Observation Planning Tools for the ESO VLT Interferometer

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ABSTRACT

Now that the Very Large Telescope Interferometer (VLTI) is producing regular scientific observations, the field of optical interferometry has moved from being a specialist niche area into mainstream astronomy. Making such instruments available to the general community involves difficult challenges in modelling, presentation and automation. The planning of each interferometric observation requires calibrator source selection, visibility prediction, signal-to-noise estimation and exposure time calculation. These planning tools require detailed physical models simulating the complete telescope system — including the observed source, atmosphere, array configuration, optics, detector and data processing. Only then can these software utilities provide accurate predictions about instrument performance, robust noise estimation and reliable metrics indicating the anticipated success of an observation. The information must be presented in a clear, intelligible manner, sufficiently abstract to hide the details of telescope technicalities, but still giving the user a degree of control over the system. The Data Flow System group[1] has addressed the needs of the VLTI and, in doing so, has gained some new insights into the planning of observations, and the modelling and simulation of interferometer performance. This paper reports these new techniques, as well as the successes of the Data Flow System group in this area and a summary of what is now offered as standard to VLTI observers.

Keywords: Very Large Telescope Interferometer, observation planning tools, modelling

1. INTRODUCTION

The European Southern Observatory operates the Very Large Telescope (VLT) Observatory on Cerro Paranal (2635 metres altitude) in northern Chile, comprising four 8.2-metre Unit Telescopes (UTs) and numerous smaller telescopes. The VLT also operates in an interferometric mode as the VLT Interferometer (VLTI), which allows the coherent combination of stellar light beams. The light is guided from the UTs via Coudé optical trains into an optical delay-line tunnel. The difference in arrival times of the light from the first telescope with respect to that from the second telescope is compensated by the delay lines so that the beams have effectively zero Optical Path Difference (OPD) at the detector, where the interferometric beam combination takes place. The VLTI is described in more detail in the work of Glindemann, *et al.*.[4]

Currently under construction are four 1.8-metre Auxiliary Telescopes (ATs), the first of which has now achieved "first light".[6] When completed, these will be the main "workhorses" of the VLTI, and will be in constant operation (unlike the UTs, which have their own individual programmes, and will not always be used for VLTI observations).

While the UTs are fixed, the ATs are designed to be relocated to any of a number of "stations", thus permitting a larger range of interferometer-spacings ("baselines") to be obtained. The movable ATs, in conjuction with the fixed UTs offer a range of baselines up to 200 metres.[6]

In addition to the UTs and ATs, which are the intended telescopes for "normal" operation, two 0.4-metre siderostats have also been constructed. These siderostats may be relocated to any of the AT stations and, with their simplicity and stability, serve as commissioning telescopes for the VLTI and its instrumentation.

The VLTI has been designed to be operated like a regular astronomical instrument: that is, detailed technical knowledge is not mandatory. This is a very important development in optical interferometry, as it allows a much wider community of astrophysicists to carry out their own observational experiments.[8] However, it does mean

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that this community must be given the opportunity and ability to plan observations so as to accomplish their data acquisition without loss due to inappropriate observing parameters. Such planning is akin to the "exposure time calculators" which are prevalent on many telescopes. However, the provision of such a tool is not a trivial task.

This paper describes the generation of a model for the calculation of observational-quality parameters, identifying those that are important and those which have negligible effect. It describes how the model may be tuned with regards to different instruments operated on the VLTI and describes how the model compares to existing VLTI data. Additionally, it describes two other tools used for VLTI observation planning.

2. VLTI INSTRUMENTS

There are three instruments which are either operational or currently being commissioned: VINCI, MIDI and AMBER.

VINCI is the VLT INterferometer Commissioning Instrument that operates at 2.2 microns. It was the first VLTI instrument to be installed, and is not offered to the general community, but rather is used for commissioning and testing, due to its relative simplicity and stability. Since first fringes with the 16-metre baselines using the siderostats (17 March, 2001) and 103-metre baselines with the UTs (30 October, 2001), most of the calibration data used in the work described in this paper was acquired using this instrument. The observations were made to assess the compliance of the instruments with the technical specifications as well as to characterise the performance of the facility in its first phase of development. In addition to these more technical tasks, a number of observations are certainly also useful for scientific purposes. In order to fully involve the community in analysing and understanding the data and its scientific and technical implications, ESO has decided to make these data available to the community through the ESO archive.

