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EDITORIAL

Future of optical-infrared interferometry in Europe

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This Topical Collection was motivated and can be seen as a synthesis of the topics discussed by the working group *Future of interferometry in Europe* (FIE) of the EC-FP7–2 OPTICON Network, work-package 14.4, funded by the Europ0an Commission. It demonstrates the current momentum in the field driven by an exciting range of new instruments, and by improved interferometric facilities becoming available to the larger astronomical community right now. The central theme of this collection is to discuss which steps are necessary to benefit from this current momentum and to focus it into an even brighter future, making eventually the 2030s the decade of optical-IR interferometry, as the natural next revolutionary step of astronomical observing tools after the construction of the 30 + m class of so-called extremely large telescopes (ELTs), which is currently under way.

The recent discoveries of very nearby exo-planets in the habitable zone of Proxima Centauri and near the snow-line of Barnard's star emphasise the need for high-fidelity interferometric imaging at the smallest inner working angles. Combining the superb angular resolution of interferometry with high-contrast techniques will be the only way to follow up observationally in the required detail the continuously rising number of exo-planets, their formation processes and interactions with their host circumstellar material. Further highlights of new scientific cases, which should drive the technological roadmap of future developments, are the fundamental physics of stars as driven by detailed images of their atmospheres, and the investigation of the physics of the most energy-efficient light sources in the Universe, namely the mass accretion onto supermassive black holes in active galaxy nuclei (AGN). Eventually, sensitive interferometric studies of AGN will allow us to bridge the cosmologically important, but elusive discrepancy of Hubble-Lemaître constant values as either measured from low-redshift supernovae, gravitational lensing time delays or the high-redshift cosmic microwave background.

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Interferometry will remain indispensable to successfully carry out all the above mentioned studies in the future and make important new discoveries, even when the monolithic ELTs become available. This Topical Collection mostly concentrates on the development of ground-based interferometric facilities, capable of combining wavelengths from the visible to the warm thermal infrared (0.5–13 μm), although several aspects discussed are certainly very relevant for interferometric space applications, too.

The contributed articles can be structured in three parts reflecting the pillars of research-driven astronomical instrumentation:

- ***Science cases***, which require interferometric observing capabilities
- ***Technical developments*** overcoming limitations of current instruments
- ***New concepts*** for next generation instruments, facilities, and community support

In the following, we give first an executive summary of these three parts, before we synthesize the presented work in a *roadmap* into the future of interferometry in Europe. Our community vision of this roadmap is largely in sync, but derived independently from the ESO internal process to plan the future of ESO's VLTI facility, which has been recently discussed separately in the ESO Messenger [1]. We conclude by listing the FIE working group membership and organizational structure, which were the basis for developing this Topical Collection.

1 Modern science cases of optical-infrared interferometry

Modern interferometric facilities respond to a wide range of astronomical questions, typically acting like a microscope, and dissecting in great detail physical processes at work in prototypical objects of their class (cf. brightest and nearest proto-planetary discs, evolved stars, active galactic nuclei, etc.). With telescope baselines of up to several hundred meters, interferometry is the only observing technique available to probe directly at visible-infrared wavelengths spatial scales down to milli-arcsec (mas), and below. Very high angular resolution has been identified at international meetings and community reviews as top priority and key toward a revolution in understanding the formation and evolution of exo-planetary systems, the fundamental physics of stars and of their atmospheres, and the structure of AGN, including cosmological applications.

The articles in this Topical Collection emphasise that with the successful construction of the 2nd generation instruments at the main European facility, the Very Large Telescope Interferometer (ESO VLTI), the further development of interferometry in Europe has reached a milestone, and turning point. Discussing its potential for the future is timely. In fact, the matured VLTI infrastructure which is now routinely bringing the photons from the first mirror surface into the scientific data archive for optimal exploitation, allows the execution of large multi-semester observing programs, and surveys, which goes along with further increased scientific impact, beyond the Rosetta-stone like investigations of the brightest and nearest objects of their class only.

Defrère et al. [2] describe the general evolution of interferometric science cases over the last decades, starting from stellar physics and evolution as the dominant science cases for the early facilities to the, now fully developed, additional fields of planet formation, testing General Relativity near our galactic black hole horizon, and the nuclear physics of AGN. This broadening of focus occurred to equal parts thanks to the general evolution of astronomy (with planet formation as a new field for observational astrophysics) and technology advancements, bringing the fainter AGN in the observable range of interferometers. Ertel et al. [3], and Hönig et al. [4] as well as the science cases of the 2nd gen VLTI GRAVITY[1] and MATISSE[2] instruments with full imaging capability now online, highlight possible future directions of these key fields of modern long baseline interferometry. While as discussed in these articles, increasing the angular resolution and imaging capabilities by longer baselines and additional telescopes allow to study new aspects, Millour et al. [5], and the community effort behind describe how doing interferometry in the visible (<0.9 μm) will unlock new areas of research thanks to the combination of higher angular resolution and different wavelengths, making new classes of (bluer) stars and eventually AGN accessible to interferometers.

