Getting ready for high accuracy measurements: The VLTI Calibrators Program

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ABSTRACT

The VLTI Calibrators Program is a common project between ESO and NEVEC. The main goal is to establish a network of measurements of calibrator objects with an accuracy high enough to fully exploit the different VLTI instruments. We started this project in 2001 by defining a list of objects to be used during the observations with the commissioning instrument VINCI. During the first year of observation (18th March 2001-18th March 2002), a total of 5060 observations have been recorded on 156 astronomical objects. More than 60% of the observations have been done on 63 calibrator objects. These calibrator data are currently analyzed to refine the measurements of the adopted diameters. After a brief description of the instrument and of the data reduction process, we describe the criteria used to establish a list of calibrators suitable for the commissioning instrument VINCI with baselines of up to 200m. We define a strategy to observe and analyze the data for the commissioning of the VLTI and of several baselines. We emphasize the difficulties of instrumental calibration to an accuracy of a few 0.1% and the necessity of a long term effort.

Keywords: VLTI, commissioning, high accuracy measurements, astronomical calibrators.

1. Introduction

Because of the emergence of several long-baseline, large-aperture ground-based interferometers such as the Very Large Telescope Interferometer VLTI [(8)], the Keck Telescope (KI) [(5)] or the CHARA array [(11)], the accuracy of the instrumental calibration is emerging as a pressing problem. The range of sensitivities and the high quality measurements available with the new instruments requires establishing a new set of good quality calibration sources.

The problem of calibration is well-known, but until now each interferometric facility uses its own list of calibrators. Efforts are being done to create and distribute lists of suitable calibrators. Richichi & Percheron [(10)] compiled a Catalog of High Angular Resolution Measurements (CHARM), which could be used as a starting point to built such a network. More recently, Bordé et al [(3)] refined the list of Cohen objects [(4)], giving criteria for the selection of calibrators for modern interferometers. But in the case of the VLTI, which is located in the southern hemisphere, only a limited number of measurements are available, and a program to create a list of calibrators with good quality measurements is essential.

2. Description of the VLTI

The VLTI is located on Cerro Paranal (Chile), at the site of the VLT observatory [(8)]. In the future, around 250 independent baselines will be available using the four 8.2 meters Unitary Telescopes (UT) and a number of Auxiliary Telescopes (AT), telescopes designed especially for interferometry. These telescopes will be positioned over an array of 30 stations. The baselines will range from 8m to 205m with different orientations.

For the first phase, the commissioning instrument VINCI [(12)] uses two dedicated 0.4m Siderostats (SID). The combination of two of the Unitary Telescopes (UT) was also achieved at the end of 2001. A number of instruments and subsystems will become available on the VLTI in close sequence. More details about the VLTI, its instruments and sub-systems can be found in these proceedings.

2.1. VINCI Data Acquisition and Data Analysis

The VINCI Data Flow System [1] is based on the standard VLT architecture. It oversees all the steps necessary for an observation: from the initial observation proposal phase through the acquisition, archiving and processing of the data. The preparation of the observation includes: the selection of the target and of its associated calibrators, and the modeling of the observation. Several tools are available for this phase: the VLTI visibility calculator and a tool for the selection of the VLTI calibrators, which will be made public in a near future. The observations are then organized in a schedule to optimize the time spent in the data acquisition.

The VLTI Data Flow System at Paranal handles the data acquisition, processing and archiving: the observation is done using a system of templates and Observing Blocks (OB) equivalent to those used during VLT observations, each OB includes the target acquisition, fringe finding and the acquisition of the fringes. Typically, one OB includes between 300 and 500 interferograms. The data produced by the instrument are transferred to different workstations for on-line processing, archiving and off-line analysis. The pipeline software runs the on-line analysis, displays the data and creates different sets of files (FITS files and Quality Control operational files). Data quantities characterizing the instrument and the observation are measured by the on-line processing and logged in a Quality Control operational files (QC log files).

