

The Very Large Telescope Interferometer v2012+

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ABSTRACT

The ESO Very Large Telescope Interferometer (VLTI) offers access to the four 8-m Unit Telescopes (UT) and the four 1.8-m Auxiliary Telescopes (AT) of the Paranal Observatory located in the Atacama Desert in northern Chile. The two VLTI instruments, MIDI and AMBER deliver regular scientific results. In parallel to the operation, the instruments developments are pursued, and new modes are studied and commissioned to offer a wider range of scientific possibilities to the community and increase sensitivity. New configurations of the ATs have been offered and are frequently discussed with the science users of the VLTI and implemented to optimize the scientific return. The PRIMA instrument, bringing astrometry capability to the VLTI and phase referencing to the instruments is being commissioned. The visitor instrument PIONIER is now fully operational and bringing imaging capability to the VLTI.

The current status of the VLTI is described with successes and scientific results, and prospects on future evolution are presented.

Keywords: Optical long baseline interferometry, Very Large Telescope Interferometer

1. INTRODUCTION

The Paranal Observatory is located on the top of Cerro Paranal in the Atacama Desert in the northern part of Chile, about 120 km south of the town of Antofagasta and 12 km inland from the Pacific Coast. A close site has been chosen by ESO as a baseline for the installation of its E-ELT (Extremely Large Telescope).

The Very Large Telescope Interferometer (VLTI) is one of the largest optical interferometer in the world with its four fixed 8.2-m Unit Telescopes (UTs) and four 1.8-m Auxiliary Telescopes (ATs) that can be relocated on any of the 30 available stations. This unique array allows access to baselines between 47-m and 130-m with the UTs, and between 8-m and 202-m with the ATs. The baselines offered by the eight telescopes and the reconfiguration capability with the ATs make the VLTI a unique interferometer. The four ATs are now offered simultaneously, giving access to six baselines each night for science observations. The array re-configuration, by moving the ATs between stations, is done in two hours during daytime and the VLTI is offered back for operation on the same night, following a pre-define set of tests done on the whole system.

The VLTI achieved in March 2011 its first ten years of operations. The VINCI commissioning instrument, and the two instruments offered to the interferometrist community, AMBER and MIDI, have marked this first decade with their scientific successes. During this period the VLTI also went through a number of changes and upgrades that have led the facility to a fully functional and operable telescope. This has been made by a strong dedicated effort from ESO to deliver the best possible interferometer for science. The ten years anniversary of the VLTI has been celebrated by the first interferometric simultaneous combination of the four UTs with the PIONIER instrument, making the VLTI really the fantastic and powerful machine that was dreamed when it was designed.

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The VLTI is now looking to the future with new challenges coming, trying to push the performances even further and we can only dream and wish for new scientific discoveries to come.

2. VLTI 2001 TO 2012+, BACK TO THE FUTURE

To anyone who ever came close to an interferometer, there is no doubt that these incredible machines present technical and operational challenges. Reaching sub-micron level measurements with a telescope which elements are spread over an area of a few hundreds meters is not an easy task. The number of interferometers in the world that have achieved scientifically ready levels shows that this technique has now reached some maturity, even if the path has often been long with many lessons learned.

2.1 2001-2011: Ten years of VLTI

The VLTI has not been an exception among the interferometers. After the first fringes [1] have been obtained on March 17th 2001, many challenges have been faced in the process of bringing accuracy and sensitivity to the system. The “first interferometric light”, that came not long after the “first light” of the UTs, has been the start of an exciting journey for ESO and the interferometric community. For the Paranal Observatory it has been the beginning of many challenges and the genesis of the system engineering approach to the work. During its first decade, the VLTI has been a living system with a continuous flow of new systems:

