Interferometric Calibrations and Astronomical Calibrators

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Abstract

This chapter gives some indications on the selection of suitable astronomical calibrators for interferometric observations. After an introduction to interferometric calibrations, we will focus on the criteria, steps and tools developed by ESO to prepare VLTI observations and to select calibrators . Although the tools described here are focused on VLTI, the problem of astronomical calibrators is the same for the other interferometers and can be approached the same way.

Key words: interferometry, calibration, preparation of observations, VLTI

1 Introduction

Long Baseline Interferometry is a method which can achieve high angular resolution from Mid-Infrared down to optical wavelengths at the level of a few milliarcseconds or less. This ground-based technique is heavily affected by the atmospheric turbulence and by the complexity of the instrument and the different sub-systems, which set limits on the accuracy of the measurements. To improve significantly the accuracy, one can adopt different techniques, like choosing sites with excellent quality for interferometry or using adaptive optics and fringe tracking. Taking good calibration is also important to improve the quality of the science data. For VLTI, these calibrations are of two different kinds: the technical calibrations to measure the characteristics of the detector (Bad Pixel Map, Flat Fields, Darks) or of the optical elements (wavelength calibrations) and provide information on the health of the instrument (overlap of the beams for example), and the astronomical calibrations measured on calibrators to retrieve the true measurement (visibility) on the science objects.

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2 Technical Calibrations

These technical calibrations are taken for two different purposes. The first is to understand the health and the behaviour of the instrument at the time of observation, they are called health checks, the second to calibrate the data taken for the user.

2.1 Health checks

These health checks are common to all the VLT and VLTI instruments (see Percheron (2006)). They are defined in the calibration plan and are performed daily by the operators in Paranal. The results are available on the ESO web at:
http://www.eso.org/observing/dfo/quality/ALL/daily_qc1.html
They include for example measurements of the dark current, of the read-out-noise (RON), of the flat fields. Some data are taken to measure the linearity of the detector, the system throughput and the efficiency and the stability of the optical elements such as the spectrograph. For the VLTI instruments, additional health checks are performed to control for example the overlap of the beams (see figure 1). These measurements are performed over several months and years.
For MIDI, the Mid-Infrared interferometric instrument for the VLTI (see Leinert (2003)), the following properties of the instrument are trended:

- Detector: RON, linearity of the detector, temperature of different cold elements,
- Optical elements: transmission of the dispersive elements, wavelength calibration, position of the beams for the different instrument settings (see figure 1),
- Photometric throughput of the instrument for the UTs (Unit Telescopes, 8.2m diameter) and ATs (Auxiliary Telescopes, 1.8m diameter),
- Instrumental Transfer Function for selected bright calibrators.

Additional health checks are performed when needed and when new instrument modes are put into operations.

For AMBER, the Astronomical Multi-BEam combineR (see Petrov (2007)), the internal transfer function is estimated for the different resolutions (Low, Medium, High) at the proposed wavelengths (J, H and K). The spatial distortion is evaluated by measuring the displacement of the spectra in pixels on the photometric channels. The position (in pixel and in angle) of the reference beams as well as their flux is measured daily.