MIDI is the MID-infrared Instrument, covering the wavelength range 8 to 13 microns and measuring spectrally-dispersed fringes. It allows resolutions (λ/B) of 20 milliarcsec at 10 microns to be achieved. The main scientific objectives include the study of protostars and very young stars, circumstellar discs, brown dwarfs, tori around galactic nuclei, the centre of our own galaxy and the search for exo-planets.

AMBER, the third VLTI instrument, operates in the near-infrared range, between 1 and 2.5 microns, using two or three Unit Telescopes. The instrument has been designed for up to three telescope beams in order to be able to perform imaging using phase closure techniques. It is anticipated that the additional operating wavelength of 0.6 microns will be added at the time the ATs become operational. The main scientific objectives are the investigation, at very high angular resolution, of disks and jets around young stellar objects, and AGN dust tori with a spectral resolution up to 10000.

3. OBSERVATION PLANNING

In order to plan an interferometric observation and to assess its feasibility, one needs adequate tools to model the visibilities for a specified array configuration, taking into account constraints like shadowing effects, the range of the delay lines, etc.. In addition, appropriate calibration stars must be selected. Two specific tools are provided for this purpose: the VLTI Visibility Calculator (VisCalc) and the calibrator selection tool (CalVin).

3.1. VisCalc

VisCalc is a web-based tool that provides calculations of simulated dispersed visibilities based on software models of the VLTI instruments. The declination and spectral energy distribution, as well as the source geometry, are parameters used to specify the observation target.

Visibilities are calculated analytically for uniform discs, Gaussian discs and binaries. Visibilities may also be calculated numerically for a user-provided brightness distribution, which is uploaded as a FITS file. The user-specified observation conditions include the starting hour angle and the duration of the observation, as well as the instrument and array configuration. Different results can be displayed including the *uv*-tracks, the input image and its Fourier transform, plots of visibility versus time, visibility squared versus time, loss of correlated magnitude and the illumination distribution.

Screenshots from a typical VisCalc session are shown in Figure 1.

