A status update of the VLTI control system

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ABSTRACT

In the last two years the Very Large Telescope Interferometer (VLTI) has, on one hand grown with the addition of new subsystems, on the other hand matured with experience from commissioning and operation. Two adaptive optics systems for the 8-m unit telescopes have been fully integrated in the VLTI infrastructure. The first scientific instrument, MIDI, has been commissioned and is now being offered to the community. A second scientific instrument AMBER is currently being commissioned. The performance of the interferometer is being enhanced by the installation of a dedicated fringe sensor, FINITO, and a tip-tilt sensor in the interferometric laboratory, IRIS, and the associated control loops. Four relocatable auxiliary 1.8 m telescopes and three additional delay lines are being added to the infrastructure. At the same time the design and development of the dual feed PRIMA facility, which will have major impact on the existing control system, is in full swing. In this paper we review the current status of the VLTI control system and assess the impact on complexity and reliability caused by this explosion in size. We describe the applied methods and technologies to maximize the performance and reliability in order to keep VLTI and its control system a competitive, reliable and productive facility.

Keywords: VLTI, stellar interferometer, control system

1. INTRODUCTION

The Very Large Telescope Interferometer (VLTI) obtained first fringes in October 2001 combining the light from two 8-m aperture VLT unit telescopes (UT). This event was preceded by first fringes using 40 cm test siderostats in March 2001. Since then the interferometer has been continuously extended with more subsystems and scientific instruments, in particular the unit telescopes have been equipped with adaptive optics and active fringe tracking has been implemented. The first of the 1.8 m aperture relocatable auxiliary telescopes (AT) arrived to the observatory and was commissioned with three more to come in the course of 2004 and 2005. The N band Mid Infrared Interferometric instrument (MIDI) was commissioned and is now being offered to the scientific community. The schedule has interleaved scientific observations (as part of commissioning and science demonstrations) with integration and commissioning activities of new subsystems and instruments.

As a consequence, the size of the control system, counted as number of computers or number of source lines of code, has increased more than a factor of three since 2001. This, together with the philosophy of ESO to build highly automated systems, put hard requirements on the system architecture, design and testing.

Below we review the status starting with the baseline configuration, which now has several years of operational experience, move to the extensions including a critical review of the performance and finally discuss the strategy to cope with the increase in size and complexity of the control system.

2. BASELINE CONFIGURATION

The baseline configuration of VLTI and its control system has been described elsewhere[1,2] and only a brief overview is given here. The stellar light is collected by two telescopes, either 8-m aperture VLT unit telescopes (UT) or 40 cm aperture test siderostats (SID). The observatory layout provides four fixed unit telescopes and 30 observing stations for relocatable telescopes. The local telescope control system (TCS) is responsible for slewing, tracking and guiding based on given stellar coordinates and absolute time. The beams are transferred through underground air light ducts to the delay line tunnel and redirected to the assigned delay line, which cancels out the optical path difference (OPD). The delay line control system (DLCS) is responsible for positioning and tracking the optical delay based on given stellar coordinates, absolute time and the configuration of VLTI. DLCS automatically computes optimal reference positions along the 60 m stroke taking into account possible vignetting of beams depending on configuration and used telescopes. The delay lines deliver a position performance of tens of nm RMS while tracking the sidereal motion. Finally the beams are redirected into the interferometric laboratory and fed to the selected beam combining instrument which, in the baseline configuration, is the VLTI near infrared commissioning instrument (VINCI) operating in K-band. The layout and baseline configuration is shown in Figure 1. All components of the VLTI control system are fully based on VLT standards[3] including electronics, computers, VLT common software and software engineering.