- **March 17th 2001: VLTI first light with two siderostats and VINCI.**
- October 30th 2001: First interferometric combination of two UTs.
- December 15th 2002: MIDI first light [2] with two UTs.
- 2003: FINITO [3] installed at Paranal. First test with ATs in November 2003 and with the UTs in August 2004.
- January 2004: First AT installed at Paranal [4].
- March 20th 2004: AMBER first light [5]
- December 2005: Fourth AT installed at Paranal. AT array is complete.
- August 2008: PRIMA first light [6].
- October 27th 2010: PIONIER first light. First VLTI visitor instrument and first simultaneous combination of four ATs [7].
- **March 17th 2011: PIONIER combines for the first time the four UTs together on the 10th anniversary day of the first fringes [8].**

The conference “Ten years of VLTI: from first fringes to core science” took place in October 2011 at ESO premises in Garching [9]. The conference was the occasion to retrace the road the VLTI has followed from its first fringes in 2001 with VINCI. From there the VLTI has been built through successful collaboration between ESO and its community of users. Over these ten years of operation, the VLTI has become a general user facility not only reserved to expert interferometrists but also delivering science ready information to any astronomer. The scientific success that the VLTI has achieved were reviewed and projection into the future was done examine the science that will be achieved with its second generation of instruments in an era where new astronomical observatories will come into operation (ALMA, JWST). Looking even further in the future, the giant telescopes will come into operation and one can start to imagine the science that will be feasible, combining the unprecedented sensitivity of the ELTs with the high spatial resolution of the interferometers.

2.2 2005 – 2012: Seven years in VLTI System Engineering

After the first fringes were obtained with VINCI, proving the functionality of the VLTI, the work started on pushing the performances of the system to satisfy the appetite of the astronomers: limiting magnitudes, signal-to-noise ratio, visibility and phase accuracy.

This is where the fringe tracking with FINITO came into the game, but also where the first main glitch arose. After its installation in 2003, FINITO failed to deliver stable fringe tracking on both ATs and UTs. FINITO has been designed as a facility for the VLTI instruments, AMBER and MIDI, with the aim of stabilizing the fringes, allowing longer integration time to reach deeper magnitudes. The first system engineering (SE) approach was then put in action with the interferometry task force (ITF), with two engineers fully dedicated to bring an answer to the “Big FINITO Question” (BFQ): Can fringe tracking work at the VLTI? A system engineering

approach was the right and necessary answer to the problem as it resulted that FINITO itself was not the core of the difficulties: no hardware modifications were made, but control was optimized. The outcome of ITF was the immediate implementation of corrective actions to the VLTi and a series of recommendations to push the limits and improve the operability of the VLTi. This specific SE effort resulted in a YES answer to the BFQ. FINITO was then delivered to regular operation with AMBER and MIDI.

Following the success of this first SE experience, a dedicated system engineering group was created at Paranal. The first aim was to implement the recommendations from ITF, bring the VLTi infrastructure performances to deliver the best possible science, and prepare the path for the next generation of instruments. The main sources of possible performances degradations were identified and studied. The effort was first focused on monitoring and understanding the behavior of the system, as the first and mandatory step to define and prioritize the actions to be taken. This deep and thorough monitoring resulted in an updated and accurate interface and control document that was delivered to the teams building the next generation of instruments, ensuring there that all needed information was available for a proper design of the instruments according to the existing infrastructure they will implemented to.

The methodology followed at SE level is described on Figure 1. The approach is used at both global VLTi sub-systems levels. Each step in the process is made to maximize the benefit for the scientific data, which is the main driver, while trying to minimize the effort. All this effort was always done in very close collaboration and exchange with the VLTi and instrument responsible on the science operation side. The community of VLTi users was also frequently consulted to ensure that the right direction was chosen.

