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ESO Strategy for the 2020s
High-precision Astrometric Studies with SPHERE
VEGAS – Exploring the Outskirts and Intra-cluster Regions of Galaxies

ESO, the European Southern Observatory, is the foremost intergovernmental astronomy organisation in Europe. It is supported by 16 Member States: Austria, Belgium, the Czech Republic, Denmark, France, Finland, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and the United Kingdom, along with the host country of Chile and with Australia as a Strategic Partner. ESO's programme is focussed on the design, construction and operation of powerful ground-based observing facilities. ESO operates three observatories in Chile: at La Silla, at Paranal, site of the Very Large Telescope, and at Llano de Chajnantor. ESO is the European partner in the Atacama Large Millimeter/submillimeter Array (ALMA). Currently ESO is engaged in the construction of the Extremely Large Telescope.

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ESO Strategy for the 2020s

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The stability that stems from ESO's intergovernmental status provides the Organisation with the remarkable ability to plan its future years. During its almost 60 years of history, the commitment of ESO Member States towards long-term plans has enabled the resourcing and successful development of world-class projects on timescales of over a decade, projects that have resulted in ESO's building and operating some of the most powerful and scientifically productive ground-based observatories in the world.

Planning is therefore an essential activity. Defining the best plan is a challenge that requires considering a hierarchy of elements that starts with the mission (why we exist), followed by the vision (what we want to be), the values (what we believe in and how we will behave) and finally the strategy (what we want to achieve).

The ESO mission was described in the Convention[1] which entered into force in 1962 and has been ratified by all Member States. In today's wording, ESO's mission is twofold: building world-class astronomical observatories on the ground and fostering cooperation in astronomy. The current ESO vision was implicitly adopted back in 2004 when Council approved the previous version of the strategy, which positioned ESO to deliver the Extremely Large Telescope (ELT) while keeping Paranal and the Atacama Large Millimeter/submillimeter Array (ALMA) at the forefront. The ESO strategy[a] approved by Council at its 104th meeting in December 2004 was formulated around the following goals:

– Retain European astronomical leadership
– Complete ALMA and start its efficient scientific exploitation
– Maintain the world-leading position of the VLT, and deploy its 2nd generation of instruments
– Exploit the unique capabilities of the VLT Interferometer (VLTI)
– Build an Extremely Large Telescope on a competitive timescale
– Continue the successful partnership between ESO and its community

The success with which ESO was able to reach these goals has been remarkable. A few indicators are worth mentioning:

– The efficient operation of its facilities coupled with its engagement with the community has allowed ESO to remain a world-wide reference in ground-based astronomy, as evidenced by more than 1000 refereed papers published every year using data obtained at ESO's facilities[2].
– ALMA construction was completed and operations are now in full swing. The ESO region is the most highly oversubscribed in regard to ALMA observing time, and astronomers from the ESO region are first authors of about 40% of all papers published with ALMA data.
– The 2nd generation of VLT instruments has been completed and is in very high demand by the scientific community, eager to use the new capabilities offered[b]. A rolling plan to keep the instrument complement at Paranal competitive is in place and resourced in ESO's long-term plan[3].
– The VLTI infrastructure overhaul has been completed and the 2nd generation of VLTI instruments delivered with here again a very high demand from the community[c].
– ESO's ELT, the largest of its kind, has been in construction since 2015[d] and is fully funded[e], and the first science observations are planned for the second half of the decade.
– Instrument development in partnership with institutions in the Member States has continued for the VLT and the VLTI, and the same model has been adopted for the ELT instruments, with the first-light instrument already well underway.

Given these outstanding achievements in meeting the goals defined in its 2004 strategy, the ESO Council decided in 2019 to revisit this strategy and the associated goals in order to keep up the organisation's momentum and success rate over the next decade (2021–2030), in particular for its ongoing flagship project — the construction of the ELT.

At its 150th meeting in June 2019, the ESO Council mandated its Strategy Working Group (SWG) to review the 2004 strategy and to propose to Council an updated document that will guide the organisation over the next decade. The SWG members included Council delegates Amina Helmi, Isobel Hook, René Michelsen, Martin Thomé, Christoffel Waelkens (Chair), and ex-officio members Willy Benz (Council President), Denis Mourard (Scientific Technical Committee Chair), and Xavier Barcons (Director General).

Following the Council mandate, the SWG met twice in the following eight months and status reports were given to Council and discussed in the Committee of Council (CoC) meetings of October 2019 and March 2020. A report detailing the findings of the SWG was presented at the Council meeting in June 2020 and a first draft of the final document discussed by the Committee of Council in October 2020. Hence, despite the difficulties caused by the inability to meet in person during most of 2020, Council invested a significant amount of time in thorough discussions about the best way to extend the strategy that led to the successes of the past decade and a half. Finally, the document outlining the strategy for 2021–2030 was met with unanimous approval at the 155th meeting of Council in December 2020 and is presented below.

In parallel, Council mandated the executive to generate a draft proposal for a statement of ESO's values, taking into account both internal and external input. A proposal is expected to be submitted to Council for approval in 2021.

Finally, Council also expressed the need to develop a collective look at the ESO vision, i.e, what the organisation should become in the long term, beyond the clear strategic milestones agreed. Discussions on this topic have been deferred to a post-pandemic era, when the necessary face-to-face meetings can be resumed.

The rest of this article is taken verbatim from the corresponding sections of document ESO/Cou-1911 conf. as approved unanimously by the ESO Council in December 2020.

Preamble

Astronomy, arguably the oldest science, is currently enjoying a golden age. Curiosity-driven astronomy has led over the last 50 years to the development of innovative technology that has not only led to a better understanding of the structure and evolution of our Universe and our place within it but also found its way in applications permeating our daily life. From enhanced image and sophisticated signal processing to the development of extreme adaptive optics and data science, astronomy has been at the very root of innovation in ideas and technology. And yet, this development process is only just beginning! The coming decades will see revolutionary observatories coming online covering the sky at different wavelengths and based on equally revolutionary technologies, many of which are still in development.

When ESO was founded in 1962, its mission was to "establish and operate an astronomical observatory in the southern hemisphere, equipped with powerful instruments, with the aim of furthering and organising collaboration in astronomy". For Europe, it was a revolution starting with five member countries and relatively modest means compared to current standards. Today, with sixteen Member States, one strategic partner, and Chile as the long-standing and trusted host state of the telescopes, ESO builds and operates the most powerful and innovative infrastructure in the world for observational astronomy from the surface of the Earth. This infrastructure edge provided by ESO to the European astronomy community translates into a world-wide scientific leadership in many areas of astronomy. Concurrently, ESO has also pushed for increased collaboration in astronomy by taking ownership of the European participation in ALMA and becoming one of its main Parties, and should continue with hosting and operating the southern array of CTA. Other examples include ESO taking responsibility in coordinating national publications towards the European journal 'Astronomy and Astrophysics' or developing science and technology joint programmes with ESA.

At the core of this success lies arguably not just the mere increase in the number of Member States but also the model of cooperation that has been developed over the years, which strongly involves the community within the Member States in all new large developments. This transparent bottom-up process has led to a culture of trust and consensus between the Member States greatly facilitating discussions, decisions, and the definition of common goals or vision.

Emerging from these successes and this culture of consensus is a common vision of the role of ESO for the decades to come: The Organisation should strengthen its position as the world-leading organisation in ground-based astronomy enabling the best opportunities for new discoveries. As such, it should consolidate its position as a key actor on the world-wide scene of existing and future large astronomical facilities regardless of wavelength or messenger by fostering collaboration and synergy. For the next decade, completing successfully the ELT with its original powerful suite of instruments is clearly a central element of strengthening this leadership.

The strategic goals define ways consistent with values prevailing in the Organisation to achieve the vision above, which itself derives from the mission statement. As the SWG embarked on its task, it was realized that while ESO's mission statement is clearly defined in the Convention and its vision shared among the members of Council, its values needed to be more explicitly defined. A separate document defining ESO's values is being prepared by the Executive for later discussion and eventual approval by Council. Notwithstanding this document, the resolution below defines the strategic goals which will allow ESO to reach its vision and fulfil its mission over the next decade.

Resolution

ESO Council, considering the report of its Strategic Working Group and recognising that:

- astronomy continuously delivers scientific discoveries of fundamental importance and with a broad societal impact, and is expected to continue doing so during the coming decade, as new cutting edge technologies enable the development of new generations of telescopes and instrumentation,
- ESO's role in astronomical research has been steadily increasing throughout the history of the Organisation, relying on highly competent and dedicated staff and fruitful collaborations with the community,
- the successful collaboration between the ESO Member States on science and technology has been of paramount importance for ESO to become the undisputed world leader in ground-based optical-infrared astronomy, and that furthering international collaboration beyond ESO's boundaries has led to a unique astronomical facility in sub/mm astronomy,
- this constructive collaboration between the ESO Member States should remain the driving force ensuring that ESO can continue its mission for future generations, with an open view on new members and collaborations,

adopts the following strategic milestones for ESO during the decade 2021–2030:

- Implement and operate the ELT as the world-leading extremely large telescope, by
  a. Enabling the delivery of the fully completed ELT on a competitive timescale;
  b. Ensuring that the telescope is equipped with the state-of-the-art instrumentation necessary to meet its overarching science goals;
  c. Engaging fully with the community to ensure the best use of the telescope and its instruments;
  d. Preparing an ELT archive consistent with ESO-wide standards.

- Ensure that the current facilities remain at the forefront of astronomical investigations, by
  e. Ensuring, in partnership with the community, that VLT, VLTI, ALMA (with ESO's partners), including their instrumentation, continue to be state-of-the-art;
  f. Allowing flexibility to adapt to the changing scientific landscape including multi-messenger astronomy and, accordingly, towards new modes of operation;

g. Considering the role of La Silla for the ESO community within this evolving landscape;
h. Maintaining a high-quality archive and data-management tools for all ESO telescopes, including ELT.

– Ensure that the Organisation is prepared for future projects when financial projections so permit, by
  i. Engaging with the community in evaluating the evolving international astronomical landscape and to assess the emerging science cases, taking advantage of the time ahead to have an open view on the nature of future projects;
  j. Maintaining some resources for conducting feasibility studies of promising projects and of their associated technologies;
  k. Developing a future-oriented human-resource policy consistent with the long-term perspectives that ensures the availability of the needed expertise;
  l. Being ready to start the selection process for a new project, possibly in collaboration, later in the decade, and only when the financial perspective is clear.

– Retaining ESO's leadership role in astronomy, by
  m. Reinforcing ESO as a stand-alone organisation with its specific domains of excellence, with emphasis on efficient governance, while ensuring ESO remains agile enough for collaborations with other organisations on a case by case basis;
  n. Outreaching effectively to the citizens in the Member States and beyond to share with them ESO's discoveries, milestones and plans for the future;
  o. Coordinating distributed centres of expertise within the ESO community (e.g. ARC nodes, VLTI centres of expertise), and exchanging expertise and training through studentships and fellowships as well as scientific meetings;
  p. Conducting a technology development programme which enables developing and operating current and future facilities, in collaboration with institutes and industry in the Member States;
  q. Exploiting the scientific synergies with other organisations (ESA, GW detectors, CTA, SKA) exploiting facilities in a multi-messenger astronomical environment.

Links

[1] The text of the ESO Convention can be found in the book Basic Texts Convention and Protocols: www.eso.org/public/products/books/book_0017/
[2] The ESO Publication Statistics is derived from the Telescope Bibliography (telbib) database and can be found here: http://telbib.eso.org/pubstats_overview.php
[3] See, for example, the Paranal Instrumentation Programme Plan and 6 Monthly report of September 2020, presented to the ESO Council at its December 2020 meeting: https://www.eso.org/public/about-eso/committees/cou/cou-155th/external/Cou-1912_162ndFC_PIP-6month_final.pdf

Notes

[a] The ESO Council resolution on Scientific Strategy from 2004 can be found in The Messenger, 2005, 119, 2.
[b] Until end of 2020 the number of refereed papers that have used data from 2nd generation VLT instruments are: MUSE (494), KMOS (83), X-shooter (796) and SPHERE (223).
[c] After the commissioning of GRAVITY and MATISSE, VLTI observing time requests reach 200–250 nights per semester, a clearly higher request than prior to P95 when the infrastructure upgrade began (F. Patat, ESO Observing Programmes Office).
[d] ESO Council confirmed the approval of the ELT Programme at its December 2012 meeting and authorised the start of Phase 1 of the ELT construction at the December 2014 meeting.
[e] At its December 2020 meeting, the ESO Council committed the funding for the entire set of activities included in building the ELT and bringing it into operation.

Juan Carlos Muñoz-Mateos/ESO

This beautiful photograph of the glimmering arch of the Milky Way as seen through a crystal ball, shining with billions of stars and entwined patches of gas and dust, offers an intriguing perspective on our home galaxy. It was taken by ESO's Photo Ambassador Juan Carlos Muñoz-Mateos, who hopes to "*help others feel what it's like to look at the night sky from one of the darkest and most barren locations on Earth*" — the Atacama Desert, home of ESO's Paranal Observatory.

The dome of the VLT Survey Telescope (VST) takes centre stage in this panorama, dominating the foreground as it sits beneath the arc of the Milky Way. Numerous nebulae can be seen dotted along the arc of our galaxy. The remarkable glow of one of the Milky Way's satellites, the Large Magellanic Cloud, can be seen above the VLT Unit Telescope. While the sky is typically dark in the Atacama Desert, a faint and colourful airglow often makes it brighter, especially over the horizon.

P. Horálek/ESO

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High-precision Astrometric Studies in Direct Imaging with SPHERE

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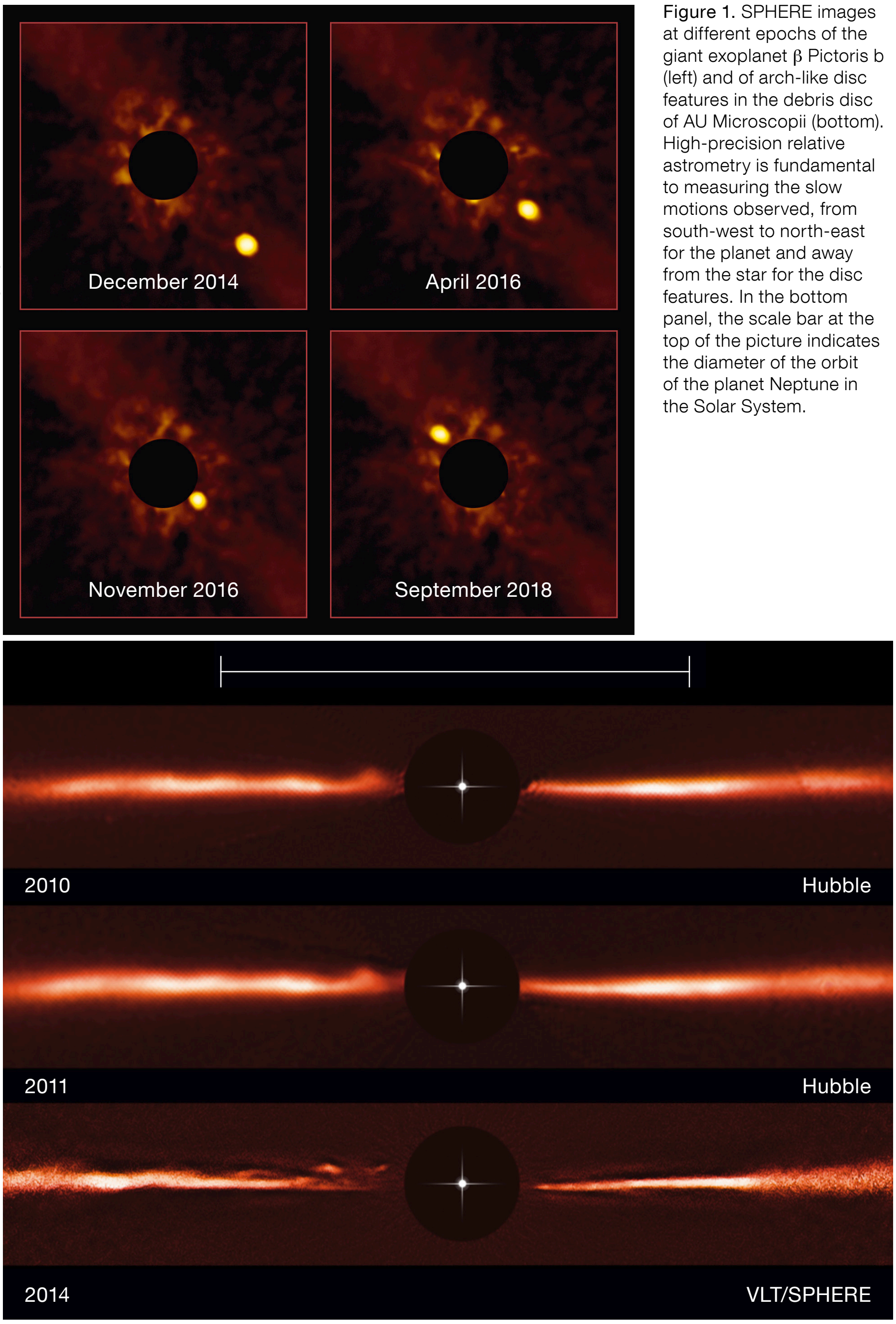


ESO/Lagrange/SPHERE consortium and ESO/NASA/ESA

Figure 1. SPHERE images at different epochs of the giant exoplanet β Pictoris b (left) and of arch-like disc features in the debris disc of AU Microscopii (bottom). High-precision relative astrometry is fundamental to measuring the slow motions observed, from south-west to north-east for the planet and away from the star for the disc features. In the bottom panel, the scale bar at the top of the picture indicates the diameter of the orbit of the planet Neptune in the Solar System.

Orbital monitoring of exoplanetary and stellar systems is fundamental for analysing their architecture, dynamical stability and evolution, and mechanisms of formation. Current high-contrast extreme-adaptive-optics imagers like the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE), the Gemini Planet Imager (GPI) and the Subaru Coronagraphic Extreme Adaptive Optics/Coronagraphic High Angular Resolution Imaging Spectrograph combination (SCExAO+CHARIS) explore the population of giant exoplanets and brown dwarf and stellar companions beyond typically 10 au, but they cover only a small fraction (< 20%) of the orbit, leading to degeneracies and biases in the orbital parameters. Precise and robust measurements of the position of the companions over time are critical, requiring good knowledge of the instrumental limitations and dedicated observing strategies. The homogeneous dedicated calibration strategy for astrometry implemented for SPHERE has facilitated high-precision studies by its users since it began operating in 2014. As the precision of exoplanet-imaging instruments is now reaching milliarcseconds and is expected to improve with forthcoming facilities, we initiated a community effort, triggered by the SPHERE experience, to share lessons learned for high-precision

astrometry in direct imaging. A homogeneous strategy would strongly benefit the Very Large Telescope (VLT) community, in synergy with VLT Interferometer instruments like GRAVITY/GRAVITY+ and future instruments like the Enhanced Resolution Imager and Spectrograph (ERIS) and the MCAO-Assisted Visible Imager and Spectrograph (MAVIS), and in preparation for the exploitation of the Extremely Large Telescope's (ELT's) first instruments: the Multi-AO Imaging CAmera for Deep Observations (MICADO), the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI), and the Mid-infrared ELT Imager and Spectrograph (METIS).

Motivation

High-precision relative astrometry in direct imaging is crucial for various science cases, beyond determining the orbital parameters of exoplanets, brown dwarf companions or multiple stellar systems. For exoplanet surveys (Langlois et al., 2020), it is instrumental in testing the nature of the faint sources detected near the targeted stars (Figure 1, top). The fields of view used are typically too small for absolute astrometry, so astrometry relative to the targeted star is used. Multiple-epoch monitoring enables one to test whether the candidate companions are comoving, with proper and parallactic motions similar to those of the host star, by rejecting contamination by stationary (or slowly moving with the local field) background or foreground sources. More precise measurements allow for faster confirmations. This approach requires a second observation, for example from archival data. One must be aware of the possibility that a candidate companion having significant proper motion might mimic a physical companion with orbital motion (for example; Nielsen et al., 2017). Multiple-epoch monitoring remains the most reliable approach to confirming a candidate companion, and ultimately resolving its orbital motion to confirm that it is gravitationally bound.

Constraining the orbital parameters of a companion provides clues to its formation and dynamical history. Orbits with small eccentricities are consistent with planet formation within circumstellar discs, and are similar to the Solar System's configuration. Larger eccentricities might be connected to star-like formation mechanisms; or they may indicate subsequent dynamical planet-planet interactions in multiple planetary systems that could explain the broad eccentricity distribution of exoplanets detected with the radial velocity technique. Another valuable output of orbital fits are predictions of positions. This is important for optimising follow-up observations at longer wavelengths (lower angular resolution) or with slit/fibre spectrometry.

There is a strong synergy between direct imaging, radial velocities and absolute astrometry for orbital fits. Firstly, it can constrain the masses of the companions, which is a fundamental step towards the calibration of models of the evolution of young giant planets, brown dwarfs, and low-mass stars. For imaged companions, most mass measurements come from evolutionary models, which suffer from large theoretical uncertainties (for example, clouds and molecular opacities for the atmosphere, initial entropy for the formation). Secondly, it allows for the breaking of degeneracies in the orbital parameters. Radial velocities are degenerate with the inclination (essential to constrain the mass), but the degeneracy is lifted by using imaging and absolute astrometry. For multiple-companion systems, direct imaging is valuable for breaking the degeneracies with radial velocities or absolute astrometry that are due to the unknown orbital phases, although analysis of the dynamical stability may also be used. Thanks to the 24-year baseline between Hipparcos and Gaia DR2, absolute astrometry can now detect massive substellar companions at the separations probed by direct imaging. Bridging these techniques will increase with Gaia and the ELT to closer-in and/or planetary-mass companions, with the prospect of a complete view of planetary and stellar systems.

Direct imaging offers a unique means to simultaneously analyse companions and their birth environment, the circumstellar discs. Determining the orbits of the companions provides insights into potential dynamical interactions. Such systems provide valuable benchmarks for planet formation and migration models. The analysis of companion-disc dynamical interactions will also help to clarify which disc features (for example, spiral arms, rings, clumps) can be reliably associated with companions. Another research field that has recently emerged involves monitoring the motion of disc features to discriminate between different production mechanisms (Figure 1, bottom). For instance, misaligned inner discs or close-in companions have been proposed to explain shadows cast on the outer discs in various protoplanetary discs.

The problem of astrometric biases

The advent of the first dedicated exoplanet imaging instruments (SPHERE, GPI, SCExAO+CHARIS; for example, Beuzit et al., 2019) has improved the precision of relative astrometric measurements of young substellar companions, from about 10 milliarcseconds to about 1–2 milliarcseconds.

Measurements with higher precision are more sensitive to underestimated biases. These can be caused by the use of different methods for the data analysis and/or calibration, our limited knowledge of the thermo-mechanical stability of the instruments, and the use of different instruments (after upgrades, for example). Given the long orbital periods of the imaged companions compared to the lifetimes of instruments, maximising the measured orbital arc is vital if we are to derive more robust orbital constraints. Underestimated biases may also affect co-motion tests of candidate companions and trigger follow-up observations by mistake, wasting telescope time.

Figure 2 illustrates the importance of a good knowledge of the biases in co-motion tests of candidate companions using different instruments. For a star with many candidate companions, the biases can be estimated by assuming that most of them are background contaminants. For a star with a single candidate companion, a new observation is required to reach a conclusion.

