VINCI : The VLT INterferometer Commissioning Instrument

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ABSTRACT

The Very Large Telescope Interferometer (VLTI) is a complex system, made of a large number of separated elements. To prepare an early successful operation, it will require a period of extensive testing and verification to ensure that the many devices involved work properly together, and can produce meaningful data. This paper describes the concept chosen for the VLTI commissioning instrument, LEONARDO da VINCI, and details its functionnalities. It is a fiber based two-way beam combiner, associated with an artificial star and an alignment verification unit. The technical commissioning of the VLTI is foreseen as a stepwise process: fringes will first be obtained with the commissioning instrument in an autonomous mode (no other parts of the VLTI involved); then the VLTI telescopes and optical trains will be tested in autocollimation; finally fringes will be observed on the sky.

Keywords: infrared interferometry, VLTI, optical fibers, commissioning.

1. INTRODUCTION

To commission the Cerro Paranal VLTI[1] complex, ESO decided to build two dedicated light collectors (the VLTI siderostats) and a specific beam combiner instrument (VINCI). The later is based on the proven concept of FLUOR[2] (Fiber Linked Unit for Optical Recombination) which has been operated since 1995 as a focal instrument of the IOTA interferometer in Arizona. Later, it was decided to extend the capabilities of VINCI to provide an artificial star and an alignment verification unit. This extended instrument is now called LEONARDO da VINCI (LdV), while the name VINCI is still affected to the beam combiner part.

As many new systems and instruments (MIDI[3], AMBER[4], Fringe Sensor Unit[5], Auxiliary Telescopes[6]…) will come on-line one after another on Cerro Paranal, VINCI will be the reference point for testing and recovering fringes after the hardware and software upgrades.

For the Technical Commissioning of the VLTI, LdV will be able to measure the zero optical path difference (OPD) point and measure the baseline vectors. It will also measure precisely the differential dispersion in the interferometer arms, the Strehl ratio fluctuations and the absolute Strehl ratio under stationary turbulence (see Section 9). In a second phase, LdV will commission the VLTI on the sky by observing selected reference stars with the siderostats. The angular diameters obtained on these sources will then be compared to existing measurements (by other interferometers, lunar occultation,…) for consistency verification.

2. INSTRUMENT OVERVIEW

LdV is a multi-purpose facility for the VLTI. It includes a set of alignment tools and artificial sources, as well as a beam combination instrument, LdV, fully remote-controlled to comply with the tight environmental stability requirements in the VLTI interferometric laboratory.

Design philosophy

As a commissioning instrument, the philosophy that guided the design of VINCI holds in three points: it has to be *simple*, *reliable* and *flexible*.

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Simplicity is highly desirable for an interferometric instrument, in order to avoid a long and tedious initial debugging period. The voluntarily simple LdV design will make its integration in the already complex VLTI environment easier. Starting end of 2000, the schedule of the implementation of the VLTI is tight, with instruments or major elements being introduced every six months. This leaves a short time to have the commissioning instrument fully operational. LdV will be delivered first in Garching by September, 2000 and then at Paranal by the end of 2000 after a commissioning period.

The *reliability* is an absolute requirement, as LdV will be used during a long period (several years), during which it will have to be on-line every night as a backup to the other instruments. If the fringes are lost during the night, LdV will have to be immediately operational to search for fringes on a bright reference star, and trace possible technical problems. Moreover, many of the functions of LdV are part of the VLTI infrastructure, and a high failure rate would directly impact on the global productivity of the interferometer. To improve the reliability, proven elements (electronics, software,…) have been preferred, and the instrument is compliant with ESO's standardization policy. The maintenance of LdV is therefore very similar to that of the other VLT instruments, and benefits from the experience of ESO.

During the lifetime of LdV, the VLTI environment in which it is operated will change dramatically from a two siderostats basic system to the most complex ground-based observatory. This will therefore require a high *flexibility* of this instrument. The design has been left as open as possible to be able to accommodate the additions that will eventually be necessary to follow this evolution. For example, the possibility has been left open to extend the capabilities of LdV to spectrally dispersed fringes if needed, or to use the instrument simultaneously with the foreseen fringe tracking system (Fringe Sensor Unit[12]).

System aspects

The LEONARDO da VINCI (LdV) ensemble is made of three subsystems with separate functions (ALIU, VINCI, LEONARDO), as listed in Table 1. The alignment verification unit (ALIU), as well as the artificial light sources set (LEO), are integral parts of the VLTI infrastructure and are used for routine alignments of the optical train. ALIU is also used during target acquisition in order to center the image of the object on the spatial filters of the VLTI instruments (including the MONA beam combiner input fibers). LEO provides the reference alignment point for all the instruments of the VLTI, as well as the reference zero optical path difference.

LdV will be used to debug the VLTI and obtain the first fringes, and then as a fiducial point for fringe recovery after changes in the VLTI or its instruments. It is also an important training tool, particularly as it can obtain interference fringes autonomously in Autotest mode.

Table 1. LEONARDO da VINCI subsystems

<table>
<tr><th colspan="4">LEONARDO da VINCI (LdV)</th></tr>
<tr><td rowspan="2">Artificial light sources
LEONARDO (LEO)</td><td colspan="2">Beam combiner
VINCI</td><td rowspan="2">Alignment verification unit
ALIU</td></tr>
<tr><td>Infrared camera
LISA</td><td>Optical correlator
MONA</td></tr>
</table>

The conception, design and construction of LdV are provided by the Observatoire de Paris-Meudon (in association with the Observatoire Midi-Pyrénées) through a contract with ESO. LISA is built by the MPE in Garching.