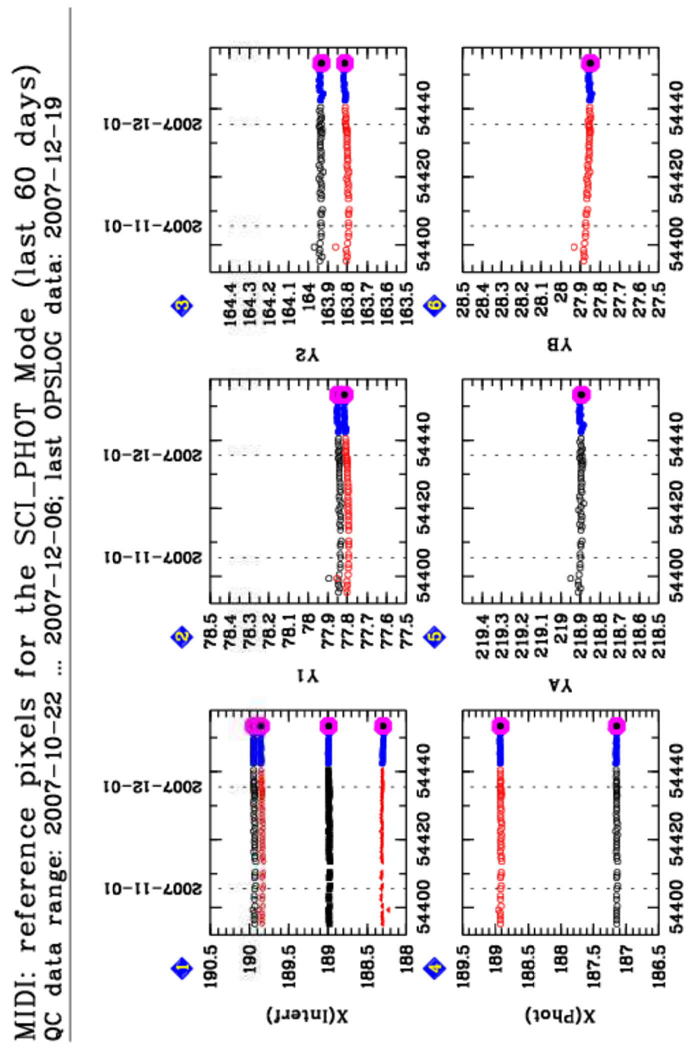

Fig. 1. Position of the reference beams for one of the MIDI instrument mode. The position of each beam is monitored for the interferometric (top) and the photometric channels (bottom) in X (left) and Y (right) directions. The position of the beams relative to each other is important for the interferometric channels to insure a good overlap. The absolute position of each beam needs also to be monitor to insure that the windowing of the detector is correct.

2.2 Technical calibrations for the science data

To obtain high quality science data, it is important to perform some cosmetics on the frames.
For AMBER, different sets of data such as the Bad Pixel Map, the Flat Field Map are used. The bias is estimated and substracted from the frames. Each time the instrument is reconfigured, a calibration matrix is recorded to evaluate the relationship between the interferogram and the observable.
In the Mid-Infrared (MIDI), the instrument is affected by the instrumental background. This needs to be estimated for each science set. Each observation is associated with data taken on the sky using chopping at a given frequency.

3 Astronomical Calibrators

The observable obtained from an interferometer (the visibility spectra for example with MIDI) is affected by the technical specifications of the instrument and by the random effect of the atmospheric turbulence which introduced a distorted wavefront over each aperture of the interferometer. To estimate these effects and calibrate the science data, one needs to observe a know calibrator object. The characteristics of a good calibrator and the different steps to choose a suitable VLTI calibrator are explained in the following sections.

3.1 Calibrators: In theory

There are several theoretical rules to choose a calibrator:

- The calibrator is a point source, the theoretical Visibility is unity at the observing baseline. The Transfer Function of the instrument is given by:

$$TF = \frac{V^2_{meas}}{1} \tag{1}$$

  where V^2_{meas} is the Visibility squared observed on the calibrator and 1 is unity (theoritical Visibility of a point source).
- The calibrator is bright in the observing wavelengths.
- The calibrator does not present spectral features at the observing wavelengths (the Visibility is the same for each spectral channel).
- The pair science object-calibrator is close on the sky, both the science object and the calibrator go through the same atmosphere.
- Both measurements are taken at the same time. There is no variation of the system (atmosphere and instrument).

- The spectral type of the calibrator should be as close as possible from the spectral type of the science object, the response of the instrument (detector and optics) is the same for the science object and the calibrator.
- The instrument setup is identical.

3.2 Calibrators: In practice

In the real world, none of the conditions described above can be fulfilled at the same time.

