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For Recommendation

VLTI Roadmap

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VLTI Roadmap

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1. Introduction

1.1 Scope
This document describes the roadmap for the VLTI and its developments from in the 2020's. It is the result of discussions with the Community at large during the “VLTI Community Days” organised by ESO every 2 years. Recommendations are made about the future direction of the VLTI.

1.2 Definitions, Acronyms and Abbreviations
This document employs several abbreviations and acronyms to refer concisely to an item, after it has been introduced. The following list is aimed to help the reader in recalling the extended meaning of each short expression:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2GFT</td>
<td>Second Generation Fringe Tracker</td>
</tr>
<tr>
<td>AD</td>
<td>Applicable document</td>
</tr>
<tr>
<td>AGN</td>
<td>Active Galactic Nucleus</td>
</tr>
<tr>
<td>ALMA</td>
<td>The Atacama Large Millimetric Array</td>
</tr>
<tr>
<td>AT</td>
<td>Auxiliary Telescope</td>
</tr>
<tr>
<td>CfP</td>
<td>Call for Proposals</td>
</tr>
<tr>
<td>CHARA</td>
<td>Center for High Angular Resolution Astronomy (by extension, its Array)</td>
</tr>
<tr>
<td>CIAO</td>
<td>Coudé Infrared Adaptive Optics (UTs)</td>
</tr>
<tr>
<td>DL</td>
<td>Delay Lines</td>
</tr>
<tr>
<td>EII</td>
<td>European Interferometry Initiative</td>
</tr>
<tr>
<td>ELT</td>
<td>Extremely Large Telescope (formerly E-ELT)</td>
</tr>
<tr>
<td>ESO</td>
<td>European Southern Observatory</td>
</tr>
<tr>
<td>FT</td>
<td>Fringe Tracker</td>
</tr>
<tr>
<td>JMMC</td>
<td>Jean-Marie Mariotti Centre</td>
</tr>
<tr>
<td>LBTI</td>
<td>Large Binocular Telescope Interferometer</td>
</tr>
<tr>
<td>LPO</td>
<td>La Silla / Paranal Observatory</td>
</tr>
<tr>
<td>mas</td>
<td>Milli-arcseconds</td>
</tr>
<tr>
<td>MROI</td>
<td>Magdalena Ridge Observatory Interferometer</td>
</tr>
<tr>
<td>NOAMI</td>
<td>New Adaptive Optics Modules for Interferometry (ATs)</td>
</tr>
<tr>
<td>NPOI</td>
<td>Navy Precision Optical Interferometer</td>
</tr>
<tr>
<td>OPD</td>
<td>Optical Path Difference</td>
</tr>
<tr>
<td>OPL</td>
<td>Optical Path Length</td>
</tr>
<tr>
<td>PDR</td>
<td>Preliminary Design Review</td>
</tr>
<tr>
<td>PFI</td>
<td>Planet Formation Imager</td>
</tr>
<tr>
<td>PI</td>
<td>Principal Investigator</td>
</tr>
<tr>
<td>RD</td>
<td>Reference Document</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>SoW</td>
<td>Statement of Work</td>
</tr>
<tr>
<td>TLR</td>
<td>Top level requirements</td>
</tr>
<tr>
<td>UT</td>
<td>Unit Telescope</td>
</tr>
<tr>
<td>VLT</td>
<td>Very Large Telescope</td>
</tr>
<tr>
<td>VLTI</td>
<td>Very Large Telescope Interferometer</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
</tbody>
</table>
2. Related Documents

2.1 Reference Documents

The following documents, of the exact version shown herein, are listed as background references only. They are not to be construed as a binding complement to the present document.

RD1  Reaching New Heights in Astronomy - ESO Long Term Perspectives; Tim de Zeeuw, Messenger, 12/2016 (also arXiv:1701.01249)

RD2  Report on recommendations regarding the coordination of the European 8-10m telescopes by the ELTSRC; Gallego et al (2015)

RD3  The Future of Interferometry in Europe; Pott J.-U., Surdej J. et al. (2017)

RD4  The 2nd Generation VLTI path to performance; Woillez et al. SPIE 990-06 (2016)

RD5  GRA4MAT SCIENTIFIC JUSTIFICATION; Jaffe W., Lopez B., Petrov R. et al. MATISSE consortium document (May 2017)
3. Context and Motivation

Within the “Long Term Perspectives of ESO” (RD1), the VLTI remains the European facility with the highest angular resolution, even in the ELT, ALMA and space instrumentation era. The ESO 2013 visiting committee wrote that the “VLTI is the future of high angular resolution at ESO”. 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 and MATISSE. With VLTI and ALMA, the ESO user has now gained access to milli-arcsecond astronomy from the near infrared to the millimetric regime.

3.1 The landscape of optical interferometers

As of 2017, only two other long baseline optical interferometers are in operations: CHARA and NPOI. A third one is under construction, MROI.

<table>
<thead>
<tr>
<th>VLTI</th>
<th>CHARA</th>
<th>NPOI</th>
<th>MROI</th>
<th>LBTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescopes</td>
<td>4x1.8m, 4x8.2m</td>
<td>6x1.0m</td>
<td>10x0.35m</td>
<td>1x1.4m (9 in construction)</td>
</tr>
<tr>
<td>Baselines length</td>
<td>8 to 220m</td>
<td>33 to 330m</td>
<td>5 to 430m</td>
<td>Up to 340m</td>
</tr>
<tr>
<td>Practical baselines</td>
<td>8 to 140m</td>
<td>33 to 330m</td>
<td>Up to 100m</td>
<td>-</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1.6-10um</td>
<td>0.5-2.2um</td>
<td>0.5-0.75um</td>
<td>2.2um</td>
</tr>
<tr>
<td>Combiners</td>
<td>4T</td>
<td>2,3,6T</td>
<td>4T</td>
<td>4T</td>
</tr>
</tbody>
</table>

Among the US based projects, at least three have active European collaboration: CHARA, MROI and LBTO. In the foreseeable future, VLTI will remain the main long baseline optical interferometer in Europe as the most sensitive, thanks to its ability to combine 8m class telescopes.

3.2 Key historic dates for VLTI

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>First light of VINCI on 2 UTs (2T, K-band)</td>
</tr>
<tr>
<td>2002</td>
<td>First light of MIDI (2T, N-band)</td>
</tr>
<tr>
<td>2004</td>
<td>First light of AMBER (3T, JHK-bands)</td>
</tr>
<tr>
<td>2008</td>
<td>FINITO fringe tracker offered for AMBER</td>
</tr>
<tr>
<td>2008</td>
<td>PRIMA commissioning starts</td>
</tr>
<tr>
<td>2010</td>
<td>PRINER first light (4T, H-band)</td>
</tr>
<tr>
<td>2014</td>
<td>MIDI decommissioned, PRIMA discontinued</td>
</tr>
<tr>
<td>2015</td>
<td>VLTI upgrade (see RD4): AT and UT STS, CIAO</td>
</tr>
<tr>
<td>2016</td>
<td>GRAVITY first light (4T, K-band)</td>
</tr>
</tbody>
</table>
3.3 Performance metrics

New astrophysical research is enabled by improved performances.

