the object's coordinates and intrinsic geometry. In particular, when objects are only marginally resolved with VLTI, it is usually better to select baselines that are along the position angles that best resolve the target. Otherwise, most measurements will yield visibilities close to unity, providing only a weak constraint on the object geometry.

As a rule of thumb, a simple "quality check" for array configurations is that the various baselines sample different visibilities, either as a function of time (for transit-long observations), projected baseline and/or position angle. Here, "different visibilites" means visibilities which differ at the several-σ level from both unity and each other. This is particularly important when little is known about the geometry of the system. For example, the preferential position angle of many astrophysical objects is not known prior to interferometric observations. In such a case, it is not sufficient to test that a certain array configuration resolves well the object **if it has an adequate position angle**. One must also check if it will be well resolved **for a large range of position angles**. For instance, to observe a tight binary, it is a good idea to use baselines that are roughly parallel to its position angle, if it is known. Otherwise, sampling the plane in "all directions" is preferable as it increases the chance of obtaining visibilities that are significantly below unity. If all visibilities are statistically consistent with unity, then the only constraint is that the object is much more compact than a certain size. While this can be a useful conclusion, this is frequently not sufficient.

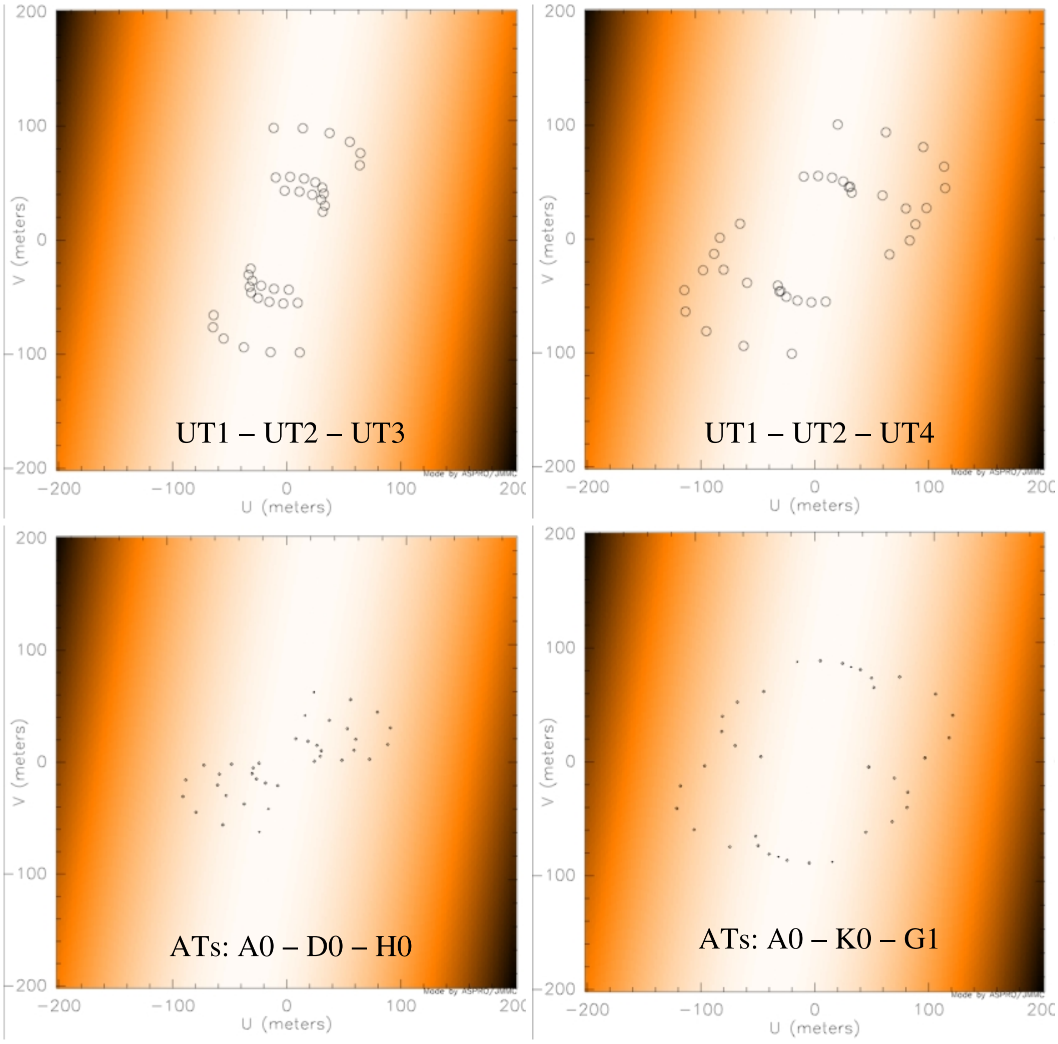

Fig. 1. Examples of UV coverage for a full transit for several 3-telescope array configurations in the case of a binary system (separation 0.6 mas, position angle 100^o, flux ratio 0.8 [0.25 mag].) *Top row*: UT1-UT2-UT3 and UT1-UT2-UT4. *Bottom row*: A0-D0-H0 and A0-K0-G1. Observations are taken at a 90-minute frequency, appropriate for AMBER during P79. The size of the symbol represents the size of the single apertures in the UV plane.

Using JMMC's ASPRO-VLTI and/or ESO's VisCalc software, it is possible to calculate the Fourier transform of the object and to overplot the (u, v) coverage provided by a certain array configuration. By testing several configurations, it is possible to determine which one will best sample an object geometry. With both software, the user can use simple parametric geometrical descriptions (e.g., [inclined] uniform disk, [elliptical] Gaussian distribution, binary system, ...) or provide his/her own model of the target, using images in FITS format.