3. SITUATION IN THE VLTI COMPLEX

LdV is installed in the VLTI coherent combination laboratory, located at the center of the VLTI array on top of the Cerro Paranal. VINCI is made of two separate optical tables: the LEO artificial light sources (1.5x0.9 m optical table) and the main table, supporting VINCI and ALIU (3.0x1.5 m). The LEO table is placed just at the entrance of the interferometric laboratory, in order to be able to provide all instruments with reference beams. The main VINCI table is in second position in the laboratory (as seen from the incoming beams) after the MIDI[12] instrument. Figure 1 shows the position of

LEONARDO and VINCI/ALIU in the coherent combination laboratory. The ZPD line marks the zero Optical Path Difference (OPD) between the incoming beams.

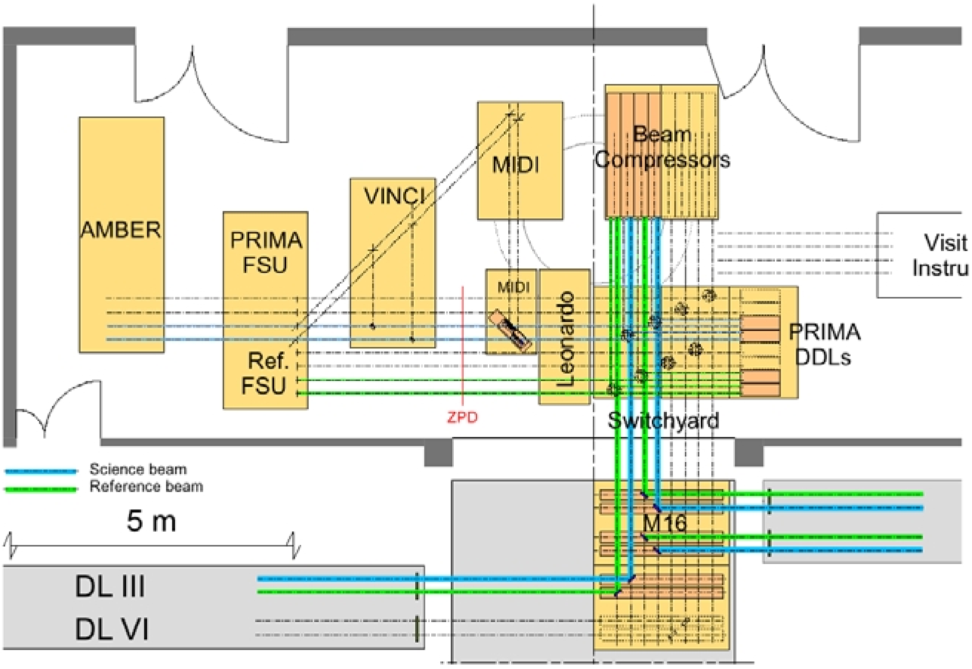

Figure 1. The VLTI laboratory, with VINCI and LEONARDO.

4. STELLAR INTERFEROMETER MODE

In this mode, VINCI operates mostly like FLUOR, and provides interferograms from external stellar sources. The trajectory of the beams in this mode is detailed in Figure 2. After the beams have been transported through the VLTI optical trains and delay lines into the laboratory, they are folded onto the VINCI table, and then injected via fibers into an optical correlator.

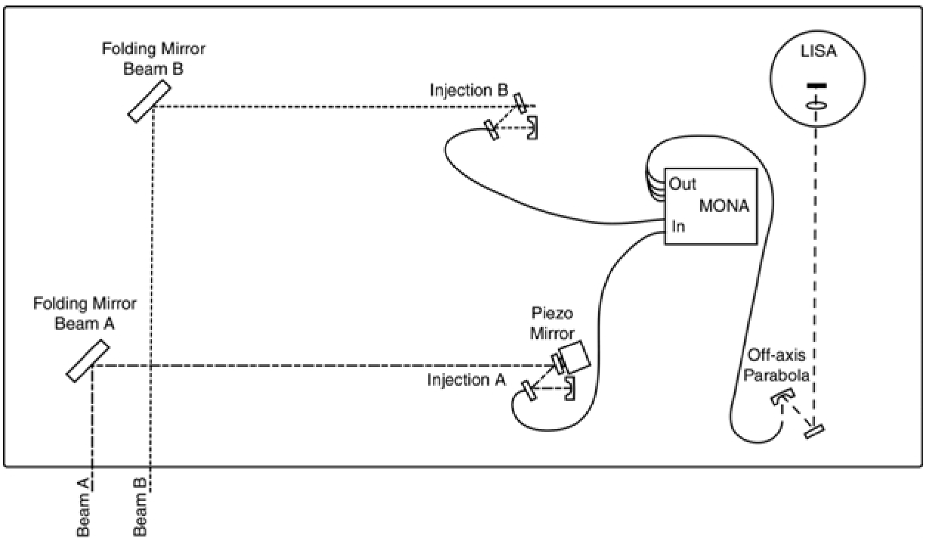

Figure 2. VINCI Stellar Interferometer mode

Beam combination

The central element of VINCI is its optical correlator (MONA), based on single-mode fluoride glass fibers and couplers, and operated in the photometric K band (2.0 – 2.4 µm). The waveguides are used to filter out the spatial modes of the atmospheric turbulence. In a coupler, the fiber cores are brought very close to each other (a few microns) and the two electric fields are added by evanescent coupling of the light waves. Motorized polarization controllers allow the matching of the beams polarizations, in order to have the best possible interferometric efficiency.