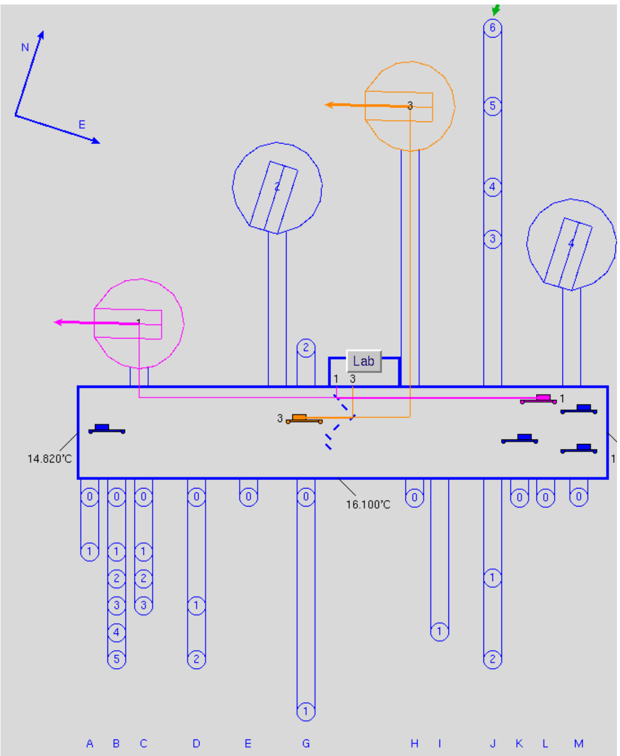


Figure 1. VLTI baseline configuration/layout

As is the case for all ESO facilities, the observation is driven by the scientific instrument through observing blocks[4] and templates commanding the VLTI. The interferometric supervisor software (ISS) is responsible for getting instructions from the instrument and orchestrate the coordination of all subsystems of VLTI. A typical observation with VLTI is then initiated by the instrument passing the stellar coordinates to ISS, which initiates the slewing of telescopes and delay lines. After the TCS has closed the tracking and guiding loops and DLCS has closed the delay line tracking loops fine acquisition of beams in the laboratory is performed using a CCD based image alignment system (Artificial Source and Alignment System, ARAL) and offsetting the telescopes. A second step of image alignment is performed internally by VINCI optimizing the injected photometric flux using tip-tilt stages. This step also compensates for any residual transversal atmospheric dispersion effects due to the difference in wavelength between K and visible. Using an internal piezo VINCI scans the OPD, typically a few hundred microns, looking for fringes. If no fringes are found an offset is sent to one delay line and the procedure repeated until fringes are found. During data acquisition the fringe envelope is re-centered between each scan, typically at ~ 2Hz, thus implementing a kind of low frequency fringe tracking.

The baseline configuration of VLTI has been operational since late 2001 and control system and operational procedures have matured such that a single operator can easily handle the complete system. This allows extracting statistically significant data on VLTI functionality and efficiency in its baseline configuration from the engineering data stream. Two such metrics are shown in Figure 2 based on one year's data. During this year data have been collected from four different baselines between 16 and 140 meters also including commissioning runs with MIDI and FINITO (see below).

The first plot shows the error in OPD, e.g. the difference between the theoretical OPD and the OPD where fringes were actually found. It shall be noted that in the VLTI baseline configuration this parameter is not very important since it will only translate in a small overhead in the fringe search phase, i.e. VINCI searches 1 mm of OPD in less than one minute, and therefore not much attention has been given to improving this. This will be different in the future, particular in astrometric mode. Dedicated commissioning runs to optimize the OPD model have demonstrated that OPD errors below 100 µm are achievable. The second plot shows the acquisition time, e.g. the time between when VLTI is requested to slew to a new object and when fringes have been detected on the instrument. A mean value of below 10 minutes is satisfactory compared to single telescope operation.