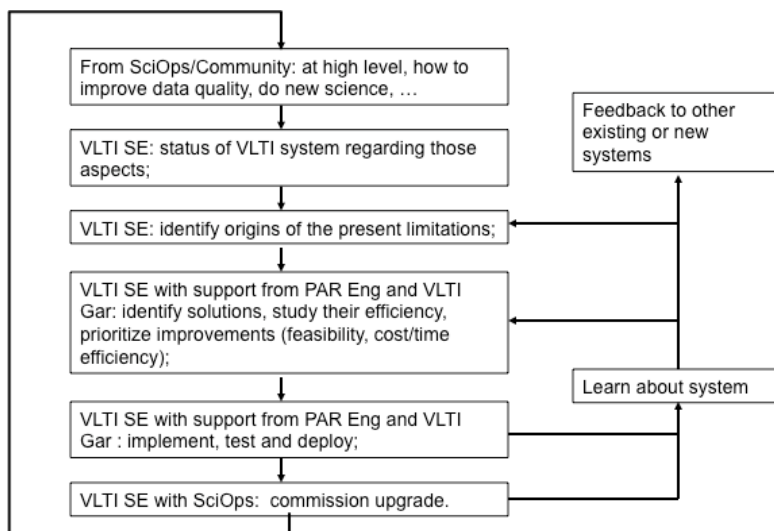


Figure 1 – System Engineering approach used at Paranal.

An important amount of time on the VLTi, both night and day, has been necessary to reach the current operation level at the VLTi, each improvement requiring testing time and validation on sky. But this time can be considered to have been wisely spent looking at the achievements. Figure 2 presents the statistics of use of the VLTi night from periods P85 (started April 2010) to P89 (current). During this period of time, the performances of the systems were improved and the operations made more reliable, resulting in less need to dedicate time for technical tests. From the figure, one can see that the time dedicated to scientific observations has been increased by almost 50%. Technical nights are still always scheduled at regular intervals in order to allow testing new procedures, bring improvements, and monitor and test the system to ensure that the performances are maintained.

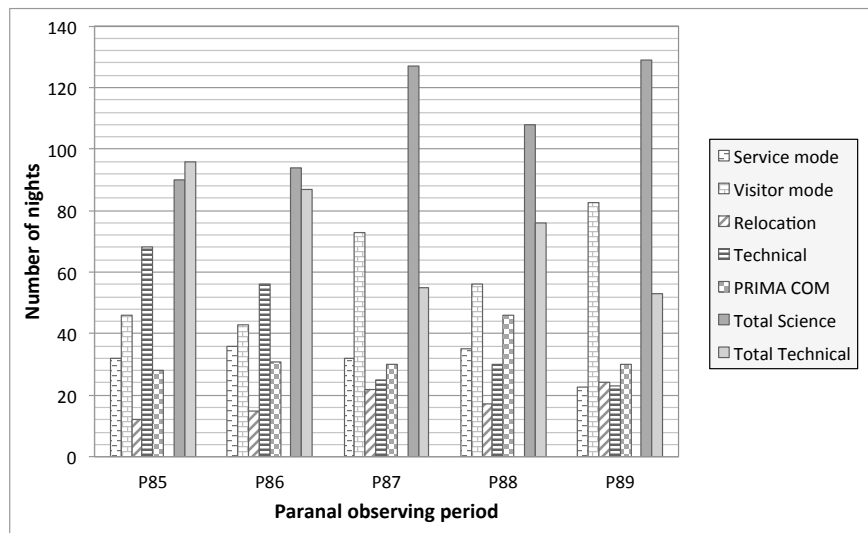


Figure 2 – Statistics of use of the VLT nights from P85 (April 2010) to P89 (current).

2.3 2012+: Ready for the future

After all these efforts, the interferometer is for some time now fully embedded in the Paranal Observatory as any of the UTs. The strong effort invested by Paranal on the VLTi has allowed very good results, bringing the VLTi to the same operability level as the UTs. The VLTi downtime is still slightly higher than the average for the UTs due to the higher complexity and the number of systems in operation together during VLTi operation. It is to be noted that the VLTi has started in P86 operation with the four ATs simultaneously, whereas before only three out of the four were offered each night. This was mandatory with the arrival of PIONIER (see later in the text). Even with the increased number of systems (one more telescope + delay line, relay optics) to be operated simultaneously in this mode, no more downtime was reported. The switch from three to four telescopes operations was made in a quite straightforward way, showing that the global VLTi system and its control is already designed to handle configurations with higher numbers of telescopes. Hybrid configurations combining ATs and UTs have also been tested without major problems; even if this mode is not 100% operation-ready, there is no showstopper to this kind of operation.