2.2. Data Analysis for the Calibrators Program

The format and the contents of the QC log files generated by the VINCI/VLTI Data Flow System and used by the VLTI Calibrators Program, have been defined to allow a quick overview of the quality of the data and of the measurements. For this purpose, several types of data are logged: the observational parameters (name of the file, date and time of the observation …), the instrument configuration (instrument mode, telescope stations, bandwidth filter, fringe rate, number of scans recorded and processed, baseline parameters), the object name and coordinates and its associated calibrator. The main results of the on-line processing are also recorded: the squared coherence factors (μ_1^2, μ_2^2) and their variances, the SNR for the photometric channels. When a calibrator is observed, the instrumental Transfer function is estimated. In the case of a scientific target, a calibrated visibility is calculated using the last instrumental Transfer Function. More sophisticated algorithms for the estimation of the Transfer Function and the calculation of the calibrated visibility are studied and will be implemented in future versions of the pipeline. The data listed above are automatically extracted from the QC log files and compiled in a Microsoft Excel Database (the VLTI full Database), which is updated regularly. The VLTI Calibrators database is extracted from the VLTI Database. The use of Excel permits to sort and filter the entries, to include tools for the analysis and to display data.

In our current version, the theoretical visibility and error of each calibrator is calculated using the diameter and error extracted from the official VLTI list of calibrators, and the computed baseline. The instantaneous instrumental Transfer Function is also evaluated using:

$$\textit{Instrumental Transfer Function} = \textit{measured Visibility} / \textit{theoretical Visibility}$$

With: $\textit{Theoretical Visibility} = 2J_1(x)/x$ and $x = \pi B \theta_{UD} / \lambda$

Where B is the interferometric baseline projected on the sky, θ_{UD} the stellar diameter (using an Uniform Disk model), λ the wavelength of observation.

3. The VLTI Calibrators Program

The goal of the ESO/NEVEC VLTI Calibrators project is to provide to the different VLTI instruments a database of suitable calibrators known with an accuracy better than the intrinsic accuracy of the interferometer (currently at the level of 0.1%). To select the preliminary list of potential calibrators, we extracted from the CHARM Catalogue [10] and from several lists of calibrators, more than 110 potential sources. Sixty three of these objects have already been observed.

Until now, the data on the calibrators have been used to understand the instrumental fluctuations on different time scales. Once the fluctuations of the instrument and their causes are better known, we will re-analyze the data with modified algorithms to provide the future VLTI users with a refined list of calibrators with more accurate measurements. The list of calibrators will also be extended to include calibrators suitable to the future VLTI instruments (MIDI, AMBER …), and to longer baselines. As with the preliminary list, a strategy of observation of these calibrators will be followed for future updates of the list.

To help during the proposal preparation, a tool for the selection of calibrators will be made available to the community.

4. VLTI: The first year of observations

The first VLTI instrument, VINCI, developed by the Paris Observatory and ESO, achieved first fringes with the Siderostats middle of March 2001 on a 16m baseline [6]. Beginning of February 2002, the position of the siderostats was changed to commission the stations E0 and G1 (66m baseline). Another milestone has been achieved with the recombination of the beam of two of the UT [7].

The statistics on the first year of observations with the VLTI are presented in the following tables (Table 1, Table 2). Some nights dedicated to technical tests are not taken into account here. In the Table 2, only the Observing Blocks recorded on the astronomical targets are mentioned.

Baseline	**Beginning of the observations**	**Number of nights**	**Number of objects (Calibrators and scientific targets)**	**Number of calibrators**
E0-G0 (16m)	March 2001	170	99	37
E0-G1 (66m)	Feb 2002	34	40	27
U1-U3 (103m)	Nights in Oct, Nov, Dec 2001 and Jan, Feb 2002	12	42	15

Table 1: Statistics on the number of objects observed with each baseline during the first year of observation (18th March 2001-18th March 2002).

Baseline	**Number of nights**	**Number of Observation Blocks (Calibrators and scientific targets)**	**Number of Observation Blocks recorded on calibrators**
E0-G0 (16m)	170	4014	2384
E0-G1 (66m)	34	648	509
U1-U3 (103m)	12	398	199

Table 2: Statistics on the number of Observation Blocks recorded for each baseline during the first year of observation. Each OB contains between 300 and 500 fringe packets (interferograms). One OB represents between 2 to 10 minutes of observation (from the target acquisition to the recording of the interferograms).