Figure 3 illustrates the importance of a good knowledge of the biases in orbital fits for the exoplanet HIP 65426 b (Chauvin et al., 2017; Cheetham et al.,

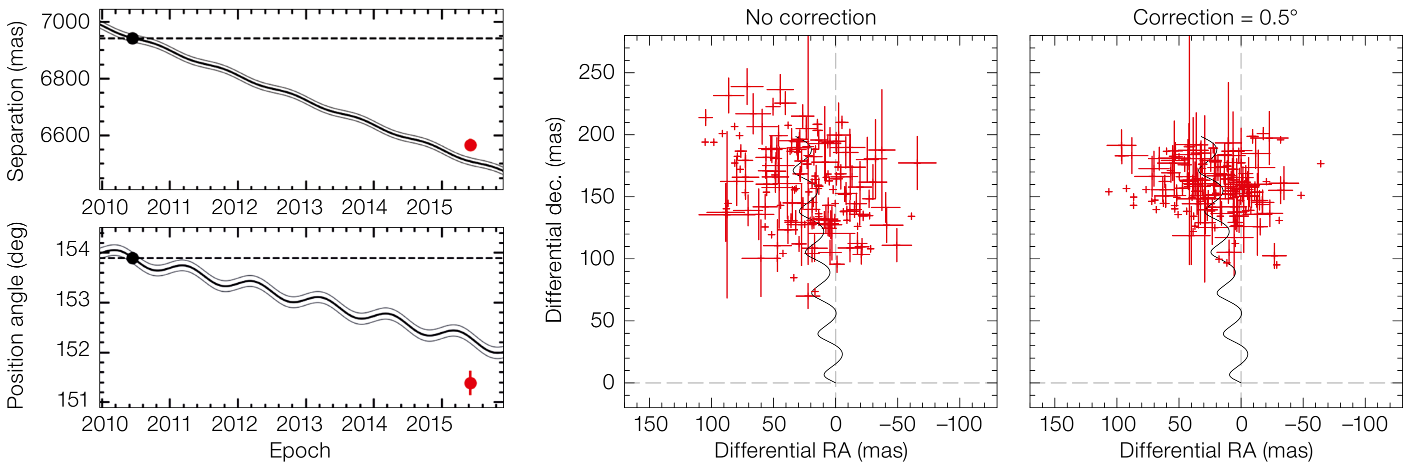


Figure 2. Tests for companionship of companion candidates detected around stars with SPHERE and NACO showing the importance of a good knowledge of the biases in relative astrometry for the interpretation. The left panel shows the temporal evolution of the separation from the star (top) and position angle relative to north (bottom, taken as positive from north to east) for a single candidate companion compared to the evolution for a stationary background contaminant (black curve with grey areas). The motion of the point source does not follow the stationary background track, suggesting a physical companion. However, underestimated systematic uncertainties could account for the discrepancies. The right panel shows the differential declination as a function of the differential right ascension for a star with many candidate companions (red data points) for two values of the assumed correction angle to the north. The black curves show the motion for a stationary background contaminant. If most candidate companions are assumed to be stationary background contaminants, a correction angle to the north is needed to make their motion compatible with the expected behaviour.

2019). Low eccentricities and a bimodal distribution of the time at periapsis are favoured when combining data obtained in 2016–2017 from SPHERE and the Nasmyth Adaptive Optics System/COudé Near-Infrared CAmera (NAOS-CONICA, or NACO), whereas the eccentricity is not well constrained and can be high and the periapsis is in the future when fitting SPHERE data obtained in 2016–2018. These discrepant results point to underestimated systematic uncertainties between the SPHERE and NACO data.

SPHERE astrometric strategy

A homogeneous and regular astrometric calibration is crucial to minimising the biases and analysing the astrometric stability over time. Good astrometric stability eases co motion tests and orbital monitoring of imaged companions. It relaxes the need to take calibration data close to the science observations and reduces the calibration overhead at the telescope.

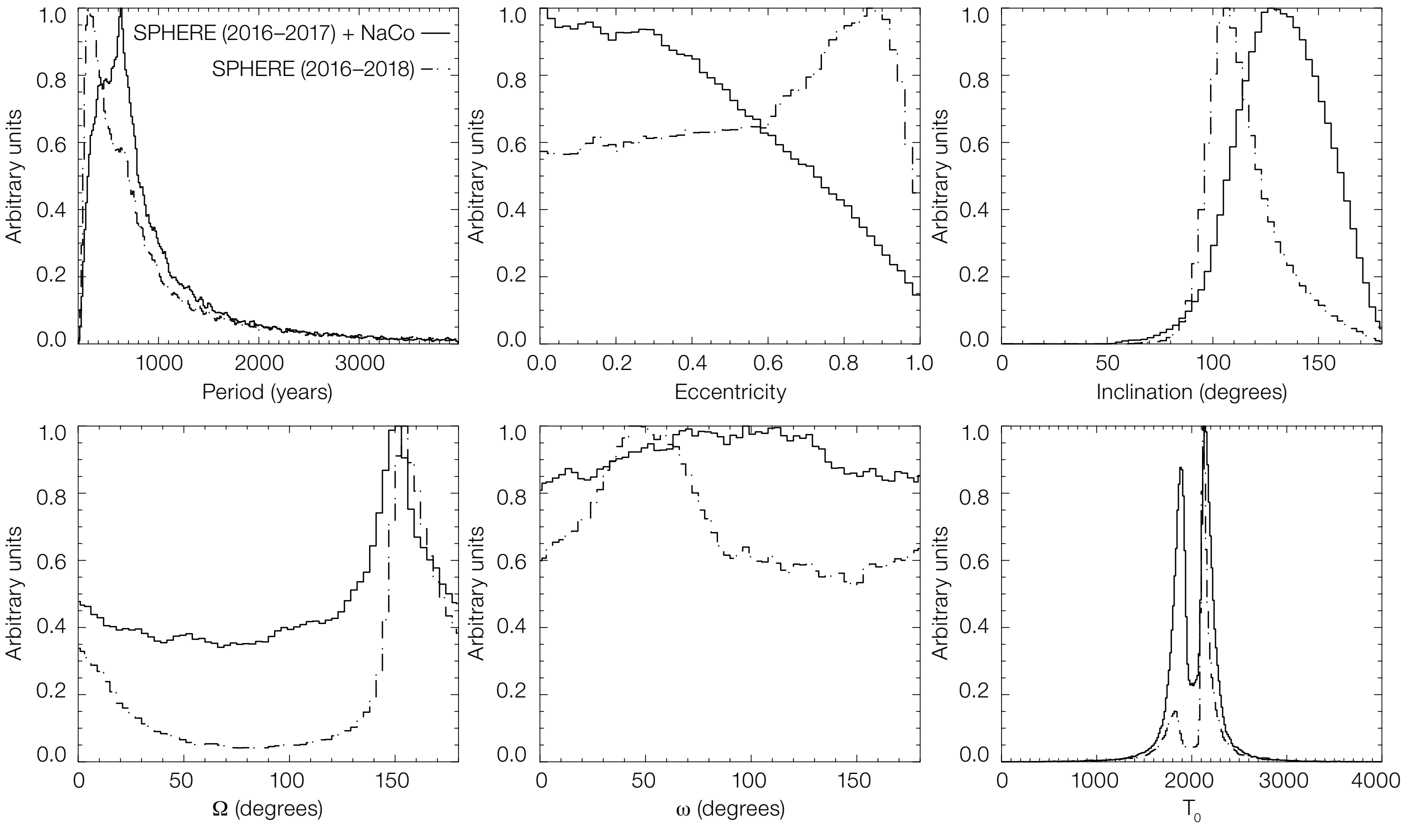
The astrometric strategy for the SpHere INfrared survey for Exoplanets (SHINE) was devised by the consortium before commissioning and was subsequently refined. It relies on: 1) an observing procedure to precisely determine the star's location behind the coronagraph (Langlois et al., 2020); 2) an accurate determination of the instrument overheads and metrology; and 3) regular observations of fields in stellar clusters for the astrometric calibration (Figure 4; Maire et al., 2016).

We chose fields in stellar clusters as main astrometric calibrators because the large number of stars available allows for precise measurements. They also allow for measuring the distortion from the telescope optics. We selected cluster fields with positions measured precisely by the Hubble Space Telescope, which has a good absolute calibration. We further selected fields with a bright star for adaptive optics (AO) guiding ($R \lesssim 13.5$ mag). Finally, we repeatedly observed two fields to cover the whole year, 47 Tucanae and NGC 3603. We chose 47 Tucanae as the reference field because the catalogue provides the stellar proper motions (Bellini et al., 2014). Langlois et al. (2020) compared the relative astrometry for widely-separated and bright candidate companions observed with SPHERE and present in the Gaia DR2 catalogue. The mean offset in separation is -2.8 ± 1.5 milliarcseconds (3.9 milliarcseconds RMS) and in position angle is 0.06 ± 0.04 degrees (0.11 degrees RMS). The RMS measures agree well with the expected uncertainties in these quantities in SPHERE data.

To analyse the astrometric data and derive the calibration, we developed a tool (Maire et al., 2016) that is included in the SPHERE Data Centre[1]. The distortion is mainly due to the optics in SPHERE and is stable in time (see Table). It produces differences in the horizontal and vertical pixel scales which amount to 6 milliarcseconds at 1 arcsecond. The astrometric requirement is 5 milliarcseconds (the goal being 1 milliarcsecond).

Figure 5 shows the temporal evolution of the pixel scale and correction angle to the north (Maire et al., in preparation). Except for pixel scale measurements obtained during commissioning, SPHERE has demonstrated a remarkable astrometric stability over five years. The standard deviation for the pixel scale measured on 47 Tucanae is 0.004 milliarcseconds pixel^{-1} and for the correction angle to the north 0.04 degrees. These variations translate into uncertainties at 1 arcsecond of 0.33 and 0.70 milliarcseconds, respectively, which is within the baseline astrometric requirements. We plan to release the measurements in the SPHERE Target Data Base [2].

The pixel scale and correction angle to the north have also been monitored in the ESO monthly calibration plan. The SHINE astrometric fields have been



observed without the coronagraph. We analysed the data at the SPHERE Data Centre to compute an astrometric table for the reduction of the open-time data. About 80% of the observations were not suitable for deriving a good calibration. Work is ongoing with the ESO staff to improve the setup of their observations.

The astrometric calibration of the SPHERE images also requires measurement of the offset angle of the pupil in pupil-tracking mode. The pupil-tracking mode allows for subtracting the aberrations in the images that are due to the telescope and the instrument. We monitored this parameter in 2014–2016 and showed that it is stable. Work is ongoing to monitor it in the ESO calibration plan.

In contrast, the astrometric calibration for NACO was heterogeneous, irregular, and mostly left to the observing teams. NACO also underwent technical interventions to commission new observing modes or fix issues, and was moved to another Unit Telescope of the VLT. This resulted in poor astrometric stability, making the use of the data for high-precision relative

Figure 3. (Above) Distributions of the orbital parameters of the exoplanet HIP 65426 b using two different sets of relative astrometric measurements. A good knowledge of the biases is mandatory in order to derive unbiased constraints. The panels show the period, eccentricity, inclination, longitude of the node, and argument and time at periapsis, from left to right and top to bottom.

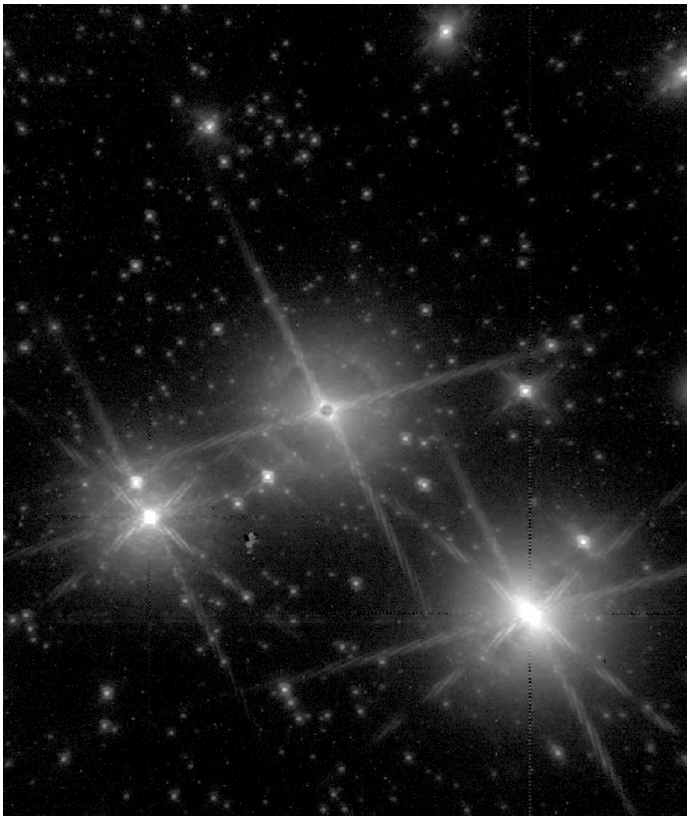


Figure 4. (Left) SPHERE image of the 47 Tucanae field used for the astrometric calibration. The field of view is ~ 11 arcseconds on one side.

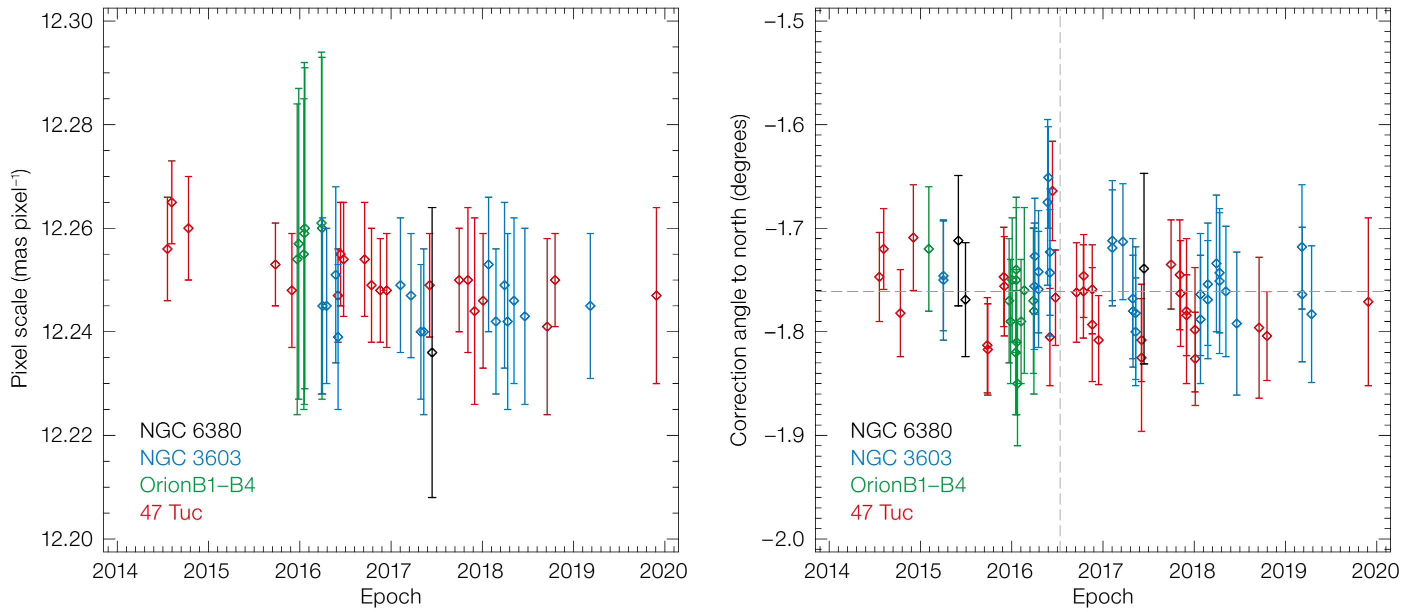


Figure 5. Evolution of the pixel scale (left) and correction angle to the north (right) of SPHERE. A good instrument stability is mandatory for high-precision relative astrometry over time because it reduces potential systematic uncertainties. Fewer measurements are shown for the pixel scale because it depends on the filter and coronagraph configuration. For the right panel, the dotted-dashed vertical line indicates the epoch when the time reference issue was solved (Maire et al., 2016). All previous measurements were corrected. The dashed horizontal line shows the weighted mean of all the measurements.

astrometry more difficult. The limitations encountered with NACO were taken into account in the astrometric strategy of SPHERE.

Required separation precision (mas)	5 (goal: 1)
Required position angle precision (deg)	0.2
Achieved precision calibration pixel scale at 1″ (mas)	0.33
Achieved precision calibration distortion at 1″ (mas)	0.2
Achieved precision calibration angle to north (deg)	0.04
Achieved precision calibration angle pupil tracking (deg)	0.06

Highlights from SPHERE results

Thanks to the good astrometric precision and stability of SPHERE, most users rely on the calibration derived by the instrument consortium. SPHERE has enabled the discovery of 15 substellar and stellar companions next to stars. It has been used for about 20 orbital studies, in combination with other imaging, radial velocity, and/or absolute astrometric measurements.

The orbital analyses of the exoplanets β Pictoris b (Lagrange et al., 2019) and 51 Eridani b (Maire et al., 2019) are good examples of where biases between different instruments had to be dealt with. β Pictoris b was monitored with NACO and then SPHERE. It was recovered in September 2018 after conjunction with the star. The SPHERE data are now probing the north-east part of the orbit, which was only covered by one NACO measurement in 2003, and they favour low eccentricities. 51 Eridani b was monitored for three years. Coupled with GPI data, orbital curvature was detected in this system for the first time and the fit suggests a high eccentricity (~ 0.3–0.6). A high eccentricity hints at dynamical interactions that perturbed the orbit of the planet, possibly by another as-yet-undetected planet.

The orbital predictions were also used for GRAVITY observations to get spectra at longer wavelengths and higher resolutions (2.0–2.4 μm, *R* ~ 500) compared to SPHERE (1.0–2.3 μm, *R* ~ 50) and to get exquisite astrometry (~ 30 times more precise), confirming the robustness of the SPHERE calibration plan. Companion-disc dynamical interactions were studied in several systems, including systems with a brown dwarf within the cavity of the debris disc. HR 2562 B could carve the disc cavity, whereas another companion may be needed around HD 206893. Disc features were monitored, such as the arch-like features moving away from the star AU Microscopii. The current scenario involves dust produced by an unseen parent body and expelled by the stellar wind. The rotation of the spiral arms of MWC 758 was shown to be compatible with a planet-driven mechanism.

Future astrometric studies with direct imaging facilities at ESO

Further monitoring of known companions and disc features will be important for refining their orbits and their formation mechanisms, respectively. Moreover, Gaia is expected to detect a large number of giant exoplanets. Young exoplanets detected from acceleration measurements will be prime targets for imaging, to confirm and firmly constrain their orbits and masses. This large sample of exoplanets beyond a few au will allow for statistical analyses of the distributions of eccentricities and relative inclinations to the stellar equatorial planes (for multiple-planet systems and also mutual inclinations). Such analyses will be crucial to understanding their formation and evolution, and the relation between planet and binary-star formation mechanisms.

The next step for exoplanet imaging will be made with the ELT and its first three instruments: MICADO, HARMONI, and METIS. They will access smaller planet-star separations, down to 1 au, to detect predominantly giant exoplanets. Thanks to the combination of increased angular resolution and larger collecting aperture, diffraction-limited ELT observations will at the same time access smaller angular separations and achieve higher astrometric precision at angular separations accessible to 8-metre-class imagers. MICADO and HARMONI will be sensitive to young planets, whereas METIS will reach mature planets. Before the ELT, ERIS, GRAVITY+, and a potential SPHERE upgrade will be operational on the VLT/I. ERIS will be suitable for imaging giant exoplanets around young stars, and more mature giant exoplanets which are too faint for the SPHERE AO system. GRAVITY+ will have better sensitivity than GRAVITY to access mature exoplanets.

A joint and homogeneous strategy shared by the exoplanet imaging facilities at ESO will enhance their use for high-precision astrometry, by minimising biases. The successful calibration plan implemented for SPHERE could be applied and adapted to these instruments. If proposed by future instrument consortia, interactions with ESO would be valuable to check whether such a calibration plan could be adopted. As SPHERE is expected to be operational during the first years of the ELT's operation, parallel observations could be used to check the astrometric consistency. GRAVITY could be used to test/validate the absolute calibration of coronagraphic instruments, thanks to the absolute calibration provided by its internal metrology system (Lacour et al., 2014).

We recently started an initiative between the SPHERE team and the teams in charge of the high-contrast imaging modes of forthcoming ESO exoplanet imaging facilities at the VLT/I and ELT to share the SPHERE experience and the lessons learned in the field of astrometric characterisation of exoplanets and discs. We firmly believe that this offers the opportunity to federate our community: 1) to revisit past studies through archival data mining, 2) to push the calibration strategy and performance of current instruments in operation, and 3) to share this expertise with consortia of forthcoming instruments at the VLT/I and ELT to optimally prepare their scientific exploitation. We expect to prepare a workshop on this topic in the future.

Acknowledgements

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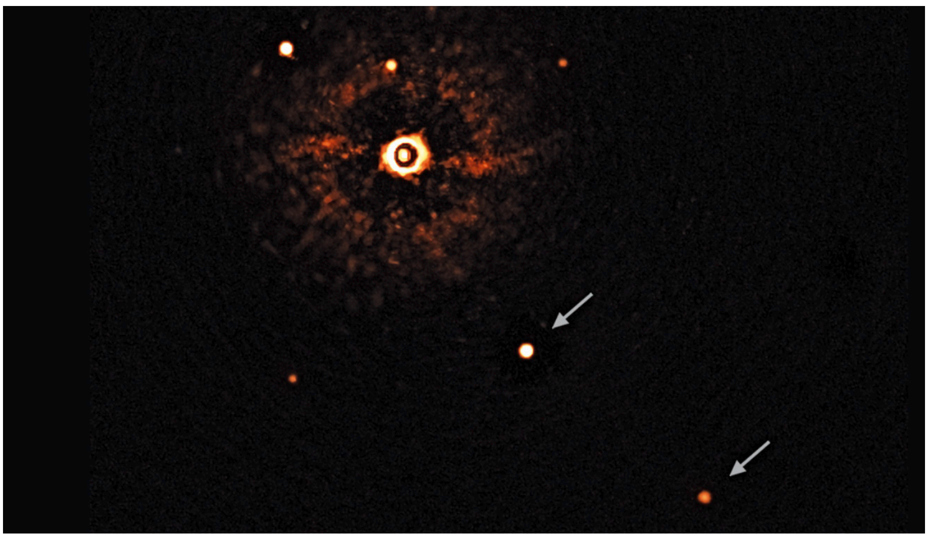
Links

[1] The SPHERE Data Centre: https://sphere.osug.fr/spip.php?article45&lang=en
[2] The SPHERE Target Database: http://cesam.lam.fr/spheretools

ESO/Bohn et al.



This image, captured by the SPHERE instrument on ESO's Very Large Telescope, shows the star TYC 8998-760-1 accompanied by two giant exoplanets, TYC 8998-760-1b and TYC 8998-760-1c (annotated with arrows). This is the first time astronomers have directly observed more than one planet orbiting a star similar to the Sun.

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Enhancing ALMA's Future Observing Capabilities

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With each observing cycle at the Atacama Large Millimeter/submillimeter Array (ALMA) new features and observing modes are offered. Here we provide some background about how these new capabilities are tested and then made available to ALMA users. These activities help to drive the cutting-edge science conducted with ALMA and to maintain ALMA's position as the foremost interferometric array operating at millimetre and submillimetre wavelengths. We focus in particular on opening up high-frequency observing using ALMA's longest baselines, which offers the highest possible angular resolution.

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Extension and optimisation of new capabilities

The global effort of adding new capabilities to ALMA is referred to as Extension and Optimisation of Capabilities (EOC). EOC was the natural progression after moving away from initial tests when ALMA was commissioned. During the final years of construction and during Cycle 0 operations, almost ten years ago, the development of new modes was called Commissioning and Scientific Verification (CSV). CSV was conducted to ensure that the capabilities offered were fully operational and valid. Following this, with ALMA as a fully operational telescope, testing as part of EOC activities has continued as an ALMA-wide effort encompassing all partners[1]: the Joint ALMA Observatory (JAO) in Chile and the ALMA Regional Centres (ARCs) in East Asia, North America and Europe. In Europe there are also contributions from the ARC network (see Hatziminaoglou et al., 2015). The entire EOC effort, including all coordination, planning and the intricate steps involved, is led by the JAO (see Takahashi et al., 2021).

In this article we provide an overview of EOC, and what features might be expected in the coming cycles, with a specific focus on pushing ALMA to achieve the highest angular resolutions possible (a study involving significant input from the European ARC). We also highlight how the ALMA community benefits from each capability potentially offered.

