The Messenger

No. 166 – December 2016

Presentation of ESO Long Term Perspectives
Commissioning Stereo-SCIDAR
ALMA image of the HUDF
ALMA detection of galaxy cluster shock

Reaching New Heights in Astronomy — ESO Long Term Perspectives

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[1] ESO

A comprehensive description of ESO in the current global astronomical context, and its plans for the next decade and beyond, are presented. This survey covers all aspects of the Organisation, including the optical-infrared programme at the La Silla Paranal Observatory, the submillimetre facilities ALMA and APEX, the construction of the 39-metre European Extremely Large Telescope and the science operation of these facilities. An extension of the current optical/infrared/submillimetre facilities into multi-messenger astronomy has been made with the decision to host the southern Cherenkov Telescope Array at Paranal. The structure of the Organisation is presented and the further development of the staff is described within the scope of the long-range financial planning. The role of Chile is highlighted and expansion of the number of Member States beyond the current 15 is discussed. The strengths of the ESO model, together with challenges as well as possible new opportunities and initiatives, are examined and a strategy for the future of ESO is outlined.

1. Introduction

Astronomy is one of the oldest sciences and can be defined as the study of the Universe and everything in it. Advances in technology during the past half-century have made it possible to build increasingly powerful facilities on the ground and in space to study the Universe across the entire electromagnetic spectrum and to detect particles and gravitational waves from celestial sources. This has resulted in tremendous advances, including: the discovery of the mysterious dark energy; probing the extreme physics of black holes, supernovae and gamma-ray bursts; understanding the formation and evolution of stars and galaxies; and the direct detection and study of planets around other stars, which may have the potential to harbour life. These discoveries address some of the most fundamental questions in science, are of enormous interest to the general public, and are instrumental in stimulating young people to consider a career in science or engineering, which is important for our society.

The construction of a major astronomical facility typically takes a decade or longer. ESO has built three such observatories (on La Silla, Paranal and Chajnantor in Chile) since its founding in 1962 and is now constructing the European Extremely Large Telescope (ELT) on Armazones near Paranal. They take advantage of developments in technology and in turn stimulate further technology development. ESO's observatories make key contributions to all aspects of astrophysics and are the main ground-based observational resource for astronomers in most of the Member States.

1.1 The 2004 Council Resolution on Scientific Strategy

ESO's current programme is guided by the Council Resolution on Scientific Strategy, which was formulated in 2004 when ESO had 11 Member States. The Very Large Telescope (VLT) had entered full operations with all four Unit Telescopes (UTs), but not all of the first-generation instruments had been completed. An additional instrument, the High Acuity Wide field *K*-band Imager (HAWK-I), was in development, and four second-generation instruments had been selected (X-shooter, the *K*-band Multi Object Spectrograph [KMOS], the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument [SPHERE] and the Multi Unit Spectroscopic Explorer [MUSE]). The VLT Interferometer (VLTI) was operational with the two-beam mid-infrared instrument MIDI. The VLT Survey Telescope (VST) was under construction but had experienced delays. The Visible and Infrared Survey Telescope for Astronomy (VISTA) had been agreed under the UK accession to ESO, and construction had started. ESO was operating three telescopes on La Silla and hosted a number of independent telescope projects there. The Atacama Large Millimeter/submillimeter Array (ALMA) was under construction by the partnership between East Asia, ESO and North America, but re-baselining was required to contain costs and place the main contracts. Phase A design studies for ESO's OWL concept and the competing EURO50 concept for extremely large optical-infrared telescopes were under development. Other giant telescope projects were gaining momentum elsewhere in the world. The ESO Council realised the need to develop a policy for the near future, which led to the Resolution on Scientific Strategy. The Resolution is included in full in the Appendix.

At the time of writing, twelve years later, ESO's programme at visual/infrared wavelengths has Paranal as its flagship, and the well-instrumented system comprising the VLT and VLTI, supplemented by VISTA and VST, is world-leading. Following extensive design studies, the 39-metre ELT is under construction on Armazones, as an integral part of the Paranal system, and is on track for first light in 2024. It has a good chance of being the first of the next generation of giant telescopes to go into operation. The venerable 3.6-metre telescope and the New Technology Telescope (NTT) on La Silla continue to produce excellent science. In the submillimetre regime, the Atacama Pathfinder Experiment (APEX) came on line in 2006 and the ALMA Partnership has completed the construction of the transformational array which is now operational on Chajnantor. In addition, ESO will host the Cherenkov Telescope Array (CTA) South in the Paranal area, and will operate it for the CTA Partnership on a cost-reimbursement basis.

ESO's internal organisation has been adapted to carry out this challenging portfolio of major programmes. Many internal processes have been streamlined and harmonised. Since early 2014 all staff at Headquarters work in a single set of interconnected buildings on the ESO premises and are no longer spread over multiple buildings on the Garching research campus. A world-leading outreach and education centre, the ESO Supernova Planetarium & Visitor Centre, donated by the Klaus Tschira Foundation, will be inaugurated in 2018.

In this same period, the accession of Spain (2006), the Czech Republic (2007), Austria (2009) and Poland (2015) increased the number of ESO Member

States to 15. The Brazilian accession agreement, signed in December 2010, was ratified by the Brazilian Congress and Senate in 2015, but still awaits the final signature by the President. Formal and informal discussions with a number of other countries regarding membership are ongoing.

The entire programme is under significant financial pressure caused by factors beyond ESO's control. These include rapidly increasing costs for labour in Chile, unfavourable exchange rates and special organisational contributions to the CERN Pension Fund.

1.2 Global context

State-of-the-art fully steerable optical/infrared telescopes with primary mirrors 8 metres, or larger, in diameter are operational at various locations around the world, supported by different organisations or partnerships. The main centre in the northern hemisphere is Mauna Kea, which hosts the two Keck telescopes, the Subaru telescope and the Gemini North telescope. The Large Binocular Telescope on Mount Graham and the Gran Telescopio Canarias on La Palma provide northern access to astronomers from (some of) the ESO Member States. The Gemini South telescope on Pachón in Chile and the VLT on Paranal cover the southern hemisphere. Two independent international partnerships aim to build the 25-metre Giant Magellan Telescope (GMT) on Las Campanas in Chile and the Thirty Meter Telescope (TMT). The latter was initially planned to be on Mauna Kea, but the location is presently in doubt. In the submillimetre radio regime ALMA has no competition (thanks to its sensitivity, baseline range, size and global character), except for the upgraded Plateau de Bure NOrthern Extended Millimeter Array (NOEMA), which can access the entire northern hemisphere.

Several new facilities will provide information complementary to that which ESO offers. The James Webb Space Telescope (JWST) will be launched in 2018, and will follow the Hubble, Spitzer and Herschel Space Telescopes as the new workhorse telescope in space. The European Space Agency (ESA) Gaia mission will provide very accurate positions and motions for more than a billion stars in the Milky Way by 2020. ESA's Euclid mission expects to provide an infrared map of the entire extragalactic sky by the middle of the next decade. The Large Synoptic Survey Telescope (LSST) on Cerro Pachón will start mapping the entire accessible sky twice per week in 2023, sensitive to new transient phenomena. At that time, the northern and southern components of the Cherenkov Telescope Array (CTA), designed to detect optical flashes in the atmosphere caused by high-energy gamma-rays from the Universe, should be operational as well. Ground-based facilities in the design phase, or on the drawing board, include the Square Kilometre Array, to be built in stages in South Africa and Australia, a large single submillimetre dish on Chajnantor, a large wide-field telescope for highly multiplexed spectroscopic surveys, new facilities to measure cosmic rays and a world-wide network of gravitational wave detectors with sufficient angular resolution to allow electromagnetic telescopes to locate and characterise the sources.

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Figure 1. Aerial view of the Paranal Observatory.

1.3 Long Term Perspectives

The approval of the ELT construction programme in December 2012, to which all Member States have committed significant additional funding despite the financial crisis of 2008, was followed two years later by the approval to split ELT construction into two phases. The first phase comprises 90 % of the project. It has been authorised, is independent of the timing of the completion of the Brazilian accession, and was enabled by the accession of Poland. A significant uncertainty in the planning for the future was removed in June 2016 when Council gave approval to place the Phase 1 ELT contracts in accordance with first light in 2024, even if this might require making use of the credit facility in place with the European Investment Bank. It is therefore timely to present ESO's Long Term Perspectives, setting out the planned development of ESO's programme over the next fifteen years, and including the organisational perspective, financial planning and risks, options for funding of ELT Phase 2, opportunities beyond the baseline programme over a longer period, and an assessment of the ESO model.

2. Optical-infrared programmes

ESO's programme started with the construction and operation of optical and infrared telescopes on La Silla, followed by the VLT system on Paranal, which is the current flagship, and will remain so for at least a decade beyond the period already foreseen in the Resolution on Scientific Strategy (Appendix). The next step in this wavelength regime is the construction of the ELT on nearby Armazones.

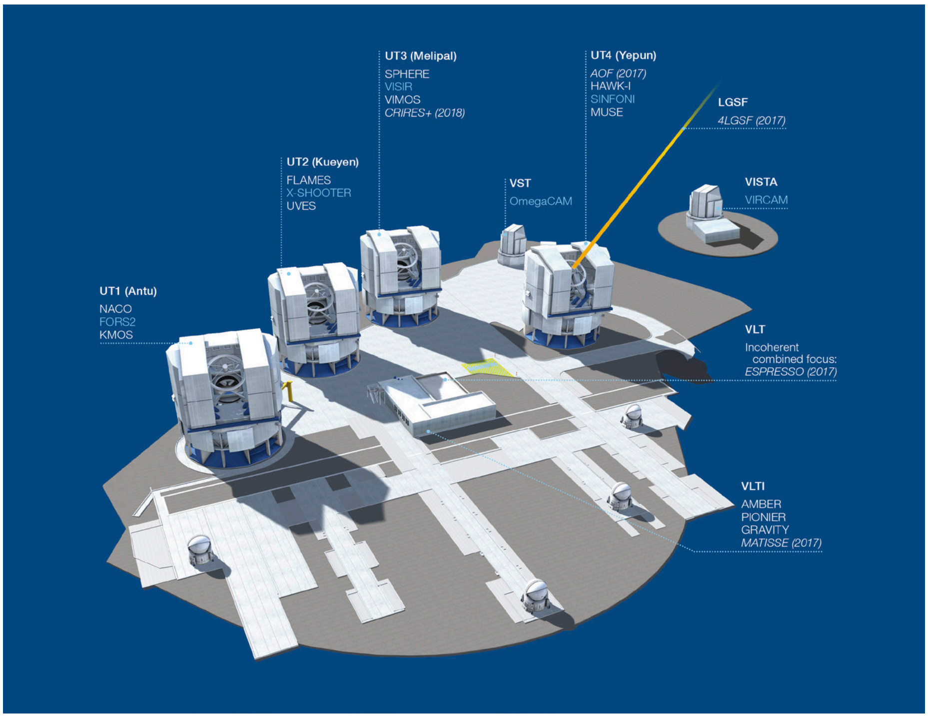


Figure 2. The Paranal system of telescopes and current instruments is shown, with the replacement instruments planned for 2017–2018 indicated (in italics).

It will be an integral part of the Paranal Observatory and will start observations by the middle of the next decade.

2.1 Paranal — the VLT system

The VLT was designed from the outset as an integrated system of four 8.2-metre UTs, including the possibility of combining the light collected by individual telescopes for optical interferometry (VLTI), either with the four UTs or with the four 1.8-metre Auxiliary Telescopes (ATs), providing superb high-angular-resolution capabilities. Most of the VLT and VLTI instruments are built in collaboration with consortia of scientific and technical institutes in the Member States, where ESO normally provides the hardware from its budget and the consortia provide the staff effort, for which they are compensated by an allocation of guaranteed time observations (GTO) with the instrument.

The VLT is currently equipped with 12 facility instruments mounted on the UTs and three VLTI facility instruments located in the coherent combined focus laboratory. VISTA and VST, each with a single dedicated camera, add wide-field imaging survey capabilities. A recent image of the VLT on Paranal is shown in Figure 1, with an annotated version of the telescopes and instruments in Figure 2. The complete system is unique among astronomical facilities world-wide.

The comprehensive coverage of parameter space in high-angular-resolution imaging and spectroscopy has led to: the detection and characterisation of planets and planetary systems orbiting other stars; the characterisation of circumstellar environments, protoplanetary discs, and stellar surfaces; high-resolution studies of the black hole in the Galactic Centre and of nearby galactic nuclei; measurements of the properties of the oldest stars; studies of interstellar and intergalactic matter; and exploration of the high-redshift Universe and early phases of galaxy formation.

The long-term instrumentation budget includes funding for a strategic programme of upgrades and new instruments every few years, maintaining the scientific capability of the Paranal system at the forefront by capitalising on developments in technology. This programme is summarised below, and is described in more detail in the Paranal Instrumentation Programme Plan[1].

2.1.1 Very Large Telescope

The mean lifetime of VLT instruments, set by technical and/or scientific obsolescence, was expected to be about ten years. In practice they have performed well for much longer, as upgrades have expanded their capabilities. The first generation of instruments was completed with the CRyogenic InfraRed Echelle Spectrometer (CRIRES) and HAWK-I in 2007. The four second-generation instruments, selected in 2002, are all operational, with X-shooter commissioned in 2009, KMOS in 2013, and SPHERE and MUSE in 2014. Figure 3 shows, for those VLT and VLTI instruments with spectroscopic capabilities, the plane of spectral resolving power and wavelength. Figure 4 displays the range of angular resolution *vs*. wavelength for the imaging modes of VLT and VLTI instruments.

In 2013 the PARSEC laser guide star was replaced by PARLA, which uses a fibre laser developed by ESO in collaboration with industry and provides a large increase in operational efficiency. The Adaptive Optics Facility (AOF) equips UT4 with four powerful sodium lasers (the 4 Laser Guide Star Facility, or 4LGSF) and a 1170-actuator deformable secondary mirror to enable diffraction-limited imaging and spectroscopy. In addition, the AOF contains two wavefront-sensor systems (the Ground Atmospheric Layer Adaptive optiCs for Spectroscopic Imaging [GALACSI] and the GRound layer Adaptive optics Assisted by Lasers [GRAAL]) to provide users with optimised adaptive optics (AO) modes with the MUSE and HAWK-I instruments, respectively. GRAAL was installed and tested at the telescope in 2015. The 4LGSF was commissioned on UT4 in April 2016 (see Figure 5), and the deformable secondary saw first light in October 2016. GALACSI will follow in early 2017.

The VLT Imager and Spectrometer for mid-InfraRed (VISIR) was upgraded in 2015/16 with new detectors and instrument modes and is now back in science operation with imaging and spectroscopy, coronagraphy, burst mode and

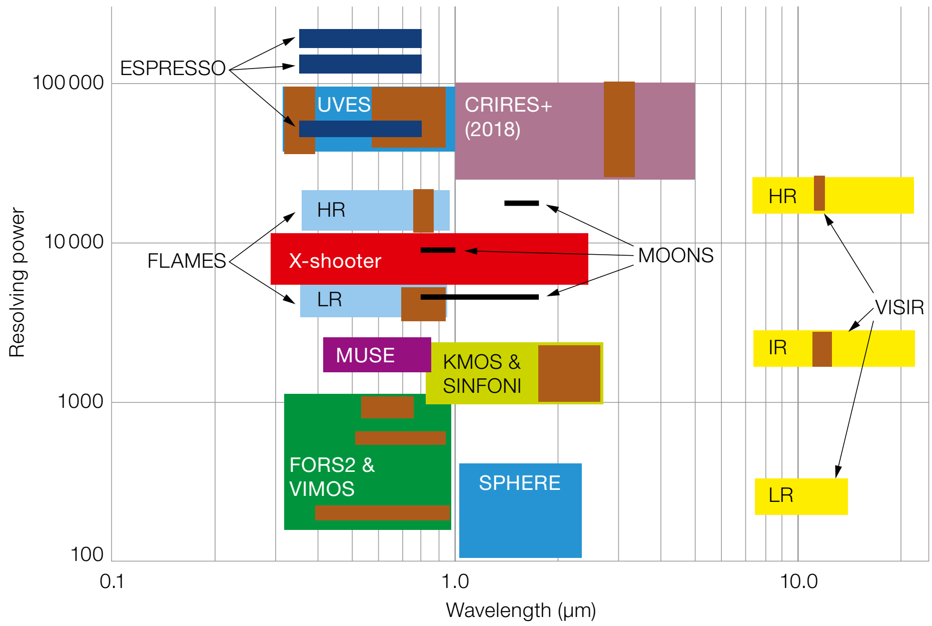


Figure 3. The spectral resolving power versus wavelength charted for current and planned VLT and VLTI spectroscopic instruments (brown areas designate higher resolution modes).

sparse aperture mask modes all commissioned.

The next instrument to reach Paranal will be the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO). It will take high-stability high-resolution spectroscopy to a new level and will be able to use any of the four UTs, or combine the light collected by all UTs simultaneously to observe an object with a 16-metre-equivalent telescope. This requires the commissioning of the four coudé trains, which is nearly completed, followed by commissioning of the instrument itself in 2017.

The upgrade of CRIRES to a cross-dispersed high-resolution near-infrared spectrograph (CRIRES+) covering the entire 1–5 μm wavelength range is on track for completion in 2018.

The Multi Object Optical and Near-infrared Spectrograph (MOONS), with wide-field and 0.8–1.8 μm coverage, is in development. It will be fibre-fed, and will have at least 800 (with a goal of 1000) fibres over a total field of 25 arcminutes in diameter. There will be two spectral resolutions: ~ 4000 spanning the full wavelength range and a higher-resolution mode which gives ~ 9000 in the *I*-band and ~ 20 000 in a region of the *H*-band. First light is planned for 2020.

In 2013 a Phase A study was completed for the Cassegrain *U*-band Brazil-ESO spectrograph (CUBES), with a strong role for Brazilian institutions. CUBES will go into development once the Brazilian ratification procedure is complete. If this should fail, other avenues could be explored.

NAOS-CONICA (NACO) was moved to UT1 in 2013 to make room for MUSE on UT4. NACO is aging and steps have been taken to allow it to continue in operation until it can be replaced by ERIS (the Enhanced Resolution Imaging Spectrometer). ERIS is a new instrument for the Cassegrain focus of UT4, consisting of a diffraction-limited infrared imager, an AO wavefront-sensor module, which uses the AOF deformable secondary mirror and any one of the four AOF lasers (for single-conjugate adaptive optics), and an upgraded version of the SPectrometer for Infrared Faint Field Imaging (SPIFFI), part of the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI), adapted to the new AO module. First light is planned for 2020.

Input for the selection of new instruments is provided via the Scientific Technical Committee (STC) and its sub-committees, at scientific conferences, or directly by the community. The emphasis is on 8-metre telescope science, rather than on technological concepts. Two recent workshops of scientists and AO experts focused on the definition of a new AO instrument in order to achieve the best possible scientific impact in an era of continuing adaptive optics developments on other telescopes and the expected availability of the James Webb Space Telescope (see Leibundgut et al. p. 62 and the Report to the STC[2]). One such idea foresees a relatively wide-field multi-conjugate AO (MCAO) imager, pushing bluewards of the traditional near-infrared MCAO regime, towards the peak of most stellar blackbodies in the optical.

The Breakthrough Foundation is interested in expediting the search for exoplanets through support of innovative approaches. It will support an experiment to search in the mid-infrared for planets orbiting in the Alpha Centauri system, by using VISIR in conjunction with the AOF. This is envisaged for 2019, and will also allow the testing of promising technologies that will benefit instruments on the ELT.

Other ideas are being developed in the community, including, for example, using SPHERE coupled with ESPRESSO for exoplanet characterisation. Other possibilities for the future are described in the STC report *Paranal in the Era of the ELT*[3].

2.1.2 VLT Interferometer

The VLTI offers a unique and world-leading capability for high-angular-resolution observations in the near- and mid-infrared, using either the UTs or the ATs (see Figures 3 and 4). The contribution of the VLTI to specific areas of stellar and extragalactic astronomy dominates the science output of all optical/infrared interferometers worldwide.

The Phase Referenced Imaging and Micro-arcsecond Astrometry facility (PRIMA), intended to enable astrometry at 10-micro-arcsecond accuracy with the VLTI, was cancelled in 2015 owing to continued delays and the prospect that completion was still at least three years away. This meant that the opportunity had been lost to carry out the foreseen science application in a timely way, given the successful launch of the Gaia mission. After an external review, the STC endorsed the proposal to cease activities on PRIMA and concentrate future efforts on ensuring the success of the second generation VLTI instruments. The lessons of PRIMA were formally reviewed and are being fed back to all ESO projects.

The VLTI was taken off line for seven months in 2015 in order to put in place all the infrastructure upgrades and new infrastructure needed to support the second-generation four-beam instruments GRAVITY and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE). This has resulted in a new AT maintenance station on the VLT platform, a comprehensive upgrade of the VLTI laboratory, installation of star separators on all ATs and UTs and global performance improvements targeted at achieving the full performance of GRAVITY (Woillez et al., 2015). The ATs will be equipped with the New Adaptive Optics Module for Interferometry (NAOMI) in the near future, and use of the GRAVITY fringe tracker for MATISSE will be a precursor to the possible development of a second-generation fringe tracker.

The Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER) was originally a visitor instrument and is now available to the community. GRAVITY is close to the end of commissioning, and has already made the first observations of the Galactic Centre with an astrometric precision which equals that achieved by classical AO techniques. MATISSE is scheduled to arrive on Paranal in 2017.

Looking further ahead, the VLTI will continue to provide the highest angular resolution, even in the ELT era. The rising demand for very high-resolution imaging of stellar surfaces, close circumstellar environments and extragalactic sources suggests a path forward which includes completing GRAVITY, MATISSE and the second-generation fringe tracker, continuing to offer a visitor focus on the VLTI (once the Astronomical Multi-BEam combineR [AMBER] is decommissioned), and exploring six-telescope imaging capabilities with the existing infrastructure (if the required funding can be identified). This

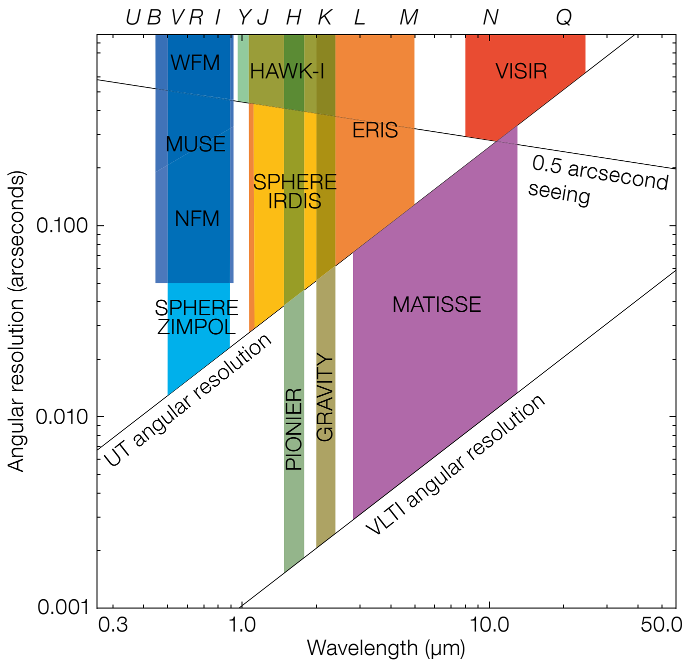


Figure 4. The angular resolution versus wavelength plane of the current and planned VLT and VLTI imaging instruments.

could be done either with a combination of ATs and UTs, or by adding two fixed ATs.

2.1.3 Survey telescopes

VISTA, equipped with the infrared camera VIRCAM, started scientific operation in early 2010. Six public survey imaging programmes, together requiring at least five years of observing time, are currently nearing completion and are already highly cited. Seven new imaging surveys, selected following peer review, are due to commence in 2017.

VST, equipped with OmegaCAM, started scientific operation in October 2011 and public and guaranteed-time surveys are being carried out. VST will be operational at least through 2021 with an increasing fraction of GTO time.

The public imaging surveys include studies of the entire sky accessible to Paranal, as well as more focused studies of the Milky Way, the Magellanic Clouds and deep extragalactic fields. These surveys are conducted by international teams, together with data centres in the Member States, coordinated by ESO.

VISTA is the ESO telescope with the largest field-of-view. In 2020/21 VIRCAM will be replaced by the 4-metre Multi-Object Spectroscopic Telescope (4MOST) instrument. With a field-of-view of more than three square degrees, 4MOST will host up to 2400 fibres, working in the optical (0.3–0.9 μm) regime. The goal is to have 1600 fibres that feed two lower-resolution (R ~ 5000) spectrographs, and 800 fibres feeding one higher-resolution (R ~ 18 000) spectrograph.

The competitiveness of the VST will need to be monitored over the coming years. There are several optical surveys planned or ongoing on more powerful telescopes elsewhere, which will cover larger sky areas and will go to greater depth than is possible with the VST. The strengths of the VST that could be exploited in the future are the image quality achievable at Paranal and the blue sensitivity of OmegaCAM. A further potentially interesting area would be narrow-band imaging. The VST agreement runs for ten years, and concludes in 2021. At present, there are no funds in the ESO budget for VST activities beyond 2021. This does not, however, preclude its becoming a non-ESO-operated hosted telescope.

Building on the public imaging surveys with VISTA and VST, teams of astronomers have recently been undertaking four extremely ambitious public spectroscopic surveys. The first of these exploits synergies with the ESA Gaia mission to provide the first homogeneous overview of the kinematics and elemental abundances throughout the Milky Way. Another, the Public ESO Spectroscopic Survey of Transient Objects (PESSTO), is building a more comprehensive understanding of the exotic, explosive Universe. The most recent surveys, VANDELS and the Large Early GAlaxy Census (LEGA-C), are using the wide-field VIsible Multi-Object Spectrograph (VIMOS) on UT3 to probe the physics in many thousands of galaxies, connecting galaxies in the early Universe with those in the present day. It is likely that even more ambitious spectroscopic surveys of stars and galaxies will be undertaken from the early 2020s in support of ESA's PLAnetary Transits and Oscillations of stars (PLATO) and Euclid missions.

2.1.4 Hosted telescopes

Since 2015 Paranal has hosted the Next Generation Transit Survey (NGTS), a small university-led robotic experiment with an array of twelve 20-cm telescopes coupled to large-format, deep-depletion CCD cameras with the prime objective of detecting transiting Neptune-size planets orbiting K and M stars. A second hosted telescope project, SPECULOOS (Search for habitable Planets EClipsing ULtra-cOOl Stars), is complementary to NGTS and will carry out a photometric survey designed to discover Earth-size planets transiting the brightest southern ultra-cool stars. SPECULOOS consists of four 1-metre robotic telescopes equipped with CCD cameras. The hosting of NGTS and SPECULOOS at Paranal is cost-neutral to ESO since all construction and running costs are reimbursed to ESO by the consortia. In return for hosting these projects, the ESO community receives high-level data products produced by NGTS and SPECULOOS that are available through the ESO Science Archive Facility (SAF).

Hosting NGTS and SPECULOOS on Paranal is an exception justified by the low water vapour content of the atmosphere, which allows these experiments to achieve the very high photometric precision required for characterising exoplanet transits. Otherwise the location of choice for robotic experiments and small telescope projects remains La Silla with its well-developed support infrastructure.

ESO/ G. Hüdepohl

Figure 5. The four laser guide stars of the Adaptive Optics Facility on VLT Unit Telescope 4.

2.1.5 Obsolescence

The VLT started operations in 1999 and many of its sub-systems are ageing. The obsolescence of devices and components in these sub-systems puts at risk the availability of the telescope systems, scientific instruments and other operational equipment. VLT technology upgrades are carried out only after careful evaluation, and aim to use industrial standards and technologies with guaranteed long-term upgrade paths and maximum independence from control software choices. An additional consideration is to maximise common technologies between VLT and ELT in view of the integration of the ELT into the existing Paranal system.

The unavailability of electronics spares for the primary mirror (M1) cells of the UTs was identified early on as one of the highest risks for VLT operations. An obsolescence project was initiated in 2012 to replace the custom-made M1 cell electronics with commercial off-the-shelf electronics that ensures the long-term availability of spares. The first upgraded systems were installed and tested on UT1 in 2014 and deployment at the other UTs followed in 2015 and 2016.

In parallel, an obsolescence project to align the VLT emergency-stop and safety-chain system with evolved safety standards required upgrading existing installations with Siemens Safety programmable logic controllers (PLCs). UT2 was upgraded in 2013, followed by the other UTs from 2014 to 2016. The new PLC-based safety-chain system allowed seamless integration of the critical safety systems of the 4LGSF on UT4. An upgrade of the safety-chain system of VISTA is planned for 2017.

Regular operations of the 8-metre coating unit were stopped in 2013 because of the steadily decreasing quality of the aluminium coatings produced. After a year of intensive testing and analysis of the root cause of the problems, a contract was placed for the complete refurbishment of the coating unit. This was completed in 2016 with the recommissioning of the coating unit and the establishment of a rigorous long-term maintenance programme. The first production coating on a UT mirror in August 2016 was entirely successful.

2.1.6 Paranal infrastructure

A significant infrastructure upgrade that is being undertaken with the support of the Chilean government is the connection of the Paranal area to the Chilean electrical grid, via a 66 kV line. This runs from Paposo, 50 km to the south, to a new substation (see Figure 7), from which 23 kV distribution lines will connect to Paranal and Armazones. The connection will provide substantial savings in operational costs and allows ESO to take advantage of future developments in the provision of green energy to northern Chile. Completion is expected in the first half of 2017, perfectly timed for the major ramp-up of ELT construction activities on Armazones.

The arrival of the 23 kV line at Paranal requires an adaptation to the existing Paranal power distribution system at 10 kV and an upgrade of the Paranal power conditioning system to the expected characteristics of the grid power. Accordingly, a project was initiated in 2015 to install a combined flywheel/diesel generator system to provide simultaneously both power conditioning and backup power by early 2017, in time for the expected arrival of the grid connection. Operation and maintenance of the current multi-fuel turbine generator and procurement of liquified petroleum gas will be discontinued shortly thereafter.

No further major infrastructure upgrades are expected in Paranal in support of the VLT. All necessary additional infrastructure upgrades are driven by and financed through the Paranal Instrumentation Programme and the ELT Programme.

2.1.7 Science operations

ESO offers facilities for projects ranging from a few hours of observing time to surveys encompassing several hundred nights. The Paranal operational model has enabled new observing modes and opened monitoring and time-domain programmes that are hard to carry out in classical visitor mode. Service observing enables users to request rare observing conditions, with the rapid response mode allowing very swift access to an 8-metre telescope, while visitor mode allows the astronomer to make real-time decisions based on the data they have just acquired. Service mode is used approximately 70 % of the time, yet the fraction of time requested in this mode continues to grow, reaching 85 % in 2016. Thanks to the evolution of network bandwidth, reliability and security, additional possibilities can be envisioned, for instance remote participation in complex observations requiring real-time decisions. Such remote observing options are being studied, and could be deployed for some programmes and/or some telescopes. They would be introduced carefully, taking into account operational and financial constraints. An analysis of performance metrics collected since the start of VLT operations allows the linking of science operations and programme implementation to science return (Sterzik et al., 2015), which provides input for further fine-tuning of future integrated VLT and ELT operations.

The following key activities are being pursued with high priority:
- A comprehensive overhaul of the Phase 1 proposal submission and handling tools to remedy shortcomings revealed by the increased capabilities of the observing facilities and the complexity of proposed observing programmes;
- Provision of web-based Phase 2 observation preparation and execution tools for service and visitor mode programmes;
- Enhancements of the services offered by the SAF enabling users to comprehensively exploit ESO's data holdings so as to increase science return;
- Further optimisation of the allocation and scheduling of observations to ensure efficient operation of the AOF and of ESPRESSO using any, or all, incoherent UT foci;
- Integration of improvements in the reliability of weather forecasting into the short-term observing scheduling system.

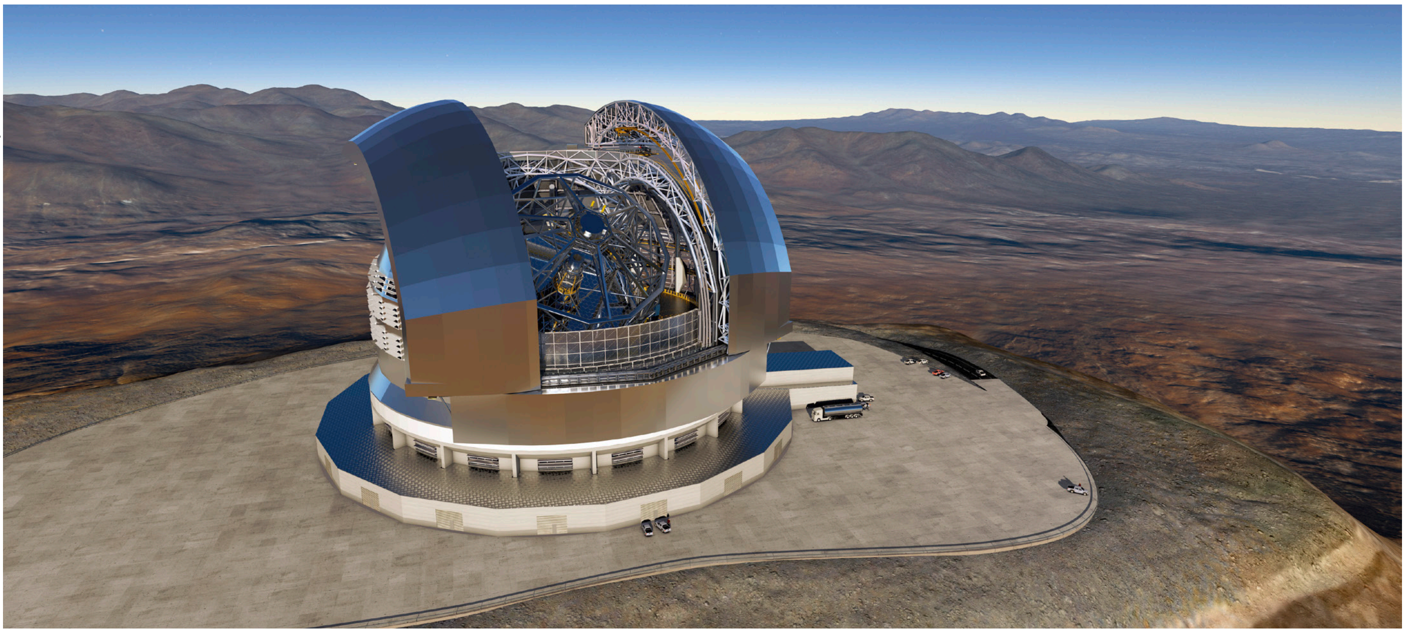
An ESO-led community working group on time allocation will report in 2017. This working group has explored potential new approaches to proposal submission and peer review, including a critical look at the existing submission channels and response times, with a view to improving the synergies with other astronomical facilities, present and future, looking towards the ELT era.