The general principle of the MONA box is shown in Figure 3. MONA contains three couplers and has four outputs: a central coupler (with two complementary interferometric outputs) is used for coherent beam combination, and two side couplers provide photometric outputs to monitor the stellar light injection efficiency at each telescope. The four output fiber cores are then arranged in a 125 µm square and imaged onto LISA's HAWAII array detector (Figure 4). Only four small windows (ideally of one pixel each) are read from the detector.

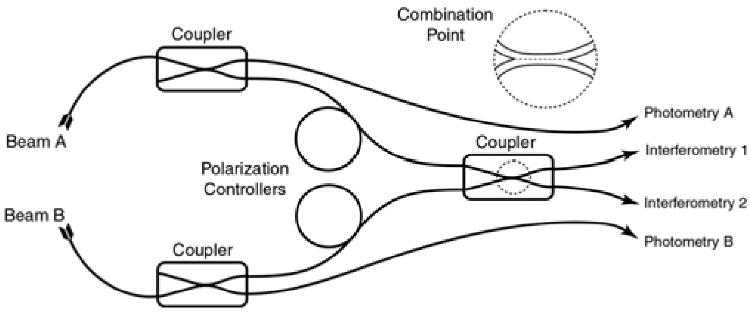

Figure 3. Principle of the MONA beam combiner

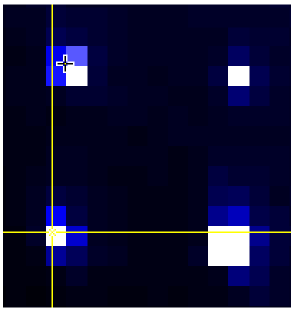

Figure 4. Fiber output images on the HAWAII array.

Fringe detection

The Optical Path Difference (OPD) between the two beams is modulated with a mirror mounted on a piezo translator. While the OPD is scanned, the four output signals are sampled at a few kHz. The resulting four time sequence signals (photometric and interferometric) are then available for processing. The interferograms acquisition rate goes from 0.1 Hz (faint targets, with fringe tracker) to 20 Hz (bright targets).

Coherencing

During the observations, a simple fringe packet centroid locator algorithm is applied to the data provided by LISA. The fringe packet center (in OPD) is measured with a precision of about one fringe (2 µm) after each scan and the resulting error is fed back to the VLTI delay lines as an OPD offset. This capability, called *fringe coherencing*, ensures that the residual OPD is much less than a coherence length despite possible instrumental drifts, yet the correction rate (once per scan, i.e. a few Hz) is too slow to remove efficiently the differential piston mode of the turbulence. A *fringe tracking* unit is anticipated for the VLTI that will remove the differential piston and stabilize the interference pattern at the sub-fringe level, thus enabling long integration times.

Figure 5a shows the effect of fringe coherencing in VINCI: all fringe packets are centered in the data acquisition window, but the differential piston causes distortion in each interferogram, preventing a coherent integration of the time sequences. In the power spectrum, the first order signature of the piston is a random shift of the fringe frequency. In this example, provided by actual FLUOR data on the M0 star κ Ser with a 37 m projected baseline, the OPD modulation rate is 480 µm/s and the readout rate of the array is 1075 Hz. The interferograms were recorded at a rate of one per second (VINCI will be able to acquire up to 20 interferograms per seconds on the brightest sources).

Visibilities computation

When the turbulent beams are spatially filtered by the single-mode waveguides, their random phase corrugations are transformed into intensity fluctuations which are monitored by the photometric signals. It is then possible to correct a posteriori each interferogram from these fluctuations and produce highly stable fringe visibility measurements that are independent of the spatial modes of the atmospheric turbulence (Coudé du Foresto et al.[7]). Squared raw fringe visibilities (modulus of the complex coherence factor between the two beams) are actually computed from the normalized energy of the fringe signal in the power spectra of each corrected interferogram, and averaged over a batch of scans to reduce statistical noise.