ALMA's process for offering new capabilities

Behind the scenes, the process that makes new capabilities possible is the ObsMode process (Takahashi et al., 2021), which is led and coordinated by the JAO. The intention of the ObsMode process is to enable all observing modes that ALMA was designed to support, as well as any additional ones identified since construction began.

Unfortunately, ALMA cannot simply test a new observing mode on the telescope and thereafter open it directly to the community. This is because all parts of the observing chain involving the so-called subsystems (Control software, Observing Tool [OT], Scheduling, Quality Assurance [QA], Pipeline, and Archive, to name just a few) must be up to the task. Before opening a new capability to the community, ALMA must be able to demonstrate the entire workflow: the correct creation of the observation files; successful, error-free observations; data reduction — first using manual scripts and thereafter with the ALMA Pipeline; and finally data and product ingestion into the ALMA Archive such that it can be delivered to any Principal Investigator (PI) and used in any future Archive mining exercises.

The ObsMode process therefore follows a yearly structure and is aligned with ALMA observing cycles. For example, the majority of work in 2021 began in October 2020 and will finish in October 2021 (Figure 1). This system includes a two-year lead time, such that any capability planned for release in Cycle 9 (due to start in October 2022) must be fully tested and verified in Cycle 7[a]. Final tests during the first half of Cycle 8, before the Cycle 9 Call-for-Proposals (CfP) pre-announcement is made, mark the final date to confirm the readiness of a capability for scientific operations. The main considerations throughout the year include:

- Proposed capabilities and priorities: A list is drawn up of capabilities aimed at science operations two years later. Given the ten years of ALMA operations, there is a natural continuation from previous years. ALMA management, together with the science and operations teams, arrange and discuss the priorities with the ALMA Science Advisory Committee (ASAC), which confirms that these align with the community input[b].
- Initial capability plan: Plans are made by the expert teams leading each capability. These must provide a technical summary, identify the on-sky time requirements, and detail each team member's role. Most importantly, the plans set the criteria for declaring a particular capability as ready.
- Test Observations: EOC observations are scheduled to have a minimal impact

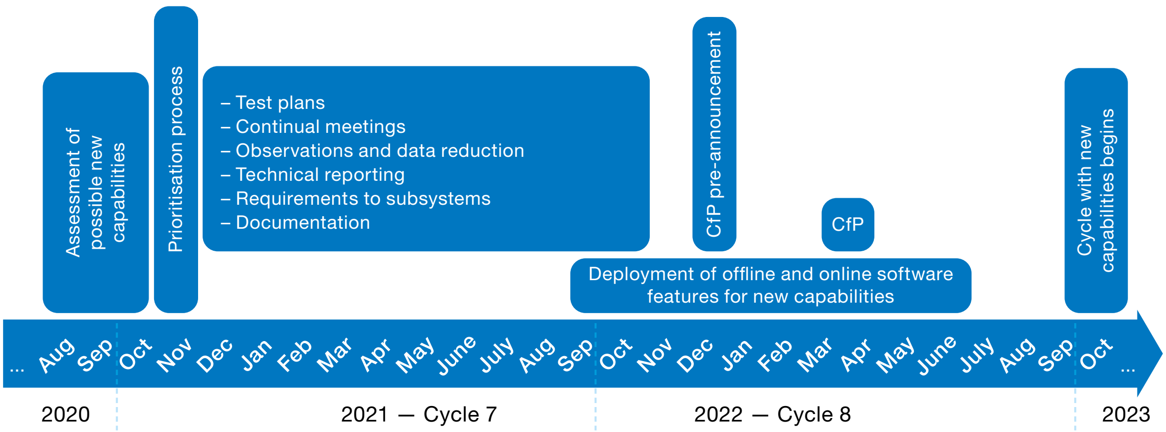


Figure 1. Simplified schematic of the general ObsMode timeline focused around the year 2021 (Cycle 7 — restarted because of the pandemic), starting from the identification of new capabilities at the end of the previous year and leading up to the point where they are planned for use in Cycle 9, two years later. In reality the EOC is a continual process as there is an intrinsic overlap of testing and development between the years.

on standard science observations, being conducted in small time windows or when science observations cannot take place. Where possible, observations use Scheduling Blocks (SBs) constructed with the OT, however some tests require custom command-line scripts to operate ALMA in a manual mode.

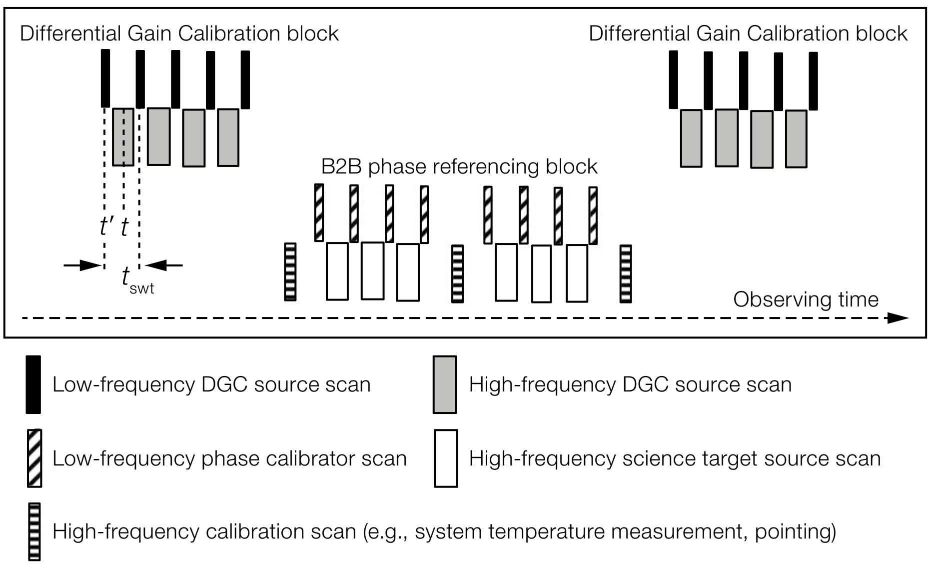
- **Data reduction and problem reporting:** Custom scripts are employed, using the Common Astronomy Software Applications package (CASA; McMullin, 2007) reduction software with extra analysis and heuristics. Extra system-level stability and data-validity checks are also made. EOC teams aim to provide QA-like reduction workflows to enable an easier transition to science operations.
- **Technical readiness:** In September and October the EOC teams report their findings and provide a technical report to specific expert reviewers. These reports are used for a readiness assessment to confirm whether the capability meets the initial readiness criteria.
- **Subsystem impact:** Requirements are created continually throughout the year for the subsystems involved. Although developments are continual, a capability can only be declared operational when all subsystems integrate the required modifications. Examples of subsystem changes are: (1) the addition of new OT features that allow SBs to be generated, and (2) modification of the QA2 process to provide the correct reduction path (see, for example, Petry et al., 2020).
- **Documentation:** Before the CfP is issued, ALMA provides users with a Proposer's Guide[2] and a Technical Handbook[3]. These documents must fully detail and explain any newly offered capabilities.

Focusing on high frequencies and long baselines with band-to-band (B2B)

The European ARC is particularly involved with EOC activities to offer high-frequency observations (Bands 8, 9, and 10, > 385 GHz) using the most extended array configurations (C-8, C-9 and C-10, with maximal baselines of ~ 8.5, ~ 13.9 and ~ 16.2 kilometres, respectively). Theoretically, the highest frequencies coupled with the longest-baseline array would achieve an angular resolution of 5 milliarcseconds. This translates to sub-au scales for sources within 200 parsecs and would provide the most detailed submillimetre picture of protoplanetary discs. For extragalactic targets, parsec scales could be resolved for sources within 40 Mpc, offering unprecedented details of galactic structures.

What is B2B? Band-to-Band (B2B) is a phase-referencing technique in which the phase calibrator, interleaved between the science target and used to correct for atmospheric variations (see, for example, Asaki et al., 2020a), is actually observed at a frequency lower than the observing frequency of the science target. The

Figure 2. Schematic of the main observing scheme employed for B2B test observations (Asaki et al., 2020a). The instrumental band offsets are solved using the Differential Gain Calibration (DGC) blocks, while the centre of the schematic shows the phase referencing for the calibrator and target alternating between low- and high-frequency bands. The time axis is not to scale.



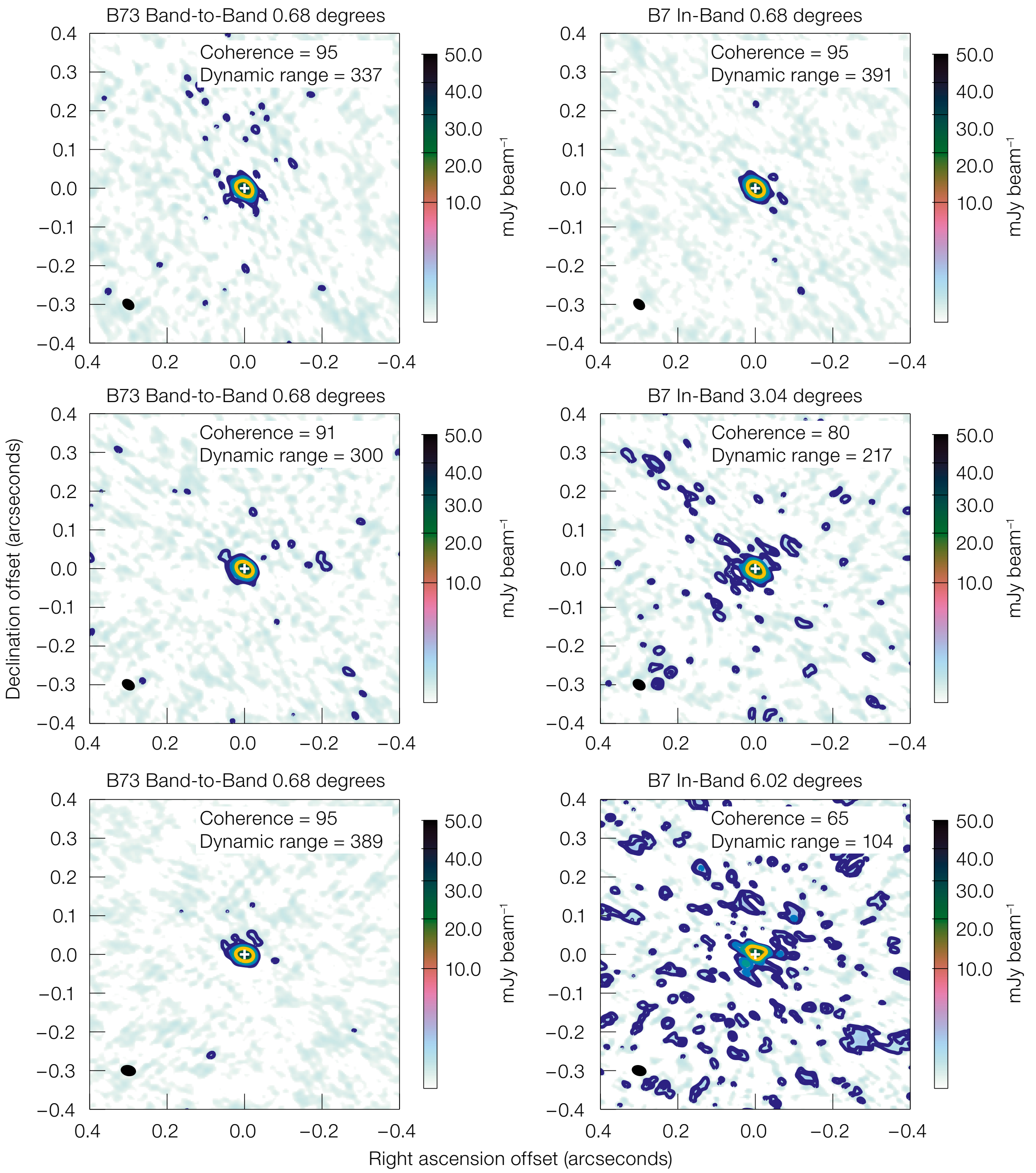


Figure 3. Images of a test-target source, the quasar J2228-0753, observed repeatedly at Band 7 using the long-baseline array for B2B studies in September 2017 (Maud et al., 2020). The left panels show the images from three different observations, all using B2B, for which the target was calibrated using another quasar only 0.68 degrees away on the sky observed at Band 3. These indicate the repeatability of accurate B2B imaging. The right panels show images from the corresponding standard In-Band observations where the calibrator and target are observed at Band 7. The calibrator-to-target separation angles are 0.68, 3.04 and 6.02 degrees (top to bottom). For these In-Band data, all using sufficiently strong calibrators, the images visibly degrade when calibrators are farther from the target, indicating the need to limit the separation.

technique also involves special calibrations, using Differential Gain Calibration to measure instrumental differences between the low- and high-frequency bands (Figure 2).

Why do we need B2B? At high frequencies, quasars used as phase calibrators are weaker, making it is rather difficult to find a sufficiently strong one close to every science target. Strong and close calibrators are paramount for providing accurate phase calibration for high-frequency and long-baseline observations where atmospheric instabilities have a larger impact and where antenna position uncertainties are amplified (Figure 3). During high-frequency observations, visits to the phase calibrators must be more frequent, while each visit must be as short as possible before shifting back to observe the science target. Quasars are generally much stronger at lower frequencies (< 373 GHz), and therefore there are many more that can act as calibrators. B2B therefore enables the use of stronger and closer calibrators for each target and will provide an accurate phase calibration of the science data for high-frequency and long-baseline observations (Figure 4).

The road to offering B2B observations at ALMA has been a long one. The major

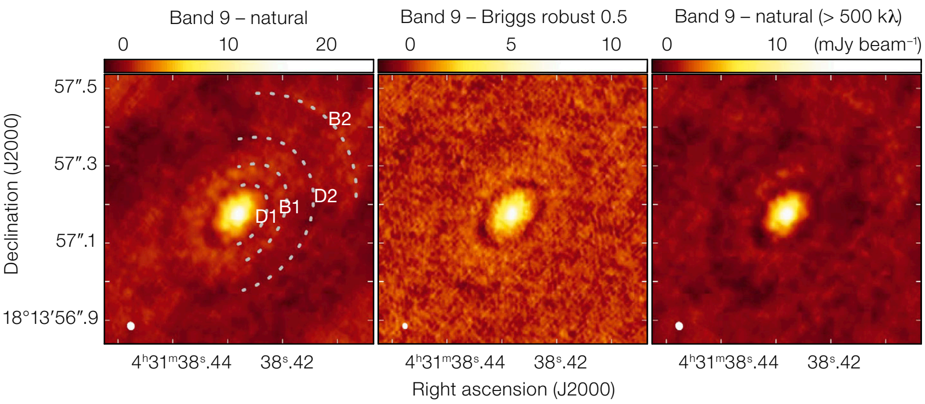


Figure 4. Band 9 images of the inner ~1 arcsecond of the well-known protoplanetary disc source HL Tau observed using B2B (Asaki et al., 2020a). The test observations are short, only 45 minutes on source, compared to the first long-baseline observations that produced the famous original image (~5 hours; ALMA partnership et al., 2015), yet still the inner dark and bright structures are clear. The spatial resolutions are 20 × 18, 14 × 11 and 20 × 18 milliarcseconds for the left, middle and right images, respectively. These tests used Band 4 for calibration, and again highlight that B2B can yield accurate, high-resolution images.

challenge was to understand the system stability and how to calibrate instrumental offsets. Significant software and hardware updates were also required to make fast frequency changes possible. It now takes only 2–3 seconds to swap certain frequency combinations, compared to the 20-second delay previously incurred. Tests over the last five years (involving all ALMA partners) required custom observing scripts and even custom Python tasks for data reduction, before CASA could handle B2B phase transfer. The JAO and European ARC efforts over the past three years have led to the use of science-like SBs for observations, while QA2-like reduction is entirely performed with CASA. The QA2 process has also been finalised, led by the European ARC, and all ARCs will now be able to calibrate B2B observations. B2B will be in use for some Cycle 7, Band 7 long-baseline observations.

The first successful Band 10 (860 GHz) B2B long-baseline observations were made in mid-2019, along with a number of Band 9 tests. These have formed the basis for the forthcoming observations, in which the final observing parameters, calibrator and weather conditions requirements will be specified with a view to acceptance for Cycle 9. A number of studies have also recently been published that highlight the progress of the B2B technique (Asaki et al., 2020a; Asaki et al., 2020b; Maud et al., 2020).

Testing new capabilities in the coming years

Below we list some of the focus areas of the work that is needed to offer new capabilities to ALMA users. From the outset it must be made clear that none of the capabilities listed below is guaranteed to be offered, and also that this list is not exhaustive. Rather, it serves as an illustration of where the activity is focused over the next few years. The final decision to offer the new modes will depend on the progress of each capability through the ObsMode process.

- High-frequency interferometric capabilities include opening the longest baselines while also optimising the currently offered modes on the 12-metre main array and the Atacama Compact Array (ACA). These studies are linked by the B2B calibration technique described above.
- Polarisation testing encompasses further ACA modes and also adds a spectral-line mode to the continuum mosaicking already offered with the 12-metre array. With the ACA, users could conduct polarisation studies that probe larger spatial scales, while spectral-line polarisation with mosaicking would provide a means to map the line polarisation of extended targets (see, for example, Hull et al., 2020).
- Solar work covers two main components. First, fast regional scanning would allow users to obtain total-power maps of solar targets in a reduced time, which is important for imaging short-lived solar features. Secondly, offering polarisation, initially in band 3, would facilitate the investigation of magnetic fields, possibly originating from thermal free-free emission above sunspots, or from gyro-synchrotron emission in solar flares (see Bastian et al., 2018 for more details of future solar capabilities).
- Very-Long-Baseline Interferometry (VLBI). Incorporating ALMA's huge collecting area in VLBI arrays has boosted millimetre sensitivity enormously (for example, Tilanus et al., 2014). VLBI with ALMA is currently offered in Bands 3 and 6 in continuum mode. Testing aims to extend the VLBI capabilities in two obvious areas: including higher frequencies, which will provide unprecedented angular resolutions, and offering the spectral-line mode[4].
- Correlator software studies aim at offering users improved sensitivity for the same observing time, as well as 12-metre main-array system temperature calibration using full spectral resolution (see, for example, Escoffier et al., 2007).
- Astrometry tests aim to investigate how special phase calibrations, with multiple phase calibrators, could offer an increased position accuracy (see the ALMA Technical Handbook[3] for the current limitations).
- Total-power observations are arranged to investigate spectral-line imaging at the highest frequencies (for example, Meyer et al., 2015). Users would then have single-dish maps to merge with corresponding high-frequency ACA and 12-metre main-array data. Another opportunity is offering the total-power spectral scan mode in certain bands.
- Band 1 testing encompasses the whole process of introducing the new receiver band that would offer observations in the frequency range ~ 35–50 GHz (for more details, see Huang et al., 2016).
- ACA Total Power Spectrometer[5] is new hardware to replace the ACA correlator for total power observations.

The 2030 ALMA Development Roadmap

The 2030 ALMA Development Roadmap[6] is not directly part of the EOC process and should instead be regarded as a preceding, or overarching, stage. In short, the Development Roadmap comes from investigations by the ASAC, who examined potential technical developments for ALMA leading up to 2030 that would significantly expand ALMA's capabilities and be able to address new fundamental science drivers. More details will be presented in a future Messenger article.

Conclusions and forward look

New capabilities continually push the forefront of science with ALMA. Each time milestones are met, the boundaries will be pushed even further. ALMA will therefore continue EOC efforts for the foreseeable future. With every new mode, when operational for at least one cycle, there are also inevitably improvements that can be made to optimise observations or efficiency — just as most new capabilities take a cautious approach during their first use. Continuous improvements will therefore be made, ultimately resulting in improved data that are taken more efficiently and thus increasing the overall number of accepted projects, benefitting the entire ALMA user community.

Acknowledgements

Prior to Cycle 0, during CSV times up to current ALMA science operations and EOC testing, the contributions have been extensive. Considerable effort comes not only from the staff of the ALMA partners, but also from external research institutes and university faculties. We extend a particular thanks to the hundreds of people involved with EOC over the last decade. In addition, we thank all staff who ensure the smooth daily running of ALMA and the Operations Support Facility. To everyone involved, for all levels of contribution, we extend our sincerest gratitude.

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Links

[1] ALMA Organization: https://almascience.eso.org/about-alma/alma-organization
[2] ALMA Proposers Guide: https://almascience.eso.org/documents-and-tools/cycle7/alma-proposers-guide
[3] ALMA Technical Handbook: https://almascience.eso.org/documents-and-tools/cycle7/alma-technical-handbook
[4] The ALMA phasing system: https://zenodo.org/record/3585360
[5] ALMA new spectrometer: https://www.almaobservatory.org/en/announcements/alma-board-approved-development-of-new-spectrometer-for-morita-array
[6] ALMA Development roadmap: https://www.almaobservatory.org/en/publications/the-alma-development-roadmap

Notes

[a] Uniquely, Cycle 7 continues through 2021 because of the COVID-19 pandemic.
[b] ALMA users are encouraged to contact their ASAC members, the Users Committee, their local ARC node or the ALMA helpdesk to engage with future ALMA capabilities.

Sangku Kim/ESO

ALMA, located in the Chilean Atacama desert, is the most powerful telescope for observing the cool Universe — molecular gas and dust. ALMA studies the building blocks of stars, planetary systems, galaxies and life itself. By providing scientists with detailed images of stars and planets being born in gas clouds near our Solar System, and detecting distant galaxies forming at the edge of the observable Universe, which we see as they were roughly ten billion years ago, it allows astronomers to address some of the deepest questions of our cosmic origins. ALMA can also be used to study Solar System objects.

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FORS-Up: May the FORS Be With Us For Another 15 Years

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The FORS Upgrade project (FORS-Up) will extend the life of the popular workhorse instrument attached to ESO's Very Large Telescope (VLT), FORS2. The project — a collaboration between ESO and INAF–Astronomical Observatory of Trieste — aims to bring to the telescope, in about three years' time, a refurbished instrument with a new scientific detector, upgraded instrument control software and electronics based on ESO's Extremely Large Telescope (ELT) standard technologies, a new calibration unit, and additional filters and grisms.

A brief history of FORS1/2

A focal reducer instrument was foreseen from the beginning of the VLT Instrumentation Plan. This led to the construction and deployment of two FOcal Reducer and low-dispersion Spectrograph instruments (FORS1 and FORS2). FORS1 saw first light on 15 September 1998 and entered regular science operations on 1 April 1999, while FORS2 had first light on 29 October 1999 and entered regular science operations on 1 April 2000 (Figure 1). FORS1 was retired on 1 April 2009 and is now in storage at La Silla, and FORS2 has been observing since then without significant interruption. In 2009 the polarisation optics of FORS1 were moved to FORS2, which thereby became an even more complete workhorse.

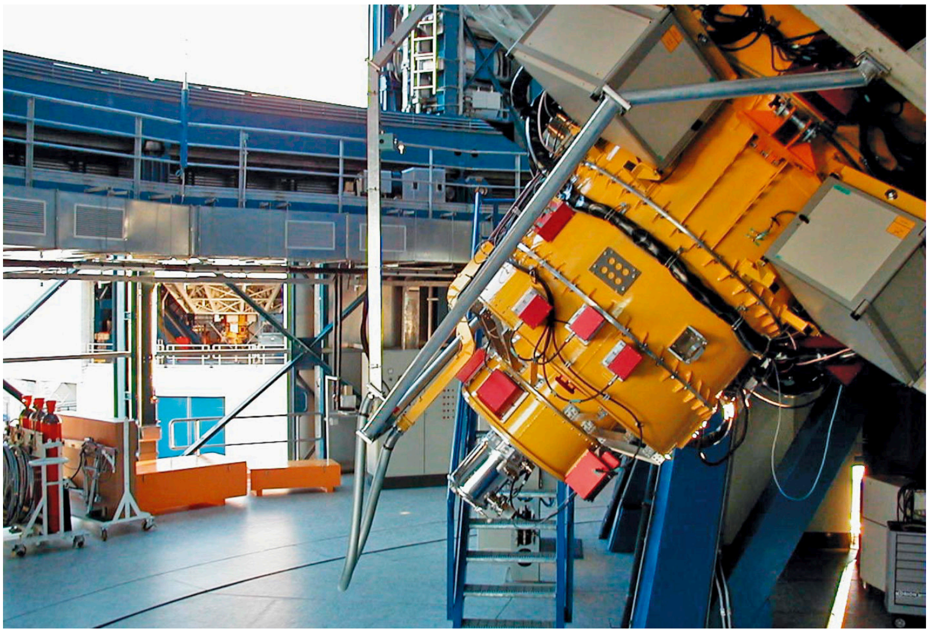

Figure 1. Prior to 2009, it was possible to see both FORS2 at Kueyen (UT2, in the foreground) and FORS1 at Antu (UT1), seen in the background through the open ventilation doors of the two telescope enclosures.