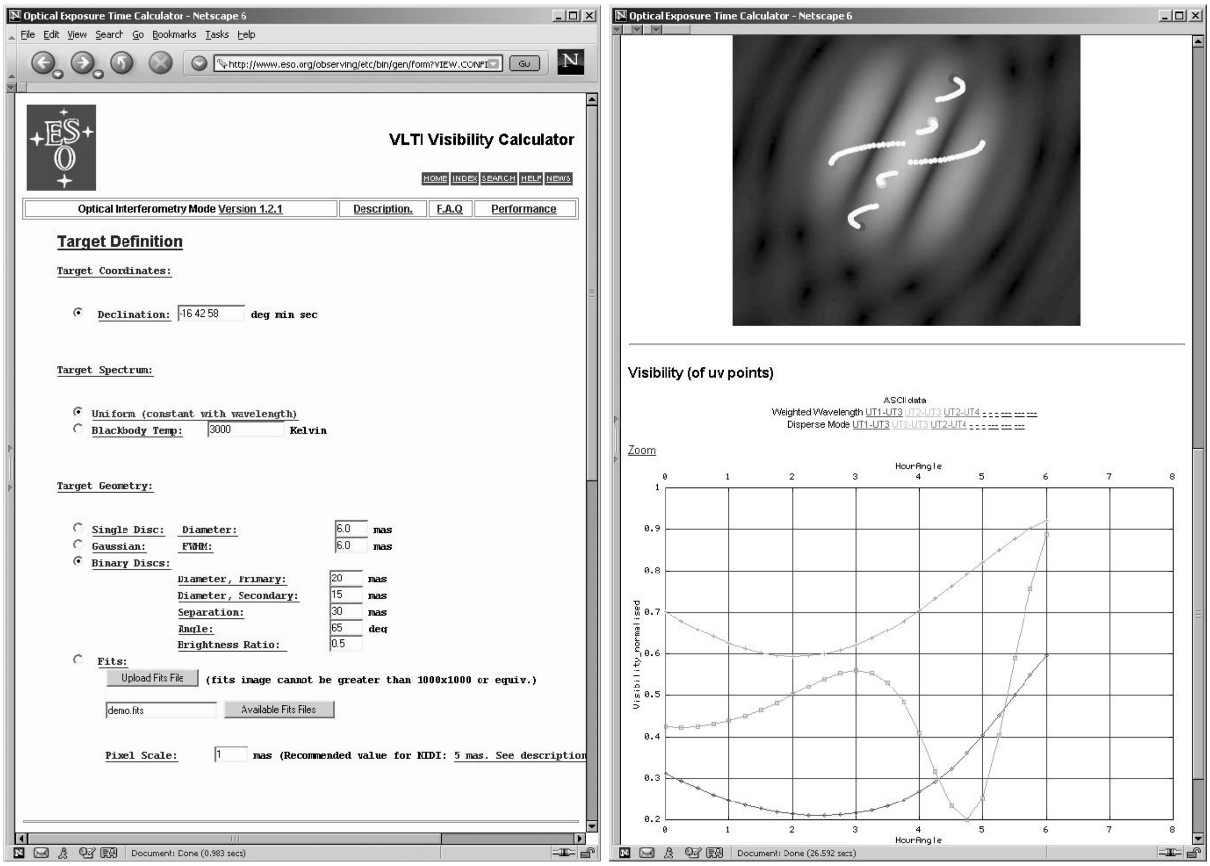

Figure 1. Screenshots from a typical VisCalc session. Part of the input page is shown to the left and part of the output page is shown to the right. The output not only includes tabulated values, but also plots indicating the expected visibilities and the path of the baseline tracks over the *uv*-plane (the Fourier transform of the source model is shown).

3.2. CalVin

The calibrator selection tool (CalVin) is used to find suitable stars that may be used to calibrate the VLTI at the time of the observation. CalVin provides a similar interface to that of VisCalc, but it involves a two-stage selection process. On the first input page, the target coordinates, the array and instrument configurations can be selected. The default search criteria are displayed on an intermediate page which allows the search parameters to be refined.

On the results page, the table of matching calibrators is listed. For all matching calibrators, the visibility and observability information are calculated and displayed. It is then possible to use VisCalc for a more comprehensive calculation of the visibility information.

Screenshots from a typical CalVin session are shown in Figure 2.

Both tools can be accessed from the VLT Exposure Time Calculators page*. The standard version shows only those configurations that are offered for the current Call for Proposals. It is updated for each new Call for Proposals in order to reflect the offered VLTI baseline configurations and instrument modes. An “expert” version, accessible from the ETC preview page†, offers an extended interface with many more choices. It supports the modes and configurations that are currently not offered.