New perspectives opened up in the last decade, thanks to the improved interferometric infrastructure, and imaging capabilities: Time-domain astronomy, discussed in Schaefer et al. [6] is nowadays possible, when full imaging information can be acquired in a single night (snapshot imaging). Likewise of interest is the ideal complementarity and synergies between the visible-infrared and mm-observing range. The ALMA facility, now in routine operation, observes molecular gas, dust, and non-thermal processes at angular resolution finally comparable to near-infrared high-angular resolution techniques. Finally, differential astrometry at micro-arcsec precision will enable to probe general relativity close to the horizon of massive black holes. This will be the most challenging goal of the GRAVITY instrument pointed towards the vicinity of the galactic centre black hole.

2 Roadmap to the future of interferometry in Europe

Studying stellar radii and multiplicity was the bread and butter science for the first generations of optical interferometers. New technological possibilities allow now to contribute to astronomical research at the smallest scales of solar system research, and gravitational microlensing for planet hunting over mapping stellar surface protoplanetary disc and planet evolution in detail, as well as of investigating the cosmic distance scale with detailed study of AGN at significant redshifts. This situation motivates scientists throughout the community to develop ideas, concepts and technology to further improve our interferometric observing capabilities, and the access to them.

In the following we cast such developments into a roadmap to the future of interferometry in Europe, reflecting the work present in this collection. To achieve the proposed interferometric roadmap, a strong collaboration between ESO, ESA, EU and other international organizations is essential.

To structure the roadmap, we separate it in time in two parts, the nearer future, parallel to the construction of the first 30 + m class telescopes, and the following decade. Despite of this separation, both phases should be tightly linked for optimal

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[1] https://www.eso.org/sci/facilities/paranal/instruments/gravity.html

[2] https://www.eso.org/sci/facilities/develop/instruments/matisse.html

use of the resources. A construction of a new interferometric facility as currently discussed for the second phase, is only feasible at reasonable time and cost, if it is prepared by developing and testing new technologies with the existing facilities in the upcoming years. This happens already now with the use of photonics and newest detector technologies in the latest generation of instruments, and should be emphasized for the next generation of instruments, as discussed below.

2.1 Before 2025: Parallel to the construction VLT 3rd generation and E-ELT 1st generation instruments

While the E-ELT and its first suite of scientific instruments are being constructed, a 3rd generation of instruments for the VLTI could emphasize particular aspects (angular and/or spectral resolution, extended wavelength coverage, multi-object), and benefit of a mature and improved telescope infrastructure, including adaptive optics[3] and piston-stabilized beam trains.[4] In Defrère et al. [7] on Hi-5, such a focused instrument concept is presented, which could be realized as a visitor-instrument, similar to the successful PIONIER.[5] This high-dynamic range imager for the thermal infrared relies on a combination of new integrated optics technology which is currently developed for thermal infrared wavelengths [8], and statistically robust data processing techniques, emphasizing the importance of technological progress.

This collection lists several topics of technological developments which should be emphasized at this epoch. The list is not complete, but addresses key elements of interferometric beam combination to extend the sensitivity, sky coverage, operational robustness, imaging capability and wavelength coverage of interferometry in the optical-infrared domain. While the last decade brought photon-counting detectors to reality as ideal sensors for adaptive optics and fringe tracking systems, using emCCD and APD technology, first integrated optics beam-combiners (IO-BCs) showed at the same time the potential for simplifying, compactifying the beam combination, and at the same time increasing the precision of the measurement process. Key steps to go for larger arrays and the thermal infrared as a sweet spot for the direct detection of exo-planets and their formation, are the development of larger APD focal plane arrays working in the infrared, and IO-BCs for such wavelengths, the latter being discussed in Labadie et al. [8]. Wavelength up-conversion, as discussed in Lehmann et al. [9], represents an alternative approach towards interferometric science at thermal wavelengths.

Furthermore, we would like to see research ideas become reality to improve on the current fringe tracking limits of the VLTI. New fringe tracking concepts are being discussed which focus on an ideal use of photons entering the beam combining laboratory. In contrast, predictive control algorithms promise to create synergies between operating adaptive optics and fringe tracking in parallel.

