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STATUS & PROSPECTS IN OPTICAL INTERFEROMETRY

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Abstract. Optical interferometry is at a critical turning point, with major instruments being successfully delivered at VLTI and CHARA, driving the need for discussions on next-generation instruments and technology developments. To fully explore the potential of these technologies, coordinated R&D efforts are essential, which ASHRA (national organization for high angular resolution astronomy) can support. This proceeding highlights the latest developments and future prospects for optical interferometry discussed during a dedicated workshop at the SF2A annual meeting. The session reviewed the status of key infrastructures like the VLTI and CHARA, and presented ongoing R&D activities in the French community, in photonic technologies, intensity interferometry, and frequency conversion. The session also included an open discussion about the future of interferometry, highlighting the importance of science-driven goals supported by simulations, funding challenges, and the complementarity of the future space missions HWO and LIFE.

Keywords: Optical interferometry, high angular resolution, research and development, technologies

1 Introduction

Optical interferometry, one of the pillars of the *Specific Action for High Angular Resolution* (ASHRA), is undergoing a phase of renewal, with a particularly open landscape for both scientific and technological advancements.

The recent successes of the GRAVITY (GRAVITY Collaboration et al. 2017) and MATISSE (Lopez et al. 2022) instruments have significantly broadened the user base for optical interferometry, opening up new scientific opportunities from exoplanet research to extragalactic observations. In addition, ongoing developments like GRAVITY+, GRA4MAT, and MATISSE-WIDE at the Very Large Telescope Interferometer (VLTI), alongside the SPICA (Mourard et al. 2017) visible combiner at CHARA, are expected to further enhance performance in the coming years.

Beyond these well advanced developments, several projects have been proposed for the next generation of instruments at VLTI, such as ASGARD/BIFROST and NOTT, or PLANETES, aiming to operate in shorter bands or with a nuller mode. In parallel, numerous R&D activities are exploring new concepts such as photonic-based recombiners, advanced wavefront control methods, and frequency conversion techniques to extend interferometric capabilities to longer wavelengths. ESA's renewed interest in space interferometry, as highlighted in its Voyage2050 scientific program, alongside the LIFE mission concept, is further stimulating R&D efforts in infrared nulling interferometry. The vast array of potential developments highlights the need to define community priorities and coordinate efforts in the development of future instruments.

To this goal, ASHRA held on June 5th, 2024, a half-day workshop focused on three main objectives: first, to review the status and development programs of the main optical interferometric infrastructures in which the French community is involved; second, to present emerging instrumental and technological opportunities developed within the French community; and third, to discuss and identify future development priorities. Our session attracted around 55 participants, including 12 women, and approximately 10 attendees joining online. In these proceedings, we report on the discussions and insights gathered during the workshop.

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2 Summary of Presentations

2.1 Infrastructures and instruments

Four invited presentations were dedicated to the major optical interferometric facilities and instruments in which the French community is involved. These presentations highlighted their current status and future developments.

VLTI Roadmap for 2030+ - *Antoine Mérand (ESO)*
Antoine Mérand outlined the ongoing ESO Roadmap for the VLTI and its developments leading up to 2030. Following the successful implementation of GRAVITY and MATISSE and the delivery of a 200m baseline, the GRAVITY+ project is set to enhance the VLTI sensitivity significantly. Key goals for 2020-2025 now include fully exploiting the current instruments and expanding imaging to 6–8 telescopes. A. Mérand highlighted the ESO landscape focused on reducing operational costs for the VLT and ELT. He announced an upcoming call for VLT instruments and the start of the definition of post-ELT projects. For the VLTI, he identified key scientific opportunities, including studies of exoplanets, AGNs, and massive stars, as well as leveraging microarcsecond astrometric data from the Gaia mission. He also called for programs revisiting established science cases (large programs, time-domain studies, etc.). To fully unleash VLTI potential, A. Mérand proposed focusing on vibration control (orders of magnitude stronger than atmospheric residuals), developing open science to engage non-experts, enhancing data analysis capabilities (image reconstruction, model fitting, exploitation of the archives), and improving operational support. He concluded by reaffirming ESO's priorities to support GRAVITY and MATISSE upgrades in the short term while providing an open framework for the next generation of instruments.

