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The VLTI Roadmap

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ESO's Very Large Telescope Interferometer (VLTI) was a unique facility when it was conceived more than 30 years ago, and it remains competitive today in the field of milli-arcsecond angular resolution astronomy. Over the past decade, while the VLTI matured into an operationally efficient facility, it became limited by its first-generation instruments. As the second generation of VLTI instrumentation achieves first light, further developments for this unique facility are being planned and are described here.

Introduction

The VLTI will remain — even in the era of ESO's Extremely Large Telescope (ELT) and the Atacama Large Millimeter/submillimeter Array (ALMA) — the European facility with the highest angular resolution. The past decade has seen ESO master the difficulties of coherent combination of an optical array with four Unit Telescopes (UTs) or Auxiliary Telescopes (ATs). These successes paved the way for the ambitious second-generation instruments: GRAVITY (GRAVITY Collaboration, 2017a,b) and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE) (see Matter et al., 2016; Lopez et al., 2014). Additionally, the VLTI facility itself has been upgraded to accommodate the new instruments, bringing improvements in both operation and performance (Woillez et al., 2016; Gonté et al., 2016).

With the VLTI and ALMA, ESO users have now gained access to milli-arcsecond astronomy from the near infrared to the millimetre regimes. Since its inception, the VLTI has pursued two goals: delivering an imaging capability at the milli-arcsecond resolution level and providing precise relative astrometry with a goal of ten micro-arcseconds precision, the latter being a much bigger technical challenge.

The scientific production of the VLTI has been vastly dominated by relatively simple but important morphological measurements of the near and mid-infrared emission of bright sources and spectroscopy with milli-arcsecond angular resolution. These reconstructed images have challenged a number of established theories in the field of stellar physics and active galactic nuclei (AGN). With these images, the VLTI can now reveal the true underlying complexity of these objects.

The VLTI offers the possibility of spatially and spectroscopically resolving a range of time-variable astrophysical processes that cannot be accessed via other techniques. It is a tool to challenge our indirect understanding of stars, explore rotation, pulsation, convection, shocks, winds, accretion, and ejection phenomena as they happen and reveal the complex interplay between a star and its environment throughout its lifetime. The capability of the VLTI to resolve the complexity of AGN, to precisely measure the central black hole mass and to pinpoint its distance with unmatched accuracy has not yet been exploited. With GRAVITY, the VLTI has become an astrometric machine, offering a unique way to observe strong gravity in action and explore physical conditions close to the horizon of the black hole at the Galactic Centre. As such, it offers a rare opportunity for ground-based astronomy to probe the nature of gravity and contribute to the field of fundamental physics. The technology required to enable such an ambitious goal will most probably open the way for more science projects exploiting micro-arcsecond astrometric capability from the ground. The powerful combination of fascinating science cases and instrumental innovation is a strong incentive to support the further development of the VLTI.

The evolution of VLTI infrastructure and the associated increase in performance should bring trust in our ability to continue developing milli-arcsecond astronomy from the ground. Whether it will be by expanding the VLTI or by developing other facilities has yet to be established.

Challenges

ESO has surmounted the difficulties associated with optical coherent combination and the VLTI is now entering a consolidation phase. The next challenge is to combine increased sensitivity and precision. The next step is phasing (also called fringe tracking) of the array of telescopes on-axis and, at a later stage, off-axis. This will considerably improve the accessible sizes of the samples and will enable high-resolution spectroscopy. As previous experience — using the Astronomical Multi-BEam combineR with the Fringe-tracking Instrument of NIce and TOrino (AMBER+FINITO) and the MID-infrared Interferometric instrument with the Fringe Sensor Unit (MIDI+FSU) — suggests, efficient phasing requires the implementation of a number of subsystems or upgrades, as well as a particular attention to global performance, including particularly good wavefront correction in the UT and AT arrays. ESO has developed sufficient expertise to tackle this crucial step for MATISSE, which cannot deliver its full potential without phasing. The dedicated project called GRAVITY for MATISSE (GRA4MAT) is using GRAVITY's own fringe tracker to phase MATISSE, and is expected to come to fruition in 2019.