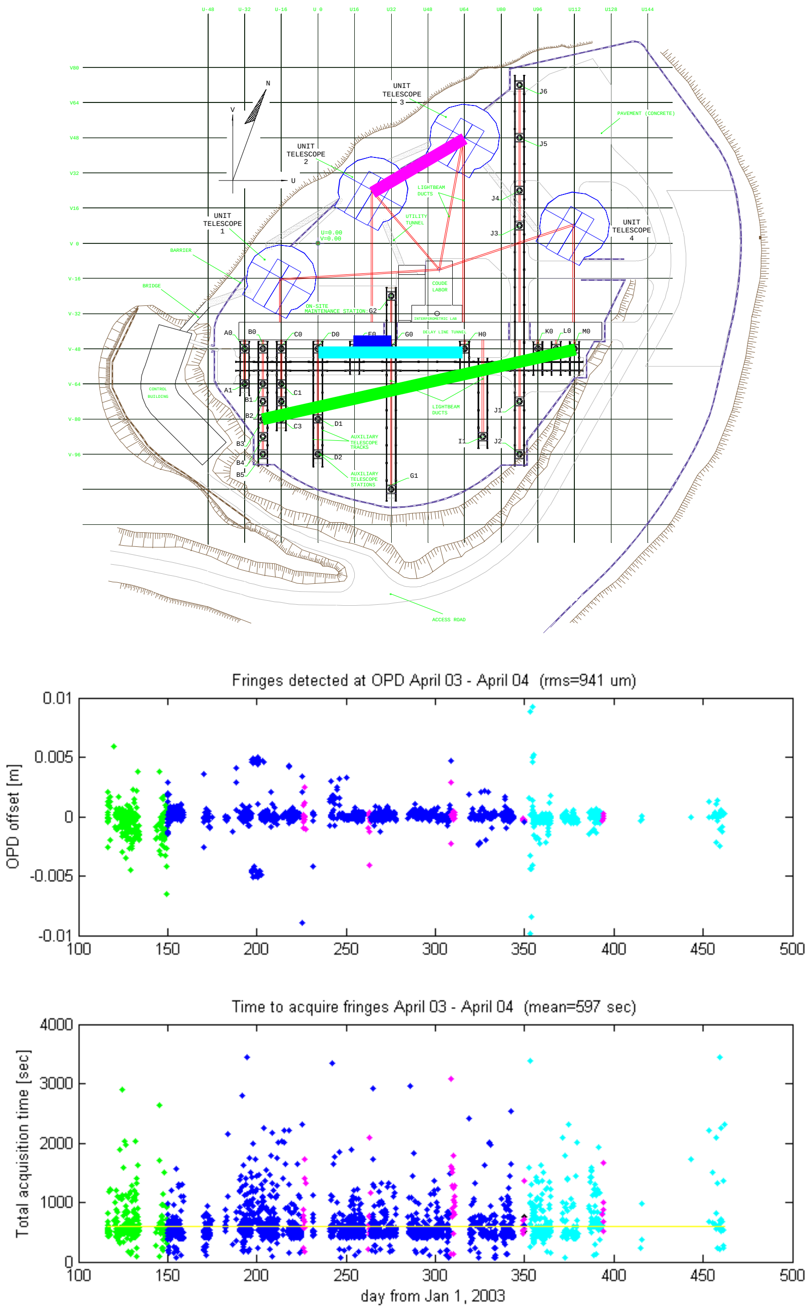


Figure 2. One year operational statistics from VLTI. The top figure shows the four used baselines ranging from 16 to 140 meters. The first plot shows error in OPD, e.g. the difference between predicted and actual OPD. The second plot shows total fringe acquisition time, from telescopes start to slew until fringes have been detected on the instrument.

3. EXTENSIONS

3.1. Adaptive Optics

The main motivation for using adaptive optics (AO) in interferometers is to increase the limiting magnitude for large apertures by injecting more photons into the beam combiner. The VLTI adaptive optics system (VLTI/MACAO)[5] is located at the Coudé focus of the unit telescopes and makes use of a 60 element curvature wavefront sensor and a 60 actuator deformable mirror (M8). The curvature wavefront sensor is placed on an XY-table behind the dichroic (M9) reflecting the infrared band towards VLTI and transmitting the visible band to the sensor. This setup allows using the science target (on-axis) as reference star or another star (off-axis) within the 2' field of view covered by the XY-table. The XY-table also implements the dispersion correction between the used visible light and the scientific wavelength transmitted to the VLTI laboratory. The sample frequency of the AO control loop is 350 Hz and the achieved Strehl larger than 50 % for V magnitude 12, decreasing to 25 % for magnitude 15. The system is highly automated limiting human interaction to a minimum. In fact AO is just defined as another guiding mode and the only difference operating VLTI with and without AO is to define, through the corresponding setup keyword, the guiding mode accordingly. Currently two MACAO/VLTI systems have been installed and commissioned with the third scheduled for July 2004 and the fourth and last in the first half of 2005.

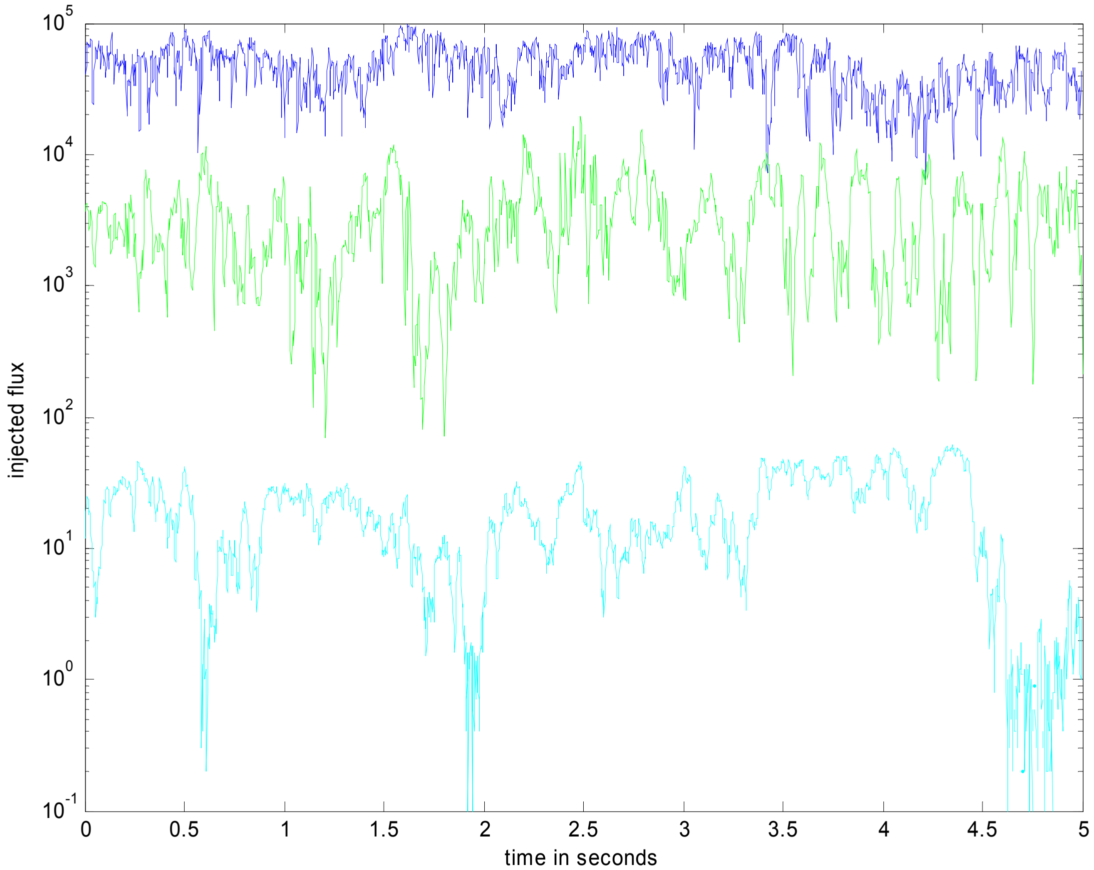


Figure 3. Injected flux in a single mode fiber located in the VLTI laboratory originating from top; a UT with adaptive optics, a UT with tip-tilt correction only and a siderostat without wavefront correction. The detector operates in H band.