All astronomical data obtained are routinely processed and rapidly made available to the user community through the SAF after quality control. Certified pipelines process the data stream for many of the instruments in unattended mode, removing the instrument signature, scaling to physical units and providing well-defined errors. A complementary stream of scientific data products is also produced by the community which greatly enhances the science archive via the Phase 3 submission process.

Managing multi-messenger, multi-wavelength, multi-facility data is an increasing challenge, yet is critical for tackling ever more complex science questions. ESO is ideally placed to meet these challenges, where open access to data is now widely recognised as an essential research infrastructure. A recent ESO-led community working group report on science data management (STC Report 580[4]) outlines how ESO should foster, coordinate and lead such collaborations, with activities directed internally and towards the community. The report recommends that ESO should maintain an active presence in activities relating to scientific data at a global level, and must also harness the expertise in its Member States, perhaps entering into collaborative arrangements with external parties for the delivery of specific data management functions.

2.2 Armazones — the ELT

The science enabled by the ELT focuses on three prominent areas: 1) detection and characterisation of exoplanets, with Earth-like planets directly accessible for



ESO/L. Calçada/ACe Consortium

Figure 6. Artist's rendering of the European Extremely Large Telescope on Cerro Armazones in 2024.

the first time; 2) probing the formation and evolution of galaxies by enabling the study of resolved stellar populations in the full range of galaxies out to Virgo cluster distances, and in integrated light to high redshift; and 3) fundamental contributions to cosmology by measuring the properties of the first stars and galaxies, the nature of dark matter and dark energy, and a direct measurement of the acceleration of the Universe. These science cases require a 40-metre-class telescope, yielding higher sensitivity and angular resolution than GMT and TMT, and they benefit from a specific instrument suite and operational model.

2.2.1 Construction in two phases

In December 2014 Council authorised splitting the construction of the ELT into two phases. Phase 1 is for the 39-metre ELT with three instruments and an adaptive optics module, but without the laser tomography adaptive optics (LTAO) system and the five inner rings of segments of the primary mirror M1. It is affordable without Brazil as a Member State and Council has authorised the construction of this phase. Phase 2 will complete the baseline ELT by providing the missing LTAO module, the five inner rings of segments, additional segments for M1 coating and maintenance, and a second pre-focal station needed for additional instruments. The ELT operations budget will provide not only for on-site operations, but also for the ongoing instrumentation programme and major refurbishments of the telescope.

In June 2016 Council authorised placing the remaining contracts for the Phase 1 ELT on a schedule that leads to first light in 2024, even if this might require borrowing from the European Investment Bank during the peak of construction activities. This decision lowers cost and risk, and significantly increases the likelihood that the ELT will achieve first light before GMT and TMT, and be on sky simultaneously with JWST.

Council set the following constraints on the cost of ELT construction (in 2016 prices):
- The Phase 1 cost-to-completion is 1033 MEUR for first light in 2024, including 93 MEUR allocated for contingency and 124 MEUR for FTE (full time equivalent) costs;
- The Phase 2 cost-to-completion is 110 MEUR.

2.2.2 Phase 1

All activities are on track for first light in 2024. A new road to Armazones and the mountaintop platform for the telescope have been completed. Contracts for the final design and qualification of the M1 segment support (two parallel contracts for selection of the best design), for the design and fabrication of the mirror shell and support unit of the adaptive quaternary M4 mirror, as well as for the polishing of the 4.2-metre secondary mirror M2, are running. The very large contract for the Dome and Telescope Structure was signed in May 2016 and final design work is under way (Figure 6). The first stone is expected to be laid in mid 2017.

Since December 2014, much work has been done towards the procurement of the opto-mechanics (for example, blanks, polishing and supports for mirrors M1 to M5). The M1 polishing contract was approved by Finance Committee in November 2016 (the second-largest ELT contract after the Dome and Telescope Structure) together with the contracts for the M2 and M3 cells, and the edge sensors as well as the M2 and M3 blanks and M3 polishing. This brings the total material budget committed through external contracts and agreements to about 80 % of the ELT Phase 1 cost-to-completion, while leaving appropriate contingency. Other calls for tender are being prepared to allow contract signature in the next two years for the remaining equipment, including the blanks and polishing for M5, the blanks and the position actuators for the M1 segments, the serial manufacturing of the M1 segment supports, the laser guide star units, the pre-focal station, and the mirror washing and coating units.

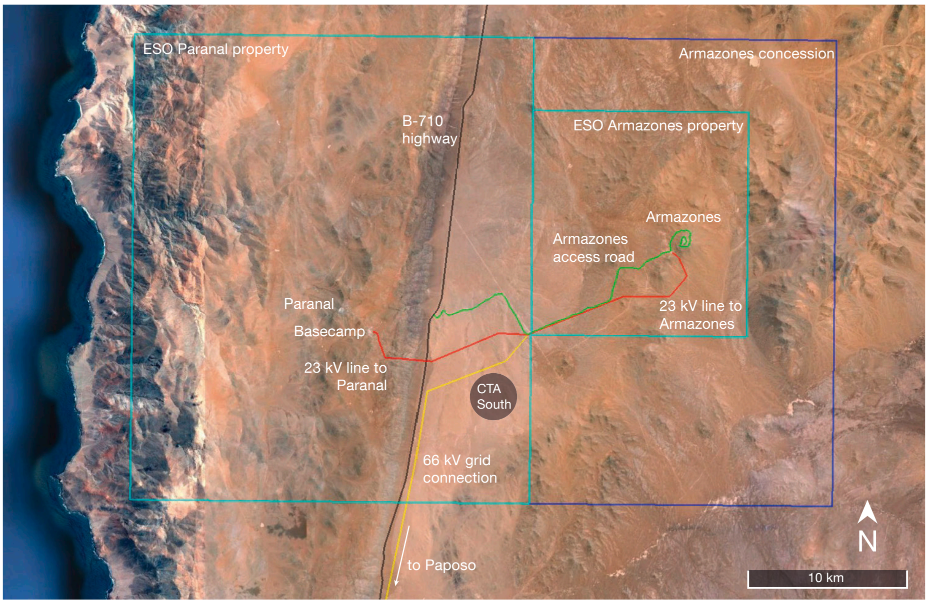
The Phase 1 instruments are: the Multi-AO Imaging CAmera for Deep Observations (MICADO), a high-spatial-resolution multi-conjugate adaptive-optics-assisted camera/spectrograph; the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI), an adaptive-optics-assisted integral field spectrograph; and the Mid-infrared ELT Imager and Spectrograph (METIS). These instruments, and the Multi-conjugate Adaptive Optics RelaY (MAORY) coupled to MICADO, will be mounted on the Nasmyth A platform of the ELT. In accordance with the successful VLT model (section 2.1), agreements with consortia were put in place in 2015 for the design, fabrication and on-site installation of the instruments and the MAORY module. These commit ESO funding for the instrument hardware and secure significant additional expenditure for staff effort in the Member State institutions involved, compensated by the award of GTO to the consortia.

Phase A studies for the Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology (MOSAIC) and the HIgh RESolution spectrograph (HIRES) started in 2016. ESO's contribution to their construction is in principle funded from the ELT operations budget line. The pivotal ExoPlanet Imaging Camera and Spectrograph (EPICS) requires extensive research and development (R&D), carried out in collaboration with institutes in the Member States.

2.2.3 Phase 2

Phase 2 for the ELT is currently unfunded but components can be proposed for Council approval if additional funding is identified. The prioritised list, established in mid-2014, of those components divides naturally into four groups:

i. The LTAO module;
ii. The five inner rings of segments for M1 as well as the seventh sector needed for re-coating and efficient M1 maintenance;
iii. The second pre-focal station, needed for the fourth, fifth and sixth instruments, and beyond;



iv. Supporting systems, including power conditioning, additional buildings, the second M1 segment coating unit and equipment for astronomical site monitoring.

Figure 7. Map of the Paranal Armazones area. The new access road to Armazones is indicated (in green), together with the tracks of the grid connection from Paposo to the south, the distribution lines to Paranal and Armazones, and the location of CTA South.

The LTAO module is crucial for bringing HARMONI to its full potential. Adding the inner rings would increase the collecting area of M1 by 26 % and hence significantly increase the sensitivity of the ELT, thus decreasing the observing time required for a number of programmes while enabling others. The inner rings also impact the point spread function, with immediate consequences for instrument design and performance (for example, coronagraphy). It is therefore highly desirable to have all M1 segments in place before first light in 2024, and to have the additional seventh sector of segments in hand soon after. This also avoids interleaving (early) operations with additional construction activities, and simplifies the regular cleaning and coating of the M1 segments, thereby lowering costs. Adding the inner rings before first light also increases the value of the GTO nights for the instrument teams. The Phase 1 contracts related to M1 (blanks, polishing, segment support) therefore have an option for the provision of the missing segments and their support. The decision to exercise the option can be delayed to late 2019 without impacting the first light date, which provides time to find additional funding. Not exercising the option, and ordering the missing segments and their supports later through new contracts, would lead to a significant cost increase, and would heavily impact the initial science capabilities and operations of the ELT.

The Phase A studies of MOSAIC and HIRES will be completed in 2018 and by that time finalisation is required on the timing of their development and the way forward for the second pre-focal station which is needed for the deployment of both instruments.

The supporting systems, deferred to Phase 2, are needed to achieve the full performance of the ELT. These include: filtering out grid power cuts (needed from 2017); providing meteorological information to optimally schedule the observations and to assist in adaptive optics use cases; and reduction of the maintenance time to achieve the required mirror reflectivity. All these systems are aimed at minimising the technical downtime of the ELT.

2.2.4 Operations

The ELT will be operated as an integral part of the Paranal Observatory. The successful VLT end-to-end science operations model will continue to evolve to accommodate the needs of the community and the requirements of the ELT to ensure its efficient scientific exploitation. On-site science operations of the VLT and ELT will be fully integrated in the back- and front-end off-site support provided at Headquarters.

General operations support will be provided through the Paranal Director's Office and the Logistics and Facilities Department, with administrative support from the ESO Vitacura Office. This support includes site management, personnel, purchasing, finance, board and lodging, cleaning, transportation and commuting services, facilities, building and road maintenance, medical services, and the safety and security of the Observatory. Technical operations support is provided by the Maintenance, Support & Engineering Department and includes preventive and predictive maintenance of telescopes, instruments and supporting equipment, troubleshooting, corrective maintenance, refurbishments, provision of technical materials, consumables and spare parts, and project support. These tasks are carried out by a dedicated workforce, consisting of international staff and local staff members recruited in Chile. Many activities that are not considered ESO core competences are outsourced as service contracts to specialised companies. In addition, Headquarters provides personnel effort and support for regular and specialist maintenance and repair of telescopes, instruments and facilities.

The existing on-site operation capacity and capabilities, including the external service contracts, will be expanded and developed according to the projected needs of the ELT. While aiming at a fully integrated operation of the VLT and ELT to maximally exploit synergies, the accounting of operation cost and effort will remain separated for both programmes to prevent cross-subsidisation.

2.2.5 Paranal—Armazones infrastructure

In 2011, the original Paranal property donated to ESO by the Chilean government in 1995 was extended towards the east by the addition of a tract of land containing Cerro Armazones and a surrounding area given in concession for 50 years. Figure 7 provides a map of this area. A new access road connecting Armazones to the public road B-710 has been constructed, cutting the driving time from the Paranal base camp to the Armazones platform to about 40 minutes. The road is asphalted and 11 metres wide, allowing heavy construction trucks to pass each other. Part of the original access track up to the top of Armazones is now a service road running next to the high-voltage cable trench.

The construction and operation of the ELT require additional infrastructure, including technical buildings, storage areas and accommodation facilities. The telescope building on the Armazones platform will host only operationally critical facilities. The nearby Armazones base camp is dedicated to the needs of construction and will be dismantled when the ELT comes into operation. Therefore, most additional infrastructure will be implemented as extensions to the existing Paranal base camp. The majority of these new installations will already be required during the ELT assembly, integration and verification (AIV) phase, and will need to be maintained for ELT operations. After the end of AIV, the available temporary accommodation will allow VLT and ELT operation staff to be hosted, while the existing Residencia and the contractor's camp are being expanded and renewed to serve the increased need for accommodation, office space, meeting rooms and work places. This expansion would also take into account the needs of CTA South.

2.3 La Silla

The La Silla Observatory (Figure 8) successfully operates according to the streamlined and lean operations model endorsed by Council in June 2007. The La Silla 2010+ model supports the continued operations of the 3.6-metre and NTT telescopes, and their instrumentation, by ESO. Both telescopes continue to be highly oversubscribed.

The High Accuracy Radial velocity Planet Searcher (HARPS) on the 3.6-metre telescope leads the world in exoplanet hunting by means of radial velocity

Figure 8. A view of the La Silla Observatory.

ESO/José Francisco Salgado (josefrancisco.org) measurements and continues to be maintained and upgraded in collaboration with external institutes. The NTT operates with the ESO Faint Object Spectrograph and Camera 2 (EFOSC2) and the Son of ISAAC infrared camera (SOFI), and the telescope is still much in demand by the community. It is currently used for the PESSTO survey (Smartt et al., 2013) and also provides opportunities for novel instrumentation by offering a visitor focus.

A call for new instruments was made in 2014, aimed primarily at replacing the ageing instrumentation at the NTT. The medium-resolution (R = 5000) optical and near-infrared (0.4–1.8 μm) spectrograph SOXS (Son of X-shooter) was selected as the future workhorse instrument at the NTT. SOXS addresses in particular — but not exclusively — the needs of the time-domain research community. Furthermore, the high-speed, triple-beam imager ULTRACAM, a visitor instrument, was offered for up to 25 % of NTT time in exchange for cash contributions to NTT operations. In addition, the Near Infra-Red Planet Searcher (NIRPS) was selected as the near-infrared extension of HARPS on the 3.6-metre telescope, creating the most powerful optical to near-infrared precision radial velocity machine for exoplanet research in the southern hemisphere.

An increasing number of small-telescope projects are hosted at La Silla. These scientific projects are developed by teams in the community; they are funded by national institutes or by the European Research Council or via private donations, and take advantage of the excellent atmospheric conditions, the available infrastructure and the lean operation-support model.

La Silla hosts the the Max Planck Gesellschaft MPG/ESO 2.2-metre telescope, the Danish 1.54-metre, the Swiss 1.2-metre Leonard Euler, the ESO 1-metre, the Rapid Eye Mount (REM), the Télescope à Action Rapide pour les Objets Transitoires (TAROT-S) and the TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST), all with dedicated instruments. An increasing number of these telescopes are operated remotely. The QUEST survey project on the 1-metre ESO Schmidt telescope (Baltay et al., 2012) was completed after eight years and operation was discontinued as planned at the end of March 2016. Recently, the Universidad Católica Norte in collaboration with the Pontificia Universidad Católica de Chile has upgraded the ESO 1-metre telescope and installed the FIber Dual Echelle Optical Spectrograph (FIDEOS).

EGP/ESO

Figure 9. The new solar photovoltaic plant at La Silla.

Two new projects, ExTrA (Exoplanets in Transit and their Atmospheres) and MASCARA (Multi-site All-Sky CAmeRA), are currently being added to the suite of hosted telescopes. All these projects can be kept cost-neutral to ESO through financial contributions by the project teams to the site operations costs, as long as the NTT and the 3.6-metre telescope are operated by ESO. An increasing fraction of the projects offer access to their high-level data products via the SAF in return for lowered hosting fees.

The La Silla 2010+ plan was envisaged for an initial period of five years without major re-investment into the site infrastructure. Modest re-investment is now needed to maintain the site infrastructure at the level required by the continued operation of the 3.6-metre, the NTT and the hosted telescopes. Operation-critical information technology (IT) infrastructure has been renewed during 2016. Savings have been made on electrical power costs, as La Silla became a regulated client in June 2015 in return for supporting the installation of a photovoltaic solar power plant on the premises. The plant started producing power in mid-2016 (Figure 9).

The science operations model for La Silla — and the corresponding infrastructure support — are being evolved to maintain basic compatibility with its Paranal counterpart, so that the overall ESO end-to-end operations also encompass the ESO-operated facilities at La Silla. This support includes the tools and methods used by the community to prepare and execute observations at La Silla, or to exploit the data in the SAF.

The availability of SOXS on the NTT (and X-shooter on the VLT) will put the ESO community in an excellent position to follow up the most interesting transients to be discovered by the LSST from 2023 onwards. The combination of HARPS and NIRPS on the 3.6-metre telescope is crucial for providing critical ground-based complementary data for the ESA/Swiss mission CHaracterising ExOPlanet Satellite (CHEOPS) and for PLATO.

The extension of La Silla operations beyond 2020 as described above requires both NIRPS and SOXS to be successful. If NIRPS were to fail for some unforeseen reason, then the 3.6-metre telescope with HARPS would still be valuable for exoplanet research, but it would be reasonable for ESO to require external contributions to the operation costs. If SOXS were to fail, then the future of the NTT would be in serious doubt. This would threaten the viability of the entire La Silla operations model, as it is not cost-effective for ESO to run the complete site for a single medium-sized telescope. External funding or support could come from (consortia of) institutes in the Member States, or from partners elsewhere including the Host State Chile.

2.4 Technology development programme

It is critical to develop and secure key technologies which will maintain the Observatories at the cutting edge of astronomy and so contribute to achieving ESO's mission. In practice, this means taking those that are at low levels of technology readiness and developing them to a level sufficient to be incorporated within new projects with manageable risk. The requirement to not only develop but also secure technology for the future means that only rarely will a technology development project take the form of a conventional procurement from industry or institutes. Usually a collaborative approach is required to ensure that the intellectual property developed in the project is either transferred to ESO, or another scheme is used to ensure that the technology will be available and further developed over the period of time that it is needed. This approach requires long-term planning to address risks such as obsolescence, loss of external manufacturers, and uncertain requirements for future development.

In addition to enabling ESO's mission, technology development also has a role in enhancing the skills, and increasing the motivation, of staff within ESO. Although this aspect will not drive the selection of specific projects, it will be considered when deciding where and how the development will be carried out.

The funding for technology development has been consolidated from a variety of small R&D budgets across the Directorates of Programmes and Engineering, from the enabling technology budget for the VLT and from the enabling technology programme formerly planned for the ELT. Current projects include the development of deformable mirrors for future ESO projects, detector development, laser R&D, ELT real-time computing and wavefront-sensor camera development, and R&D for the ELT EPICS instrument.

The availability of state-of-the-art detectors is critical for ESO. Infrared devices have traditionally been single-source procurements from US companies who serve the defence market and are under significant ITAR (International Traffic in Arms Regulations) restrictions. The next-generation devices are extremely expensive and start to dominate the budgets and limit the scope of new instruments. In the optical, the situation is less urgent, but the traditional charge-coupled device (CCD) technology is now being replaced with Complementary Metal Oxide Semiconductor (CMOS) technology. This represents a viable alternative for commercial applications and in principle also for astronomy, but currently no such devices meet ESO's needs. A first step in mitigating these risks is participation in the ATTRACT initiative, which aims to obtain funding from the European Commission for developing imaging and detection technologies in Europe.

3. Submillimetre Programmes

ESO's activities in the submillimetre wavelength regime, traditionally associated with radio-astronomy, started with the Swedish-ESO Submillimetre Telescope (SEST) on La Silla (1987–2003). This led to participation in ALMA and APEX (Figure 10).

3.1 Chajnantor — ALMA

ALMA evolved from separate regional plans to a global partnership between ESO (37.5 %), the US National Science Foundation (NSF, representing USA, Canada and Taiwan; 37.5 %) and the National Institutes of Natural Sciences in Japan (NINS, representing Japan, South Korea and Taiwan; 25 %). The host state Chile receives 10 % of the observing time. ESO's counterparts at the executive level are the US National Radio Astronomy Observatory (NRAO), managed by the Association of Universities Inc. (AUI), and the National Astronomical Observatory of Japan (NAOJ).

3.1.1 Construction

ALMA construction on the Array Operations Site (AOS) at 5050 metres altitude and the Operations Support Facility (OSF) at 2950 metres formally ended in December 2013, except for, as regards ESO, the ALMA Residence and a site-security surveillance system. NAOJ completed delivery of the Band 4, 8 and 10 receivers soon after this date. NRAO continued after 2013 with the investigation of the astigmatism affecting the North American antenna performance and a number of other activities. Commissioning activities of the array are continuing and extend into the operations phase for more advanced observing modes, including solar observations and participation in global very long baseline interferometry (VLBI) experiments.

The ALMA Residence will be completed and handed over to ALMA in early 2017, and procurement of the site-security surveillance system will follow. The permanent power system started operations in November 2012 and is now in reliable 24/7 operation, after some initial technical and operational difficulties in 2013. Previous ESO infrastructure deliveries include the Technical Building for the OSF, the Santiago Central Office (SCO) at the ESO Vitacura premises, 192 antenna foundations, and the access road to the OSF and AOS.

Front End and Back End deliveries were complete by the end of 2013. These included 73 receiver cartridges each for Band 7 and Band 9, 58 water vapour radiometers, 83 Front End power supplies, 26 fully integrated and tested Front End assemblies, 70 cryostats, more than 500 cartridge bodies, more than 600 photo mixers, the complete fibre management system, 550 tuneable filter boards, and 58 sets of cryogenic helium lines. Two custom-made antenna transporters have been in routine operation since 2008. The contract with the AEM Consortium for the antennas provided by ESO was formally closed in early 2016, when the warranty period of the twenty-fifth antenna expired. All AEM antennas are within specification and operating reliably.

Council set the cost-to-completion for ESO's ALMA construction in 2005, at an amount equal to 489.5 MEUR in 2014 prices. The entire programme was delivered over the next nine years with only a 1.5 % cost increase. A workshop on

ALMA (ESO/NAOJ/NRAO) and J. Guarda (ALMA)

Figure 10. The ALMA antennas on the Chajnantor plateau, with APEX visible on the right. The Licancabur volcano towers in the background.

Lessons Learned from ALMA Construction[5] took place in 2015, and the results are being applied in the ELT programme.

The AEM prototype antenna, which was tested at the NRAO site near Socorro, New Mexico in the period 2006–2009, was transferred by ESO to Steward Observatory in Tucson, to be part of the Arizona Radio Observatory. It has replaced the venerable 12-metre antenna on Kitt Peak. In return, the ESO community receives a total of 3600 hours of guaranteed time on the refurbished prototype and on the 10-metre Heinrich Hertz Submillimeter Telescope on Mount Graham.

3.1.2 Operations

ALMA on-site operations are carried out by the Joint ALMA Observatory (JAO), whose personnel comprises both international and local staff, and are complemented by off-site operations activities at the three executives. The scientific results are transformational but there is still further to go to reach ALMA's full scientific potential and activities continue to test advanced modes of observation. Improvements in observing and data reduction efficiency are needed to achieve a long-term sustainable operations model.

The ALMA-wide governance for the operations phase has been agreed and established. In December 2015, the ALMA Trilateral Agreement was signed by ESO, the US National Science Foundation (NSF) and the Japanese National Institutes of Natural Sciences (NINS). It supersedes previous bilateral agreements between the ALMA partners. For the daily interactions and management of ALMA, a structure of Integrated Teams across all ALMA partners and JAO has been established. These Integrated Teams operate for Management, Science, Science Operations, Engineering, Computing, and Outreach, replacing the construction-oriented Integrated Product Teams (IPTs).

ALMA operations support at ESO formally started in early 2008 with the establishment of the European ALMA Regional Centre (ARC). The ESO ALMA Support Centre (EASC) was created in 2009 to centrally coordinate the overall ESO off-site operation support. It provides user support, data processing, technical hardware and software support and maintenance, a development study programme and upgrades for ALMA, and the delivery and archiving of data. The EASC also supports ALMA Science and Outreach activities.

ALMA Early Science observations started with Cycle 0 in September 2011 using 16 antennas, leading to a number of high-profile discoveries including the detection of interstellar sugar, planet-forming discs, and water in star-forming galaxies at redshift 5.7. During the long-baseline campaign in late 2014, an iconic image was obtained which reveals unprecedented fine detail in a planet-forming disc around the young star HL Tauri (see Figure, p.27). It attracted tremendous public interest worldwide.

ALMA science operations adopted an annual cycle starting with Cycle 3 in October 2015. Cycle 4 has configurations comprising at least forty 12-metre antennas, as well as the 7-metre antennas of the Morita Array (previously known as the Atacama Compact Array), extended baselines and seven (of the final ten) receiver bands. The oversubscription continues to be highest for the ESO Member State astronomers and they have had involvement in around three quarters of the ALMA papers already published. The ARC is engaged in helping ALMA users to prepare their observations and reduce the resulting data, and in testing of observation preparation and data processing software.

The distributed model for the ESO ARC, with the central hub at ESO and a network of locally funded nodes in several Member States, has proven to work very well (Hatzminaoglou et al., 2015). It provides ALMA users with high-quality data products in a timely manner, in addition to face-to-face support. An external review in January 2015 confirmed the value of this model while also outlining some risks and challenges for the future. One of these is the potential closing of an ARC node and the corresponding reduction in data processing effort.

In the area of data reduction, the calibration pipeline has been in use since late 2014, but, contrary to initial plans, the imaging pipeline is not yet available. This poses a significant challenge for the ARCs. It is essential that more than 75 % of the data can be efficiently pipeline processed in the near future to ensure that the workload of the ARC staff remains manageable and they can continue to provide a high level of support to users.

ESO has undertaken (with support of the ALMA partners) the planning for, and construction of, a pipeline to connect the OSF turbines to the nearby North Andino gas pipeline. This will provide natural gas at a competitive price, reducing operational costs. It will also reduce the traffic of heavy trucks on the road to the OSF (which lowers maintenance needs and increases safety), improves the working efficiency of the multi-fuel turbines and limits pollution.

3.1.3 Further developments

The current ALMA operations plan contains off-site development funding of which ESO's 37.5 % share ramped up to approximately 3.2 MEUR/year in 2015. The use of this budget for development efforts in the software and hardware areas follows the agreed principles for the ALMA Development Programme, which include an ALMA-wide approval process and governance. The EASC plays a key role in representing the interests of the ESO Member State communities and managing the ESO part of the development programme.

ESO issued calls for ALMA development studies to the technical and scientific community in the Member States in 2010, 2013 and 2016. These studies include science investigations (such as the scientific value of a possible Band 11), design studies for new hardware and software, and preparations for series production of components. Similar initiatives were taken in North America and East Asia. The first resulting full-scale projects are underway or already completed (for example, the fibre link from the OSF to SCO). ESO has taken the lead on the Band 5 project following the successful development and pre-production of six receivers funded over the period 2008 to 2012 by the European Union Sixth Framework Programme for the ALMA Enhancement. Within the ALMA Development Programme, ESO provides 73 Band 5 cartridges and NRAO provides the local oscillator (as in the ALMA construction phase). The Band 5 cartridge work is contracted to a European consortium and started in 2012. Equipping all 66 ALMA antennas with Band 5 receivers should be finished in late 2017. The integrated alarm system to be developed by ESO will be operational by the end of 2018, improving the overall reliability and safety of the Observatory.

In the coming decade, ALMA will begin upgrading the receivers and signal transport and processing chain. ESO's ALMA development studies are already addressing the possibilities of building a next-generation receiver for the 67–116 GHz range (Band 2+3), as well as upgrades to Bands 7 and 9. The development of a new digitiser system is also well advanced. Studies of possible upgrades to the software systems are also being carried out.

ALMA-wide activities are under way to define a coordinated long-term development plan across the ALMA Partnership to ensure maximum gain for the available funding. The ALMA Scientific Advisory Committee (ASAC) and ALMA programme scientists have elaborated development paths in the ALMA 2030 process resulting in three documents, covering: 1) the major science themes in the 2020–2030 decade; 2) the landscape of major facilities by 2030; and 3) the pathways to developing ALMA. In 2015, the ALMA Board created an ALMA Development Vision Working Group to translate these plans into a realistic path for ALMA development. A draft report is expected in April 2017.

On ESO's side no major upgrade of ALMA (other than those funded in the development plan) is foreseen until the ELT construction is completed, unless an additional partner joins ALMA. It is noted that this would further increase the oversubscription for observing time.

3.2 Chajnantor — APEX

The Atacama Pathfinder Experiment (APEX) is a 12-metre antenna for submillimetre astronomy located at an altitude of 5065 metres on Llano Chajnantor in northern Chile. APEX is a partnership between the Max-Planck-Gesellschaft (MPG), the Onsala Space Observatory (OSO) and ESO, with 50, 23 and 27 % shares respectively, and it saw first light in 2006. It is operated by ESO from a base in Sequitor near San Pedro de Atacama, as part of the La Silla Paranal Observatory.

APEX celebrated its tenth year of science operations in January 2016. It is an ideal wide-field mapping facility, complementary to ALMA, and allows testing of innovative instrumentation. It has an important role as source finder for ALMA and also enables fast spectroscopic follow-up of ALMA discoveries. APEX continues to be highly oversubscribed and produces a steady output of scientific publications. APEX is operated in service mode and employs support astronomers from the partners and Chile; it has consequently become an important facility to train a new generation of astronomers in submillimetre-wavelength expertise.

The APEX Partnership is currently agreed until the end of 2017. The partners have reviewed the possibility of extending the agreement for five years from 2018 to 2022. An external critical review was carried out in early 2016 to assess the scientific and technical competitiveness of APEX beyond 2017. With the positive feedback from the review, the ESO Council has just approved a new agreement for a further extension through to 2022. As part of this agreement, the APEX Partnership plans for additional investments in antennas, instrumentation and infrastructure to ensure the scientific and technical competitiveness of the facility. The aim is to offer a state-of-the-art suite of heterodyne receivers across the accessible submillimetre window, together with kilopixel continuum multi-colour wide-field cameras. The partnership will adjust the partner shares of MPG/ESO/OSO to 55 %/32 %/13 % as of 2018. The cost to ESO of the APEX extension is included in the financial planning (see Figure 16).

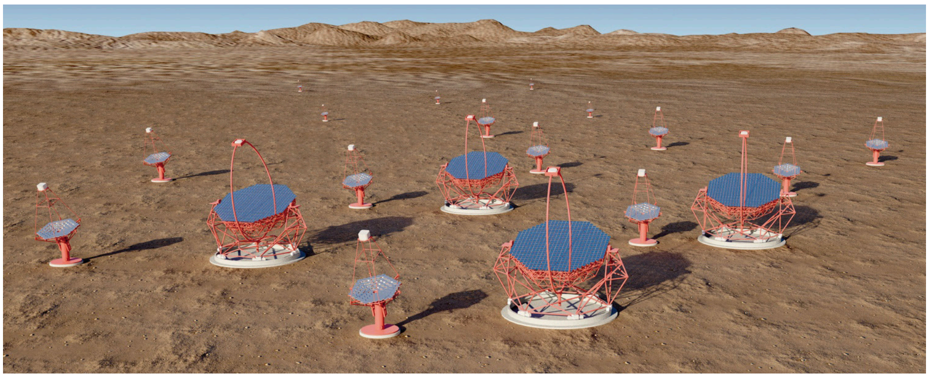
If the APEX Partnership decided to cease operations after 2022, the facility could either be decommissioned and removed from the site or could transition to a new initiative that builds on the existing APEX infrastructure at Chajnantor and Sequitor and on the available expertise in operating such a facility. A large single-dish submillimetre antenna with massive wide-field continuum imaging capabilities could be such a future initiative.

4. Participation in a high-energy programme

Very high energy gamma radiation from celestial objects can be studied from the ground by observing the optical Cherenkov flashes generated when the gamma rays interact with the Earth's atmosphere. Pioneering work in this area was done by the High Energy Stereoscopic System (HESS), the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) and the Very Energetic Radiation Imaging Telescope Array System (VERITAS) experiments. The CTA project aims to take the next step in energy range, sensitivity and resolution by means of a northern and a southern array of many simple, but large, open-air optical telescopes with segmented mirrors.

4.1 CTA project

The scientific goals of CTA are extremely broad, ranging from understanding the role of relativistic cosmic particles to the search for dark matter and probing environments from the immediate neighbourhood of black holes to the cosmic voids on the largest scales. Covering a huge range in photon energy from 20 GeV to 300 TeV, CTA will improve on all aspects of performance with respect to the precursor experiments. Wider field-of-view and improved sensitivity will enable CTA to survey hundreds of times faster than previous TeV instruments. The angular resolution of CTA will approach one arcminute at high energies — the best resolution of any space or ground instrument operating above the X-ray band — allowing detailed imaging of a large number of gamma-ray sources. An improvement in collecting area of between one and two orders of magnitude also makes CTA a powerful instrument for time-domain astrophysics, and three orders of magnitude more sensitive on hourly timescales than the Large Area Telescope on the Fermi Gamma-ray Space Telescope at 30 GeV. The two arrays will provide full sky coverage, and hence maximise the potential for observing rare phenomena including the nearest supernovae, gamma-ray bursts or gravitational wave transients.



G. Pérez, IAC, SMM

Figure 11. Artist's impression of the Cherenkov Telescope Array South at Paranal.

The CTA project carried out a worldwide site selection process in 2013–2014 which resulted in the identification of La Palma as the preferred northern site and the Paranal area as the ideal southern site (the location is shown in Figure 7). In the baseline plan, the southern array will cover approximately ten square kilometres, and will consist of telescopes of three sizes: 70 small (4-metre), 25 medium (12-metre) and 4 large (23-metre). The northern array will have 15 medium-sized and 4 large telescopes. Construction is expected to take approximately four years.

Unlike the precursor experiments, both arrays will be operated as a proposal-driven facility, with all data available in a public archive after a one-year proprietary period. A core programme of key science projects will use about 40 % of the available observing time in the initial years to provide legacy data products. With 99 telescopes on the southern site, very flexible operation will be possible, with sub-arrays available for specific tasks.

