

The Very Large Telescope Interferometer: status and plans

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Abstract. The Very Large Interferometer is undergoing an important mutation. In this paper we present an update on the status of the VLTI and a description of the technical roadmap to prepare for the arrival of its second generation instruments GRAVITY and MATISSE.

1. Introduction

1.1 VLTI Infrastructure

The Very Large Telescope Interferometer (VLTI) is located in Cerro Paranal, Chile. It provides the VLT with an interferometric capability. With the maximum baselines in operation (i.e $\approx 150\text{m}$) angular resolution of the order of 2 milliarcseconds in the near-infrared and 10 milli-arcseconds in the mid-infrared can be reached. As of today the interferometric infrastructure of the VLTI consists of the following main elements (see Haguenaer et al. 2012 for a detailed description):

- Four Unit telescopes (UTs, 8m diameter) providing up to four simultaneous beams to the VLTI beam combination laboratory;
- Four relocatable Auxiliary telescopes (ATs, 1.8m diameter) providing an enhanced uv plane coverage capability;
- Six delay lines in their tunnel with the distributing optics;
- Four adaptive optics system at each UT focus (MACAO);
- A beam combination laboratory where focal instrumentation is located including beam compression, beam selection and routing, infrared-tip/tilt sensor, coherent four beam source and fringe tracker. (FINITO).

1.2 Observing and telescope configurations

VLTI users go through the exact same proposal submission and OB preparation process as for the other VLT instruments. The VLTI users can rely on two main observing modes Service and Visitor. The first guarantees that the observations will be repeated by VLTI astronomers until the data quality has reached the

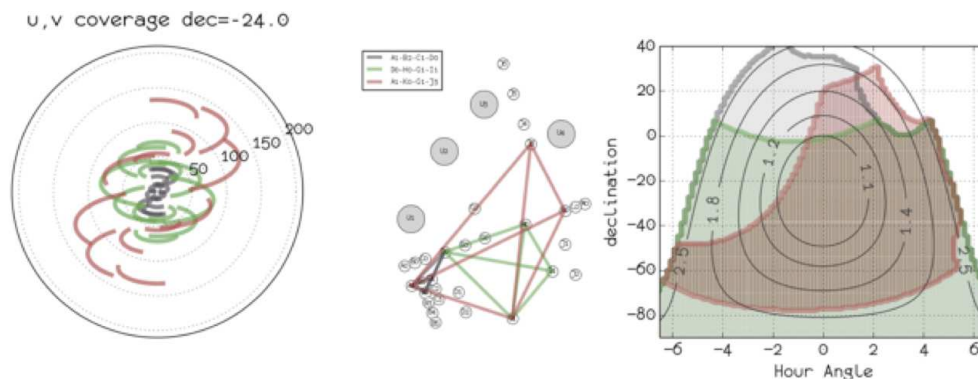


Figure 1.: Currently offered AT stations and corresponding u,v and sky coverage for a source at $\text{dec} -24^\circ$ for the three telescope quadruplets

guaranteed level. The second one is usually allocated in situations where the expertise of the PI is requested on the mountain or if the time has been allocated through a GTO¹ agreement. It allows the observing strategy to be optimised based on a real-time appreciation of the situation but does not guarantee the best seeing conditions. All raw data are immediately stored in the ESO archive.

In order to provide the possibility of a well covered u,v plane the PI can choose among three AT telescope quadruplets (currently A1-B2-C1-D0, D0-H0-G1-I1, A1-G1-J3-K0) and the four fixed UTs (c.f. figure 1). The quality of the u,v mapping will depend on the position of the source in the sky which can be a strong limitation if the location is in the North (declination $\geq 10^\circ$). This is due to a combination of technical constraints i.e delay line stroke ($\approx 100\text{m}$), pupil relay (field of view), beam distribution. Moreover, the AT relocation capability is limited to two per days which sets the limit of how many reconfigurations can be done. The reader is referred to the presentations by Antoine Merand in the VLTI community days (<http://vlti-pionier.sciencesconf.org/>) for a better understanding of the configurations constraints.

1.3 Instrumentation

In addition to the ongoing PRIMA project there are currently three instruments in operation at Paranal. MIDI and AMBER are official instruments that can be operated either in service or visitor mode under the responsibility of ESO. PIONIER, the most recent one, is a visitor instrument also offered to the community.