The second challenge is to bring GRAVITY up to its ultimate astrometric performance. This remarkable scientific outcome will be delivered thanks to a significant technological and system effort. Early results indicate that the short-term astrometric precision is of the order of 50 micro-arcseconds (GRAVITY Collaboration, 2017a,b), but the final accuracy long-term (over a timescale of months) still needs to be assessed.

The third challenge is to democratise access to the VLTI by providing user assistance to help with observation preparation, data reduction and image reconstruction. The VLTI community has made considerable progress in this direction, for example, through the development of reliable software and by running dedicated training schools. However, as revealed through polling of the ESO Users Committee, handling VLTI data is still perceived as an expert-only activity. ESO is addressing this by streamlining the process of preparing VLTI programmes, with the goal of shielding users from the complexity inherent in earlier VLTI operations, when combiners used only two or three telescopes and telescope configurations were restrictive.

The VLTI benefits from a particularly active and dedicated community. Both ESO and the VLTI community should explore a comprehensive interface that provides users with easier access to data reduction and image reconstruction. Without a doubt, expanding the user community will bring new ideas for the scientific exploitation of the VLTI. Between 2004 and 2017, nearly 350 individual Principal Investigators (PIs) applied for VLTI time. As with any facility, the broadening of the user base also comes when new capabilities are offered; the first few semesters over which GRAVITY has been offered have brought almost 25 PIs who had never used the VLTI before.

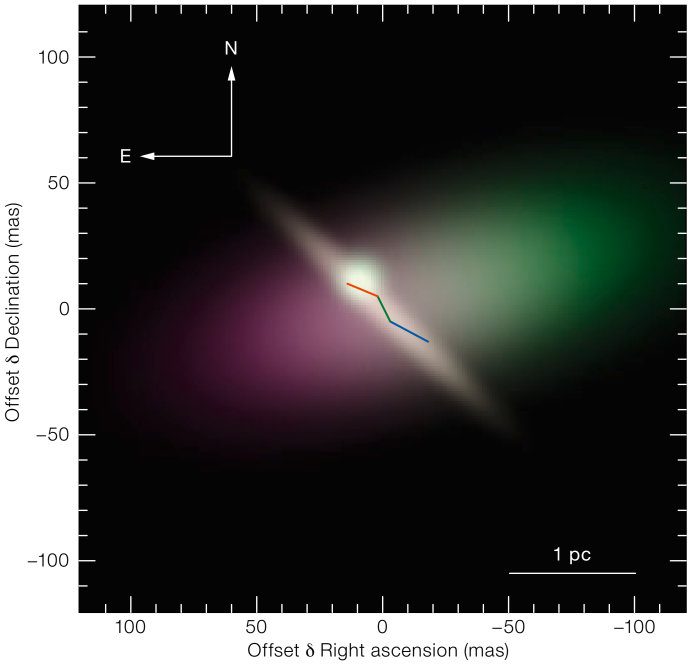

Figure 1. Three-component model of the dusty environment in the Circinus galaxy based on MIDI observations (Tristram et al., 2014). Red, green and blue correspond to wavelengths of 13 μm, 10.5 μm and 8.0 μm, respectively. Despite their low surface brightness, polar outflows account for 80 % of the mid-infrared flux in this synthetic image. The water maser disc is deduced from centimetre Very Long Baseline Interferometric (VLBI) observations. Reproduced with permission of K. Tristram.

Key scientific questions for VLTI second-generation instruments

During the next decade, the second generation of VLTI instruments — GRAVITY, MATISSE, and to a certain extent, the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER) — are expected to contribute to many astrophysical domains. We explore a few of the important ones here.

The inner parsec of Active Galactic Nuclei

GRAVITY and MATISSE are both expected to contribute to the study of AGN. Historically, VLTI observations of AGN have been limited to a handful in the *K*-band by VINCI (Wittkowski et al., 2004) or AMBER (Weigelt et al., 2012). MIDI has observed several AGN in the *N*-band but the results are puzzling because they imply that most of the mid-infrared emission comes from the polar regions, not the dusty torus as expected (Hönig, 2016). Since MIDI was limited to a single baseline, effective imaging of AGN was not possible.