*http://www.eso.org/observing/etc

†http://www.eso.org/observing/etc/preview.html

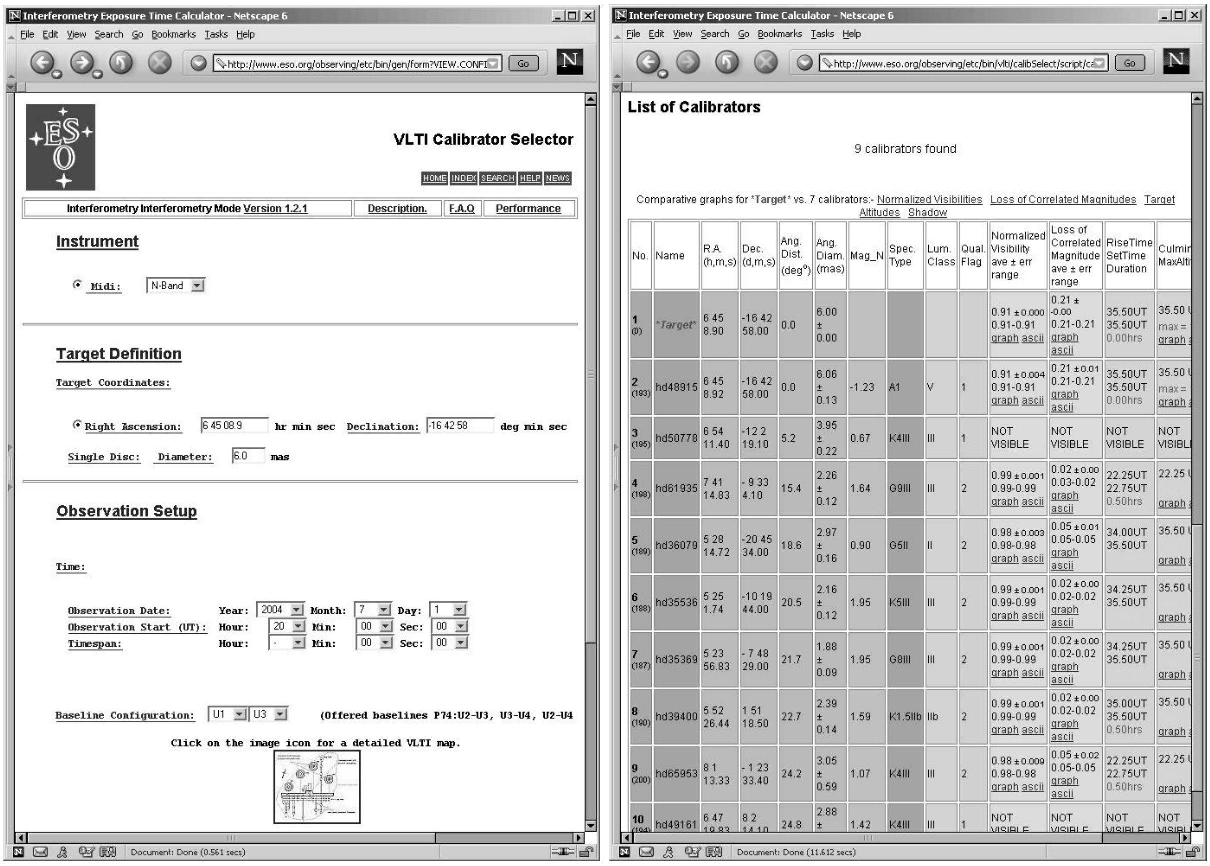

Figure 2. Screenshots from a typical CalVin session are shown, with part of the input page shown on the left and the output on the right. Colour-coding makes the table easier to follow, and links within each of the entries allow the display of tabulated and graphical data.

4. THE PROBLEM OF AN EXPOSURE TIME CALCULATOR

In order to plan astronomical observations, one typically uses some sort of software tool to specify the observing options and expected conditions, to thus predict the observation quality (signal-to-noise ratio, etc.) and anticipate the amount of observing time necessary to achieve the required sensitivity for the scientific target.

While exposure time calculators (ETCs) are a well-established idea, their use in the world of optical interferometry is new. As the VLTI was designed to be run as a standard — rather than specialist — instrument, the provision of such tools is crucial to its integration. Furthermore, the calculations are not straight-forward, and involve modelling the atmosphere, telescopes, delay lines, instrument, detector, non-physical and combined parameters, that cannot be independently measured or calibrated.

Additionally, it is not simply a matter of calculating the total number of photons, but it is also necessary to incorporate the concept of *visibility*.

However, to make things even more complex, it was decided to attempt to derive a generic algorithm. In other words, one that was capable of simulating the expected performance of all three VLTI instruments. The advantage of this is several-fold:

- By modelling the general case, it helps understand the VLTI better.
- It forces individual parameters to be properly explored and understood, rather than just hiding them in "empirical factors" that emulate the performance characteristics.

- There are many parameters that are common to all three instruments, and this work need not be replicated, either in terms of mathematical modelling or by way of additional code.
- A uniform model will be easier to implement as part of a unified tool for predicting VLTI performance.

5. DEFINITIONS

How does one quantify the performance of a telescope (or telescope interferometer) system? This value must be a physical quantity (and not just a Quality Parameter — good, okay, poor, etc.) and must be understandable by astronomers. The value must be such that it can be predicted, but also so that it is able to be translated into a measurable quantity in the final observed data; thus, the quality of the observation can be quickly assessed, and easily compared to the predictions. In the case of conventional imaging and spectroscopy, this is generally characterised by a signal-to-noise ratio. However, this does not suffice for the interferometric results of the VLTI.

The VLTI produces an average of the square of the modulus of the complex coherence factor, which is associated with the baseline and position angle of the interferometer elements with respect to the object being observed. The square of the coherence factor is measured based on photon counts as the mirror mounted on the piezo translator of the VLTI sweeps back and forth through the fringe.