PRIMA PRIMA is a VLTI infrastructure project that was motivated by three main science cases:

1. providing AMBER and MIDI with better sensitivity through on/off axis infrared two telescope fringe tracking;

¹Guaranteed Time Observations

2. enabling narrow-angle astrometry at the ten microarcsecond level in order to detect the exoplanet-induced wobble of host-stars (a project led by the ESPRI science consortium);
3. experimenting phase referencing imaging with AMBER and MIDI by measuring the astrometric distance of the science object with a joint reference source.

In order to reach that goal the PRIMA infrastructure project had to develop a series of new subsystems for the VLTI:

- a fast data transmission ring network (RMN);
- four star separator systems on the UTs and the ATs that provide dual feed capability and allow the light of two objects separated by up to 30" (science and reference) to be sent to the VLTI combination lab;
- four differential delay lines to record the fringes on both dual feed targets;
- two two-telescope fringe sensor units operating in the K band (FSU-A, FSU-B);
- PRIMET a two telescope metrology system linking both FSUs and measuring the internal optical path difference up to the ATs M2 mirrors.

PRIMA is currently almost fully operational in its two telescope configuration. However the astrometric commissioning process of PRIMA has been interrupted in 2011 because some major issues with the metrology endpoints were identified that precluded to reach the final astrometric performances. The following years, an in-depth technical and system analysis has lead to several recommendations on how to reach the accuracy goals. In particular the recommendation to push the metrology endpoints to the M2 space was pointed out as a significant improvement. The PRIMA team implemented several of these recommendations and was able to carry on the first astrometric measurements with the new metrology endpoints in october 2013. While the improvement in performance was very significant (e.g $\approx 100\mu\text{arcsec}$ on a single one hour measurement and with two bright sources) it was still not sufficient for the exoplanet science case. Based on the results the PRIMA team proposed a full recovery plan that will be presented for evaluation in the context of a "gate review" process

MIDI² is a mid-infrared (N band) two telescope beam combiner that provides two observing modes HIGH SENS and SCI PHOT that allow the observer to choose to privilege sensitivity or photometric calibration (i.e precision). Two spectral resolutions PRISM (R=30) and GRISM (R=230) are available. MIDI can also provide self-coherencing, i.e track its own fringes. MIDI's performance on the ATs have considerably improved with the use of the PRIMA-FSU that compensates the random atmospheric optical path difference fluctuations. A gain of a factor of a $\approx 5 - 10$ in sensitivity is currently reported. MIDI will eventually be decommissioned to make way to MATISSE.

²see <http://www.eso.org/sci/facilities/paranal/instruments/midi/overview.html> for an overview

AMBER³ is a three telescope beam combiner originally planned to cover the J,H and K bands with small, medium and high spectral resolutions. The user can choose between Low Resolution (35, J,H,K filters), Medium Resolution (1500, H, K filters) and High Spectral Resolution (12000, K band). In practice, due to the sensitivity to fast atmospheric conditions of the fringe tracker FINITO, and probably coupling issues at those short wavelengths the J band is not exploitable and high spectral resolution is limited to K band. The Medium and High spectral resolution often require the external fringe tracker FINITO to be operational. Like MIDI, AMBER possesses a self-coherencing algorithm that allows the fringes to be centered with low frequency correction. AMBER provides visibility and closure phases measurements together with differential visibilities, phases and closure phases. Mérand et al. (2012) have demonstrated how the phase measurements of FINITO could be used for an *a posteriori* calibration of the visibilities. The improvement is very significant in low spectral resolution and relies on the computation of a *jitter* corrective term for each AMBER frame measurement. More recently a Fourier method developed at Observatoire de la Côte d’Azur was demonstrated to lead to significant improvement in sensitivity. However the quality of calibration is currently under review at ESO.

PIONIER⁴ stands for Precision Integrated-Optics Near-infrared Imaging Experiment. PIONIER is a 4-telescope visitor instrument for the VLTI that combines four ATs or four UTs using an integrated optics combiner. It provides low spectral resolution in H band (1, 3 or 7 spectral channels) and occasionally in the K band. PIONIER is designed for imaging with a specific emphasis on fast fringes recording to allow precision closure-phases and visibilities to be measured. It is currently offered to the whole VLTI community either in visitor or delegated visitor mode. The latter mode is a contribution from ESO that allows the PI to have its observations carried by one of the VLTI operations astronomers. PIONIER data are now stored officially in the ESO raw data archive.