MATISSE will provide snapshot imaging of AGN, allowing a much more detailed view of the morphology of the dust in the central parsec of galaxies hosting AGN, thereby possibly ruling out the simple dusty torus model, as MIDI observations seemed to imply (Tristram et al., 2014; see Figure 1). GRAVITY is also expected to contribute to the study of AGN, as it has greater sensitivity than AMBER, particularly in its spectrally resolved mode using the fringe tracker. The gas in the inner regions of AGN produces a so-called broad line region that can be imaged directly by GRAVITY. So far, the only way to study the broad line region has been to use reverberation mapping, which requires months of photometric monitoring. The VLTI can directly resolve the size of the broad line region, and early observations with GRAVITY as well as pioneering work on AMBER indicate that broad line regions are more likely to be compact than originally estimated by reverberation mapping studies (GRAVITY Collaboration, 2017; Pribulla et al., 2011).

Strong gravity in the Galactic Centre

The VLTI instrument GRAVITY has been designed to observe the Galactic Centre. The unprecedented angular resolution of the VLTI will help to address several questions. The first goal is to measure the effects of General Relativity as the star S2 undergoes peribothron in 2018 — i.e., the point in its elliptical orbit at which it is closest to the supermassive black hole Sgr A*. Another goal is to understand the origin of the Sgr A* flares which occur daily. GRAVITY will help to discriminate between different scenarios, for example, disc accretion events, accretion of stars, and fluctuations in a jet. Early results are very promising and call for long-term monitoring of the Galactic Centre (GRAVITY Collaboration, 2017a).

Binarity across the Hertzsprung Russell diagram

Increasingly, multiplicity is believed to play a fundamental role in stellar evolution and stellar dynamics. An example of the fundamental contribution of the VLTI is the definitive evidence that massive main sequence stars are all in multiple systems (Sana et al., 2014). The contribution to high angular resolution imaging is not limited to binary statistics and also probes massive star binaries (Figure 2). Other classes of stars are yet to be studied to determine their multiplicity fractions; the VLTI could be used to conduct surveys of statistically complete samples of stars with different spectral types.

The VLTI is also frequently used to conduct in-depth studies over a range of binary systems, for example, the determination of independent distances and masses at the 1 % level using double-lined eclipsing binaries (Pribulla et al., 2011) and resolving wind-wind interactions in Luminous Blue Variables (Weigelt et al., 2016). GRAVITY, with its sensitivity and spectral coverage (encompassing the full *K*-band, a significant increase on the *K*-band coverage with AMBER) offers the unique capability of spectrally disentangling binaries. This was pioneered with AMBER and proved invaluable in modelling complex systems, such as the Wolf-Rayet γ2 Velorum (Lamberts et al., 2017).