The VINCI instrument generates four time-sequence signals — two photometric and two interferometric — the latter of which are used to derive the square of the coherence factor, μ^2. Each observation is actually made up of many scans of the fringe, typically 500, and so a series of μ^2 values are determined. Based on the photometric signals, only high-quality measurements are accepted by the data reduction pipeline, which are in turn averaged and a variance determined, $\langle \mu^2 \rangle$ and $\langle d\mu^2 \rangle$ respectively. The number of scans, n, that was used for these data, along with the data themselves, are also recorded in the processed data file.

The term *signal-to-noise ratio* is used to refer to the data quality of the photometric channel. The term *precision* is used to convey a measure of the quality of the interferometric data.

$$\text{Precision} = \frac{\sqrt{\langle \mu^2 \rangle + \langle d\mu^2 \rangle \sqrt{n}} - \sqrt{\langle \mu^2 \rangle}}{\sqrt{\langle \mu^2 \rangle N}} \tag{1}$$

where n is the number of measured scans, and N is the number of scans to which the system is normalised.

Note that, initially, all quantities are calculated for a single scan of a given exposure time. However, in reality, the VLTI takes single observations with several hundred scans, which are averaged to create a single measurement. As the exact number of scans is regulated, with rejected scans occurring when low signal-to-noise is detected on the photometry chanels, the exact number of scans will fluctuate according to the conditions.

6. MODELLING

The model that has been developed addresses the five major areas that influence the performance of the VLTI. These are shown in Figure 3.

Of course, with a unified model, it is possible to have a unified simulation utility — a single Exposure Time Calculator (ETC), to compute the expected signal to noise ratio of the selected instrument. Such a utility acts as a planning tool for astronomers, allowing them to test instrument performance against predictions, to explore the available parameter space when devising observations and to assist in planning observations to get the best results for the allocated time.

However, there is a nasty cyclic problem. While astronomers need the ETC to make useful observations, the useful observations are needed to make a realistic model.

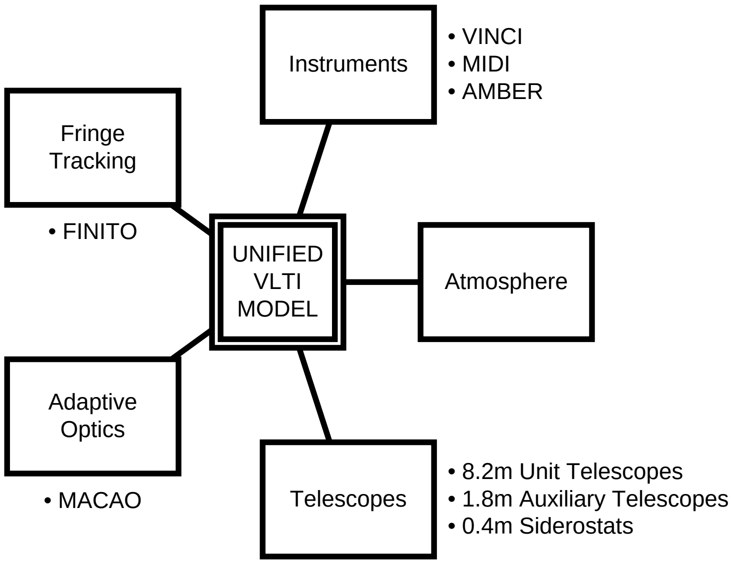

Figure 3. The five major components of the VLTI performance model.

6.1. Developing a model

The model that has been developed uses a subset of the VINCI data archive, collected over the period from March 2001 to November 2002. These data represent 7793 independent measurements. These data are applicable to the AMBER instrument, as well as VINCI. However, modifications to the model were required for MIDI, due to the fact that it has a spectral capability, thus involving channel-based calculations, and that it operates at N-band ($\lambda \sim 10\mu$m).

Initially, the model needs to predict $\langle d\mu^2 \rangle$.

In order to get an accurate prediction of the visibility, one needs an accurate diameter of the astronomical target. Obviously, this is usually not known at the time that the observations are planned.

The model is also dependent on the projected baseline; something that will change not only due to the selection of telescope station positions but also on the topocentric position of the source. As this changes with hour angle, it is not always possible to estimate this parameter at the time of observation planning. Furthermore, observations will typically wish to observe such that a range of visibilities are measured. This will allow the astrophysical quantities to be determined, whether this is the fitting of a stellar disk model or the ascertaining of binary system parameters.