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[3] Visible (MACAO) and infrared (CIAO) adaptive optics wavefront sensing for the UTs as well as a visible AO module NAOMI for the ATs:
MACAO: https://www.eso.org/sci/facilities/paranal/telescopes/vlti/subsystems/ao.html,
CIAO: http://www2.mpia-hd.mpg.de/GRAVITY/
NAOMI: https://www.eso.org/public/teles-instr/vlt/vlt-instr/naomi/

[4] https://www.eso.org/sci/facilities/paranal/telescopes/vlti/subsystems/control/fringecontrol.html

[5] https://www.eso.org/sci/facilities/paranal/instruments/pionier.html

The other key area of technological progress is in optimizing and automatizing the process of image reconstruction to derive model-independent images, and a reliable snapshot imaging mode (getting an image in less than a night), to eventually open the usage of arrays of 4–6 telescopes to the area of the time-domain astronomy [6]. Interferometric imaging hugely benefits from the availability of chromatic multi-baseline datasets, as provided now by the VLTI 2nd generation instruments, and the coming years will augure a new era of interferometric imaging with reliable image quality benchmarking (Sanchez-Bermudez et al. [10]).

While emphasis shall be put on these technological advancements to fully exploit the scientific potential of the current suite of instruments and infrastructure, and prepare for future instrumentation, we discuss in this collection as well, how the near-term future can benefit from improved community building, teaching and interaction. An overview of various topics to maximize the scientific community exploitation of the VLTI, and the idea of building a network of expertise centres in Europe are discussed in Kraus et al. [11]. Such centres, not unlike the ALMA regional centres, shall lead the process of training users, and bringing established expert knowledge to the broader astronomical community. This effort is supported by EII and the Horizon 2020 programme via the new OPTICON network grant, and is seen as a key element not only to fully exploit the current investments in interferometry, but also to prepare for a future facility beyond the VLTI, either ground and/or space-based [12].

2.2 2025–2035: Towards a new facility

After exploiting Gaia, bringing JWST and Euclid in orbit, and having the ELTs on sky, the 2025–2035 decade should focus on making accessible the highest angular resolutions, only attainable with optical-infrared long-baseline interferometry. Currently, these plans have merged into the planet formation imager (PFI[6]) project [13], but the identified science cases will evolve over the coming years, for instance due to the new results delivered by the above mentioned upcoming facilities. Nevertheless, the science driven PFI initiative needs to progress now to design a 10+ telescope interferometric array to allow for routine and sensitive imaging of complex sceneries like planet-forming systems. Many of the technological advancements, discussed in this collection, will contribute to a proper design and cost model of such a future interferometric facility.

As an intermediate step towards the PFI, longer baselines, and additional telescopes are discussed as an extension to the VLTI as it is today. Given the likely focus of the PFI on longer wavelengths, exploiting visible interferometry at the VLTI will allow for a complementary scientific use. Millour et al. [5] discuss opto-mechanical upgrades of the current VLTI infrastructure that would be needed to control the wavelengths leading to a 2–3 times higher angular resolution, as a prerequisite for visible-wavelength interferometry. Important technological pathfinding is currently done at the CHARA facility.

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[6] http://www.planetformationimager.eu

At this early stage of developing post-VLTI facilities, also alternative approaches to high-dynamic range interferometric imaging at highest angular resolution should be studied [14], also [15]. A future facility like PFI [13] will eventually become feasible as an international facility if building on the experience of today's optimized arrays, choosing the best fringe tracking concepts, focusing on simple light weight telescopes and mass production of now standard technology to co-phase apertures (adaptive optics) and arrays (fringe tracking).

3 Who is the *Future of interferometry in Europe working group* (FIE-WG)

The working group *Future of interferometry in Europe* (FIE) of the EC-FP7–2 OPTICON Network, work-package 14.4, was funded by the European Commission.

Advised by a community-wide search, the working group[7] consisted of

> *Jörg-Uwe Pott*, *Jean Surdej* (chairs)
> *Lucas Labadie*, *Hervé Le Coroller*, *John Monnier*, *Florentin Millour* and *Antoine Mérand* (as current ESO VLTI programme scientist)

with further significant contributions by Stefan Kraus (then EII president), Jean-Philippe Berger (former ESO VLTI programme scientist until August 2016), and all the authors of this Topical Collection.

A lively initial set of discussions and ideas presented here occurred at a community-open meeting organized in 2013 at the Observatoire de Haute-Provence (OHP, France), with most presentations and contributions online.[8] Although we received wide support and input from the community throughout the existence of the FIE-WG, we do not claim at all this Topical Collection to be fully representative of all the work and ideas circulating in the community.

Last but not least, we would like to thank the excellent editorial and managerial support we received throughout the preparation of this Topical Collection by Peter von Ballmoos, Ramon Khanna, and their team of Experimental Astronomy at the Springer publishing house.

Heidelberg, 21.11.2018 Jörg-Uwe Pott, and Jean Surdej

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[8] http://interferometer.osupytheas.fr

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