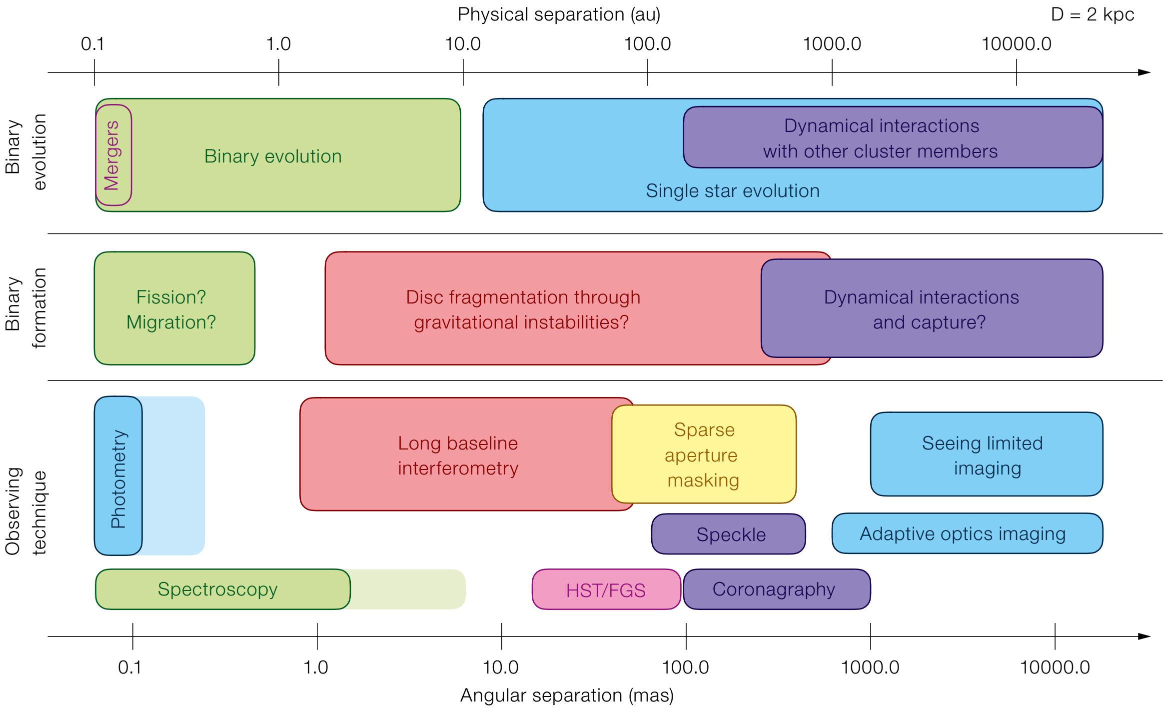

Figure 2. A schematic diagram to compare the angular scales associated with different observing techniques (bottom row), binary formation processes (middle row) and binary evolution (top row) for hot O-type stars at a typical distance of 2 kpc. This illustrates the unique role that the VLTI's long baseline interferometry can play in probing disc fragmentation in early systems. Thanks to its unsurpassed angular resolution, VLTI imaging is the only way to probe close binary systems that are interacting. Reproduced with permission of H. Sana.

During GRAVITY commissioning new phenomena were observed, including a micro quasar (Petrucci et al., 2017) in which relativistic jets could be resolved, and the accretion zone in a high-mass X-ray binary (Waisberg et al., 2017). High-precision interferometric instruments yield high dynamic ranges; PIONIER offers a detection limit up to a contrast of 500, which enables the measurement of dynamical masses of unexplored stellar classes, such as Cepheids (Gallenne et al., 2015). GRAVITY is expected to reach a similar dynamic range performance that, combined with its spectral resolution, will allow for a better characterisation of companions.

Mass loss from evolved stars

Evolved stars play a crucial role in enriching their host galaxies in heavy elements. Little is known about the actual mass loss mechanisms involved since all models underestimate mass loss rates. It is believed that mass loss is linked to pulsation, convection and/or shocks in the upper atmosphere of dusty stars (Höfner et al., 2018). The VLTI is uniquely positioned to resolve the photospheres and dust shells around evolved stars (Figure 3). The advent of 3D modelling and early imaging with optical interferometry suggest a strong departure from a symmetric central geometry, advocating for more advanced models than the typical 1D models and 1D morphological analysis of previous observations (Chiavassa et al., 2010).

PIONIER, GRAVITY and MATISSE are expected to continue targeting evolved stars, especially when all available wavebands (from *H*- to *N*-bands) are used simultaneously. An important obstacle to studying mass loss so far was that stars must be resolved both spatially and temporally in order to disentangle convection and pulsation, which have timescales of weeks. The availability of four-telescope observations offers the possibility of snapshot imaging on a timescale of a few days, which can reveal mass loss in all its spatial complexity, potentially tying dust patches above the atmosphere to phenomena at the surfaces of stars. PIONIER will resolve the photosphere, GRAVITY will probe the molecular wind and hot dust close to the sublimation temperature, and MATISSE will resolve the oxygen- and carbon-rich dust. ALMA can probe the larger-scale structure with H_2O and OH maser observations. SPHERE on the VLT could also provide complementary imaging, revealing interactions of the mass loss with the interstellar medium (Kervella et al., 2017; Figure 3).

Young stellar objects

Young stellar objects are among the targets of choice for the VLTI; the combination of high angular resolution (~ milli-arcseconds) and the spectral range (*H*- and *K*-bands) makes it the perfect machine to study the central regions of protoplanetary discs. For example, PIONIER recently revealed the universality of the truncated inner-ring structures in the hot dust discs of Herbig AeBe stars via a survey of 51 objects (Lazareff et al., 2017).