The time needed to execute an observation has also been drastically reduced by this effort (*add OB time improvement*). This was made possible through the knowledge acquired on the system, improvement of reliability and automation of processes. The effort made in improving the efficiency of observation was of course of prime importance for the interferometer to ensure that data can be well calibrated and to improve the number of measurement points in the UV plane.

The important effort already invested by ESO into the VLTi can of course still be completed to continue improving the facility, reliability, performances, but the operation level shown today is already showing the readiness of the VLTi for its future challenges.

3. VIBRATIONS CONTROL

3.1 Vibrations status

One factor that has plagued the VLTi science with the UTs, preventing to reach the performances that could be expected, were the vibrations. The jitter of the optical path difference (OPD) created by the vibrations of the UTs is decreasing the transfer function of the system. It makes some systems and control loops to be less robust and it lowers the maximum integration time possible with the instruments.

As such an important part of the SE effort has been dedicated in identifying and reducing the sources of vibrations, while implementing at the same time real time corrections. The following describes the main actions that have been implemented to tackle the vibrations problem:

1. Telescope characterization and identification of vibration sources:
 - The accelerometers (Manhattan2) implemented on M1, M2, and M3 for OPL measurements are used before each UT run to determine the telescope “signature”, i.e. the OPL power spectral density (PSD).
 - Several measurement campaigns with FINITO and AMBER in parallel have been performed to determine the OPD PSD.
 - Tests of switching off several instruments were used to identify their contributions to OPL and OPD.
 - The wind contribution on the telescope and vibrations has also been studied.
2. Main corrective actions:
 - Accelerometers system Manhattan2 (MN2): brings typically an 80-150 nm RMS improvement.
 - New close cyclo-coolers suspension for CRIRES (good improvement) and HAWK-I (lower impact).
 - Optimization of the Cassegrain and Nasmyth rotators (parking) positions.
 - Damping of pumps (FLAMES, UT2).
 - Modification of the M4 mirror mount and design of a damper for the M5 mount.
 - Modification of fans and auxiliary cooling fluid pumps and piping (ongoing).

The status of the OPD residuals is summarized in Table 1, for the UTs alone and per baselines. The OPD rms per UTs is given for frequencies higher than 5Hz as the measurements at lower frequencies cannot easily be disentangled from effects other than vibrations. The values per UT are the ones provided by MN2. The MN2 OPD for the baseline is calculated as the quadratic sum of the measurement of the UTs alone. The FINITO OPD corresponds to the residual after fringe tracking correction. The rms is given over an integration time of 290 ms. Only measurements of three out of the six baselines are presented. The values for baselines UT1-UT3 and UT1-UT4 are expected to be close to UT2-UT3 and UT2-UT4. The baseline UT3-UT4 combining the two noisiest telescopes in terms of vibrations should be close to 380-400nm RMS. The OPD presented in the table are only considering the vibrations part. If the weather degrades and/or if the different control loops used in operation cannot be used at their optimum (lower integration time on the IRIS guiding camera and FINITO fringe tracker), the OPD residuals will be higher.

Table 1 – Status of the OPD generated by vibrations, per UTs and per baselines.