CHARA optical network developments - *Denis Mourard (OCA, Lagrange)*
Denis Mourard presented the latest developments at the CHARA interferometric array, focusing on its current instruments and future expansion. The upgraded MIRC-X (Anugu et al. 2020) and recently commissioned MYSTIC (Setterholm et al. 2023) instruments, combining all six telescopes in the H and K bands, provide observations with spectral resolutions ranging from R=50 to R=1700. The SPICA instrument, currently in its science verification phase, also combines six telescopes and provide high-resolution observations at visible wavelengths (R=14000) with a sensitivity of V=5.5 (limited by vibrations). D. Mourard then described the on-going installation of new capabilities: SPICA-FT, which includes an integrated optics beam combiner (ABCD-type), and Silmaril (Lanthermann et al. 2024), a new instrument designed to enhance sensitivity in the H band. He highlighted the main science cases at CHARA, focusing on stellar populations, rapid rotators, and the convection processes in supergiant stars. For its development roadmap, CHARA plans to add two new telescopes – one fixed (on a 1km baseline) and one mobile, upgrading the adaptive optics systems, and replacing existing 1m telescopes to 2m. These enhancements aim to improve overall sensitivity and angular resolution within the CHARA array.

From GRAVITY+ towards a kilometers baseline - *Frank Eisenhauer (MPE)*
Frank Eisenhauer presented an update on the ongoing implementation of the GRAVITY+ project, followed by a reflection on extending VLTI baselines to a kilometer scale for increased angular resolution. GRAVITY+ aims to boost performance by increasing the sky coverage (Gravity wide), enhancing VLTI adaptive optics (AO) systems with high-density deformable mirrors for an 80% Strehl ratio, and deploying three laser guide stars at Paranal. The science cases now include studying black holes at redshifts of $z \sim 2$, exoplanets, and faint stars around Sagittarius A*–up to 100 times fainter than currently detectable. F. Eisenhauer then emphasized the need for kilometric baselines to resolve structures at the microarcsecond level, such as regions around the black hole itself, broad line regions, and accretion disks at parsec scales. He also discussed the challenges posed by the intrinsic faintness of small objects, which require both larger telescopes and extended baselines to study them at high angular resolution. The km-baseline concept was further presented in a contributed talk by G. Bourdarot. F. Eisenhauer concluded by urging the community to focus on the scientific cases opened by this interferometric concept rather than technical challenges, aiming to spark enthusiasm for the science first.

Advances of MATISSE at the VLTI - *Bruno Lopez (OCA, Lagrange)*
Bruno Lopez discussed the significant progress made with MATISSE at the VLTI, highlighting both astrophysical results and instrumental optimizations. Warm optics and thermal background present challenges in the L, M, and N bands, but MATISSE has successfully built on the legacy of earlier mid-IR instruments like SOIRDETE, ISI, and MIDI, extending spectro-imaging capabilities at the VLTI up to 13 μm. Key science cases include

YSO environments, disk cavities at AU scales and spectroscopic searches for elements like iron, carbon, and silicon. MATISSE also complements GRAVITY in the study of AGNs, quasars, and exoplanet atmospheres, a case that was further developed in a contributed talk by M. Houllé. Looking ahead, B. Lopez outlined the ongoing implementation of MATISSE-Wide, including the fine optical realignment completed in March 2024, new observing templates, and the upcoming assessment of MATISSE's performance with the GRAVITY+ upgrades. Future improvements focus on optimizing MATISSE's performance beyond 11 μm and enhancing sensitivity with a new fringe tracker (HFT). To conclude, B. Lopez emphasized the key role of solid carbon in planet core formation, suggesting it as a potential science case to help define a first-generation mid-IR space interferometer.

2.2 R&D activities

The rest of the session then highlighted a diversity of innovative developments in interferometric technologies. A first area of focus was the revival of intensity interferometry. While this technique can leverage large Cherenkov telescopes, recent efforts in Nice are combining it to modern detectors and photonics technologies to make it compact and transportable (Matthews et al. 2023). After successful on-sky demonstrations at Calern and Paranal, the efforts are now to increase sensitivity and baselines, with goal to offer it as visitor instrument at VLTI with the ATs.

In parallel, photonics technologies and in particular photonic lanterns are being adapted for combination of large number of beams, where optimization of coupling efficiency remains crucial (Lallement et al. 2023). The FIRST instrument at Subaru has recently integrated a 19-fiber photonic lantern in its architecture, and obtained first on-sky measurements at high throughputs (Vievard et al. 2024). Next steps include refining injection efficiency and optimise image reconstruction.