4.1. Selection of the potential VLTI calibrators

4.1.1. Definition of a calibrator

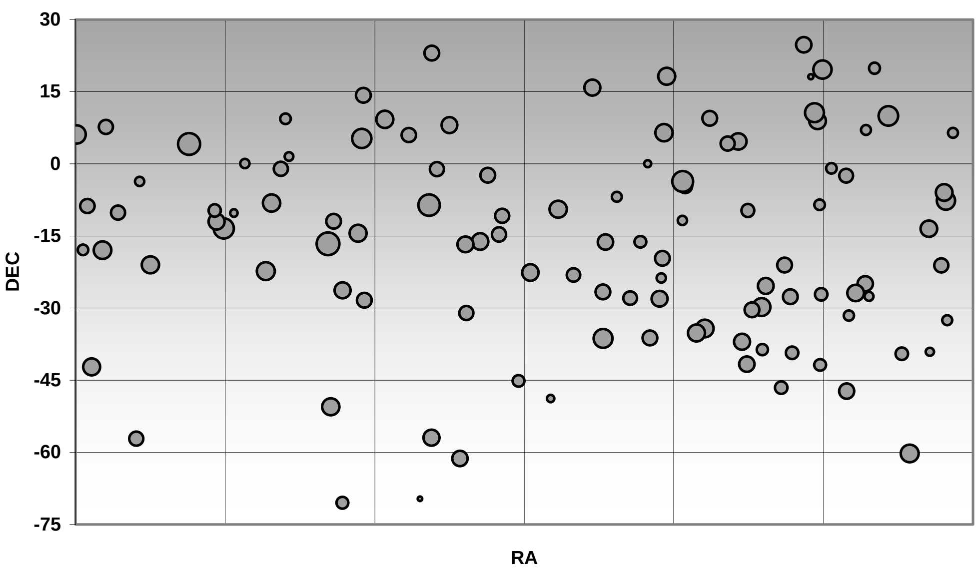
A calibrator is an object with the following characteristics:

- A single source, unresolved at the instrument configuration or with a well known diameter measured at the same wavelength than the instrument,
- The angular distance to the target is small,
- The magnitude is high enough for the instrument,
- The spectral type is comparable to the science target (less strenuous if a dispersive element is used),
- The luminosity class is comparable,
- There is no evidence of Infrared excess and of a compact atmosphere,
- There is no evidence of multiplicity,
- There is no evidence of photometric variability.

4.1.2. Calibrators for the first year of observations with VLTI

Because of the characteristics of the configuration used during the first year (to obtain a good SNR with the Siderostats, we limit the brightness of the calibrators to K<1), we choose to include in the preliminary calibrators list only bright objects which have a known diameter. These diameters are mostly extracted from the CHARM Catalogue [10], and have been measured by direct measurements (Lunar Occultations (LO), Long baseline Interferometry (LBI)) or indirect measurements[4],[2] . The number of these objects being limited, to obtain a better sky coverage we did not strictly limit our choices to non-variable sources (see

Fig. 1). The objects showing no evidence of variability or multiplicity are chosen as primary calibrators, these include



the objects estimated by Cohen [4], the other calibrators are categorized as second and third quality.

Fig. 1: Sky distribution of the calibrators selected for the first year of observation, the size of the dot is proportional to the brightness of the object.

The present list includes 116 potential calibrators. As shown in Fig. 2, around ¾ of the calibrators are brighter than K=1. Data on calibrators fainter than K=2.5 have been acquired during the observing runs with the UT.

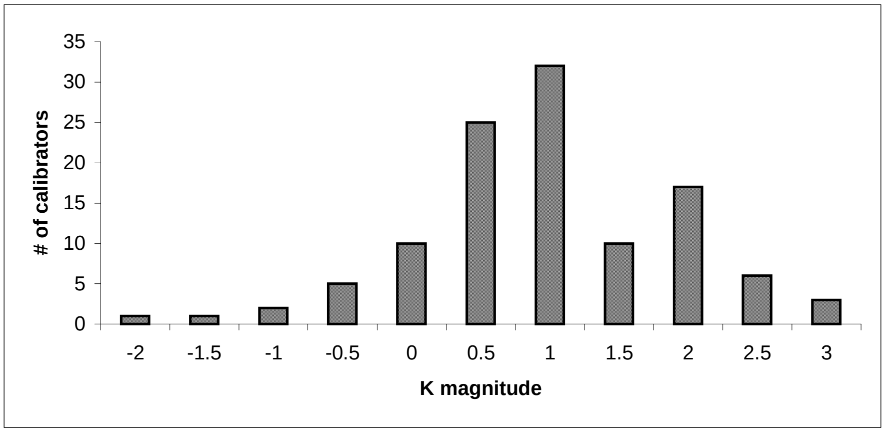


Fig. 2: Brightness distribution of the calibrator objects. Most of the observations have been done in the first year with VINCI associated with the Siderostats, some calibrators of magnitude up to K=2.6 have been observed with the UT.