In our example, the position angle of the binary is known from previous observations, which helps significantly. Since the object will be only marginally resolved given its size (see Sect. 3), the user should try to use baselines that are *roughly elongated along the binary position angle. Considering UTs as a first step, one can readily see that UT1-UT2-UT3 is a poor choice, as it runs almost perpendicular to the binary position angle. Using this configuration would yield visibilities that are all very close to unity, which would poorly constrain the binary model. On the other hand, UT1-UT3-UT4 or UT1-UT2-UT4 are better choices as they provide a better general orientation. Note that, if the position angle of the binary had not been known, we would probably have concluded that UT2-UT3-UT4 is the best choice for this proposal because it spans more uniformly all position angles. Since sensitivity allows it, we can also consider ATs as a second step. Among the configurations offered during P79, A0-D0-H0 and A0-K0-G1 are good configurations for this program. Among these, the latter would be the best suited if no prior information on the binary position angle were available. Several transit-long (u, v) coverages are presented in Fig. 1.*

To reach a conclusion as to which array configuration is best for this project, we must also consider that it is probably easier to obtain 1 entire night with an AT configuration, yielding the whole coverage presented in Fig. 1, than with the UTs, with which we would probably be restricted to a single (snapshot) observation. We therefore conclude that either of the two AT-configurations listed above are best for this project, as they will narrowly constrain the binary parameters. We would probably choose A0-K0-G1, which samples slightly longer projected baselines and therefore better resolves the system.

While this reasoning remained very qualitative, we will move on to quantitative estimates of the visibilities in Section 8. Nonetheless, it is notable that we could readily conclude that some configurations hold a better prospect for our scientific goal.

7 Finding an appropriate interferometric calibrator

Interferometric observations, more than any other type of astronomical observation, require calibrations. The absolute visibility of interferometric fringes cannot be measured directly from an interferogram: there are various sources of signal losses that require observations of a star with known visibility just prior to and/or immediately after the observations of a scientific target.

A good calibrator is a star whose angular size is accurately known. Usually, calibrators are selected either because they have been previously observed with an interferometer or because it is possible to determine their size on the basis of other astrophysical quantities (luminosity, effective temperature, distance, ...). It is not necessary that the calibrator be unresolved at the resolution of the interferometer, although this is a better choice to avoid trouble. Resolved objects may have a wavelength-dependent apparent size, such as bright giants or supergiants (that may even have different apparent sizes in and out of spectral features), and larger uncertainties may arise from a partially resolved calibrator. If there is a choice of calibrator, it is better to use the least-resolved one (visibility closest to unity).