Figure 3 illustrates the difference when injecting beams originating from a fixed magnitude star under similar atmospheric conditions in three different configurations. The injection is in a single mode fiber with 10 µm diameter located in the VLTI laboratory with the other end of the fiber projected on a single pixel on an infrared array, which is read out at 500 Hz. From top to bottom the plot shows UT with AO, UT without AO but with tip-tilt correction and 40 cm aperture test siderostats. The fluctuations of the signals are due to scintillation and thermal effects in the light duct and tunnels. Currently VLTI has no active beam tracking system from the Coudé focus to the interferometric laboratory. These data were obtained as a side result during the first combination of AO corrected beams in November 2003 and no attempts were made to optimize the involved systems with respect to injection.

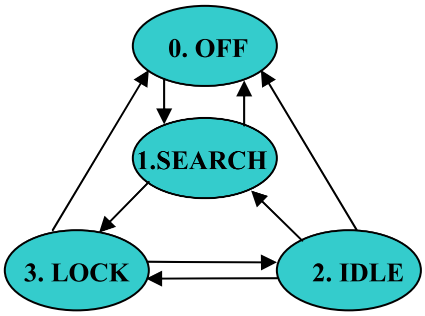
Computing statistics on these data we find that mean injection efficiency increases by a factor 14 with adaptive optics with respect to only tip-tilt correction. We also note that the fluctuation for the AO corrected beam is less, as expressed in RMS/mean, 0.37 vs. 0.79. The latter is important for fast control algorithms.

3.2. Fringe Tracking

VLTI fringe tracking is based on the following architecture. A portion (spectral band) of the light is directed to the fringe sensor, which measures the presence and position of the fringes. This information is delivered over a deterministic reflective memory network to the OPD controller, which is a dedicated local control unit responsible for implementing the control law but also to administrate which fringe sensor and which delay lines are currently used. Like is the case for adaptive optics the used fringe sensor is simply specified by the user in a setup keyword and the system reconfigures itself accordingly. Based on the input from the fringe sensor the OPD controller computes a correction signal, which is passed over the same reflective memory network to the tracking delay lines(s). This signal, which is called real-time offset, is superimposed by the delay line control system on the blind trajectory as demanded position. The reflective memory network is synchronized by the VLT timing system at a maximum rate of 4 kHz. Note that this architecture is compatible with the baseline operation scheme, where the instrument (VINCI, MIDI) acts as fringe sensor and implements a low frequency (few Hz) fringe tracking.

FINITO[6] is an optical "instrument" operating in H-band considered as a fringe sensor in the VLTI context. The H-band portion of the light from the interferometric arms are extracted by dichroics and injected into the FINITO single mode fibers, which act as spatial filters. The OPD is temporally modulated internally by FINITO using a piezo driven expansion ring changing the length of the fiber on one (or two) of the beams. Modulation is triangular, in closed loop with sampling frequency 12.5 kHz, using an auxiliary metrology system operating at 1313 nm. The metrology signal is inserted into and extracted out of the scientific beams using dichroics. The maximum modulation stroke is 20 µm programmable in odd steps of scientific fringes (~1640 nm). The optical setup in two beam operation provides four "scientific" signals; two photometric signals from the two beams and two interferometric signals in opposite phase. The signals are projected on single pixels on a Picnic array read out synchronously with the modulation. Typical exposure time, which defines the sampling frequency, is 0.5 - 2 ms and using the ABCD method there are four samples per fringe. The output of FINITO are three signals; SNR used for fringe detection and decision to close/open the fringe tracking loop, phase and coherence. The three outputs are written on the reflective memory network. FINITO hardware supports operation with three beams, but this has not been used up to now.

The OPD controller implements a state machine similar to that used at PTI and Keck[7,8]. The fringe search is initiated by applying a geometrical spiral on the tracking delay line around the predicted fringe position. In parallel the SNR signal supplied by FINITO is fed into a four and twelve sample sliding boxcar filter (SNR4 and SNR12) used as triggers for the state machine. Transition from SEARCH to LOCK state occurs when SNR4 > T_1 and the system enters fringe tracking delivering computed control signals to the tracking delay line. If SNR4 < T_3 for a selectable timeout, i.e. 20 ms, a transition to IDLE state occurs. In this state the control history is maintained and the output control signal is frozen. If SNR4 > T_2 an immediate transition back to LOCK state occurs. On the other hand, if in state IDLE and SNR12 < T_3 for a selectable timeout, i.e. 20 ms, a transition back to SEARCH state occurs. This will generate an immediate search trajectory around the point fringes were last seen, e.g. when transition LOCK to IDLE occurred, and the control history is reset. This ensures that fringes are immediately found again after a temporary loss of flux. The state machine is summarized in Figure 4. The controller itself is currently a standard PI controller. All applications associated with fringe tracking have been implemented using the VLT standard "Tools for Advanced Control" (TAC)[9].