The angular diameter (Fig. 3) of the selected targets extends from less than 2.5 to more than 10milliarcseconds, with a peak between 2 and 6 milliarcseconds. The smaller ones are studied with the 66m and the UT baselines.

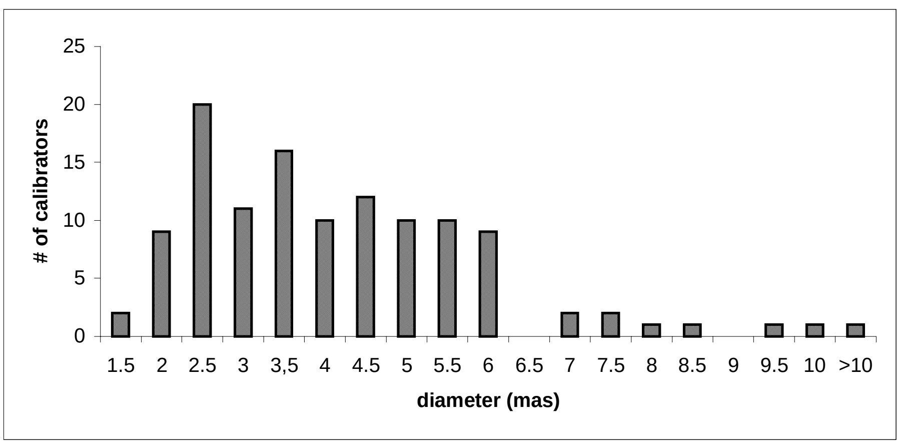


Fig. 3: Repartition of the angular diameters of the calibrator objects.

The goal of the VLTI is to obtain visibility measurements with an accuracy of less than 10^{-3}, this implies that the diameter of the calibrator must be known with an accuracy better than a few tenth of milliarcsecond for a baseline of 100m.

A large number of the diameters in the preliminary list have been measured by the other instruments with an error of a few percents. The Fig. 4. shows, that for long baselines, the error on the theoretical Visibility of the calibrator source is bigger than the internal accuracy of the VLTI, which is routinely measured with VINCI to be around 0.1%.

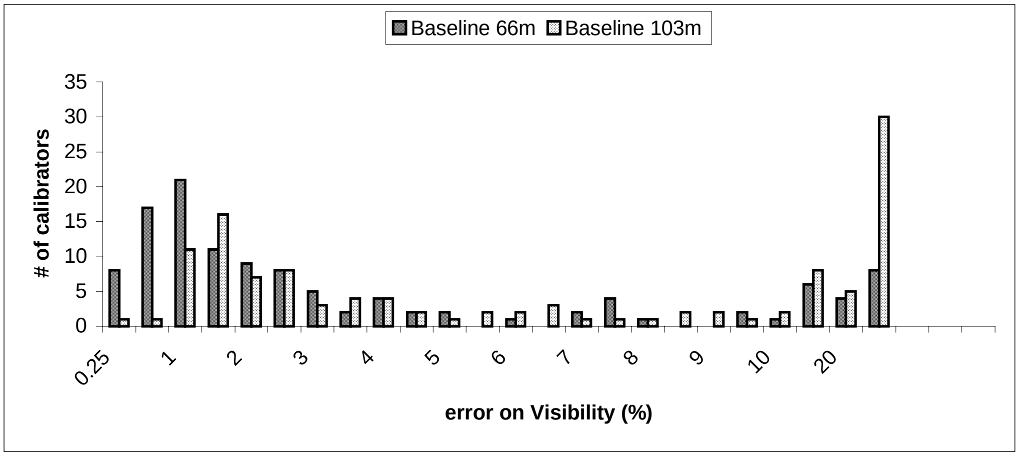


Fig. 4: Accuracy on the Visibility of the calibrators for the E0-G1 (66m) baseline, and the UT1-UT3 (103m) baseline.

This limitation will be overcome by systematically observing the calibrator objects with the VLTI, the accuracy obtained on the measurements will be comparable with the internal stability of the instrument.

Another problem, which will be resolved by dedicated and systematic observations of the calibrators at several baselines, is the value of the adopted diameter itself. As previously stated, the diameters adopted in the preliminary list of calibrators are extracted from the catalogue CHARM. When several measurements were available on the same object, we sometimes use an average of all or some of these measurements, or only one of them. Table 3 shows the example of the object onΨ Virginis, which has been measured several times using different methods and at different wavelengths. The diameter is also estimated using different models (UD and LD diameters).