- first condition: bright point source
  Unfortunately, the point source like objects are far so are not the brightest objects in the sky. We need either to relax the constraint on the size of the calibrator (not a point-like source) or to relax the constraint on the brightness. The solution is to take a calibrator brighter than the science object, a single object (no multiplicity), simple (for example comparable to an uniform disk), with a known diameter associated with a high accuracy, non variable, without infrared excess.
  Bright objects can be extracted from catalogs, but the multiplicity, variability and the infrared excess are not always known. It is frequent that the multiplicity and the infrared excess are measured by the interferometer. The diameter is obtained either from existing measurements or from modelling.
  The Transfer Function of the instrument is now:
  $$TF = \frac{V^2_{meas}}{V^2_{theor}} \tag{2}$$
  with V^2_{theor} the theoretical Visibility squared expected for the observation in the absence of turbulence and instrumental effects and V^2_{meas} as described in equation 1.
- Conditions: same spectral type than the science object and no spectral features.
  In this case the magnitude of the calibrator and of the science object will be comparable which is not compatible with the fact that the calibrator needs to be brighter than the science object.
  Furthermore if the calibrator is of the same spectral type it is possible that it will presents some spectral features. This condition has to be relaxed as well.
- Condition: close on the sky.
  The sky coverage of bright, non-multiple, simple objects with a known diameter is rather limited. The calibrator will be chosen as close as possible from the science object.
- Last condition: same instrument setup and characteristics.
  The setup should be the same for the observation of the science and cali-

brator objects and the instrument should be stable.
When it is difficult to insure a perfect stability of the instrument, it is possible to monitor its pricipal characteristics to detect any changes.

4 Choosing VLTI calibrators

4.1 VLTI characteristics

The VLTI has some specific characteristics. The baselines range from a few to hundreds of meters at different projection angles. The position of the telescope stations is shown in figure 2

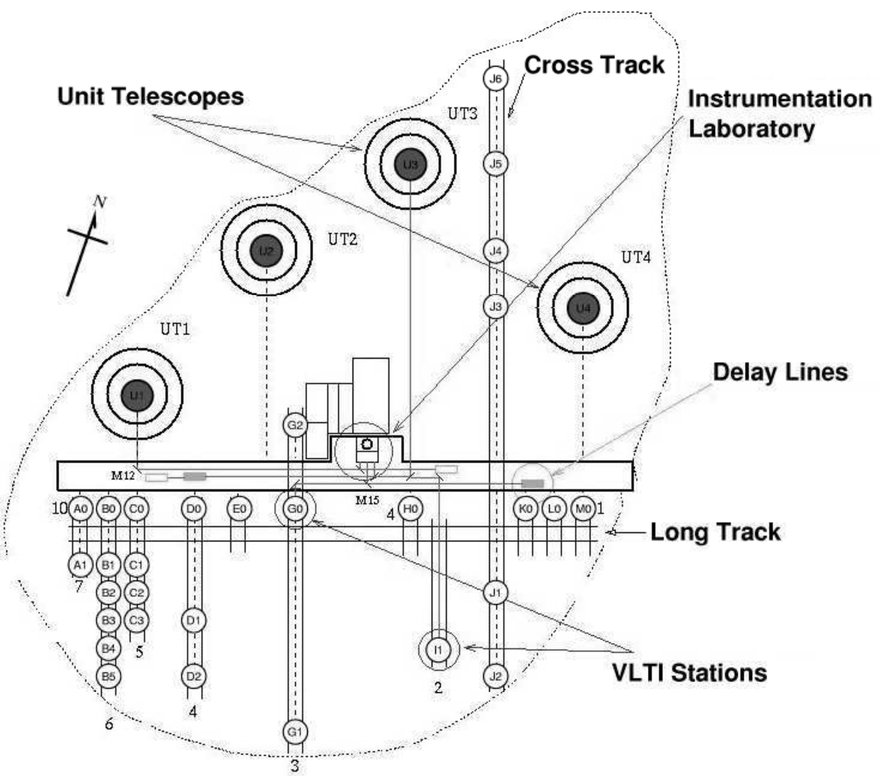

Fig. 2. Position of the UTs and of the different ATs stations. The UTs baselines range from 46 to 130m while the length of the ATs baselines varies from 8 to 200m. For the Service Mode observations, the number of offered baselines is restricted. For example from April 2007 to October 2008, all the UTs baselines and ATs baselines from 16m to 128m are offered.