A critical property of a good calibrator is that its brightness in the observing band be similar (to within $\sim$1 mag or so) to that ot the target. That way, the entire acquisition and observing process is reproduced, with similar biases introduced in the process. **Using a calibrator that is much brighter or fainter than the target is not appropriate for interferometric observations**.

Finally, the calibrator should be located close to the target in the sky. Ideally, the optical path for light coming from the scientific target and the calibrator should be identical, both in the atmosphere and in the interferometer. It is therefore important to match the airmass but, more specifically, the azimuth and elevations angles. That way, the delay lines and other optical elements of the interferometer are placed in the very same situation as for the target itself. Typically, a good calibrator is located at the same declination and 30–45 minutes ahead/behind in right ascension (depening on whether it is observed before/after the target).

There are at least 2 available software to find interferometric calibrators: ESO's CalVin and JMMC's SearchCal, which is included within ASPRO-VLTI. CalVin runs through a list of previously validated calibrators (referenced on the ESO website) to extract those that comply with a number of user-defined constraints on the calibrator's brightness, spectral type, distance to the scientific target, etc... On the other hand, SearchCal runs through a number of stellar properties catalogues at CDS to recover spectral and photometric information on all stars in the vicinity of the target and, for each of them, estimates their angular size at the desired wavelength. Those for which accurate predicted visibilities can be estimated are considered possible calibrators and returned.

Typical uncertainties of the predicted visibilities of calibrators should be (well) below 1%, so that measurement uncertainties on the scientific target dominate the error budget. If the proposed calibrator has an uncertain size resulting in large uncertainties on the predicted visibility, it should be replaced by a better-known calibrator.

In our example, using CalVin to find calibrators for HD 147889, we only obtain HD 143900. With SearchCal, several calibrators are found that satisfy all criteria using reasonable search ranges ($\pm$1 mag in brightness in the K band, $\pm 60'$ in declination, $\pm 5^o$ in right ascension), the closest to our target being HD 148605. Both proposed calibrators have accurate predicted visibilities, typ-

ically to within 0.1–0.3%, so it is possible to calibrate well the observations we propose.

If the target is relatively faint, many potential calibrators are available as there are many more faint stars in the sky than bright ones and the request can be long to process as the cross-correlation between catalogs depends on the number of objects found. In this case, one can narrow down the search ranges.

8 Testing the relevance of the proposed/planned observations

Once the user has verified that it is actually feasible to observe his/her favorite target, that a scientifically useful instrumental configuration can be achieved (e.g. sufficient spectral resolution) and that a good calibrator can be found, it is time to determine whether the proposed observations would provide good constraints on the geometry of his/her target. As discussed above, variations of the visibility/phase as a function of time or position angle, for instance, is a key element. Most importantly, departure from unity for the visibility are critical to constrain the geometry of targets. For 3-telescope configurations with AMBER, the closure phase can also be an important additional observable to test the geometry of a target.

Snapshot observations only provide 2 or 3 visibilities per spectral bin and, in the case of AMBER, a closure phase (which measures departures from axisymmetry of the source). This is a relatively limited amount of information if nothing is already known about the object. Generally speaking, such observations are used either to simply determine whether the object is spatially resolved at the interferometer's resolution, or to constrain a single parameter in cases where the object geometry is already well constrained from prior observations. On the other hand, transit-long observations with the ATs allow a more extended (u, v) coverage, from which simple models can be constrained even with little or no prior information.

Both JMMC's ASPRO-VLTI and ESO's VisCalc software produce plots of synthetic visibilities as a function of projected baselines and/or time. From these plots, the user can determine whether significant variations and departures from unity will be obtained with the proposed observations. With ASPRO-VLTI, it is also possible to plot phases, from which closure phases can be reconstructed and plotted. Such plots are key to decide whether to observe the target with VLTI and with which configuration.