The CTA Partnership consists of a Governing Council, a Consortium and a Project Office. The CTA Consortium comprises over 1200 scientists working in 200 institutes from 32 countries, among which are 12 ESO Member States as well as Brazil and Chile. In mid-2016, the Istituto Nazionale di Astrofisica (INAF) centre in Bologna was selected as the site for the CTAO Headquarters and the Deutsches Elektronen-SYnchrotron (DESY) centre at Zeuthen (Germany) as the site for the Science Data Management Centre. The Partnership is making progress in securing funding for construction, and expects to start with partial arrays in each location. These will already be able to do exciting science by increasing the exposure time.

4.2 Role for ESO

The ESO financial plan does not include funding for construction and operation of new facilities on the timescale planned for CTA. However, ESO has tremendous experience in maintaining and operating optical telescopes in remote areas, which is valuable for the CTA project, and will enhance the science return on the investment in CTA.

Following the identification of the Paranal area as the preferred southern site, detailed discussions took place with the CTA Partnership to clarify the practicalities of hosting the southern array on the Paranal property, and to develop a formal agreement between ESO and CTA. The agreement stipulates that ESO joins the CTA Partnership with an 8 % voting share, and operates the southern array on behalf of the partnership on a cost-neutral basis, with funding provided by the CTA Partners. In return, 10 % of the observing time on both the southern and the northern array on La Palma would be made available to scientists in the ESO Member States (in addition to the CTA partner shares that 12 of the 15 Member States have), and 10 % of the observing time on the southern array would be reserved for Chilean scientists. The agreement was ratified by the ESO Council in its December 2016 meeting. If ESO were to further cover the cost of site operations (estimated at about 4 MEUR per year), this could add approximately

10 % of observing time to the ESO share, but no such funding is identified at present.

The operation and technical facilities of CTA will be located close to the telescope array itself unless clear synergies with ELT and VLT facilities at the Paranal base camp can be identified. Provision of accommodation to CTA staff in the expanded Paranal facilities is one of the most obvious possibilities.

Operating CTA South provides an exciting expansion of the overall programme, opening a new window on the Universe for astronomers in the Member States. CTA South will be integrated into the Paranal Observatory, which will guarantee its sustainability and control any risks of conflict for ESO resources during ELT construction. It is also fully in line with ESO's mission of building and operating world-class facilities for astronomy and fostering collaboration in astronomy.

5. The Organisation

Since its foundation in 1962, ESO has established the structure required to conceive, develop, build and operate advanced ground-based astronomical observatories. It has created a close collaboration with the Member States in respect of the supporting astronomical and technical research and development work, modelling, systems engineering, etc. necessary to deliver not only the hardware but also software and pipeline-reduced data to its community. The 15 Member States with Brazil and Chile account for about one third of the world's astronomical community.

5.1 Organisational structure

ESO Headquarters is the focus for interaction between the Member States and the Organisation and provides support for the governing and advisory bodies. It hosts approximately 420 personnel and is the centre for development of telescopes and instruments, operations support, archives, scientific and technical research, education and public outreach, human resources, financial management and procurement. It includes data centres and laboratories for the development of key technologies as well as state-of-the-art integration halls and equipment to test instruments before shipping to the Observatories. A map of the Headquarters buildings is shown in Figure 12.

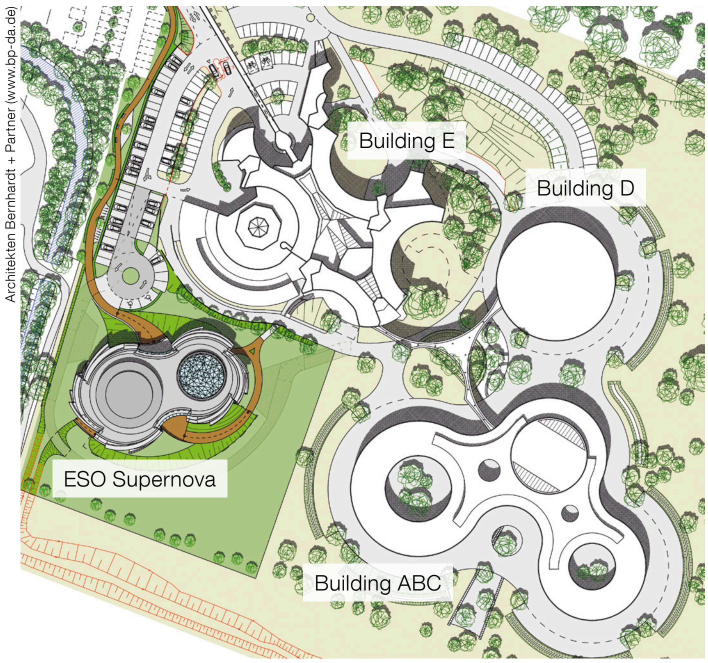


Figure 12. Map of ESO Headquarters in Garching. Building E is the original Headquarters building, connected by bridge to the extension Buildings ABC (containing offices, a larger auditorium, and a new Council Room) and D (the Technical Building, containing a new, larger integration hall).

Approximately 275 personnel work in Chile, distributed over the three sites of the La Silla Paranal Observatory (La Silla, Paranal and Sequitor), the ALMA sites, and the ESO premises in Vitacura (Figure 14). The latter covers administrative activities, human resources, public outreach and official representation in Chile, together with the ALMA Santiago Central Office, and provides an environment for the fostering of science for staff astronomers and visitors. The ESO Guesthouse hosts visitors and Garching staff on their way to and from the sites and provides an additional channel for interaction with the community (Figure 15).

ESO's organisational structure consists of five Directorates: Science, Operations, Programmes, Engineering, and Administration. The Science Directorate provides scientific oversight across all programmes in the Organisation, handles observing proposal selection and telescope time allocation, education and public outreach and provides a research environment for interaction with the community. The Operations Directorate handles all La Silla Paranal Observatory needs, from user support for execution of science observations to delivery of pipeline-reduced science data, as well as the ESO support of ALMA operations. The Programmes Directorate contains programme and project management to define and execute major telescope and instrument projects in collaboration with the communities and industries in the Member States. The Engineering Directorate provides resources and services for the design, manufacturing, installation, corrective maintenance, upgrades and support of the telescopes, instruments and utility systems, and provides IT services across the Organisation. The Directorate of Administration includes human resources, finance, contracts & procurements and facility, logistics & transport. The Cabinet of the Director General, the Internal Audit Office and the Office for Representation in Chile provide support for the ESO Council and Finance Committee and to the Director General. A more detailed description can be found in the ESO High Level Organisational Structure document[6].

Staff astronomers at ESO are required to maintain an active research profile to be able to fulfil their functional duties. The studentship, fellowship, visitor and workshop programmes provide opportunities for close interaction with the

Figure 13. A 360-degree panorama of the ESO Headquarters, Garching, Germany.

astronomical community. The fellowship programme has been in place for 40 years and has trained many young scientists who return to institutions in the Member States. The support of VLT and ALMA operations by ESO fellows provides them with valuable experience for their careers. A pilot engineering fellowship scheme will start in 2017 and is expected to similarly increase the interaction with the engineering community in the Member States.

Much work was done in the past decade to define and further develop internal processes and policies. These include, for example, the ESO People Policy, the ESO Code of Conduct, new Financial Rules and Regulations, Rules of Procedure for all governing bodies, a Technology Transfer policy, a Data Classification policy, a new ESO Safety Policy with associated safety manuals for Headquarters and the Observatory sites, translations of the Basic Texts into the languages of all the Member States, and a Protocol Manual. To optimise the structure of the Organisation in order to efficiently develop concurrent projects in a resource-constrained framework, the matrixing of engineering services was implemented. This development led to clarification of the role of programme and project management, one of the results of which was the ESO Project Management Framework, defining how ESO carries out projects in the era of ELT construction.

The Representation in Chile represents the Director General in all matters with the Chilean governmental, regional and local authorities, as well as with the diplomatic legations of the Member States in Chile. A newsletter for foreign missions in Chile keeps the legations up-to-date with scientific, strategic and organisational developments and builds knowledge about ESO.

The Cabinet of the Director General works on a broad range of projects including legal and international affairs, internal communication, corporate risks and intellectual property management, and protocol. The Cabinet also produces the Annual Report, the quarterly journal The Messenger, and the ESO Science Newsletter. Established over 40 years ago, The Messenger continues to provide news of ESO's telescopes and instrumentation, a selection of recent scientific work carried out with ESO facilities, and reports on workshops, along with profiles of ESO fellows. More rapid communications on all scientific activities are provided by the Science Newsletter[7], which collects announcements on the science webpage into a newsletter mailed approximately monthly to about 9000 subscribers with ESO User Portal accounts. The internal communication office supports and coordinates communication flow across ESO, including ESO-wide internal announcements.

5.2 Evolution of staff skills

In the past three years the core competences required to carry out ESO's programme were identified, looking forward 15 years and involving extensive consultation with the community. These core competences depend on the top-level requirements of the ESO projects, on the strategic share of work between ESO and industry or technical and scientific institutions in the Member States, and on technical developments worldwide. ESO's overall core competence is the ability to design, build and operate state-of-the-art astronomical facilities that produce front-line science. As a large part of the work is done by the community and by industry, the ESO scientists and engineers must have the system knowledge and the experience required to initiate, and effectively manage, the procurement of telescopes, instruments and associated equipment. Engineers must be capable of carrying out specialised design and analysis in telescopes and instrumentation, while scientists must be available to provide cradle-to-grave operational support to the Observatories. Finally, the community relies on ESO to procure specific items such as detector systems.

Developing and maintaining these core skills requires training as well as increased internal mobility. This has the added advantage of further increasing the motivation and drive of the staff. Areas of attention include adaptive optics technologies, real-time computing, laser development, wavefront control, phasing & metrology, ultra-high-contrast imaging, as well as expertise in project management and instrument systems engineering.

ESO will continue to participate in the development of instrumentation and other facilities, delivering major subsystems as a consortium partner. The goal is to lead at least one project at any time. This aim depends on available resources,

ESO/J. Girard (djulik.com)

Figure 14. The Santiago site, located in Vitacura, houses the ESO offices and the ALMA Santiago Central Office.

but is key to the long-term retention and development of ESO staff, and the ability to work effectively with the community.

ESO built the VLT test camera, the Infrared Spectrometer And Array Camera (ISAAC), the UV-Visual Echelle Spectrograph (UVES) and HAWK-I for the VLT in-house, and was a consortium partner in X-shooter. The Organisation has been a partner on every instrument built for the VLT, delivering the detector systems and often also key cryo-vacuum and AO subsystems. ESO staff have led the AOF project for UT4 from its start in 2004, including the development of the 4LGSF, and carried out the VLTI facility upgrade project in 2015 to prepare for the arrival of GRAVITY and MATISSE. Once these are completed, the test camera for the ELT will be built in-house and will require the full suite of core competences. Furthermore, the technology development programme, as well as prototyping activities, will provide ESO staff with additional means to develop their hands-on experience. For instance, it is natural for ESO to coordinate the technology development needed to bring the EPICS concept, with its technology readiness, to the level needed to start construction in 2020.

5.3 Age distribution and gender balance

A long period of sustained increases in staff complement ended in 2011, when ALMA construction activities ramped down at a time when ELT construction had not yet started (see Figure 17). This meant a reduced influx of junior staff, with, as a net result, an increase in the median age of ESO's international staff and a significant increase in the ratio of indefinite to fixed-term contracts. This will need attention in the years to come, as it is important to ensure an appropriate mix of junior and senior staff and to have the ability to react in a timely fashion to changes in qualifications and skills required by operations and projects, taking into account the required evolution of the skill mix previously described.

Gender balance is good in the administration area. It is also good amongst the population of students and fellows, but decreases amongst the more senior science and Observatory support staff. It is poor in the engineering and project management areas, and in senior management. This depends on a number of factors, some of which are beyond ESO's control. Work continues on improving gender balance, in particular within the technical and scientific professions as well as in the management of the Organisation. A gender diversity and inclusion plan is being prepared around three pillars, namely the recruitment and career development process, an enabling environment for women, and an improvement in the working conditions. A gender steering committee has been created and the existing participation in gender networks will be intensified.

5.4 Collaborations

ESO works closely with its communities and has a number of collaborations and partnerships, including those for instrumentation development and for ALMA support, as well as for cross-allocation of observing time with ESA, education, outreach and other activities.

ESO is a member of EIROforum, a partnership of eight of Europe's premier intergovernmental scientific organisations (the European Organisation for Nuclear Research [CERN], the European Molecular Biology Laboratory [EMBL], ESA, ESO, the European Synchrotron Radiation Facility [ESRF], the European Consortium for the Development of Fusion Energy [EUROfusion], Institut Laue–Langevin [ILL] and the European XFEL Free-Electron Laser Facility). These organisations have similar governance structures and serve a huge scientific community. As EIROforum, they support European science by sharing their experience, resources and facilities. Together, they interact with the European Commission, national governments, industry, science teachers, students and journalists. ESO chairs EIROforum from 1 July 2016 to 30 June 2017.

ESO has a considerable overlap of interests with ESA, Europe's leader in space research and technology, and with CERN, the pre-eminent centre for particle physics research. CERN and ESO share common interests in many technologies, and the potential for fruitful scientific collaboration is growing as the astroparticle and fundamental physics communities draw closer to astronomy. Joint ESO–ESA activities have been in place for a long time, including cross-allocation of observing time between the XMM/Newton X-ray observatory and the VLT, nightly VST monitoring of the position of

Figure 15. The garden of the Santiago Guesthouse.

the Gaia spacecraft, as well as ambitious public spectroscopic surveys such as Gaia-ESO, which have enhanced the tremendous impact of both Gaia and VLT.

From 1981 to 2010, ESO hosted the Space Telescope European Coordinating Facility, with which the ESO Science Archive Facility was jointly developed, and ESO continues to generate outreach material in support of the Hubble Space Telescope. The next generation of L(arge)- and M(edium)-class ESA missions will require even closer cooperation, since provision of supporting ground-based data is evolving from desirable to essential. An example is the crucial role of ground-based radial velocities for the transiting exoplanets that will be found by PLATO. The organisations also share a number of technology development goals, such as curved optical detectors, and high-speed, low-noise infrared detectors. ESO concluded two cooperation agreements, one with ESA in August 2015, which includes the exchange of observers for the relevant advisory bodies, and another one with CERN in December 2015, providing a framework for closer bilateral cooperation and exchange of information. ESA and CERN had previously concluded a bilateral agreement in March 2014.

The ESO–ESA and ESO–CERN agreements address scientific research, technology, and education and public outreach activities and promote the strategic coordination of the three organisations' long-term plans, as well as the coordination of scientific and training programmes. Both agreements encourage the coordination of services, tools and resources, in addition to the sharing of best practice in many areas. The organisation of joint seminars and workshops is another area of coordination, along with possible exchange of staff.

The Astronomy & Astrophysics (A&A) Journal is one of the leading astronomy publications. It was created in 1969 by combining a number of national journals. From the start, ESO has acted on behalf of the A&A Board of Directors in contractual matters and provides legal and administrative services, with the restriction that ESO does not commit itself to any direct financial sponsorship of the Journal, nor does it interfere in the scientific policy of the Journal. In return, ESO has one representative on the A&A Board of Directors. In view of the accession of numerous sponsoring bodies to the Journal, a renewal of the initial agreement between ESO and the sponsoring bodies became necessary in order to establish new terms and conditions for the continued publication of the Journal; the new agreement entered into force on 1 March 2016.

ESO collaborates with the International Astronomical Union (IAU) on topics related to outreach and supports the IAU web site. ESO is an observer on the United Nations Committee for the Peaceful Uses of Outer Space and is a member of the International Asteroid Warning Network which coordinates monitoring of potentially hazardous near-Earth objects.

ESO is also involved in various activities that aim to coordinate long-term planning of European astronomy and astroparticle physics through participation in the Optical Infrared Co-ordination Network for astronomy (OPTICON), RadioNet, ASTRONET and the Astroparticle Physics European Consortium (APPEC) networks. Several ESO staff hold European Research Council grants.

5.5 Outreach

ESO plays an important role in stimulating astronomical awareness through its education and outreach programme, which is coordinated closely with similar activities in the Member States. Outreach to the media and general public increases the visibility of, and support for, ESO and astronomy in the Member States and beyond. Harnessing the enduring appeal of astronomical discoveries can also draw young people into science and technology and contribute further to the efforts of the Member States in developing a technologically literate workforce, capable of meeting their future skill needs in a high-tech environment.

Public outreach tuned to the interests of the Chilean public and authorities is an essential component in the relationship between ESO and its Host State, giving visibility to the benefits that Chile's partnership with ESO has brought to the country's scientific development. It is also necessary to maintain ESO's identity among the major projects (for example, LSST and GMT) being built in Chile by other organisations.

The outreach activities will acquire an additional dimension in 2018 when the ESO Supernova Planetarium & Visitor Centre — a cutting-edge astronomy centre for the public, with free access — opens its doors. The heart of the ESO Supernova is a planetarium with state-of-the-art projection technology and a scientifically accurate three-dimensional astronomical database, ensuring a unique and authentic immersive experience. A large exhibition space and seminar rooms for interactive workshops provide the opportunity for ESO to become a leader in supporting and enhancing science education and literacy. Training workshops at the ESO Supernova Planetarium & Visitor Centre will inspire, and engage directly with, primary and secondary teachers from the Member States. ESO will provide key resources, encouraging teachers to interact with ESO's scientists and engineers, thereby fully exploiting the educational multiplier where teachers bring back their enthusiasm and knowledge to the classroom and thence to the tens to hundreds of pupils they teach each year.

The number of public weekend visitors to Paranal is approximately 8000 per year, and is expected to grow further when ELT construction activities ramp up on Armazones (and for CTA South). The current visitor centre is inadequate for this influx, and a new centre has been designed. There is no provision for construction funds in the long-term financial plan, but the hope is that external funding can be raised to realise this visitor centre in the near future. Activities are in train aimed at interesting (Chilean) philanthropists in this opportunity. Some of the content developed for the ESO Supernova Planetarium & Visitor Centre could be re-used here.

In the late 1990s, ESO and the municipality of Vitacura agreed to build an astronomy museum in the future Parque Bicentenario, close to the ESO premises. The park was established in 2007–11 and has become a popular recreational area for eastern Santiago. External funding to build and operate the museum would help ESO to honour its commitment and would provide the opportunity to promote astronomy and ESO at this optimal location.

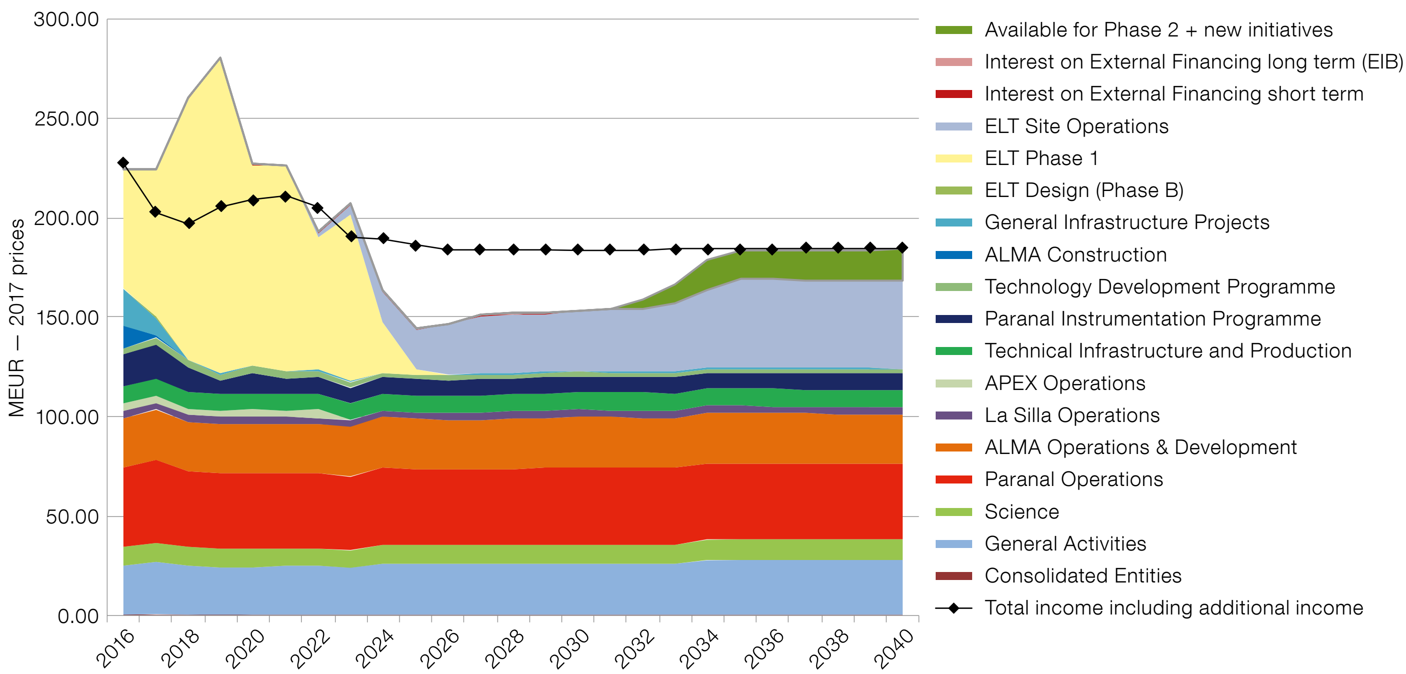
6. Financial planning

The baseline plan for the next 15 years assumes that ESO's income is provided by the 15 Member States, contributing according to the principles for funding the ELT programme approved by Council: a year-on-year 2 % increase in the contributions by the Member States, on top of normal indexation, starting in 2013 and continuing through 2022; an additional contribution of 268.5 MEUR (2017 prices) by the Member States in the period 2013–2022, spread over the ten-year period. This baseline plan does not include any contribution from Brazil or from new Member States.

The planning assumes the following boundary conditions on the overall programme:
- Only the construction of the Phase 1 ELT and its instruments is included;
- Paranal operations and instrumentation are fully protected;
- The ALMA contribution remains at the 2016 level (including development);
- La Silla income includes a stable contribution from partners for hosted telescopes;
- APEX participation continues through 2022;
- Participation in CTA is cost-neutral for ESO.

In addition, the following assumptions are made:
- The cost of the Phase 1 ELT, including contingency, is 1033 MEUR (2016 prices) with first light in 2024;
- The special organisational contribution to the CERN Pension Fund is set at 1.3 MCHF per annum for the entire period considered;

Figure 16. Expenditure and overall income for the period 2016–2040 in graphical form.



– The interest rates for borrowing and investment are at the European Investment Bank levels.

The assumed values of the exchange rates are based on long-term averages prior to the recent financial crisis. If the euro (EUR) does not recover as expected, then this will increase the pressure on the overall programme. The risk on the US dollar (USD) exchange rate has dropped considerably, as from 2017 onwards the ALMA on-site budget is no longer prepared in USD but in Chilean pesos (CLP). Hedging action in June 2016 made it possible to remove the risk on the CLP exchange rate for the ELT Dome & Telescope Structure contract, as well as for 50 % of the normal operations costs in CLP through 2023.

6.1 Income and expenditure

Figure 16 provides a graphical overview of the income and expenditure in the main budget lines to 2040 (in MEUR, 2017 prices). The regular income consists of the normal annual contributions, the remaining instalments of the special contributions from the Austrian and Polish accessions, and extra income from third parties.

The funding model for ELT construction was developed in 2008, and the specifics were approved by Council in 2011. Since that time, substantial additional costs have been absorbed through a series of measures, including staff reductions and termination of activities, the reduction of the period to calculate the average Swiss Franc (CHF) to EUR exchange rate for the contributions to the Pension Fund, a new Euro-based pension scheme for international staff joining ESO after 1 January 2014, the connection of both La Silla and Paranal to the Chilean electricity grid, and securing the exchange rate of the CLP. Nevertheless, in the baseline plan, building Phase 1 of the ELT with first light in 2024 will require taking up loans to cover the peak expenditure. They will be repaid without having to increase the regular contributions. Advance contributions by the Member States would lower the borrowing burden, and some Member States have already made such contributions.

Phase 2 of the ELT is not funded in the baseline plan. The required 110 MEUR will have to come from new Member States or collaborations with non-Member States, or, if all this were to fail, from the current Member States. Funding of the LTAO unit, which is the highest priority item, could be done by a slight increase in the above mentioned borrowing.

The accession of a new Member State in the near future is not unlikely. Should this occur, it would provide extra resources and hence reduce the risk on the overall programme. It would also lower the borrowing needs during the peak of ELT construction. Depending on the economic size of the new Member State(s), it might be possible to procure some elements of ELT Phase 2.

6.2 Budget lines

The long-term development of the main budget lines is summarised in Figure 16 and the items are summarised below.

Science activities continue at the current level with no major changes planned in the coming decade. There is no room for an expansion of the student and fellowship programmes. Education and outreach activities have been increased in order to provide services for the ESO Supernova Planetarium & Visitor Centre. However, the increase will be partly offset by additional income to be generated through fundraising, sponsorship and sales.

The cost of *La Silla Operations* has stabilised owing to the connection to the Chilean power grid and the construction of the photovoltaic plant.

The cost of *Paranal Operations* includes all operations effort in Chile and Garching for the VLT, VLTI, VISTA and VST. Site operations includes expenditure for avoiding obsolescence of critical components. The end-to-end operations remain stable.

Concerning the cost of *APEX Operations* until the end of 2022, ESO's share will increase from 27 % to 32 % in 2018. Additional investments are being made to enable APEX to continue through 2022 (section 3.2).

ESO's share of *ALMA Operations* is expected to remain at a stable level. The expenditure is no longer influenced directly by the EUR/USD exchange rate as the JAO budget is now set in Chilean Pesos. This budget line includes on-site operations by the JAO, off-site operations, the development programme and the ESO ALMA Support Centre.

The *Paranal Instrumentation Programme* is approaching a steady state in the coming years. The approved VLTI programme is nearing completion. The peak of effort associated with the completion of the entire second-generation instrumentation suite (including the AOF and ESPRESSO) will soon be over, allowing a transfer of effort to support the ELT whilst still providing cash and effort to support a healthy ongoing programme. The budget for the latter includes MOONS, ERIS and 4MOST, and will stay flat as of 2021.

The *Technology Development Programme* is set to be flat and will allow continuation of some in-house activities, hopefully matched by funding from external sources and by R&D activities in Member State institutions.

The *Technical Infrastructure and Production* line will also stay flat. This will allow the effective maintenance of the laboratories, workshops and integration halls required to carry out projects. Furthermore the budget will allow small R&D activities, prototyping and hands-on training required to align the skills of the staff to the needs of the ESO programme. This line includes the production of systems (for example detector controllers) funded from external sources.

General activities will remain flat over the years despite the expansion of the overall programme with ELT construction. They are subdivided into:
– Garching Headquarters and Santiago operations (maintenance of the various sites, the buildings, electricity, water and heating);
– IT Support and Communication;
– Management and Administration (services provided by the departments of Finance, Contracts & Procurements, and by Human Resources as well as the support of the Director General);
– Governing Bodies and Committees;

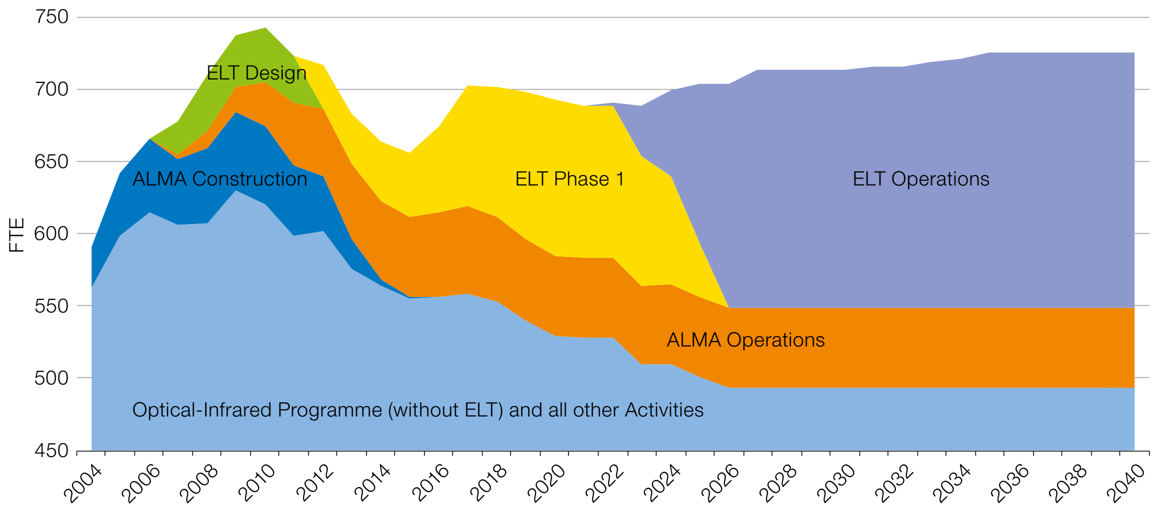


Figure 17. Development of staff complement over the period 2004–2040 focusing on ALMA and ELT. Note that staff numbers begin at 450 FTE.

– Centralised Personnel Budget, containing personnel costs not allocated to projects and activities.

ELT Construction commenced in 2013 with the start of work on the new road to Armazones and the preparation of the platform, together with the procurement of the adaptive M4 mirror. ELT Phase 1 construction is proceeding consistent with first light in 2024 (section 2.2). The spending profile is matched to the procurement schedule. Formally, construction is assumed to continue until 2027 to allow for final payments and the completion of warranty periods.

ELT Operations on-site, including off-site support, will begin in 2022 and ramp up to full operations as of 2027. The upgrade paths, which include the fourth instrument and beyond, will start ramping up from 2030. The slow ramp-up of operations funding and the delayed start of the upgrade paths are required to maintain the financing of Phase 1 with first light in 2024 and to limit the total amount of borrowing.

6.3 Staffing

The staff requirement consists of 440 international staff members and 160 local staff members. The former includes approximately 20 ESO staff members supporting ALMA on-site operations and 19 for APEX (until 2022). Approximately 90 further positions for ESO Fellows, PhD students, and paid and unpaid associates in Garching and Chile support the programmes and their related science. Figure 17 shows the evolution of staff numbers over the period 2004–2040.

7. Looking ahead

ESO's baseline programme supported by the 15 Member States is financially constrained, and does not allow delivery of the Phase 2 components of the ELT in a timely manner. It is therefore useful to summarise developments regarding potential new Member States. This section also considers the relationship with Chile, and describes opportunities in the longer term that are of interest to the astronomical community, and that would be compatible with ESO's mission.

7.1 Brazil and new Member States

The anticipated accession of Brazil has had a major positive influence on ESO, namely the approval of the ELT programme, but the slow progress towards ratification has resulted in challenges for the future, such as the funding of Phase 2 of the ELT, and the availability of sufficient operational funding to allow timely construction of MOSAIC, HIRES and EPICS. Brazil's membership would enable the ELT Phase 2 *in toto*, and would lower the amount of borrowing during ELT construction.

An important milestone for the ratification of the Brazilian Accession Agreement to ESO was reached on 14 May 2015, when the Brazilian Senate approved the ratification proposal. The only remaining steps to conclude the ratification procedure are the signature by the Brazilian President and the deposit of the instrument of accession at the French Ministry of Foreign Affairs. Owing to the political developments in Brazil in 2016, progress on the ratification has stalled. At the time of writing, the final signature by the Brazilian President is still pending. Efforts by Brazilian astronomers and press, supported by ESO, continue in order to further the ratification process.

Informal expressions of interest in a closer association with ESO have been received in past years from many countries, including Armenia, Australia, Canada, China, Hungary, Ireland, Israel, Mexico, Norway, Russia and Turkey. Some of them appear to be moving steadily towards a formal application to join, in particular Hungary, Ireland and Norway. A possible strategic cooperation with Australia is under discussion. Accession of new Member States would provide additional funding and could cover the cost of (part of) the ELT Phase 2, as long as the Council continued the long-standing tradition of adding the annual contribution and the special contribution of new Member States to the existing income.

7.2 Relation with and the role of Chile

ESO decided in 1963 to place its planned observatory in Chile, and the

Chilean government was immediately supportive by donating land for the Vitacura premises and for the La Silla Observatory. This was followed by donations for Paranal (1995), for ALMA (2004) and for Armazones (2011). The continued support of the Chilean government, together with the superb natural conditions and the commitment to preserve them, are the main reasons why all ESO observing facilities up to the present are in Chile. The Chilean government has also provided very helpful infrastructure, including paving the public B-710 road that runs through the Paranal area (Figure 7) and enabling the electrical grid connection to Paranal, as well as placing a photovoltaic plant on the La Silla land. It is committed to protect the extraordinary treasure of its clear and dark skies and fosters public appreciation of the night sky as a part of Chile's cultural heritage.

In return, ESO supports a number of activities in Chile, including reserving 10 % of the available observing time for Chilean proposals*. ESO provides funding for postdoctoral fellowships, technology development programmes, outreach and educational activities, conferences and other initiatives which help the growth of Chilean astronomy. In collaboration with Chilean government agencies and the other international observatories, ESO contributes to a joint Office for the Protection of the Quality of the Skies of Northern Chile. About 40 % of ESO's annual budget is spent in Chile, and ESO employs approximately 160 Chilean nationals.

The Chilean astronomical community has grown tremendously in size and quality in the past two decades. There are now astronomy departments at many universities across the country. Reserved access to observing time at world-class facilities has attracted many foreign astronomers to Chilean universities. The quality of proposals from Chilean institutions is nowadays on a par with those from ESO Member States, to the extent that they regularly win more than the reserved share. In the past few years there has also been a push to become involved in the more technical aspects of ESO's activities, including instrument development.

ESO also has an important role in Chile as a leading example of successful intercontinental co-operation between Europe and Latin America. ESO's activities in Chile are a focus of interest for the diplomatic missions and visiting European government representatives, building further support in the current and potential Member States.

The Council invited the Republic of Chile to become a Member State in 1995, but this invitation was declined. The topic was raised again in 2012 by the Chilean President Piñera. Both ESO and Chile have developed considerably over the past two decades, so it is timely to reexamine the arguments.