3.3.1 Observation efficiency

The roadmap argues to continue developing the VLTI to improve its capabilities to produce scientific results. It should be recognised that great efforts have already led to improvement in the past decade. For example, one can devise the number of observations per hour, or cadence as an observation metric. As seen on Table 1, the observation cadence has increased by a factor 5.7 (from 0.15 to 0.85 observations per hour) between 2006 and 2013 (before the VLTI refurbishment). If one considers the diversity of AT configurations, the number of unique uv-points covered per hour has increased by a factor of 10 in seven years, allowing VLTI to collect data efficiently enough to produce images since 2013.

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2009</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction science time</td>
<td>30%</td>
<td>45%</td>
<td>56%</td>
</tr>
<tr>
<td>Observations / hour</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Yearly obs. / hour</td>
<td>0.15</td>
<td>0.45</td>
<td>0.85</td>
</tr>
<tr>
<td>Unique uv-/ config.</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Unique uv-/ hour</td>
<td>0.5</td>
<td>1.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 1: Execution performance metrics for VLTI for 3 different years. The actual metrics are the two shaded rows, the other rows are numbers used to compute the metrics. The fraction of time on sky accounts for the losses due to weather, technical issues, time spent checking after relocating telescopes and for technical activities.

3.3.2 Transmission

Optical interferometers use large number of mirrors to transport photons from the telescopes to the beam combiners. For VLTI, this number is of the order of 24, from M1 to the feeding optics of instruments. For this reason, maximising the transmission of the VLTI is key to monitor and maintain, because even slight degradations of mirrors’ coatings have a cascading effect when it comes to the overall transmission.
As seen on Figure 1, the transmission of VLTI is regularly measured. The normal aging of coatings is counteracted by cleaning and re-coating of the various exposed mirrors (typically M1 to M6) to maintain the total transmission of the order of 40% for K band. In 2015, the addition of several new optical surfaces (by switching to star separators relay optics) led to an expected drop in efficiency. The continuing decrease in transmission was attributed to accelerated aging of mirrors coating, which led to the replacement of the whole ATs’ Coudé train in 2016-2017. This restored the transmission to between 30% and 40% in K-band. Additional re-coating activities are expected this year (M1, M2, M3), to bring all telescopes above 40% transmission in the K band, which is our reference.

### 3.3.3 Instruments’ characteristics

<table>
<thead>
<tr>
<th></th>
<th>MIDI</th>
<th>AMBER</th>
<th>PIONIER</th>
<th>GRAVITY</th>
<th>MATISSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>First light</td>
<td>2002</td>
<td>2004</td>
<td>2010</td>
<td>2016</td>
<td>2018</td>
</tr>
<tr>
<td>N Telescopes</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Observables</td>
<td>2</td>
<td>7</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Bands</td>
<td>N</td>
<td>H,K</td>
<td>H</td>
<td>K</td>
<td>L,N</td>
</tr>
<tr>
<td>Spectral Res.</td>
<td>32,230</td>
<td>35,1500,12000</td>
<td>5,32</td>
<td>22,500,4000</td>
<td>30,500,950,30,220</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>~10</td>
<td>~50</td>
<td>~200</td>
<td>~100*</td>
<td>~40, 10 ^g</td>
</tr>
<tr>
<td>Sensitivity Ats</td>
<td>0.8, 0.3</td>
<td>5.5, 4.0, 4.0</td>
<td>7.7, 7.0</td>
<td>8.0*</td>
<td>5.7, 1.0 ^g</td>
</tr>
<tr>
<td>Sensitivity UTs</td>
<td>4.0, 2.8</td>
<td>7.5, 6.0, 6.0</td>
<td>7.7, 7.0</td>
<td>10.0*</td>
<td>8.2, 4.0 ^g</td>
</tr>
</tbody>
</table>

Table 2. Typical performances of VLTI instruments. Number of observables is the sum of visibilities, differential phases and independent closure phases. Limiting magnitudes are given for each spectral resolution, or each band (for MATISSE, without fringe tracker). Some numbers for GRAVITY (marked with *) can still improve. Numbers for MATISSE (marked ‘g’) are based on the design goals. Numbers with same colours are directly comparable and show the recent improvements in terms of sensitivity.

The performance of VLTI is also improving thanks to the 2nd generation of instruments (see Table 2):

- In low spectral resolution, PIONIER offers a better sensitivity of H~7.7 on ATs compared to K~5.5 for AMBER. Not only that, PIONIER doubles the amount of spatial information (4T instead of 3T) and improves the dynamic range (~200 instead of ~50).

- For spectro-interferometry, GRAVITY own fringe tracker is much more sensitive than FINITO which is used for AMBER: GRAVITY reaches K~10 on the UTs, whereas FINITO reaches H~6. Being 4T, GRAVITY also boosts by a factor of 2 the amount of spatial information collected at once, compared to AMBER (3T). This is due to optimized beam combination (integrated optics), better detectors (infrared APDs) and vibrations active correction (Kalman filtering).

- MATISSE will greatly boost the imaging capabilities compared to MIDI. The main gain in sensitivity will come from the use of GRAVITY’s fringe tracker. This is because detectors and beam combination is essentially the same as in MIDI.
3.4 The VLTI Community
Between 2004 and 2016, VLTI has seen close to 330 individual principal investigators applying for time, with some 280 successful. Close to 350 refereed papers have been published using VLTI data. The VLTI community has met regularly with ESO. The most recent such meeting took place on March 6-10 2017 and saw more than 50 participants. An earlier version of this document was presented and discussed with the community. Some of these discussions are reflected in the final version of the roadmap.

3.5 3 epochs for the VLTI roadmap
At the time of this writing, several important technologies are being implemented and several upgrades are being carried out that will improve the VLTI performance in terms of sensitivity, robustness and data quality. The extension of the VLTI capability clearly depends on the success of MATISSE and GRAVITY. Nevertheless, the future perspectives for VLTI can be decomposed into three epochs:

- **Epoch 1 (until 2020):** make MATISSE and GRAVITY successes and optimize the scientific return of VLTI.
- **Epoch 2 (2020-2025):** explore possible third generation VLTI instrumentation and minor infrastructure upgrades.
- **Epoch 3 (beyond 2025):** explore the interest of expansion of the infrastructure in the ELT era and/or plan for future of ground-based optical interferometry.

4. Key scientific questions
Mapping into the four “Science Vision” questions of ASTRONET or into the US decadal survey priorities, the top ESO scientific priorities recalled in document STC 551 are:

- Cosmology and Fundamental Physics
- Large Scale Structure of the Universe
- Structure and Evolution of Galaxies (incl. AGN)
- Milky Way dynamics and evolution
- Life cycle of interstellar matter
- Life cycle of stars
- Search for life outside Earth
- Pre-biotic chemistry
- Extreme states of matter
- The Sun and Solar System
- Time-domain astronomy

The VLTI, and its suite of second generation instruments, is expected to contribute significantly in the upcoming decade.