The calibrator object which will be used to calibrate the science observation has to be selected by the Principal Investigator (PI). For VLTI, the pair calibrator-science will be observed under certain conditions and they both have to follow some constraints. Some of these contraints are linked to the observing conditions (sky transparency, seeing or moon constraints), others are directly related to the VLTI instruments.
One of these limitations is the pointing restriction. Because of the important number of baseline combinations, one should be careful when using some of the ATs stations to avoid shadowing with the UTs. There is also a pointing restriction due to the delay lines (the maximum delay line path difference is +105.000 or -105.000m). An example is shown on figure 3. This information is provided to the user by the ESO tools.
To insure that the science object will be observed at the desired projected

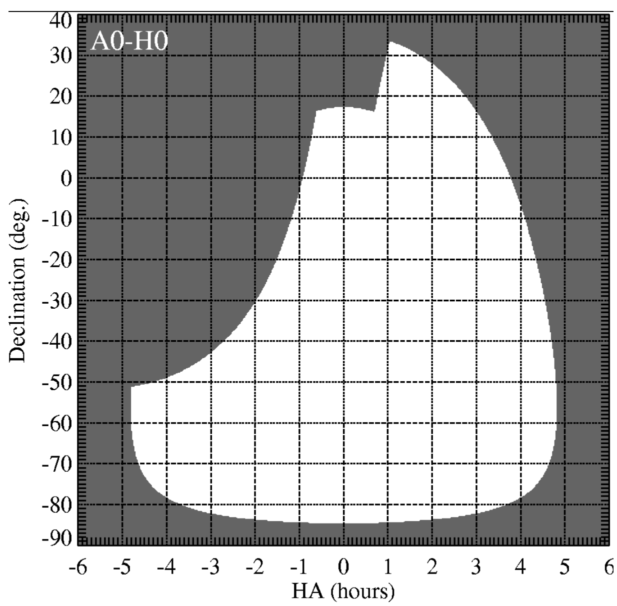

Fig. 3. Because of the position of the stations and the delay lines, there are some pointing restrictions when using some specific baselines. The example is shown here for the baseline A0-H0 (96m)

length and azimuth angle of the baseline, ESO imposes constraints on the Local Sideral Time. A LST range has to be selected by the user for the science object. To insure that the calibrator is observed close in time, its LST range must reach from 30 minutes before the start of the LST range to 30 minutes after the end of the LST range of the corresponding science OB.

ESO offers two different tools for interferometry: VisCalc and CalVin available from the ESO ETC (exposure time calculators) page:
http : //www.eso.org/observing/etc
These tools are both available in the normal version and the expert version. The normal version has pre-selected inputs depending on the Service Mode (SM) observations at the time of the preparation of the observation. For example in the normal mode, only specific baseline configurations can be selected, they are the ones offered for SM. Using the expert mode, additional VLTI instruments (such as VINCI) and configurations are available. It is also possible to select an abitrary Location for the observation site, to select calibrators to observe on another interferometer. One should be carefull in using this option, the static list of calibrators contains object only visible from Paranal. The expert version is accessible through the normal page using the links "CalVin-expert" or "VisCalcexpert"

4.3.1 Preparing the scientific observation: VisCalc

VisCalc is the VLTI Visibility Calculator. It should be used to estimate the feasibility of the observation. The inputs are the astrophysical characteristics of the science object (coordinates, spectrum and geometry) and the observation setup (instrument, observation filter and baseline configuration). The output gives informations on the pointing restrictions (shadowing, optical path differences (OPD)), on the observation (time window, target altitude, airmass, UV tracks, projected baseline length), on some of the sub-systems performances (such as the visibility at FINITO wavelength: 1640 nm) and on the expected results (visibility estimated with the parameters given by the user, loss of correlated magnitude). One of the output plots is given in figure 4.