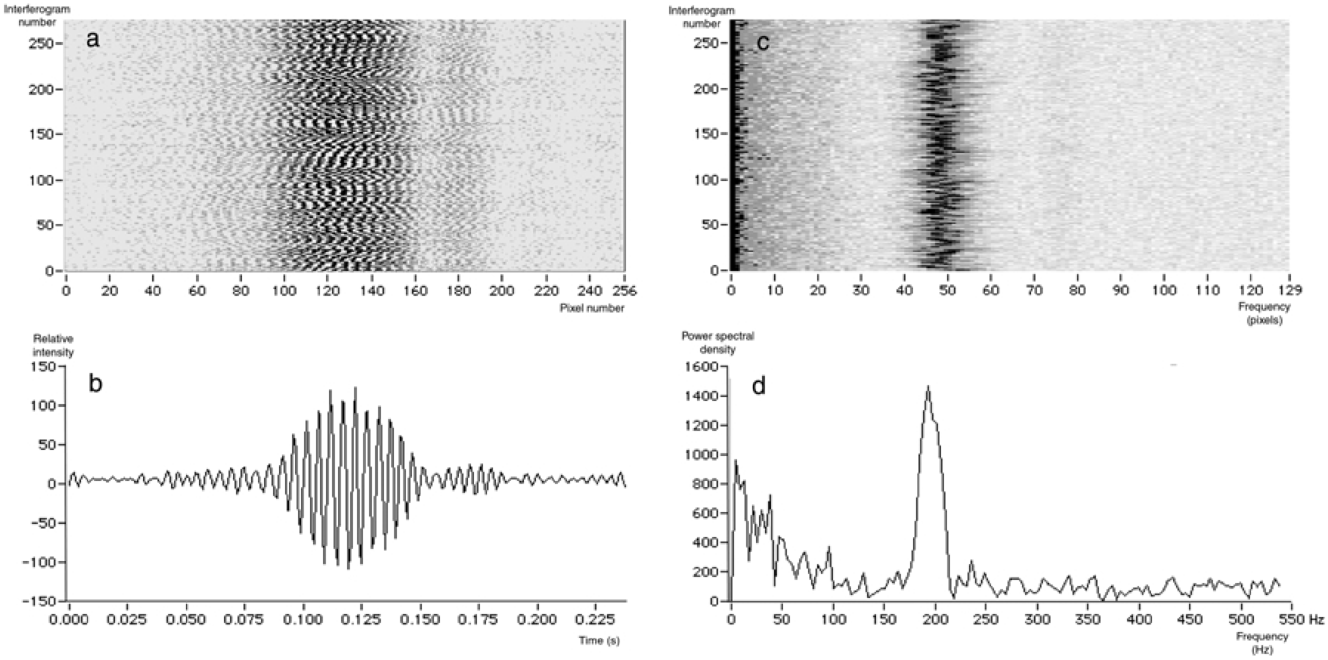

Figure 5. An example of VINCI data: (a) waterfall display of a batch of 275 interferograms and (b) a single filtered time sequence; (c) waterfall display of the power spectra and (d) a single full power spectrum, containing the fringe signal and the low frequency signature of the photometric fluctuations.

5. ALIGNMENT UNIT (ALIU)

The function of the Alignment Unit (ALIU) is to image either the image plane or the pupil plane of each individual VLTI telescope, for alignment verification purposes. ALIU uses a refractor telescope with computer controlled variable focus, coupled to an ESO Technical CCD (TCCD) detector (290x386 pixels). Beam selection is performed by means of sliding mirrors.

Image Alignment

The light from the astronomical objects observed with the VLTI goes through a large number of mirrors before reaching the interferometric laboratory. The rough alignment is done only once in a while, but it is foreseen to have to do some adjustments after every baseline configuration change. The LdV setup in Image Alignment mode is shown on Figure 6. ALIU is also used to image the astronomical object before the interferometric observations, in order to center it precisely on the instruments spatial filters (optical fibers or pinholes) using the fiber injection optics. Both the object and the artificial light source can also be visualized together, thanks to beam splitter cubes.

Pupil alignment

The nominal position of the pupils is (simultaneously) on the entrance cold stop for MIDI[3] and on the injection parabolas for VINCI. As the pupil position is maintained on these mirrors by the Variable Curvature Mirrors[12] of the delay lines, it is possible to obtain its image just by focusing the TCCD refractor on these mirrors. This gives the capability to image directly any vignetting in the beams, as well as possible optical aberrations.

The pupil longitudinal alignment is done using a ground glass zone surrounding the injection parabolas of the INA and INB injection mirrors. The calibration of the TCCD focus is done in autocollimation by using a light inside the refractor, and by observing the diffused signal coming back from the ground glass. Any longitudinal position error of the pupil is thus measurable by the focus difference with the ground glass zone.

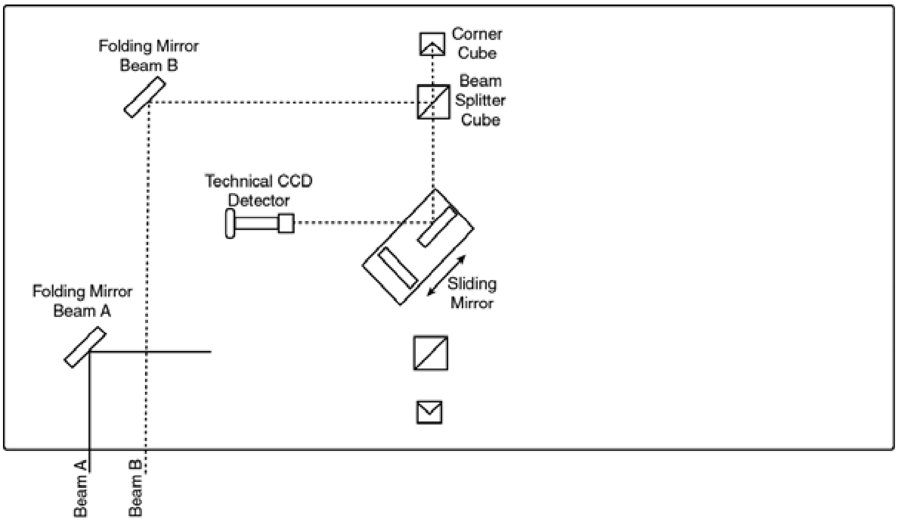

Figure 6. VINCI Image Alignment mode(beam B)

6. ARTIFICIAL SOURCES (LEONARDO)

Overview

LdV provides a set of reference sources (referred to as LEONARDO) for the other VLTI instruments. They include several types of single-mode (point-like) artificial stars, multi-mode light sources, and alignment lasers. The two beams provided by LEO have a fixed optical path difference, conjugated to the MONA beam combining point, in order for the other VLTI instruments to have a fixed and stable OPD reference.