4.1 Strong gravity in the Galactic Centre.
The VLTI instrument GRAVITY has been designed to observe the Galactic Centre (GC). The unprecedented angular resolution of the VLTI will be used to address several questions. The first goal is to measure the effects of General Relativity as the star S2, which orbits the super massive black hole Sgr A*, will experience its peri-bothron in 2018. Another question is the nature of the daily flares experienced by Sgr A*: GRAVITY will help discriminate between different scenarios such as disk accretion events, accretion of stars,
fluctuations in a jet etc. Early results are very promising (Eisenhauer et al. 2017A&A...602A..94G).

### 4.2 The inner parsec of AGNs

GRAVITY and MATISSE are both expected to contribute to studying Active Galactic Nuclei (AGNs). Historically, VLTI observations of AGNs have been limited to a handful in K-band (VINCI, AMBER), because of sensitivity issues in K band. MIDI has observed several AGNs in N-band but the results are puzzling because they do not confirm the widely-accepted model of AGNs based on a dusty torus. Since MIDI was limited to a single baseline, the study of AGN did not allow effective imaging: MATISSE will provide snapshot imaging of AGNs, allowing a much more detailed view of the morphology of the dust in the central parsec of galaxies hosting AGNs, possibly ruling out the dusty torus model, as MIDI observations seem to imply.

GRAVITY is also expected to contribute to studying AGNs. It offers improved sensitivity compared to AMBER, particularly in spectrally resolved mode using the fringe tracker. AGNs have a so called “broad line region” (BLR) which GRAVITY can image directly. Early observations of GRAVITY (Eisenhauer et al. 2017A&A...602A..94G) as well as pioneering work on AMBER (Rakshit et al. 2015MNRAS.447.2420R), indicate that BLRs are likely more compact than originally extrapolated from reverberation mapping observations.

### 4.3 Binarity across the HR diagram

Increasingly, multiplicity is believed to play a fundamental role in stellar evolution and stellar dynamics. An example of fundamental contribution of the VLTI is the definitive evidence that main sequence massive stars are all in multiple systems (Sana et al. 2014ApJS..215...15S). This has transformed the field since all massive stars’ phenomena must now include stellar multiplicity. Other class of stars are yet to be studied to determine their multiplicity fraction: VLTI should run in the future survey-type programs to reach statistically complete samples of different stellar types.

VLTI is also use nightly to study in detail binary systems of all sorts. Double line eclipsing binaries provide unique opportunities to determine independent distances and masses at the 1% level (Pribulla et al. 2011A&A...528A..21P); wind-wind interaction in Luminous Blue Variable can be resolved (on eta Car for instance, Weigelt et al. 2016A&A...594A.106W).

GRAVITY, with its combined sensitivity and spectral coverage (full K band, as opposed to AMBER) offers the unique capability of spectrally disentangling binaries. This has been experimented with AMBER and proved invaluable in modelling complex systems such as the Wolf-Rayet γ Velorum (Lamberts et al. 2017MNRAS.468.2655L). Commissioning data of GRAVITY observed at least two new categories of binaries: a micro quasar and an X-ray binary. These observations resolve for the first time the relativistic jets (Petrucci et al. 2017A&A...602L..11G) and the accretion zone (Waisberg et al. 2017ApJ...844...72W), respectively. PIONIER offers detection limit up to a contrast of 500 which allowed to measure dynamical mass of unexplored stellar classed (e.g. Cepheids, (Gallenne et al. 2015A&A...579A..68G). GRAVITY is expected to reach a similar performance which, in addition to the spectral resolution, will allow better characterization of companions.

### 4.4 Mass loss in evolved stars

Evolved stars play a crucial role in enriching their host galaxies in heavy elements. Little is known on the actual mass loss mechanism since all models underestimate the mass loss rates by order of magnitudes. It is believed that the mass loss is linked to pulsation,
convection and/or shocks in the upper atmosphere of dusty stars. VLTI is uniquely positioned to resolve the photosphere of evolved stars, and already provided insight to the mass loss, such as the ubiquitous presence of dust shell around evolved stars. However, the advent of 3D modeling and early imaging with optical interferometry suggest a strong departure from central-symmetric geometry, advocating for a generalization of imaging AGBs and RSGs rather than using 1D models and observations (Figure 2).

PIONIER, GRAVITY and MATISSE are expected to continue the legacy of VLTI at studying evolved stars, especially when all bands (H, K, L and N) are used. An additional obstacle to study mass loss is that stars must be resolved both spatially and temporarily, to freeze the convection and pulsation (which have time scales of weeks). The generalization of 4-Telescopes observations will offer the possibility of “snapshot” imaging, on a time scale of a few days, which will reveal mass loss in all its spatial complexity, tying dust patch above the atmosphere to phenomena at the surface of the star (such as convection cells): PIONIER resolving the photosphere, GRAVITY the molecular wind and the hot dust (close to sublimation) and MATISSE the oxygen and carbon rich dust. ALMA will provide the larger scales with the H2O and OH masers observations.

4.5 How do planetary systems form and evolve?

Young Stellar Objects have been traditionally targets of choice for VLTI: the combination of angular resolution (few mas) and waveband (H and K bands) makes it the perfect machine to study the central region of proto-planetary disks. PIONIER has revealed the universality of the inner-ring truncated structures in the hot dust of Herbig AeBe disks (Lazareff 2017A&A...599A..85L) by surveying 51 objects of this class.

GRAVITY and MATISSE are expected to continue this legacy. GRAVITY offers the unique possibility to study winds or jets, thanks to its sensitive fringe tracker allowing observations in the Brγ, HeI or CO lines at R=4000. The gas and dust have very different dynamics in proto-planetary disks and play different roles in planet formation scenarios. GRAVITY commissioning observations of S CrA revealed a Brγ emitting region of r~0.06 au, located in the inner gaseous disk but twice as big as the truncation radius, tracing a wind. Detailed modelling also indicates the presence of magneto-thermic accretion. The sensitivity of GRAVITY will allow to go beyond the study of the Br gamma line, which sometimes is tracing both the disk and the inner region of the stellar/disk wind. The availability of the full K-band will enable the study of the CO band-head emission long-ward of 2.3um. The infrared CO emission traces warm gas in the inner regions of protoplanetary disks and constrain the disk-star interaction (e.g. van der Plas 2014, A&A 574, 75; Ilee et al. 2014, MNRAS 445, 3723).