1.4 Operations statistics

Figure 2 summarizes in three plots some VLTI statistics extracted from the night-logs since 2004. The top figure represents the distribution of night status between No Operation, Commissioning, Technical time, Service and Visitor mode. The middle one describes the scientific science time breakdown between the four instruments operated at VLTI (VINCI, MIDI, AMBER and PIONIER). The last one represents the distribution of time-loss. All these quantities are given as a function of time.

Two main conclusions emerge from these plots:

- the technical time losses at VLTI have been brought to a very low level ($\approx 10\%$) thanks to a considerable investment of system engineering;
- the fraction of time devoted to science has considerably increased and represents on average now 70% of the observing time;

³see <http://www.eso.org/sci/facilities/paranal/instruments/amber/overview.html> for an overview

⁴<http://ipag.osug.fr/twiki/bin/view/Ipag/Projets/Pionier/WebHome>

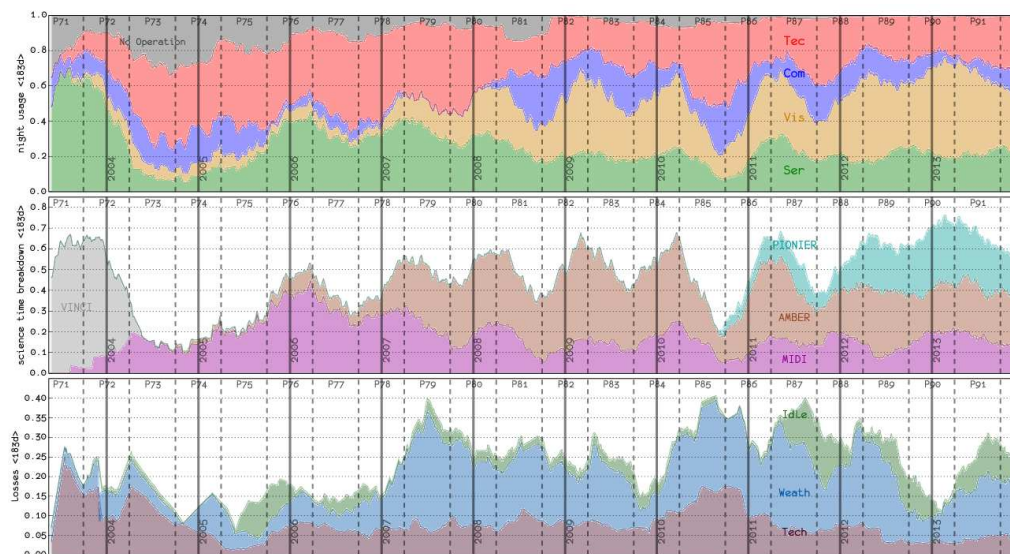


Figure 2.: *Operational statistics for VLTI (see text).*

1.5 VLTI 1.0: Lessons learnt

The last years has demonstrated that bringing such a complex infrastructure to an operational level requested an significant investment in system engineering to hunt down systematically any sources of unreliability. Considerable progresses have been made in the delay-lines, ATs, tip/tilt sensors, global setup procedures etc. Without this effort VLTI would still be plagued with significant technical downtime.

Weather Cerro Paranal is known to be a fast seeing site. High seeing will lead to the degradation of the amount of light couple into the AMBER, FINITO or PIONIER singlemode fibers. Low temporal coherence times affect severely the capability to fringe track and therefore reach interesting limiting magnitudes or spectral resolutions. Statistics on weather measurements show the following:

- January/February is the best time for interferometric observations (low seeing but high coherence time);
- July/August in general correspond to very fast turbulence;

The weather-induced limitations have lead to define seeing constraints 0.6", 0.8" and 1.0" in the call for proposals that will determine the limiting magnitude. This is currently an important limitation in VLTI overall performance. It is a strong incentive to develop NAOMI and adaptive optics system for the ATs and a robust four telescope fringe tracker.

Imaging The interest of carrying on image reconstruction out of interferometric data is motivated by the fact that these will bring additional value to the astrophysical interpretation. In particular the usual limitation of model-fitting

techniques relies in the strong *a priori* knowledge on the object brightness distribution. Aperture synthesis aims at reducing as much as possible a priori information in the analysis process.

Experience has shown that a large and efficient u,v coverage is mandatory to carry on such an effort. VLTI offers the possibility to use four quadruplets of auxiliary telescopes and combine it with earth-rotation synthesis to pave the u,v plane. This has proven successful in a handful of cases in the AMBER case but the advent of four telescope combination with PIONIER has clearly shown a quantitative jump in efficiency. The operational constraints of allowing four telescope reconfigurations are strong. Only two can be moved per day, if wind conditions permit and are accompanied with the subsequent telescope pointing models.