Therefore it is necessary, in the presentation of results to users, to indicate model results over the range of possible visibilities. That is, the visibility (or, alternatively, the measured coherence factor $\langle \mu^2 \rangle$) is maintained as a free parameter and the results are presented as a function of this, or the source-independent quantity *correlated magnitude*, m_c, which is defined as:

$$m_c = -2.5 \log(\mu^2 10^{-\frac{m}{2.5}}) \quad (2)$$

where μ is the coherence factor and m is the photometric magnitude.

However, development of the model to match the existing data has proved problematic. In addition to the data generally being noisy, the instruments are still being commissioned, and the data were interspersed with the remnants of acquisition problems and poor hardware setup and conditions.

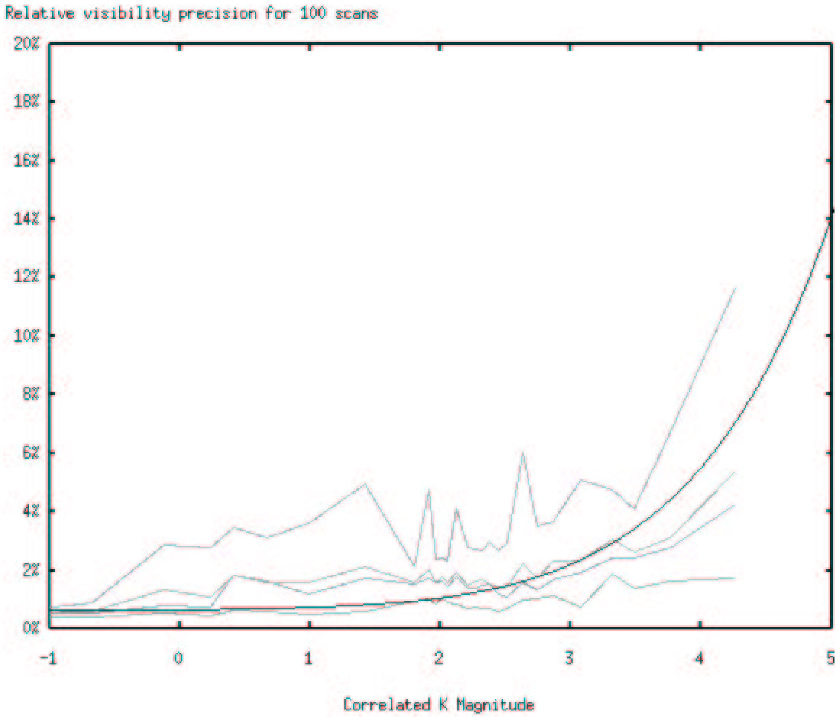

Figure 4. Predicted and measured visibilities of the VINCI instrument, using the 0.4-metre siderostats. The grey lines indicate the actual data, binned in groups of 100 measurements according to correlated magnitude. From top to bottom, the worst 10%, mean, median and best 10% of the measurements, within each bin, are shown. In total, 7793 measurements were used to compile these data, encompassing observations between 19 March 2001 and 24 November 2002.

7. UNIFIED MODEL

The unified model devised is ultimately driven by four effects:

- The loss of fringe contrast due to the atmosphere (this is what is commonly referred to as the piston noise). This source of noise dominates the noise of bright sources.
- The photometry (both in terms of the system transmission as well as the actual object brightness). This dominates the noise observed for faint sources.
- The thermal background and read-out electronics.
- The loss of fringe contrast due to the complete telescope system.

This model was implemented and used to calculate performance predictions for the VINCI instrument. The results are shown in Figure 4.

From the investigations and modelling it became apparent that interferometry presents a new layer of complications over conventional "photon counting" observation predictions. While these "normal" exposure time calculators deal with noise in a linear fashion, the existence of interferometric data within the Fourier domain means that the traditional calculations break down, and that the combination of visibility (due to variations in the projected baseline length, in combination with the normal variations in brightness between sources) make direct comparisons difficult.