It is possible to use these sources as artificial stars to obtain interference fringes in Autotest and Autocollimation modes. This is especially interesting for the first tests in the laboratory, and to validate the optical elements of the VLTI during daytime. Using this set of sources, all VLTI instruments are able to obtain fringes for test purposes at any time. Moreover, the thermal light sources are specified to be stable, and can be used as detector calibration references by the instruments.

LEO can be operated without the main VINCI optical table being online. As a general rule, LEO is an integral part of the VLTI infrastructure. The light sources available include a 2.3 µm laser and several short coherence length sources in an integrating sphere. The light is then injected in an interchangeable waveguide (single or multimode, K band, N band, visible). Collimated into a parallel beam, it is then split and distributed to the two beams.

Autocollimation

This mode gives the capability to send light in the whole VLTI optical system up to the telescopes. The light is then retroreflected to VINCI or the other instruments by means of carefully positioned mirrors (located near the light collectors) and interference fringes are measured in the laboratory. The injection of the artificial source light in the VLTI requires inverting the beam splitter cubes. This is achieved by sliding their supports (see Figure 7). This mode switching is available remotely, without requiring any manual operation in the laboratory. In case it is not possible to find the fringes on an object, and that a technical failure is suspected in the optical train, this mode makes it possible to identify the problem quickly.

Autotest

It is also possible to send the light directly into the instruments (Autotest mode, Figure 8). This is useful for preliminary tests, when a high signal to noise ratio is required. LEO provides a constant zero OPD between the two beams. It is therefore possible to obtain fringes in the laboratory for the test phase of LdV and other VLTI instruments. Their behavior will be tested extensively without requiring other systems or telescope time. In case a technical problem arises, the Autotest mode will make it possible to determine quickly if the VLTI or the instrument is defective.

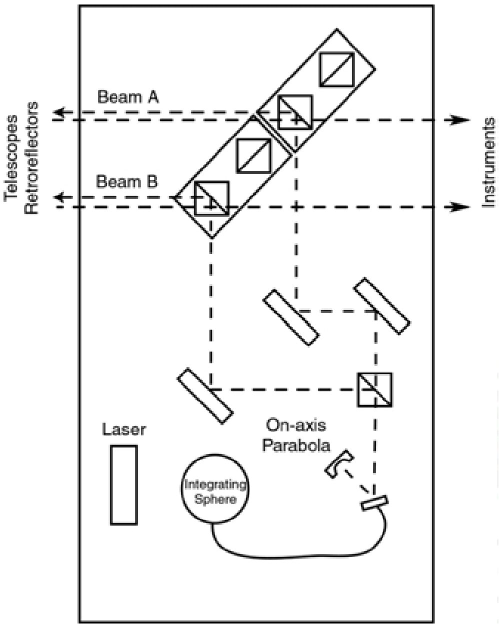

Figure 7. LEONARDO Autocollimation mode

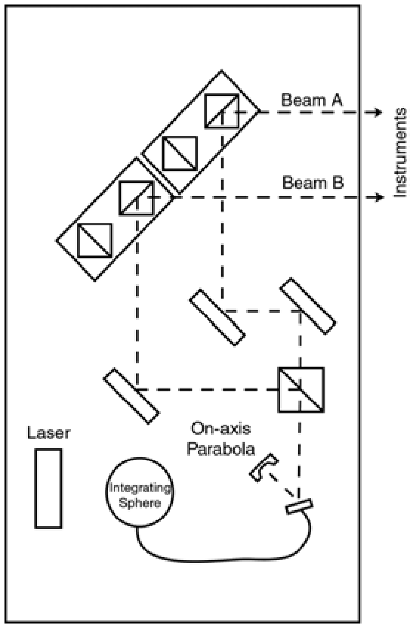

Figure 8. LEONARDO Autotest mode

7. OPTO-MECHANICAL LAYOUT

Main optical table

As shown on Figure 9 the main optical table supports both the beam combiner and alignment unit functions of VINCI. The optical layout of VINCI has been kept as simple as possible, considering the many requirements it has to fulfill.

The left part of the table is used for the folding optics (COMA3 and COMB3), and for the beam selection optics of the alignment unit (ALI1, ALI5, and ALI3-ALI4). The alignment detector (Technical CCD, or TCCD) is attached to the focusing refractor ALI7. ALI13 and ALI12 are retroreflectors (corner-cubes), which enable to image the light coming from the fibers back lit input, from the telescopes, or both at the same time. The optical elements ALI12 and ALI13 are made of calcium fluoride (CaF_2).