To go beyond these statements, it is necessary to perform some model fitting on the synthetic visibilites to determine quantitatively how constraining the observations would be. ASPRO-VLTI includes a "model fitting" package that

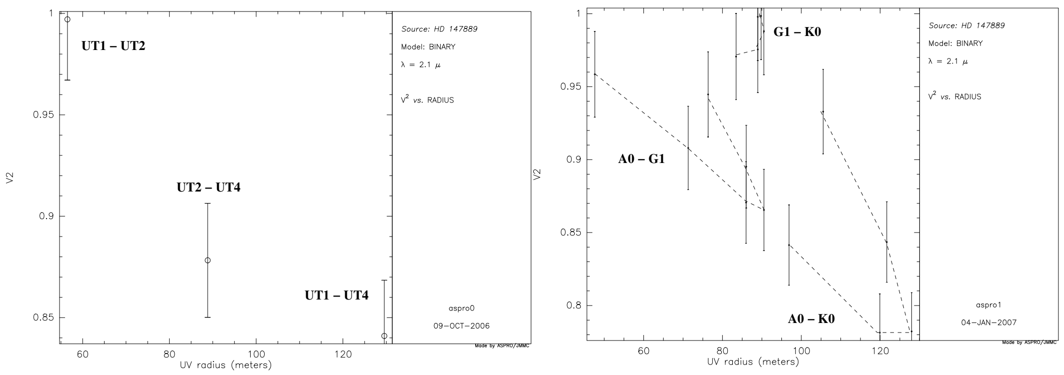

Fig. 2. Visibility plot for the projected observations of HD 147889: snapshot observation with the UT1-UT2-UT4 array (*left*), and transit-long observation with the A0-K0-G1 array (*right*, successive measurements with a given baseline are connected with dashed lines). Significant departures from unity can be found in both cases, but a much tighter constraint on the binary parameters is obtained with the ATs.

gives estimates of the uncertainties on the fit parameters if the user were to fit a certain geometrical model to his/her synthetic dataset. We do not explore this aspect here and refer the reader to chapters 5.1 and 5.2 dedicated to model fitting.

In our example, Fig. 2 illustrates that observing in snapshot mode with the UTs results in visibilities ranging from 1 to 0.85 (assuming the binary is at apastron), clearly resolving the system at the $\approx 5\sigma$ *level. However, the amount of information is limited due to the poor* (u, v) *coverage, and it is likely that the binary parameters would only be partially constrained, considering the expected measurement uncertainties shown in Fig 2 (uncertainties may depend on the absolute visibilities). On the other hand, observing during one entire transit with the A0-K0-G1 configuration, visibilities in the same range are obtained, but the increased* (u, v) *coverage yields large excursions in visibilities as a function of time. The binary parameters can be nicely constrained by such observations, with a ≈10% accuracy on the flux ratio and ≈0.1 mas on the projected separation (as estimated from the simple visibility fit routine included within ASPRO-VLTI). Even tighter accuracies will likely be obtained as, in the "low resolution" mode, AMBER also simultaneously covers the H-band: at 1.65μm, squared visibilities as low as ≈0.7 will be measured.*

It must be noticed that observing at a random time during the binary's orbit, with the system about 3 times as tight, would yield visibilities that all are in the range 0.97–1.0, i.e. undistinguishable from unity: it is not possible to resolve sufficiently the binary in this case. This means that the proposed program is only feasible when the binary is at apastron passage, implying that an important time-constraint should be included in the preparation of the observations.

Finally, regarding the possibility of studying the presence of a third component in the system, we produced synthetic visibilities adding a third component to