MATISSE will continue the mineralogy studies MIDI had initiated early, detecting different dust types at different radii in the disk (von Boeckel, 2004Natur.432..479V). MATISSE will provide much better insights on the morphology thanks to its 4T imaging capabilities, removing assumptions on the disk geometry. VLTI will complement ALMA which offers similar angular scales, to draw a complete picture of protoplanetary disks dust and gas.
4.6 Future opportunities

ASTRONET’s "Report on recommendations regarding the coordination of the European 8-10m telescopes by the ELTSRC" (RD2) sets 3 goals for the future of VLTI:

1. Going towards the visible
2. Imaging planets, with UT/AT
3. Specialised niche complementary to space missions

Going towards the visible offers unique science cases not covered currently by VLTI. The European Interferometry Initiative report “the Future of Optical Interferometry” (RD3) contains the most comprehensive overview of the science case for optical interferometry. We can however outline that the visible offers a unique window on stellar surfaces of main sequence stars. Currently, VLTI barely resolves any stellar surfaces (apart from very evolved stars), because of the insufficient angular resolution. Additionally, spectral resolution sufficient to resolve velocity fields (rotation, pulsation) will open an all new domain of study for VLTI. See section 6.3.3 for the current instrumental developments in the community.

GRAVITY and MATISSE will have to be pushed far beyond their specifications to reach a comfortable dynamic range to detect planets, and both instruments’ consortia will attempt such observations. However, a dedicated instrument will have to be built to routinely detect planets and to observe a statistically significant sample. The most favourable configuration to directly image planets is in the L-band (3-5 microns): youn planets are expected to have contrast to their parent stars of 1,000 to 10,000, orders of magnitude beyond MATISSE specifications (see Table 2). A visitor instrument project is currently aiming at this (see section 6.3.1).

5. Epoch 1 (until 2020)

5.1 GRAVITY, MATISSE and the new VLT infrastructure

GRAVITY and MATISSE required the VLTI to be significantly transformed:

- Removal of MIDI to make room for MATISSE: completed in 2014
- Commissioning of 4 AT-STS (to deliver the field for GRAVITY): completed in 2015
- Construction of an AT maintenance station: completed in 2015
- Move of PIONIER above FINITO to make room for GRAVITY: completed in 2015
- Installation of 4 UT-STS for GRAVITY+CIAO operation: completed in 2016
- Refurbishment of the AT Coudé trains: to be completed in 2017

GRAVITY was delivered to Paranal in July 2015, integrated the following month and saw its first light in September of that year. Since then, the instrument has undergone commissioning, Science Verification (June and September 2016) as well GTO and open time observations (since October 2016). The four CIAO adaptive optics systems have also been installed and commissioned (in Sept 2016), allowing GRAVITY to observe its first Galactic Centre flare in October 2016, detected at magnitude K=15.

As of mid-2017, the transformation of the VLTI is mostly going according to plan, and its performance is improving as expected (see RD4).
5.2 NAOMI

NAOMI (the New Adaptive Optics Modules for Interferometry) will be installed on the four ATs starting mid-2018, replacing the original STRAP sensor (System for Tip/tilt Removal with Avalanche Photodiodes). The goals of NAOMI are twofold.

First, NAOMI will increase the range of seeing for which VLTI is usable. Currently, VLTI instruments do no work in poor seeing (high atmospheric turbulence) conditions, due to the resulting poor injection in single mode fibres. Also, the ATs suffer from dome seeing when the wind speed is below a few meters per seconds. NAOMI will allow VLTI to operate in both conditions more efficiently.

Secondly, even under average atmospheric conditions (seeing ~1”), NOAMI will provide improved performance of fibre-fed instruments. The GRAVITY Fringe Tracker is expected to reach even fainter limiting magnitudes.

5.3 AMBER+FINITO

The AMBER instrument has been in operation since 2005. It is a three-way beam combiner. Its initial wavelength coverage included J, H and K bands. However, with performance dropping rapidly at shorter wavelength, the bulk of the scientific exploitation was done in the K band and a smaller fraction in the H band.

AMBER is still the VLTI instrument with the highest spectral resolution in the K-band (12000 vs. 4000 for GRAVITY). It has produced superb results in the field of massive stars on accretion, winds and mass loss studies. However, the under-performing FINITO fringe tracker does not allow integrations longer than a few seconds. The low and unstable instrumental contrast makes absolute visibilities hard to calibrate. This limitation must be compared to GRAVITY’s capability to integrate for up to a hundred seconds, while delivering an instrumental contrast of several x10%. In addition, AMBER and its three baselines only deliver half as many baselines as GRAVITY. Finally, whereas AMBER-HR only covers a very limited spectral window, limiting most of the studies made by AMBER to the hydrogen Brackett-gamma line, GRAVITY covers the whole K-band. Early GRAVITY observations show that it can observe at R=4000 2 to 3 magnitudes deeper than AMBER at R=500, because of the poor performance of FINITO.
The number of nights requested on AMBER has steadily decreased over the last periods, from 100 night per semester in 2010, down to a dozen nights per semester in 2017 (see Figure 3). Being more sensitive, more precise and combining four telescopes, PIONIER has become the preferred instrument of the H-band broadband (R~30) science cases. The competition with GRAVITY is worsening the trend in the K band and AMBER will probably remain a niche instrument for those requesting the highest spectral resolution, for objects much brighter than what GRAVITY is capable of. Maintaining FINITO and AMBER is not a zero-cost operation for Paranal: it requires not only everyday maintenance which involves realignment, but the VLTI software has also to be maintained to be backward compatible with the frozen AMBER software.

Therefore, AMBER will be decommissioned soon. The Call for Proposals (CfP) for P102 (published in September 2017) already contains wording indicating that AMBER will be decommissioned. ESO did not received calls from the community to delay this decision.

Ideally, the failure of the J band mode of AMBER to deliver should be investigated before this decommissioning. It is very likely that the infrastructure itself (fringe tracker, vibrations, wavefront…) was not performing sufficiently well for this short wavelength regime. This analysis is important considering that some of the J band science cases remain intact (jet formation, accretion, pulsation studies, rapid rotators …) and could be revived by a potential future third generation instrument.

**Recommendation 1:** Investigate the origin of the poorly performing AMBER J-band mode.

**Recommendation 2:** Decommission AMBER and FINITO to make room for a Visitor Instrument.
5.4 Vibrations of the UTs and ATs

Vibrations have been plaguing VLTI/UT performance since first fringes in 2001. Mitigation efforts started in 2008. Accelerometers were installed on the UTs to measure the motion of M1, M2 and M3 and correct the OPD in open loop with the delay lines. This system, called Manhattan2, reduced the OPD vibrations from more than 500nm rms to 200 to 300nm per telescopes (Haguenauer et al. 2010SPIE.7734E..04H). Other actions have consisted in measuring the excitations sources (mainly cryogenic systems of the VLT instruments) and reducing their contribution by passive damping (Poupar et al. 2014SPIE.9145E..2MP).

Today, this effort continues: the GRAVITY fringe tracker is used to identify and steer the mitigation efforts in the right direction. In parallel, a vibration metrology is under development to investigate vibrations in day-time (RD4). It will eventually become an active compensation system operated at night, if the passive mitigation alone does not deliver the required performance.