7.3 New opportunities

The ESO in the 2020s survey (Primas et al., 2015) demonstrated that the astronomical community in the Member States is very happy with what ESO offers, and would like ESO to provide additional facilities. One of these is a large (12–15-metre) optical/infrared telescope dedicated to wide-field spectroscopy which would provide a major step forward in the study of the Milky Way, following up on the Gaia mission, and the deep Universe, complementing imaging data obtained with LSST and the Euclid mission. Innovative designs are being developed. An ESO-led community working group analysed various options in 2015–16 and the conclusions are provided in their report[8]. Such a facility would cost approximately 400 MEUR and might be placed near Paranal, perhaps on La Montura, the mountain behind VISTA. There is interest from various parts of the world, including Australia, Canada and China, in this project, so a partnership could be investigated.

There is also considerable community interest in a large single-dish telescope to complement ALMA, which cannot efficiently study sufficiently large samples of galaxies across wide fields, and will not be able to map degree-scale filamentary Galactic structures in key diagnostic lines. A study, carried out in 2014–15 by another ESO-led community working group, compared various alternatives[9]. It concluded that a 40-metre single dish on the Chajnantor plateau, with a higher-accuracy surface in the inner 25 metres of the dish to enable work at 450 μm, would be the ideal successor to APEX. It would be equipped with panoramic array detectors both for interferometry and for rapid wide-area raster imaging, possibly with a multiplexed direct-detection spectrometer. Such a facility might cost approximately 300 MEUR. Teaming up with one or both of ESO's ALMA Partners should be investigated.

The construction of the ELT will allow the Paranal Observatory to continue to be the centrepiece of ESO's optical/infrared programme well into the 2030s. The STC Paranal White Paper[3] describes possible opportunities for instruments on the UTs driven by technologies that are currently under development. Another area examined was potential new ways of operating the UTs, in the timeframe 2025+, taking into account the plans for the ELT and its instrumentation. For example, pushing high-order adaptive optics into the blue wavelength regime on the UTs, or replicating instruments for the UTs to allow massive surveys on rapid timescales.

Any further expansion of ESO's programme can only come after a reduction of risks on the baseline programme and securing the funding for Phase 2 of the ELT. This expansion should be in line with ESO's mission, and could include participation in one or more of the projects mentioned above. It might also include a further strengthening of the VLTI, with, for example, additional (fixed) ATs and third-generation instrumentation, or an ESO contribution to the cost of site operations of CTA South, or a major upgrade of ALMA beyond the capacity of the development line in the ALMA operations budget.

8. The ESO model

ESO started with five Member States with the goal of building a 3-metre-class telescope in the southern hemisphere. This became the La Silla Observatory in Chile and put the fledgling Organisa-

* For the VLT, at least half of the reserved 10 % observing time should be for meritorious proposals in collaboration with astronomers in the ESO Member States; for the ELT this fraction is three-quarters.

tion on a par with a handful of similar observatories in the world. This was followed by the development of the VLT, ALMA and the ELT, involvement in APEX and now also CTA, accompanied by an expansion to 15 Member States, with more expected to join. The increased programmatic scope has made the Organisation attractive to countries and user communities that would not have considered ESO membership earlier. At the same time, ESO's programmatic expansion would not have been possible without the additional Member States. The two trends — more Member States and programme expansion — are thus inter-related and mutually reinforcing, and have enabled ESO and European astronomy to take the lead in many areas of astronomy. The VLT is the most advanced optical/infrared ground-based facility in the world, ALMA is a transformational radio interferometer and the ELT is on track to be the first and most powerful of the next generation of giant telescopes.

8.1 The keys to success

The ESO programme is carried out in strong partnership with the community. This includes joint development of instrumentation, where ESO works closely with institutions in the Member States that provide most of the staff effort in return for guaranteed-time observations. This model was developed soon after 1987 for the VLT instruments and has resulted in a strong and growing network of technical and scientific institutes capable of building very powerful instruments, not only for the VLT but also for the ELT. Further components of the partnership with the community are: an active and attractive student and fellowship programme; a steady flow of small and innovative telescopes and experiments on La Silla, supported by ESO's infrastructure; strong user support of ALMA with a key role for nodes in many of the Member States which are locally funded and provide much additional effort; and the Large Programmes and Public Surveys carried out by international teams who also produce advanced data products adding to the value of the SAF.

Over the past decades, ESO has developed the capability to carry out multiple projects in parallel. The presence of all these activities in one organisation allows: engineering skills to be re-used, benefiting from the lessons learned to work effectively with industry and community partners; testing of new technologies on ESO's own telescopes before applying them to the next-generation projects; and the maximisation of the scientific synergy between the facilities. It has led to significant cross-programme synergy and associated cost savings. This multi-project capability is the result of long-term support by the Member States and can be of value for other ground-based astronomy projects in a cost-effective way, provided the necessary funding is available.

The intergovernmental structure of the Organisation ensures support at the highest level in the Member States and in Chile. This contributes to budget stability and enables the long-term planning ability required for the development of world-leading telescopes. Having all Member States participating in all ESO's programmes is a key additional strength.

The annual contributions are in cash, and set by simple principles. The Organisation is trusted to run an effective industrial competition in the Member States for the procurement of the various components of the telescope systems, to agreed specifications enforced by ESO, aiming at a fair distribution over the Member States. This avoids the significant additional cost and challenges of Juste-Retour** or of one-off projects with a new governance structure and the strong wish that every partner contributes mostly in kind, including for operations.

A further key factor for ESO's development over the past decades is the strong motivation and commitment by all staff to deliver high-quality support and services to ensure the Observatories continue to be world-leading.

** Defined in the ESA Convention as: to ensure that all Member States participate in an equitable manner, having regard to their financial contribution.

8.2 Challenges

The health of the overall programme requires full implementation of the ELT funding principles as approved by Council on 6 December 2011. This means that the Member States need to provide the agreed additional contributions on top of regular indexation. Any future non-indexation of the income can only be absorbed by taking a larger loan or by cessation of core activities. Furthermore, it is important to secure the funding for Phase 2 of ELT construction in a timely manner, to reduce the cost of both construction and operations, to increase the scientific return and to bring additional instruments forward.

There are two additional financial risks. The first is that the steady-state operational model for ALMA becomes more expensive than anticipated. The first mitigation step would be to re-discuss with the ALMA partners the level of the off-site development line, which is part of the overall budget line for ALMA. The second risk is the possibility that CERN asks ESO to increase the special organisational contribution to the Pension Fund. It is assumed that the Member States would help ESO in resolving this situation, should it arise.

It is recognised that national budgets in the Member States are under pressure from many directions. Astronomy, and in particular the search for habitable exoplanets, excites many in the general public, and is a good vehicle to attract young people to engineering and the physical sciences, which in turn is critical for the continued well-being of our society. ESO's role in this may be considered an additional argument for continued support.

The multi-project capability developed by the Organisation in the past years must be used with care as it might be interpreted as the capability to do everything at the cost of the quality of the deliverables as well as the motivation of the staff. In addition, it is increasingly difficult to attract sufficiently qualified engineers and technicians from the Member States, as ESO is competing directly with very successful industries. This requires attention in terms of staff development and training and the evolution of the working conditions so as to ensure that ESO continues to be an attractive employer.

Finally, the growth in membership, which has enabled the expansion of the programme including external partnerships, has also increased the complexity of ESO's governance. While national representation is mandatory for Council and Finance Committee, it might be reconsidered for other governing and advisory bodies.

8.3 Strategy for the future

ESO's mission is to (continue to) operate and build world-class facilities enabling astronomical discoveries. This can be done from the ground at optical, infrared and radio wavelengths, and by detection of other messengers from the Universe, be they particles or gravitational waves. ESO's optical/infrared observatories were built by and are operated by ESO. The radio facilities APEX and ALMA are partnerships; ESO operates the former while ALMA is operated by a joint entity created by the ALMA Partnership. Potential new facilities can similarly be "all-ESO" or a partnership. The participation in CTA is an example where ESO will operate the site in Chile on behalf of the CTA Partnership.

It is clear that a moderate further growth in membership would secure Phase 2 of the ELT, and would be necessary for any further increase of the scope of the entire programme. Candidate Member States would be countries with high-quality scientific communities that are keen to join, provide added value, and have government support. ESO currently serves about 30 % of the world's astronomers so there is room for a gradual expansion while keeping a healthy scientific and technical competition with other major observatories.

Whether a new facility would be "all-ESO" or would be developed in a partnership depends on a number of factors. For ALMA the partnership approach was driven by the fact that the power of an interferometer scales proportionally to the square of the number of antennas. Building a larger array with a partner is therefore more cost-effective than building two smaller stand-alone arrays. A partnership may also be preferred when the partners each bring different critical expertise, or when it is the only way to raise the required funding. This could apply to the large single submillimetre dish or to the multi-object spectroscopic telescope mentioned earlier. In other cases, such as a further development of the VLTI, it would be natural to follow the "all-ESO" route.

9. Conclusions

In less than a decade from now, ESO will start operating the ELT, the world's largest optical/infrared telescope and most likely the only one with the ability to image Earth-like exoplanets. The ELT will be an integral part of the Paranal Observatory system, which includes the VLT and VLTI together with a very powerful arsenal of instruments. ALMA will continue to enable tremendous advances in our understanding of the birth of galaxies, stars and planets. Moreover, CTA will have opened a ground-based window on the high-energy Universe to regular observations with ESO operating the southern array in the Paranal area.

This programme implements the Council Resolution on Scientific Strategy of 2004, and in fact goes beyond it by maintaining the VLT as a world-leading instrument well into the next decade and adding CTA South to the programme. This is perfectly in line with ESO's mission, and can be carried out with the support of the 15 Member States, as long as the funding principles agreed by Council are implemented in full. While it may require borrowing during the peak of ELT construction, it will ensure ESO's undisputed leadership in ground-based astronomy into the next decades.

Accession of additional Member States will allow the timely completion of the ELT Phase 2, and with further instruments, which will enhance the scientific power of the ELT, lower its cost and so strengthen the entire programme further. It may also allow ESO to take on another programme soon after ELT construction is completed, and perhaps even a little earlier.

Acknowledgements

Many people contributed in large and small measure to these perspectives. To name them all would be to include a not-insubstantial fraction of ESO staff. In particular the ESO Directors — Rob Ivison (Science), Andreas Kaufer (Operations), Adrian Russell (Programmes), Michèle Peron (Engineering), Patrick Geeraert (Administration) — and the ELT Programme Manager, Roberto Tamai, provided the core of the document. Inputs by Renate Brunner, Mark Casali, Laura Comendador Frutos, Fernando Comerón, Roberto Gilmozzi, Nikolaj Gube, Douglas Pierce-Price, Michael Sterzik, Ewine van Dishoeck, Andrew Williams and Wolfgang Wild were also vital. The Scientific Technical Committee provided helpful feedback on an earlier version. Mafalda Martins and Jeremy Walsh are thanked for layout and editing.

References

Baltay, C. et al. 2012, The Messenger, 150, 34
Hatzminaoglou, E. et al. 2015, The Messenger, 162, 24
Primas, F. et al. 2015, The Messenger, 161, 6
Smartt, S. J. et al. 2013, The Messenger, 154, 50
Sterzik, M. et al. 2015, The Messenger, 162, 2
Woillez, J. et al. 2015, The Messenger, 162, 16

Links

1. Paranal Instrumentation Programme Plan (Cou-1681): https://www.eso.org/public/about-eso/committees/cou/cou-141st/external/Cou-1681_PIP_6-Month-Report_Sep-2016.pdf
2. Report from the VLT AO Community Days (STC-581): http://www.eso.org/public/about-eso/committees/stc/stc-88th/public/STC_581_VLT_AO_Community_Days_Report_88th_STC_Meeting.pdf
3. Paranal in the Era of the ELT (STC-515): https://www.eso.org/public/about-eso/committees/stc/stc-80th/public/STC-515.pdf
4. Report of the ESO Working Group on Science Data Management (STC-580): https://www.eso.org/public/about-eso/committees/stc/stc-88th/public/STC_580_Data_management_working_group_report_88th_STC_Meeting.pdf
5. Lessons Learned from ALMA Construction: https://www.eso.org/public/about-eso/committees/cou/cou-135th/external/ESO_ALMA_Construction_Lessons_Learned_public.pdf
6. High Level Organisational Structure: https://www.eso.org/public/archives/static/about-eso/organisation/eso-high-level-structure-2016.pdf
7. ESO Science Newsletter: http://www.eso.org/sci/publications/newsletter.html
8. Report of the Multi-Object Spectroscopy Working Group (STC-579): https://www.eso.org/public/about-eso/committees/stc/stc-88th/public/STC_579_MOS_WG_Report_88th_STC_Meeting.pdf
9. ESO Sub-millimetre Single Dish Scientific Working Group Report (STC-567): https://www.eso.org/public/about-eso/committees/stc/stc-87th/public/STC-567_ESO_Submm_Single_Dish_Scientific_Strategy_WG_Report_87th_STC_Mtg.pdf

Public ESO Council and STC documents can be found at: https://www.eso.org/public/about-eso/committees/

Appendix

Resolution approved by Council on 07–08 December 2004

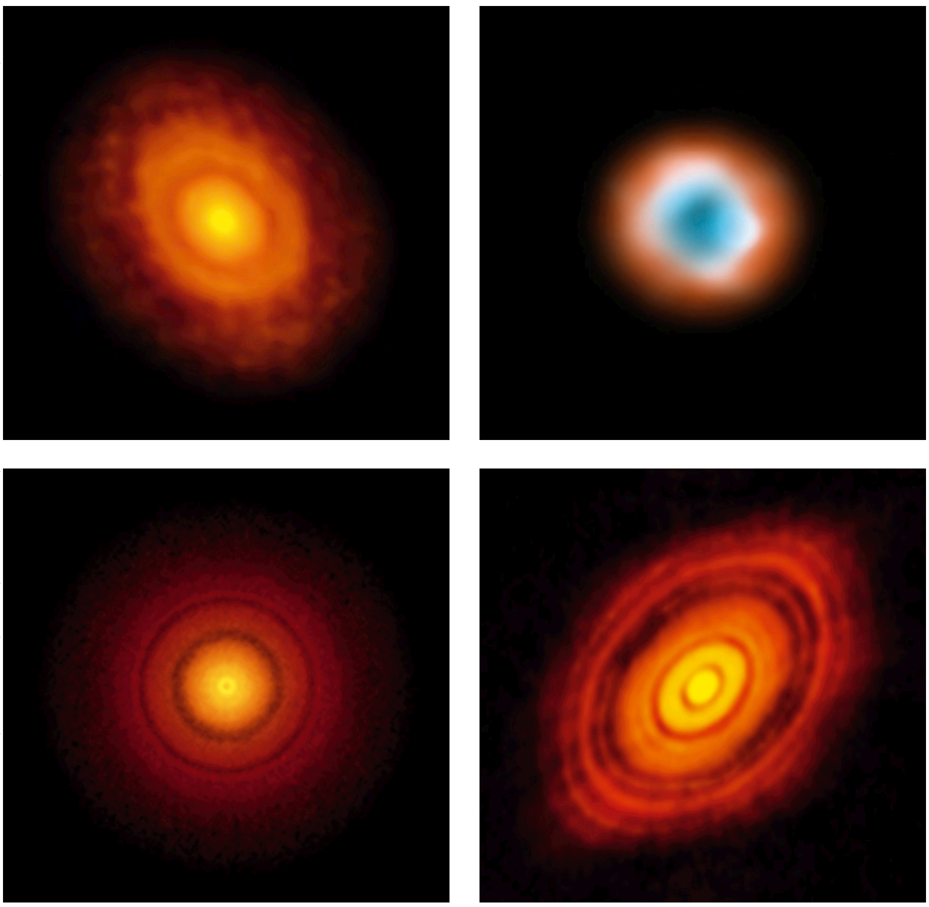
ESO Council, considering the report of its Working Group for Scientific Strategic Planning (Cou 990), and its recommendations, agrees that:

- Astronomy is in a golden age with new technologies and telescopes enabling an impressive series of fundamental discoveries in physics (e.g., dark matter, dark energy, supermassive black-holes, extrasolar planets)
- Over the last decade, the continued investment of ESO and its community into the improvement of ground-based astronomical facilities has finally allowed Europe to reach international competitiveness and leadership in ground-based astronomical research
- The prime goal of ESO is to secure this status by developing powerful facilities in order to enable important scientific discoveries in the future
- Only the continued investment in cutting edge technologies, telescopes, instruments and IT will enable such scientific leadership and discoveries
- ESO will continue to be open to new members and collaborations, following the principle of furthering scientific excellence

and accordingly adopts the following principles for its scientific strategy:

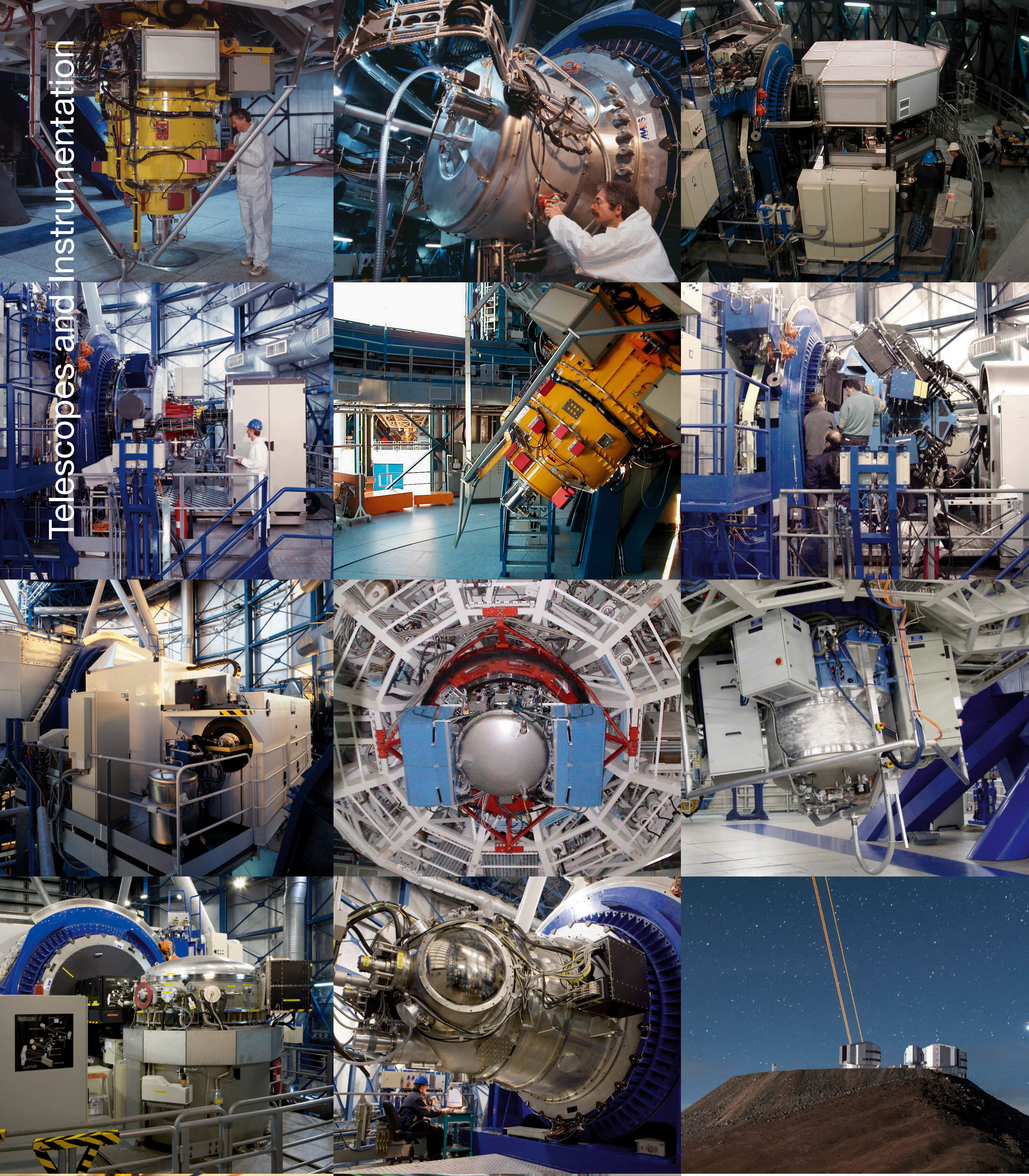
- ESO's highest priority strategic goal must be the European retention of astronomical leadership and excellence into the era of Extremely Large Telescopes by carefully balancing its investment in its most important programmes and projects
- The completion of ALMA is assured and conditions for an efficient exploitation of its superb scientific capabilities will be established
- The VLT will continue to receive effective operational support, regular upgrading (especially to keep it at the forefront in image quality through novel adaptive optics concepts) and efficient 2nd generation instrumentation in order to maintain its world-leading position for at least ten more years
- The unique capabilities of the VLTI will be exploited
- The construction of an Extremely Large Telescope on a competitive time scale will be addressed by radical strategic planning, especially with respect to the development of enabling technologies and the exploration of all options, including seeking additional funds, for fast implementation.

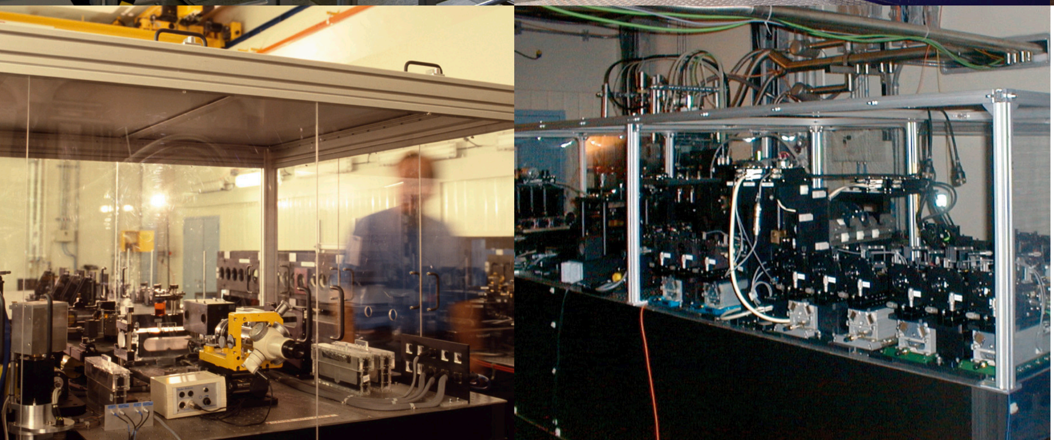
ESO and its community will continue their successful partnership and seek effective intercontinental collaborations in developing the most important and challenging technologies and facilities of the future.



ALMA (ESO/NAOJ/NRAO)/L. Cieza
ALMA (ESO/NAOJ/NRAO)
S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)
ALMA (ESO/NAOJ/NRAO)

Circumstellar discs with ALMA (left to right, top to bottom): V883 Oronis (1.4 mm); DoAr 44, (870 μm and ^{13}CO emission); TW Hydrae (870 μm); HL Tauri (1.3 mm).





Album of the VLT first-generation instruments: FORS1, ISAAC, UVES, NACO, FORS2, VIMOS, FLAMES, VISIR, SINFONI, CRIRES, HAWK-I (left to right, top to bottom); with the VLT shown in the lower right corner. The first-generation VLTI instruments MIDI and AMBER are shown lower left.

FORS1: ESO/H. Zodet
ISAAC: ESO/H. Zodet
FLAMES: ESO/H. H. Heyer
HAWK-I: ESO/H. H. Heyer
VLT: F. Kamphues/ESO

VLT/VLTI Second-Generation Instrumentation: Lessons Learned

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[1] ESO

The five second-generation instruments already delivered for the Very Large Telescope (VLT) represent worthy successors to the first generation of instrumentation development. Despite this success, it is still possible to learn many lessons for the future. A review, preceded by a workshop, on the lessons learned from the second-generation instrumentation for the VLT and VLT Interferometer took place in November 2015, following a previous review twelve years ago on lessons learned from the first-generation instruments. The aim of the workshop was to identify lessons in order to help define/refine good practice and make recommendations for the future. This article briefly reports on the workshop and summarises the findings of the review panel, their recommendations and some of the steps to implement them.

The five second-generation instruments already delivered for the VLT have been a great success and taken as a whole they represent a worthy successor to the first generation of instrumentation developed for the VLT. Despite this it is still possible to learn many lessons for the future. A review of the second-generation VLT/VLTI instrumentation lessons learned took place in Garching between 25 and 27 November 2015. The first two days of the review were in the form of a workshop, with the third day devoted to drafting the report. The aim of the workshop was to identify lessons to help define/refine good practice and to make recommendations for the future. The workshop focused on four main areas:
– interaction between partner institutes/consortia and ESO (both Europe and Chile);
– design, construction, test in Europe, shipment, integration, commissioning, verification on site;
– operational aspects, post-delivery support, maintenance, training, upgrades;
– overall cost, schedule and performance of each project.

Five second-generation instruments now in operation[1] were discussed: X-shooter (Vernet et al., 2011), KMOS (Sharples et al., 2013), MUSE (Bacon et al., 2010), SPHERE (Beuzit et al., 2008) and PIONIER (Le Bouquin et al., 2011).

The review panel consisted of a representative of the ESO Council (Christoffel Waelkens, vice-chair), Hans Van Winckel as representative of the ESO Scientific Technical Committee (STC), the chair of the STC at the time when much of the second-generation instrumentation was approved (Linda Tacconi) and two past directors of the Paranal Observatory — Roberto Gilmozzi, who acted as chair of the panel, and Jason Spyromilio. The panel was supported by a panel secretary (Fabio Biancat Marchet). This article summarises the findings of the panel, their recommendations and some of the steps already taken in response.

The workshop

Members of the consortia that built the instruments, as well as the ESO Project Managers (PMs), were invited to present their experiences and the collective input from their teams. The chair of the Users Committee (Stefano Covino) also presented input from the user community. Paranal instrumentation and Paranal science operations also made general and per-instrument presentations. The workshop was organised such that each instrument was presented separately and each round of presentations was followed by a round-table discussion involving all present. The meeting took place in a very collaborative and constructive spirit and the panel stressed that they had been particularly impressed with the openness of the workshop and the inter-consortium discussions.

The panel report, after summarising the sessions and the issues of interest for each instrument, details 26 lessons learned by the panel, from which 12 recommendations were distilled (i.e., not all lessons resulted in recommendations). A comparison between the recommendations resulting from the lessons learned from the VLT first-generation instrumentation and their implementation, during the time of the second-generation instrumentation, is included. The report ends with a number of instrument-specific lessons learned at Paranal, with recommendations to avoid recurrence in future projects. This article summarises aspects of the report and provides the community with a first reaction from the management of the ESO Programmes Directorate to the report.

Lessons learned and recommendations

The second-generation instruments arrived over a timespan of seven years, during which time several aspects of instrumentation procurement have evolved, in particular the implementation of the lessons learned from the first-generation instruments (see Monnet & Bacon, 2003). In addition, the second-generation instruments were developed in a variety of configurations: X-shooter was led by ESO with the support of external consortia; KMOS, MUSE and SPHERE were led by consortia with ESO supervision and support; while PIONIER was fully developed in the community and arrived at ESO as a visitor instrument first. On account of this variety, some of the lessons learned were specific to an instrument or mode of procurement rather than being general.

The following sections summarise the broad findings of the panel report.

Interaction between partner institutes/consortia and ESO

It is evident that ESO is playing various roles in the instrumentation programme: ESO is the contracting authority, the specifier of the programme, the provider of subsystems and the final client and operator. It was clear from the input by the consortia during the workshop that, while in some cases these roles have conflicting interests, ESO staff have been proactive in seeking solutions. The situation, however, has not been uniform, with some instruments being managed as formal agreements and others as if they were partnership agreements.

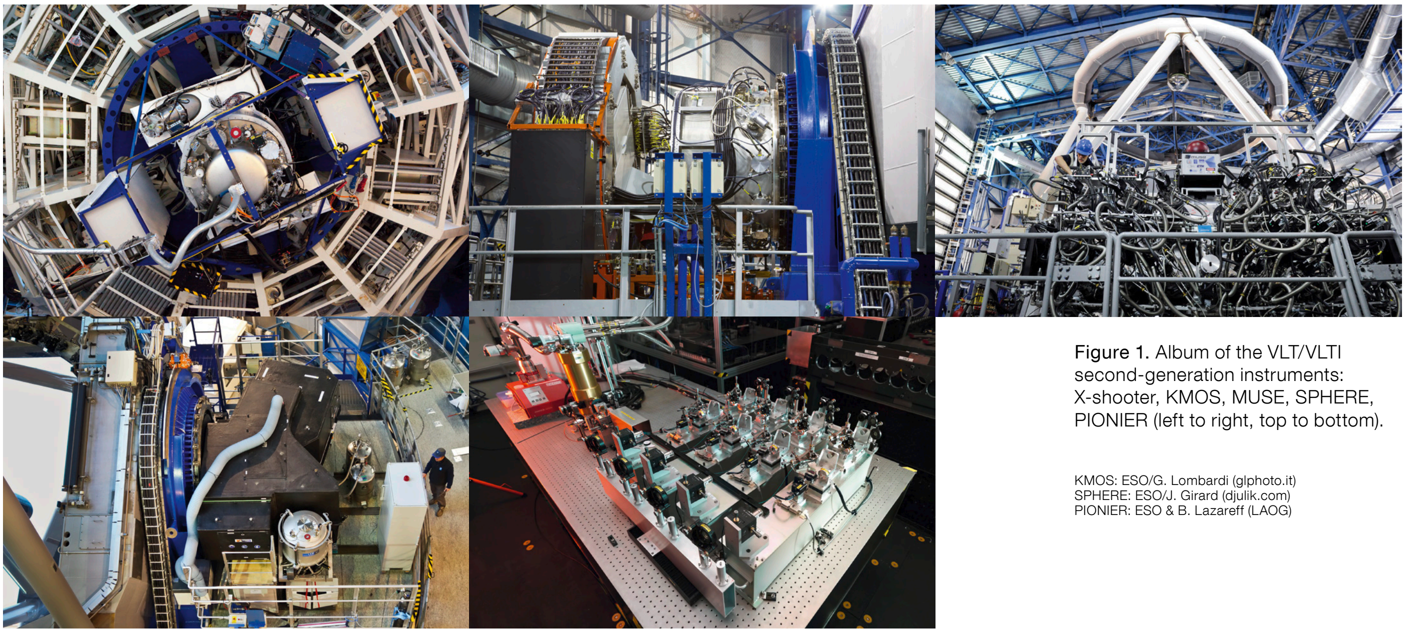

Figure 1. Album of the VLT/VLTI second-generation instruments: X-shooter, KMOS, MUSE, SPHERE, PIONIER (left to right, top to bottom).

KMOS: ESO/G. Lombardi (glphoto.it)
SPHERE: ESO/J. Girard (djulik.com)
PIONIER: ESO & B. Lazareff (LAOG)

As instruments increase in size, complexity and cost, the consortia that are created to build them also increase in size and complexity. This may be an unavoidable consequence of pressure from the community to be involved and a need for resources, both manpower and, in some cases, funds. The skills to manage such large consortia are not yet broadly available in the ground-based astronomical community.

The participation of ESO in the development of instruments was highlighted by the presenters as a key factor in their success, albeit with a request for a more structured input. The panel noted that the depth of ESO's expertise in optics, optomechanics, adaptive optics, software and detector systems was considered vital by the consortia, and, in general, greater involvement of ESO engineering staff is welcomed by both the ESO Project Managers and the consortia.

However, this greater involvement has clashed with the work within the Organisation. One of the main factors behind several reported problems was the limited ESO manpower available to cover unforeseen needs of the instrumentation projects. In particular, when the consortia wanted to include ESO technical and engineering expertise into their designs and development processes, this seemed to be addressed on a best effort basis. The panel recognised that, in order to mitigate this problem, ESO has adopted stricter planning and resource controls, and that VLT instruments, including those developed by external consortia, will continue to have an associated follow-up team internal to ESO.

ESO participation in consortium-led instruments sets a requirement for a clear separation between ESO as "customer" and ESO as "partner". In practice, since ESO the customer cannot find fault with ESO the supplier, complex issues arise.

As the operator, ESO maintains the authority and technical competence to guide the consortia in areas associated with operations, whether scientific or technical. ESO will need to retain the ability and credibility to guide consortia in technical matters associated with the development of new instruments. This issue will be exacerbated in the European Extremely Large Telescope (ELT) first-generation era, where ESO is not leading any of the instrumentation. Two recommendations explicitly addressed these aspects:

1. ESO should partner with the consortia in the development of instrumentation whenever possible. The customer–supplier relationship often hinders this process, and the context in which the development takes place should be reconsidered in light of the reports from the consortia.

2. If ESO is to provide support in the future, as it has done for the second-generation instrumentation, then it must retain the in-house expertise for managing and constructing large complex instrumentation, built according to the same rules that apply to external consortia.

In the course of the review, it was also noticed that the Instrument Science Teams (ISTs), the teams of scientists from the community who meet about once a year to provide input to the ESO instrument scientists on instrument development and requirements, had a limited role. On this topic the panel recommended that:

3. The ISTs for the second-generation instruments have had limited input and authority. Either the role should be abolished or strengthened with a direct mandate and resources.

Independent of the fate of ISTs, it seems good practice to regularly review (for instance at major design reviews) the instrument science cases and verify the validity of the original requirements and specifications.

ESO/ESO relationship

One important aspect of the organisation of projects is the relationship between the two ESO sites, at Garching and Paranal. This aspect is also addressed in the section below on Operations. It was clear that communication channels within ESO had not always operated correctly. The consortia and the ESO presenters indicated that sometimes Paranal had been presented with a *fait accompli* and often Garching had been unaware of the requirements and restrictions (operational implementations) on Paranal. The Garching-based presenters were found to be keen to bring the Paranal expertise into the projects at an earlier stage, while the Paranal experience was that input during the design was not always satisfactorily taken on board. The panel recommendation in this area was that:

1. Communications between Paranal and Garching should be evaluated institutionally and regularly.

Instrument development

This section covered a fairly broad range of aspects, including the use of development standards, the effectiveness of reviews, the timing of specific developments and the evolution of specifications.

There was general praise for the ESO software standards. The presence of engineers in the community with experience of the ESO software is sufficient that the software environment, despite its obvious age (e.g., the use of Tcl/Tk), is considered to be a good platform for the development of instruments.