Performance. Performance is an umbrella term that encompasses sensitivity, observing efficiency, robustness to internal or atmospheric conditions. VLTI has a very decent transmission that is regularly monitored and is of the order of 30% in K. However the final throughput efficiency is given also by the instrument transmission. In particular the coupling into single mode fibres is a strong factor. A significant effort has been put into improving AMBER’s limiting magnitude by conducting a full realignment of its internal optics. More recently the introduction of differential birefringence compensators inspired by PIONIER’s have allowed the polarising beam splitters to be removed. Overall AMBER has gained about two magnitudes in sensitivity over the course of the last few years. The addition of a self-coherencing mode in AMBER has permitted the centering of the fringes. This has led to significant improvement of visibility and closure phase accuracy. The FINITO fringe tracker, operating in the H band, has enabled to exploit the high spectral resolution of AMBER. Unfortunately its performances are overall disappointing because of high detector readout noise, throughput and a significant sensitivity to atmospheric flux coupling dropouts. More recently PRIMA Fringe Sensor Unit (FSU), operating in the K band, has demonstrated the capability to track on $K \approx 8$ sources and has been offered in combination with MIDI (K band is better suited for MIDI "red" objects than the FINITO H band). The sensitivity has been shown to increase by a factor of $\approx 5 - 10$. This is obtained through a posteriori coherent integration of the signal (Pott et al. 2012). Unfortunately, vibrations in the UTs prevent the efficient use of the fringe sensor on the UTs. Therefore this possibility is currently used mostly on the ATs.

Scheduling The VLTI users are currently offered full freedom in their choice of telescope configurations and instrument parameters. The current scheduling is based first on the highest ranked visitor mode. This can generate clear conflicts between proposals with different goals. For example an imaging proposal will privilege fast u,v coverage while temporal monitoring will request several measurements on regular temporal sampling with the same telescope configuration. This is currently an important limitation since it has conducted to reject highly ranked service mode proposals because the telescope configuration was not available at the time of the planned observations.

Vibrations Vibrations have been identified as the major performance offender for VLTI instruments when used on the UTs. Among the three currently offered

instruments AMBER is suffering the most since it has shorter wavelengths than MIDI (hence a similar vibration jitter will lead to stronger contrast decrease and transfer function instability) and lower frame rates than PIONIER. Both tip/tilt and piston vibrations contributions have been measured. Systematics studies of the possible sources of vibrations (telescopes, instruments, wind) have led to a much clearer picture of their origins. Both active and passive strategies have been employed to tackle the problem and have led to significant performance improvement (see Haguenaer et al. 2012 and Poupar et al. 2010 for detailed information). Instruments are now monitored and their design corrected once vibration contributors are identified. Accelerometers are in place and are used to provide the measurements for an active optical path compensation. However, a recent internal study was able to study the vibrations once all VLT instruments of the UT1-UT3 pair were shutdown and concluded that the level of vibrations remained sufficiently high to be incompatible with GRAVITY's request. Reducing it further would require a dedicated active control covering all the optical path thanks to a metrology system. As of this writing the exact nature of such a control system has not been defined but could find inspiration from the solution adopted at Keck Interferometer.

2. Scientific use of VLTI

At the end of 2012 approximately 205 PIs had submitted proposals to use the VLTI. Among this list 137 were recurrent users (i.e. had more than 1 program). The PIs home institution belonged to 22 countries (see fig. 3) showing that VLTI had succeeded in reaching out a wider community than the core interferometric institutions.

The angular resolutions and precisions permitted by VLTI AMBER and MIDI (≈ 2 mas in the K band, 10 mas in the N band) have led mostly to studies of circumstellar environments and fewer stellar surfaces ones which very often are only marginally resolved. However prior to that, VINCI the VLTI commissioning instrument with its accurate precision measurements was extensively used to reach a number of milestones. Among those achievements VINCI was used to establish a precise measurement of the surface-brightness relationships in dwarf stars (Kervella et al. 2004). The traditional strengths of the VLTI are the studies of giants/supergiants, hot stars, evolved stars, young-stellar objects, massive young stars, B_e , [e] with astronomical unit resolution (or even better). In particular, AMBER, with its spectral resolution has permitted several emission lines to be spatially resolved in diverse environments. This was done either directly through visibility measurements but also through the powerful spectro-astrometry technique. This led to the discoveries of wind emission around intermediate-mass young stars (Herbig AeBe), shocks in Novae, Keplerian rotation in B_e disks etc. MIDI was used to probe the dust distribution and composition in circumstellar environments. Of particular significance was the discovery of a dependence of the fraction of dust crystallinity as a function of the distance from the star in young stellar objects disks which is related with the dust processing and probably the planet formation process. MIDI has now surveyed a significant amount of young intermediate mass stars of all evolutionary status as well as evolved stars.