Per UT	MN2 OPL (> 5Hz)	Per Baseline	MN2 OPD	FINITO OPD (over 290 ms DIT)
UT1	200	UT1-UT2	250	265 / 315
UT2	145	UT2-UT3	270 / 410	380 / 470
UT3	230-380	UT3-UT4	410	450 / 485
UT4	320		-	-

Figure 3 presents the evolution of the OPL rms generated by the vibrations for the four UTs, from January 2009 to today. Thanks to the work done by Paranal on reducing the sources of vibrations and optimizing the systems, UT1 and UT2 have reached a good level that has been maintained equal for the last two years, despite modifications were made on the telescopes and instruments during this period. UT3 and UT4 still have a higher level of vibrations, mainly due to more noisy instruments. This also makes them more sensitive to the correct adjustment of the parking position of their instruments when they are used in the VLTI configuration, and a more careful and constant control is needed.

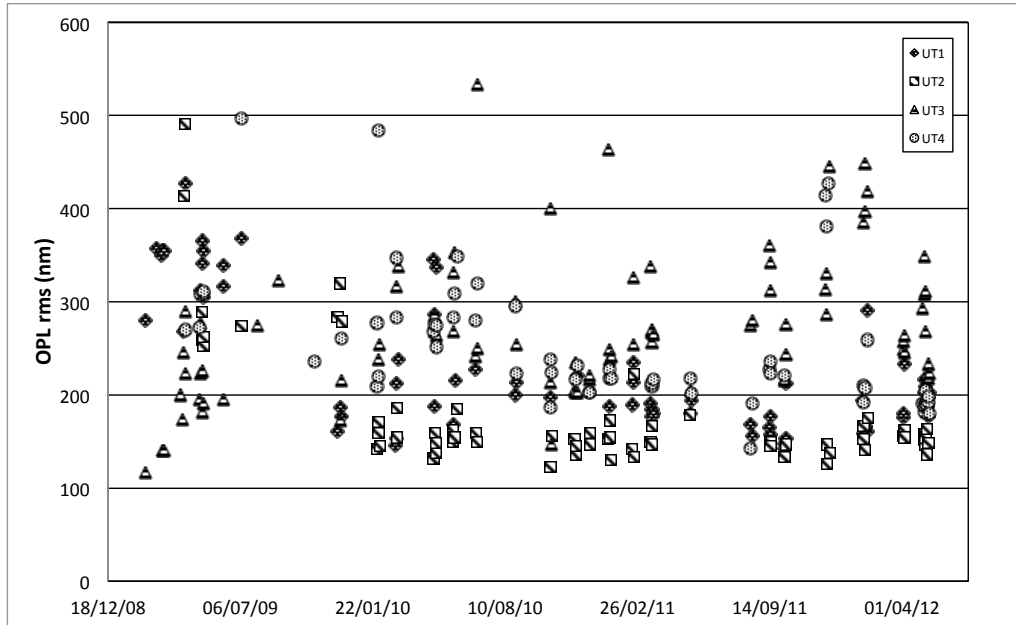


Figure 3 – Evolution with time of the OPL rms for the four UTs.

3.2 MAMMUT

MAMMUT (Mirror vibrAtion Metrology system for the UTs) is a fiber interferometer designed to measure the vibrations of the mirrors in the optical train of the UTs. The system will provide a real time measurement of the OPD for a single telescope with a frequency range up to 100 Hz and a resolution of 1 nm. MAMMUT is composed of a fringe sensor unit providing the OPD measurements and a coherent source beacon. The coherent light source consists of a 250+250 m long fiber interferometer with active internal OPD stabilization. The OPD is measured in free space in the telescope, between fibered launcher and receiver. The part coming from the free space propagation interferes in the fringe sensor unit with the signal delivered by the second arm of the interferometer used as phase reference. MAMMUT operates at 1300-nm, within the gap between the H and J bands. Figure 4 present a schematic view of the MAMMUT system with its different components.