ATs also suffer from vibrations: excitations from sub-systems is less than in UTs, since ATs do not do have their own instruments. However, the most prominent issue with ATs is the wind shake (Figure 4). Wind affects performances for speeds above 7m/s (which occur 50% of the time) and starts to be significant above 10m/s (which occur 20% of the time). There is no plan currently to address the wind shake at the telescope level, but NAOMI will include a vibration suppression algorithm, which should reduce the contribution of harmonic vibrations.

**Figure 4:** GRAVITY fringe tracker performance on ATs (phase residuals, lower is better), as a function of wind speed. Above ~7m/s, the performances degrade, independently of atmospheric turbulence (bluer is better).

**Recommendation 3:** Continue the long-term effort to reduce the vibrations on the UTs and ATs.

5.5 GRAVITY for MATISSE (GRA4MAT)

MATISSE absolutely needs a fringe tracker to deliver its promised scientific potential. The GRA4MAT project aims at using the GRAVITY fringe tracker to stabilise the fringes for MATISSE. It will allow 1) part of the science program of MATISSE on the UTs to be carried on the ATs, better suited for imaging, and 2) improve the sensitivity of MATISSE to a level required to observe Young Stellar Objects and possibly Active Galactic Nuclei. Initially, ESO was supposed to develop a so-called “Second Generation Fringe Tracker”. Three phase A studies were even funded, but a lack of resources has prevented its development and forced consideration of the GRA4MAT alternative. In the present case, it seems that the GRAVITY fringe tracker performs sufficiently well for a significant fraction of the proto-planetary disk and AGN science to be carried out. It is very important to note that, if successful, the GRA4MAT project paves the way for an extended use of this fringe tracker for other instruments. This would enable e.g. a spectroscopic capability at shorter wavelengths (by upgrading PIONIER for example), which is key to study stellar-surface (see AD-2).
GRA4MAT provides 2 key performance boosts to MATISSE (see Table 2). First, an improved sensitivity will allow to access more objects or to use high spectral resolution. Second, a better dynamic range can be reached by improving the minimum fringe contrast that can be reached. This opens MATISSE to unique science cases, as described in details in RD5. The highlights are:

1. AGNs: MIDI has shown that AGN dust might not be organised in a torus. To image AGN dust, MATISSE requires GRA4MAT to reach enough sensitivity and dynamic.
2. YSOs: by allowing imaging (high dynamic) and spectroscopy, GRA4MAT will allow to perform detailed mineralogy of proto-planetary disks
3. Dusty stars: without GRA4MAT, MATISSE will only image the dustiest stars, AGBs. By adding fringe tracking (higher dynamic), MATISSE will extend its study of dusty environment object with more subtle mass loss, such as red super giants, Be stars, Cepheids, etc.

**Recommendation 4:** Investigate the performance and limitations of the GRAVITY fringe tracker after two years of GRAVITY for MATISSE operation; Decide on the scientific need to explore other fringe tracking concepts and possibly extend the GRAVITY fringe tracker use to other instruments (e.g. PIONIER upgraded to short wavelengths).

### 5.6 VLTI operation and scheduling

In 2018, VLTI will have three four-telescopes instrument in operation, and ESO currently offers three 4-AT configurations (small-medium-large). GRAVITY adds additional requirements related to its astrometric operation. This makes the scheduling of VLTI observations extremely difficult. This is exacerbated by the small number of telescopes in the array and the scientific demands often generate conflicting requests. For example, **temporal monitoring** (e.g. stellar convection or pulsation, binary orbital motion) requires the same array configuration on a weekly/monthly basis while **imaging** proposals tend to request all configurations in a short amount of time. Since the scheduling of the VLTI is based on OPC ranking, it is often possible to have highly ranked proposals being rejected because they cannot be scheduled. In addition, up to 30 nights are under-used every semester during AT telescope relocation. An optimum scientific exploitation of the VLTI facility and its instruments requires dedicated tools that deviate substantially from what is currently available for VLT. The VLTI requirements need to be considered.

Until recently, VLTI was operated in visitor mode (VM) around 80% of the time. This was in part due to PIONIER being a popular visitor instrument. This led to a great inefficiency in the service mode (SM) execution, left with only a handful of nights each semester. Since P98, the observatory has discouraged VM but this has led to some complaints from the community that operations are not perceived as efficient as in VM. It can be expected that imaging programs will put more pressure on the VLTI SM scheduling by imposing the schedule of AT movements. Possible adaptations in scheduling lay in the trade-off between what users can requests and the freedom at the execution by the operators. The current SM models rely on four key aspects for the users to define their observations:

1. Observing programs are organized in observation blocks (OBs) which are a snapshot observation
2. Each OB has a telescope configuration set explicitly to one (and only one) of the 3 AT quadruplets offered or one of the 12 triplets.
3. Each OB has a set local sidereal time range (as low as one hour), to account for the limited sky coverage and/or specific uv-plane
4. Allowed dates are given to ensure good time coverage for time variable objects
5. Execution prioritization does not take into account efficiently of the already time and/or \(uv\)-coverage, only the current configuration, the weather conditions, the priority of the program etc.

This approach works well for VLT instruments (from which it is inherited), but is not well adapted to VLTI: users are forced to detail their observation blocks with scheduling information, whereas what they are really interested, for example for imaging, is a certain range and density of \(uv\)-coverage.

An updated operation model should shield users from scheduling constraints, and let the observatory handle dynamically the details of the optimization of scheduling. \(uv\)-coordinates could be defined in term of range and density, allowing the observatory to handle scheduling more efficiently. Similarly, the requirements in terms of time coverage could be entered by users explicitly giving the period and phase coverage or time intervals required.

**Recommendation 5:** Establish an updated operation model on the VLTI and develop the adequate scheduling strategy to balance imaging and time monitoring SM programs.

5.7 VLTI Expertise and user support centre

The 37\(^{th}\) ESO User’s committee (UC) in 2013 had a special session on VLTI. This included interventions from community experts and VLTI power-users. One of the recommendations of the UC was:

"The UC recommends that ESO should provide users with high-quality VLTI data reduction up to averaged calibrated visibilities."

This did not come as a surprise as it has been known from the early exploitation of MIDI and AMBER that reducing the data of these instruments was tricky. Despite the remarkable goodwill of the consortia to support users on a best effort basis even after the contractual phase ended; the accessibility of VLTI observations to non-experts was altered by the perception (often justified) that reducing the data was a difficult task. While data reduction user support was always "built-in" in radio interferometric facilities, VLTI was established on the VLT model with no such support. This has clearly prevented non-interferometry experts from making use of the VLTI. This extends to the use of the VLTI archival data, which ESO only offers in the raw format.

Despite this, the VLTI European community represented by the European Interferometry Initiative has been very active in helping astronomers become familiar with VLTI. Popular VLTI schools are organised every 1-2 years and the Fizeau program funds VLTI-related science travels\(^1\). The Jean-Marie Mariotti Centre\(^2\) (JMMC) has developed a popular suite of tools for observation preparation and data analysis, used by most (if not all) VLTI users.