From \ To	**OFF**	**SEARCH**	**IDLE**	**LOCK**
OFF	-	START	N/A	N/A
SEARCH	STOP	-	N/A	SNR4>T_1
IDLE	STOP	SNR12<T_3 for 20 ms	-	SNR4>T_2
LOCK	STOP	N/A	SNR4<T_3 for 20 ms	-

Figure 4. OPD controller state machine for fringe detection and locking

FINITO was installed at Paranal in 2003 and two test runs using the siderostats were performed in November 2003 and March 2004. It is currently still in commissioning and not offered for science operation with the next important milestone scheduled for August 2004 using two UTs with AO.

Figure 5 illustrates the current functionality and performance of VLTI fringe tracking when using FINITO as fringe sensor. The used setup was 2 ms exposure time, e.g. 500 Hz sampling frequency, and five fringes modulation amplitude. The first plot shows the four inputs to FINITO, two photometric and two interferometric signals. We note the fluctuation in detected flux with occasional total drop outs. The next three plots are the FINITO outputs, SNR, phase and coherence. We note that the SNR signal detects the loss of flux and that the coherence signal indicates that we are one wavelength off the central fringe. The coherence signal is not yet used by the controller, but intended to ensure tracking is on the white light central fringe. The next plot is the state of the OPD controller, where 3 mean LOCK, 2 IDLE and 1 SEARCH. The fringe tracking loop lock ratio is 0.94 in this 30 seconds sequence. We note also that the fringes are immediately found again after they have been lost due to transient loss of flux. The next plot is the unwrapped and filtered phase, expressed in OPD, which is the input to the controller. The final plot shows the control signal sent to the tracking delay line. If we compute the RMS of the unwrapped phase during the ten seconds (19-29) continuous loop closure we get 206 nm, which is a factor three out of specification.

3.3. Interferometric Laboratory and Beam Routing

The specification of the thermal environment of the interferometric laboratory prevents human presence. The beam routing must therefore be under remote control and with the addition of more instruments and facilities and combination of those the configuration becomes complex. To maintain alignment and thermal stability the requirements of corresponding translation and rotation stages are demanding.

VLTI supports a maximum of eight beams, defined by the physical space in the delay line tunnel. The beams enter the laboratory (20.4 m * 6.7 m) from the delay line tunnel as illustrated in Figure 6. The switchyard rotation stages allow routing the beam directly to the instruments or via a beam compressor or, in the future, to a differential delay line. The beam compressor reduces the diameter of the beam from 80 mm to 18 mm and reimages the pupil into PRIMA FSU, MIDI and VINCI. The calibration source Leonardo, which is part of ARAL[10], allows injecting artificial light towards the instrument (auto test) or via some retroflectors in the optical train (auto collimation). The MIDI feeding optics rotation stages allow routing the beams to MIDI either by mirrors or dichroics. ARAL feeding optics allows picking up any beam for initial acquisition on a CCD by inserting a beam splitter. The VINCI feeding optics translation stages allow routing the beams to VINCI either by mirrors or dichroics. The FINITO feeding optics rotation stages allow routing up to three beams to FINITO either by mirrors or dichroics and finally AMBER feeding optics rotation stages allow routing up to three beams to AMBER. In total twenty motorized stages are currently involved in the beam routing with twelve more to be added in the coming year.