FORS2 is currently the only visible-light (broad- and narrow-band) imager with a field of view of 7 × 7 arcminutes (Figure 2), the only multi-object spectrograph in the blue and the only polarimeter on an 8-metre telescope available in the ESO instrument suite, at least when dealing with faint objects. It is still one of the most in-demand instruments in Paranal and most of its capabilities will not be covered by forthcoming instruments.

The FORS-Up project

Thanks to the versatility of FORS2, the ESO Scientific Technical Committee has identified it as a high-demand workhorse that shall remain operative for the next 15 years, a decision that has been confirmed by the ESO Council. This cannot be achieved, however, without a full upgrade of the instrument. This led to the FORS-Up project, which was approved in August 2020. The main goals of the project, besides upgrading the FORS2 scientific detector, are to upgrade the instrument control software and electronics to the standard developed for the forthcoming ELT, the replacement of motors, sensors and all of the cabling, and the procurement of some additional optical components.

New detector

The upgrade foresees replacing the two (red and blue) science detectors that are each composed of two 2k × 4k chips, with a single 4k × 4k chip with an excellent response in both the blue and red parts of the spectrum. The proposed chip is a variant of the CCD used in the Multi Unit Spectroscopic Explorer (MUSE) instrument, the Teledyne e2v CCD231-84, with fringe suppression technology and an enhanced anti-reflection coating. Most importantly, the current FORS2 cryostat and optical mount are compatible with the selected new detector, which simplifies the design, development and operation of FORS-Up.

ESO has developed the New General detector Controller (NGC), which is the new standard controller for the second generation of VLT instruments. The NGC offers improved performance compared to the Fast Imager Electronic Readout Assembly (FIERA) controller currently

Figure 2. A montage of some of the most iconic VLT images, obtained with FORS1 or FORS2.

used: it has smaller size, lower weight and less heat dissipation, includes the shutter control and allows the implementation of more complex readout patterns. In the framework of the new ELT technologies, ESO is currently developing a new version (NGC II) and it is expected that this version will be used with the new detector on the upgraded FORS.

Control architecture

Although it was initially foreseen that the FORS-Up control software would be based on the latest VLT software release, following the recent developments in software and hardware technologies for the ELT it has been decided that the upgrade of the FORS control software will adhere to the ELT standards and will be based on the ELT Instrument Control Software (ICS) Framework. It will be the first ESO instrument to do so! The aim is to develop a fully-fledged control system able to efficiently resist hardware obsolescence, and offer modern software tools, lower costs, less integration and maintenance effort and easy installation.

The proposed baseline does not foresee changes in the mechanical architecture, except for the use of brushless DC motors, chosen from the Beckhoff catalogue. This choice, following modern trends in control systems, should ensure long-term support for the components employed.

The baseline Beckhoff configuration was tested on FORS1 at La Silla in February 2020. This first-fit check confirms that the Beckhoff configuration can be mechanically integrated on FORS1 and that the selected motors are fulfilling their function. This test was performed with basic control and will be repeated in detail when FORS1 is in Europe.

Finally, the ESO-MIDAS routines used by the alignment algorithms during night-time operations will be re-implemented using the Online Data Processing (ODP), a component of the ELT ICS Framework which aims to provide a flexible data processing toolkit.

New grisms and filters

In addition to the main goals of the upgrade, namely replacing the detectors, motors, sensors and cabling and upgrading the control software, Phase A of the FORS-Up project also identified the usefulness of adding new grisms and filters to the instrument. This requirement will be established more precisely during Phase C of the project, which has just started.

Concerning grisms, three elements are identified for a possible upgrade, one with low dispersion to replace the current GRIS 600B+22, and two new ones with moderate dispersion (covering the Na I lines and the K I line, respectively).

Concerning filters, the lack of Sloan Digital Sky Survey (SDSS) filters or equivalent for FORS2 is potentially an issue. These filters have become widely adopted by many facilities (including the more recent ESO instruments, such as the VST/OmegaCam and the X-shooter acquisition camera) and will be of even greater importance when the Vera C. Rubin Observatory starts operating, as it will use a modified version based on six filters instead of five. Accordingly, Phase A has identified the need to consider whether FORS-Up should be provided with SDSS or Rubin Observatory filters.

Upgrade plan

The best option for the upgrade is to work on the decommissioned FORS1 instrument, by completely refurbishing it in Europe. The availability of the instrument structure and mechanics should allow complete refurbishment and exchange of every control system component, without impacting the operation of FORS2. FORS1 lacks the Mask eXchange Unit (MXU) part and the polarisation optics, but still has all the other parts that could be used for full system testing and validation before reintegration at the VLT. Only the top section of FORS2 and the polarisation optics will then be recovered, upgraded and moved to the refurbished FORS-Up instrument.

Phase A of the FORS-Up project was completed in August 2020 and the project was given a green light to proceed. This should extend the lifetime of the instrument by another 15 years and it is expected that the refurbished FORS-Up will be on sky in 2023 or 2024.

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Colour Transformations for ESO Near-Infrared Imagers

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ESO operates four near-infrared (NIR) imagers, namely the High Acuity Wide-field *K*-band Imager (HAWK-I), the VISTA InfraRed CAMera (VIRCAM), the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE), and Son OF ISAAC (SOFI). In addition, data for the two decommissioned instruments the Infrared Spectrometer And Array Camera (ISAAC) and the Nasmyth Adaptive Optics System/COudé Near-Infrared CAmera combination (NAOS-CONICA, or NACO) are available from the science archive[1]. Because these instruments have different effective bandpasses, the magnitudes measured with them are difficult to compare and doing so can lead to inconsistencies if the colour of an object is not taken into account. In this article, we present colour transformations between the ESO NIR imagers and the Two Micron All-Sky Survey (2MASS) photometric system in the *J*, *H*, and *Ks* bands. The coefficients can be used to compare and convert magnitudes derived from different ESO and non-ESO instruments.

Introduction

ESO telescopes are equipped with several NIR imagers, some of which have been serving the community for decades. Although these instruments share the most used photometric bands (for example, *J*, *H*, and *Ks*), it is not straightforward to compare 2MASS magnitudes obtained with different instrumentation to a precision of few percent. This is because of differences in the filter transmissions and detector efficiency. Over the years, many authors have computed colour transformations to allow comparison between NIR observations carried out with ESO telescopes and the most commonly used photometric systems (for example, van der Bliek, Manfroid & Bouchet, 1996). For all ESO NIR imagers with the exception of ISAAC, the colour transformations to the 2MASS photometric system (Cohen, Wheaton & Megeath, 2003) are available in the literature, and we reproduce them here. We also compute the colour transformation between ISAAC and 2MASS, previously not available in the literature. Another ESO NIR imager, SPHERE, is not included in this comparison because these data cannot easily be photometrically calibrated, nor is this necessary for typical science use cases.

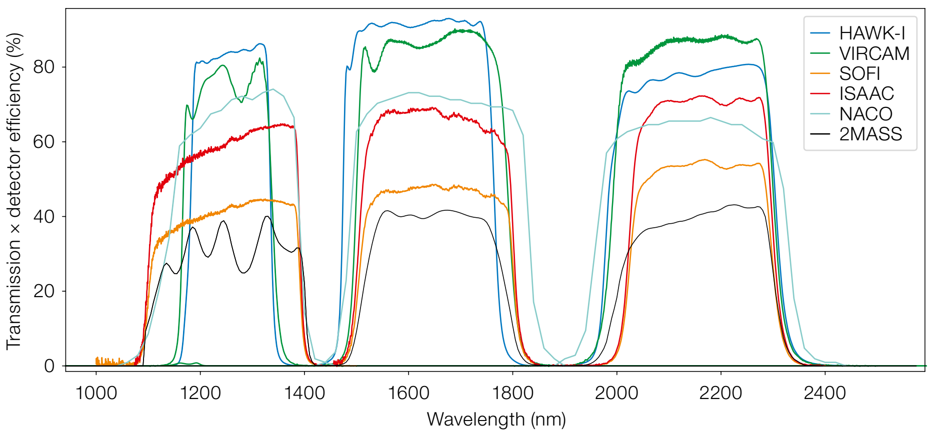

Figure 1. Comparison between the combined contribution of the filter transmission and detector efficiency for the *J*, *H*, and *Ks* filters of ESO near-infrared imagers and 2MASS. Filter transmissions and detector efficiencies are available online for ESO filters[5,6,7] and for 2MASS[8]. The curves do not include atmospheric transmission.

Colour transformations between all ESO NIR imagers and 2MASS.

In Figure 1 we compare the *J*, *H*, and *Ks* filter efficiencies of the ESO imagers with those of 2MASS. The curves include the detector efficiency but do not include atmospheric transmission. The filter shapes are quite different, although one can see that the HAWK-I *J*-band filter is the one that deviates most from 2MASS, and that there is a certain similarity between SOFI and ISAAC, and between all instruments except NACO in the *Ks* band. In principle, these curves could be used to compute colour transformations, assuming specific input spectra. However, in practice it is often more useful to compute the difference between catalogued and observed magnitudes as a function of colour from observed spectra. In this section, we list the results for each of the above-mentioned imagers.

HAWK-I

HAWK-I has been offered since Period 81 and is currently mounted on Unit Telescope 4 (UT4) of the Very Large Telescope (VLT). It is a wide-field imager with a field of view of 7.5 × 7.5 arcminutes, and a pixel scale of 0.1064 arcseconds $pixel^{-1}$ mapped onto a 2 × 2 detector mosaic with a 15-arcsecond gap. It operates in the range 0.85–2.2 μm and has several broad-band (*Y*, *J*, *H*, and *Ks*) and narrow-band (Brγ, CH_4, H_2, 1.061 μm, 1.187 μm, and 2.090 μm) filters. The HAWK-I archive processing done by the Cambridge Astronomy Survey Unit (CASU) and the new ESO HAWK-I imaging pipeline v2.1 uses the 2MASS catalogue to astrometrically and photometrically calibrate the science fields (Neeser et al., 2016). The computation was done using the entire ESO HAWK-I archive up to October 2017, collecting a total of ~ 1.5 million point-like sources in common with 2MASS and covering a colour range of $-0.5 \lesssim (J-H)_{2MASS} \lesssim 3.5$. The colour transformations between the HAWK-I and the 2MASS photometric systems[2] are:

$$J_{HAWK\text{-}I} - J_{2MASS} = -0.15 \times (J_{2MASS} - H_{2MASS})$$
$$H_{HAWK\text{-}I} - H_{2MASS} = 0.06 \times (J_{2MASS} - H_{2MASS})$$
$$Ks_{HAWK\text{-}I} - K_{2MASS} = 0.03 \times (J_{2MASS} - K_{2MASS})$$

The equations do not include constant terms because the filter zero points of HAWK-I are scaled to match to those of 2MASS by the data reduction pipeline. For point-like sources detected in the pipeline output catalogues, an aperture correction has to be taken into account before applying the above transformations. The above equations are also valid for data reduced prior to pipeline version 2.1, although additional constant terms might need to be added because of the different set of standard stars used in the calibration.

VIRCAM

VIRCAM is an imager mounted on the Visible and Infrared Survey Telescope for Astronomy (VISTA), a 4-metre-class telescope mainly used for public surveys that began operating in 2009. It has 16 detectors organised in a 4 × 4 array. Each detector covers 11.6 × 11.6 arcminutes on the sky with a spatial sampling of 0.339 arcseconds pixel^{-1}. A sequence of 6 offset exposures ensures a uniform sky coverage of 1.501 square degrees. It operates in the range 0.8–1.2 μm and has several broad-band (*Z*, *Y*, *J*, *H*, and *Ks*) and narrow-band (NB980, NB990, and NB118) filters. The VIRCAM archive processing routinely carried out by CASU using the VIRCAM imaging pipeline (v2.3) includes photometric and astrometric calibration with the 2MASS catalogue (Neeser et al., 2016). A compilation of data taken on photometric nights, with good seeing and for fields with low extinction ($E(B-V) < 0.1$) and high galactic latitude ($|b| > 35$ deg), was used. The colour range of the sources in 2MASS used in the computation is $0 < (J-Ks)_{2MASS} < 2$. In the process, all detectors were normalised to the same approximate gain using the flat-field exposures. The colour transformations used for the conversion between the VIRCAM photometric system and the 2MASS system are:

$$J_{VIRCAM} - J_{2MASS} = (-0.077 \pm 0.006) \times (J_{2MASS} - H_{2MASS})$$
$$H_{VIRCAM} - H_{2MASS} = (0.032 \pm 0.005) \times (J_{2MASS} - H_{2MASS})$$
$$Ks_{VIRCAM} - Ks_{2MASS} = (0.010 \pm 0.007) \times (J_{2MASS} - Ks_{2MASS})$$

The same procedure was also used by González-Fernández et al. (2018), who updated the VIRCAM colour terms using $(J-Ks)_{2MASS}$ colour:

$$J_{VIRCAM} - J_{2MASS} = (-0.031 \pm 0.006) \times (J_{2MASS} - Ks_{2MASS})$$
$$H_{VIRCAM} - H_{2MASS} = (0.015 \pm 0.005) \times (J_{2MASS} - Ks_{2MASS})$$
$$Ks_{VIRCAM} - Ks_{2MASS} = (0.006 \pm 0.007) \times (J_{2MASS} - Ks_{2MASS})$$

The equations do not include constant terms because the filter zero points of all 16 VIRCAM detectors are scaled to match to those of 2MASS by the data reduction pipeline. For point-like sources detected in the pipeline output catalogues, an aperture correction has to be taken into account before applying the above transformations. The above equations are also valid for data reduced prior to pipeline version 2.3, although additional constant terms might need to be added because of the different set of standard stars used in the calibration. Updates to the above relations are available on the CASU webpage[3].

SOFI

SOFI is an imager and spectrograph that has operated since 1998. It is mounted on the New Technology Telescope (NTT) at La Silla. Its imaging mode covers a field of view of 4.92 × 4.92 arcminutes with a sampling of 0.288 arcseconds pixel^{-1}. In the past, it also offered a finer resolution of 0.144 arcseconds pixel^{-1} over a field of view of 2.46 × 2.46 arcminutes. It operates in the range 1.08–2.3 μm and has several broad-band (*J*, *H*, and *Ks*) and 15 narrow-band filters. The SOFI instrument webpages[4] give colour conversions between SOFI magnitudes and the Persson et al. (1998) photometric system (LCO). Stars with *J–Ks* colour between 0.24 and 1.28 were used and the data were corrected for atmospheric extinction. Residuals of the SOFI-LCO colour transformations are about 0.01 magnitudes. In addition, Carpenter (2001) provides the colour conversion between the LCO system and 2MASS, using 83 stars from the original list of Persson et al. We therefore used the two colour conversions to derive the conversion between SOFI and 2MASS:

$$J_{SOFI} - J_{2MASS} = (-0.005 \pm 0.002) \times (J_{2MASS} - Ks_{2MASS}) + 0.013$$
$$H_{SOFI} - H_{2MASS} = (0.015 \pm 0.002) \times (H_{2MASS} - Ks_{2MASS}) + (0.023 \pm 0.002) \times (J_{2MASS} - H_{2MASS}) + 0.006$$
$$Ks_{SOFI} - Ks_{2MASS} = (0.006 \pm 0.002) \times (J_{2MASS} - Ks_{2MASS}) + 0.006$$

The above relations are valid if the SOFI observations are flux-calibrated using the standard stars from Tables 2 and 3 of Persson et al. (1998). The constant terms in the equations represent the zero point offset between 2MASS and LCO.

ISAAC

ISAAC is an imager and spectrograph that operated from 1999 to 2013 on UT3 and was then decommissioned. Its imaging mode covers a field of view of 152 × 152 arcseconds with a sampling of 0.148 arcseconds pixel^{-1}. It also had a high-resolution mode with a quarter of the field of view and half the pixel scale. It operated in the range 1–5 μm and had several broad-band (*SZ*, *Js*, *J*, *H*, and *Ks*) and 16 narrow-band filters. We employed archival ISAAC data from the ESO-Great Observatories Origins Deep Survey (ESO-GOODS) because it provides a photometric catalogue with accurately characterised uncertainties (Retzlaff et al., 2010). Because there are few sources in common between the ESO-GOODS field and 2MASS, we make use of VIRCAM observations of the same field from the VISTA Hemisphere Survey (McMahon et al., 2013). We then compute the conversion between ISAAC and VIRCAM, and then use the known VIRCAM-2MASS relations to retrieve the ISAAC-2MASS colour terms.

For the ISAAC data, we used the archival file ADP.2014-12-12T10:41:18.833.fits. Magnitudes in the AB system were converted to the Vega reference system (by applying the following offset corrections: $J_{VEGA} = J_{AB} - 0.96$, $H_{VEGA} = H_{AB} - 1.426$, and $Ks_{VEGA} = Ks_{AB} - 1.895$) and corrected for an aperture of 2 arcseconds using the coefficients in Table 3 of Retzlaff et al. (2010). For the VISTA data, we used the catalogue ADP.2018- 02-01T00:59:24.360.0.fits in the ESO archive, that covers 1.9 square degrees. It contains 280 sources in common with the ESO-GOODS catalogue.

We first computed colour transformations between ISAAC and VIRCAM, and then we derived those between ISAAC and 2MASS by exploiting the known transformations between VIRCAM and 2MASS. To that end, we compared the magnitudes of the common sources and then applied an additional filter to remove outliers, bright saturated sources and faint sources with a large magnitude error. That left 84 objects in common. The comparison of their magnitudes in the 3 bands is shown in Figure 2. In Figure 2 we also show the colour relations between the ISAAC and 2MASS filters, as obtained from the 84 sources in common. We used the orthogonal distance method that accounts

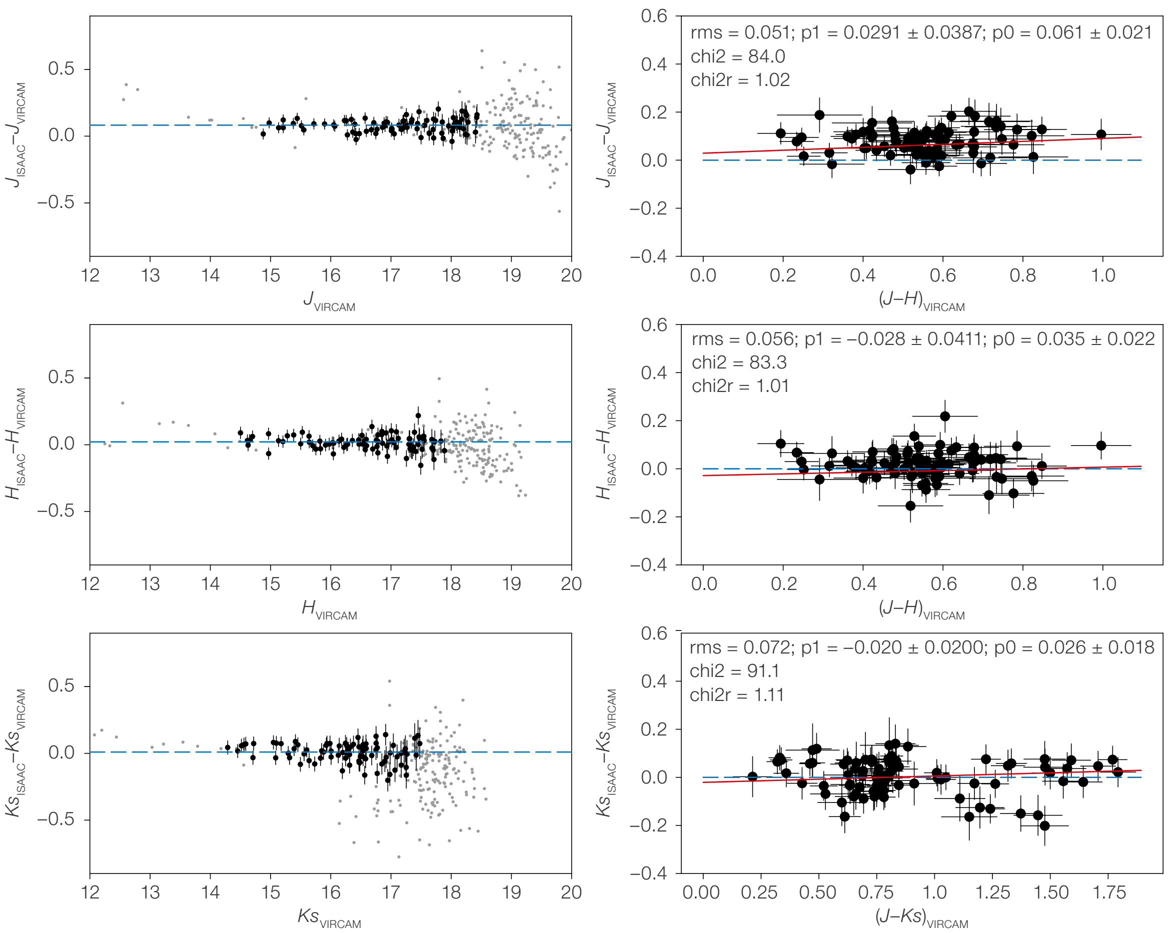

Figure 2. Relations between ISAAC and VIRCAM magnitudes for the *J* (top panels), *H* (middle panels), and *Ks* (bottom panels) bands. Left panels: difference between ISAAC and VIRCAM magnitudes; the grey points indicate all the 280 matches between the 2 catalogues; black circles with error bars show the 84 final matches after the filtering. The horizontal dashed lines indicate the median of the difference between the two magnitudes, computed considering only the 84 final matches. The offsets (ISAAC–VIRCAM) are: 0.083 mag (*J*), 0.022 mag (*H*), and 0.010 mag (*Ks*). Right panels: colour relations between ISAAC and VIRCAM; only the 84 matches in the top panels are used to fit the relations. The best-fit relation (Δmag = p1·colour + p0) is shown in red, and the coefficients and errors are indicated in the panel. The zero (dashed blue) line is indicated as a reference.

for errors on both axes to fit linear relations between the colours. The computed coefficients are then plugged into the known relations between VIRCAM and 2MASS to derive the relations between ISAAC and 2MASS, which are:

$$J_{\mathrm{ISAAC}} - J_{\mathrm{2MASS}} = (-0.05 \pm 0.04) \times (J_{\mathrm{2MASS}} - H_{\mathrm{2MASS}}) + 0.061$$
$$H_{\mathrm{ISAAC}} - H_{\mathrm{2MASS}} = (0.007 \pm 0.04) \times (J_{\mathrm{2MASS}} - H_{\mathrm{2MASS}}) + 0.035$$
$$Ks_{\mathrm{ISAAC}} - Ks_{\mathrm{2MASS}} = (-0.01 \pm 0.02) \times (J_{\mathrm{2MASS}} - Ks_{\mathrm{2MASS}}) + 0.026$$

The constant terms in the equations are not part of the colour transformation but are included for completeness; they represent the difference in zero points between the ISAAC and VIRCAM filters for objects with 0 colour in the Vega system.