A prototype of the system has been delivered to Paranal and has been re-assembled and tested in laboratory to verify its performances in the Paranal conditions. The interface to one UT is being prepared. MAMMUT will be used as a daytime system to measure the vibrations in the Coudé train, for mirrors M5 to M9. This will provide important information on vibrations, combined to MN2, which is providing information for mirrors M1 to M3. Information on vibrations for the Coudé train alone will there be available. Amplitude and frequencies of the vibrations detected at this level should allow an easier identification of the sources and a better optimization of the solution to counteract their effects.

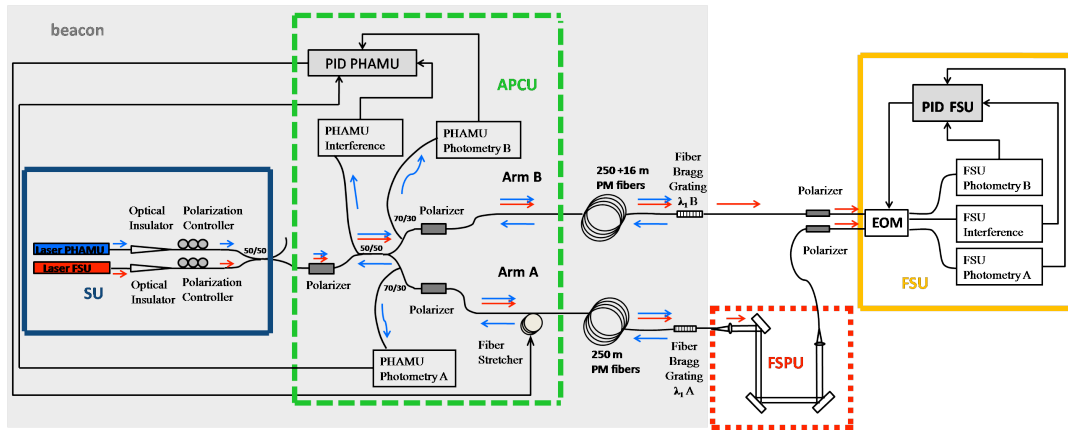


Figure 4 – Schematic view of the MAMMUT system.

4. AMBER

4.1 Coherencing

At the end of 2009, tests were done to enable the group delay tracking capability in AMBER. Until then, the centering of the fringes in the instrument was done manually by adjusting the internal OPD. But AMBER provides its own OPD estimation for all three baselines and this information can be used to send low frequency corrections to the delay lines. This mode is of course not as efficient as the fringe tracking provided by FINITO, but is intended to be used on faint targets or with bad weather conditions when the fringe tracking is not possible or not efficient enough.

After technical testing of this coherencing mode to assess the possible improvement for the performances, the mode has been integrated into regular operation of AMBER and offered for P89 (April 2012). The mode has proven to increase the scientific performances in the range of operation it is designed for. Further improvement might be done to increase the performances even further, but the mode is now fully available to VLTI observers.

4.2 Blind mode

During year 2011, some technical time has been granted by ESO to the Lagrange Laboratory and the Max Planck Institute for Radioastronomy to test on AMBER a “blind mode” which aimed at pushing further the limiting magnitude of the instrument. The mode was tested on the ATs and also on the UTS during GTO and open time. The method uses a 2D Fourier Transform of the fringes to detect the fringes and center them in the instrument.

Fringes were detected with the UTs down to magnitude 11.7 in K, and to a magnitude 7 with the ATs. The different tests performed on sky have allowed improving the observing strategy thanks to the experience acquired. A preliminary analysis of the data has been performed and will require further work before fully concluding on the exact improvement brought by the method, checking the scientific analysis and use of the data. But the increased limiting magnitude shown by the method is encouraging.

5. PIONIER

In 2009, ESO opened for proposal a VLTI focus for a visitor instrument, following the same scheme as what had been offered earlier on the UTs. The opening of the visitor focus came through a window of opportunity in the gap between the first and second generation of instruments. PIONIER became the first VLTI visitor instrument [10].