GRAVITY and MATISSE are expected to continue this legacy. GRAVITY offers the unique possibility of studying winds or jets thanks to its sensitive fringe tracker, which allows observations of Brγ, He I or CO lines at high spectral resolution (R ~ 4000). The gas and dust have very different dynamics in protoplanetary discs and play different roles in planet formation scenarios.

GRAVITY commissioning observations of S CrA revealed a Brγ emitting region of *r* ~ 0.06 au that was located in the inner gaseous disc but was twice as big as the truncation radius, tracing a wind (GRAVITY Collaboration, 2017c). Detailed modelling also indicates the presence of magnetospheric accretion. The sensitivity

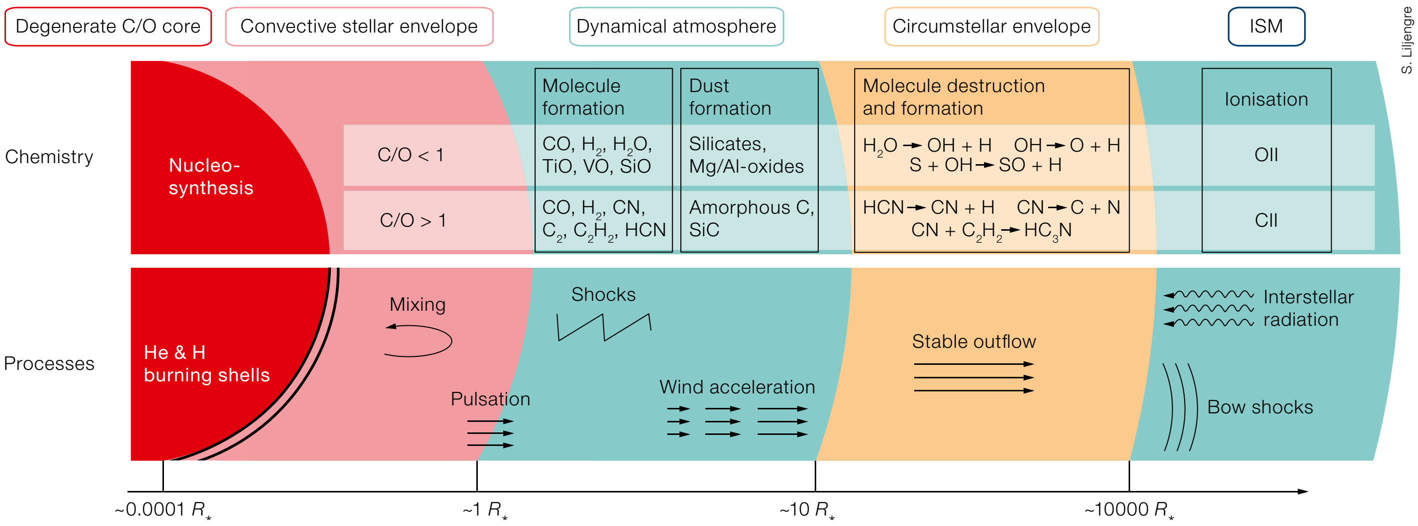

Figure 3. Schematic diagram of an asymptotic giant branch star from interior to circumstellar environment, showing the chemical and physical processes involved in mass loss. VLTI instrumentation (PIONIER, GRAVITY and MATISSE) can resolve these stars from their surfaces (at 1 R_*) to their circumstellar envelopes (out to ~ 10 R_*), probing convection, pulsation, shocks and dust formation. ALMA can resolve the circumstellar environment and molecular processes. VLT imaging at high angular resolution accesses the outer scales (100–1000 R_*). Reproduced here with permission of S. Lijengre.

of GRAVITY will allow this study to be extended further as the Brγ line can trace both the disc and the inner region of the stellar and/or disc wind. The availability of the full *K*-band will enable the study of the CO bandhead emission longward of 2.3 µm. The infrared CO emission traces warm gas in the inner regions of protoplanetary discs, potentially tracing the disc-star interactions (van der Plas et al., 2014; Illee et al., 2014).

MATISSE will continue mineralogy studies that MIDI initiated earlier, detecting different types of dust at different disc radii (van Boekel et al., 2004). MATISSE will provide much better insights into the morphology of the dust thanks to its four-telescope imaging capabilities, which will remove assumptions about the disc geometry. The VLTI will complement ALMA, which offers similar angular scales, to draw a complete picture of the dust and gas in protoplanetary discs (Figure 4).