The positive feeling towards ESO software was not, however, repeated with respect to hardware standards. The consortia have suffered the development of new ESO standards. In particular, but not exclusively, the area of motor controllers was generally felt not to have been a successful endeavour. The consortia pushed strongly for the adoption of industrial off-the-shelf solutions to replace custom ESO systems.

Modelling was used to varying degrees by the consortia. In all cases the advantages of modelling seemed to justify the investment. In some cases it was felt that additional modelling would have been useful, such as for specific cases (for example, thermal modelling), but this was not a global issue.

Early development of pipelines and software was not universally considered to be a useful endeavour. Indeed, the panel noted that, for some teams, early definition led to excess code being generated owing to unstable requirements, and to subsequent difficulties in finding resources by the time the requirements had stabilised.

It was noted that the Paranal science operations staff had not been sufficiently involved in the development process of instruments; Paranal's involvement in the analysis of problems arising during the construction phase of an instrument would help identify issues that could be critical to operations. The list of anomalies and the non-conformance reports should be provided to the project team and reviewed.

It was noted that occasionally reviews failed to catch design errors and not enough time was allocated to discussing issues in depth. Possibly a different format for the reviews (for example, preceded by in-depth engineering meetings) could address some of these issues. It was felt that the design reviews would be more effective if sufficient time were allocated for ESO engineering staff to actively, rather than superficially, engage in the proposed design and analysis.

Changes to specifications during the design phase were a cause of concern, disappointment and extra cost. It is apparent that management of the evolution of ESO standards is lacking. Some issues of obsolescence take a long time to address and the consortia felt that standards were only good when they were directly applicable.

The consortia presenters were unanimous in their praise of the spirit and working relationship that existed once they arrived at Paranal. The panel noted that, although the re-integration, installation and commissioning of the instruments is often a very intense and difficult period, there seemed to be consensus that for the second-generation instruments these were relatively smooth and successful activities. Much credit was given to the support on Paranal and the extensive Provisional Acceptance in Europe (PAE) process.

The panel recommendations in the area of instrument development were:

1. The instrument specific research and development (R&D), for example in the case of slicers, is currently part of instrument Phase A studies, which extends the time needed to build an instrument. ESO should, in collaboration with the community and with a strategic plan for instrumentation, fund more R&D independent of a specific instrument.

2. The final operator of instruments is Paranal and Paranal representatives should comprise a significant part of the executive authority in the reviews.

3. Evolution of the specifications takes place during development. Irrespective of the wisdom of this approach, if it is to continue then the existing procedures for configuration management (e.g., the timely and correct application of change requests [CREs], requests for waiver [RFWs], etc.) should be followed.

4. ESO, in collaboration with the instrumentation community, should determine and clarify the right level of standardisation and the management thereof.

Operations and post-operations

One important finding has been that, in general, neither the start of operations, nor the instrument acceptance in Chile, sees an end to the work needed by the instrument teams and Garching staff and the completion of the handover of an instrument to the Observatory. A longer involvement of the consortia, beyond installation, was considered to be necessary to complete the process. Also, time constraints make it difficult to implement a full training programme on Paranal and therefore the transfer of expertise from the consortium to the operations team on Paranal was often not satisfactory. This was considered a problem for both Paranal and the consortia, and it was felt that a follow-up by the consortium after handover would help to resolve this issue.

Much discussion focused around the pipelines. The input from the Users Committee was for more emphasis on improvements to the pipelines and documentation. The current agreements do not follow through with pipeline development into the period when improvements from the team and the community can be merged. It is clear that the area of instrument pipelines is one where development (rather than maintenance) beyond the start of operations is key to the success of the instrumentation and gaining the support of the community. In this case, as opposed to hardware and control software, it appears that the formal deliverables by the consortia are not always the products that ESO and its community would prefer. This has been an outstanding issue since the early days of the VLT programme.

The acceptance of the instrument into operation appears to be connected to the formal acceptance of the instrument. This creates obstacles to doing early science. The panel noted that Provisional Acceptance Chile (PAC) appears to have taken on a greater importance, at odds with earlier practices.

One specific point noted is ESO's limited ability to translate some operational aspects into clear requirements and specifications. This, in conjunction with the instrument builders' limited experience of Paranal operations, has produced some unnecessary tensions and duplication of work.

The panel recommendations concerning operations were:

1. The entire operation of the Observatory is complex, and changes that may appear, or even ought to be, trivial (e.g., component or instrument names) have an impact beyond what may be assumed. There appears to be much that is unwritten or unread. The earliest possible involvement in the instrument development by science operations, both from Garching and Paranal, is critical.

2. The "after-sales" period of the agreement (after start of operations/usage of GTO time, whichever comes first) needs more clarity. For complex instrumentation it may be advisable that technical staff of the consortium be seconded to Paranal for a period of time to improve the transfer of expertise and training.

Cost and schedule

The hardware costs of the instrument projects always turned out to be very close to the values originally estimated, so there was not much discussion on this at the workshop (apart from the cost impact of some of the issues discussed above). A common feature with the instruments presented was the occurrence of problems in the manufacture of one or more critical components. This impacted mostly on the project timeline. Several instruments had rather long development times, and were late, leading to an increase in the FTEs needed by the consortia. This cost was not born by ESO and was not part of the review. The general appreciation was that the quality of the instruments is satisfactory and nobody advocated a trade-off between quality and faster development.

A very special case was PIONIER, which was the culmination of a rather long R&D process at the Laboratoire d'Astrophysique de Grenoble (LAOG), but then resulted in a very cheap and fast instrument development. The PIONIER experience has shown that very fast, very cheap, specific-goal instruments are still possible.

The recommendations in the area of cost and scheduling were:

1. Faster instrument deployments, based on the PIONIER example, should be encouraged.

2. The availability of a visitor focus across the La Silla Paranal Observatory system is a functionality that should be present to enable novel instruments to be tested.

Additional findings

Guaranteed Time Observations (GTO) formed a large part of the discussion. It is evident that, with very large allocations of GTO time, the rules and procedures to ensure that both the wider community and the consortium get to exercise their rights of access to the instrument and the sky have not reached an equilibrium accepted by all parties. It was noted that the distribution of GTO and instruments on the VLT creates occasional anomalies that reduce the available open time to inadequate levels. The panel recommended that GTO time and target allocation should be subjects for a separate working group.

VLT first-generation instrumentation lessons learned

The follow-up of the previous lessons learned exercise (Monnet & Bacon, 2003) is an important check on the effectiveness of the process. The workshop panel analysed the extent to which the lessons learned from the first-generation instruments have been implemented, compared with the execution of the second-generation instruments, as described during the workshop. The analysis is summarised here.

Simpler instruments, fewer mechanisms and modes

This recommendation has not been followed and the second-generation instruments have, in general, become significantly more complex, encompassing more mechanisms and combining multiple modes. This seems, however, to be an unavoidable consequence of the need for higher performance, exploiting the available technologies to the limit. It is the opinion of the panel that this recommendation should be interpreted in the sense that unnecessary complexity should be avoided, and at least the complexity of the instruments should be reflected in a suitable organisation of the project, including commensurate managerial and technical resources.

More standardisation (for example, for cryo-vacuum systems)

This recommendation has been followed to a reasonable extent. Although, as described above, there have been flaws, it was the general opinion of the participants that the adoption of standards is beneficial, provided they are properly managed. The standards should refer as much as is feasible to solid and proven technologies, be kept up to date, and be communicated to the project teams.

Phase A studies to minimise technical/cost/schedule risk

Phase A studies are now routinely undertaken and are an unavoidable phase in the inception of a project.

Compact consortia

This recommendation has not in general been followed for the second-generation instruments. As with the first point above on simpler instruments, these are major undertakings both in terms of technical challenges and financial exposure, which can only be afforded by consortia with a large number of members. The emphasis should rather be on the proper management of large partnerships.

More ESO/consortium collaboration during development

It has been lamented by some consortia that the attitude of ESO was excessively client-like, and therefore this recommendation has not been completely followed and rather depended on ESO management. On the other hand, there is some pressure internal to ESO to have clean formal relationships.

Stricter provisional acceptance and PAE

For PAE, this recommendation has been followed in general, although with some exceptions.

More involvement of Paranal

During the development of the second-generation instruments, an effort has been made to ensure early and effective involvement of the Paranal staff in the projects. This, however, has been limited by operational priorities and the availability of manpower. When properly accomplished, the benefit for the projects has been evident and therefore the panel strongly recommends increasing such effort for the new projects.

More parallel interaction with the Data Management & Operations Division

An improvement in this interaction has been noted in respect of the second-generation instrumentation.

Increased possibility for early science

On account of their complexity, the second-generation instruments could not really follow this recommendation.

Implementing the lessons learned

Here we report on the reaction of the management of the ESO Programmes Directorate to the second-generation lessons-learned panel report.

Issues relating to the Paranal instrumentation programme

As noted by the panel, the delivery of the second-generation VLT/I instruments has been spread over some seven years, during which the development of instrumentation at ESO has gone through a significant evolution, with the creation of the Directorate of Programmes and the institution of an independent Paranal Instrumentation Programme (Pasquini et al., 2013). Some of the panel findings and recommendations have been (partially) implemented, or at least addressed, in this period, while some of the panel recommendations have triggered a prompt response, and we emphasise them in this section.

Much attention has been devoted to relationships with the consortia, which have evolved in the direction of partnerships, and ESO is now directly involved in all projects as a partner institute. At the same time, ESO remains the final client and must guarantee the performance of the instruments to the community and safely operate them for decades; this role cannot be delegated or removed. Nevertheless, the relationships have evolved towards a more collaborative status than pure customer–contractor, focusing on the common aim, which is the success of the projects. This collaborative attitude has been especially evident when major problems occurred, when ESO experts have directly supported the projects at a level beyond what was stipulated in the formal agreement. Some project control aspects have been improved, and a stricter Configuration Management (CRE, RFW, etc.) policy is in place, in order to fully evaluate the impact on the project of proposed changes in specifications or performance.

Paranal–Garching communications have been the subject of intense work over recent years. A tension was recognised quite some time ago, as communications became more and more critical for those projects which heavily impact the existing Observatory infrastructure — such as the Phase-Referenced Imaging and Micro-arcsecond Astrometry (PRIMA) instrument, the VLTI facility, GRAVITY, the Adaptive Optics Faciity (AOF) and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) instrument. In order to improve communications, several actions have been taken over the past few years:

- for all major projects it is now standard to temporarily transfer key people from Garching to Paranal for substantial parts of the project lifecycle;
- monthly coordination meetings are held between Paranal and the Instrumentation Programme management;
- a Change Request process is in place and projects need to have CREs submitted and “approved in principle” by Paranal before Provisional Design Review (PDR), and approved in their final form by the Final Design Review (FDR).

It is, however, clear that more effort is needed to improve the communications between the sites, as well as to make the process smoother for the consortia. Managing the relationship between Garching and Paranal, proactively planning and resolving problems, is a major part of the role of the Paranal Instrumentation Programme Engineer in Garching.

It is fully recognised that Paranal staff should continue to form part of the composition of review panels, but the concept of shared executive authority, as recommended by the panel, is not supported by the Programmes Directorate management. We believe that the right balance is achieved by keeping Paranal as the executive authority for all change requests to the infrastructure, whilst maintaining one executive authority with responsibility for the full project in the Paranal Instrumentation Programme.

The recommendation to guarantee strong support after the start of operations has triggered an immediate response: for the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE), Multi Unit Spectroscopic Exlorer (MUSE), AOF, GRAVITY and ESPRESSO, instrument experts have been (or will be) transferred to Paranal for several months after the handover. This will become a standard procedure for the future. These activities are being implemented in the Programmes Directorate's planning, by allocating programme resources beyond the start of operations.

The point about needing to retain in-house instrumentation expertise is fully agreed, and this is discussed further below. ESO has always led and implemented all instrument upgrades, although they can be developed in collaborations with consortia (for example, the CRyogenic high-resolution InfraRed Echelle Spectrograph upgrade, CRIRES+). Clearly ESO's involvement must be compatible with the resources needed to successfully develop and build the ELT and its instrumentation.

Pipelines and science data products have been an outstanding issue since the early days of the VLT programme. Specific projects (for example, MUSE, ESPRESSO and the 4-metre Multi-Object Spectrograph Telescope 4MOST) have agreed to produce science data products, but this is not standard for all instruments. Once science data products are delivered from the consortia, the long-term policy clearly becomes important.

The possibility of making a VLT focus permanently available for visitor instruments has been debated on several occasions and addressed in the Paranal Instrumentation Programme development plan (Pasquini et al., 2013). At that stage a permanently free focus was considered a waste of opportunity, and it was proposed to offer a VLT Cassegrain focus for visitor instruments, in conjunction with the CUBES spectrograph (which will be easy to dismount). Visitor instruments can in the meantime be proposed at any Call for Proposals for the New Technology Telescope (NTT), ESO 3.6-metre telescope and the VLTI. The updated plan, which includes the recommendations for decommissioning VLT instruments (STC-569[2]) foresees that, in about 2019, one Nasmyth focus may become free.

Issues of strategic importance

Two major issues of strategic importance, which transcend the Paranal Instrumentation Programme, came out of the review:

1. ESO's role in ELT instrumentation — both the management of ELT instrumentation and ESO's level of participation in ELT instrumentation;
2. Retaining and developing ESO's in-house expertise.

It is clear from the review that all instrument projects get into difficulties at some point, when it is expected that the Principal Investigator (PI) institute will take the lead in resolving the issues. However, it is also clear that the PI institute needs to be able to find at ESO the strength and depth that will fill holes in the consortium that the PI institute cannot. There is in fact a dual role for ESO — both as partner in the consortium (to fill known gaps as a member of the consortium at the start of the project) and to be able to assist in times of crisis.

ESO's role in ELT instrumentation

The request for ESO's continued involvement in instrument consortia is clear from the review. For the Paranal Instrumentation Programme, this is essentially an endorsement of the current philosophy. For the ELT, however, this will represent a change. It is now clear that ESO should increase its support of the instrument consortia on the ELT. In the first instance this effort should be targeted at the interfaces between the instruments and the telescope, since this is the most critical area. However, we need to be able to help the consortia in times of crisis in the same way as has been the tradition on the VLT. The ELT planning is being updated to meet this objective. Of course a critical issue will be the availability of funding and of key staff.

Retaining and developing ESO's in-house expertise

In order to retain the core skills in instrumentation and be able to develop the next generation of experts, three strategic objectives for ESO have been identified and are discussed in turn below.

1. Instrumentation leadership

With the complexity of modern instrumentation, consortia will continue to be the vehicle for delivery of major new instruments. ESO should continue to participate in the development of instrumentation, delivering major subsystems as a consortium partner, and should in addition have a goal of always leading one major instrument at any time. Presently ESO is leading two major instrumentation initiatives for Paranal — the AOF and the VLTI facility project to prepare for GRAVITY and the Multi-AperTure mid-Infrared SpectroScopic Experiment (MATISSE). Once these are completed, ESO should look to take a leadership role in another new instrument (either on the VLT or the ELT). Such a leadership role will of course depend on available resources, but it is viewed as fundamental to the long term retention and development of ESO staff.

2. Be world class in several areas of technology

One of the best ways to retain and develop experts is through ESO's role in technology development. The immediate r&D (small r, big D) focus should be on those areas which are needed by the ELT. ESO should be the spider at the centre of the web, providing leadership and (some) funding to influence the direction of the community (who will do big R and small d). For example, ESO will lead and facilitate the technology development needed to bring the ELT Planetary Camera/Spectrograph concept and technology readiness to the level needed to be able to start construction in 2019+.

ESO must have the in-house expertise to drive or facilitate the development of, and later be able to support, the instrumentation activities and the operation of the telescopes. Areas which ESO will target with the objective of being/continuing to be world class are, *inter alia*:
- detectors/controllers;
- adaptive optics (AO) technologies:
  - AO high-order deformable mirrors (DMs);
  - wavefront sensor (WFS) cameras;
  - real-time control (RTC) systems;
  - laser systems;
- wavefront control, phasing and metrology;
- interferometry.

In addition, ESO will continue to develop its expertise in project management, instrument systems engineering and ultra-high-contrast imaging.

3. Retain the basic skills for instrumentation in all disciplines

Finally, ESO should pursue a balance in its overall work to ensure that all the basic skills for instrumentation are retained. This means that the choice of subsystems that ESO delivers to consortia should be cognisant not only of the availability of effort, but of the need to retain core skills. In the short term, ESO will build the ELT Commissioning Test Camera. Although it is a commissioning camera, with no science capability, it will require the full suite of core instrumentation skills. The timing of this work (no significant effort before 2019) is consistent with not increasing the overheating of the current programme.

References

Bacon, R. et al. 2010, Proc. SPIE, 7735, 7735E08B
Beuzit, J.-L. et al. 2008, Proc. SPIE, 7014, 701418
Le Bouquin, J.-B. et al. 2011, A&A, 535, A67
Monnet, G. & Bacon, R. 2003, The Messenger, 113, 10
Pasquini, L., Casali, M. & Russell, A. 2013, The Messenger, 154, 2
Sharples, R. et al. 2013, The Messenger, 151, 21
Vernet, J. et al. 2011, A&A, 536A, 105

Links

[1] List of all VLT/VLTI instruments: http://www.eso.org/sci/facilities/paranal/instruments.html
[2] STC-569 VLT instrument decommissioning guidelines: http://www.eso.org/public/about-eso/committees/stc/stc-87th/public/STC_569_Guidelines_for_decommissioning_of_VLT_instruments_87th_STC_Mtg.pdf

The four Unit Telescopes and three of the Auxilliary Telescopes of the VLT on Paranal.

Science-Grade Imaging Data for HAWK-I, VIMOS, and VIRCAM: The ESO–UK Pipeline Collaboration

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A new chapter for ESO science-grade data has begun with the implementation of three new pipelines developed for the HAWK-I, VIMOS and VIRCAM instruments. The HAWK-I and VIMOS image archives at ESO have been completely reprocessed using these new pipelines, and these data are now publicly available. This article introduces the work done to bring these pipelines to the level of science-grade, their use in reprocessing ESO archival data, and their dissemination into ESO science operations and to the ESO community.

In early 2012, a project was started with the Cambridge Astronomical Survey Unit (CASU), at the University of Cambridge, to make significant improvements to a number of ESO data processing pipelines. The goal was to develop state-of-the-art pipelines that can deliver science-grade data for the High Acuity Wide-field *K*-band Imager (HAWK-I), the Visible and Infrared Survey Telescope for Astronomy (VISTA) IR Camera (VIRCAM) and the VIsible Multi Object Spectrograph (VIMOS) imaging, and to use these pipelines to reprocess the entire HAWK-I and VIMOS (imaging) archives.

Expertise within CASU covers a broad range of ground-based and space-based projects ranging from data processing and image analysis techniques, through to data curation and access to UK facility data archives. Modern-era wide-field digital surveys produce vast amounts of data and CASU is at the forefront of automatically processing and archiving these legacy products. Data processed by CASU include all of the public surveys being carried out at the VISTA telescope (Emerson et al., 2006), some surveys from the Very Large Telescope (VLT) Survey Telescope (VST), the European Space Agency Gaia and Planck surveys, the Isaac Newton Telescope (INT) wide-field survey and the UK Infrared Telescope (UKIRT) infrared deep sky survey, to name but a few.

The ESO–UK project has now passed its final review. The deliverables have included three new pipelines for VIRCAM, VIMOS imaging, and HAWK-I, along with the associated Reflex[1] workflows that will allow an individual user to run these pipelines. Also included are the pipeline manuals and the tutorials for the Reflex workflows. Further, CASU has used these new pipelines to reprocess the HAWK-I and VIMOS imaging archives. They have delivered all of the pipeline products (science and calibration) from April 2008 to October 2015 for HAWK-I and from April 2003 to the end of 2015 for VIMOS. All these high-level science-grade images are now publicly available via the Phase 3 interface to the ESO Science Archive Facility (SAF[2]).

The project

CASU's first involvement with software at ESO was its delivery of an operational pipeline for the VISTA/VIRCAM imager in 2008. This pipeline is currently in operational use on Paranal and by Garching quality control (QC[3]), not to provide science-grade data but to quickly assess the quality of the observations and the health of the instrument. However, much of the functionality available to the VIRCAM pipeline currently used by CASU to process the data from the VISTA public surveys does not exist in the operational version.

The consortium agreed to upgrade the ESO operational pipeline to a level of sophistication equivalent to that used by CASU to process the data from the public surveys. In essence, CASU would improve on the ESO VIRCAM pipeline so that the data produced is science-grade, with de-striping across multiple detectors, advanced sky correction, on-field astrometric and photometric calibration, creation of source catalogues, and an optimised combination of multiple dithered images into tiles. According to the original agreement, this effort was also to be extended to the creation of completely new pipelines for HAWK-I and the VIMOS imager with pipeline routines to be written to ESO's Common Pipeline Library (CPL). Finally, once the new HAWK-I and VIMOS pipelines were completed, they were to be used to reprocess all of the data from these two instruments stored in the SAF to the end of 2015.

Using the VIRCAM pipeline as the starting point of the collaboration, ESO and CASU worked towards improving it, and adapting its modules to the peculiarities of the HAWK-I and VIMOS instruments. Among these improvements is the computation of an error budget through each stage of the data processing. Each pipeline, each Reflex workflow, and all of the reprocessed data submitted have been intensively tested at ESO and CASU.

The pipelines

All three pipelines offer significant improvements over those currently in ESO operation, and have been thoroughly tested to ensure that they deliver science-grade products. A major improvement in the new pipelines is that they combine dithered images to deliver tiles (HAWK-I and VIRCAM) or image stacks (VIMOS). The images are astrometrically and photometrically calibrated using catalogue standard stars in the field of the science exposure. This is a significant improvement as it allows images to be calibrated even when photometric conditions are less than ideal. Of course, the pipelines can also process dedicated standard star fields for instrument quality control and site monitoring, and for the cases in which the science fields do not contain catalogue sources.

To date, the calibration plan for HAWK-I was to observe a single standard star sequentially in each of its four detectors. With the new HAWK-I pipeline this very inefficient observing mode will be supplanted by observations of dedicated Two Micron All-Sky Survey (2MASS) touchstone fields. Not only is this a four-fold improvement in observing efficiency, but the multiplicity of stars observed (some fields have more than 1300 2MASS stars within the field-of-view of HAWK-I) will greatly improve the photometry statistics.

The relative astrometric accuracy achieved is about 0.3 arcseconds root mean square (RMS) for HAWK-I and 0.4 arcseconds RMS for VIMOS (see below for an analysis of the reprocessed archive data). This is at least a five-fold improvement over the current pipelines, which simply rely on the world coordinates written by the telescope and have no astrometric correction routines.

Further pipeline improvements include a de-striping routine to detect and remove the pick-up noise across the rows of the VIRCAM detectors, a master twilight flat routine that is significantly faster than what is currently available in the HAWK-I pipeline, a sophisticated sky background correction routine that can chose from a number of sky correction algorithms based on the type of science observation, and a fringe correction routine for VIMOS. The latter improvement is particularly relevant for data obtained with the *I*- and *z*-band filters using the old VIMOS detectors.

A comparison between several hundred HAWK-I images in the SAF and their counterparts processed with the new pipeline has revealed that improvements in the flat-fielding and sky background correction reduced the background standard deviation by, on average, 20%. This improvement is visually evident in Figure 1.

Throughout the entire data reduction cascade, the new pipelines also compute an error budget that is saved as a variance map associated with the final science products. This can act as a useful diagnostic when comparing the actual image noise statistics to these computed values. The image stacks and tiles produced by the pipelines also include confidence maps.

Each pipeline product generated includes a comprehensive number of quality control parameters, useful to the operational monitoring of these instruments, and culminating in science product parameters, such as average stellar image full width at half maximum (FWHM) and ellipticity, limiting magnitude and sky background brightness, to name but a few. The image stacks and tiles culminate in source extraction catalogues that include 62 scientifically useful parameters, including a number of flux measures, a series of 13 aperture fluxes stepped through a progression of radii, object classification and statistics.

It is fortuitous that HAWK-I now has a new and vastly improved pipeline since the Adaptive Optics Facility (AOF) and the GRound layer Adaptive optics Assisted by Lasers (GRAAL) are expected to begin commissioning in early 2017 (see Arsenault et al., 2016). This four-laser guide star system and deformable secondary mirror, will provide HAWK-I with almost space-based observatory image quality. The new HAWK-I pipeline will be needed to assess the performance of the AOF and GRAAL during commissioning, and to provide science products worthy of the expected image quality.

The Reflex pipeline workflows

In order to make the new pipelines readily accessible to the entire ESO community, the CASU team has integrated them into the Reflex workflow environment (Freudling et al., 2013). The Reflex workflows allow the user to gain an immediate and intuitive understanding of the structure, flow and products produced by these complex pipelines. The workflows delivered by CASU are state-of-the-art in terms of their multi-level interactive actors and in the large number of ways by which a user can modify the underlying process and adapt it for use with the peculiarities of their data. For example, when running the HAWK-I Reflex workflow, the user can conveniently modify 46 individual pipeline parameters, and is presented with interactive product plots and diagnostics to optimise the science results.

These new Reflex workflows will be made publicly available following the April 2017 pipeline release[4]. They will include the Reflex workflow and its underlying pipeline, a workflow specific tutorial, and a demonstration data set that can be processed right out of the box. A screen capture of the HAWK-I Reflex workflow is shown in Figure 2.

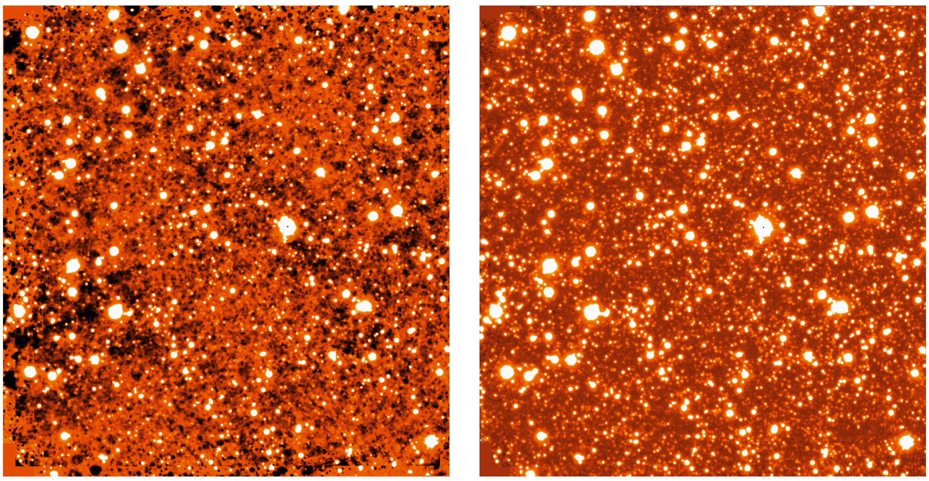


Figure 1. A comparison of a field processed with the current ESO HAWK-I pipeline (left panel) and with the new HAWK-I pipeline (right panel). The improvements in the twilight flat fields and in the sky background subtraction are evident in the new pipeline.

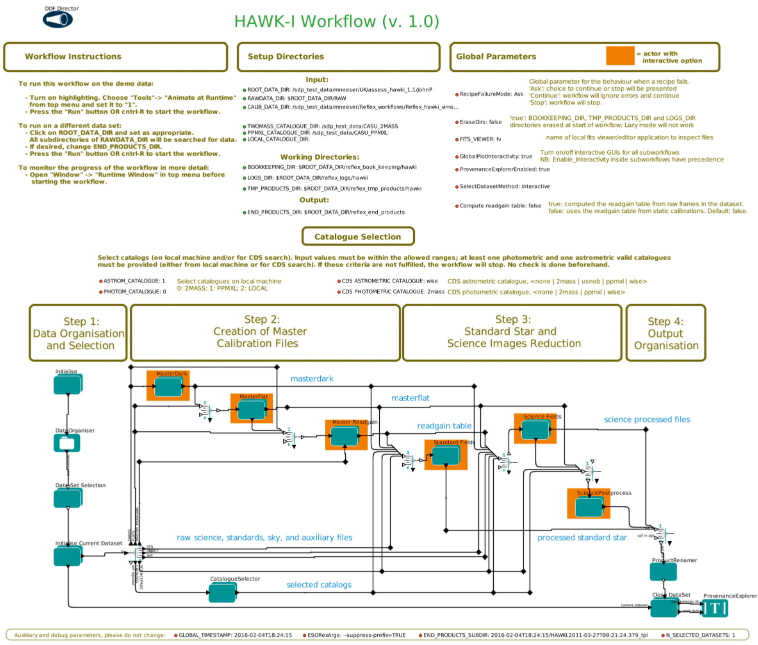


Figure 2. Screenshot of the Reflex workflow for the HAWK-I pipeline. Similar workflows also exist for the VIMOS imaging and VIRCAM pipelines.

HAWK-I and VIMOS imaging archive reprocessing

The CASU team has reprocessed the complete ESO image archives for HAWK-I (almost eight years of data) and VIMOS (12 years of data) using the new pipelines. Spanning the observing Periods P81 to P96, the more than 40 000 HAWK-I science frames consist of:
- stacked jittered images of the individual exposures at the detector level;
- variance arrays for the stacks;
- confidence maps for the stacks;
- source catalogues for the stacks;
- fully tiled images of all of the individual exposures;
- variance arrays for the tiles;
- confidence maps for the tiles;
- source catalogues for the tiles.

Spanning the Periods P71 to P96, the more than 37 000 VIMOS science frames consist of:
- stacked jittered images of the individual exposures at the detector level;
- variance arrays for the stacks;
- confidence maps for the stacks;
- source catalogues for the stacks.

Along with these science products, the CASU team has also delivered all of the master calibration frames (including the standard star fields and their source catalogues) used to process these data. The combined 5.1 Tb of reprocessed science data and 4.3 Tb of master calibrations are a significant contribution to the ESO science and calibration archives.

The challenge in processing these data lay in the tremendous inhomogeneity of the HAWK-I and VIMOS raw data. The data consisted of 290 and 456 unique observing programmes for HAWK-I and VIMOS, respectively, containing observations from many different projects and surveys, using various filters and observing methods. A summary of the statistics related to the science data from the archive reprocessing is given in Table 1.

To determine the overall astrometric quality of the images, a source-by-source match was made between all of the HAWK-I and VIMOS object catalogues and the 2MASS catalogue. The astrometric solutions are generally good to 300 milli-arcseconds, with no discernible systematic residuals; however, because some projects used defocused images, some images can give significantly worse solutions with residuals as large as 500 milli-arcseconds.

Similarly, a photometric comparison was made between the sources in the HAWK-I object catalogues and the 2MASS catalogue. This comparison was done using all of the 11 available HAWK-I filters (including the narrow-band filters). It was found that 82.4 % of sources have magnitude differences of less than 0.1 mag. (92.3 % have $|\Delta m| < 0.2$ magnitudes).

For both the astrometric and photometric quality, it is apparent that these results are slightly worse than the internal errors of the 2MASS catalogue (Skrutskie et al., 2006). The slightly larger mean internal RMS can be explained by the fact that the bright catalogue stars are invariably saturated in the HAWK-I and VIMOS images and therefore only the fainter, less reliable, catalogue stars are available for calibration. Also, a better photometric result can be achieved by limiting the matching to the core broad-band HAWK-I filters. These astrometric and photometric comparisons are summarised in Table 2 and in Figures 3 and 4.

	HAWK-I	VIMOS
Time span	April 2008 to October 2015	April 2003 to August 2015
Number of unique programmes	290	456
Number of raw science images	86 054	79 947
Number of delivered science products	40 552	37 168
Volume of science data products (Tb)	3.24	1.85
Non-contiguous sky coverage (square degrees)*	102.4	501.8
Number of detected sources†	19.1×10^6	150.6×10^6

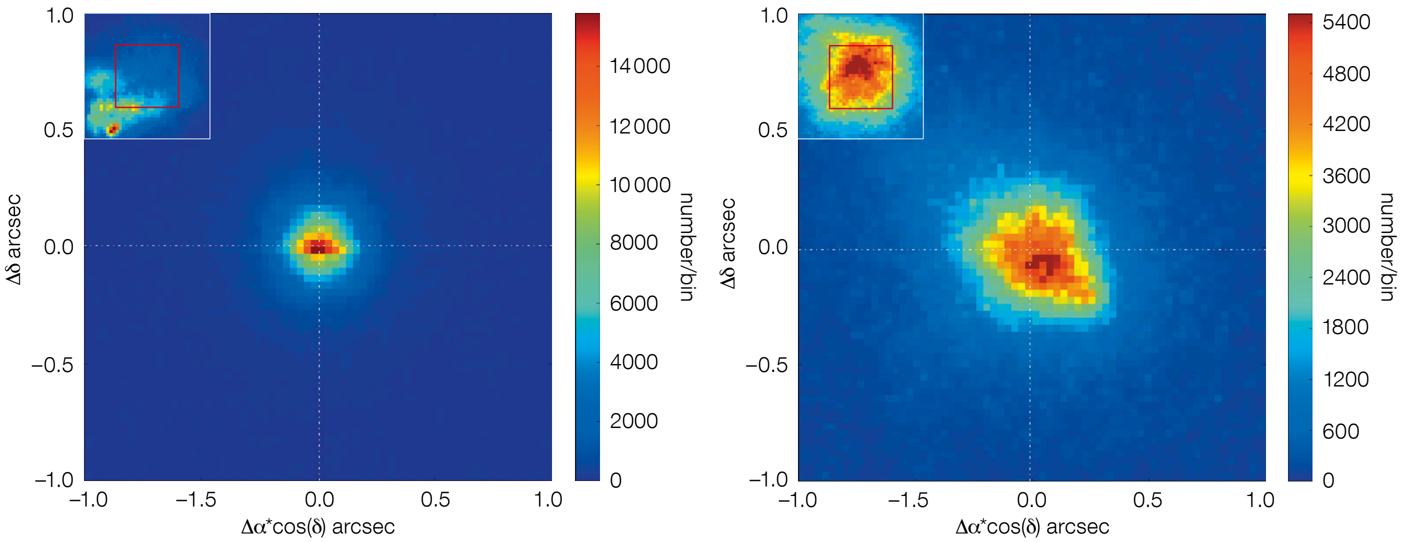
Table 1. Phase 3 statistics for HAWK-I and VIMOS science reprocessing.

* Computed from the sum of the area occupied by all HAWK-I tiles and VIMOS stacks.
† Sum of sources contained in all of the catalogues.