The Institute of Planetology and Astrophysics of Grenoble (IPAG) proposed PIONIER (Precision Integrated-Optics Near-infrared Imaging Experiment) in May 2009 and the project was presented to the Science and

Technical Committee in April 2009. The instrument was accepted as a fast track project for the window of a few years before the arrival of GRAVITY and MATISSE. As PIONIER allows to combine four telescopes at the same time, the project was also of high interest for ESO as it would allow to test the VLTI in this mode required by the second generation instruments in an early phase. The procurement phase for PIONIER started in September 2009 and the integration at IPAG was conducted during the first half of 2010. PIONIER was integrated at Paranal between October 20th and 24th, and its first fringes obtained during the first two hours of its first night on sky. The instrument showed to be immediately ready to deliver data at scientific level. PIONIER has since then been used routinely on the VLTI with the ATs, with new science coming out thanks to the imaging capability it enabled. A first technical test of PIONIER on the UTs was performed on March 17th 2011 and PIONIER is now also used on the UTs since April 2012.

PIONIER is an integrated optics (IO) based 4-telescopes beam combiner. Its simple and compact design together with the use of well-known and tested technologies provides a very good stability to the instrument. The original design was made to cover the H band wavelength range, but the possibility to switch to K band has been demonstrated in April 2012, showing at the same time the easy reconfiguration of the instrument thanks to its fibered IO combiners. PIONIER has limited spectral resolution, with two modes: $R=5$ or $R=45$. Polarization analysis is also possible thanks to a Wollaston that can be inserted between the combiner and the detector. Figure 5 presents the schematic view of PIONIER and a picture of the instrument installed in the VLTI laboratory.