Beyond GRAVITY and MATISSE

The need for milli-arcsecond resolution observations will not disappear once GRAVITY and MATISSE yield their

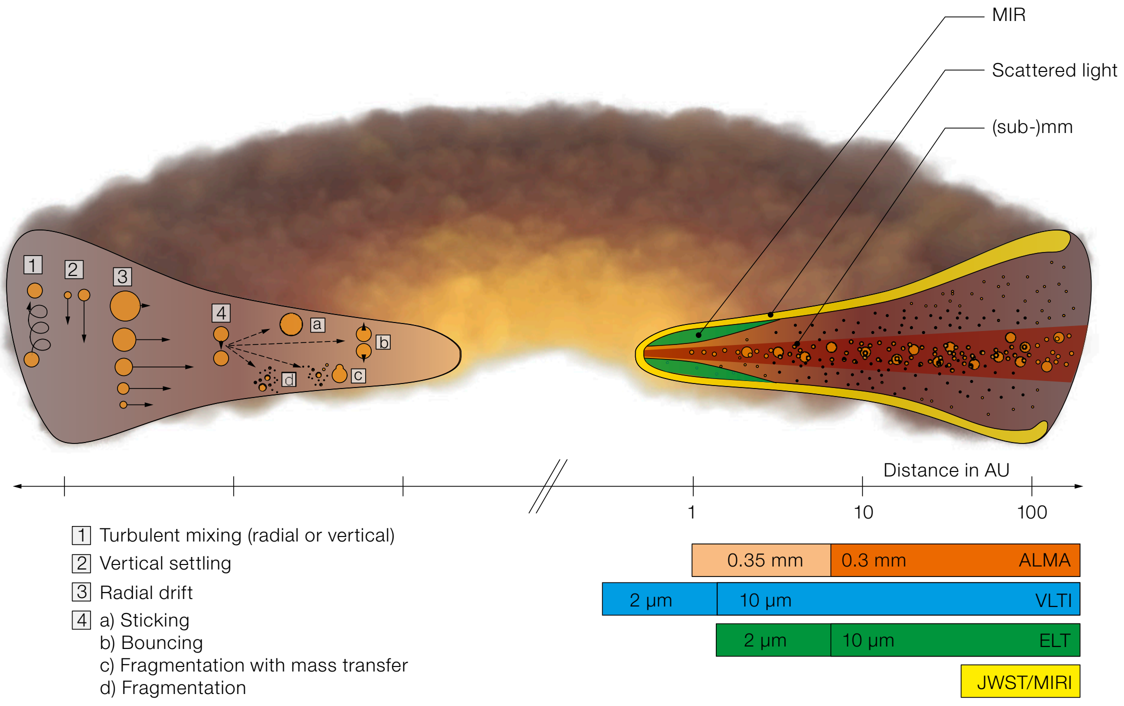

Figure 4. Protoplanetary disc structure, grain evolution processes and observational constraints for protoplanetary discs (the central star is omitted for illustration purposes). The left side shows the dust grain processes, while the right side shows the area of the disc that can be probed using different wavelength ranges and facilities. The VLTI uniquely probes the inner disc in the near infrared (~ 2 µm using PIONIER and GRAVITY), and in the mid-infrared (~ 10 µm using MATISSE). Adapted from Testi et al. (2014), with permission.

expected treasure trove of results. We can already anticipate that both instruments will open up new avenues. The VLTI should aim to be a major contributor to the following astrophysical questions well beyond the immediate horizons:
- Do we understand stars?
- How do planetary systems form?
- How do stars enrich galaxies?
- How do massive stars interact with their environment?
- How do supernova progenitors work?
- What is the prevalence and role of stellar multiplicity?
- Do we understand the immediate surroundings of the Galactic Centre and strong gravity in action?
- Do we understand the interactions between supermassive black holes and their host galaxies?