4.3.2 Selection of the calibrators: CalVin

The second tool offered by ESO is CalVin, the VLTI Calibrator Selector. This tool is used to choose suitable calibrators for the science objects. It is based on a static list of calibrators.

- History:
  For VINCI, suitable calibrators have been selected by ESO based on the CHARM and CHARM2 catalogs (see Richichi (2004)). These catalogs present a compilation of existing measurements in Long Baseline Interferometry.
  For MIDI, suitable calibrators have been selected by the MIDI consortium

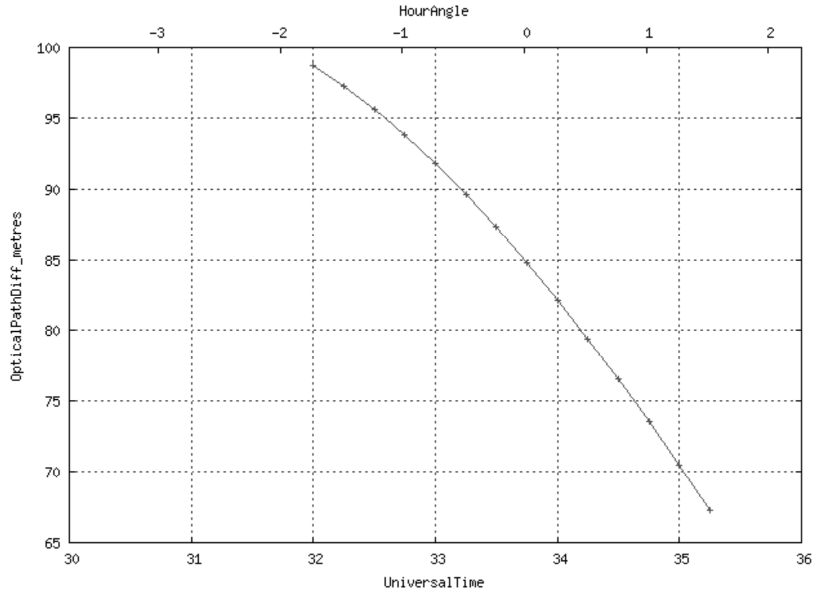

Fig. 4. One of the VisCalc plot: the OPD for the given observation. In this case the requested observing time was 8hours, because of the restriction due to the Delay Lines, the observation was shortened to around 3 hours

and ESO
(see *http : //www.eso.org/ arichich/download/vlticalibs−ws/lists/index.html*).
The first selection was based on Cohen stars (see Cohen (1999)), and objects selected from infrared data (IRAS and MSX) according to specific criteria (brighter than 5Jy in N band, absence of circumstellar matter emitting in the Mid-IR). The list was then filtered to keep only potential calibrators as specified in section 3.1. The diameters of the selected objects were estimated from the available photometry using model fitting. The result is a list of more than 400 objects. This list was further restricted based on accuracy.
The AMBER calibrators are part of the Mérand-Bordé Catalog described in Borde (2002) and Merand (2005). The objects are also selected from the list by Cohen Cohen (1999). Angular limb-darkened and uniform disk diameters are provided by the authors in the J, H or K bands.
Working on a static list limits the sky coverage but it is also easier to monitor them and detect "bad" calibrators.

- Input parameters:
  Once the science object is defined, the user must find at least one suitable calibrator. The first CalVin page allows the user to enter different input parameters:
  – Instrument: either MIDI N Band or AMBER J, H and K Band
  – Target definition: Coordinates and estimated diameter of the target
  – Observation Setup: Date, Start, timespan and Baseline configuration.

The second page is an intermediate page where the setup is summarized and where additional search filter criteria can be entered. This is shown in figure 5. The filtering can be done by specifying an angular distance between the science object and the calibrator, a range of magnitude, spectral type and luminosity class. The user can also specify the value for the quality flag attached to the calibrator. In most of the cases, a quality flag of 1 means that the calibrator has not been found multiple, variable and that the photometry and the diameter is known with a certain accuracy. The quality 2 objects could be variable within a certain range or the accuracy on the photometry and the diameter is less accurate.