Table 2. Summary of the astrometric and photometric accuracies resulting from matching the HAWK-I tile source lists with the Wide-field Infrared Survey Explorer (WISE) and 2MASS catalogues, and the VIMOS stack source lists with the PPMXL catalogue (Roeser et al., 2010) and the American Association of Variable Star Observers (AAVSO) Photometric All-Sky Survey (APASS) catalogue.

	HAWK-I	VIMOS
Median Δα x cos(δ) (arcseconds)	0.006 +/− 0.3	0.000 +/− 0.4
Median Δδ (arcseconds)	0.008 +/− 0.3	−0.018 +/− 0.4
Median Δmag (mag)	0.003 +/− 0.2	0.02 +/− 0.3

Figure 3 (below). The astrometric quality of the HAWK-I reprocessed tiles (left panel) and VIMOS stacks (right panel). The HAWK-I source lists have been compared with the 2MASS catalogue and the VIMOS source lists with the PPMXL catalogue. The standard deviation of the Δα∗cos(δ) and Δδ distribution is 0.3 arcseconds for HAWK-I and 0.4 arcseconds for VIMOS. The same plots for data from the old pipelines are shown as insets, where the scale of the insets is two times greater (4 arcseconds per side) to accommodate the standard deviation of the Δα∗cos(δ) and Δδ distributions of > 1.7 arcseconds. The relative sizes of the new pipeline distributions are shown as red squares in the insets.



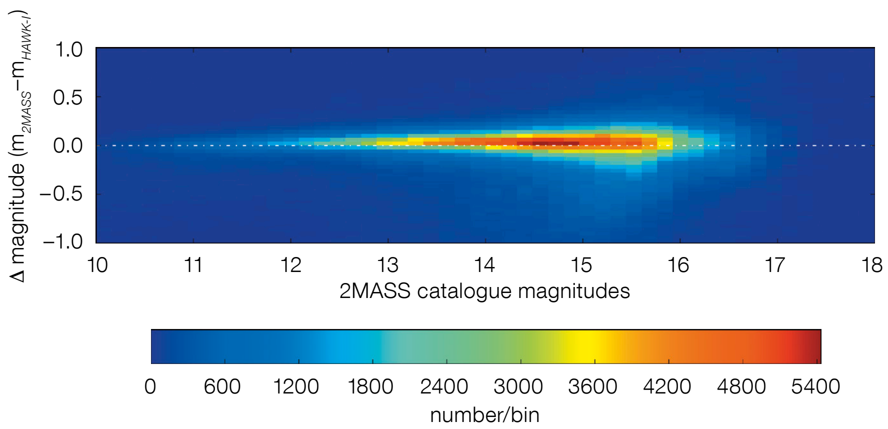


Figure 4 (right). A magnitude–Δmagnitude density plot showing the photometric quality of the HAWK-I source catalogues. The data are derived from sources in all 11 filters from reprocessed HAWK-I tiles matched with 2MASS catalogue stars. The standard deviation of the magnitude difference distribution is 0.2 magnitudes, with 82.4% of sources having |Δm| < 0.1 magnitudes.

Conclusions and access to products

The collaboration between ESO and CASU has been very positive and has provided ESO and its community with three state-of-the-art pipelines, three Reflex workflows, and a significant upgrade to the HAWK-I and VIMOS science archives. The success of this collaboration was due, in part, to intensive interactions on testing the pipelines, Reflex workflows and archive reprocessing at many intermediate steps and not only on the delivered products.

The design, testing, and data processing were always done from the perspective of an astronomer. For the Reflex workflows this meant that only the most relevant pipeline products and modifiable pipeline parameters are presented to the user, and that the default parameters are as close to their optimum as possible. For the archive reprocessing, this means that the data are as close to science grade as possible, irrespective of the scientific goals of the original programme; some example images are shown in the Appendix (Figures X.1 to X.4). As a concrete example, the archive reprocessing revealed about 2100 raw HAWK-I and VIMOS images with erroneous world coordinate headers. With considerable effort, the correct image pointings were deduced and the raw frame world coordinate headers were corrected. These corrected raw files have been re-ingested into the ESO SAF.

The new pipelines are now ready for operation and are being implemented by the quality control group in Garching and at the telescopes in Paranal. The intention is that ESO will continue to populate the Phase 3 science archive for HAWK-I and VIMOS where CASU has left off.

The reprocessed HAWK-I and VIMOS image archives are now publicly available via the ESO Phase 3 archive[2] or via the archive news release[5]. For individual pipeline users, the HAWK-I, VIMOS, and VIRCAM Reflex workflows and their associated tutorials can be downloaded from the Reflex webpage following the April 2017 release[1].

References

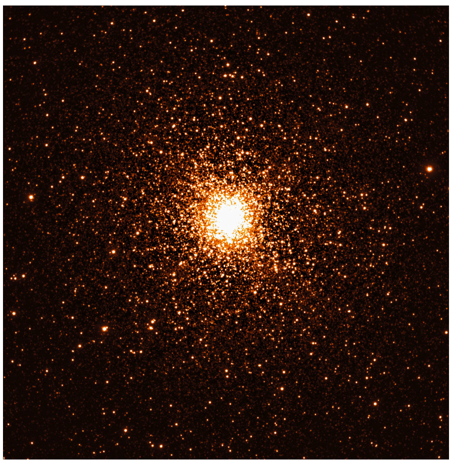
Arsenault, R. et al. 2016, The Messenger, 164, 2
Emerson, J., McPherson, A. & Sutherland, W. 2006, The Messenger, 126, 41
Freudling, W. et al. 2013, A&A, 559, A96
Roeser, S., Demleitner, M. & Schilbach, E. 2010, AJ, 139, 2440
Skrutskie, M. F. et al. 2006, AJ, 131, 1163

Links

[1] ESO Reflex pipeline workflow environment: http://www.eso.org/sci/software/reflex
[2] ESO Science Archive Facility: http://archive.eso.org/cms.html
[3] VLT Quality Control: http://www.eso.org/observing/dfo/quality/
[4] Instrument pipelines and manuals: http://www.eso.org/sci/software/pipelines/index.html
[5] Archive news release: http://archive.eso.org/cms/eso-archive-news/Release-of-pipeline-processed-HAWK-I-images-as-part-of-the-UK-in-kind-reprocessing-project.html

Appendix

A number of HAWK-I and VIMOS example images from the archive reprocessing are shown to exemplify the quality of the delivered pipelines. It is important to note that these images are created using unaltered archive science data products. Other than a scaling of intensities and cropping, no other manipulation of the images was performed, attesting to the quality of these science pipeline products.



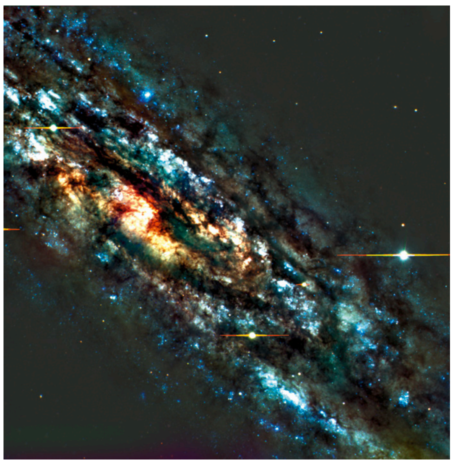


Figure X.1 (upper left). Composite HAWK-I *Y*-, *J*- and *H*-band colour tile of the spiral galaxy NGC 1232.

Figure X.2 (upper right). Composite HAWK-I *J*-, *H*- and *Ks*-band colour tile of the globular cluster NGC 1261.

Figure X.3 (bottom left). Single *R*-band VIMOS image of the globular cluster NGC 2808.

Figure X.4 (bottom right). Composite VIMOS *U*-, *B*- and *V*-band colour image of the southwest area of the spiral galaxy NGC 253.

Stereo-SCIDAR: Instrument and First Commissioning Results

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The vertical distribution of atmospheric optical turbulence has a significant impact on the performance of wide-field adaptive optics systems. Stereo-SCIDAR is an instrument capable of measuring the vertical profile of the turbulence strength and velocity with high sensitivity and altitude resolution. Stereo-SCIDAR, developed in close collaboration with Durham University, was successfully tested at the La Silla Paranal Observatory in mid-2016. This visitor instrument is located at the coudé focus of one of the Auxiliary Telescopes and will record atmospheric turbulence profiles above Paranal for one year starting in October 2016. These measurements are required for the specification and implementation of adaptive optics for the European Extremely Large Telescope.

Limited statistical data, with high vertical resolution, exists for the optical turbulence strength and velocity profile above the Paranal Observatory. Recently, the University of Durham proposed an extended campaign to obtain more complete statistical data, relevant to the implementation of adaptive optics at Paranal and Armazones, through the operation of a new SCIDAR (SCIntillation Detection And Ranging) system at a coudé focus of one of the Auxiliary Telescopes (ATs) of the Very Large Telescope (VLT).

A SCIDAR is a type of instrument that measures the optical atmospheric turbulence profile using a “crossed-beam” technique, by observing double stars. A SCIDAR system was previously deployed at Paranal for a successful campaign in 2008, in the form of the Cute-SCIDAR instrument of the Instituto de Astrofísica de Canarias (C-SCIDAR: Vásquez Ramió et al., 2008).

The Centre for Advanced Instrumentation (CfAI) at the University of Durham has developed a new variation of the SCIDAR profiler. Stereo-SCIDAR (Shepherd et al., 2014) makes use of separate, synchronised, low-noise detectors for each component of the double star target, whereas in previous SCIDAR instruments the light from the two stars was superposed on the same detector. Separating the light from the two stars enhances the sensitivity for turbulence profiling and facilitates automated profiling of the turbulence velocity. It also increases the sky coverage of the instrument as larger brightness differences between the two target stars can be tolerated. Operation of the Stereo-SCIDAR instrument is largely automated and will require limited Telescope and Instrument Operator (TIO) support only, an essential requirement for an extended observing campaign. Observations with the instrument are possible under a wide range of seeing conditions (up to seeing values of at least 1.5 arcseconds) and the turbulence profile and wind velocity data are available in near real time.

Objectives and performance requirements

The overall scientific goal is to provide a statistically representative database of the turbulence profile required for adaptive optics (AO) development at the VLT and the European Extremely Large Telescope (ELT). Accurate modelling for the advanced AO systems of the ELT and, in particular, for tomographic systems, requires statistical data for the full vertical profile (up to approximately 20 kilometres) with high resolution. The main concern is the conditions at higher altitudes, above ~ 1 kilometre, which are less affected by local orography than the ground-layer turbulence.

Under the hypothesis that data obtained from observations at Paranal are representative of the ELT site at Armazones, 30 kilometes distant, ESO decided to install the Stereo-SCIDAR optical turbulence profiler instrument at a single coudé focus of one AT. Operation of the SCIDAR on a 1.8-metre AT will provide profiles of the optical turbulence strength and wind speed with a vertical resolution of approximately 300 metres or better, to a maximum altitude of around 20 kilometres. Cross-comparison of the SCIDAR output with existing instruments on site (Multi-Aperture Scintillation Sensor [MASS], Differential IMage Motion [DIMM], SLOpe Detection And Ranging instrument [SLODAR], AO telemetry, etc.) will be an important aspect of the project.

The typical required performance and environmental conditions of Stereo-SCIDAR are summarised here. The parameters to be measured are the optical turbulence strength profile $C_n^2(h)dh$ and the turbulence speed and direction *V(h)* profile at a sampling rate of one minute. The parameters to be computed/displayed are the isoplanatic angle (θ_0) and the temporal coherence scale (τ_0). The sequence acquisition time is required to be 3–5 minutes for telescope preset and the typical observation time per target is 2 to 4 hours, thus 2–5 targets can be measured per night. The telescope preset and open-loop tracking accuracy/stability needs to be 5 arcseconds on sky (peak-to-valley) in seeing conditions up to 1.5 arcseconds. Stereo-SCIDAR is required to operate about 4 nights per month over an operational period of one year. Targets should be (optical) double stars with separations in the range 10–20 arcseconds where each component has *V* mag ~ 7.0 or brighter. The double star needs to be visible over the whole observing session of 2–4 hours and the declination range of targets is –60 to 0 degrees.

Planned test campaign

In order to obtain statistically valuable information about the full vertical profile, ESO decided to conduct a one-year test campaign with Stereo-SCIDAR. The instrument will be operated on a few nights per month over observing periods 98 and 99. Stereo-SCIDAR runs will coincide with the VLT Interferometer Unit Telescope (UT) runs for which the ATs are not required. A high degree of automation of the instrument, long observation runs on the same target and good tracking of the telescope in blind mode will greatly simplify the operation. But for safety reasons the telescope and instrument will be operated and supervised by a TIO. As for all instruments, the data (in this case the turbulence profiles) will be archived at ESO following the standard procedure. The subsequent data reduction to prepare for science publication will be done by the University of Durham.

Instrument design

The dual-detector approach of Stereo-SCIDAR has advantages over the conventional approach, specifically increasing the signal-to-noise ratio of the recovered turbulence profile by a factor of ~ 2–20 depending on the differential brightness of the two target stars. The two-camera system can therefore detect weaker turbulent layers. The vertical resolution of the profile is improved and a larger number of useable target stars are available. Furthermore, measurement of the turbulent layer velocities is simpler with the two-camera approach, so that wind velocities can be calculated in real time, even for weak layers.

The Stereo-SCIDAR instrument comprises two major sub-systems. The first is the instrument located at a coudé focus of the AT and consisting of:
1. a dedicated support structure (UROS) for the SCIDAR instrument;
2. a custom mechanical interface between UROS and SCIDAR, providing tip-tilt adjustment of the instrument;
3. a focusing mechanism and controller common to both image planes;
4. instrument (de)rotator mechanism and controller common to both image planes;
5. focal-plane optics featuring a charge coupled device (CCD) detector (Andor Luca-S 658M EM-CCD) for each image plane (Peltier cooled so no cooling liquid is required);
6. an off-axis camera system to assist with target acquisition and tracking;
7. local control computer (for camera control and data acquisition, rotator mechanism control, and focus control).

The second sub-system is located in the VLTI computer room and consists of a supervisor workstation for real-time data analysis and display.

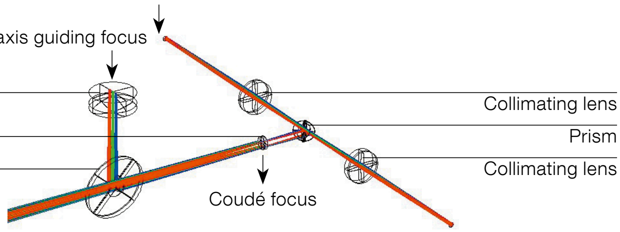


Figure 1. Schematic of the optical design of the Stereo-SCIDAR instrument.

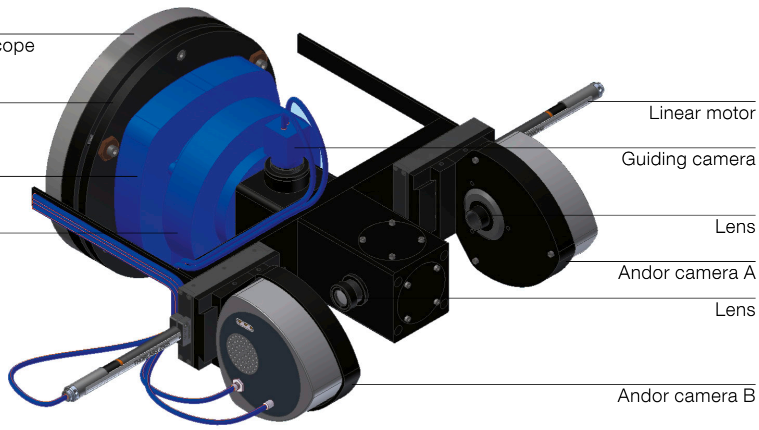


Figure 2. Mechanical design of the complete Stereo-SCIDAR focal plain instrument.

The optical design of Stereo-SCIDAR is very simple (see Figure 1): the only powered optical component is a collimating lens in each arm of the instrument. A reflecting (coated) right-angle prism directs the light from each component of the double star onto a separate detector. In each arm, the telescope entrance pupil is re-imaged onto the detector by the collimating lens. Each detector is mounted on a motorised stage for accurate positioning (along the optical axis) at the pupil image (or slightly away from it, to re-conjugate the observing plane effectively below the telescope level). A dichroic beam-splitter feeds an additional camera for target acquisition and guiding.

Mechanical layout

The interface with the telescope is made by a kinematic mount, consisting of two circular plates, which provide tip-tilt and focus adjustment of the entire instrument by means of a "push-pull" type mechanism. Figure 2 shows a view of the mechanical layout. The adapter plate provides a dovetail-style mounting interface for a heavy-duty Atlas focuser, manufactured by Finger Lakes Instrumentation. This stepper-motor-based focuser enables the instrument to accommodate shifts in telescope focus between observing runs.

An Optec Pyxis 3″ Camera Field Rotator is attached to the focuser by means of a custom-made dovetail-style mounting

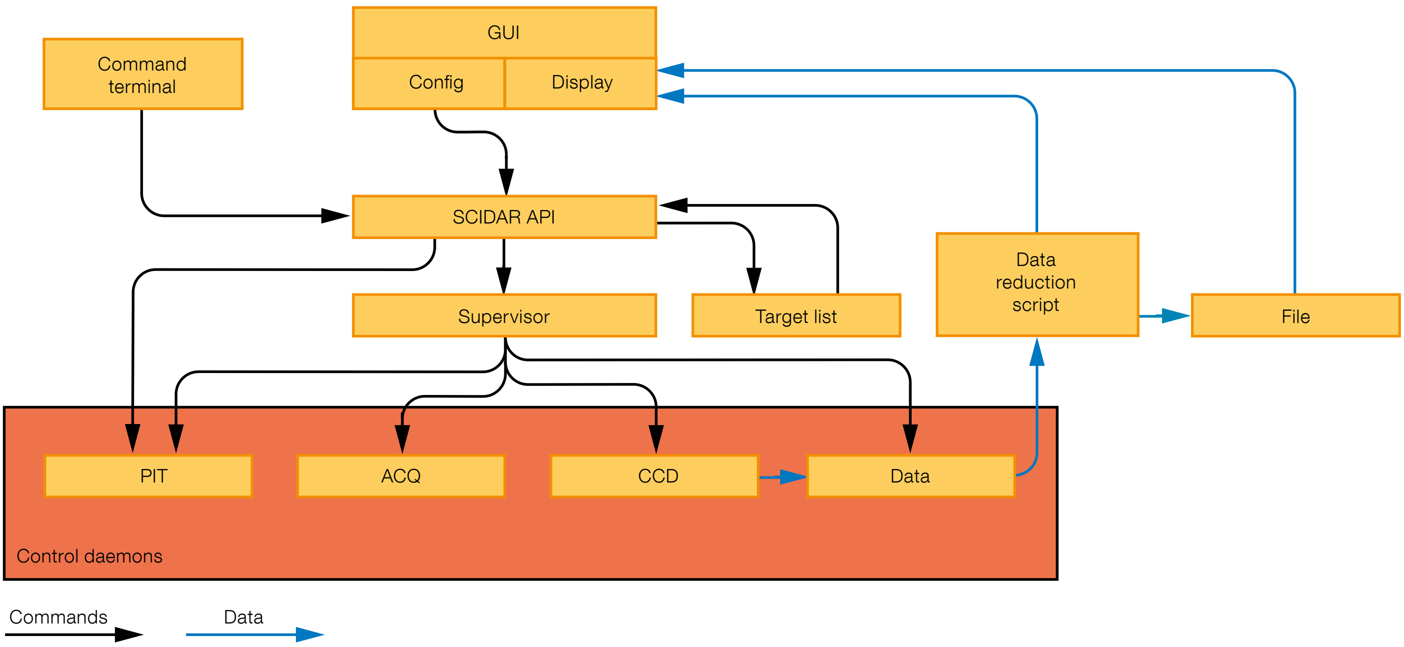


Figure 3. Schematic illustration of the structure of the Stereo-SCIDAR control software.

adapter. This stepper-motor-driven rotator is used to rotate the instrument to align it with the orientation of the binary star on the image plane, such that both components are centred within the rectangular aperture of the spatial filter. In addition, the rotator is used to track rotation of the field during an observation. Closed loop feedback is provided by the off-axis camera.

The main structure of the instrument is formed by the front cube which is attached to the rotator by means of a custom-made flange. The front cube features mounting ports for the dichroic beam splitter and the off-axis camera. This camera is attached to a lens barrel by means of a custom-made dovetail-style mounting flange. The compressor lens is also mounted inside this lens barrel by means of a threaded retaining ring. The distance between the lens and the detector surface is fixed. The use of the dovetail mounting flange then allows the orientation of the camera to be adjusted independently of focus, such that the aperture of the spatial filter is aligned with the long edge of the detector.

Control software

The software package is built around four daemon processes that run in the background (see Figure 3). These daemons initiate, monitor and control all of the instrument devices and processes:
- ccd_daemon — to control the two Andor Luca EMCCD cameras;
- acq_daemon — to control the Point-Grey Blackfly acquisition camera;
- pit_daemon — to control the rotator, focuser and actuator mechanisms;
- data_daemon — to process the SCIDAR raw data into turbulence profiles.

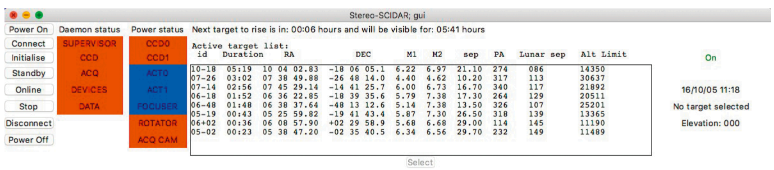
A supervisor script runs on the supervisor personal computer (PC) in the telescope control room. This script monitors the status of the system as a whole, gathering data returned from the daemons and displays these data to the user.

An interface script allows the user to control the SCIDAR system via a small number of commands, entered on the command line of the supervisor PC. These commands, for example to start or stop data acquisition, are checked and then passed on to the relevant daemon. The software is designed so that the instrument is as automated as possible and the following utilities are automated: rotation; focus; pupil conjugation; region of interest selection; gain of the SCIDAR CCD; and exposure of the acquisition camera.

User interface

The graphical user interface (GUI, see Figure 4) displays the following data to the user via the terminal of the supervisor PC:
- images from the acquisition camera (Figure 5);
- images from the two SCIDAR pupil (science) cameras (Figure 5);
- the turbulence profile through the night;
- some data on the current target and atmospheric conditions (target identifi-

Figure 4. The Stereo-SCIDAR control GUI.



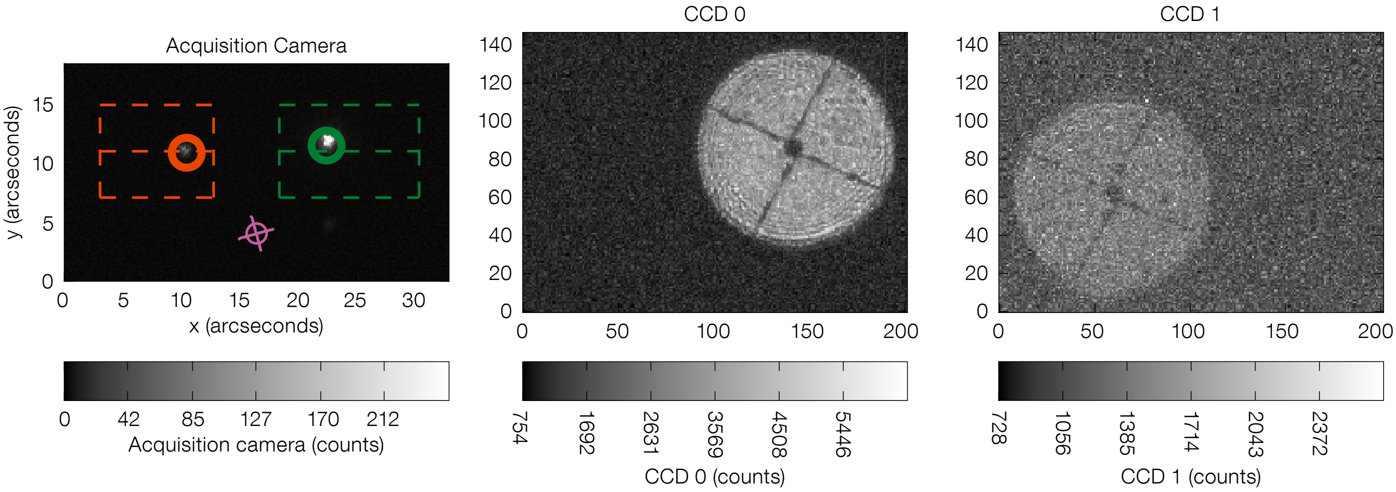


Figure 5. Examples of Stereo-SCIDAR camera images. The acquisition camera is on the left. The rotation should be such that the green circle (indicating the brighter star) is on the green (right hand side) of the frame. This is to ensure that the system knows the orientation on the sky. Each of the two pupil images are shown in the centre and right panels.

cation, time until it sets, time at which it sets, and the current atmospheric parameters — Fried parameter (r_0), θ_0, τ_0 and the scintillation index).

Data reduction

The data reduction pipeline runs on the supervisor PC. It processes the images from the science cameras in real time to yield the optical turbulence strength and wind velocity profiles, as well as derived atmospheric parameters such as θ_0 and τ_0. The data reduction pipeline is identical to that used by existing Stereo-SCIDAR instruments and details can be found elsewhere (Shepherd et al., 2014).

Commissioning results

Having been successfully integrated at the coudé focus of the VLT AT, Stereo-SCIDAR achieved first light in April 2016, delivering its first turbulence profile ofthe atmosphere above the Paranal Observatory. A second campaign of five nights was conducted in July 2016. The commissioning team (Figure 6) had the opportunity to operate Stereo-SCIDAR for a total of 11 nights in order to test functions, interfaces, operation and data archive of the instrument, confirming the readiness of Stereo-SCIDAR for the one-year test campaign starting in October 2016.

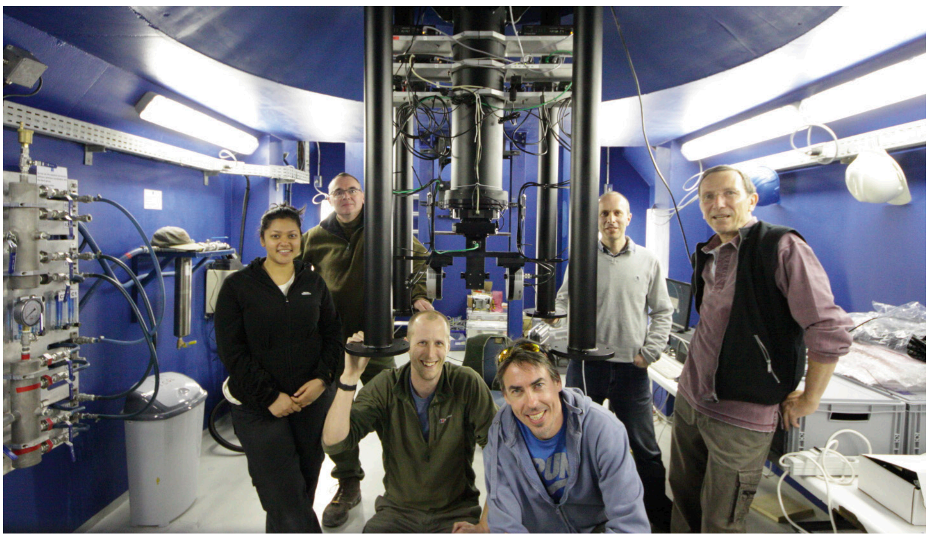
All the functions and performance of Stereo-SCIDAR were tested, and demonstrated full compliance with the requirements. During the commissioning nights the GUI was optimised, taking into account the remarks and requests of the TIOs.

Profiles were recorded each night when the weather allowed. We did not identify any major problems with the AT interface and operation, or with the instrument that resulted in any downtime. Atmospheric profiles (Figure 7) recorded during the first commissioning phase demonstrated the reliability of the data reduction software.

First profiles

A screen shot from the commissioning run on 29 April 2016 is shown in Figure 7. The many short vertical breaks seen in the lower panel on Figure 7 are pauses for field de-rotation to correct for the sky rotation, due to the altitude-azimuth telescope; the longer breaks (approximately 5 minutes) are for target changes. As can be seen from the lower panel on Figure 7, some turbulent layers appear stable and are visible for almost the whole night, for example at ground level and at 2.5 kilometres. Other layers are more transient, with layer strengths and altitudes varying over the course of minutes.

Figure 6. The Stereo-SCIDAR commissioning team at Paranal.



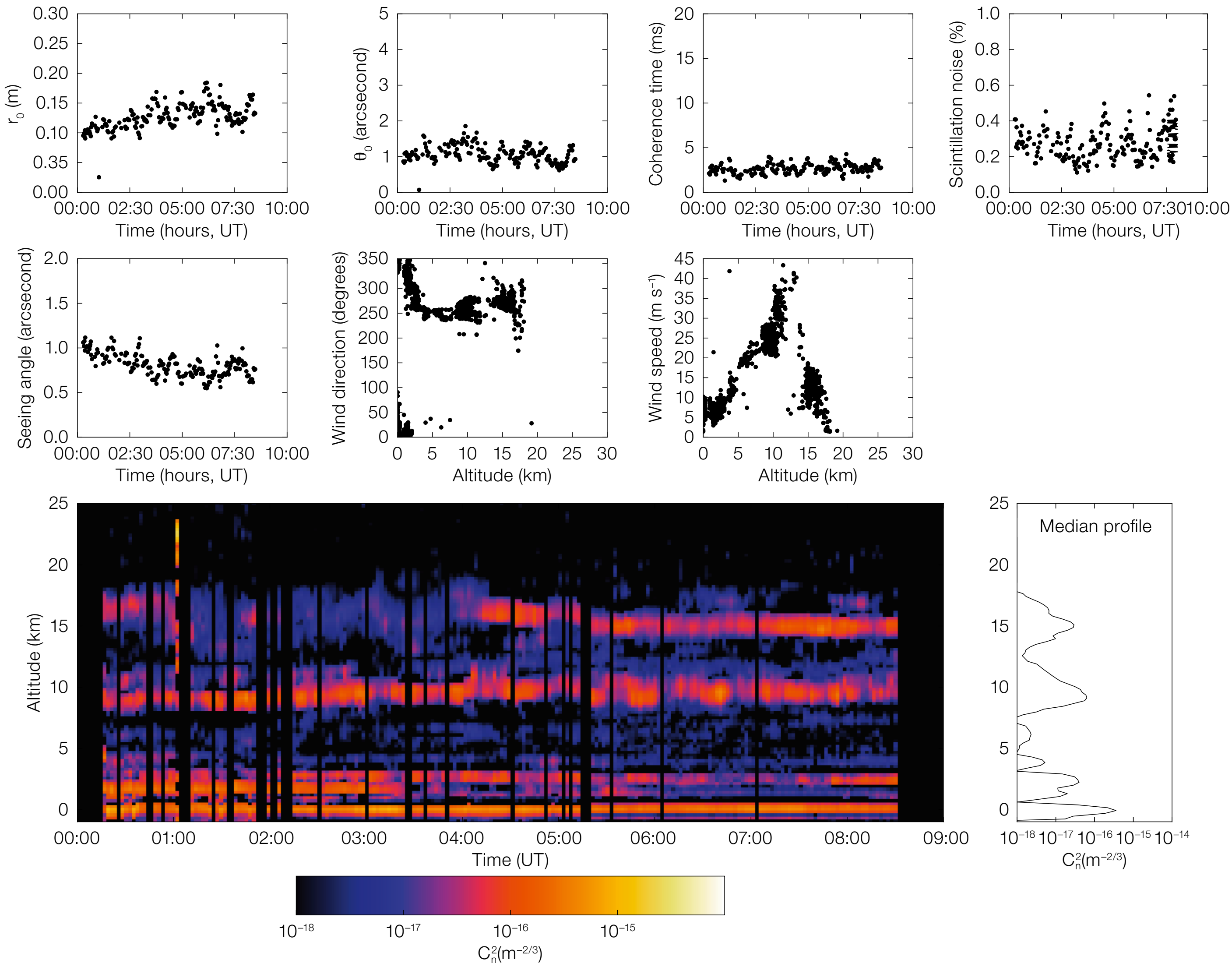


Figure 7. Stereo-SCIDAR real-time display, showing commissioning data from the night beginning 29 April 2016. The top two rows of panels show the evolution of the integrated atmospheric parameters throughout the night as well as the turbulence speed and direction profile. The lower panel shows the evolution of the turbulence altitude distribution, with altitude shown vertically and time running horizontally. The colour indicates the strength of the turbulence, and the upper magenta line marks the maximum profile altitude. The lower right hand plot shows the time-integrated C_n^2 value with altitude.

Wind velocity identification

In order to validate the wind velocity identification, we compared wind and turbulence velocity profiles from the Stereo SCIDAR instrument (via its automated wind velocity detection algorithm) with wind data from the European Centre for Medium-Range Weather Forecasts, (ECMWF) numerical forecast for Paranal. Figure 8 shows the comparison of identified layers for these data sources. The correlation is high for both turbulence speed and velocity, confirming the validity of the Stereo-SCIDAR automated wind velocity identification algorithm.

Conclusions

Stereo-SCIDAR, a high resolution atmospheric turbulence profiler, has been commissioned on one of the 1.8-metre ATs at Paranal, situated only 22 kilometres from the site of the future ELT. The data from Stereo-SCIDAR are critical for design studies of ELT instrumentation as well as performance monitoring and optimisation of existing VLT and future ELT operations. Stereo-SCIDAR will operate at Paranal for several nights per month for at least one year.