The right half of the table carries the INA and INB optics, which are used to inject the light of the incoming beams into the single-mode fibers of the MONA beam combiner. The injection itself is done using on-axis parabolas. INA3 is a flat mirror mounted on a high precision piezo-electrical translation stage. This mirror is used to modulate the optical path difference between the two beams, before the combination of the light inside the MONA box. The output of the MONA box is a bundle of four fibers mounted in the same cable, whose extremity is imaged on the HAWAII detector using the off-axis parabola OUT. An autocollimation mirror (ALI8), used to adjust the ALI7 refractor and an engineering folding mirror

(ALI9) complete the optical layout of the main VINCI table. For interferometric observations, ALI8 is removed from the optical path. LISA is a classical infrared camera, enclosed in a classical two stages evacuated cryogenic Dewar. The cooling is obtained by liquid nitrogen. Six filter slots are available in the Dewar, and the different positions are remotely selectable.

All beams are 18 mm in diameter. Some of the optics are oversized for manufacturing practical reasons. The VLTI pupil, re-imaged by the Variable Curvature Mirror[12], is always located on the injection on-axis parabolas of VINCI. This particularity of the VLTI allows having both a non-zero field of view and small optics in the instruments, despite the very long distances that the beams have to cover before entering the laboratory (up to 270 meters in the tunnels and delay lines).

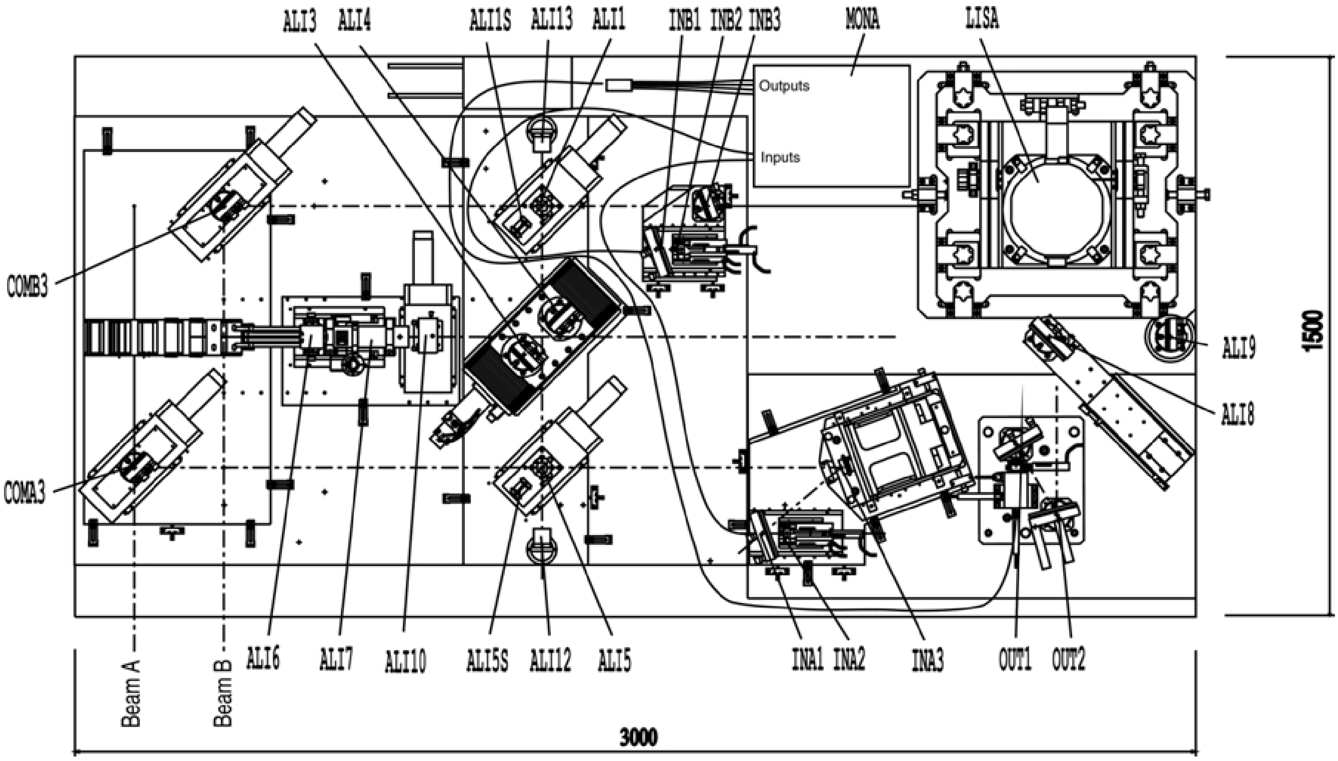

Figure 9. VINCI/ALIU table

LEO table

The thermal light sources (see list section 6) used for the alignment and calibration of the near and mid-infrared instruments (VINCI, AMBER and MIDI), are enclosed in an integrating sphere (ART3). Twelve outputs are available on this sphere to plug various kinds of optical fibers (single or multi-mode, K band, N band, visible). The outputs of these optical fibers are available at different points on the instrument for engineering and tests purpose. All fibers used on VINCI are connected using Diamond™ E-2000™ connectors.

Coming out of the integrating sphere, the light from the fiber is collimated into a parallel beam by the on-axis parabola ART2. After division (intensity splitting) by the beam splitter cube ART4, the light is folded by the ARTA1-ARTA2 and ARTB1 mirrors, and finally by the BSA/BSB cubes (Figure 10). The choice of either BSA1/BSB1 or BSA2/BSB2 makes it possible to send the light either to the telescopes for Autocollimation or Autotest (section 6). The beams going to the instruments have a zero OPD relatively to each other, which means that the two wavefronts cross the right side of the table with the same optical path length from the source. All VLTI instruments will therefore be able to obtain fringes on a single reference source, providing a stable OPD value. Ultimately, this common OPD reference will enable the simultaneous operation of several instruments.