NACO

NACO is a NIR imager and spectrograph equipped with an adaptive optics system that operated on UT4 (from 2001 to 2013) and UT1 (from 2014 to October 2019). Its field of view and spatial resolution depend on the filter used, ranging from a field of view of 14 × 14 arcseconds sampled at 13.3 milliarcseconds pixel^{-1} with filters below 2.5 μm, to a field of view of 56 × 56 arcseconds sampled at 54.7 milliarcseconds pixel^{-1} with the NB 3.74 and NB 4.05 filter set. The reference photometric system of the reduced data depends on the standard stars used in the observations and data reduction. The pipeline uses static calibration files that contains photometric stars from several systems (UKIRT, SAAO, MSSSO, LCO, Van Der Blieck, and Arnica). Carpenter (2001) provides colour conversions between 2MASS and all these photometric systems; therefore, the user has to adopt the correction from the Carpenter list that matches the photometric system of the stars used in the calibration. However, several authors use stars from the InfraRed Survey Facility (IRSF) system (Tokunaga, Simons & Vacca, 2002) to calibrate NACO observations, despite the fact that these stars are not used by the data reduction pipeline. This choice has the advantage that there is no significant colour dependency between NACO and IRSF (Janczak et al., 2010). The conversion between IRSF and 2MASS is provided by Kato et al. (2007), which can therefore be extended to NACO if the observations are calibrated using IRSF stars. We indicate below only the colour relation obtained for the IRSF system, as its photometric standard stars are not listed in the NACO static calibration. For the other system covered by the NACO pipeline we refer to Carpenter (2001).

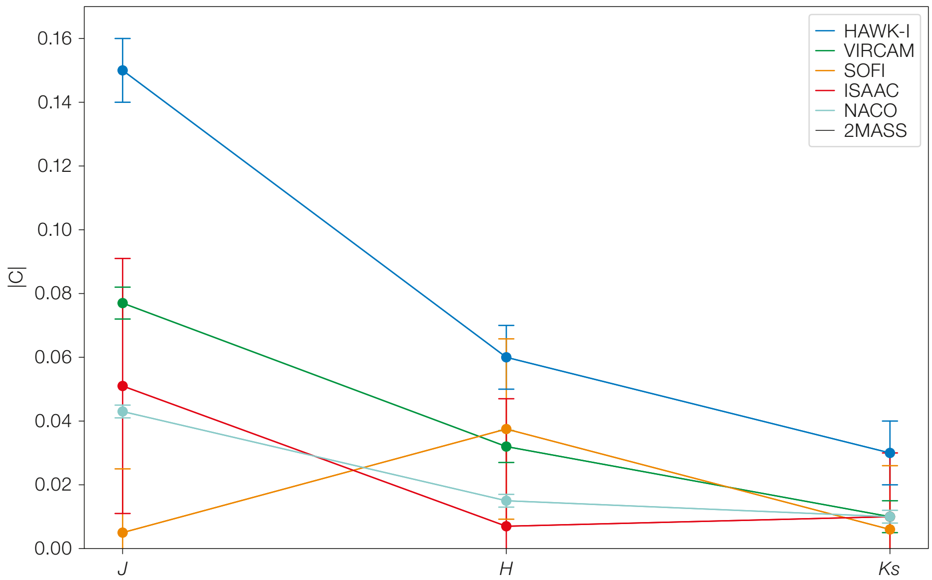

Figure 3. Comparison between the absolute values of the *J*–*H* (for the *J* and *H* bands) and *J*–*Ks* (for the *Ks* band) colour terms of all instruments except SOFI, for which the *J*–*Ks* colour term is given for the *J* band and the sum of the *J*–*H* and *H*–*Ks* colour terms is given for the *H* band. Coefficients |C| closer to 0 indicate that that instrument is closer to 2MASS for that filter.

$$J_{NACO} - J_{2MASS} = (-0.043 \pm 0.002) \times (J_{2MASS} - H_{2MASS}) + 0.018$$
$$H_{NACO} - H_{2MASS} = (0.015 \pm 0.002) \times (J_{2MASS} - H_{2MASS}) + 0.024$$
$$Ks_{NACO} - Ks_{2MASS} = (0.010 \pm 0.002) \times (J_{2MASS} - Ks_{2MASS}) + 0.014$$

The above relations were obtained using thousands of sources in the Magellanic Clouds covering a wide range of colours ($0 < J–H < 0.45$; $0 < H–Ks < 2.7$). The constant terms in the equation represent the zero point offset between 2MASS and IRSF.

Discussion

Depending on the instrument, the colour of a source has a significant impact on the difference between instrumental magnitudes and magnitudes listed in 2MASS. The values of the colour terms are listed for each instrument in Figure 3. These values measure how much effective filters deviate from those of the 2MASS system. A coefficient equal to 0 implies no colour correction and indicates that the filters of an instrument are equivalent to those of 2MASS. For an object with 1 magnitude colour (either *J*–*H* or *J*–*Ks*) in the Vega system, the colour terms typically represent a few percent of the total magnitude (with the exception of HAWK-I) and they depend on the band. Figure 3 shows that HAWK-I is the instrument most different from 2MASS, in particular for the *J* band in which a ~ 15% difference is observed. This result is qualitatively consistent with Figure 1, which shows that the HAWK-I *J* and *H* filters are those that deviate the most from 2MASS. The transformations provided above, along with transformations for filters other than *J*, *H*, and *Ks*, are also given and constantly updated in the data processing FAQ section of the ESO webpage[9].

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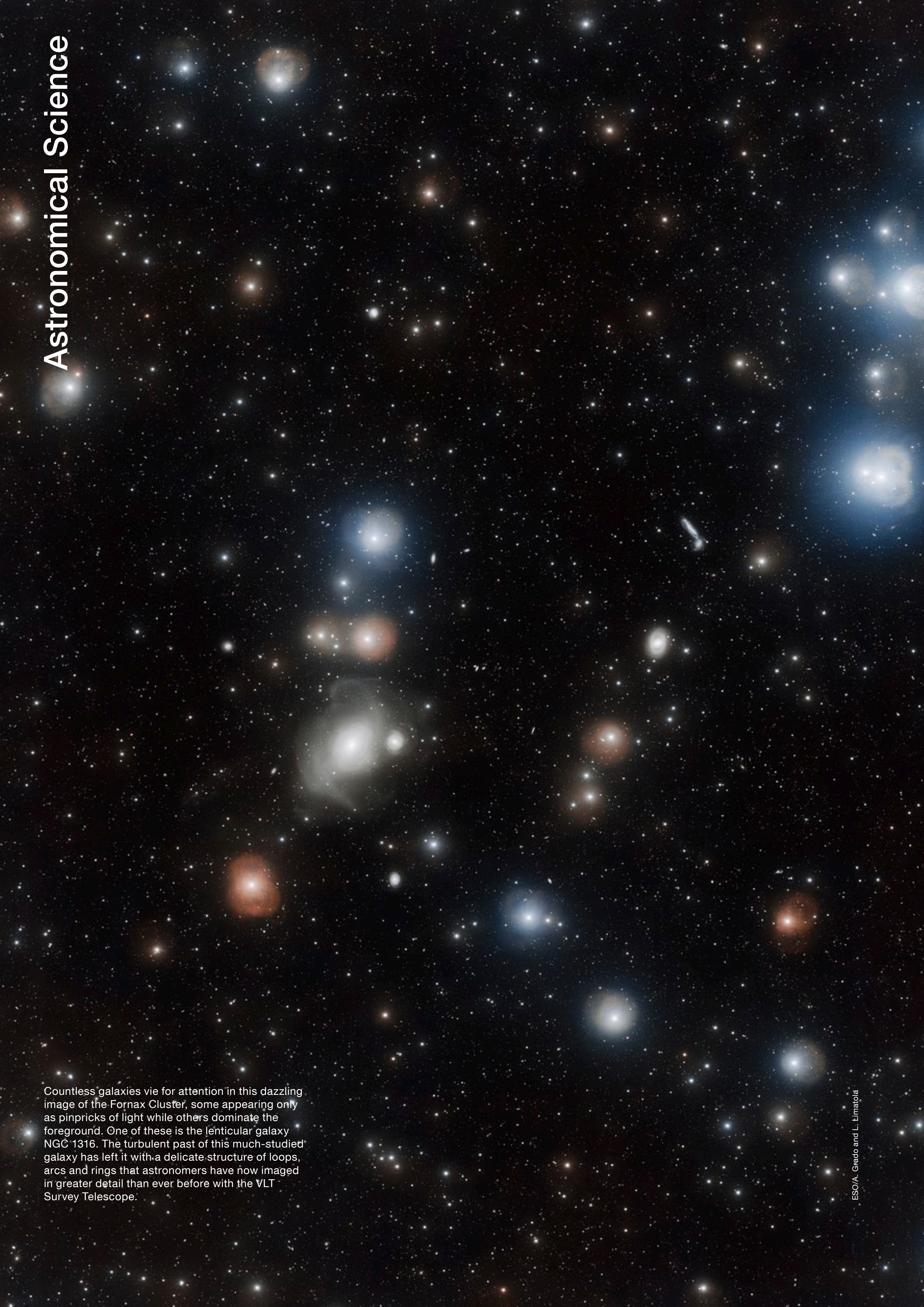
Links

1 ESO Archive Science Portal: http://archive.eso.org/scienceportal/home
2 Colour transformations between HAWK-I and 2MASS: https://www.eso.org/rm/api/v1/public/releaseDescriptions/87
3 CASU webpage: http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/photometric-properties
4 SOFI webpages: https://www.eso.org/sci/facilities/lasilla/instruments/sofi/inst/setup/Zero_Point.html
5 ESO Paranal instruments: https://www.eso.org/sci/facilities/paranal/instruments.html
6 ESO Paranal decommissioned instruments: https://www.eso.org/sci/facilities/paranal/decommissioned.html
7 ESO La Silla instruments: https://www.eso.org/sci/facilities/lasilla/instruments/sofi/inst.html
8 2MASS filter details: https://old.ipac.caltech.edu/2mass/releases/allsky/doc/sec3_1b1.html
9 ESO data processing FAQ: https://www.eso.org/sci/data-processing/faq.html

This composite image shows part of the famous star-forming region of the Orion Nebula. It combines a mosaic of millimetre wavelength images from ALMA and the IRAM 30-metre telescope, shown in red, with a more familiar infrared view from the HAWK-I instrument on ESO's VLT, shown in blue.

Astronomical Science



Countless galaxies vie for attention in this dazzling image of the Fornax Cluster, some appearing only as pinpricks of light while others dominate the foreground. One of these is the lenticular galaxy NGC 1316. The turbulent past of this much-studied galaxy has left it with a delicate structure of loops, arcs and rings that astronomers have now imaged in greater detail than ever before with the VLT Survey Telescope.

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The VST Early-type GAlaxy Survey: Exploring the Outskirts and Intra-cluster Regions of Galaxies in the Low-surface-brightness Regime

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The VST Early-type GAlaxy Survey[1] (VEGAS) is a deep, multi-band (*u*, *g*, *r*, *i*) imaging survey, carried out with the 2.6-metre VLT Survey Telescope (VST) at ESO's Paranal Observatory in Chile. VEGAS combines the wide (1-square-degree) field of view of the VST's OmegaCAM imager and long integration times, together with a specially designed observing strategy. It has proven to be a gold mine for studies of features at very low surface brightness, down to levels of $\mu_g \sim 27$–30 magnitudes arcsec^{-2}, over 5–8 magnitudes fainter than the dark sky at Paranal. In this article we highlight the main science results obtained with VEGAS observations of galaxies across different environments, from dense clusters of galaxies to unexplored poor groups and in the field.

VEGAS in the panorama of deep imaging surveys

Exploring the low-surface-brightness (LSB) Universe is one of the most challenging tasks in contemporary astrophysics. It is important for mapping the mass assembly of galaxies in all environments and thus constraining their formation within the Lambda Cold Dark Matter (ΛCDM) paradigm. In this framework, clusters of galaxies are expected to grow over time by accreting smaller groups along filaments, driven by the effect of gravity generated by the total matter content. In the deep potential well at the cluster centre, the galaxies continue to undergo active mass assembly. As a result, gravitational interactions and merging between systems of comparable mass and/or smaller objects play a fundamental role in defining the galaxies' morphology, the build-up of the stellar halos, and the intra-cluster light (ICL). Stellar halos are extended (≥ 100 kpc) and faint ($\mu_g \geq 26$–27 magnitudes arcsec^{-2}) components made of stars stripped from satellite galaxies, in the form of streams and tidal tails, with multiple stellar components and complex kinematics (see the review by Duc, 2017). The ICL forms during the infall of groups of galaxies into the cluster potential as material is stripped from the galaxies' outskirts. This diffuse and very faint component ($\mu_g \geq 28$ magnitudes arcsec^{-2}) grows over time with the mass assembly of the cluster, to which the relics of the interactions between galaxies (stellar streams and tidal tails) also contribute.

In the last two decades, deep imaging surveys have given a huge boost to the study of mass assembly in different environments by providing extensive analyses of the light and colour distributions of galaxies out to the regions of stellar halos and the intra-group/intra-cluster space (see the review by Mihos, 2019). Investigations of mass assembly in the outskirts of galaxies have also been conducted by means of stellar kinematics and population properties of discrete tracers like globular clusters (GCs) and planetary nebulae.

The main goal of imaging and spectroscopy surveys is to provide a set of observables that can be directly compared with detailed theoretical models of the structure and stellar populations of stellar halos, the formation of the ICL and the amount of substructure in various environments (see the review by Arnaboldi et al., 2020). In this context, VEGAS has played a pivotal role in exploring the properties of galaxies as a function of environment down to the LSB regime. To date, using about 400 hours of observing time, VEGAS has already collected data on 35 groups and clusters of galaxies, covering a total area on the sky of ~ 70 square degrees. About 30% of the VEGAS observing time was dedicated to the Fornax Deep Survey (FDS; Peletier et al., 2020). The FDS covers the Fornax cluster out to the virial radius (~ 0.7 Mpc), taking in an area of 26 square degrees around the central galaxy NGC 1399 and including the SW subgroup centred on NGC 1316.

Based on the analysed data, VEGAS and the FDS have allowed us to a) study the outskirts of the galaxies and detect the ICL and LSB features in the intra-cluster/group space (see Iodice et al., 2016; Spavone et al., 2018; Iodice et al., 2020a and references therein), b) trace the mass assembly process in galaxies by estimating the accreted mass fraction in the stellar halos and provide results that can be directly compared with the predictions of galaxy formation models (see Spavone et al. 2020), c) trace the spatial distribution of candidate GCs (see Cantiello et al., 2020 and references therein), d) provide the largest size- and magnitude-limited catalogue of dwarf galaxies in the Fornax cluster (Venhola et al., 2018), and e) detect ultra-diffuse galaxies (UDGs; Forbes et al., 2020; Iodice et al., 2020b).

With the first data release (DR1) of VEGAS we have provided the reduced VST mosaics of 10 targets, recently published by the VEGAS collaborations (Capaccioli et al., 2015; Spavone et al., 2017, 2018; Iodice et al., 2020a; Cantiello et al., 2018). The data products (i.e., images in all observed bands) are available via the ESO Science Portal[2].

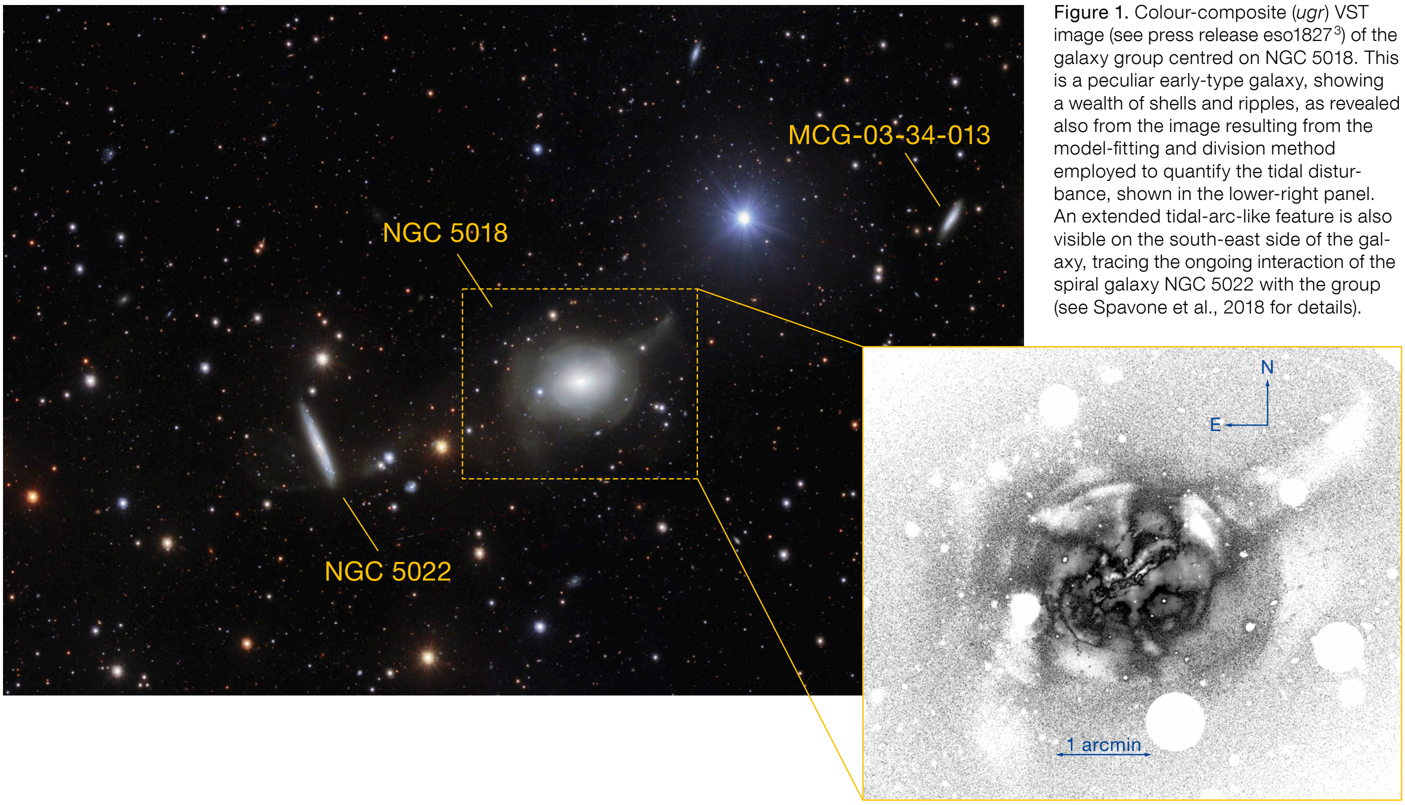

Figure 1. Colour-composite (*ugr*) VST image (see press release eso1827[3]) of the galaxy group centred on NGC 5018. This is a peculiar early-type galaxy, showing a wealth of shells and ripples, as revealed also from the image resulting from the model-fitting and division method employed to quantify the tidal disturbance, shown in the lower-right panel. An extended tidal-arc-like feature is also visible on the south-east side of the galaxy, tracing the ongoing interaction of the spiral galaxy NGC 5022 with the group (see Spavone et al., 2018 for details).

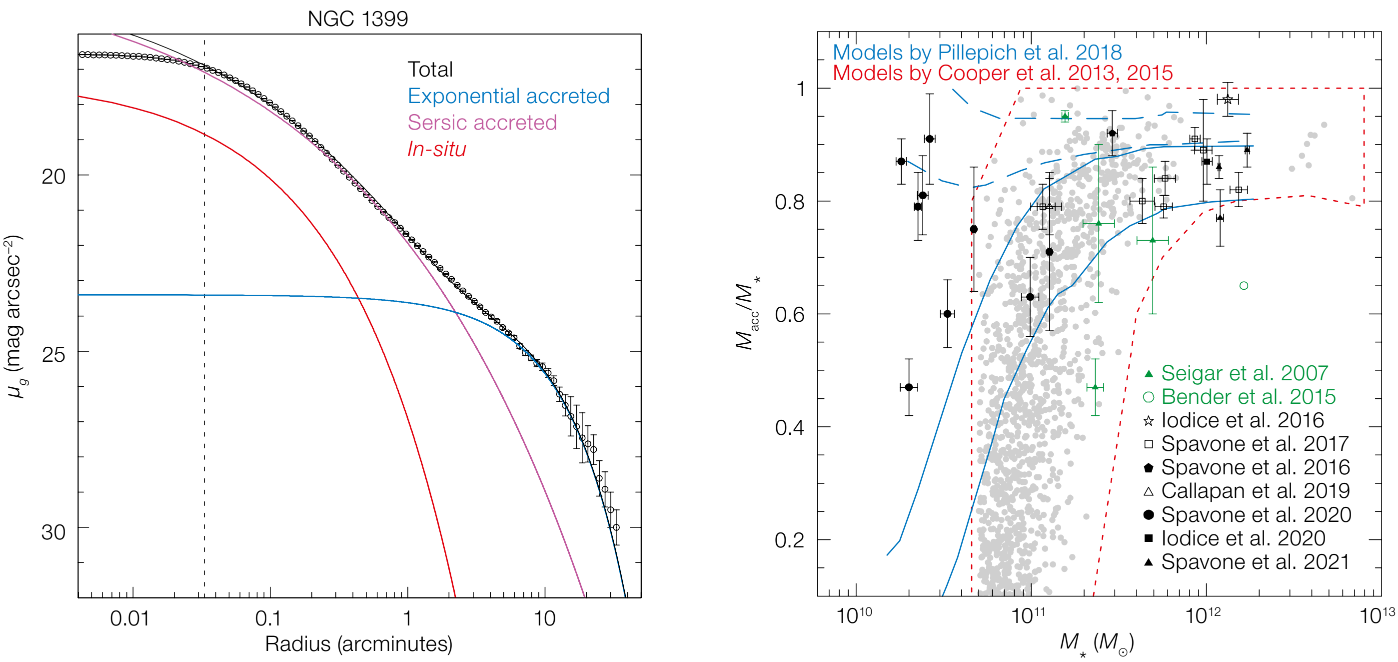

Figure 2. Left panel: VST *g*-band profile of NGC 1399 (from the FDS, Iodice et al., 2016: see also press release eso1827[4]) fitted with a three-component model motivated by the predictions of theoretical simulations. The total accreted mass fraction (shown in the right panel) is derived from the contribution of the Sérsic accreted and exponential accreted components with respect to the total luminosity of the galaxy (see Spavone et al., 2020 for details). Right panel: Accreted mass fraction (M_{acc}/M_*) versus total stellar mass (M_*) for early-type galaxies. Green points correspond to the brightest cluster galaxies from the literature. Black symbols are for VEGAS galaxies. The region outlined by the red dotted line encloses the predictions of cosmological galaxy formation simulations, which are indicated as grey dots. Blue continuous and dashed lines indicate the accreted mass fraction measured within 30 kpc and outside 100 kpc, respectively, in Illustris simulations. For further details, see Spavone et al. (2020) and reference therein.

Methods: what observables can be derived from deep imaging data?

To trace mass assembly on all scales, i.e., in galaxies and clusters, we need to derive observables that can be directly compared with theoretical predictions. They are listed below.

- **Galaxy morphology:** in order to detect any asymmetry in the outskirts of a galaxy and the remnants of past accretion/merging events (such as tidal tails, stellar streams and shells) and also the ICL, a 2D model of the light distribution is derived by fitting the isophotes and it is then subtracted from the parent image. An example is given in Figure 1. All steps are described in detail in VEGAS papers (for example, Capaccioli et al., 2015; Iodice et al., 2016).
- Azimuthally averaged surface brightness (SB) profiles: these are derived from the isophote fit and, by performing a 1D fit using multi-component empirical laws, they are used to set the scales of the different components in the galaxy that dominate the light distribution, i.e., the stellar envelope and ICL versus central *in-situ* stars. The fitting algorithm and tools are presented in Spavone et al. (2020) and references therein. An example is shown in Figure 2.
- Colour gradients: average colour profiles are derived from the SB profiles in order to address the contribution of different stellar populations in the outskirts of the galaxies (Spavone et al., 2020).
- Inventories of GCs, dwarf galaxies and UDGs: in the intra-cluster regions, by using automatic detection tools, we can map the number density and structural properties of the small stellar systems, since they are the main contributors to, and are prominent tracers of, the build-up of the stellar halos and the ICL. An extensive description of the strategy and tools used for the detection and analysis, based on VST data, of the GCs and dwarf galaxies is provided by Cantiello et al. (2020) and Venhola et al. (2018), respectively. The 2D density map of GCs in the Fornax cluster obtained by Cantiello et al. (2020) is shown in Figure 3.