The VLTI can develop strong synergies with ALMA in all of these areas. In addition, the VLTI could be a significant contributor to the following areas, with the development of new capabilities and exploitation of synergies:
- Improving the cosmological distance scale, by studying Cepheids, the tip of the red giant branch stars, eclipsing binaries, asymptotic giant branch stars, and other distance indicators such as AGN.
- Ground-based astrometric follow up of exoplanet detections post-GAIA.
- Characterisation of host stars in the context of exoplanet and asteroseismology transit missions (for example, via the PLAnetary Transits and Oscillations of stars mission [PLATO]).
- Direct imaging of transient phenomena, such as microlensing events, detected by current and future large-scale photometric surveys (for example, with the Large Synoptic Survey Telescope [LSST]).

Possible future developments

It is of the utmost importance to maintain an active research and development programme in interferometric instrumentation. Taking an example from millimetre interferometry, one can already consider the expansion of the VLTI's capabilities in four areas: imaging, sensitivity, instrumentation, and astrometry. Unlike traditional single-dish instrumentation, which has already developed a number of capabilities, optical interferometry still has a considerable margin for development, as discussed in the recent European Interferometry Initiative report entitled "Future of optical-infrared Interferometry in Europe"[1].

The following capabilities would help to pursue the goals mentioned earlier:

Imaging with a larger number of telescopes

The history of sub-millimetre arrays shows that imaging complex sources can become routine with arrays of seven to eight telescopes. The VLTI is already equipped with eight telescopes (four ATs and four UTs) and six delay lines, even though current instrumentation (PIONIER, GRAVITY, MATISSE) can only combine up to four of these at a time. Additionally, the VLTI delay line tunnels can accommodate two more delay lines. Alternatively, the VLTI platform can host several additional telescopes without major infrastructure modifications.

A first step before expanding VLTI baseline capabilities is to fully exploit the current facility. One of the current limitations for imaging with the ATs is the spatial frequency (uv-plane coverage); the VLTI can only be offered with a maximum baseline length that is 70 % of the longest possible baseline (202 m), and the possible quadruplets of telescopes are limited by their sky coverage. Extending the delay line length could solve both issues. Although the delay line tunnel cannot be extended, delay lines can have their optical path length doubled by folding the optical beam and passing twice through the delay line cart. This would allow the longest AT baseline (202 m) to be offered, and increase the number of possible AT quadruplets with full sky coverage.

Sensitive co-phasing

This improves imaging by allowing the longest baselines (with lowest fringe contrast) to be used, thanks to baseline bootstrapping; it also improves sensitivity and/or spectral resolution, in particular when off-axis fringe tracking, or fringe tracking in a different waveband, is implemented. The VLTI is at the forefront of the development and operation of fringe trackers, thanks to its experience with AMBER+FINITO, the PRIMA Fringe Sensor Units (used with MIDI) and now GRAVITY.

MATISSE requires a fringe tracker to achieve its full scientific potential, for which GRAVITY's fringe tracker will be used initially. However, this might not be optimal and the performance of this combination should be assessed a few years into MATISSE operation. Building a new fringe tracker might be the ultimate solution to improving performance. Improving the facility should also help. The optical transmission not only affects the sensitivity, but fringe trackers are also susceptible to wavefront perturbations that lower their sensitivity. Reaching the diffraction limit and a Strehl ratio of more than 50 % using adaptive optics (AO) will improve fringe tracking sensitivity.

The UTs are equipped with AO dedicated to the VLTI with visible (MACAO) and infrared (CIAO) wavefront sensors. NAOMI, the AO system for the ATs, will be deployed a year from now. Fringe trackers correct for atmospheric perturbations, but the UTs' vibrations still dominate over atmospheric turbulence. Continuous efforts will be required to mitigate and reduce the telescope vibrations in order to maintain and improve the VLTI's sensitivity and dynamic range.

High dynamic range

The current dynamic range of VLTI instruments (about 1:500) limits the ability to address some particularly exciting science cases. The advantage of a dynamic range of 1:1000 to 1:10 000 in the mid-infrared (i.e., *L*- and *M*-bands) was demonstrated at a recent workshop for a new VLTI instrument project (HI-5)[2]. This capability could lead to the direct imaging of planet formation or even young planets.

A wealth of instrumentation developments are currently underway to build high-contrast beam combiners in the *L*- and *M*-bands using single-mode fibres and integrated-optics components, which could lead to simple yet transformative visitor instruments, following in the footsteps of PIONIER. The forthcoming decommissioning of AMBER will open up space for a visitor instrument. The requirements for high dynamic range are intimately linked to the performance of the infrastructure.