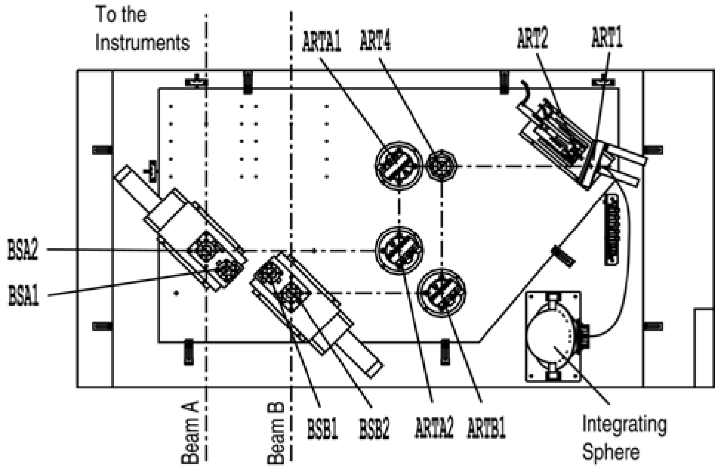

Figure 10. LEONARDO table

Control electronics

The electronics system of VINCI is based on a VME architecture running under VxWorks real-time operating system. Three Power PC 200 MHz processors (Local Control Units, or LCUs) are used to control the different subsystems of the instrument: one for the Technical CCD control (LCU1), one for all the motors of the VINCI/ALIU table and the piezo mirror (LCU2), and one for the LEONARDO table (LCU3). In addition, one Sun Sparc workstation is used with IRACE for the control of the infrared camera. The OS is running on a Hewlett-Packard workstation, connected to the LCUs through the Ethernet LAN of the Paranal Observatory. A dedicated TTL link is used between the Sun workstation and the LCU2 to synchronize the start of the acquisition by the LISA camera and the start of the motion of the piezo mirror at less than 1 millisecond precision.

8. CONTROL SYSTEM

Instrument and Detector control software

All motors used on VINCI are computer controlled by the Instrument Control Software (ICS), to allow remote-control of the instrument during normal operations, and thus avoid any disturbance of the interferometric laboratory. The role of the ICS is to move the optical elements of LEONARDO and VINCI (including the piezo mirror used to modulate the optical path difference) when the OS sends a command.

The main detector of VINCI is an engineering grade HAWAII 1024x1024 pixels infrared array, of which only one of the four quadrants is used. It is controlled via an IRACE[8] system. The DCS accepts commands for data acquisition directly from the OS, and receives the trigger synchronization signal from the LCU controlling the piezo mirror (LCU2).

Observation Software

The sequencing of the commands sent to the ICS is done by the OS, based on input template files (Figure 11). This design allows easy modifications of the observing procedure to adjust it to the needs. This is the standard structure of all VLT instruments, and is part of the flexibility philosophy that guided the design of LdV.

Data Reduction and Analysis

The data reduction system of VINCI consists in four parts: the Data Pipeline, the Engineering Display, the Scientific Display and the Data Processing Workbench.

Table 2. VINCI data products

Level	*Name*	*Content*
1	**Raw data**	Raw interferograms (stellar, autotest,…), photometric calibration data, TCCD images, HAWAII array full images, logbooks
2	**Structured raw data**	Raw interferograms grouped with the relevant photometric calibration data.
3	**Raw visibilities**	Instrumental coherence factors for each star and calibrator observation taken individually (without cross calibration)
4	**Calibrated visibilities**	Calibrated fringes visibility for each star observation (scaled by the transfer function of the instrument)

The Data Pipeline is executed automatically on the raw data produced by the instrument, as soon as it is available. It gives several intermediate data products, together with the final calibrated visibilities (Table 2). Other files will also be created for the commissioning measurements (see Section 9).

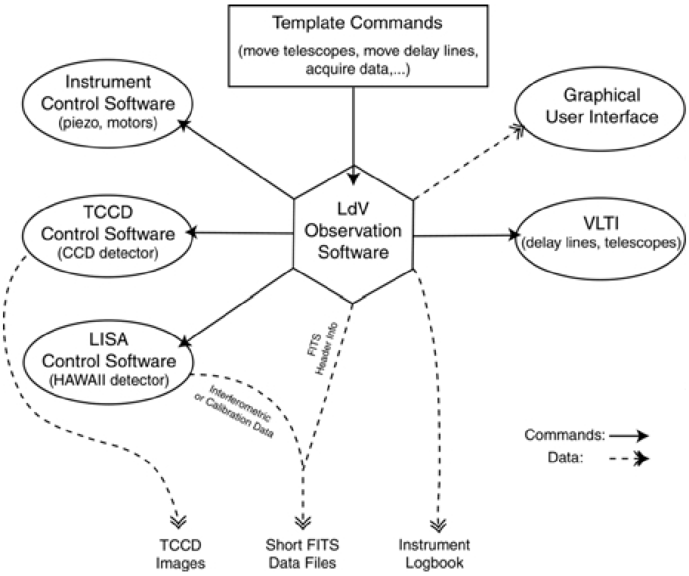

Figure 11. Principle of the LdV Observation Software

9. COMMISSIONING MEASUREMENTS

Overview

During the first weeks of the VLTI operations, LdV will play a key role in debugging the facility. The design of LdV makes it suitable for tracking the failures and technical problems and locate them in the optical train. Figure 12 shows the parts of the interferometer that are accessible to testing via LdV modes. After this first debugging phase, all VLTI active subsystems will be tested in order to estimate their performances and compare them to what is expected (Table 3).