Past and current VLTI programme scientists have been discussing with the EII bureau and ESO’s DMO management about the possible next step in support. It is agreed that the actual data reduction expertise lies in the consortia and that instrument contracts do not bind consortia to provide support or pipeline updates beyond the instrument acceptance. Similarly, the image reconstruction expertise lies in the community and ESO has little expertise available. The concept of "VLTI Expertise and User Support Centre" has emerged as a lightweight version of ALMA nodes. There is an overall agreement that it should not be too hard to establish such centres and there is already one such proposal discussed (JMMC). The possible main missions of these centres would be to 1) provide data reduction

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\(^1\) [http://www.european-interferometry.eu/fizeau-program](http://www.european-interferometry.eu/fizeau-program)

\(^2\) [http://www.jmmc.fr/](http://www.jmmc.fr/)
support; 2) provide support for image reconstruction; 3) reduced the data on a yearly basis and populate a phase 3 products database to improve the scientific return of the archive.

The questions of the interface with ESO and the resources are the main ones to be settled. The development of such centres should be encouraged as they will provide the necessary push to expand the VLTI user base and exploit optimally the investment made in the VLTI infrastructure and instruments (PIONIER, GRAVITY and MATISSE). Synergies with extreme AO (SPHERE) and/or ALMA should be strengthened. There are still too many PIs that do not consider VLTI in the observing suite tools due to lack of understanding of its capabilities.

**Recommendation 6**: Explore the conditions for the creation and support of VLTI Expertise and User Support centres in Europe.

### 5.8 Development of large programs

Only three large programs have been executed at VLTI in the last decade. Yet, a look at the most impacting results of long baseline interferometry shows how important the statistical aspect is. Whether it is stellar diameter, AGN tori, exozodi fluxes or binary parameters measurements the impact of many interferometric measurements take their importance when they can provide a statistical view.

Consultations at VLTI community meetings, VLTI schools and other venues point toward a certain reluctance to submit large programs. The lack of a systematic data reduction strategy and modelling is often quoted. There is also a lack of knowledge in the community that VLTI has now the efficiency to carry surveys of hundreds of objects. There are still numerous fields that would benefit from surveys, such as pre-main sequence binary monitoring to calibrate stellar evolutionary tracks, mass loss in massive stars etc.

Large programs could also be considered as “consolidated programs” in the form of several teams coming together to share blocks of time which they schedule dynamically themselves.

For that reason, it is recommended to dedicate, at least for a few years, a significant fraction of time per semester (30 nights) to large programs.

**Recommendation 7**: Dedicate at least 30 nights per semester to large programs starting as early as the first year of an instrument operation.

### 6. Epoch 2 (2020-2025)

This epoch starts when GRAVITY and MATISSE have already been in operation for a few years. At that time, a better understanding will exist of the performance and limitations of the VLTI as a global system, in terms of sensitivity, robustness and image reconstruction capabilities. **Extrapolating from the successes of PIONIER and more recently of GRAVITY, it is very likely that the facility will be mature enough to warrant a third generation of instruments.** The following section explore the possible areas which VLTI could develop into.

### 6.1 Maximising angular resolution and overcoming the sky coverage issue

Since the early days of the first-generation instruments, the community has expressed interest in addressing two limiting properties of the offered VLTI configurations.
1. Increase the sky coverage of the long baselines;
2. Enable the full angular resolution of the VLTI by offering the northernmost stations (J6)

The limited sky coverage is well documented and is illustrated in Figure 6. This has severe implications on imaging programs by limiting the uv coverage and moreover deprive VLTI of northern sources (e.g. star formation regions such as Orion and Taurus). There are some well identified topics that would considerably benefit from complementary observations between CHARA (Mt Wilson, California) and VLTI. One of the most emblematic is the temporal follow-up of novae (T Pyx, Delphini 2013) and the study of proto-planetary discs where both facilities could provide extensive uv-coverage. This limitation is well understood and is related to the intrinsic design of the VLTI optimized for UT use and limited to the summit platform.

![Figure 5: Offered AT quadruplets, optimized for uv and sky coverage, taking into account operational constraints (as of 2017).](image)

The need for higher angular resolution has been a recurrent request from community users. The current maximum AT baseline is 132m (Figure 5) while technically the VLTI could offer 202m, which represents nearly 50% gain in angular resolution. This limitation is well understood: a lack of sufficient optical delay which cannot be solved without an upgrade of the facility, namely increasing the optical delay capacity of VLTI.

Exploring a double passage of light through the delay lines would likely solve this issue. The technical details have not been worked out. Clearly it would be a significant effort requiring a major infrastructure upgrade. Given the direct impact on the scientific productivity it should be considered as a worthwhile VLTI infrastructure improvement (Figure 6).
Recommendation 8: Study the feasibility of using the dual field capability of delay lines to improve the sky coverage and enable the VLTI longest baselines.

6.2 A visitor focus at VLTI

Optical interferometry is still one of the very few techniques where visitor instruments can open new scientific avenues. A certain number of parameters in the instrumental mode space have never (or little) been explored such as polarimetry, short wavelengths (J band), “wide field” interferometry, very high spectral resolution. **They correspond to very specific scientific goals of limited time duration.** They can also be technical demonstrators for future instrumentation impossible to test outside of a real operating facility. The flexibility offered by a visitor focus is considerable (as demonstrated with PIONIER) and its impact on ESO resources lower than standard instrumentation.\(^3\)

The probable presence of a VLTI facility fringe tracker (GRAVITY’s) simplifies considerably the life of a visitor instrument since it can focus on its core scientific goal and the facility makes sure the fringes are there. The recommended decommissioning of AMBER+ FINITO would liberate room in the VLTI laboratory that could be used for that purpose. However, it is probably not a zero-cost operation and it would be certainly important to invest time to define properly interface guidelines that visitor instrument would have to follow to shorten the installation and commissioning time.

It should be noted that the PIONIER control software was developed using the ESO standard VLT software. This is not (currently) a requirement of visitor instruments. This made the integration of the instrument, and later its transfer as an offered instrument, much

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\(^3\)see [https://www.eso.org/sci/facilities/paranal/instruments/vlti-visitor/applications.html](https://www.eso.org/sci/facilities/paranal/instruments/vlti-visitor/applications.html)
easier. A full-fledge instrument, i.e. “third generation instrument” would be, from the start, open to the community and integrated into ESO end-to-end operations.

**Recommendation 9:** Open an additional visitor focus at VLTI.

### 6.3 Possible third generation instrumentation

After the considerable investment in the VLTI infrastructure for GRAVITY and MATISSE, including the addition of adaptive optics and fringe tracker to the facility, it is important to evaluate if this investment could benefit further scientific topics. Over the course of several discussions with community members and in the context of the European Interferometry Initiative “Future of interferometry” working group several possibilities have emerged as potential candidates for third generation instruments (see RD3). There is clearly a scientific interest to exploit further VLTI capabilities. While ESO is not able to commit today that a third generation of VLTI instruments will be possible it should certainly encourage the community to put together strong cases for the 2020 horizon. This justifies the following recommendation:

**Recommendation 10:** To give time for preparation inform the community that ESO will consider a possible extension of the VLTI instrumentation at the horizon 2020 in a dedicated conference.

