The VLTI roadmap for the next decade

Antoine Mérand[a]
[a]European Southern Observatory

ABSTRACT

The Very Large Telescope Interferometer (VLTI) is a 4x8m + 4x1.8m telescopes array which has been operating as an optical interferometer for more than a decade now. We offer a prospective for the upcoming decade (2018-2028) taking into account the current state of VLTI, the science cases of the 2nd generation instruments (which started to be deployed in 2015), as well as the untapped possibilities offered by this unique facility.

Keywords: Facility: VLTI; prospective;

1. INTRODUCTION

The European Southern Observatory (ESO) Very Large Telescope (VLT) has been conceived in the 1980's, built in in 1990's and started operation in the 2000's. Although 8m class optical and infrared telescopes are a common thing nowadays, the interferometric mode of the VLT, allowing to recombine coherently large aperture telescopes, remain unique to VLT/VLTI. For the foreseeable future, the VLTI remains the European facility with the highest angular resolution (~0.001 arcseconds, or 1milli-arcsecond), even in the Extremely Large Telescope (ELT), Atacama Large Millimeter Array (ALMA) and space instrumentation era. The last decade has seen ESO mastering the difficulties of coherent combination of an array with four Unit or Auxiliary telescopes. These successes have paved the way for the ambitious second-generation instruments: GRAVITY[1][2] and MATISSE[3][4]. With VLTI and ALMA, the ESO user has now gained access to milli-arcsecond astronomy from the near infrared to the millimetric regime. Additionally, the VLTI facility itself has been upgraded to accommodate the new instruments, bringing improvements in both operation and performance[5][6].

With the VLTI and ALMA, ESO users have now gained access to milli-arcsecond astronomy from the near infrared to the millimeter regimes. Since its inception, the VLTI has pursued two goals: delivering an imaging capability at the milliarcsecond 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.

The detailed science cases for the next decade of VLTI have been published elsewhere[7], so we will not detail them here.

2. THREE EPOCHS FOR VLTI

The roadmap for the VLTI, recommended in October 2017 by ESO's Scientific and Technical Committee4, 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 centers that are fostered by ESO and the European Interferometry Initiative.
  - Organize 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.

3. POSSIBLE IMPROVEMENTS TO VLTI

3.1 Summer Schools and Expertise Centers

Optical interferometry is a complicated technique, not only for the observatory which carries the observations, but also for the astronomer who receives the data. Whereas this difficulty was recognized early in the ALMA developments, leading to the inclusion of support centers from the beginning, the VLTI has followed the traditional optical/infrared observatory route. ESO does provide tools to check feasibility of observations, exposure time calculators and pipelines to reduce and calibrate data. To this day, however, some steps necessary to obtain an astrophysical result from an idea still require an investment to master the skills to define observation strategy, interpret data interpretation and model them. These skills are more demanding and less widespread in the astronomical community at large for interferometry than, say, long slit spectroscopy or classical imaging.

This has led the interferometric community (that is, people who originally built and operated interferometers) to spread their knowledge through summer schools worldwide. In the USA, six "Michelson Summer Schools" were organized between 1999 and 2006[8]. In Europe, seven "VLTI Summer Schools" were organized between 2002 and 2018[9]. An analysis of the past European Schools shows that nearly 25% of the alumni end up publishing a VLTI paper. Furthermore, alumni represent 20% of the VLTI papers lead authors, which is a testament to the impact these schools have.

Expertise centers, inspired from the ALMA model, are now being funded by national funding agencies as well as an OPTICON H2020 networking activity[10]. The support offered will be complementary of what ESO supports. In particular, the Expertise Centres aim at supporting two aspects not supported by ESO: the proposal preparation and the reduced data modeling, including image reconstruction.

3.2 Streamlining operations to optimize image reconstruction

Image reconstruction is the inverse process aiming at deriving an image from interferometric visibilities collected from a partial coverage in spatial frequencies (u,v plane). In practice, this is an ill-posed problem and *a priori* are required for algorithm to converge. One way to improve image reconstruction is to collect data with most complete u,v coverage. Optical interferometers traditionally combine only a handful of telescopes at a time and rely on super-synthesis (*i.e.* u,v changes with the local sidereal time) and/or telescopes reconfigurations. VLTI offers both and let the user define the LST range and specific configuration for each Observing Block (one OB consists typically of one hour of science/calibrator observations). On the other hand, VLTI operations are organized to meet these constraints strictly. The lack of flexibility sometime leads inefficiencies. This process is not optimized for imaging and is mostly inherited from a time when 2 or 3 telescopes out of 4 were recombined. Now that all instruments recombine all telescopes (that is, the 4 UTs or 4ATs), operations have to evolve. Starting in 2018, VLTI will accept imaging proposals for which the u,v coverage will be loosely defined in the OB but optimized continuously during operations, based on an active monitoring of collected data, rather than relying a pre-defined LST and configurations.