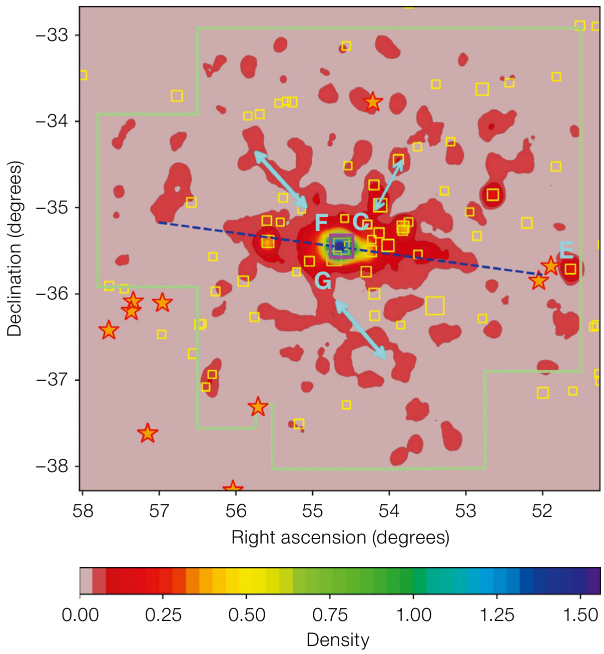

Figure 3. Single-panel view of the 2D globular clusters surface distribution over the FDS area by Cantiello et al. (2020). The density is in number of candidates per square arcminute. East is left, north is up. The light green line shows the FDS footprint. Five-pointed stars mark stars with $m_V \leq 7$ mag; yellow squares show galaxies brighter than $B_T = 16$ mag, with symbol size scaled to galaxy total magnitude; NGC 1399 is marked with a magenta square. Light blue arrows and the labels C, F, G indicate the globular cluster overdensities found in the Fornax cluster area. The blue dashed line shows the ~ 10-degree tilt in the direction of NGC 1336 (labelled E in the figure).

Outcomes: observations versus theoretical predictions

Combining the observables derived from the VST data with theoretical models of the structure and stellar populations of stellar halos, ICL formation and the amount of substructure in various kinds of environment leads to the main results of VEGAS, as summarised below.

- Based on the detection and characterisation of the fine structures and average colours in the outskirts of galaxies, we have been able to trace the **formation history of the stellar halo** (see Iodice et al., 2017; Spavone et al., 2018; Iodice et al., 2020a and references therein). Figure 4 shows some examples of the brightest galaxy in the centre of a group, showing that the outer envelope still hosts the remnants of the accreted satellite galaxies that are forming the stellar halo. For these objects, we examined possible formation scenarios by comparing the observed properties (morphology, colours, gas content) with predictions from cosmological simulations of galaxy formation. This allowed us to address the formation of stellar halos from the accretion of small satellites or as the result of past major merging events.
- Based on 1D fitting of the SB profiles, we have provided an **estimate of the accreted mass fraction** in the brightest and most massive galaxies. The right panel of Figure 2 shows the accreted mass fraction estimated for the most massive galaxies in groups and clusters from VST deep images, recently published by Spavone et al. (2020). This represents one of the major achievements of VEGAS, as it is the first attempt to compare this quantity with theoretical predictions of mass assembly as a function of the total stellar mass in galaxies. The results suggest that, in agreement with theoretical models, the largest accreted mass fraction is found in the most massive galaxies.
- We have derived the **ICL fraction in several groups and clusters**. This is related to the look back time of the mass assembly, since for more evolved structures (groups or clusters of galaxies) we expect a larger amount of ICL. In Figure 5 we show all the ICL estimates we have derived for the analysed VEGAS targets. In accordance with simulations, the ICL fraction ranges from 10% to 45% in massive ($\geq 10^{12}$ $M_{\odot}$) groups or clusters of galaxies. The lower-mass regime remains quite unexplored, from both the observational and theoretical sides.
- By studying the structure and colours of late-type disc galaxies, we have addressed the role of the environment in driving the **evolution of galaxies** (see Raj et al., 2020 and references therein).

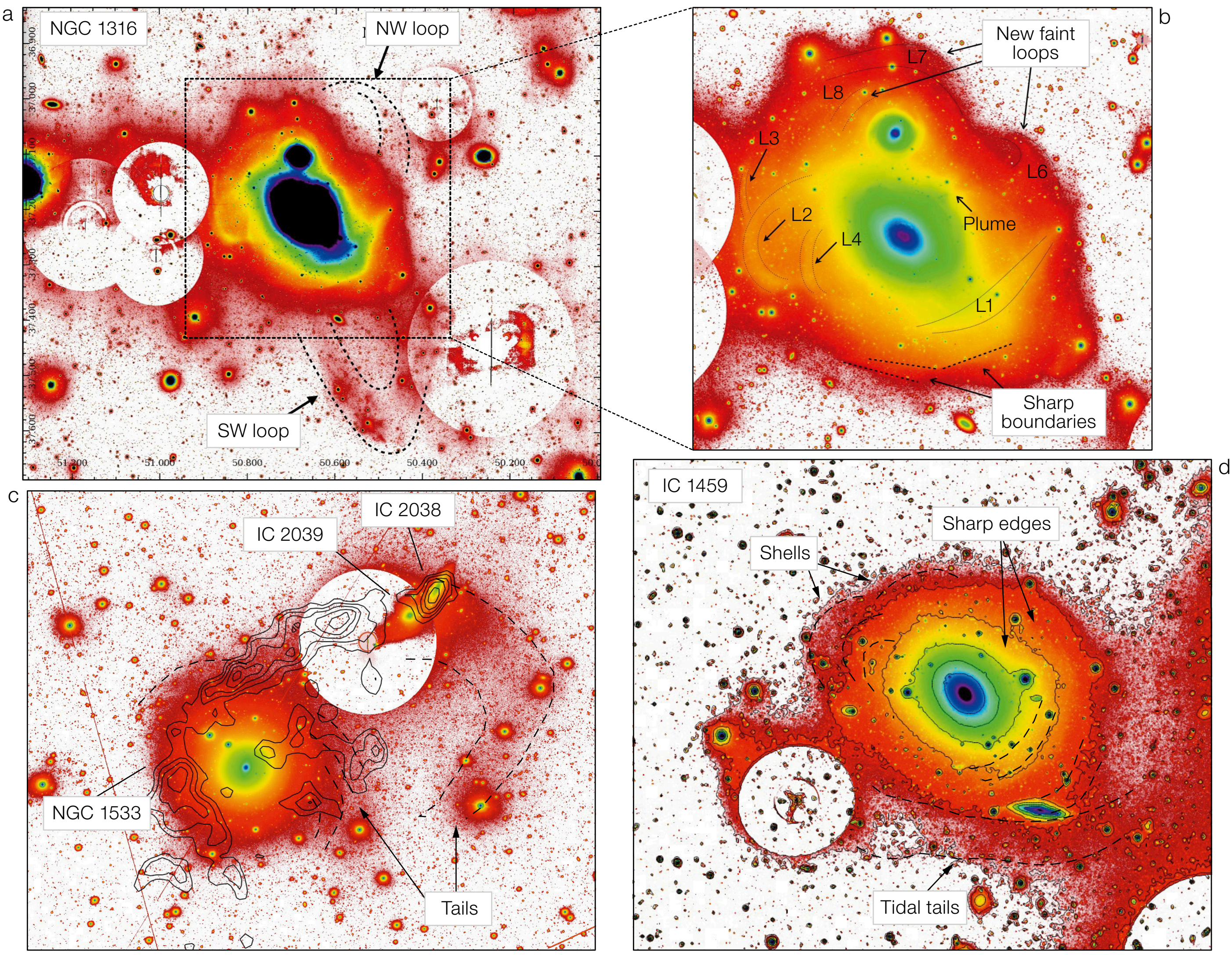

Figure 4. (Above) Galaxies from VEGAS showing the remnants of accreted satellite galaxies in their outskirts (see Iodice et al., 2020a and references therein). Panel a shows the *g*-band image of NGC 1316[5], the brightest galaxy in the centre of the SW subgroup in the Fornax cluster. The giant (160 kpc) SW loop and the faint NW loop (90 kpc) are marked with long dashed lines. The enlarged region in panel b shows the wealth of loops and shells at smaller radii in NGC 1316, which are probably due to the disruption of dwarf galaxies (see Iodice et al., 2017). Panel c shows the *g*-band image of NGC 1533, the brightest of the triplet of galaxies in the Dorado group. The H I map from the Australia Telescope Compact Array (ATCA) is superimposed (black contours). The faint stellar tails, which trace the accretion in the outskirts, are marked as dashed black lines. Panel d shows the *g*-band image of IC 1459, the brightest group member, where the shells and tails in the outskirts are signs of ongoing accretion and interactions.

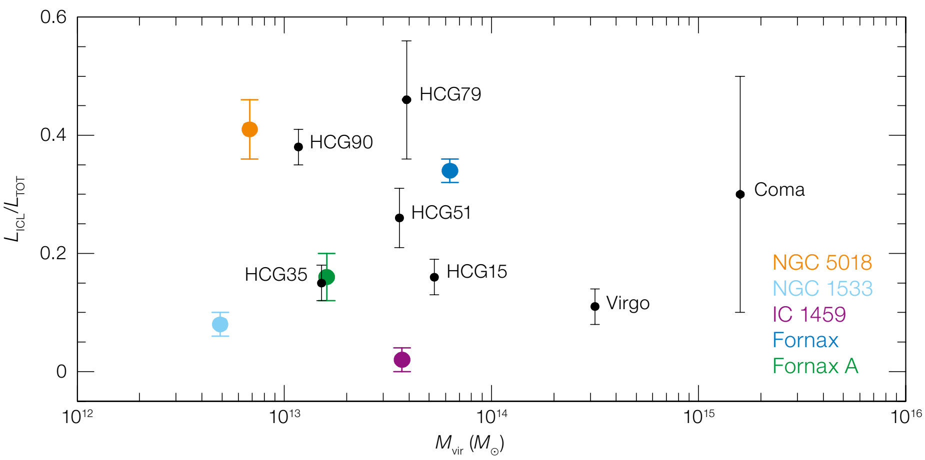

Figure 5. Intra-cluster light (ICL) fraction as a function of halo mass for VEGAS targets and for the Fornax cluster from the FDS. These are compared with other measurements for the Virgo and Coma clusters. Values are also compared with those for several Hickson Compact groups (HCGs) (see references in Iodice et al., 2020a and Spavone et al., 2020).

Figure 6. Colour-composite image of a UDG candidate detected in the Hydra I cluster from the deep VST images (see Iodice et al., 2020b). The image size is about 16 × 16 kpc.

Ultra-diffuse galaxies

UDGs have a special role in the realm of the LSB Universe, since they are amongst the faintest bound systems in groups and clusters of galaxies. UDGs are empirically defined to be faint ($\mu_{0,g} \geq 24$ magnitudes arcsec^{-2}) and diffuse ($R_e \geq 1.5$ kpc) objects, with stellar masses similar to those of dwarf galaxies (10^7–10^8 $M_\odot$; van Dokkum et al., 2015). They constitute the extreme tail of the size-luminosity distribution of dwarf galaxies.

Although the detection and analysis of UDGs are challenging, owing to their LSB nature, a significant population of UDGs has been found in dense environments such as clusters and groups of galaxies as well as in the field (for example, Janssens et al., 2019). The discovery of a number of UDGs with very low dark matter content raised new questions about the whole framework of galaxy formation in order to account for such long-lived, large and baryon-dominated stellar systems (van Dokkum et al., 2016).

Using FDS and VEGAS data, UDGs were discovered in groups and clusters of galaxies (see Prole et al., 2019; Forbes et al., 2020 and references therein). In particular, Iodice et al. (2020b) presented the first sample of UDG candidates in the Hydra I cluster (see Figure 6). For each UDG, we analysed the light and colour distribution, estimated the stellar mass, and provided a census of the GC systems around it. Based on the GC populations of these newly discovered UDGs, we conclude that most of these galaxies have a standard or low dark matter content, with a halo mass of $\leq 10^{10}$ $M_\odot$, comparable to dwarf galaxies of similar stellar masses. These results represent an important step in our project to enlarge the number of confirmed UDGs.

Future perspectives

By the end of the survey (2022), VEGAS will have collected a total of 55 targets, with a spatial coverage of ~ 90 square degrees and spanning a halo mass range of 10^{10}–10^{14} $M_\odot$. With such a large dataset we have started two new projects: the study of the lowest stellar mass regime ($\leq 10^{10}$–10^{12} $M_\odot$), typical of the low-density environments, such as groups of galaxies, which allows us to fill the gap in the comparison with the theoretical predictions across this range of stellar mass; and the detection and analysis of a large number (~ 1300) of UDGs using the entire VEGAS sample, named Ultra-VEGAS, which will provide a statistically relevant UDG sample with which to constrain the nature and formation of these systems.

In addition, for the extension of VST operations beyond 2022 and in the footsteps of VEGAS, we have proposed a deep multi-band imaging survey that aims to map the large-scale structure of two superclusters in the nearby Universe: the Fornax-Eridanus and the Hydra I-Centaurus superclusters. This project, named VEGAS-LSS, aims to exploit the excellent photometric wide-field capabilities of the VST to study the unexplored regions of voids and filaments in the large-scale structure around groups and clusters down to the LSB regime. Based on the uniform deep survey of the large-scale structure, the main science goal of VEGAS-LSS is to provide the key observables needed to trace the infall of groups into clusters and, thereby, important clues as to the clusters' assembly histories. The proposed projects will give a timely and valuable return on the large effort dedicated by the astronomers and engineers of INAF, University of Naples and ESO, to building and maintaining the VST facility, as well as to the international astronomical community in planning and pursuing innovative science at the threshold of future survey telescopes.

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Links

[1] VEGAS survey website: https://www.na.astro.it/vegas/VEGAS/Welcome.html
[2] VEGAS first data release acess via the ESO Archive Science Portal: https://www.eso.org/sci/observing/phase3/news.html#VEGAS-DR1
[3] ESO press release eso1827: https://www.eso.org/public/news/eso1827/
[4] ESO press release eso1612: https://www.eso.org/public/news/eso1612/
[5] ESO press release eso1734: https://www.eso.org/public/news/eso1734/

ESO/P. Horálek

The Sun setting though sparse cloud cover over ESO's Paranal Observatory brings with it a delightful multicoloured show. The foreground silhouette is of one of the four VLT Auxiliary Telescopes. High above it the Moon, less than a quarter full, shines brightly through the thin clouds.

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Report on the ESO Workshop

Ground-based Thermal Infrared Astronomy — Past, Present and Future

held online, 12–16 October 2020

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This ESO workshop was originally planned as a traditional in-person meeting at ESO in Garching in April 2020. It was rescheduled and transformed into a fully online event in light of the COVID-19 pandemic. With 337 participants from 36 countries the workshop was a resounding success, demonstrating the wide interest of the astronomical community in the science goals and the toolkit of ground-based thermal infrared (IR) astronomy.

Motivation

Observations in the thermal IR regime (3–30 μm) provide a powerful tool for discovering and characterising warm environments in the Universe, from protoplanetary discs — the building sites of planets, to active galactic nuclei (AGNs) — the surroundings of accreting supermassive black holes. The thermal IR is also the wavelength range of choice in which to peek through exoatmospheric clouds to characterise exoplanet atmospheres. Although space-based instruments offer the ultimate sensitivity, observations from the ground provide unrivalled spatial and spectral resolution. Thanks to regular upgrades, they are also the preferred testbed for new technologies or exciting experiments — as recently demonstrated by the Near Earths in the AlphaCen Region (NEAR) experiment at ESO's Very Large Telescope (VLT) (Kasper et al., 2019).

Astronomers working in the field routinely push instruments to their limits, demanding better sensitivity, stability over longer timescales and higher contrast, all of which ultimately rely on complete instrument characterisation and calibration. This is very relevant for all major astronomical observatories which currently host thermal IR cameras or spectrographs, such as the VLT Imager and Spectrometer for the mid-InfraRed (VISIR), the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE) at the VLT Interferometer, and CanariCam at the Gran Telescopio Canarias. Calibration in the thermal IR will be an even more important prerequisite for reaching the ambitious science goals of the next-generation facilities; for example, characterising exoplanets is one of the prime science goals of the Mid-infrared ELT Imager and Spectrograph (METIS), a first-generation instrument for ESO's Extremely Large Telescope (ELT) and of the Mid-IR Camera, High-disperser and IFU spectrograph (MICHI) on the Thirty Meter Telescope (TMT).

The workshop brought together experts to present two complementary types of review talks. Some of the speakers summarised the state of the art in individual fields significantly reliant on observations in the thermal IR, such as Solar System planets, studies of young stellar objects and evolved stars, the centre of the Milky Way galaxy and more distant active and star-forming galaxies. Other speakers presented individual facilities, described their capabilities and paraded the most successful science cases addressed with these instruments. There was also a talk about the history of the field and a diversity and inclusion session. Last but not least, three discussion sessions on topics selected by the participants allowed for a lively exchange of opinions[1].

Lessons from the online workshop format

The workshop was hosted online because of the ongoing COVID-19 pandemic, but also to increase inclusivity and sustainability. Three platforms facilitated communication between the participants during the workshop (Figure 1). Talks and discussion sessions were transmitted live via Zoom. Slack was used to exchange text messages and to post files (for example, PDFs of posters). Gather.town allowed video, audio and text interaction during the virtual coffee breaks, the virtual welcome reception and the dedicated poster viewing session. It was most popular during the poster session; during the breaks the participants preferred to spend time offline. After the conference, two platforms were — and are being — used for distributing content: video recordings of the presentations were placed on YouTube within 24 hours, to allow participants in different time zones to watch them and to participate in the discussions. Most of these talks remain publicly available on our YouTube channel[2]. As of April 2021, still more than four hours of recordings are watched every month. Slides and posters were uploaded to Zenodo[3] to create a permanent record of the workshop that is also indexed by the SAO/NASA ADS service.

The chosen workshop format was very well received by the conference attendees. In our exit survey, answered by a representative subset of 107 participants, about 90% responded that they rate as good or excellent the quality of the talks, the meeting format and the overall experience. We also asked how this workshop compared to traditional in-person meetings and 85% of the respondents said that the legacy value of our online meeting was equally high or (much) higher than that of a traditional meeting. There were mixed reactions, however, to the question about networking aspects. 60% said they had (much) fewer interactions; 40% found the quality of interactions (much) worse. But, a noticeable 22% reported (much) more interactions and 27% reported (much) better quality of interactions. Curiously, this answer depends significantly on the career stage of the researcher. Senior scientists (and to a lesser degree postdocs) were more likely to answer less or lower quality of interactions, while for (PhD and master) students, the situation was reversed. Therefore, at least for our participants, it does not seem to be true that online meetings are particularly harmful for networking aspects of junior researchers.

The online discussion sessions were especially lively, with more than a thousand messages exchanged daily between the participants via Slack. However, having participants in many different time zones proved to be a challenge. Some participants from, for example, the United States or Chile joined the live Zoom sessions in what was for them the middle of the night. Others preferred to watch the talk recordings at a more convenient time; although they were unable to participate fully in the live discussions, Slack helped them to follow up on discussions the next day. Based on our exit survey, there was a clear preference (~ 85% of students, postdocs, and senior scientists alike) for reducing the amount of (synchronous) online time to three to four hours per day for a possible follow-up workshop.

Last but not least, the online format very significantly reduced the carbon footprint of the workshop. If all 337 participants had travelled to Garching, an equivalent of 564 tons of CO_2 would have been emitted. Online conferences — and this one is no exception — are known to reduce emissions by at least a factor of three thousand compared to traditional in-person meetings (Burtscher et al., 2020).

Demographics and inclusion

The workshop was well attended, with 337 registered participants from 36 countries (see Figure 2a). As many as 160 people were online at the same time. For comparison, the typical number of participants for in-person ESO workshops in recent years was 80–120. ESO Member States dominated the demographics with 189 participants (56%); all ESO Member States were represented. Women constituted 33% of the attendees, and the Scientific Organising Committee formulated a scientific programme that reflected this percentage (35% of the contributed talks were delivered by female speakers). A conscious effort was made to increase the fraction of invited female speakers, reaching 39%. The selection of contributed talks was made without considering the gender or country of origin of the applicants. In addition, with 31% students, 23% postdocs and 46% senior researchers, the workshop achieved a good balance of career level and seniority (see Figure 2b) — in fact, it was among our goals to promote the thermal IR field amongst early-career astronomers.

Diversity and inclusion issues in astronomy were addressed specifically during a podium discussion led by Angela Speck in which a number of good practices were recommended. It is often already a good start to simply begin paying more attention to issues of diversity and inclusivity, to use inclusive language, and to be a "good bystander", for example to intervene when microaggressions[a] happen. The gender balance in astronomy was discussed, as well as specific issues such as the effect of the COVID-19 crisis on gender diversity. In addition, attention was paid to geographic and language barriers, and access by developing nations to the (expensive) infrastructure required to do observational astronomy in the thermal IR.

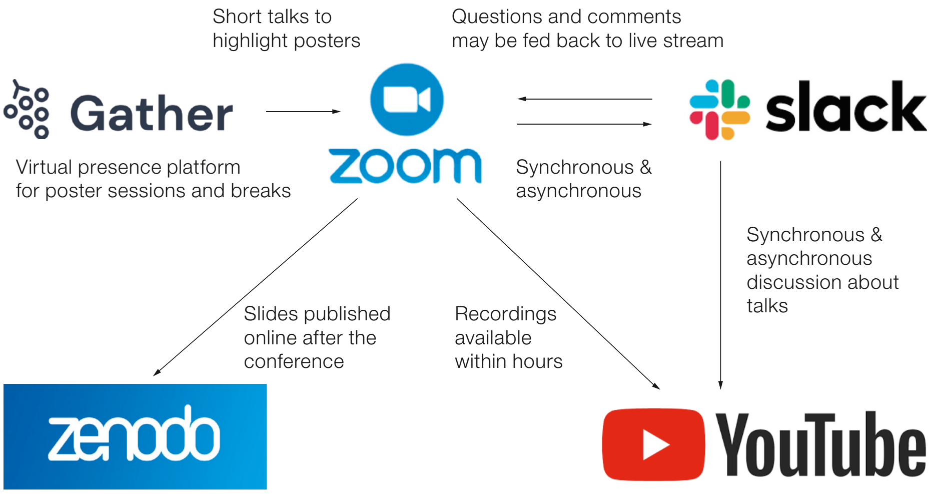

Figure 1. Platforms and services used to organise the online conference.