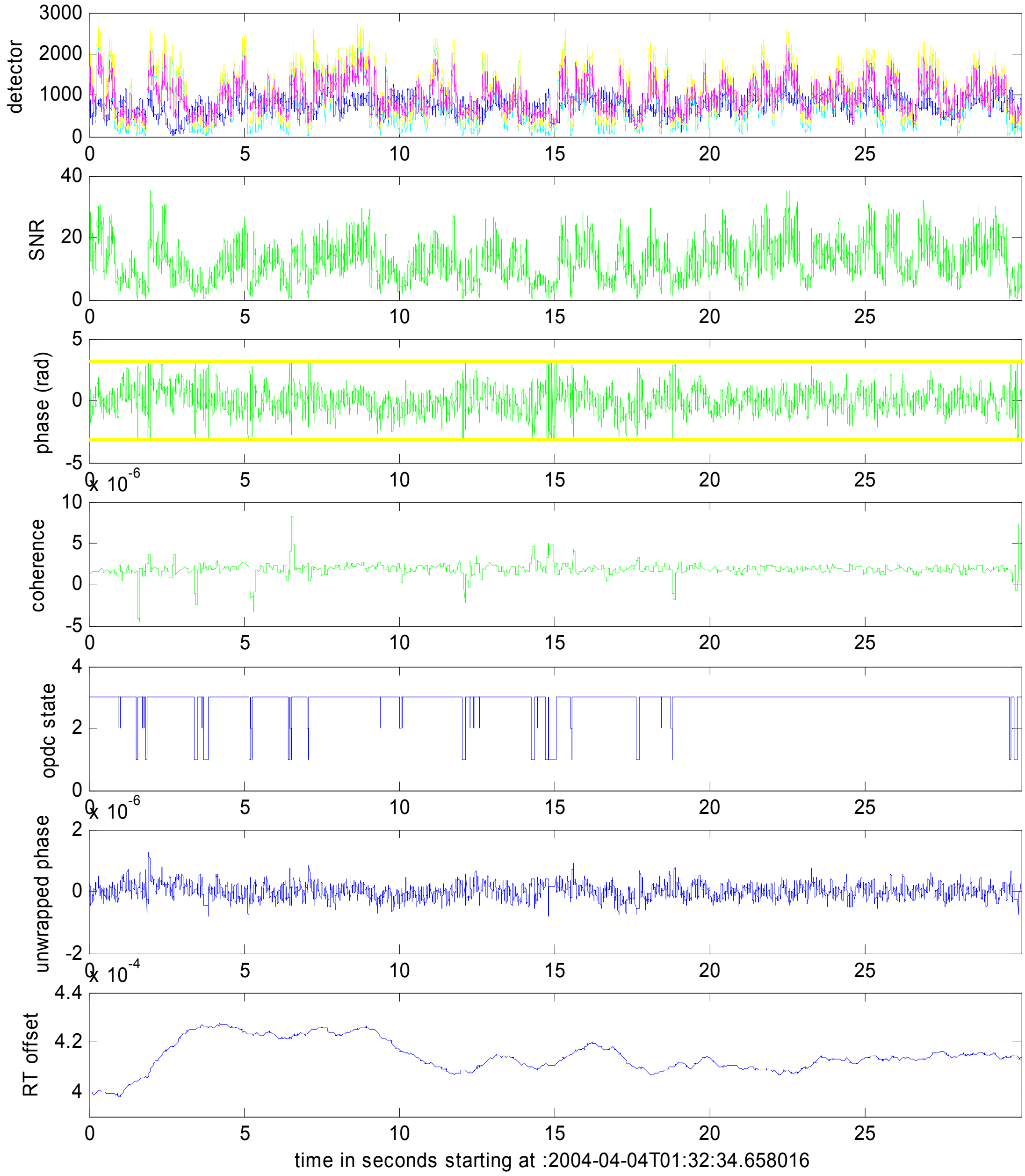


Figure 5. Dataflow for fringe tracking using FINITO as fringe sensor. The plots show from top to bottom the four detector signals, the three outputs from Finito SNR, phase and coherence, the OPD controller state, filtered phase expressed in OPD and the control signal sent to the tracking delay line (in meters).

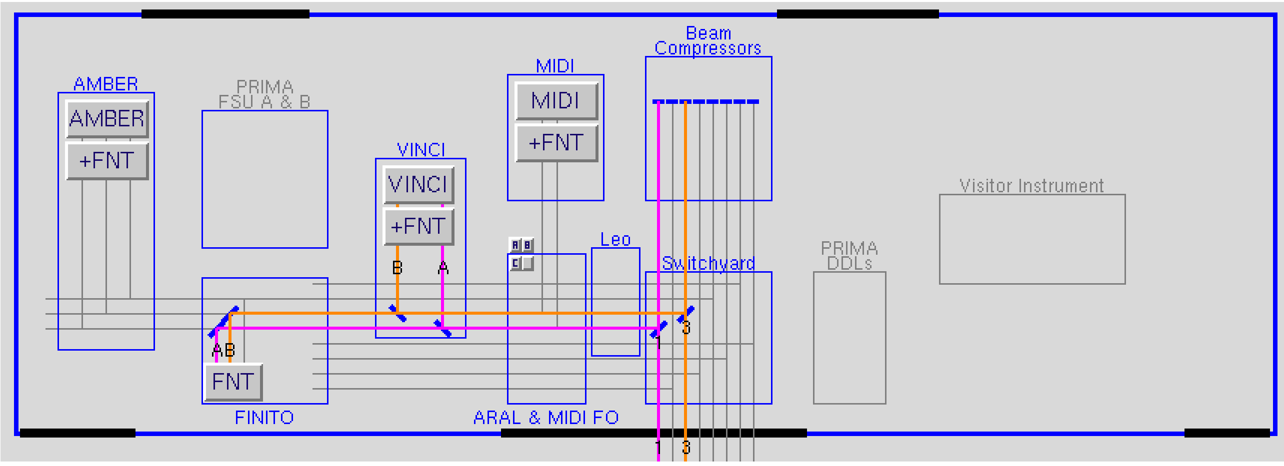


Figure 6. Layout of the interferometric laboratory. This example shows two beams routed to the beam compressor and then to VINCI (K band) and FINITO (H band)

3.4. Auxiliary telescopes

The first 1.8 m aperture auxiliary telescope (AT)[11] arrived to Paranal late 2003 and had first light in January 2004. The associated telescope control system provides nearly identical functionality and interface to VLTI as for the unit telescopes and siderostats. Integration of the ATs in the existing VLTI control system is therefore straight forward. The second AT is expected later 2004 and the first beam combination with ATs in early 2005.

Figure 7. Auxiliary telescope 1 located in the maintenance station outside the interferometric complex. The rails used during relocation are visible to the right.