Method	Wavelength (in µm)	Uniform Disk diameter	Limb darkening diameter
LO	0.63		6.1 +/- 0.3
LO	0.69		6.5 +/- 0.3
LO	1.6	4.92 +/- 0.39	5.11 +/- 0.39
IND (Cohen list)		5.58 +/- 0.2	

Table 3: Measurements extracted from CHARM onΨ Vir. This object was measured by Lunar Occulations and Indirect method. The diameter is also given at different wavelengths and estimated using different models.

In the case of multiple measurements, we adopt in priority an average of the measurements made in the near-infrared in Long Baseline Interferometry. If none of these diameters are available, the COHEN diameter is used. For some objects none of these measurements are available. This was for example the case for α CMa whose diameter has been measured by Hanbury Brown [(9)] with the intensity interferometer. These objects are flagged as secondary or third quality calibrators, even if they fulfill all the criteria for a primary calibrator.

4.2. Calibrator observation and Data Analysis

4.2.1. Strategy

To overcome the limitations described above, a strategy to obtain calibrators data has been defined. Each night, systematic observations of calibrators are done alternatively with the scientific target. In a normal observing mode, these calibrators data are used to estimate the instrumental transfer function to calibrate the visibilities obtained on the scientific objects. For the calibrators program, we use these data to monitor the instrument and understand the fluctuations on different time scales. To better overcome the problems described above, several nights are also dedicated exclusively to calibrators observations. During these nights, data are acquired on at least one primary calibrator and on secondary calibrators. The data on the secondary calibrators are calibrated using the primary calibrators.

4.2.2. Monitoring of the instrument

The systematic observations of calibrators objects during the night is of course important for the calibration of the scientific data, but in our case it also allows us to monitor the instrumental fluctuations. The Fig. 5 shows the Instrumental Transfer Function measured during the first year. The Transfer Functions estimated on one or several calibrators are averaged each night. Each night, the calibrators could be different. As described above, we know that for some objects, the value of the diameter of the calibrator in our preliminary list was wrong for VINCI because averaged using different values measured with different methods or even measurements done at a different wavelength, this explains some of the night to night fluctuations of the Transfer Function.

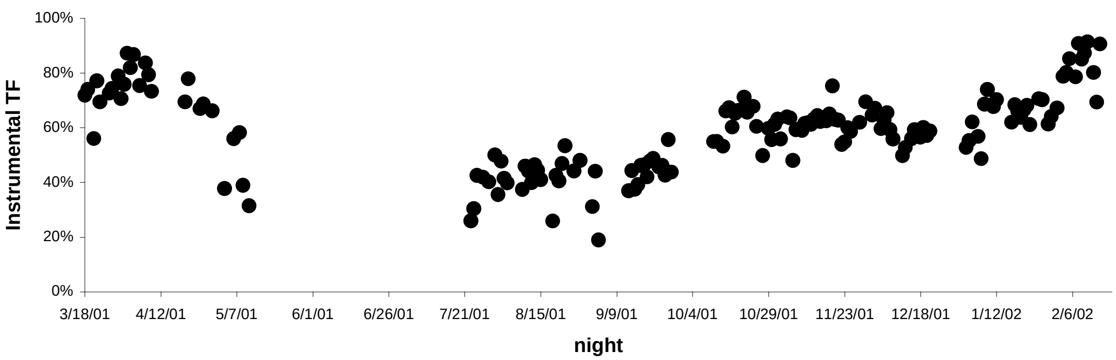


Fig. 5: Instrumental Transfer function obtained during the first year of observations. Each point represents one night. On this figure, only the Instrumental Transfer Functions obtained with the Siderostats is represented. After the beginning of February 2002, the 66m baseline was used.

This figure illustrates the loss of instrumental visibility, which occurred during the summer 2001. The internal visibility dropped from 80% to 40% due to problems with the beam combiner. The problem was solved during the summer and the instrumental visibility reached again the level of 70%. Currently, a new beam combiner based on integrated optics is being tested.