Science highlights

Over the five days of the workshop a total of 66 talks were given (23 invited, 43 contributed) and 18 online posters were presented, divided into ten scientific areas (Active Galactic Nuclei, Dust/Interstellar Medium, Exoplanets, Galactic Centre, Galaxies, Instruments, Protoplanetary Discs, Solar System, Stars/Circumstellar Environments and Young Stellar Objects). In this short article, we cannot give a comprehensive review of all these fields, but based on a number of both scientifically and visually striking examples, we would like to highlight the diversity of science fields to which ground-based thermal IR astronomy is contributing and how this observing technique provides a unique perspective on these fields. Figure 3a–g illustrate these examples, as follows:

a) Observations of the giant planets from VISIR: Jupiter, Saturn, Uranus, and Neptune (left to right, top to bottom: Fletcher et al., 2017, 2018; Roman et al., 2020; Sinclair et al., 2020). The observations use wider waveband coverage, denser temporal sampling, and more modern technology than available on space probes.
b) VLT/NEAR image of the α Centauri A/B system as observed behind a coronagraphic vortex mask. No planet has been detected in this image, but a detection would have been possible down to ~ 400 μJy, corresponding to a contrast of 3.2×10^{-6} compared to α Cen. A candidate (C1) has been detected that requires follow-up observations for confirmation (Wagner et al., 2021). Ground-based adaptive-optics coronagraphic imaging in the thermal IR has a unique potential to detect faint Earth-like planets at more extreme contrasts than possible from space.
c) A wide-field (~ 5 × 3.5 arcminutes) mosaic of the Orion nebula in the mid-IR showing the Trapezium region to the bottom-left of the centre and the BN/KL complex just above the centre of the image, as well as significant filamentary structure in between. Owing to the requirement to remove the thermal background in a crowded field, the processing of these observations was technically challenging and to the best of our knowledge it represents the widest-angle observation taken in the thermal IR from the ground with a large telescope so far, i.e., it is both wide-angle and high-spatial-resolution (Robberto et al., 2005).
d) Reconstructed image of FS CMa as observed with VLTI/MATISSE. The *L*-band aperture-synthesis image shows the inclined disc of the unclassi-

fied B[e] star FS CMa. One can see the central star and the bright, inner edge of the disc with an angular resolution of about 4 milliarcseconds (the field of view is 60 × 60 milliarcseconds and the wavelength range 3.4–3.8 μm). The north-western disc rim is brighter than the south-eastern one as we are looking directly at the north-western, inner disc rim wall. The inner dust-depleted hole has a size of about 6 × 12 milliarcseconds (Hofmann et al., in preparation). The spatial resolution afforded by VLTI/MATISSE is unequalled by other thermal IR facilities. Only in the thermal IR is the bulk of the disc seen.

e) Deepest image of the Galactic centre at 8.6 μm: ~ 2-hour on-target exposure with VISIR in the PAH1 filter, July 2017; reduction with speckle holography for maximum spatial resolution. Sgr A* itself is undetected since it is confused with the "Sgr A* ridge" at these wavelengths (Schödel et al., in preparation).
f) Stratospheric Observatory For Infrared Astronomy/High-resolution Airborne Wideband Camera Plus (SOFIA/HAWC+) magnetic field lines overlaid on a visible (Hubble Space Telescope, Sloan Digital Sky Survey) image of the nearby prototypical AGN NGC 1068. The image supports the "density wave theory" for how the spiral arms are forced into their iconic shape (Lopez-Rodriguez et al., 2020).
g) Observations of a sample of mid-IR-bright active galaxies showing that the central, AGN-heated dust continuum emission is elongated along the same direction as the polar axis of the AGN, indicated by a green bar that is 100 pc in length. The AGN-heated dust can only be resolved in thermal IR observations from the ground (Asmus, Hönig & Gandhi, 2016; Asmus, 2019).

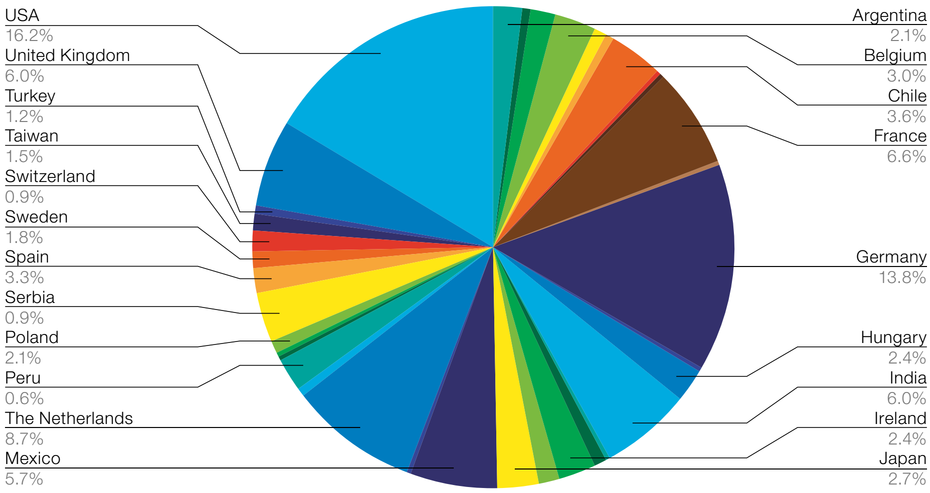

Figure 2a. (Above) Geographic distribution of workshop attendees.

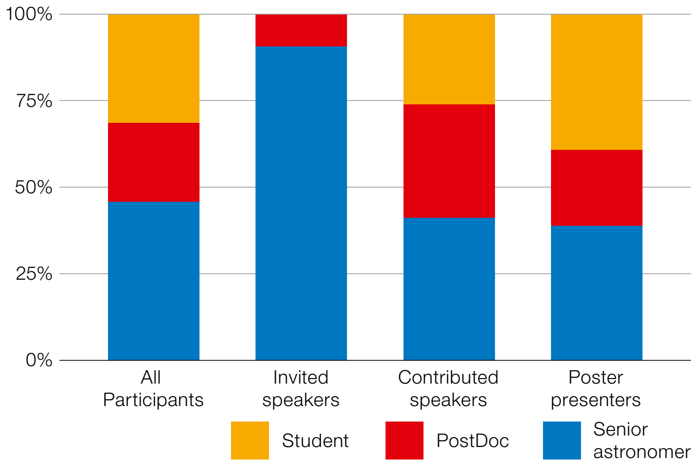

Figure 2b. (Left) Seniority level of workshop participants and presenters.

In addition, three discussion panels were held sequentially and with good and very lively participation from the community. In the first, we asked what the different science areas can learn from each other: for example, can we apply young stellar object (YSO) disc+outflow models to AGNs or evolved stars? We found both similarities (for example, how to link observables to models and which radiative transfer codes to use under which conditions) and differences (for example, the apparent ubiquity of polar-oriented outflows in AGNs was contrasted with the disc morphology of YSOs). The second discussion panel was devoted to instrumentation development and addressed the question of what instrumentation is required in order to pursue our research (and how to get it). In this session we discussed, amongst other suggestions, polarimetry and high spectral resolution in the *N* band (8–13 μm) on extremely large telescopes. The third discussion panel was devoted to community building and investigated what support early career researchers require to enter the field of thermal IR astronomy, in particular whether they need more broad conferences (like this one), a new textbook or more extensive user support (like, for example, the ALMA support nodes). There was agreement among the participants that a follow-up conference in 1–2 years would be useful.

Public outreach event and social media

To further the workshop's goal of promoting awareness of thermal IR astronomy, a public outreach event[4] was held as part of the workshop in collaboration with the Haus der Astronomie in Heidelberg. Nine public talks, given in seven different languages, were streamed live via the Haus der Astronomie's YouTube channel, reaching more than 2500 viewers. The videos are still accessible in their dedicated YouTube playlist[5]. In addition, highlights from the workshop were communicated via the @ESO_IR2020 channel on Twitter, with 155 tweets generating a further 18 900 impressions.

Future outlook

Thermal IR astronomy is entering a new era, both on the ground and in space,

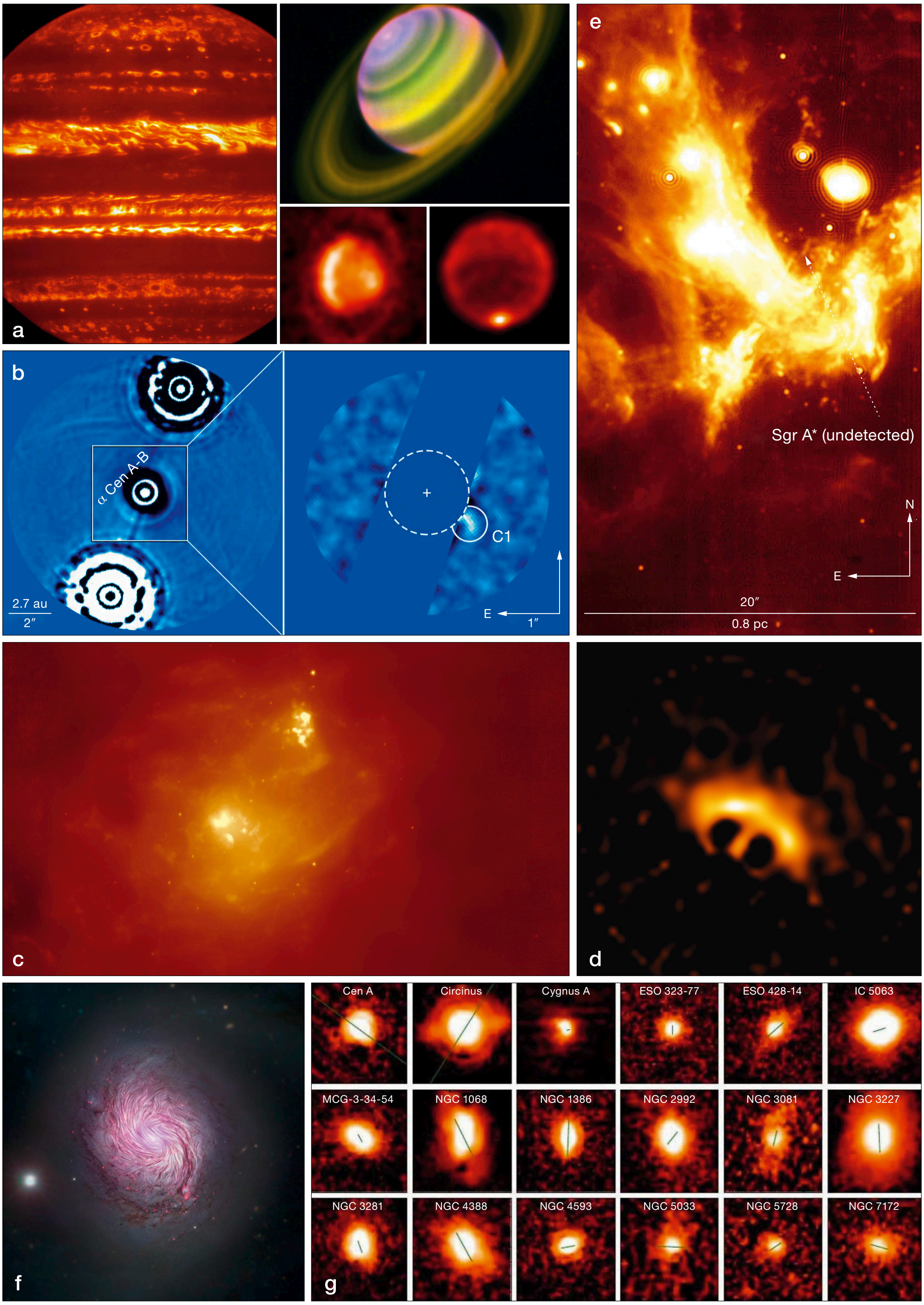

Figure 3. Visual and scientific highlights from ground-based thermal IR observations at large facilities, ordered by distance from the Earth. See text for description.

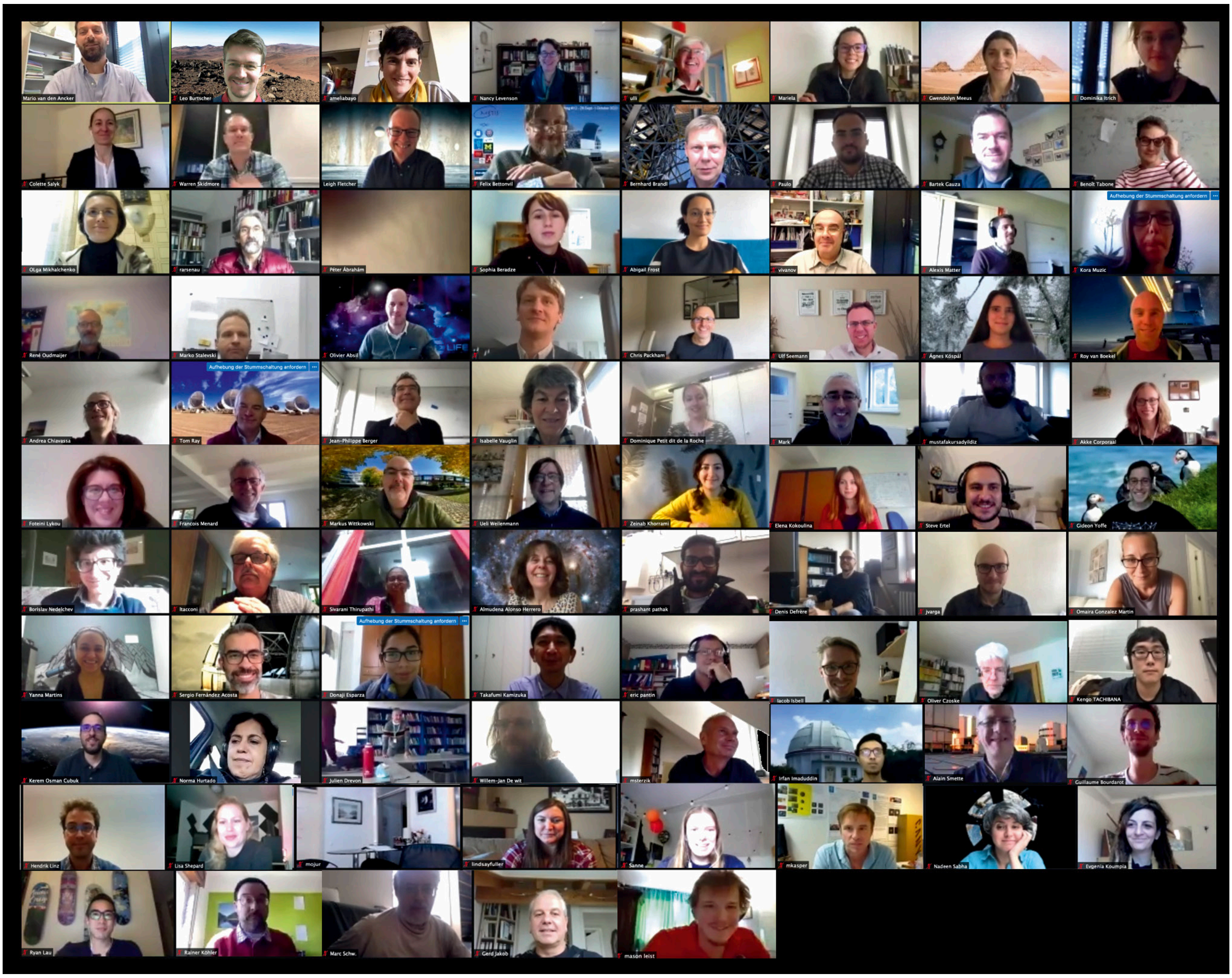

Figure 4. Virtual conference picture showing some of the participants following the live talks.

with the arrival of a number of new facilities. The James Webb Space Telescope is expected to launch later this year. It will provide access to a wavelength range up to 29 μm and will maximise sensitivity thanks to the low thermal background achievable in space. METIS at the ELT is currently expected to see first light in 2028 and will cover the range from 3 to 13 μm, delivering both diffraction-limited imaging at the ELT's resolution of 23 milliarcseconds at 3.5 μm and spectroscopy with resolving powers from a few hundred to a hundred thousand.

A number of innovative smaller instrument projects are also progressing well. For example, the Mid-Infrared Multi-field Imager for gaZing at the UnKnown Universe (MIMIZUKU) at the Tokyo Atacama Observatory (TAO) 6.5-metre telescope at 5640 metres altitude will reach the ultimate (ground-based) transmission, particularly in the challenging *Q* band (~ 20–30 μm). It is planned to upgrade the Mid-InfraRed Array Camera 5 (MIRAC-5) with the novel HgCdTe-based "GeoSnap" detector by Teledyne, possibly a breakthrough in thermal IR detector technology. It will be operated both on the Multiple Mirror Telescope (MMT) and at the Magellan Telescope — both with adaptive optics support — and will pave the way for the use of this novel detector technology in METIS at the ELT and MICHI at the TMT.

Nancy Levenson, in her invited review talk, made the point that the space- and ground-based facilities complement each other in sensitivity, collecting area, cost and rate of technological innovation. She underlined that big facilities serve as natural loci to form active user communities that use the telescopes, but also contribute via various mechanisms — decadal surveys, user committees, etc. — to their planning, development and operation. Our workshop demonstrated the existence of a vibrant thermal IR community (some of whom are seen in Figure 4). The meeting will help to ensure its growth and the inclusion of young astronomers, and to foster close ties amongst the community members for the future. A follow-up workshop is being planned by our Japanese colleagues for early 2022. A decision on the format (fully online or hybrid) is pending.

Acknowledgements

The organisers would like to thank ESO and Leiden Observatory for sponsoring the workshop. We also thank the SOC, Nelma Silva, Véronique Ziegler and Jutta Boxheimer from ESO, as well as Josh Carr of Three Counties Media without whose scientific and administrative support, help with the graphic design of the poster and video editing it would not have been possible to organise the workshop.

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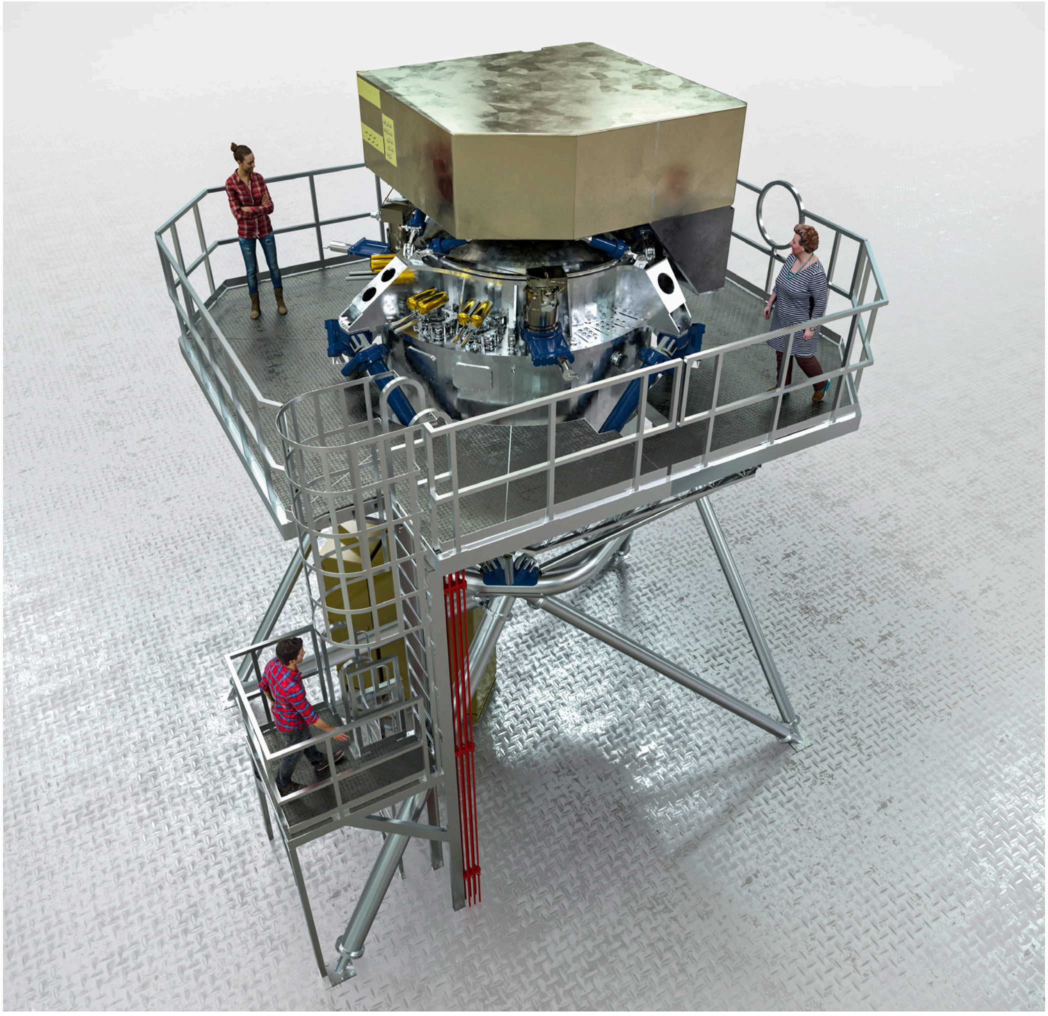
Links

[1] Link to workshop programme: https://www.eso.org/sci/meetings/2020/IR2020/program.html
[2] YouTube channel with recordings of most talks: https://www.youtube.com/channel/UCsTNXi_Sa1j8HQaJAtpmLjg/playlists
[3] Presentations archived at Zenodo: https://zenodo.org/communities/ir2020
[4] Public Outreach Event: https://www.eso.org/sci/meetings/2020/IR2020/public_talks.html
[5] YouTube playlist for the nine public talks organised for the IR 2020 workshop: https://www.youtube.com/playlist?list=PL6v1Ej3QgEXU6L0culH0Imu-_8vpcTSB2

Notes

[a] Microaggression is a statement, action, or incident regarded as an instance of indirect, subtle, or unintentional discrimination against members of a marginalised group such as a racial or ethnic minority.



ESO/METIS Consortium/L. Calçada

METIS, named after the Greek goddess of wisdom, will be one of the first-generation instruments of ESO’s Extremely Large Telescope. It will cover the infrared wavelength range and make full use of the giant, 39-metre main mirror of the telescope to study a wide range of science topics, from objects in our Solar System to distant active galaxies.

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Report on the ESO Workshop

20th Anniversary of Science Exploration with UVES

held online, 21–22 October 2020

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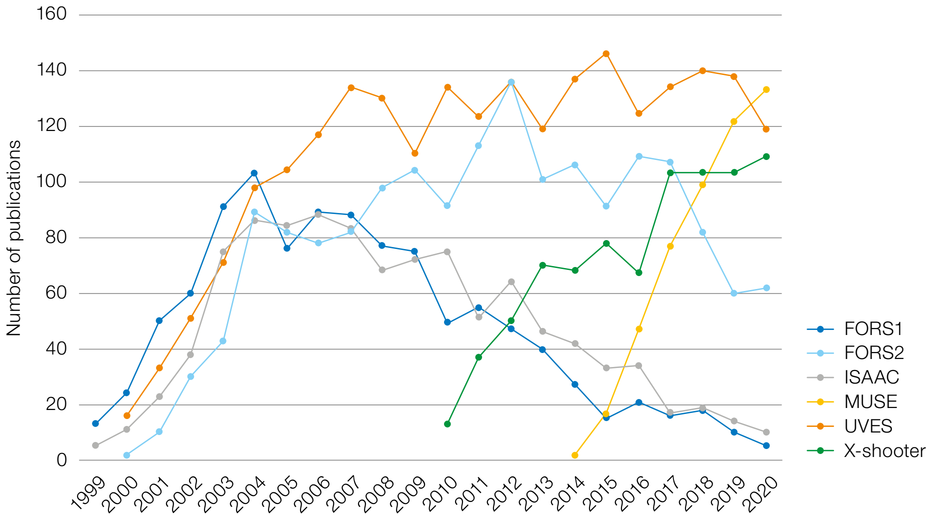

Figure 1. Publication statistics for some of VLT's instruments. UVES is on average the most productive instrument.

The UltraViolet-Visual Echelle Spectrograph (UVES) was first offered to the ESO community in 2000. A workhorse covering a vast range of topics from Solar System objects to cosmology, it quickly became one of the most productive instruments at Paranal. For the 20th anniversary of UVES's entering into service, over 100 astronomers from across the world convened in a virtual workshop to celebrate the instrument's achievements and to reframe its role, in a profoundly changed instrumental and scientific landscape, as it enters its 3rd decade of operation at the Very Large Telescope (VLT).

Motivations

UVES was originally designed as a highly configurable, multi-purpose instrument able to cover most, if not all, science cases for high-resolution optical spectroscopy. Over the years it proved a stable, reliable instrument with very little downtime and excellent operational efficiency. Its class-leading light-gathering efficiency, extensive wavelength coverage and reliable automatic reduction pipeline have made UVES the most productive ESO instrument (in terms of published papers, see Figure 1) during most of its lifetime.

However, in the 20 years since UVES began observing at Paranal, both the needs of the science community and the technologies deployed by UVES's competitors have, obviously, evolved. At ESO, the ultra-stable Echelle SPectrograph for Rocky Planet and Stable Spectroscopic Observations (ESPRESSO) has comparable limiting magnitude in the red and offers superior resolution, while being inefficient in the blue and renouncing the spatial resolution offered by the UVES slit. The X-shooter spectrograph has for many years offered superior efficiency and simultaneous spectral coverage, at the cost of resolution. Even higher efficiency, but at lower resolution and in a narrow UV range, will be offered by the Cassegrain U-Band Efficient Spectrograph (CUBES). In addition, forthcoming high-multiplex facilities such as the 4-metre Multi-Object Spectroscopic Telescope (4MOST) and the Multi-Object Optical and Near-infrared Spectrograph (MOONS) will screen enormous numbers of targets, but at the expense of signal-to-noise, spectral coverage and resolution: this will put pressure on UVES (and similar "workhorses" such as X-shooter and the FOcal Reducer and low-dispersion Spectrograph [FORS]) to follow up a constant stream of high-interest targets.