4. INTEGRATED CONTROL SYSTEM

At time of VLTI first fringes with UTs in late 2001 the control system comprised 24 computers (UNIX workstations and VME based Local Control Units) and 200 000 source lines of code dedicated to VLTI applications, on top of VLT common software. In April 2004 these numbers had grown to 60 computers and 750 000 source lines of code. Figure 8 illustrates the evolution of code size, divided in subsystems, from the first day of deployment at Paranal up to time of writing. We note that the largest subsystems are the delay line control system (including FINITO) and the adaptive optics followed by the instrument MIDI and the Interferometric Supervisor Software. The fact that individual subsystems continue to grow after initial deployment also indicates that new functionalities are added and more and more configurations are supported as time passes. Only with good software engineering and configuration control[2] can such a system survive.

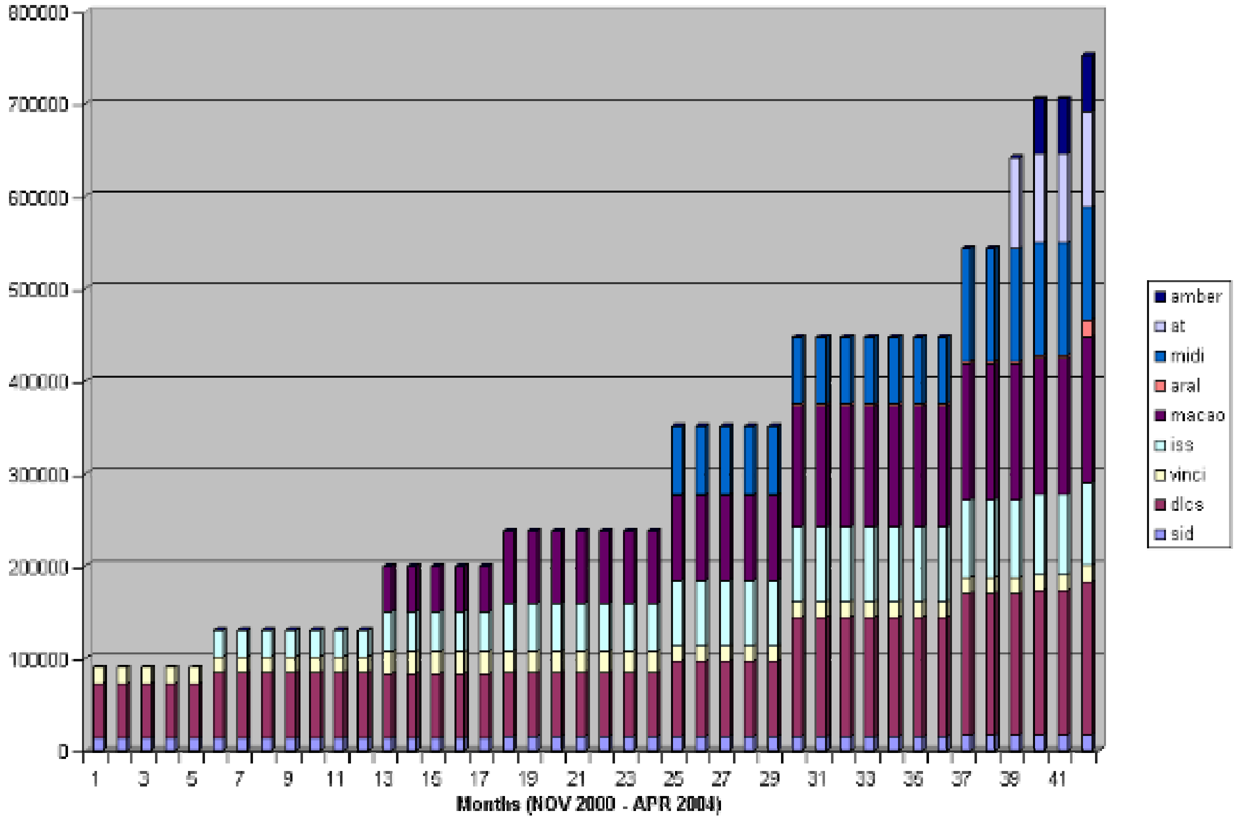


Figure 8. Evolution of VLTI application source lines of code since first deployment at Paranal

The pressure on Paranal and particular the oversubscription of the unit telescopes prevents allocation of sufficient sky test time to safely maintain and develop the control system. It becomes essential to have sophisticated enough off-line test beds to minimize the required sky test time. The VLTI control model at the headquarters in Garching is a duplication of the control system including UNIX workstations and Local Control Units, but obviously without field hardware. All applications provide a good level of simulation allowing the execution of complete observing sequences in the control model exercising a maximum amount of code. This test-bed allows validating any functionality not requiring stellar light, but is still not enough. The large combination of possible configurations calls for automating this testing. We have implemented system integration regression tests exercising all known operation configurations and modes. These tests are fully automatic and typically executed during night time. This allows a high level of confidence that new functionalities can be added, without side effects, before deployment at Paranal.

One metric of the quality of the control system can be extracted from the software problem report (SPR) database. Figure 9 shows the cumulative number of SPRs, classified as problem reports or change requests, throughout the last four years of development of the system. The following observations can be made from this plot. Although the size of the code shows almost an exponential trend (Figure 8) the cumulative number of SPRs is rather linear. The split between problem reports and change requests are equal. And most important, the number of currently opened SPRs is constant. The latter indicates that, at least up to now, the system has coped with the increased size and complexity.