3.3 Expanding sky coverage and maximum baseline length

The sky coverage and maximum baseline of an optical interferometer is usually limited by amount of optical path delay compensation of the delay lines. In the case of VLTI, the delay lines were optimized to maximize sky coverage for the 4xUTs operations within the linear space available at the Paranal mountain submit. Since it was originally planned to recombine only 2 ATs, the delay lines length was found acceptable. However, the delay lines length does not allow for good sky coverage for 4 ATs, and limits the practical maximum AT baseline to 130m or so, whereas the largest possible baseline is actually 200m.

In order to offer the maximum baseline within AT quadruplets, the amount of optical delay needs to be doubled. This can be obtained by doubling physical length of the delay line or, more practically, double the number of trips the light takes in the delay lines. VLTI delay lines were conceived with dual field capabilities, which means they accept two beams at the same time. Since current instruments only use one of these beams, the light path can be folded in the second beam to offer double passage in the delay line, effectively doubling the optical path delay which can be compensated. This is exemplified on **Figure 1**, showing the gain for an AT configuration with baselines up to 200m. Such configurations are not currently offered to the very limited sky access.

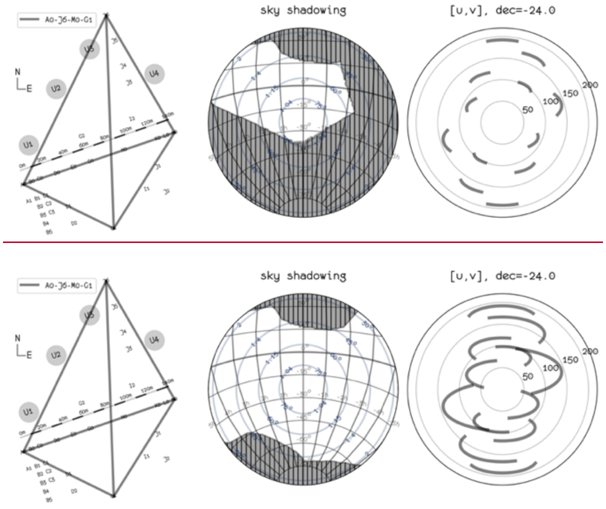

Figure 1. Sky shadowing and u,v coverage of AT configuration A0-G1-J6-M0, with current delay lines (three leftmost panels) and with double-pass delay lines (three rightmost panels).

A feasibility study of doubling the delay line optical path length is currently underway at ESO.

3.4 Hosting visiting instruments

VLTI once offered a visitor focus which resulted in the PIONIER project[11]. The upcoming of AMBER and its fringe tracker FINITO will free space in the focal laboratory which can be used for a visitor instrument. ESO is planning to offer the visitor focus in the late 2018 call for proposals. In particular, there is a strong interest in the community for high dynamic range instruments such as Hi-5[12] or VICKING[13]. Since these instrumental concepts are combining 4 Telescopes in the near infrared, they could be deployed at VLTI without infrastructure modifications.

3.5 Upgrade existing instruments

As of 2018, the instruments suite of VLTI is composed of PIONIER, GRAVITY and MATISSE (Table 1).

	PIONIER	**GRAVITY**	**MATISSE**

Number of Telescopes	4	4	4
Band(s), spectral resolutions	H, R=5/20	K, R=22/500/4000	20<R<1000 in L 20<R<550 in M 20<R<250 in N
Fringe Tracker	No	Yes	GRAVITY

Table 1. VLTI instruments as of 2018 (AMBER has been omitted since it will be decommissioned at the end of 2018).

GRAVITY and MATISSE are very recent addition to VLTI and do not justify yet major upgrades. On the other hand, PIONIER has been operated for 8 years now, and one could think of several possible improvements. Since AMBER could never be operated in J band (most likely due to poor internal transmission in this band), the astrophysical potential of this band remains untapped. The first gain of a PIONIER operating in the 1.0-1.2 µm wavelength regime, would be the increase in angular resolution. If this is combined with the offering of 200m baseline (section 3.3), the angular resolution of VLTI could be doubled. This has clear advantages: angular-diameter limited science cases would directly benefit from such an improvement, for example. Extending to much shorter wavelength is not yet feasible due to guiding strategy adopted at VLTI: the visible light (wavelength shorter than roughly 1.0 µm) stays in the telescopes and is used for adaptive optics wavefront sensing, only the near-infrared is transmitted to the focal laboratory.

A first step towards any instrumental upgrades, including the one we briefly outlined for PIONIER, will be the establishing a proper science case.

3.6 Expanding VLTI

In the long term, beyond 2025, VLTI can be expanded to combine more than four telescopes at a time. 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 each at a time. Additionally, the VLTI delay line tunnels can accommodate two more delay lines. The VLTI has still some unexploited flexibilities: the current AT network of stations can host several additional telescopes without major infrastructure modifications. VLTI can also develop towards visible wavelength, though it might be at the cost of infrastructure upgrades. The science case for visible interferometry is mostly unexplored but full of potential, as a recent review showed[14].

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