The ASGARD suite (Martinod et al. 2023) is a combination of four systems aiming at expanding the capabilities of VLTI and recently recommended as a visitor instrument. Within ASGARD, the BIFROST (Kraus et al. 2022) is a YJH high-resolution combiner that will complement GRAVITY in the K band, while NOTT, a L-band nuller, will open high-contrast observations to the VLTI. The Bald and HEIMDALLR (Ireland et al. 2018) systems are respectively a fiber injection module and K band fringe tracker to optimise the suite performance. The system is currently integrated in Europe and will be integrated in Paranal in 2025.

Further efforts to optimize VLTI's performance were discussed, including the PLANETES project. This concept consists in a passive upgrade of the existing PIONIER instrument to bring it to the J band, using a new beam combiner, camera, spectrometer, and injection module based on wavefront optimization. The instrument would use GRAVITY as a fringe tracker and dual-field observations. Such upgrades will be key in advancing studies of exoplanets and stellar environments.

Another emerging technique is heterodyne interferometry. The key science driver is the exploration of the inner parts of protoplanetary disks, which requires 1 au angular resolution at 10 μm. Recent progress in this area is bolstered by new technologies, including photonic correlators, quantum cascade lasers as local oscillators, and the prospect of using quantum well detectors. This technology is currently being tested at IPAG, where encouraging correlations of infrared signals were recently demonstrated (Allain et al. 2022).

Non-linear optics techniques also present a promising avenue for shifting mid-IR signals to near-IR wavelengths. This method, demonstrated on sky at CHARA with the ALOHA (Magri et al. 2024) prototype, has achieved initial success in the H band, and now works at 3.5 μm. While the current version is limited in bandwidth and sensitivity, ongoing efforts investigate using frequency comb technology and better detectors to reach deeper limits.

Finally, the LIFE mission was presented, a concept designed to study the atmospheres of terrestrial exoplanets using a space-based mid-infrared nulling interferometer. The mission will consist of four collector spacecraft and a beam combiner, enabling direct observations of exoplanets thermal emissions, with a higher detection yield than reflected light missions (Carrión-González et al. 2023). Key technologies under investigation include advanced wavefront control, broadband starlight suppression, and low-noise mid-infrared detectors.

Overall, this session highlighted the exciting technological advancements being developed in the community to push the limits of current interferometric facilities. These developments also lay the groundwork for future instruments capable of addressing a number of essential science cases.

3 Discussion

The discussion session began with a summary of the key points from the "Roadmap to the Next-Generation Infrared Interferometric Facility" workshop three months earlier, reported by M. Nowak. The workshop emphasized the critical need for sensitivity improvements and long baselines in future facilities, highlighting key scientific questions that interferometry could address, such as exoplanet formation and AGN dynamics. While existing facilities can still be pushed to their limits, a new facility designed with these challenges in mind could lead to significant breakthroughs. In the discussion that followed, participants reflected on the future of interferometry, particularly beyond VLTI. Funding challenges were brought up, with the ESO budget allocations post-VLT expected to provide clarity soon. However, any project that aims to go beyond the VLTI would require finding independent funding, possibly for facilities with kilometer-scale baselines. The importance of science drivers, supported by robust simulations, was underscored as essential for justifying such investments.

There was a consensus on the need to further develop science simulations. While there is excitement about the potential for a more sophisticated interferometric facility, participants noted that detailed science case simulations are crucial, particularly in engaging other communities that have yet to fully embrace interferometry.

In discussing the LIFE mission, it was emphasized that this ambitious facility would serve not only exoplanet science but a wide range of other scientific fields. However, concern was raised about the lack of involvement from the French community, despite its expertise. The complementarity between space missions such as LIFE and HWO was also discussed, particularly in the context of their potential for investigating different aspects of planetary atmospheres, such as chemistry and planetary radii. However, some participants emphasized that complementarity alone is not enough; to justify a new facility, it must offer unique capabilities that go beyond what other instruments can achieve. The importance of developing a clear vision of what interferometry can achieve that is distinct from other instruments, like the ELT or JWST, was a recurring theme.

The discussion also touched on the next steps for space interferometry. While large-scale missions like LIFE and HWO are still in early stages, the need for intermediate steps, such as smaller two-telescope space missions, was raised as a way to bridge the gap between current capabilities and the long-term vision. Participants highlighted that post-ELT planning and upcoming decadal surveys will be critical in shaping the future of optical interferometry, and the community needs to be prepared to present well-justified cases backed by simulations and clear scientific goals.

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