4.2.3. Calibration of the calibrators with the primary calibrators

During the nights dedicated to the observations of calibrators, the instrumental transfer function is first estimated for each observations of a calibrator object. The example of the night of January 22nd, 2002 is shown in Fig. 6 and illustrate clearly that for some of the objects, the adopted diameter is either overestimated or underestimated. The Transfer Function estimated on these objects can vary of up to 20% under the same observing condition, while the internal fluctuations of the instrument during the night are of the order of a few percents. than the fluctuations on the Transfer Function measured for each calibrator. Some of the adopted diameter are either overestimated or underestimated, and will be recalculated. In some cases, it is also possible that the object can not be used as a calibrator because of variability or the presence of interstellar material. These objects will be removed from the calibrator list.

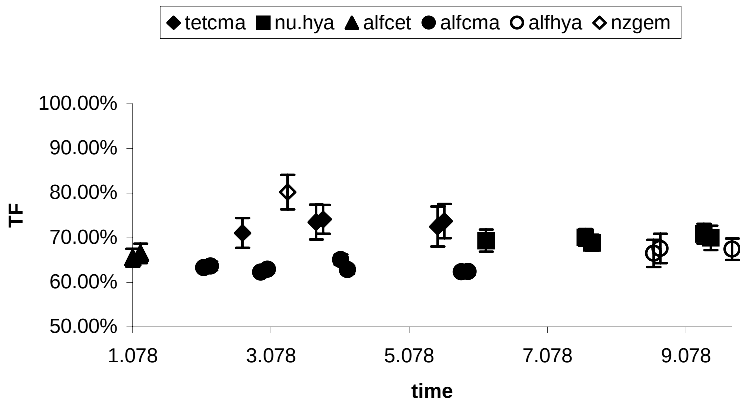


Fig. 6: Instantaneous Instrumental Transfer Function for one of the dedicated nights. As illustrated here, the Transfer Function is stable when studying each calibrator independently, while the fluctuations of the Transfer Function varies by around 20% between 2 calibrators.

The strategy used for the data analysis is to define a set of main primary calibrators. In the present analysis, we use some of the Cohen objects as main primary calibrators. A weighted averaged instrumental Transfer function is estimated to calibrate the visibility obtained on the other calibrator objects observed during the night. In the present analysis, the weight is only function of the time between the observations of the main calibrators. We are studying what are the effects of other parameters on the fluctuations. For example, during the dedicated nights when the coherence time was fluctuating , we can notice important fluctuations of the instantaneous Instrumental Transfer Function. The weight applied to calculate the averaged Transfer Function will also be function of some of the turbulence parameters . The effects of the turbulence on the Transfer Function are currently under study.

Fourteen calibrators have been observed with the 16 and 66m baselines. Using a bootstrapping method, we can further constraint their diameters. The future strategy includes observations of each calibrator object with several baselines.

4.2.4. Future

Until now, only a small number of data has been processed to define and test new methods of analysis. In a near future, the whole set of VLTI calibrators data will be reprocessed using the updated, improved version of the Pipeline software. Together with the estimation of a new set of more accurate diameters, we will also re-investigate the quality of the calibrators. This updated list will be available for the shared-risk observing period, which will start in October 2002.

With the coming on-line in a near future of the next VLTI instruments such as MIDI and AMBER, we will need to compile a new extended set of calibrators data to be used with more baselines, with instruments operating at different wavelengths (J,K,L,N bands) and with different modes (such as high dispersion mode). A tool for the selection of the calibrators associated to a given target will be made available for the preparation of the observation.

4.2.5. The VLTI Calibrators selection tool

Because of the limited number of calibrators in the preliminary list, the selection of the calibrator is done manually by the user during the preparation of the observation. The main selection criterion is the distance calibrator-target. The number of potential calibrators close to the scientific target is often less than 3 objects, the user can easily choose the calibrator object.

In the near future the list of VLTI calibrators will be extended to several hundreds, and we propose to build a tool to select automatically the calibrators associated to a given target to be observed with a VLTI instrument. Unlike some of the calibrator selection tools currently tested or built by different teams, which used on-line databases (SIMBAD), the VLTI tool will be stand alone and the calibrators will be extracted from an internal VLTI list updated regularly. A prototype of this tool is currently built and tested. Because of the large number of instrument configurations, the preliminary list is compiled with only the calibrators suitable with the instrument mode. The estimated diameters are calculated on-line depending on the instrument mode parameters. This list could be narrowed down using some criteria such as spectral type and luminosity class, the distance calibrator-target, the size or the brightness of the calibrator. For the non-expert user, typical default values for the observing mode will be proposed for these parameters.

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