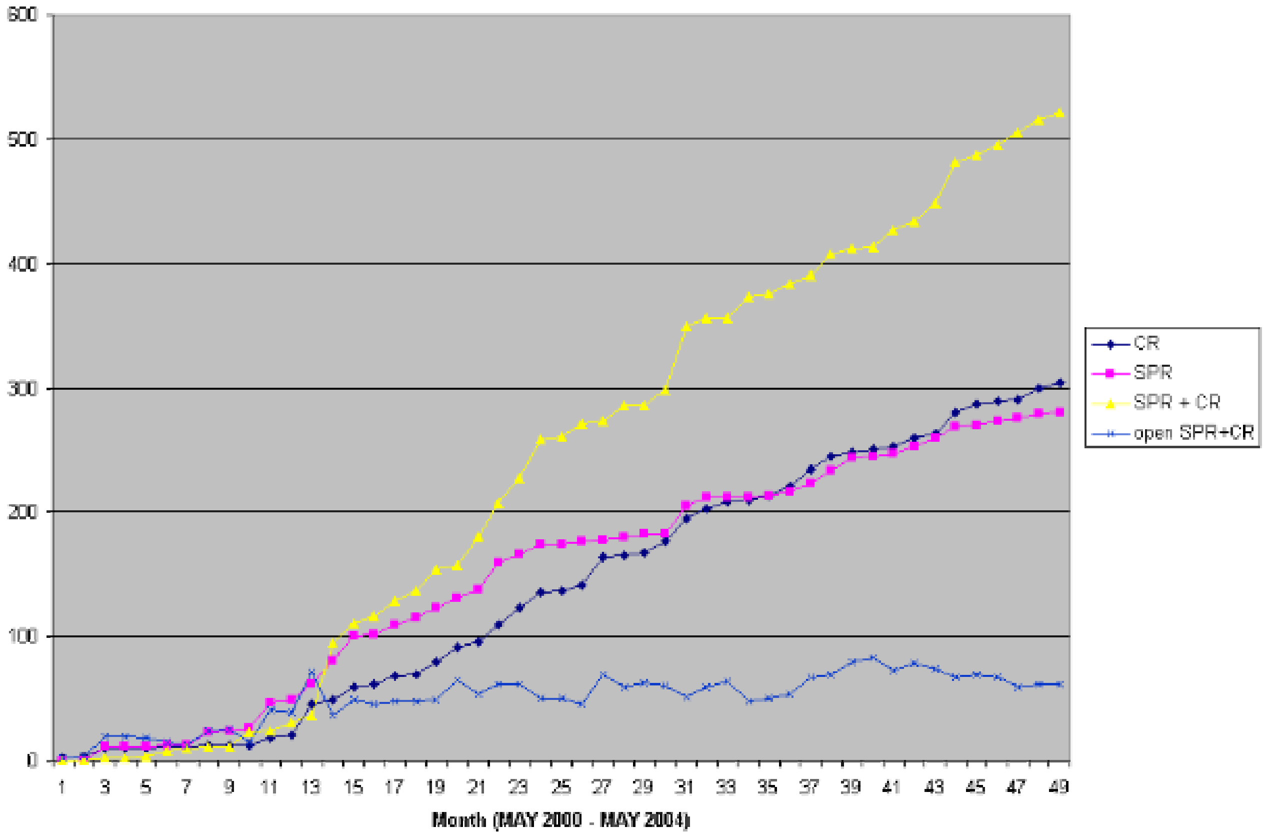


Figure 9. Number of cumulative software problem reports (SPR) and change requests (CR) for the VLTI control system over four years of development. The number of currently opened SPR and CR remains constant even if the system grows.

5. FUTURE

In the immediate future VLTI will be further extended with an active beam tracking system in the laboratory (IRIS)[12] and the integration of the first two auxiliary telescopes. The implementation of adaptive optics will be completed on all four unit telescopes and the AMBER instrument will be commissioned and start science operation. In parallel currently known problems, i.e. beam injection and fringe tracking, will be further addressed.

The main design activities over the next years will focus more and more on the dual feed PRIMA facility adding star separators, fringe sensor units, metrology system and differential delay lines to the system. A successful integration of PRIMA also puts a lot of new requirements on the existing control system.

6. CONCLUSIONS

The last couple of years have demonstrated that VLTI in its baseline configuration can be operated with good performance by a single operator. We believe this is due to sound basic engineering applied from the first day VLTI was envisaged and a high level of automation in the control system. However, we have encountered many more problems than expected when moving to more advanced functionalities like fringe tracking and when trying to push the limiting magnitude. We now believe this is due to, on one hand a lack of real world experience in these, for ESO, new fields and on the other hand some design problems in the system, mainly the lack of fast beam tracking in the laboratory and combat of light duct and tunnel turbulence. It is clear that in order to be successful in the future there is some catching up to be done in these areas as well as identifying and implementing better means to inject the photons into the beam combining instruments.

ACKNOWLEDGEMENTS

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