One of the most spectacular achievements of VLTI was to provide, through MIDI's mid-infrared observations, the possibility to survey the brightest Active

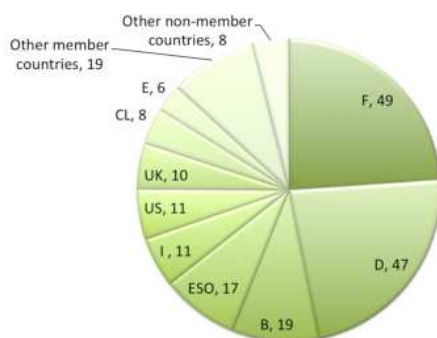


Figure 3.: *Number of VLTI proposal PIs per country.*

Galactic Nuclei with milli-arcseconds resolution. These observations challenged the traditional image of a dusty torus obscuring the view to the central hot accretion disk and black hole by revealing an important variety of objects and in particular in some cases evidence for strong polar elongations most probably caused by winds. The challenge of the AGN unification model is certainly not a small feat and should pursue with the arrival of MATISSE.

3. Preparing for the second generation instruments

3.1 Instrumentation

GRAVITY (Eisenhauer et al. 2011) is a four telescope beam combining instrument operating in the K band. It includes a science combiner and a fringe tracking combiner. GRAVITY allows for "standard" interferometric observation like AMBER or PIONIER but also narrow-angle astrometric observations. The later mode requires the presence of a reference source in the $\approx 2''$ field of view of the VLTI on the UTs.

The top science case of GRAVITY is focused on the Galactic Center and aims at tackling the following topics:

- uncovering the true nature of Sgr A* flares probing spacetime close to the black-hole (BH) horizon;
- testing General Relativity with stellar orbits and ultimately in the strong gravity regime;
- address the paradox of youth of galactic center stars.

But GRAVITY is also a powerful spectro-imager with milli-arcsecond resolution that will open new scientific avenues from the measurements of AGN's broad-line regions to the detection of young-stellar objects jets at the spatial scales where they form.

GRAVITY requires a significant modification of the VLTI infrastructure in order to reach the astrometric capability. The following subsystems will have to be implemented:

- infrared wavefront sensors for the MACAO adaptive optics at each UT focus in order to peer through extinct environments (e.g the Galactic Center);
- star separators (STS) at each telescope focus (UTs and ATs) in order to feed the adaptive optics systems (UTs) and to provide a pupil control capability thanks to the STS' variable curvature mirrors;
- a metrology system that projects a laser light all-the-way down to the primary space (telescope spiders) where the optical path distance will be measured.

GRAVITY is currently scheduled to begin operations in ≈ 2016 .

MATISSE is a four telescope beam combiner that will be operating in the L, M and N bands. It will be opening the $[3, 5]\mu\text{m}$ window for the first time in interferometry offering a unique window at warm $\approx 700\text{K}$ dusty and gaseous environments (spectral resolutions 30, 50, 2000). The spatial scales probed will correspond to those of ALMA at its maximum resolution providing a complementary insight at the properties of stellar environments. With MATISSE the considerable increase in u,v coverage will be instrumental to lift the usual degeneracies one is faced with when using a few two-telescope observations.

MATISSE is particularly expected in the following domains:

- circumstellar environments of young low and intermediate mass stars;
- formation of massive stars (usually deeply embedded);
- exozodiacal dusty disks;
- dusts and winds from evolved stars;
- the close environments of hot stars;
- the dusty environment of active galactic nuclei.

In particular the imaging capability of MATISSE is expected to play a role in revealing the exact morphology of AGNs mid-infrared and confirm the recently discovered elongated structure along the polar axis (Hoenig et al. 2013) that could be attributed to a wind component. This could trigger a significant revision of the unification scenario.

Matisse is currently scheduled to begin operations in ≈ 2017 .