#### 6.3.1 Low-mass companion hunter:

PIONIER most emblematic recent results have been in the field of exo-zodiacal light detection and companion hunting around massive stars. The instrument dynamic range has been pushed to its limits and shows an illustration of the detection performances compared to other NACO modes extracted from Sana et al. (2014ApJS..215...15S). VLTI is characterised by an unmatched angular resolution and an inner working angle that allows it to search for companions within the inner astronomical units of debris-disk or exo-planet bearing stars or more generally a factor of 10 to 20 closer to the primary star. However, the dynamic range is limited (best published limits is 1/500) and understanding why is still a work in progress but is likely dominated by calibration issues. While GRAVITY and its fringe tracker might improve contrast detection performance, it was not designed with that specific goal in mind. The same comment applies to MATISSE.

The advent of a fully phased VLTI with damped vibrations and injection fluctuations raises the question of whether one could design an instrument capable of increasing the dynamic range to 1/1000 or even further. There has been significant progress in the field of nulling interferometry in the United States (Keck Nuller, Palomar fibre Nuller, LBT) that justify a re-examination of its interest for future VLTI instrumentation.

**Figure 7.** Flux ratio of companion stars in the massive star binary survey of Sana et al. 2014 as a function of angular separation.
A near to mid-infrared carefully designed instrument (with a possibility of nulling) would have a significant impact in the following fields:

- **Exozodiacial dust characterization.** A dynamic range of 1000:1 would allow faint exozodiacial disk emissions to be detected around nearby main-sequence stars (at the 50 zodis level, where one zodi is the density of the solar zodiacal cloud).

- **Young self-luminous or irradiated gas giant planets.** With the VLTI angular resolution five times better than what future extremely large telescopes such an instrument would be capable to resolve young self-luminous or irradiated gas giant planets. Low-resolution spectroscopic observations of such planets in the thermal near-infrared are ideal to derive the radius and effective temperature of the observed planets and provide critical information to study the non-equilibrium chemistry of their atmosphere via the CH4 and CO spectral features. Moreover, the ability to combine spatially resolved observations and radial velocities would offer the possibility of unambiguous mass measurements that would lead to direct constraint of atmospheric planet models.

- **Planet formation signposts in the inner astronomical units.** PIONIER has now observed about 60 pre-main sequence stars at VLTI resolving the inner rim of the disk while MIDI observed 40 protoplanetary disks. In the first case the central star and disk inner rim dominate the emission and prevent to explore further away the inner astronomical units while in the second poor precision in the measurements hamper the sensitivity to planet formation signposts. Improving both the precision of the measurements and introducing nulling would allow to probe the presence of planet-induced structures in the inner astronomical units of the disks. The synergy with ALMA and SPHERE would be very strong, and

- **Improved binarity studies:** the binarity fraction of intermediate and low mass stars could be addressed with a statistically complete sample.

This type of instrument would fall in the second category of development for VLTI recommended by ASTRONET (“Imaging exoplanet” in RD2). At the VLTI 2017 community days, a science case was presented by O. Absil (for D. Defrère, both from Liège) and updates on integrated optics developments were presented by L. Labadie (Bonn).

**Recommendation 11:** Stimulate the community to explore the science cases and technical feasibility of a high dynamic range 4T beam combiner at VLTI. Include the possibility to upgrade GRAVITY and MATISSE for that purpose.

### 6.3.2 iShooter: VLTI simultaneous observation across the spectrum

It is interesting to note that after 10 years of operation only a small fraction of the VLTI publications (<10% on average) have made use of the near-infrared and mid-infrared instrument (e.g AMBER, PIONIER, MIDI). Yet, since most of these publications are focused on very close circumstellar environments studies, the interest of having such a wide wavelength coverage is obvious. For example, in evolved stars the short-wavelength probe processes close to the photosphere (convection, pulsation, condensation …) while mid-infrared observations provide constraints on dust mineralogy and mass loss rates. For young stars, accretion and ejection processes, dust sublimation, are best probed in the near-infrared while mid-infrared probes the surface of the disc in the putative planet forming regions.

One of the reasons often quoted for users not using both instruments is the investment required in mastering data reduction of each instruments. It is not always obvious to have specialists of two instruments in a team. It is proposed to address this with recommendation
6 (Expertise Centres). The other reason is that the poor uv-coverage of first generation instruments provided datasets with limited information that hampered a self-consistent modelling across wavelengths.

With the advent of GRA4MAT ESO is going to demonstrate that two instruments operating at two different wavelengths can operate simultaneously. To a certain extent, MIDI+FSU (Müller et al 2014A&A...567A..98M) was already a successful (though short lived) demonstration of this concept by using the 2T K-band fringe tracker with the 2T N-band MIDI instrument.

This functionality paves the way for operating various instruments at the same time while the fringe tracker stabilises the fringes for all of them. The benefits of this external fringe tracker could be extended to PIONIER (H band) and enable higher spectral resolution while the extension to the J band (richer in spectroscopic lines) would become realistic. The simultaneous recording of data in the H, K, L, M and N would provide a unique milli-arcsecond data set to observers taken at the same time which would avoid time-variability issues which affects most of these objects at milli-arcsecond level. Moreover, the productivity of the VLTI would be greatly increased.

The analogy to the VLT XShooter spectrograph prompted to call this potential project the iShooter mode of the VLTI.

**Recommendation 12:** Explore further the scientific interest and feasibility of the “iShooter” mode for the VLTI.

6.3.3 Visible interferometry at VLTI

By design, VLTI cannot operate in the visible: light with wavelength below 1 µm is used for guiding and adaptive optics; only redder light is transmitted to the VLTI laboratory.

This has severely limited the ability to develop advances in fields such as stellar physics where processes such as rotation, convection, turbulence and transport are still poorly understood. This also prevented VLTI to participate to the exoplanet discovery revolution by characterising planetary systems host stars. In this latter field VLTI main competitors CHARA and NPOI are now well ahead with almost a decade of observations in the visible.

A strong community working group is currently exploring the science cases for the VLTI in the visible (Stee et al. arXiv:1703.02395). The VLTI has still interesting advantages with its access to the UTs and a genuinely superior uv-coverage capability. The availability of efficient fringe tracking opens the way for very high spectral resolution, a key element for stellar physics studies. This possible axis of development of VLTI instrumentation cannot be ignored but should be weighed against the cost of turning the facility into a “visible” one.

Recently, instruments at other optical interferometric facilities have demonstrated the feasibility of single mode fibre visible combination: FRIEND at CHARA (Berio et al. 2014SPIE.9146E..16B) or VISION at NPOI (Garcia et al. 2016PASP..128e5004G), paving the way to high contrast imaging in the visible.