Outside ESO, among UVES's competitors are the HIgh Resolution Echelle Spectrometer (HIRES) at the Keck I telescope and the High Dispersion Spectrograph (HDS) at the Subaru Telescope, whose performances are largely comparable to that of UVES, while the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope exploits that telescope's exceptional spatial resolution and ability to observe in the far-UV, but reaches only intermediate resolutions (R ~ 20 000).

At the same time, UVES is projected to remain in operation for the foreseeable future, and will thus require significant hardware upgrades both to fight component obsolescence and to maintain, and perhaps upgrade, its performance to meet the current needs of the community. These considerations defined the core purpose of the workshop: to survey the long list of fields where UVES has been and still is a crucial instrument, and to define which of its capabilities make it competitive and what could be improved to better meet the challenges of the decade(s) to come.

Workshop organisation

The workshop was originally foreseen as a 1-day event to be held (in person) at ESO's headquarters in Garching, Germany, but owing to the COVID-19 pandemic it was re-scoped into a virtual meeting using Microsoft Teams and reformatted into two ~ 3-hour sessions. Care was taken to choose times of day that facilitated world-wide participation, particularly from ESO Member States and partner and host countries, which spread across time-zones from + 10 hours (the east coast of Australia) to −4 hours (Chile).

Given the broad range of fields UVES is used for, and the limited length of the workshop, the 13 speakers and 4 panelists were all invited.

Figure 2. Building and installing UVES. Left: November 1998, in the integration hall in Garching. The image was taken by Bob Fosbury and shows, from right to left, Gianni Zamorani, Sandro D'Odorico, Lukas Labhardt, Yannick Mellier, Tim de Zeuw, Max Pettini, Hans Kjeldsen. Upper and lower right: in Paranal during integration and commissioning in September 1999. For details of these images, see D'Odorico (2000).

The online format proved very successful and attracted around 200 registered participants from all over the world, up to 120 of whom were connected at any given time.

Sessions were recorded and the videos of each presentation have been made available via YouTube[1]. The PDF versions of each presentation have been uploaded to Zenodo[2]. The videos and PDFs are also available via the workshop website[3].

Each day's presentations were followed by a round-table session, led by two panelists — different people on each day — and chaired by ESO's VLT Programme Scientist Bruno Leibundgut.

Summary of talks and discussions

After a warm welcome from ESO Director General Xavier Barcons, the original project manager, Sandro D'Odorico, recapped the evolution of the UVES project from its inception in 1986. As per the VLT instrumentation programme, the original plan was to build two UVES instruments with different specifications. These were subsequently consolidated into a single instrument, which was shipped to Paranal in 1999 and fully commissioned by January 2000 (Figure 2). Manufacturing the large échelle gratings and the fluorite glasses for the blue-arm camera were the most significant technical challenges. D'Odorico also noted that the high quality of UVES, a 100%-internal ESO project, was instrumental in giving ESO the prestige and authority to subsequently review the work of instrument partners.

Johan Kosmalski detailed the optical design of UVES, and the choices and innovations (such as the design of the collimator optics) that made it such an efficient instrument. He also described an early design for an updated blue-arm configuration that would permit capture of the whole blue wavelength range in a single shot by reducing cross-dispersion — whilst still allowing an approximately eight-arcsecond slit length — and building a new blue camera with an increased field of view. Newer optics and an improved detector would increase the blue-arm efficiency by an estimated 50%.

The first of the talks on scientific achievements with UVES was given by Emmanuel Jehin, who described the impact of UVES on Solar System, and in particular cometary, science. UVES has been instrumental in the study of long organic molecules released by comets and their dissociation by solar radiation as they move along the cometary tail.

Else Starkenburg described the important contribution of UVES to the study of Local Group dwarf galaxies, and Milky Way streams. This important field grew dramatically during the lifetime of the instrument, which was ideally suited to provide crucial data on their stars' chemistry, thanks to its high efficiency, large telescope diameter and southern hemisphere placement.

Laura Magrini covered the role of UVES in the study of the disc of the Milky Way and its open clusters. Here UVES saw a broad range of uses, covering H II regions, low- and high-mass stars, exoplanet host characterisation, studies of nucleosynthesis, chemical clocks, and the formation and evolution of the disc. Again, the large spectral coverage, flexibility and high resolution were crucial in this field.

John Pritchard presented a brief history of UVES from the operational point of view and an overview of key performance-related statistics, the most striking of which is possibly the approximately four years of cumulative open-shutter time achieved over the 20-year lifetime of the instrument (to date).

Michael Murphy summarised the important contribution made by UVES to the search for cosmological variability of the fundamental constants α (the fine structure constant) and μ (the proton/electron mass ratio): these two fundamental physical quantities are not derived from any other deeper physical principle, and as such they are only *assumed* to be constant across the lifetime of the Universe. However, this can be tested observationally since they subtly affect atomic and molecular lines superimposed at high redshift over the spectra of bright quasars. The availability of VLT-UVES (and Keck-HIRES) in the early 2000s improved on the precision of previous measurements by a factor of about 10. Highly stable instruments like ESPRESSO have since replaced UVES in the measurement of α, but μ can only be studied in the extreme blue part of the spectrum and remains within reach of only blue-sensitive spectrographs like UVES.

Pasquier Noterdaeme addressed the role of UVES in the study of molecular absorption systems in quasar sightlines: the evolution of molecular gas over the lifetime of the Universe is crucial, since it is the fuel for star formation in galaxies. Before UVES, only a handful of H_2 detections had been achieved, but the high resolution of UVES down to the atmospheric cutoff was crucial, and to this day about 60% of detections have been made from UVES observations.

Valentina D'Odorico described the contribution of UVES to the study of deuterium abundances. Deuterium is a crucial baryometer, whose abundance in high-redshift absorption systems is fundamental to constraining Big Bang nucleosynthesis. It is, however, a highly challenging measurement that requires high efficiency in the extreme blue: to date, deuterium has been measured in roughly 20 absorption systems.

Norbert Christlieb summarised the studies exploiting UVES in the field of low-metallicity, ancient stellar populations. The properties of the first generation of stars, long disappeared, are imprinted in the low-mass, second-generation stars they enriched chemically. These elusive objects are thus extremely precious for understanding the early phases of the Universe. Together with this, UVES crucially contributed to all topics related to old stars, such as Na-O anticorrelation in globular clusters and heavy element nucleosynthesis. Here again, the blue sensitivity of UVES, coupled with its high resolution, was, and still is, crucial.

Annalisa De Cia presented the contribution of UVES to the study of transients, such as novae, supernovae and gamma-ray bursts (GRBs), objects that present the opportunity to study both the source itself and the absorption systems along its line of sight. The challenge of course is that these objects are unexpected, rare and faint, and they fade quickly, necessitating a prompt response. UVES contributed to studying the evolution of SN1987A's rings over a period of seven years (from first-light to 2007; a spectrum of SN1987A was in fact used for the workshop poster and logo). UVES provided evidence for Luminous Blue Variables as supernovae type IIn progenitors, and evidence of ^{7}Be, and hence Li, production in novae, a key piece in the puzzle of Li production at high metallicity. UVES was also instrumental in the study of GRBs, producing the first high-resolution spectrum of a GRB. In this field, the availability of Target of Opportunity and Rapid Response Mode (RRM) observing schemes on UVES was crucial. It was remarked how RRM on UVES is now becoming even more powerful: X-shooter has been moved to Unit Telescope 3 (UT3), removing potential trigger conflicts, and the new RRM implementation now permits changing focus from another instrument to UVES, greatly increasing the likelihood that the trigger will be activated.

Finally, Magda Arnaboldi and Isabelle Percheron described the availability of science-ready one-dimensional UVES spectra in the ESO Science Archive Facility. UVES was the first instrument for which this service was introduced, in 2013, beginning with a subset of slit data. In subsequent releases, image slicer data were added and some issues resolved, and finally in 2020 the whole 20 years of science data were reprocessed homogeneously. Perhaps more importantly, stacked, reduced spectra for multi-exposure observing blocks were added then, as well as improved calibration. A total of roughly 100 000 primary reduced spectra, and 35 000 stacked spectra are now available (and these numbers are growing)[4].

Discussions, and plans for the future of UVES

One of the main purposes of the workshop was to collect feedback and suggestions about which UVES capabilities and characteristics are most important, and how to enhance them in the years to come so as to maintain UVES as a competitive facility in the instrumental landscape. For this reason, each speaker was asked to include a final slide on this topic. In addition, at the end of each day roughly 45 minutes were dedicated to two discussion sessions, during which four panelists (Amelia Bayo and Lorenzo Monaco on the first day, Sebastian Lopez and Sandra Savaglio on the second day), collected these suggestions and added their own in a brief presentation, after which the floor was opened to the participants for discussion. The main suggestions put forward can be summarised as follows:

– Maintain and improve blue-arm performance: the capability of UVES to observe down to the atmospheric cutoff at 300 nm, coupled with its high resolution, was deemed crucial for many science cases, such as studies of the variation of fundamental constants, high-redshift deuterium and molecular absorption, abundance analysis in low-metallicity stars, and beryllium and heavy-element abundances. This point was strongly stressed, since there is no existing or foreseen replacement for this UVES capability: ESPRESSO does not reach the bluest part of the visible spectrum, while X-shooter and CUBES lack the resolution needed to disentangle the highly crowded line systems frequently encountered in the blue. Plans towards a "single shot" blue arm with improved efficiency were very positively received.

- **Improve the quality and reliability of wavelength calibration:** the stability and repeatability of wavelength calibration are considered less than optimal, particularly in the blue. This is an issue that was also identified as being pertinent to fighting obsolescence: the currently available ThAr lamps are less than optimal for calibrating the large UVES spectral coverage. The implementation of an ESPRESSO-like Fabry-Perot (FP) calibration source was discussed, since it has the potential to provide a highly regular wavelength reference across the whole range. Since UVES has limited stability requirements, the FP-drift calibration could be performed with a simple ThAr reference.
- **UVES as a follow-up machine:** several speakers emphasised the need for spectroscopy to follow up observations with forthcoming massive survey facilities such as ESO's 4MOST and MOONS and the WHT Enhanced Area Velocity Explorer (WEAVE) at the William Herschel Telescope. 4MOST, for instance, will produce spectroscopy for millions of sources over a 5-year timeframe, potentially detecting thousands of targets every year that will need to be followed up with higher resolution, larger/different spectral coverage, or higher signal-to-noise ratio. Concerns were expressed that the current operational paradigm for Paranal instruments (UVES is clearly not the only instrument that will be requested for these follow-ups) might not be ready to handle the large number of requests from survey consortia.
- **CUBES-UVES fibre link:** the forthcoming CUBES spectrograph will cover the 300–400 nm range with much higher efficiency but lower resolution than UVES (the CUBES resolution is foreseen to be about 20 000), but it will not cover the rest of the visible range. There was strong support for installing CUBES at the UT2 Cassegrain focus and connecting it to UVES via a fibre link similar to the one used with the Fibre Large Array Multi-Element Spectrograph (FLAMES), observing simultaneously with both spectrographs — to produce UVES spectra with $R \sim 47\,000$.
- **Long-slit spectroscopy:** it was noted that while many forthcoming instruments reflect a strong focus on the advantages of fibre-fed spectrographs, there are nonetheless certain science cases which require a long slit such as UVES has.

Based on the lively discussion and clear ideas about possible futures for UVES the workshop was a real success. It is evident that the instrument is considered highly relevant and competitive in its current form, but also that clear support — along with readily identifiable science cases — exists for a number of possible hardware upgrades. This input will prove invaluable in defining any possible future upgrade project.

Demographics

The scientific organising committee sought fair representation from the community. The committee itself was 50% male and 50% female, the local organising committee being 60% male. 46% of the speakers were female, as were 50% of the panelists. Otherwise, we did not request gender information during registration, so we don't have statistics on the attendees. The workshop was well attended with registered participants from 30 countries (see Figure 3); of particular note was a strong contingent from India.

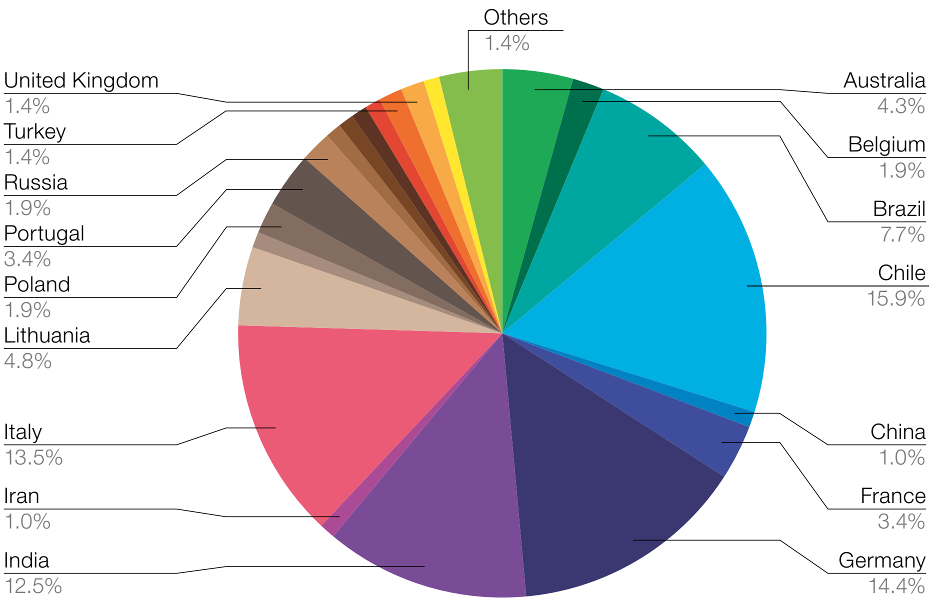

Figure 3. Registrants by country of affiliation.

Acknowledgements

We wish to warmly thank the workshop speakers, panelists, and Bruno Leibundgut as chair of the discussion sessions, for their help and the wealth of ideas they all brought forward. We also wish to thank ESO Director General Xavier Barçons for his warm message of welcome, and ESO's IT support, together with Paulina Jiron, Nelma Silva and Veronique Ziegler for logistical support.

References

D'Odorico, S. 2000, The Messenger, 99, 2

Links

[1] Workshop Youtube playlist: https://www.youtube.com/playlist?list=PLDNJqjce4cUzFGinXDWtIZeOT-BWpolaFW
[2] Workshop presentations: https://zenodo.org/communities/uves2020
[3] Workshop programme: https://www.eso.org/sci/meetings/2020/uves2020/program.html
[4] Access to science-ready UVES spectra at the ESO Science Archive Facility: http://archive.eso.org/wdb/wdb/adp/phase3_spectral/form?collection_name=UVES

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Fellows at ESO

Aleksandra Solarz

I was born in Krakow, Poland. Like in other cities, the sky there is not very spectacular, with only a few stars visible on a clear night. Instead of early stargazing, my interest in astronomy was born from an early and brief obsession with dinosaurs. Earth was the domain of those stunning creatures for at least 230 million years and yet it seems like all dinosaurs suddenly ceased to exist about 66 million years ago (with a few exceptions). Almost three-quarters of life on Earth was claimed by a mass extinction event. After learning that their demise could have been caused by the impact of a massive asteroid with a size of ~ 10 km that hit the Earth and drastically changed the climate, my curiosity quickly shifted to astronomy. It was when I started to wonder about other bodies roaming our Solar System, gravity and then, going deeper into the rabbit hole, to distant galaxies. Thankfully, my father has always been very inquisitive himself, and he had answers to all the questions a peculiar 6-year-old could have. He was so adamant about providing explanations that he procured a small telescope for me, through which he showed me the Moon, Venus and Jupiter's moons during summer holidays away from the city. Frequently he would urge me to search for my own solutions by putting doubt in my head and giving me a gentle nudge in the right direction.

When the time came to choose a career path for myself, without any hesitation I applied to study astronomy at Jagiellonian University in Krakow. The astronomy department has its headquarters in the Astronomical Observatory located on the outskirts of the city and is rich not only in optical and radio telescopes but also in violent history. Most of the classes were given inside an old military stronghold (Fort Skala) built in the 19th century. Exploring its many corridors and rooms was one of the highlights between the maths and physics lectures, as it holds many secrets and is shrouded in many mysteries. My favourite one is almost a ghost story about a missing crew of watchmen. When Poland wasn't in a state of war, strongholds across the country were not staffed with soldiers but were manned only by guards. The legend says that during the summer of 1910 the shift change of guards arrived at Fort Skala but they found the place empty. The door was barred from the inside but the current crew was nowhere to be found, and there were no signs of a struggle. Despite an extensive investigation, no one could establish what happened to the missing crew. As an undergraduate student, I had great pleasure in guiding tourists through both the telescopes and the stronghold.

For my master thesis, I worked under the supervision of Agnieszka Pollo on an infrared photometric sky survey of the north ecliptic pole (NEP) made by the AKARI satellite. AKARI was launched by the Japan Aerospace Exploration Agency (JAXA), and its name is derived from a kanji word meaning "warm light". At that time the NEP field had been observed only at near- and mid-infrared wavelengths, and no optical information was available. My work was focused on developing a method to extract and characterise different types of astronomical objects like galaxies, quasars and stars and create catalogues of these sources for further analysis. This task led me to learn different computing techniques, such as machine learning, which, among other things, automates classification tasks by finding patterns within the data. These techniques have proved to be remarkably more precise and efficient (in terms of time and resources) than the manual approach usually undertaken by a researcher. The machine learning algorithm can not only deal with significantly more data sets at once but also ensembles in multidimensional parameter space to search for (dis) similarities between different types of celestial objects. Thanks to this work and Agnieszka Pollo's vast collaboration network I was able to continue my work on AKARI data as a PhD student at Nagoya University in Japan, under the supervision of Tsutomu Takeuchi. With the catalogues of different mid-infrared-selected star-forming galaxies I created previously, an investigation of how these types of objects trace the large scale structure of the Universe came naturally.

When I was applying for a PhD position abroad, I wasn't sure how I would handle uprooting myself from Poland and moving to a completely different country with a vastly different culture from my own. From the time perspective, I can honestly say that this has been, by far, the best decision of my life. Not only could I get my PhD degree in the field of my direct interest, continuing the previous work (realised by means of top-notch technology), but also I got a chance to explore the beautiful continent of Asia and meet amazing people.

Despite fulfilling many of my goals I still felt I was missing the experience of working with ground-based data. I have always been at the 'top of the data food chain', where I was working on a science-ready product. I strongly believe that being familiar with different types of data (be it ground- or space-based) is necessary to become a true modern astronomer. I was always fascinated by peeking behind the scenes of the observatory's work and seeing what challenges the crew faces on a nightly basis. This was my main motivation to apply for an ESO fellowship in Chile. As a second-year fellow, I still think I have only seen the tip of the iceberg of what the observatory's work is. At the same time I must honestly admit that ever since have I joined ESO, every day I go to sleep more knowledgeable than when I woke up. I am both amazed and humbled by having the chance to work with people here, who every day dedicate themselves to creating the smoothly operating organism that Paranal Observatory truly is!

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External Fellows at ESO

In addition to the ESO fellowships, a number of external fellows are hosted at ESO.

Maria Kalliopi Koutoulaki

Born in the Greek island of Crete, a place that is not affected much by light pollution, I remember always being fascinated by the night sky. Being raised in a family working at the archaeological Museum of Heraklion, I would spend my summers at excavation sites learning about the Minoan civilisation. We would go to isolated places without electricity and although in the beginning I was interested in becoming a tomb archaeologist I was unable to resist the night sky above me. I remember looking at the Moon with my first telescope. I was mesmerised by the details I could see and it made me wonder what else could be out there.

Following my passion as a child, I decided to pursue a degree in physics at the University of Crete. I was motivated to learn more about astronomy, so I joined the astronomy club at the university, where we would have discussions about astronomy, do outreach activities to engage the public in astronomy, and of course go every week into the mountains of Crete with our telescopes to explore the night sky. As part of my undergraduate thesis, I had the opportunity to work on the characterisation of interacting galaxies using optical spectroscopy and near-infrared imaging under the supervision of Andreas Zezas. I had the unique experience of taking my own data from Skinakas Observatory where I learned to operate a professional telescope. This, along with a summer I spent at the University of Texas at Austin, made me realise how wonderful it is to work as part of a research group. Being able to exchange ideas, trying to understand what our results meant, along with finding new ways to answer them convinced me that I wanted to continue working in such an environment.

In order to gain more experience, I decided to take my research to the next level by moving to Dublin for my PhD. I got a scholarship at the Dublin Institute for Advanced Studies (DIAS) and the University College Dublin (UCD) to conduct research under the supervision of Tom Ray, Rebeca Garcia Lopez, Antonella Natta, and Deirde Coffey. During my PhD, I focused on the inner regions of protoplanetary discs using near-infrared interferometry. I focused on understanding the physical properties at sub-au scales using the hydrogen Brackett-gamma line and the molecular CO ro-vibrational emission at 2.3 microns using the Very Large Telescope Interferometer with the Astronomical Multi-BEam CombineR (AMBER) and GRAVITY in the *K* band. Being part of the GRAVITY GTO consortium, I had the unique experience of spending many nights at Paranal Observatory and be trained in how to conduct observations with GRAVITY. I will never forget gathering with the staff and other visitor astronomers to watch the sunset and wait for the green light to appear. Needless to say, the night sky in the Atacama Desert is one of the most beautiful I have ever seen. During my time at the observatory, I could appreciate how much manpower and organisation is needed for an observatory to run smoothly and deliver the data to the astronomical community, which made me realise that I wanted to be part of it.

After defending my PhD at the end of 2019, I moved to ESO in Garching to start a position funded by the DFG (German Research Foundation) grant "Planet Formation Witnesses and Probes: Transition Disks" led by Leonardo Testi. I am currently working on understanding the dust properties of the discs around young protostars using the Atacama Large Millimeter/submillimeter Array (ALMA). I am extremely grateful to be part of ESO. It is a very vibrant place, where interactions can be established with many different universities and institutes, as well as researchers visiting from all over the world. By being there I have learned a lot about operations and the observatory; knowledge that I wouldn't have had if I had gone somewhere else. In my free time, I take every opportunity to relax by hiking in the mountains around Munich, visiting the lakes, and exploring the city and its culture. I also enjoy baking, practicing Taekwondo and doing yoga.

Personnel Movements

Arrivals (1 April 2020–30 June 2021)

Europe

Scherbarth, Malte (DE)	Mechanical Technician
Popesso, Paola (IT)	User Support Astronomer
Lammen, Yannick (DE)	Mechanical Engineer
Hofmann, Anja (DE)	ELT DMS Deputy Project Manager
Seal, Madeleine (FR)	Council Secretary/Administrative Assistant

Chile

Racz, Gregory (CA)	Head of Logistics
Caro, Patricio Alejandro (CL)	Electronics Engineer
Ortega, Marcos (VE)	Maintenance Engineer
Fluxa, Pedro (CL)	Data and Quality Control Specialist
Molina, Faviola (VE)	Data and Quality Control Specialist
Fuentealba, Christian (CL)	Facilities Technical Assistant

Departures (1 April 2020–30 June 2021)

Europe

Downing, Mark Desmond (AU)	Electronic Engineer
Mancino, Sara (IT)	Student
Bittner, Adrian (DE)	Student IMPRS

Chile

Gilliotte, Alain (FR)	ERP Support Specialist
De Luca, Giuseppe (VE)	Hospitality Operations Supervisor

This striking image shows the Milky Way streaked across the sky, with its bright gas, dark dust, and sparkling stars standing out vibrantly against the darker surroundings. The plane of our cosmic home is framed perfectly by the entrance to ESO's flagship observatory, Paranal, one of the best observing sites in the world. It sits over 2600 metres above sea level in Chile's Atacama Desert, far away from the light pollution associated with human activity. It hosts a selection of world-class telescopes, including the Very Large Telescope.

ESO/Y. Beletsky