Extension to shorter wavelengths (< 1.4 μm)

The main driver for such an extension would be the improvement in spatial resolution, opening up the domain of stellar surface imaging of main sequence stars, which remains mostly unexplored. A visible-light instrument with high spectral resolution would be able to resolve velocity fields, such as rotation or pulsation, at the surface of stars. Other science cases and instrumentation developments are detailed in the recent white book *Science Cases for a Visible Interferometer* (Stee et al., 2017), showing the growing interest from the community. Such developments would require not only new instrumentation, but also significant facility upgrades, since the VLTI only transmits near- and mid-infrared light to the delay lines and laboratory, leaving the shorter wavelengths at the telescopes for guiding purposes.

The roadmap for the VLTI, recommended in October 2017 by ESO's Scientific and Technical Committee[4], can be divided into three epochs:

Epoch 1: until 2020

- Make GRAVITY and MATISSE a success by providing an efficient, optimally scheduled VLTI array. Demonstrate robust fringe tracking and increase sensitivity.
- Expand the VLTI user base by improving accessibility to non-experts, possibly through dedicated VLTI centres that are fostered by ESO and the European Interferometry Initiative[2].
- Organise a conference before 2020 to involve the community in a discussion of possible third-generation instrumentation and upgraded infrastructure for VLTI.

Epoch 2: 2020–2025

- Fully exploit the existing infrastructure by upgrading the existing instrumentation.
- Increase sky coverage and angular resolution by doubling the delay line optical path.
- Host visiting instruments to push interferometric techniques in new directions.

Epoch 3: beyond 2025

- VLTI imaging capability might be expanded by adding more telescopes and building a six- to eight-telescope beam combiner, driven by the ability of the community to propose strong science-driven projects.
- The VLTI could be used as a development platform for next-generation optical interferometers.

This roadmap aims to pave the way for future VLTI developments at ESO, as well as to encourage the community to drive the long-term future of the VLTI.

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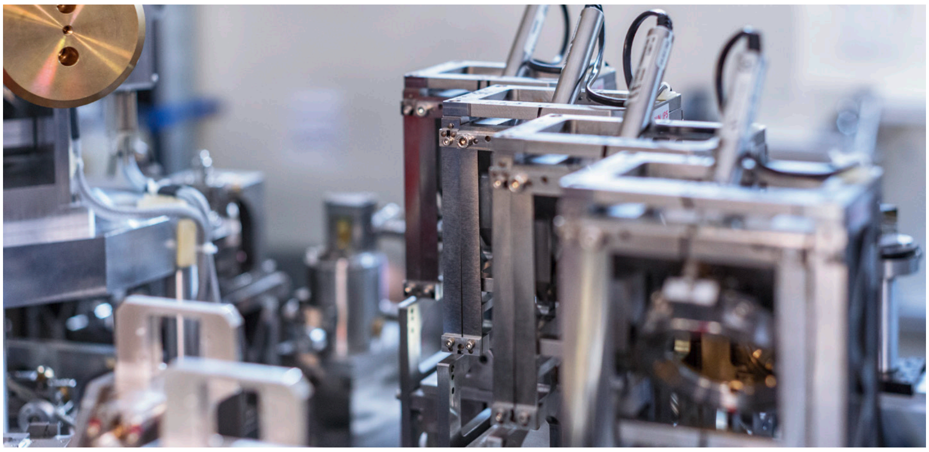
Links

[1] Working group on the future of interferometry in Europe: http://www.european-interferometry.eu/working-groups/the-future-of-interferometry-in-europe

[2] Hi-5 Kickoff Meeting website: http://www.biosignatures.ulg.ac.be/hi-5

[3] The European Interferometry Initiative: www.european-interferometry.eu/

[4] ESO Scientific Technical Committee report on VLTI Roadmap STC-599: https://www.eso.org/public/about-eso/committees/stc/stc-90th/public/STC_599_VLTI_Roadmap_90th_STC_mtg_Oct_2017.pdf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Complex optics on the MATISSE instrument on the VLTI. Many components are repeated four times, one for each beam of light being fed into the instrument.