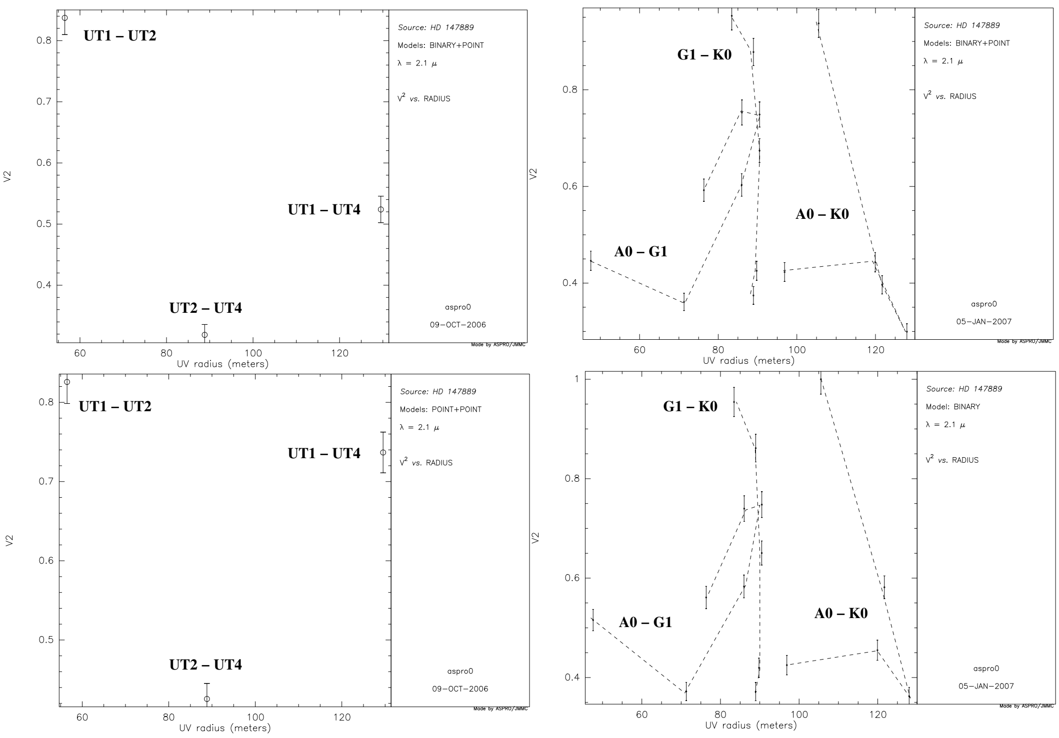

Fig. 3. *Top row*: Same as Fig. 2, but including a third component in the system, located at 4mas, at position angle 135^o. The flux ratio is assumed to be 4:1 between the tight binary and the distant companion. Despite its relative faintness, it drives the visibilites to much lower values compared to the case of the tight-binary-only. *Bottom row*: synthetic visibilities produced with only a 4mas binary system with the same position angle and flux ratio as the "wide companion". In other words, the bottom row mimics the case in which the tight binary itself is not resolved at all. Very similar visibilities are obtained as when the 0.6 mas-binary is resolved and it is unclear whether precise model fitting to these visibilities would be able to identify the three components present in the system.

the system (see top row in Fig. 3). Clearly, the visibilities are very different, as this companion is well within the field-of-view of the interferometer. Since the wide companion is half as faint as either of the components of the binary, it drives the square visibility down to $\approx$*0.4. This wide companion will be nicely resolved and its presence and properties well constrained (at least with AT observations). However, it is noteworthy that replacing the marginally resolved tight binary by a single point source yields fairly similar visibilities, with only 3 individual AT baselines out of 16 yielding different visibilities at the* 2σ *level. In other words, if there is a wide companion, it is quite possible that the signal associated to the tight binary will be much harder to pick up and constrain, even though it can be easily detected if no companion is present. Of course, this depends on its actual location and this is only a test case to illustrate the level of change induced by an additional component to the system.*

In this case, however, it is possible to determine that there is more than a tight *binary within the system as fitting a simple binary to a model with three point sources (with both the tight and distant companions) yields poor residuals with either the UTs or ATs. The proposed observations would therefore prove that a two-point-source model could not represent the actual geometry of the target. However, with a single snapshot UT observation, there is not enough independent datasets (even including the closure phase) to fit a more complex geometry which would have too many degrees of freedom; it would be possible to exclude a binary geometry but impossible to constrain further the actual geometry. With a full transit with the ATs, one can reach a similarly good constraint on the tight binary's parameters if the third component is located in a favorable location. In summary, only AT observations could probe and constrain the presence of a third component in the system, but even that may prove insufficient, depending on the location of the third star. In any case, this is the configuration that the astronomer should require in his/her proposal as it is the only one that may prove useful for this project.*

All together, this test case illustrates the need for prior information and detailed visibility modeling before writing ESO proposals and conducting the observations. Order-of-magnitude calculations are not sufficient to make sure that a certain interferometric observation will solve a particular astrophysical question!