From the analysis it is clear that the primary trade-off in setting the exposure time of an observation, is that between the piston noise and the photometric signal-to-noise ratio. Obviously an increase in the exposure

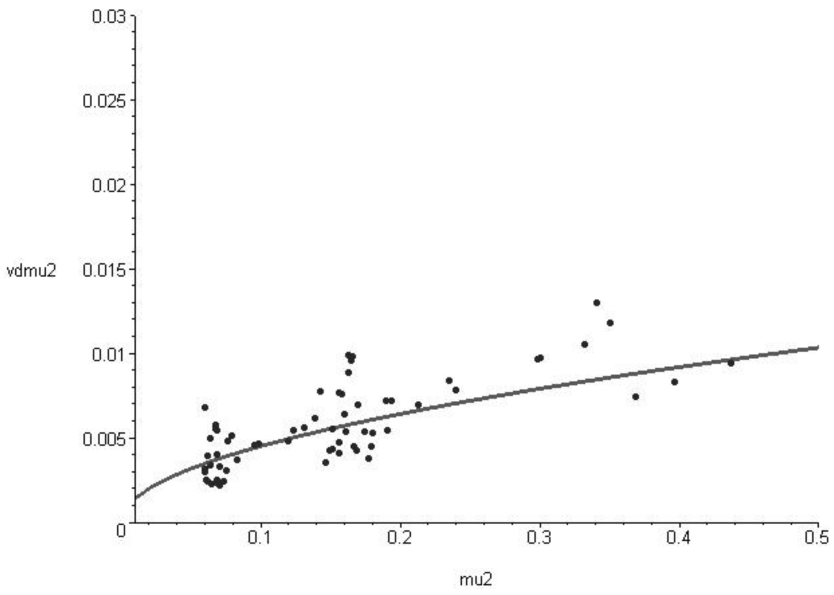

Figure 5. Observations of the star α Psa (20 October, 2002). The points indicate the measured data, and the line is the values predicted by the model.

time will result in improved photometric statistics, but this also means that the longitudinal phase noise due to the atmosphere will "blur out" any fringes. Conversely, the reduction of the exposure time will effectively "freeze" the fringes, which are combined in the Fourier domain where the phase (piston) noise will no longer contribute. However, there is inevitably a point where the degradation in signal-to-noise of the photometry curbs this selection.

As can be seen, there is a large variation in the best and worst results for any given correlated magnitude. However, the prediction closely matches the median result.

We note that the detector noise contributes to, but doesn't dominate, the VINCI data at any given magnitude/visibility regime. However, for fainter sources (or those observed which result in low values of the visibility), the detector noise is a significant fraction of the overall noise component.

There is a point when the detector noise becomes dominant, but this occurs only at such faint magnitudes that the existing data-reduction software of the VLTI instruments rejects such data as being of no worth long before this theoretical point is reached. That is why, within the current model and observing parameter space, there are only references to the piston-noise and photon-noise dominated scenarios.

The two main sources of noise at the detector level are the readout noise on the detector and the detected background. The latter is not strictly a detector noise as such, but it represents the linear combination of the sky background, the instrument emission and the intrinsic thermal noise from the detector itself. These are difficult to segregate, and so were modelled together.

Additionally, a study of a single observation under good conditions was performed in order to verify parts of the model. The objective here was to remove the ambiguity of non-uniform calibration, which occurs with data from multiple nights; different hardware configuration and calibration can cause major shifts in the system performance, which are difficult to factor into any model.

The data chosen were from a single star α Psa, observed on 20 October, 2002.[3] Good hour-angle coverage provided a large range of baselines and, subsequently a large range of μ^2.

The results are shown in Figure 5.