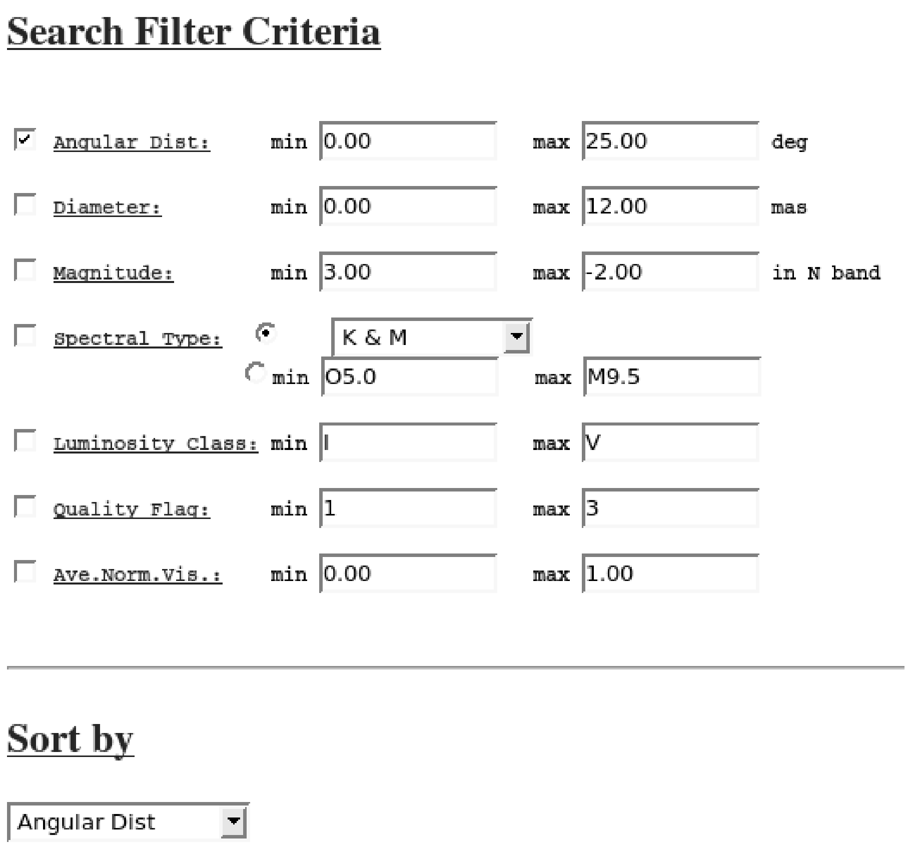

Fig. 5. On CalVin intermediate page, the user can specify some search criteria.

- Choosing the best calibrators:
  The last page shows the results obtained for the specified science target (RA 7h00m00s, DEC -16d42m58.00s and estimated diameter 6mas) with the search criteria from the intermediate page.

9 calibrators found

ASCII file format - the first column is the universal time

Comparative graphs for *Target* vs. 7 calibrators:- Finito Normalised Visibilities Normalised Visibilities Loss of Correlated Magnitudes Target Altitudes Shadow