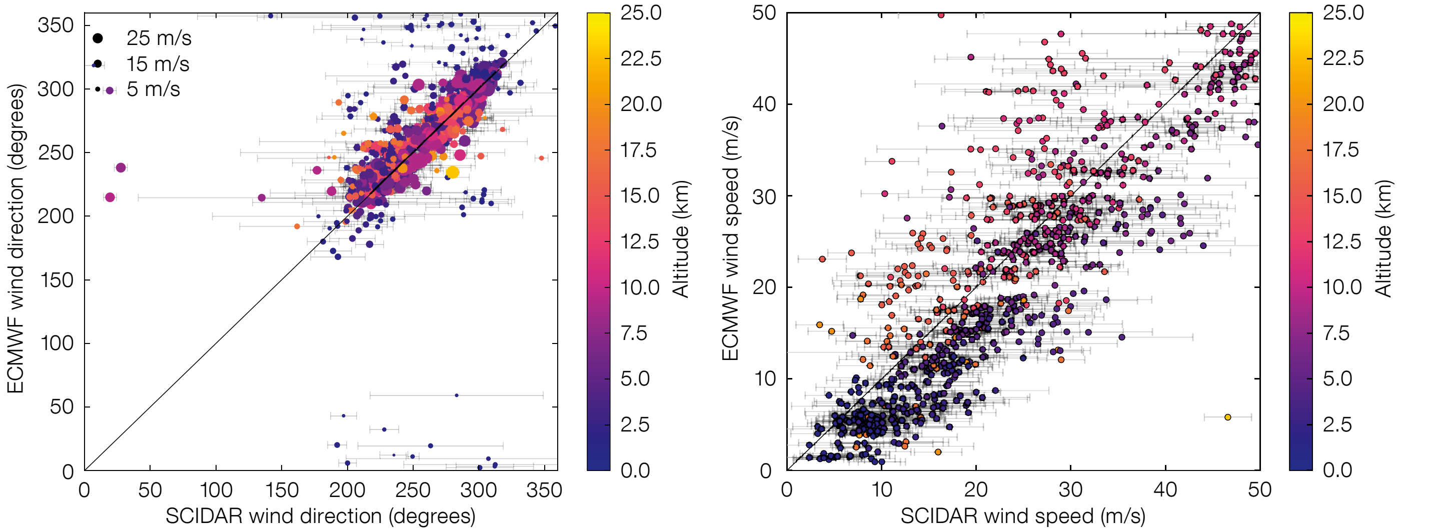


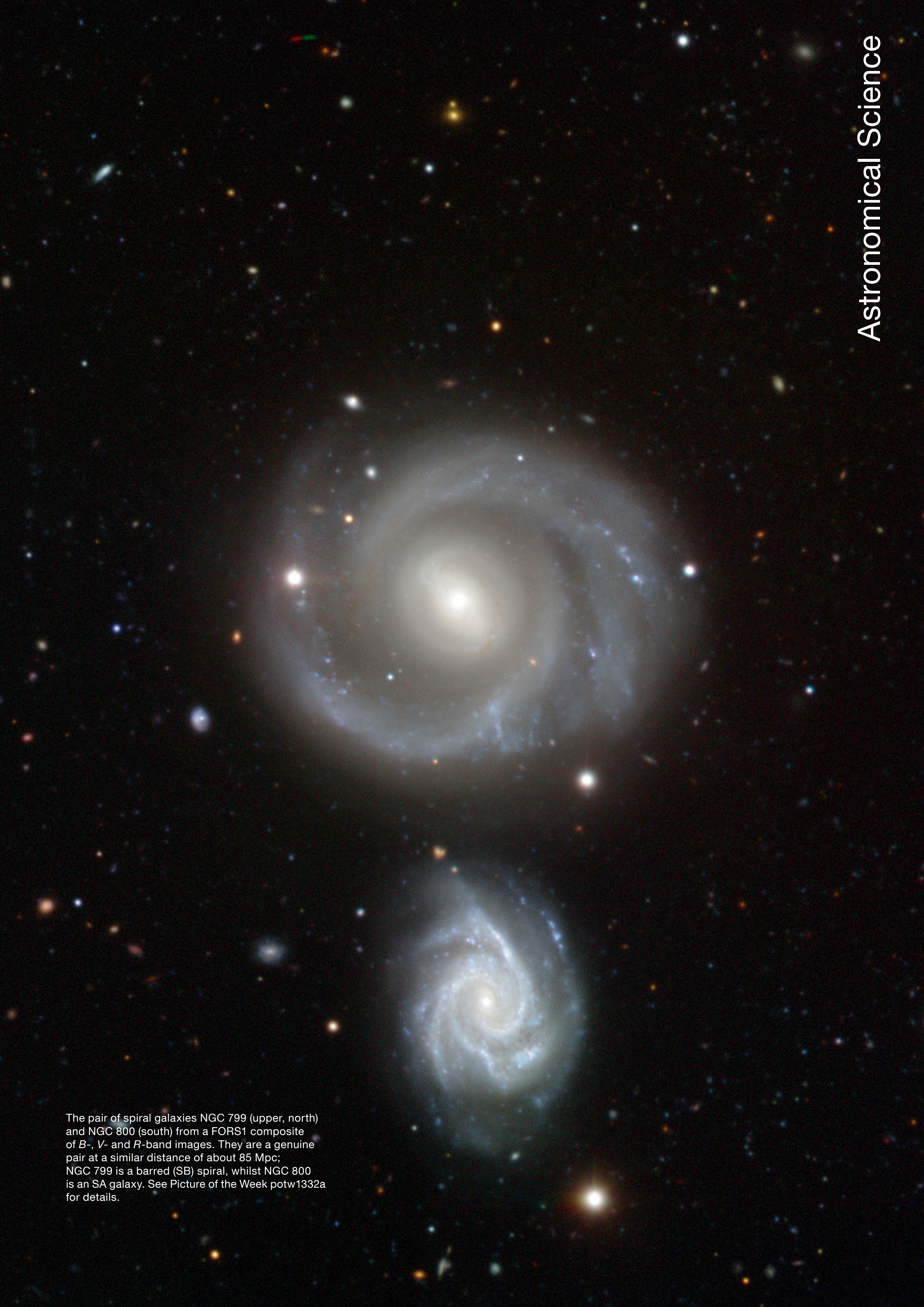
Figure 8. Comparison of SCIDAR and ECMWF wind velocities (direction, left, and speed, right) for the commissioning data. The colour denotes the altitude of the identified turbulent layer. For the wind direction (left) the size of the data point denotes the wind speed.

References

Shepherd, H. W. et al. 2014, MNRAS, 437, 3568
Vásquez Ramió, H. et al. 2008, The Messenger, 132, 29

G. Ávila/ESO

High altitude cirrus cloud can give rise to a circumhorizontal arc from refraction by ice crystals, here photographed at Paranal above the Astronomical Site Monitor.



The pair of spiral galaxies NGC 799 (upper, north) and NGC 800 (south) from a FORS1 composite of *B*-, *V*- and *R*-band images. They are a genuine pair at a similar distance of about 85 Mpc; NGC 799 is a barred (SB) spiral, whilst NGC 800 is an SA galaxy. See Picture of the Week potw1332a for details.

A Deep ALMA Image of the Hubble Ultra Deep Field

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Although primarily designed as a high-resolution imaging spectrometer at submillimetre/millimetre wavelengths, the Atacama Large Millimeter/submillimeter Array (ALMA) has a vital role to play in producing the key deep, unconfused, submillimetre/millimetre continuum surveys required to bridge the current gap in our understanding of visible and dust-obscured star formation in the young Universe. The first such survey has now been completed, comprising a mosaic of 45 ALMA pointings at a wavelength of 1.3 mm, covering the Hubble Ultra Deep Field (HUDF). This deep, homogeneous ALMA survey, combined with the wealth of existing data in the HUDF, has already provided new clarity on the nature of dusty star-forming galaxies, and the relative evolution of dust-obscured and unobscured star formation over cosmic time.

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Background: the importance of ALMA as a survey instrument

The Atacama Large Millimeter/submillimeter Array (ALMA) on the high Chajnantor plateau is now delivering on its promise to revolutionise astronomy and astrophysics in the challenging wavelength regime between ~ 0.3 mm and ~ 3 mm. Since the Earth's atmosphere is both a strong emitter and absorber of submillimetre radiation, observations at these wavelengths would ideally be conducted from outer space. However, creating submillimetre/millimetre (sub-mm/mm) images with an angular resolution comparable to the best optical images, as delivered, for example, by the Hubble Space Telescope (HST), requires a telescope aperture hundreds of times larger than can currently be launched into space. Indeed it requires a telescope aperture much larger than any single-dish telescope ever constructed on the ground. However, through the technique of aperture synthesis, the signals from many moderate-size telescope dishes can be combined to mimic the imaging capability of a single enormous telescope. Thus ALMA, with 66 moveable dishes, located above much of the atmosphere at an altitude of 5050 m, represents humanity's current best effort to realise the potential benefits of a giant sub-mm/mm telescope in space.

One might reasonably ask why so much effort and finance have been invested in creating what is currently the world's largest astronomical project. One answer, at least from the perspective of extra-galactic astronomy, is that approximately half of the optical/ultraviolet starlight emitted over cosmic history has been absorbed and then re-emitted at infrared-millimetre wavelengths by cosmic dust. Thus, a complete history of star and galaxy formation/evolution requires observations at both optical and far-infrared wavelengths, and the expansion of the Universe means that the dust emission from early/distant galaxies is redshifted from the far-infrared into the sub-mm/mm regime.

The importance of dust emission from galaxies became clear towards the end of the 20th century, first through the discoveries of the Infra-Red Astronomical Satellite (IRAS), and then with the advent of sub-mm imaging on large ground-based single-dish telescopes, such as the 15-metre diameter James Clerk Maxwell Telescope (JCMT) in Hawaii. The first deep blank-field sub-mm surveys of the sky, undertaken with the Submillimetre Common-User Bolometer Array (SCUBA) camera on the JCMT, revealed a population of distant galaxies which were almost completely dust-obscured, and whose far-infrared luminosities implied star formation rates of ~ 1000 $M_\odot$ yr^{-1} (for example, Hughes et al., 1998). In the intervening years the prevalence/importance of extreme dusty star-forming galaxies in the young Universe has been confirmed through surveys with the Submillimetre Common-User Bolometer Array (SCUBA), the Astronomical Thermal Emission Camera (AzTEC), and now SCUBA-2, all on the JCMT, with the Large APEX BOlometer Camera (LABOCA) on the Atacama Pathfinder EXperiment (APEX) telescope, and with the Herschel Space Observatory (for example, Coppin et al., 2006; Weiss et al., 2009; Burgarella et al., 2013; Michalowski et al., 2016).

Despite these impressive advances, with a maximum aperture diameter of 15 metres, these single-dish facilities have only been able to deliver sub-mm/mm imaging of very modest quality (for example, in the case of the JCMT, imaging with a full width half maximum [FWHM] of 14.5 arcseconds at wavelength ~ 850 μm). This unavoidable technical/physical limitation has two serious consequences. First, distant galaxies appear as unresolved blobs, with somewhat uncertain positions, making accurate comparison with optical imaging extremely problematic. Second, the large image size means that the achievable imaging depth is limited not by integration time, but by source confusion, where the blurred images of fainter galaxies ultimately overlap, forming an impenetrable background against which the brightness of only the most luminous rare sources can be measured with acceptable accuracy. As a consequence, our sub-mm/mm view of the distant Universe has remained somewhat disconnected from our optical/near-infrared view.

While deep HST surveys are sensitive to faint galaxies with (unobscured) star formation rates smaller than 1 $M_{\odot}$ yr^{-1}, single-dish sub-mm/mm surveys have only really been effective at uncovering rare, extreme star-forming galaxies with dust-obscured star formation rates of several hundred $M_{\odot}$ yr^{-1}. While the latter objects present an interesting and important challenge to theoretical models of galaxy formation (for example, Narayanan et al., 2015), they provide only ~ 10 % of the measured far-infrared/mm background, and attempts to complete our inventory of dust-obscured star formation have had to rely on stacking experiments (for example, Geach et al., 2013; Bourne et al., 2016).

Since its individual 12-metre diameter dishes can be driven to separations of several kilometres, ALMA is more than capable of transforming this situation: it can deliver angular resolutions of a few milli-arcseconds and also high-resolution spectroscopy at sub-mm/mm wavelengths. However, from the perspective of survey astronomy, this stunning resolution comes at a price. First, because ALMA is an interferometer (rather than a single telescope and multi-pixel camera) the angular field-of-view imaged in a single pointing is relatively small (FWHM ~ 17 × λ(mm) arcseconds). Second, in its more extended configurations, the resolution delivered by ALMA can be "too good", running the risk of detecting only compact features, while resolving out the more extended emission.

Thus, to use ALMA as an effective deep sub-mm/mm survey instrument, we actually need to use it in a relatively compact configuration, and to mosaic together several individual ALMA pointings in order to create a homogeneous image of significant size. Nonetheless, this effort is worthwhile, because only ALMA can break through the confusion limit of existing single-dish sub-mm/mm surveys, and enable us to properly connect our ultraviolet (UV)/optical and IR/mm views of the young Universe.

ALMA and the Hubble Ultra Deep Field

As ALMA gradually came on line, the early mosaicing options on offer were understandably limited, with maximum mosaic size initially restricted to 45 pointings. Coincidentally/fortuitously, the size of such an ALMA mosaic, if constructed at mm wavelengths, corresponds closely to the ~ 4.5 square arcminute field of view of the Wide Field Camera 3 (WFC3) instrument on HST, which has recently been used to complete the deepest ever optical-near-infrared image of the sky, the Hubble Ultra Deep Field (HUDF; see, for example, Ellis et al., 2013).

The HUDF was therefore the obvious location for the first deep, blank-field survey with ALMA, and in Cycle 1 we successfully proposed to use 20 hours of ALMA observing time to create a 45-pointing mosaic image of the HUDF at 1.3 mm. This project was, by some margin, the largest project approved in ALMA Cycle 1, and in the end was (understandably) not undertaken until ALMA Cycle 2. However, data taking was finally completed in summer 2015, and we were able to use the data to produce the image shown in Figure 1 (from Dunlop et al., 2016).

In this first ALMA map of the HUDF, the noisy edges of the 45-pointing mosaic can be clearly seen, but it is also apparent that we have succeeded in achieving the desired homogenous coverage of the region previously imaged with the HST. The image shown here has an RMS depth of 35 μJy, and an angular resolution of 0.7 arcseconds (FWHM). It contains 47 > 3.5σ peaks, but source-finding on the inverted (negative) image revealed 29 apparent "sources" down to the same significance level, suggesting that < 20 of the apparent sources in the positive map were real.

Fortunately, the positional accuracy of the ALMA sources, combined with the exquisite depth of the HST imaging (reaching > 30 AB mag), enabled us to isolate the real ALMA sources from the interlopers by looking for counterparts in the HST imaging within a small (< 0.5 arcsecond) search radius. The result of this process is a sample of 16 robust sources. These are marked in Figure 1, and shown in more detail in Figure 2, where contours from the ALMA 1.3 mm imaging are overlaid on colour images created from the optical-near-infrared HST images (*i*+*Y*+*H* bands). As an interesting aside, this ALMA+HST cross-matching revealed that the coordinate system of the HST imaging in the HUDF had to be moved south by ~ 0.25 arcseconds; this offset has been applied in Figure 2 (Dunlop et al., 2016; Rujopakarn et al., 2016).

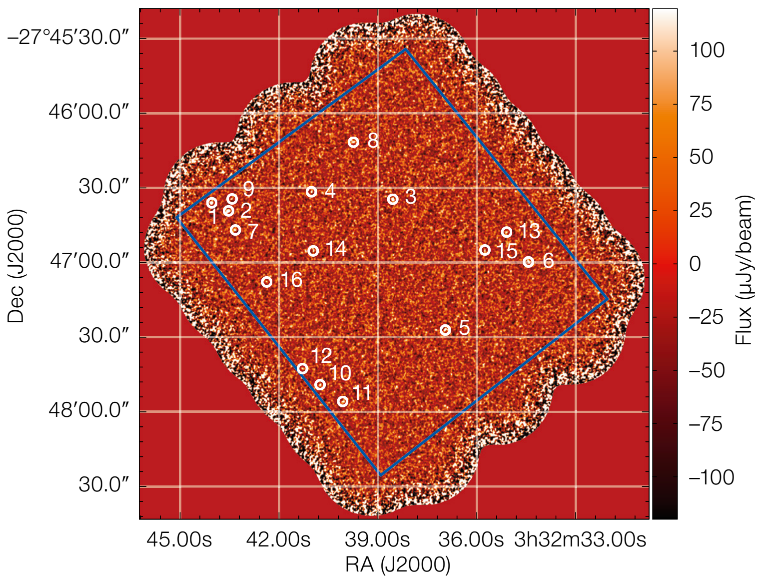

Figure 1. The ALMA 1.3-mm map of the HUDF, with the positions of the 16 detected sources marked by 3.6-arcsecond diameter circles. The border of the homogeneously deep region of near-infrared WFC3/IR HST imaging is indicated by the dark-blue rectangle.

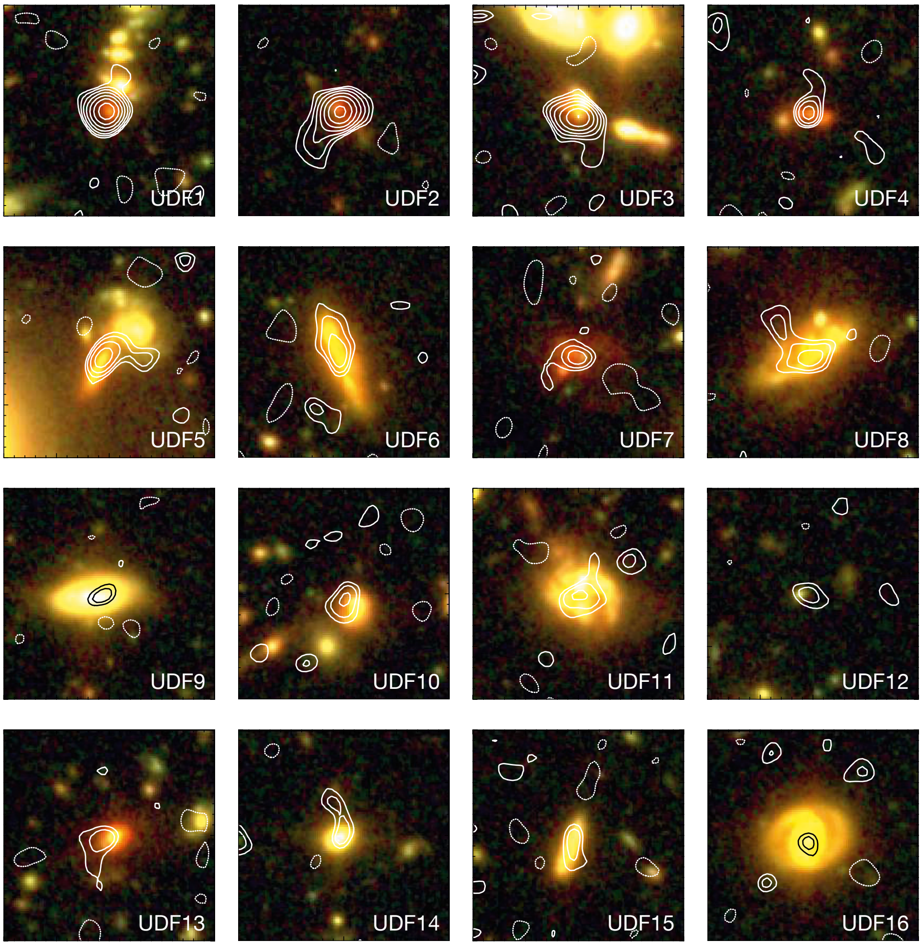

Figure 2. Colour (i_{775} + Y_{105} + H_{160}) HST postage-stamp images of the 16 ALMA detected galaxies in the HUDF, with the contours from the ALMA 1.3-mm imaging overlaid. Each stamp is 6 × 6 arcseconds in size, with north to the top and east to the left.

The nature of the ALMA-detected galaxies

Although we did not quite achieve our desired depth of 30 μJy, this cannot explain the fact that our ALMA-detected sample of 16 sources was substantially smaller than anticipated based on pre-existing estimates of the source counts from other studies (for example, Fujimoto et al., 2016). This finding may mean that the HUDF is somewhat under-dense compared to typical regions of the sky, but it is almost certainly at least partly due to the fact that most previous studies have lacked the quality of supporting data required to separate real from fictitious sources.

Nevertheless, our analysis has revealed that the detected sources form an interestingly homogeneous sample of galaxies. From Figure 2 it can be seen that most are red clumpy galaxies in the HST imaging. Their red colour is partly due to the impact of dust obscuration, but also reflects their redshifts, with 13/16 sources lying in the redshift range $1 < z < 3$. This mirrors the findings of previous studies of brighter sub-mm galaxies, which have generally yielded a median redshift of $z = 2$–2.5.

Aided by the fact that we already know the redshifts and physical properties of the ~ 2000 galaxies previously uncovered by HST in the HUDF, we can explore further the nature of the ALMA-detected sources in the context of the general galaxy population. This is illustrated in Figure 3. In the first panel it can be seen that the ALMA-detected galaxies appear thoroughly unexceptional in terms of UV luminosity (and, hence, raw unobscured star formation rate). However, the true nature of these sources is revealed in the second panel of Figure 3, where it can be seen that they are confined to the high-mass regime. Indeed, in the redshift range $2 < z < 3$, our ALMA image has detected virtually all (7/9) of the galaxies in the field with stellar masses $M_* > 2 \times 10^{10}\ M_\odot$ (assuming a Chabrier (2003) stellar initial mass function [IMF]). Also interesting is the fact that we have detected only one galaxy at $z > 3$, which happens to lie at $z \sim 5$. However, it can also be seen from Figure 3 that the HUDF probes too small a cosmological volume to contain any galaxies with $M_* > 2 \times 10^{10}\ M_\odot$ at $z > 3$, so the absence of higher-redshift sources may simply reflect the evolution of the underlying galaxy mass function.

While many of the physical properties of the ALMA-detected galaxies can be determined from the pre-existing optical-near-infrared data in the HUDF, we need to use the ALMA measurements themselves to estimate the far-infrared luminosities of the sources, and hence their dust-enshrouded star formation rates. Unfortunately this requires some extrapolation from the ALMA flux densities because, for sources at $1 < z < 3$, the peak of the far-infrared spectral energy distribution (SED) lies significantly shortward of the observed wavelength of 1.3 mm (for any reasonable dust temperature). Additional ALMA imaging, reaching down to observed wavelengths of 350 μm, would be helpful in this regard, but for now we must make do with highly uncertain/de-blended Herschel and Spitzer detections/limits for the sources, which span the observed wavelength range 24–500 μm.

In practice, most of our sources are too faint to establish a reliable far-infrared SED for each individual object, and so instead we have created and modeled the typical SED of the objects in our sample by using the available photometry and redshift information to create a pseudo-spectrum. This is shown in Figure 4, where the data have been modeled by a composite source for the purpose of inferring star formation rates from the ALMA photometry. The best-fitting SED shown here has a 20 % (in terms of bolometric luminosity) contribution from an

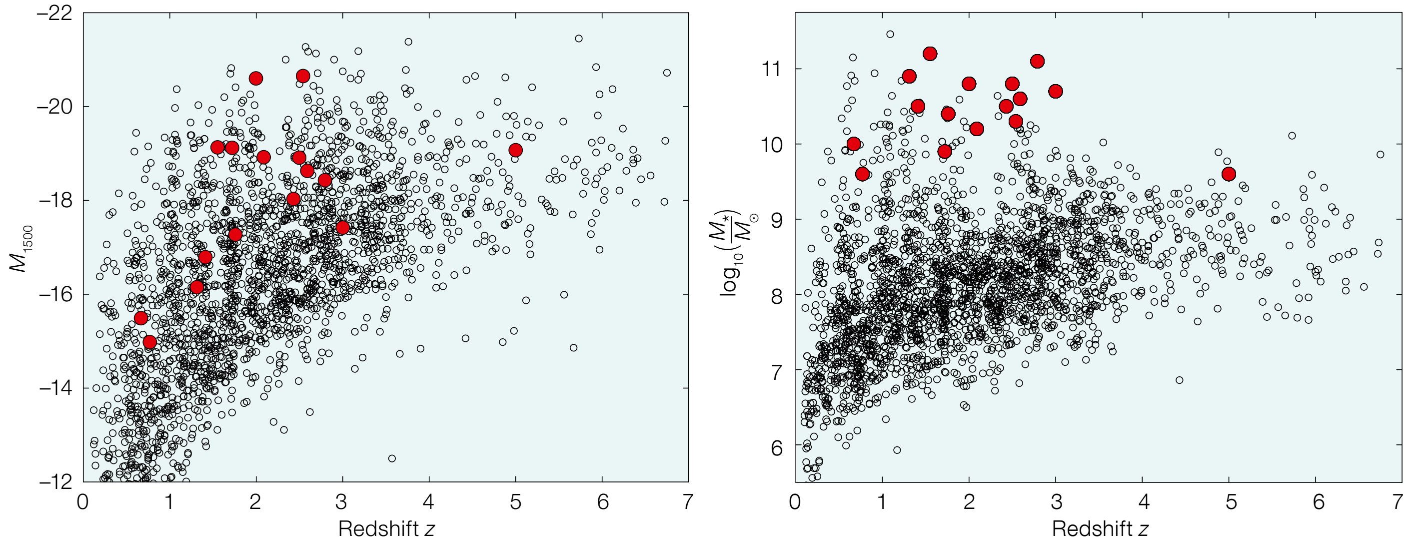

Figure 3. (above) The ALMA sources in the context of the general galaxy population in the Hubble Deep Field. The left panel shows UV absolute magnitude (at λ_{rest} = 150 nm) versus redshift, while the right panel shows the logarithm of stellar mass versus redshift. In both plots the ALMA-detected galaxies are highlighted in red.

AGN, but at longer wavelengths is entirely dominated by dust-obscured star formation (Kirkpatrick et al., 2015). The star formation rates inferred from this SED reveal that our sources have dust-obscured star formation rates ranging from ~ 300 down to ~ 30 $M_\odot$ yr^{-1} (for a Chabrier [2003] IMF).

Astrophysical implications

It is already clear from Figure 3 that stellar mass is a good predictor of a large amount of dust-enshrouded star formation at z ~ 2. However, after calculating the star formation rates as described above, it becomes even clearer that this is the case. If we calculate specific star formation rates (sSFR) by dividing star formation rate by stellar mass, we find that the ALMA-detected objects have, on average, exactly the sSFR expected from the so-called main sequence of star-forming galaxies first discussed by Noeske et al. (2007) and Daddi et al. (2007). Our derived average value of sSFR for the ALMA-detected sources at $1 < z < 3$ is 2.2 Gyr^{-1}, and a stack of the galaxies in the same redshift range and next decade in stellar mass reveals an identical value (see Dunlop et al., 2016). This result favours a simple star-forming main sequence at z ~ 2, with star formation rate proportional to stellar mass out to the highest stellar masses. Interestingly, without the ALMA data, one would infer a flattening of the main sequence at high stellar masses, as has been suggested in several previous studies (for example, Speagle et al., 2014).

It is also apparent that the ratio of dust-obscured to unobscured star formation is a steep function of stellar mass, apparently increasing by a factor of about 10 between M_* ~ 3 × 10^9 $M_\odot$ and M_* ~ 3 × 10^{10} $M_\odot$. Together, these two factors combine to produce a very strong dependence of ALMA detectability on stellar mass (proportional to ~ M_*^2), with the result that the detectability of galaxies at sub-mm/mm wavelengths drops off very rapidly below M_* ~ 10^{10} $M_\odot$.

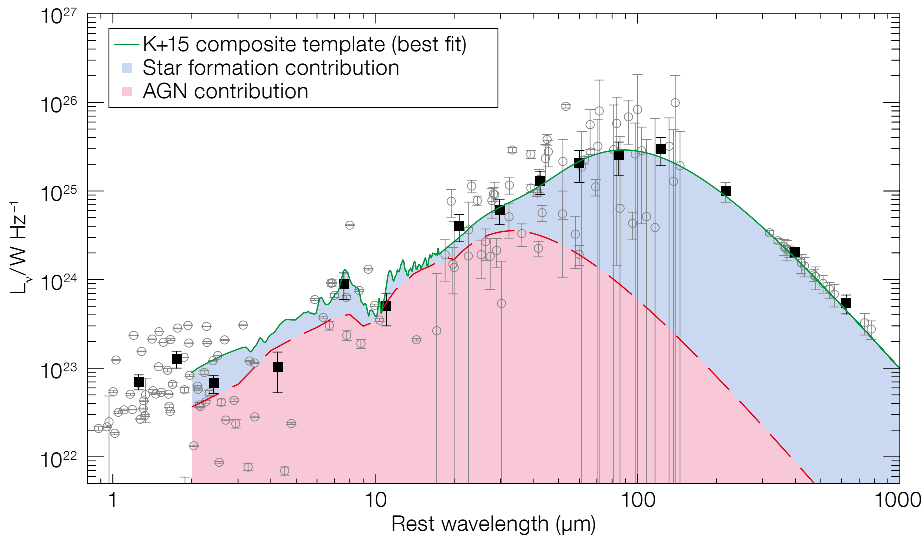

Figure 4. The combined Spitzer+Herschel+ALMA photometry of the 16 ALMA sources, (after de-redshifting and scaling to the same rest-frame 1.3-mm luminosity), fitted by the composite star-forming+AGN template of Kirkpatrick et al. (2015). The solid black squares indicate the weighted mean of the scaled multi-source photometry within a given wavelength bin. The accuracy of the redshift information results in the 8 μm feature being clearly visible in the observed combined rest-frame SED.

Cosmic star formation history

Finally, we can use these results to derive the evolution of the co-moving UV luminosity density and the co-moving

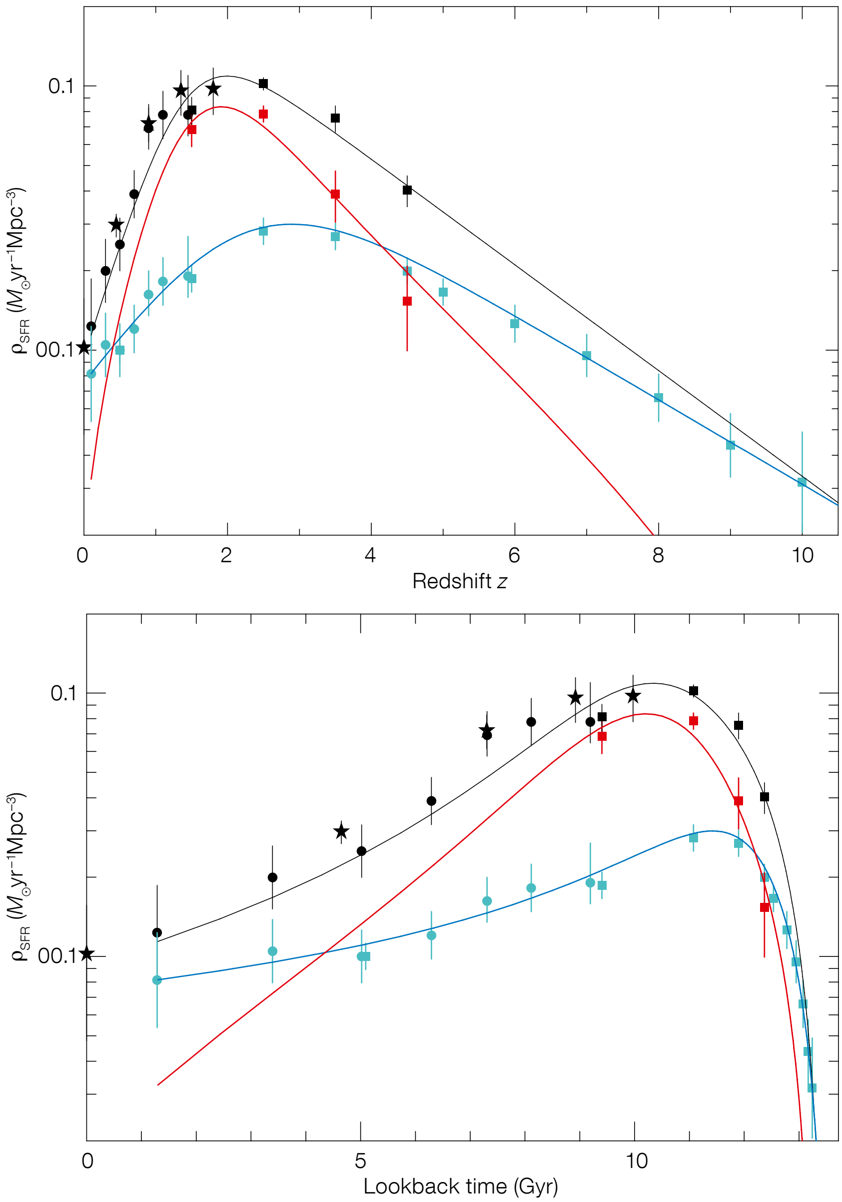

Figure 5. The evolution of co-moving star formation rate density (ρ_{SFR}) as a function of redshift (upper panel) and cosmic time (lower panel). The blue points and blue (double power-law) fitted curve show the raw, unobscured UV-derived values of ρ_{SFR} (derived from: Cucciati et al., 2012; Parsa et al., 2016; McLure et al., 2013; and McLeod et al., 2015). The red points and curve indicate the dust-obscured estimates of ρ_{SFR} derived from the present ALMA study of the HUDF (Dunlop et al., 2016). The black points and curve show total ρ_{SFR}; at $z < 2$ the data are from Cucciati et al. (2012) and Burgarella et al. (2013), while at $z > 2$ the black data points are simply the sum of the blue (unobscured) and red (dust-obscured) values.

far-infrared luminosity density as a function of redshift, converting the luminosity densities to visible and obscured star formation rate densities respectively (see Kennicutt & Evans, 2012).

Our knowledge of the evolution of the cosmic star formation rate density following the first results from WFC3+HST and Herschel (both of which came into operation in 2009) was reviewed by Behroozi et al. (2013) and Madau & Dickinson (2014). However, the deeper census of dust-obscured star formation enabled by the new ALMA results allows us to better determine the relative evolution of obscured and unobscured star formation at redshifts z = 2–5. The implications of our new results are summarised in Figure 5. The upper panel shows the evolution of unobscured, obscured and resulting total star formation rate density as a function of redshift, with the lower panel simply showing the equivalent information as a function of cosmic time. Now it can be seen clearly that, while the star formation density around the peak epoch at z = 2–2.5 is overwhelmingly dominated by dust-obscured emission from massive galaxies, at redshifts higher than $z \sim 4$ the dust-obscured component drops off rapidly, with the consequence that the star-forming Universe is primarily unobscured at earlier times (i.e., within 1.5 Gyr of the Big Bang).