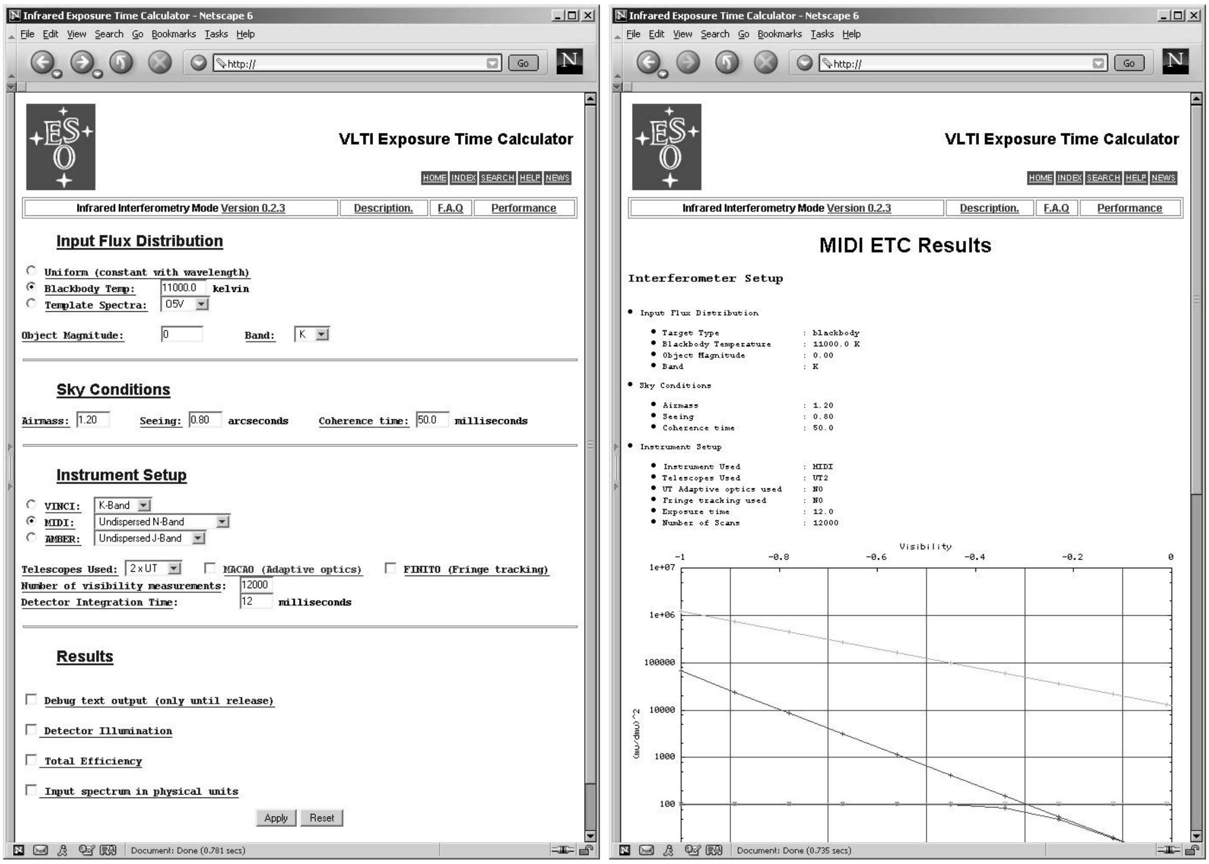

Figure 6. The input and output pages of the prototype VLTI Exposure Time Calculator.

7.1. MIDI and AMBER

We currently have insufficient data to make a reliable study on MIDI. At the time of writing, MIDI integration continues, and it is hoped that a larger database of reliable measurements may be acquired as the instrument stabilises and operations become routine.

As the AMBER system has not yet been commissioned, integration of its performance into the model may only be derived from the design documentation. However, the provision for supporting this instrument is incorporated into the model, and it is believed that integration of actual performance data should be straight-forward.

8. EXPOSURE TIME CALCULATOR

A prototype exposure time calculator has been developed that uses this model to calculate expected observing performance. Based on the web-interface of existing ESO observation preparation tools, it presents an initial input screen, where users can select the basic parameters of the observation and a results page, which is displayed on submission of the input data. Figure 6 shows a typical session.

The input page allows the specification of the input flux distribution (spectral profile and magnitude), the sky conditions (airmass, seeing and coherence time) and the interferometer configuration (instrument, instrument mode, telescopes, adaptive optics, fringe tracking and exposure/scan-time control).

The output summarises the input data for verification (and association in the case of printing the page) and displays the data as a series of graphs. This is done in preference to tabular or numerical results, as it allows a better appreciation of the limiting factors involved in an observation, and allows the user to quickly assess cut-off points and regions of the parameter space that would be optimal.

9. CONCLUSION

With the development of a unified model, it has been possible to generate a generic algorithm to predict the performance of the VLTI for each of the three instruments: VINCI, MIDI and AMBER. The model caters for different telescopes, adaptive optics, fringe-tracking and atmospheric conditions, in addition to the astronomical characteristics of the object whose observations are being simulated.

A prototype, HTML-based simulator has been developed, which acts as an exposure time calculator for the VLTI. With the acquisition of a larger database of quality measurements, it will be possible to refine the model to generate more accurate results.

Together with a visibility calculator and calibrator selection tool, the ETC will complete a suite of observation preparation tools allows the VLTI to be readily accessed by the astronomical community as a "standard observation" system.

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