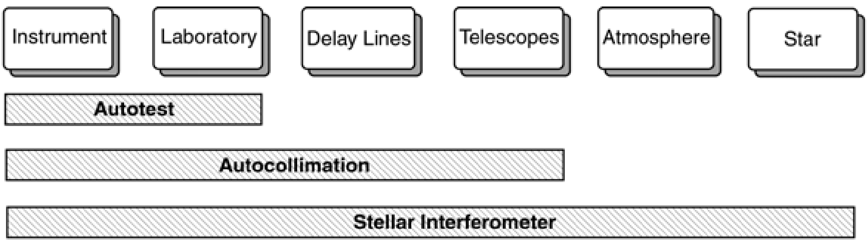

Figure 12. LdV Commissioning modes testing capabilities

Interferometric efficiency

The stellar light transit in the VLTI optical train causes a degradation in the final visibility of the stellar fringes as measured by the instruments. The causes for this degradation can be longitudinal vibrations, polarization mismatches…VINCI will measure the visibility transfer function by observing stars of known diameters, and comparing the measured visibility to the expected value. It is also possible to use LEONARDO as a point-like source for internal measurements without piston.

Optical path length stability

To have a minimal fringe contrast loss, it is essential to avoid any longitudinal vibration in the VLTI optical train. The measurement is done by obtaining fringes in autocollimation mode, and checking in the Fourier spectrum of the interferograms for the presence of significant peaks other than the fringes themselves. Any periodic vibrations will then be traceable to their source (vibrating motors, hydraulic systems…) using their frequency signature. The slow drifts are detectable by measuring the evolution of the fringes positions during a continuous observation of a star. On the sky, it is possible to estimate the external scale of the atmospheric turbulence, by measuring the effect of the differential piston between the two beams.

Table 3. LdV Commissioning tests

Test capability	Performance	Application on the sky	Application in autocollimation
Baseline vector determination	500 nm rms in one night on the *B* vector and internal OPD	-	-
Interferometric efficiency	Accuracy better than 1%	Determine the transfer function of the VLTI	Determine polarization induced contrast losses
Optical path length stability	Detection of fast longitudinal vibrations or optical path length drifts	Piston measurements, external scale of turbulence	Detect longitudinal vibrations in the system (vibrations, delay lines…)
Differential dispersion	Sensitivity equivalent to 1mm of glass thickness	Check atmospheric dispersion models	Check differential dispersion in the VLTI arms
Strehl ratio fluctuations	Fluctuations of more than 1% and slower than a few kHz	• Qualify tip-tilt and Adaptive Optics (AO) systems • Detect fast lateral vibrations in the telescopes	• Check internal seeing • Detect lateral vibrations in the interferometer
Absolute Strehl ratio	Possible only if turbulence is stationary over several minutes	Qualify tip-tilt and AO systems	Check optical aberrations

Strehl ratio

Light injection into the single mode fibers is very sensitive to deviations from the perfect Airy pattern. Therefore, it is foreseen to use LISA to estimate the Strehl ratio (instantaneous differential value and absolute value). The injection of the light in the fibers is made imperfect by the atmospheric (with a natural star) or internal turbulence (with LEO only in autocollimation), and it causes detectable variations of the illumination of the photometric channels of LISA. These tests will be used to validate the adaptive optics systems, and detect possible lateral vibrations of the telescopes or in the optical train.

Longitudinal dispersion

The long optical path followed by the light beams in the VLTI tunnels causes some longitudinal dispersion of the light. VINCI can measure this dispersion precisely, by observing its effect on the interferograms. By taking the unwrapped phase value of Fourier transform of the interferogram and fitting a second order polynomial to this phase, it is possible to derive the value of the dispersion from the second order term coefficient. A detailed description of the method to estimate the dispersion can be found in Coudé du Foresto et al.[12].

10. VLTI SCIENCE VERIFICATION

Assuming conservative performances based on the FLUOR instrument results, VINCI will provide a very high precision on the visibility measurements (a few 0.1%). This will enable a thorough testing of the typical data acquisition procedures for the VLTI. The first light collectors available at Paranal are 0.40-m diameter siderostats. They provide enough light to observe unresolved objects up to a K magnitude of about 5.

The commissioning of the VLTI is based on the idea that this new facility has to be validated scientifically by linking its measurements to those obtained with previous instruments and other techniques. This will be achieved with VINCI through the comparison of the angular diameter measurements of stable stars with reference instruments values.

The measurements obtained with FLUOR/IOTA give a good preview of what can be achieved with VINCI (see Perrin et al.[11] for example). The precision reached on the calibrated visibilities by this instrument is routinely better than 0.5%. The longer baselines accessible on Paranal will provide a high precision even on the smallest angular diameters (down to less than 1 mas). Another example of the type of work that will be possible with VINCI is the Cepheid stars pulsation study[12], which requires a very high precision on the visibility measurements.

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