These developments fall in the first category of development for VLTI recommended by ASTRONET (“going to the visible”, see RD2). At the VLTI 2017 Community Days, F. Millour presented both the science case and the instruments developments the Nice team is pursuing at the CHARA Array (e.g. Mourard et al. 2017 in JOSA) which could lead to a VLTI instrument.
Recommendation 13: Further develop the science cases for visible interferometry at VLTI and establish the requirements for the infrastructure.

7. Epoch 3 (2025 and beyond)

7.1 Three decades of optical interferometry at VLTI

At the 2025/2030 horizon, large facilities like JWST, ELTs, LSST, PLATO and ALMA will be dominating. VLTI will still have an angular resolution 5 times greater than ELT but with a much lower sensitivity. **There are still numerous fields where angular resolution is still the key parameter to enable discoveries and there is little doubt that optical ground based interferometry has a future.** For example: planet formation, Active Galactic Nuclei or Galactic Centre studies. It could also be key to follow up class of objects newly discovered by facilities like LSST or PLATO.

However, in fifteen years from now, a 4T VLTI will suffer from a shortage of spatial information when compared to adaptive optics or ALMA. A limited $uv$-coverage often corners astronomers into interpretations and parametric modelling of the data when the object is too complex and/or time varying. The risk of being “informative” rather than “conclusive” is high. A possibility is to add more ATs, which is readily feasible.

![Figure 8. Possible future 6AT configurations](image)

Additional ATs can be envisioned for extending $uv$-coverage (Figure 8), but beyond 4T combination can also be achieved using AT+UT combination which has been demonstrated with MIDI (at the cost of polarisation mismatch between the two beams): if two additional delay lines are built, VLTI can combine up to 8T. Naturally, a new instrument would have to be built to combine from 6T or even 8T.

7.2 Optical Long Baseline Interferometry beyond VLTI

Several working groups have already stressed the need for kilometric baselines, increased sensitivity and better $uv$-coverage to revolutionize their respective fields (see EII report, AD-2). In 2020, we will have a fair understanding of the limitations of VLTI in terms of sensitivity and image reconstruction capability with GRAVITY and MATISSE. We already know that pushing the angular resolution cannot be done through construction of longer baselines at
VLTI and can be only partially achieved through observations at shorter wavelengths, which limits the type of objects observable and not probe the same physical processes.

The scientific interest of VLTI beyond 2030 is clearly a question that should be asked. One of the possible axis of development should be the combination of a significantly increased uv-coverage (i.e. more telescopes on the mountain) with increased dynamic range thanks to baseline bootstrapping. This would provide an imaging capability at angular resolutions better than ALMA longest baselines and therefore would provide ESO community with a true milli-arcsecond imaging capability from the optical to the millimetric regime. It is already interesting to notice how most of the published ALMA results in the fields of stellar physics or close-by AGN are perfectly observable with the VLTI. The question of how many telescopes would be needed to offer a true complementarity is still open and can only be addressed after GRAVITY and MATISSE have been operational for some time.

At the time where this discussion will take place, the cost of such a VLTI infrastructure expansion should be weighed against the interest of developing a new kilometric-baseline facility that would be truly game changing. The Planet Formation Imager (PFI), for example, is a project aiming at imaging the birth of extra solar planets. The angular resolution and wavelength required call for a 10+ telescopes, kilometric-baseline mid-infrared (N-band) interferometer. Though it is unrealistic to transform VLTI to match PFI requirements, the VLTI facility could play a role in testing key technologies.

A conference at the horizon 2020 would be useful to evaluate the scientific landscape, as well as the lessons learned from MATISSE and GRAVITY, to project into the future either by expanding the infrastructure with more telescopes (and corresponding instrumentation) or investigating the possible involvement of ESO in a new facility (e.g. PFI).

**Recommendation 14:** At the 2020 conference, discuss expanding the infrastructure with more telescopes balanced with the need for a new facility.

### 8. Summary: timeline for the VLTI

The following timeline is proposed for the future of VLTI:

**Epoch 1: until 2020**
- Make GRAVITY and MATISSE a success by providing a well-performing, well scheduled VLTI array. Demonstrate robust fringe tracking and push sensitivity.
- Expand the VLTI user base by improving the accessibility to non-experts through dedicated “VLTI Centres”;
- Organize a conference in 2020 to discuss with the community a possible third generation instrumentation / upgraded infrastructure for VLTI.

**Epoch 2: 2020-2025**
- Exploit fully the existing infrastructure by upgrading the existing instrumentation.
- Increase the sky coverage and angular resolution capability by doubling delay line optical path
- Host visiting instruments pushing the technique in new directions.

**Epoch 3: beyond 2025**
- VLTI imaging capability might be expanded by adding more telescopes, and building a 6-to-8T beam combiner.
- VLTI might be used as a development platform for a next generation optical interferometers.
9. Recommendations
The following table summarizes recommendations made.

<table>
<thead>
<tr>
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<th>Recommendation</th>
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<tbody>
<tr>
<td>1</td>
<td>Investigate the origin of the poorly performing AMBER J mode</td>
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<tr>
<td>2</td>
<td>Decommission AMBER + FINITO to make room for visiting instruments</td>
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<td>3</td>
<td>Continue the long work to reduce the vibrations on the UTs and ATs</td>
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<tr>
<td>4</td>
<td>Investigate the performances and limitation of the GRAVITY FT after two years of GRAVITY for MATISSE operation. Decide on the scientific need to explore other fringe tracking concepts.</td>
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<td>5</td>
<td>Establish an updated operation model on the VLTI and develop the adequate scheduling tools</td>
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<td>6</td>
<td>Explore the conditions for the creation of VLTI Expertise and User Support centres in Europe</td>
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<td>7</td>
<td>Dedicate at least 30 nights per semester to large programs</td>
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<td>8</td>
<td>Study the feasibility of using the dual field capability of delay lines to improve the sky coverage and enable the VLTI longest baselines.</td>
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<td>9</td>
<td>Offer a visitor focus at VLTI.</td>
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<tr>
<td>10</td>
<td>Organise a conference to discuss the lessons learned from GRAVITY and MATISSE, discuss possible third generation instrumentation and the future of the infrastructure.</td>
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<tr>
<td>11</td>
<td>Community to explore the science cases and technical feasibility of a high dynamic range 4T combiner at VLTI. Include the possibility to improve GRAVITY and MATISSE for that purpose.</td>
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<tr>
<td>12</td>
<td>Explore further the scientific interest and feasibility of the iShooter mode for the VLTI.</td>
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<tr>
<td>13</td>
<td>Community to further develop the science cases for visible interferometry at VLTI and establish the requirements.</td>
</tr>
<tr>
<td>14</td>
<td>At the 2020 conference, discuss expanding the infrastructure with more telescopes balanced with the need for a new facility</td>
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