PIONIER is expected to stay on the mountain after the laboratory has been adapted to GRAVITY and MATISSE. A specific location has to be found in the laboratory. A possible evolution for PIONIER could be to implement medium resolution (e.g a few 100) to enable observations of dusty environments with dusty molecular composition such as Mira stars.

3.2 Challenges for the VLTI

In the coming year the VLTI will be confronted with several important challenges starting with the preparation of the infrastructure for GRAVITY and MATISSE. This includes, among others, the completion of all STS, the laboratory modification, the re-commissioning of the ensemble together with a revision of operational procedures.

Following that four main challenges will have to be tackled.

The challenge of performance. In order to improve VLTI instruments overall performances a certain number of actions are considered.

1. provide ATs with an adaptive optics system called NAOMI to reduce VLTI sensitivity to weather conditions and in particular to improve the coupling into single-mode instruments and limit the flux dropouts in fringe trackers. The project is currently preparing for PDR at the fall 2014;
2. an active, metrology-based, vibration control is currently considered for the UTs. It should start with a phase A study.
3. a second generation fringe tracker was initially envisioned. It is mandatory for MATISSE to reach its ultimate performances. Based on resources constraints it is currently delayed. It is expected that the GRAVITY fringe tracker will bring significant expertise once in operation.

Another item relevant of performance will be the overall capability to schedule programs. A modification of the scheduling to better address this problem will probably lead to certain limitations in the configuration flexibility offered to the PI with the advantage of better scheduling of more OBs. Increasing service mode is another way to improve the scientific return and best-seeing exploitation at the VLTI.

The challenge of imaging. Paving homogeneously the u,v plane is a critical demand of imaging programs. The currently offered configurations are probably not far from the optimum of what can be realistically done operationally. Some progress can probably be made in offering better u,v -filling ones. The possibility to choose between four telescope out of two UTs and four ATs is an interesting idea that is currently being evaluated but that will probably be facing hard technical limitations (different static opd, beam stopping etc.).

The preparation and observing tools will have to evolve since a typical imaging program will request several tens (hundreds ?) of OBs. Following the progresses of the program throughout the service mode schedule will be a first challenge. The user will have also to generate an important quantity of OBs in a user-friendly way. Finally image reconstruction softwares will have to become widely available although it is very probably that the expertise on how to use them correctly will remain the knowledge of a few.

From the astrophysical point of view the temporal variability of the objects will be a strong constraint in the scheduling. It is probable that it will hard to get a full u,v configuration in less than three weeks.

The challenge of narrow angle astrometry The PRIMA team has accumulated a lot of expertise in understanding issues related to the calibration of astrometric measurements. GRAVITY's astrometric requirements will be equally tough even though in practice the exact system implementation and requests are not identical. The PRIMA knowledge will have to be passed onto the GRAVITY project

The challenge of growing the community A considerable effort has been done to provide the VLTI users with easy to use observation preparation and data reduction software. Both ESO and Jean-Marie Mariotti Center (JMMC) are accompanying the users. However optical interferometry still requires a significant technical knowledge. Increasing the community of users will require to carry-on a significant effort to provide services similar to ALMA nodes. The accessibility to reduced data directly from the archive or to specialists capable of reducing the data or carrying on the image reconstruction should be an ambitious goal set in agreement between the community and ESO.

4. Concluding remarks

As can be seen it is very probably the next decade will be busy bringing VLTI and its three instrument GRAVITY, MATISSE and PIONIER to their full performance.

It is hard to project the VLTI in the Extremely Large Telescope era not knowing exact timescales. However one can envision a few incentives to continue the exploitation of VLTI:

- no faint companion instrument has been contemplated so far at VLTI. Although PIONIER has shown very good capability at searching for companion it is clear that there is an important margin of progress if the instrument is properly designed for this sole purpose.
- the combination of the intrinsically diffraction limited VLTI observations, the spectro astrometry technique and maximum baselines of 150m will keep VLTI has the european instrument with the highest resolving power. Going towards shorter wavelengths (e.g the visible) with high spectral resolution, while challenging, could open new windows complementary to other techniques such as asteroseismology. This could pave the way of direct characterisation of stellar surfaces in the transit missions context.
- extending the array combination capability to six or eight telescope, while probably unrealistic in the current funding situation, would probably be a considerable progress to restore the true complexity of close circumstellar environments and in particular monitoring time-variable astrophysical flows (accretion, winds, jets, shocks) on the scale of a few days. It would also reduce considerable the telescope reconfiguration requirements on the mountain.

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