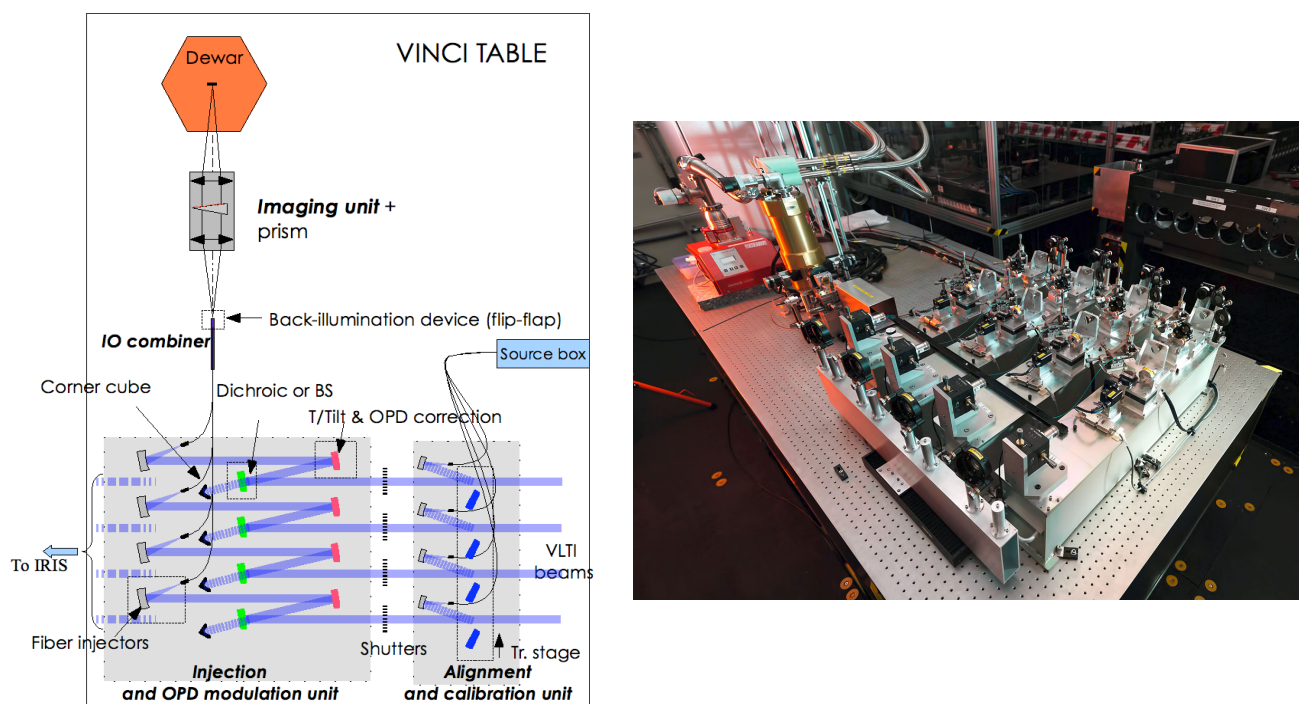


Figure 5 – Schematic view of PIONIER and the instrument installed in the VLTI laboratory.

6. ONGOING & FUTURE

6.1 PRIMA

The initial AIV (Assembly, Integration, Verification) of PRIMA (Phase Referencing Imaging and Microarcsecond Astrometry, [11,12]) took place in July/August 2008, and a number of technical, commissioning and astrometric runs have been scheduled since then. PRIMA achieved readiness of its subsystems for first science measurement in September 2011 and the first astrometric measurements were performed. The performances obtained then were quite far from the needed ones to allow the scientific goal of the instrument. From March to May 2012, a system analysis of PRIMA was performed to try to identify the

causes of the limitations in the measurement accuracy. The analysis team has delivered its recommendations and implementation and future steps are being discussed.

In parallel to the astrometric mode, tests have been performed in October 2011 with MIDI using the fringe sensor unit A (FSUA) in on-axis and single-feed mode [13]. The test has been performed as collaboration between ESO and the Max Planck Institute for Astronomy of Heidelberg. Targets about 20 times fainter in N-band than what is usually obtained with the ATs and MIDI alone could be observed. A significant gain in sensitivity has been obtained by using the FSUA as fringe tracker. The possibility to offer this mode to the community in P91 is being looked at by ESO.

6.2 GRAVITY

GRAVITY [14] is a four-beam combiner, dedicated at imaging with a 10-microarcsec astrometric capability. Spectrometric and polarization analysis capabilities will also be available. GRAVITY will use the light in K-band of the on-axis beam as a reference for fringe tracking, while measuring on the off-axis beam. The combination of the two times four beams (on and off-axis) will be performed with a fibered integrated optics component, performing the modal filtering, compensation of differential delay and adjustment of polarization. A low-resolution (5-pixels) spectrometer provides internal phase- and group-delay tracking on the fringe-tracking star, so that long integrations become possible on the second channel, usually a fainter science object. A dedicated metrology will monitor the optical path length from the beam combiner to the M2 spider. A more detailed description is given in [1].

The final design review of GRAVITY has been done in December 2011 and March 2012. A list of actions has been identified to complete the final design study. Its installation at Paranal is planned for the horizon 2013-2014.

6.3 MATISSE

MATISSE [15] will be a mid-infra-red spectro-imager working in L, M and N bands and combining up to four telescopes beams. It will thus open new wavelength windows with the M and N bands, and also bring closure phase capability to the N band. MATISSE will allow to perform interferometric spectroscopic with three different spectral resolutions in the range $R \sim 30$ -1250. A more detailed description is given in [1].

MATISSE went through its final design review in April 2012, concluding on a list of actions and tasks to be performed before it is granted. Its installation at Paranal is planned for 2016.

ACKNOWLEDGMENTS

We would like to thank here all the work done by the VLTI groups in Garching and Paranal. The continuing support of the AMBER and MIDI consortia after the installation of the instruments was very valuable in the improvement of the scientific data quality. Fruitful discussions over the years with the interferometric community have brought valuable inputs to the development of the VLTI. The current and future VLTI status also benefited from collaboration with the teams studying the second generation of instruments.

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