No.	Name	R.A. (h,m,s)	Dec. (d,m,s)	Ang. Dist. (deg°)	Ang. Diam. (mas)	Mag_N	Spec. Type	Lum. Class	Qual. Flag	Normalized Visibility ave ± err range	Loss of Correlated Magnitude ave ± err range	Normalized Visibility *FINITO* ave ± err range	RiseTime SetTime Duration	Culmination MaxAltitude	Shadowing
1 (0)	*Target*	6 45 8.90	-16 42 58.00	0.0	6.00 ± 0.00					0.91 ± 0.000 0.90-0.94 graph ascii	0.21 ± -0.00 0.24-0.13 graph ascii	0.12 ± 0.000 0.07-0.13 graph ascii	23.75UT 34.00UT 10.25hrs	28.75 UT max = 81° graph ascii	max = 0% graph ascii
2 (272)	hd48915 simbad	6 45 8.92	-16 42 58.00	0.0	6.06 ± 0.13	-1.23	A1	V	1	0.91 ± 0.004 0.89-0.94 graph ascii	0.21 ± 0.01 0.25-0.13 graph ascii	0.12 ± 0.003 0.08-0.13 graph ascii	23.75UT 34.00UT 10.25hrs	28.75 UT max = 81° graph ascii	max = 0% graph ascii
3 (274)	hd50778 simbad	6 54 11.40	-12 2 19.10	5.2	3.95 ± 0.22	0.67	K4III	III	1	0.96 ± 0.004 0.95-0.97 graph ascii	0.09 ± 0.01 0.10-0.07 graph ascii	0.08 ± 0.045 0.02-0.23 graph ascii	23.75UT 34.00UT 10.25hrs	28.75 UT max = 77° graph ascii	max = 0% graph ascii
4 (277)	hd61935 simbad	7 41 14.83	- 9 33 4.10	15.4	2.26 ± 0.12	1.64	G9III	III	2	0.99 ± 0.001 0.98-0.99 graph ascii	0.03 ± 0.00 0.03-0.03 graph ascii	0.58 ± 0.037 0.52-0.63 graph ascii	24.50UT 34.00UT 9.50hrs	29.50 UT max = 74° graph ascii	max = 0% graph ascii
5 (288)	hd36079 simbad	5 28 14.72	-20 45 34.00	18.6	2.97 ± 0.16	0.90	G5II	II	2	0.98 ± 0.002 0.97-0.99 graph ascii	0.05 ± 0.01 0.06-0.03 graph ascii	0.35 ± 0.049 0.28-0.58 graph ascii	23.75UT 32.75UT 9.00hrs	27.25 UT max = 85° graph ascii	max = 0% graph ascii
6 (287)	hd35536 simbad	5 25 1.74	-10 19 44.00	20.5	2.16 ± 0.12	1.95	K5III	III	2	0.99 ± 0.001 0.99-0.99 graph ascii	0.03 ± 0.00 0.03-0.02 graph ascii	0.60 ± 0.037 0.56-0.69 graph ascii	23.75UT 32.50UT 8.75hrs	27.25 UT max = 75° graph ascii	max = 0% graph ascii
7 (286)	hd35369 simbad	5 23 56.83	- 7 48 29.00	21.7	1.88 ± 0.09	1.95	G8III	III	2	0.99 ± 0.001 0.99-0.99 graph ascii	0.02 ± 0.00 0.02-0.02 graph ascii	0.69 ± 0.026 0.65-0.74 graph ascii	23.75UT 32.25UT 8.50hrs	27.25 UT max = 73° graph ascii	max = 0% graph ascii

Fig. 6. On the result page of CalVin, potential calibrators are identified. The user must choose the best object following the VLTI constraints and the criteria as described in section 3.1.

In this case the instrument was MIDI, the calibrators are extracted from the MIDI list (see section 4.3.2). In the example shown here (see figure 6), nine potential calibrators have been found. The best calibrator will have to be chosen following the different VLTI constraints and making some compromises on the selection of the best calibrator. First constraint, as specified in 4.2, the LST range of the calibrator has to be within half an hour of the LST of the science object. For example, if the RA coordinate of the science target is 7h00m and the user wants to observe between HA -1 to +1, the requested LST range will be from 6 to 8, the LST range of the calibrator must be from 5h30 to 8h30. To observe the calibrator with HA between -1 and 1 with the specified LST range (5h30-8h30), its RA should be between 6h30 and 7h30. In this case only the first 2 calibrators are suitable for this constraint.

Of these 2 calibrators, none of them have shadowing (last column). The calibrator hd48915 has a diameter of 6.06mas which is comparable with the estimated size of the target (set to 6mas), the theoretical visibility of the calibrator will be in this case comparable with the expected visibility of the science object. This calibrator is not the best choice. The object hd50778 is fainter than the previous (non-suitable) object but the user should choose this one.

5 Conclusion

The different steps to select VLTI calibrators with the ESO tools have been shown here. The selection of the best calibrator is often a compromise between the best one in theory and one more suitable for the given observation.

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