Deeper imaging (for example, Walter et al., 2016) and wider-area surveys with ALMA have the potential to clarify this behaviour still further, and in particular to determine the evolution of dust-obscured star formation activity as a function of redshift at fixed galaxy stellar mass. In addition, the sources uncovered by these deep ALMA surveys are obvious attractive targets for further ALMA pointed imaging+spectroscopy extending to shorter wavelengths, and for future study with the James Webb Space Telescope (JWST).

References

Behroozi, P. S., Wechsler, R. H. & Conroy, C. 2013, ApJ, 770, 57
Bourne, N. et al. 2016, arXiv:1607.04283
Burgarella, D. et al. 2013, A&A, 554, 70
Chabrier, G. 2003, PASP, 115, 763
Coppin, K. E. K. et al. 2006, MNRAS, 372, 1621
Cucciati, O. et al. 2012, A&A, 539, 31
Daddi, E. et al. 2007, ApJ, 670, 156
Dunlop, J. S. et al. 2016, MNRAS, in press, arXiv:1606.00227
Ellis, R. S. et al. 2013, ApJ, 763, L7
Fujimoto, S. et al. 2016, ApJS, 222, 1
Geach, J. E. et al. 2013, MNRAS, 432, 53
Hughes, D. H. et al. 1998, Nature, 394, 241
Kennicutt, R. C. & Evans, N. J. 2012, ARA&A, 50, 531
Kirkpatrick, A. et al. 2015, ApJ, 814, 9
Madau, P. & Dickinson, M. 2014, ARA&A, 52, 415
McLeod, D. J. et al. 2015, MNRAS, 450, 3032
McLure, R. J. et al. 2013, MNRAS, 432, 2696
Michalowski, M. J. et al. 2016, arXiv:1610.02409
Narayanan, D. et al. 2015, Nature, 525, 496
Noeske, K. G. et al. 2007, ApJ, 660, L43
Parsa, S. et al. 2016, MNRAS, 456, 3194
Rujopakarn, W. et al. 2016, arXiv:1607.07710
Speagle, J. S. et al. 2014, ApJS, 214, 15
Walter, F. et al. 2016, ApJ, in press, arXiv:1607.06768
Weiss, A. et al. 2009, ApJ, 707, 1201

First ALMA Detection of a Galaxy Cluster Merger Shock

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We report on the first ALMA measurement of a galaxy cluster merger shock, observed at the location of a radio relic in the famous El Gordo galaxy cluster at redshift $z \sim 0.9$. Located at about half the current age of the Universe, this is also the most distant example of a directly measured astrophysical shock. ALMA Band 3 was utilised to measure the Sunyaev–Zel'dovich (SZ) effect signature that confirms a small-scale change in pressure as expected from the passage of a shock in the intracluster medium. The results support a previous radio-based estimate of the shock Mach number and display similarities, and also some mild tensions, with the X-ray based results. Most importantly, these results show the potential of ALMA to detect galaxy cluster shocks, observations that will advance our knowledge of cluster formation, non-thermal particle acceleration and amplification of magnetic fields across the entire observable Universe where such relic shocks can be found.

Scientific context

Shock phenomena are ubiquitous in astrophysics, from the Earth's bow shock in the solar wind to supernova remnants and accretion shocks in the jets of active galactic nuclei (AGN). They signify supersonic gas motions. The largest coherent shock structures known form in and around clusters of galaxies and can be up to megaparsecs in length. One expected example of such a large-scale shock is the accretion shock that occurs at the outer boundary of a galaxy cluster where the denser intracluster gas meets the infalling inter-galactic medium; however, such shocks have not yet been observed directly. Another type of cluster shock is the merger shock, occurring when galaxy clusters collide at supersonic speeds, generating low-Mach-number shocks in the hot intracluster plasma. Studies of merger shocks are important because they provide an understanding of the heating processes in the intracluster medium, point to cluster merger dynamics, including infall velocities, and provide insight into the production mechanism of high-energy cosmic ray particles at the shock fronts.

The observation and modelling of galaxy cluster merger shocks became possible during the last two decades thanks to the superb capabilities of the X-ray spectral/imaging instruments on-board the Chandra and X-ray Multi-Mirror (XMM) Newton satellites. However, it is also possible to detect these shocks in the millimetre/submillimetre (mm/sub-mm) wavebands, by means of the so-called Sunyaev–Zel'dovich (SZ) effect. This is a small modification in the spectral intensity of the Cosmic Microwave Background (CMB) radiation in the direction of galaxy clusters.

The SZ effect is proportional to the line-of-sight integral of the thermal gas pressure, and hence is an ideal tool for measuring the pressure variation created by the passage of a shock. Another very attractive property of the SZ effect is that its surface brightness is independent of redshift, because it depicts a spectral distortion of the CMB as a result of scattering. This makes the SZ effect suitable for measuring structures in the cluster pressure distribution out to very high redshifts. With the fully operational Atacama Large Millimeter/submillimeter Array (ALMA), the mm/sub-mm astronomy community now has a tool to study cluster merger shocks that is as powerful as the X-ray instruments, and a method that is also far more efficient at high redshifts.

One problem with ALMA is its small field-of-view: even in the lowest frequency band currently available (84–116 GHz) the field-of-view is only about one arcminute, while most galaxy clusters are several times larger than that. This makes it difficult to survey a large number of galaxy clusters as far as their outer radii to search for the merger shocks, where a shock front might be observable under favourable projection angles. In this regard a promising approach is to observe galaxy cluster radio relics. Like all other astrophysical shocks, cluster merger shocks accelerate particles and accelerated electrons gyrating in the shock-boosted magnetic field produce megaparsec-long synchrotron emissions, known as radio relics. The connection between cluster merger shocks and the radio relic signals has been established in numerous theoretical works as well as X-ray observations in the low-redshift Universe (see, for example, Skillman et al., 2013; Vazza et al., 2015; Akamatsu & Kawahara, 2013).

We initiated the study of relic shocks in the SZ effect using low-resolution Planck data for the very nearby Coma cluster (Erler et al., 2015), but ALMA has the capacity to truly open up this research frontier, particularly for the great many radio relics expected to be discovered in the southern sky by the Square Kilometre Array (SKA) Pathfinder surveys. This brief article gives a summary of the very first ALMA observation of a cluster merger shock, in the famous $z = 0.87$ cluster ACT-CL J0102-4915 (commonly known as "El Gordo"; see Menanteau et al., 2012) and discusses the future outlook for such measurements. More details on these results can be found in Basu et al. (2016).

ALMA observations of El Gordo

The prominent NW radio relic of the El Gordo cluster was observed with the ALMA main array in December 2015, and also with the ALMA Compact Array (ACA) between January and September 2016. Here we present images and analysis results from the main array data (12-metre diameter dishes) only. The total duration of the observations was 5.2 hr (3 hr on-source time after calibration), which represents a modest amount of telescope time compared to the typically > 100 hours that X-ray telescopes spend on high-z clusters. The ALMA observations were made with thirty-five antennas and reached a root mean square (RMS) noise of 6 μJy/beam at the centre of a CLEAN image (with a synthesised beam size of 3.6 × 2.7 arcseconds), or equivalently, an RMS brightness sensitivity of about 0.1 mK.

Figure 1 shows some of the multi-wavelength data that are available for the El Gordo cluster and puts our ALMA observation in perspective. The background is a colour composite image made of multiple pointings from the Spitzer Infra-Red Array Camera (IRAC) at 3.6 μm, showing the concentration of red galaxies in this distant cluster. The purple contours are derived from a Chandra soft-band (0.5–2 keV) X-ray brightness image and the green contours come from a low-frequency (2.1 GHz) radio observation made with the Australia Telescope Compact Array (ATCA). The opposing pairs of diffuse, extended radio emission can be seen clearly, indicating a merger that happened roughly in the plane of the sky. The most prominent of these radio relics is the NW one, roughly 0.7 Mpc long, which we observed with ALMA in Band 3 (the ALMA primary beam is shown by the white circle). The observed intensity distribution after image deconvolution (the dirty image) is shown as a zoomed-out inset, where a ripple-like signal with peak amplitude of roughly 20 μJy/beam can be identified.

The origin of the faint, ripple-like signal, signifying a shock as seen by ALMA in the SZ effect, is explained in Figure 2. The pressure boost associated with a shock in the intracluster medium creates a step-function-like change in the Comptonisation profile after projection along the line of sight. This is measured as a temperature or flux decrement with respect to the background CMB signal at 100 GHz (Band 3). Since this local pressure boost scales roughly as the shock Mach number squared (typical Mach numbers for cluster merger shocks are ~ 2–4), the change in the SZ signal is non-negligible and ALMA, as the world's most sensitive mm/sub-mm interferometer, can easily detect such signal variations.

However, owing to the incomplete data coverage in the visibility plane (*uv* plane), a direct deconvolution to the image plane generates a ripple-like pattern. This is known as a dirty image and is shown in the right panels of Figure 2 for two mock ALMA observations: one for a realistic noise level comparable to that in our data (peak signal-to-noise in the image is roughly two) and one for data with five times better signal-to-noise. The ripple-like pattern is more evident in the second case whereas in our actual data it is mostly obscured by noise. The extended, cluster-wide SZ signal is practically invisible owing to a lack of sufficiently short baselines in the current interferometric observation.

Using standard synthesis imaging techniques, such dirty images are further processed with methods like CLEAN to approximate the actual intensity distribution on the sky. However, in the case of our weak and diffuse signal, with both positive and negative amplitudes, a blind application of CLEAN does not produce any significant improvements. On the other hand, selecting specific regions to perform the CLEANing operation can cause significant biases in the location and amplitude of the shock jump that we are trying to measure. Hence we developed a method to fit the cluster shock models directly to the data from the interferometer in the visibility plane that bypasses all these imaging steps. The ALMA images shown here are only for illustration; the actual results are based on this *uv*-fitting technique which is novel for ALMA data analysis and particularly suitable for modelling the extended SZ signal in galaxy clusters. The selection of the best-fit model (with the associated uncertainties) is carried out using a Bayesian Monte Carlo Markov Chain (MCMC) method that was implemented using the CASA software and is readily adaptable for combining results from multi-wavelength data.

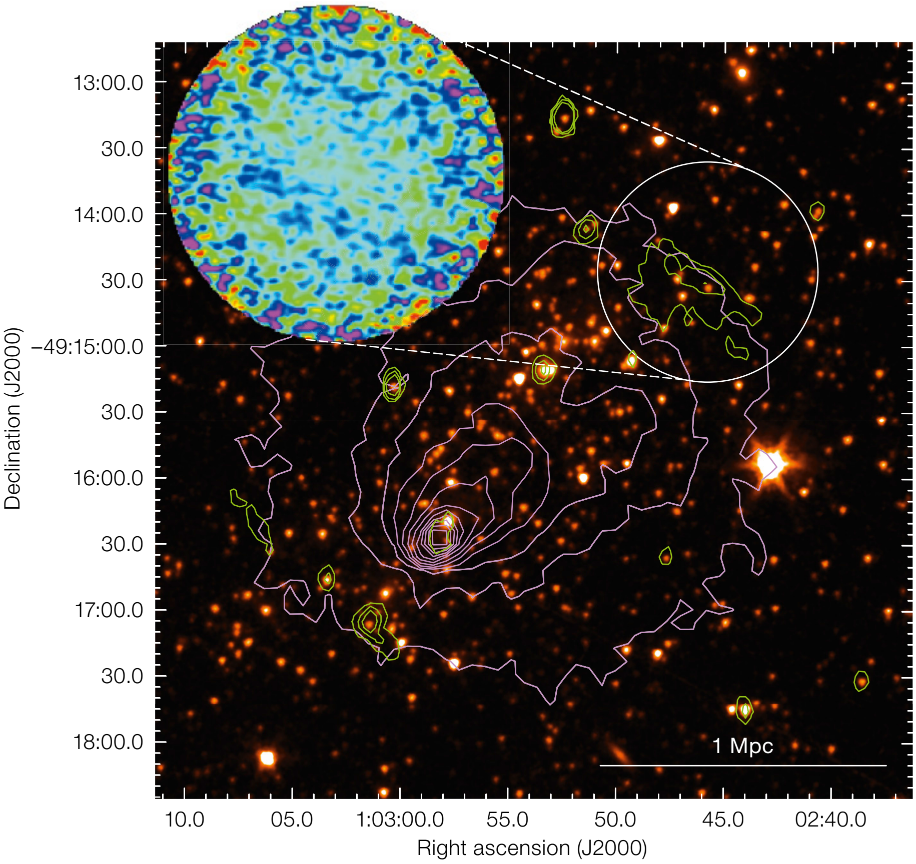


Figure 1. A panchromatic view of the El Gordo cluster and its NW radio relic. The background image is a mosaic from multiple Spitzer/IRAC pointings at 3.6 μm, overlayed with X-ray brightness contours from Chandra data (purple) and 2.1 GHz radio contours from ATCA data (green). The white circle marks the region imaged by ALMA and the zoomed-out inset shows a deconvolved image.

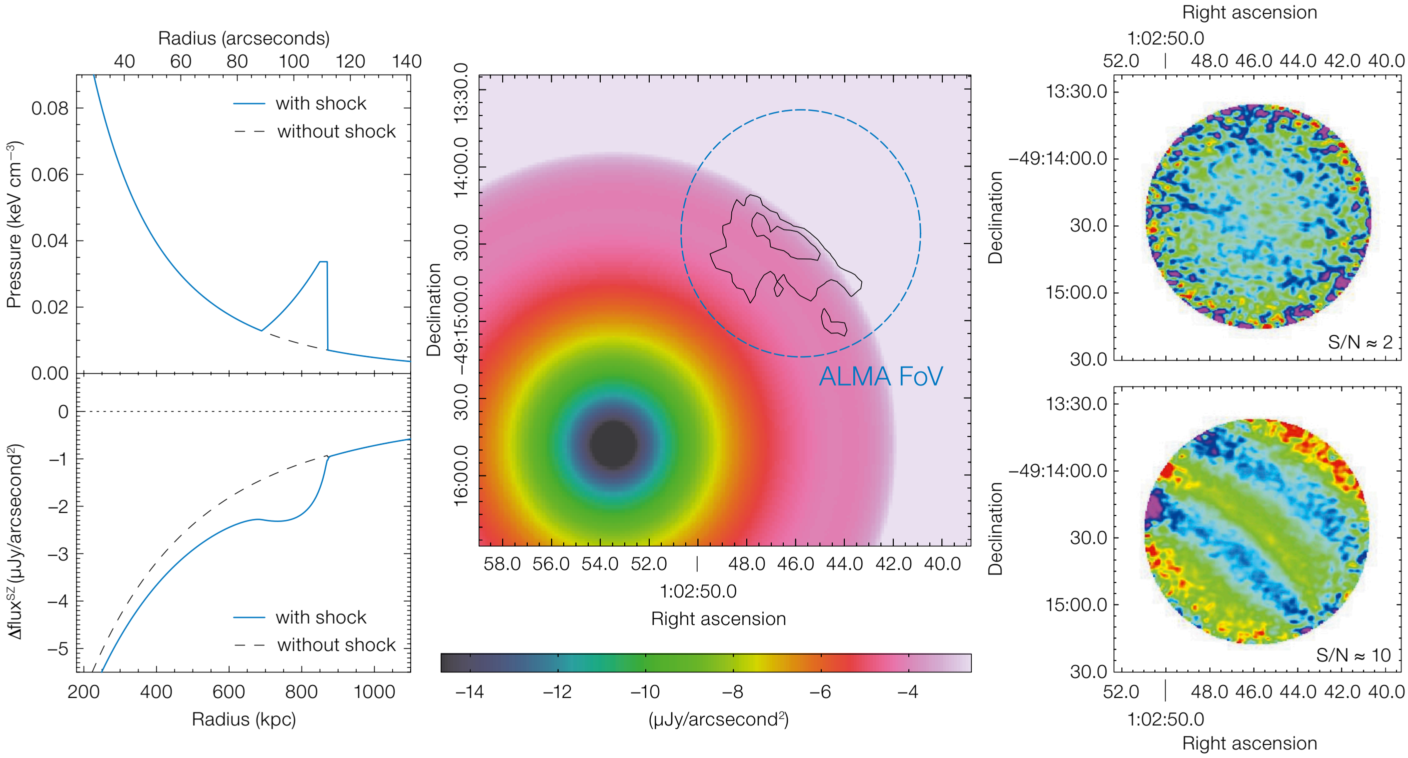


Figure 2. ALMA imaging of a cluster merger shock, illustrated by simulations. The shock-boosted pressure creates a step-function-like change in the SZ flux decrement, shown in the left panels. In the centre a mock SZ image made from this pressure model with the actual relic contours is shown. The ALMA field-of-view (FoV) is shown by the blue circle. On the right are two simulated ALMA observations with different signal-to-noise levels. In reality, we do not use such images but rather fit our shock model directly to the ALMA visibility data.

Shock profile and Mach number

A panchromatic view of El Gordo's NW relic shock is shown in Figure 3. This Figure presents for the first time a consistent picture of the non-thermal (radio synchrotron) and thermal (X-ray emission and SZ effect) signal variations across a cluster merger shock. The top panel is the 2.1 GHz radio profile (Lindner et al., 2014) which was fitted with a phenomenological synchrotron emissivity model. The two middle panels depict the Chandra X-ray temperature and brightness profile measurements. Owing to the high redshift of this cluster, most of the outer X-ray profile lies below the instrumental and astrophysical photon background (denoted by the blue dotted line in the third panel) and hence there are only marginal constraints on the gas temperature from the pre-shock region. In the bottom panel the SZ flux modulations at 100 GHz as observed by ALMA are shown. The green lines show the respective best-fit theoretical models and the red dot-dashed lines are the observed profiles after beam smoothing (radio) or image deconvolution (SZ).

The Chandra brightness data provide a clear measurement of a profile discontinuity that is indicative of a shock. However, such brightness edges can in principle also occur from large-scale contact discontinuities in galaxy clusters, commonly known as cold fronts. Since the X-ray temperature measurements are inconclusive, the cold front scenario can be ruled out using the ALMA SZ data. Indeed, our ALMA data analysis by itself provides support for the existence of a shock at more than the 98 % confidence level. The vertical grey line running through the four panels in Figure 3 is the best-fit shock location from the ALMA data and is fully consistent with the radial shock profiles we derived individually from the radio and X-ray data sets. The accuracy of the determination of the shock location by ALMA is comparable to that from the Chandra X-ray measurement and is better than the best radio data currently available.

We can model the shock Mach number independently, either from the ALMA SZ or the Chandra X-ray brightness measurements, and a comparison between these two is shown in Figure 4. The main Figure presents the joint posterior probabilities for the shock Mach numbers and the pre-shock gas pressure values, where the latter is also denoted as a function of the total cluster mass (assuming a specific intracluster pressure model). While the current ALMA data are very good at detecting the small-scale variations in the pressure profile, they cannot constrain the overall normalisation of that pressure owing to a lack of complementary short-spacing or single-dish data. This creates a strong anti-correlation between the Mach number and the upstream pressure estimates (seen from the green contours). The SZ modelling by itself points towards a weak shock, with the peak probability for the shock Mach number around $M \sim 1.5$. The X-ray brightness modelling, on the other hand, suggests a stronger shock, with $M \gtrsim 3$. When the results from the X-ray analysis are used as a prior in the SZ shock modelling, we get an intermediate value which is shown by the yellow contours in the main panel. The inset Figure shows the marginalised probability distributions

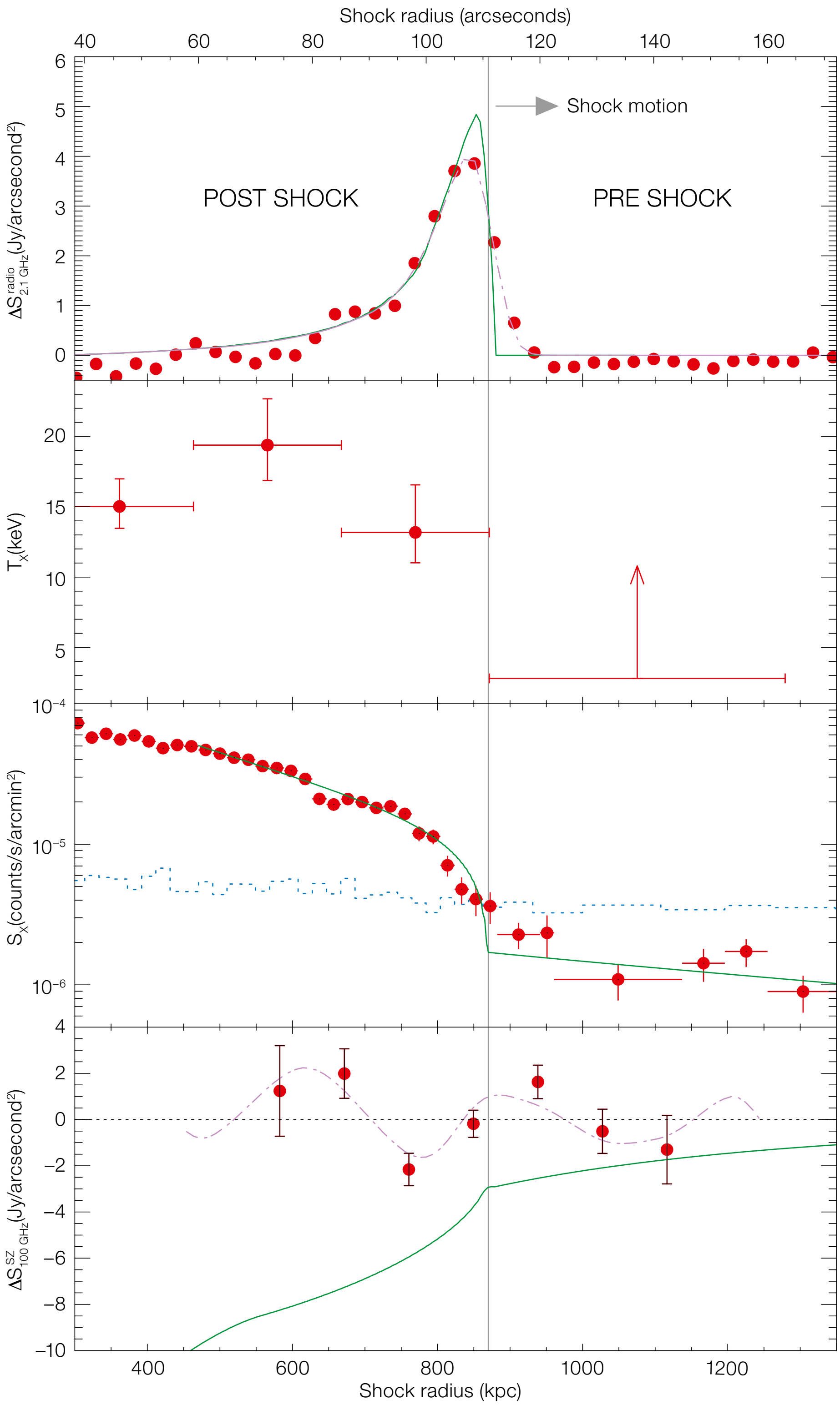


Figure 3. The profile of the NW shock in the El Gordo cluster across three wavebands. From top: radio synchrotron emission from the relic at 2.1 GHz; X-ray temperature estimates from Chandra data; X-ray surface brightness in the soft band (0.5–2 keV); and the SZ effect measurement from the 100 GHz ALMA observation. The vertical line at 870 kpc is the shock boundery, as determined from the SZ data.

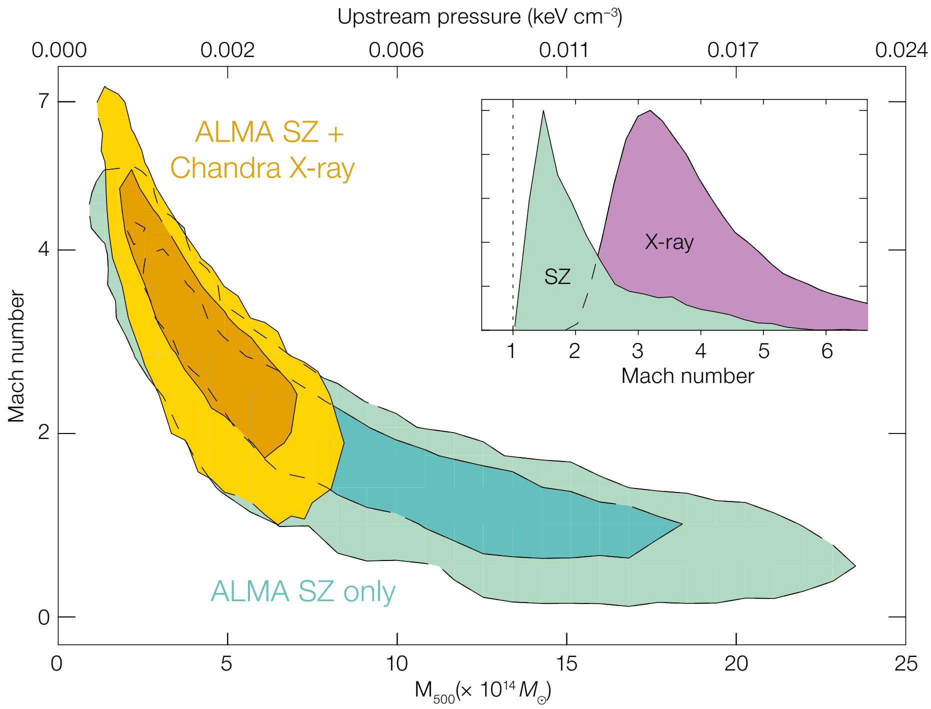
of only the Mach number values derived from the SZ and X-ray modelling independently.

The combined SZ/X-ray peak likelihood for the Mach number is $M \sim 2.5$ and this is fully consistent with a previous estimate made from the synchrotron spectral slope at the leading edge of the relic (Lindner et al., 2014). While this can be used as a justification for the standard diffusive shock acceleration paradigm (DSA; Blandford & Eichler, 1987), at least for this high-*z* radio relic, the mild tension between the SZ and X-ray best-fit estimates could also point to more interesting physics that might be happening at the shock front. This could be, for example, a non-equilibrium between the electron and ion temperatures or a boost in the observed X-ray brightness jump due to an inverse-Compton component. The slight mismatch could also be indicative of the different systematic dependences of the SZ and X-ray signals on the assumed shock geometry. These possibilities are currently under investigation and such joint analyses of SZ and X-ray signals suggest a promising future path for modelling the astrophysics of cluster merger shocks and their connection to the growth of cosmic structures.

Future outlook

We have described the ALMA SZ measurement of a galaxy cluster merger shock at the location of a radio relic. The cluster target is the famous El Gordo, which was detected from the Atacama Cosmology Telescope (ACT) cluster survey via the SZ effect and is likely the most massive high redshift cluster above $z > 0.5$. This object also hosts the highest-redshift radio relics (and radio halo) known to date. The detection of a merger shock at the location of one of these relics is therefore a clear demonstration of the advantages of using the SZ effect to detect high-*z* shock features. The multi-wavelength analysis method employed in our work also provides an example of how to systematically probe the non-thermal and thermal radiation associated with a cluster merger shock, and possibly detect new physical effects that cannot be disentangled from the data at any single waveband.

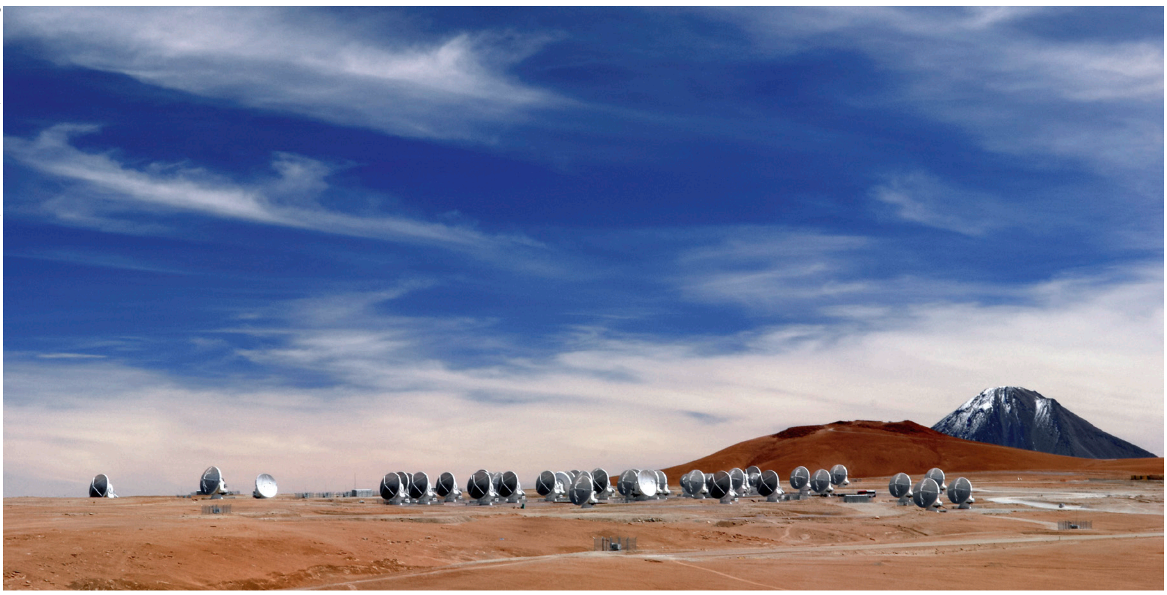
Figure 4. Joint constraints on the shock Mach number and the pre-shock pressure. Green contours are the result of ALMA SZ modelling only, whereas the yellow ones result from using an additional X-ray prior. Darker and lighter colours mark the 68 % and 95 % credibility regions. In the inset are shown the probability distributions for the Mach number as obtained from fitting the SZ and X-ray data.



The ALMA results outlined here are the product of only a moderate amount of observing time (3 hours on-source) and are a clear demonstration of the power of ALMA to study galaxy cluster substructures in the SZ effect. The precision of the current results has been limited by a lack of constraints on the overall normalisation of the SZ signal, but it can be improved by using data from the ALMA Compact Array or single-dish instruments. Even though SZ measurements alone cannot provide a full thermodynamical description of the intracluster medium, as is generally possible from the analysis of X-ray spectral/imaging data, for the purpose of modelling shock Mach numbers the SZ effect is sufficient. In this regard ALMA provides an excellent tool to complement the X-ray shock measurements of many low- and intermediate-redshift objects and to find shock signatures for the first time in many high-redshift ones. Another promising method would be to combine ALMA SZ data with short-duration X-ray observations, where the latter provide estimates for the gas density but not necessarily the temperature, in order to study features present in the intracluster medium through a joint SZ/X-ray analysis. Being the most sensitive sub-arcminute resolution SZ instrument currently available, and also the only one in the southern hemisphere, ALMA is uniquely positioned to make many such observations in the near future.

References

Akamatsu, H. & Kawahara, H. 2013, PASJ, 65, 16
Basu, K. et al. 2016, ApJ, 829, L23
Blandford, R. & Eichler, D. 1987, PhR, 154, 1
Erler, J. et al. 2015, MNRAS, 447, 2497
Lindner, R. R. et al. 2014, ApJ, 786, 49
Menanteau, F. et al. 2012, ApJ, 748, 7
Skillman, S. W. et al. 2013, ApJ, 765, 21
Vazza, F. et al. 2015, A&A, 580, A119



The Atacama Large Millimeter/submillimeter Array on the Chajnantor plateau.

ALMA (ESO/NAOJ/NRAO)/ESO (W. Wild)

ESO/W. Wild

The ALMA Residencia, the last ESO deliverable of ALMA construction, is nearing completion.

Report on the joint ESO/NRAO Conference

Resolving Planet Formation in the Era of ALMA and Extreme AO

held at ESO Vitacura, Santiago, Chile, 16–20 May 2016

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ALMA in its long-baseline configuration, as well as new optical/near-infrared adaptive optics instruments such as SPHERE and GPI, are now able to achieve spatial resolutions considerably better than 0.1 arcseconds. These facilities are enabling us to observe for the first time the regions around young stars where planets form. Already, complex structures including holes, spiral waves and extreme asymmetries are being found in these protoplanetary discs. To discuss these newly-imaged phenomena, and to enable cross-fertilisation of ideas between the two wavelength ranges, a joint ESO/NRAO workshop was held in Santiago. We present here a summary and some highlights of the meeting.

The understanding of how planets form around young stars is an increasingly popular subject, particularly now that that it is appreciated that most stars harbour planetary systems. However, the nearest regions containing stars less than 10 Myr old are generally more than 100 pc distant. This means that typical planet-forming discs subtend an angle of less than 1 arcsecond. Observing these protoplanetary discs requires both sub-arcsecond resolution and the ability to discriminate against the bright stellar photospheric emission. The recent impressive advances in both high-contrast adaptive optics (AO), in particular extreme AO (XAO), and sensitive long-baseline millimetre-wavelength interferometry, in particular using the Atacama Large Millimeter/submillimeter Array (ALMA), are now enabling such studies on angular scales of 0.1 arcseconds or less. This workshop brought together 130 astronomers from both the AO and the millimetre communities to discuss the exciting new results starting to emerge from these facilities.

The workshop was held over one week in May 2016 and both the ESO Vitacura conference room and an overflow 'lounge' in the library were needed to house the audience (see Figure 1). Exemplifying the level of interest and the recent rapid developments in the field, there were 65 contributed talks and 28 posters in addition to the 21 invited talks. A poster session was held on the Monday evening (sponsored by the Centre National de la Recherche Scientifique, CNRS) and the Wednesday afternoon was kept free to give attendees a break from the packed programme. The posters were also judged, and an award was given to Elie Sezestre for a poster entitled "Could the stellar magnetic field explain the structures in the AU Mic debris disc?".

The programme was divided into sessions on: embedded discs; classical "protoplanetary" discs; disc theory; transition discs; disc surveys; planetesimals; disc dispersion and evolution; and finally debris discs and young planets. In addition there was a session focusing more on instrumentation, particularly ALMA and AO facilities including the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) on the Very Large Telescope (VLT), the Gemini Planet Imager (GPI) and coronagraphs on the Keck and Subaru telescopes, as well as future XAO instrumentation.

Dust images

Highlighting the meeting were the many high-resolution continuum images recently obtained at submillimetre (sub-mm) and infrared/optical wavelengths. As

Figure 1. Over 130 participants taking the photo break outside during the typical Santiago winter weather.

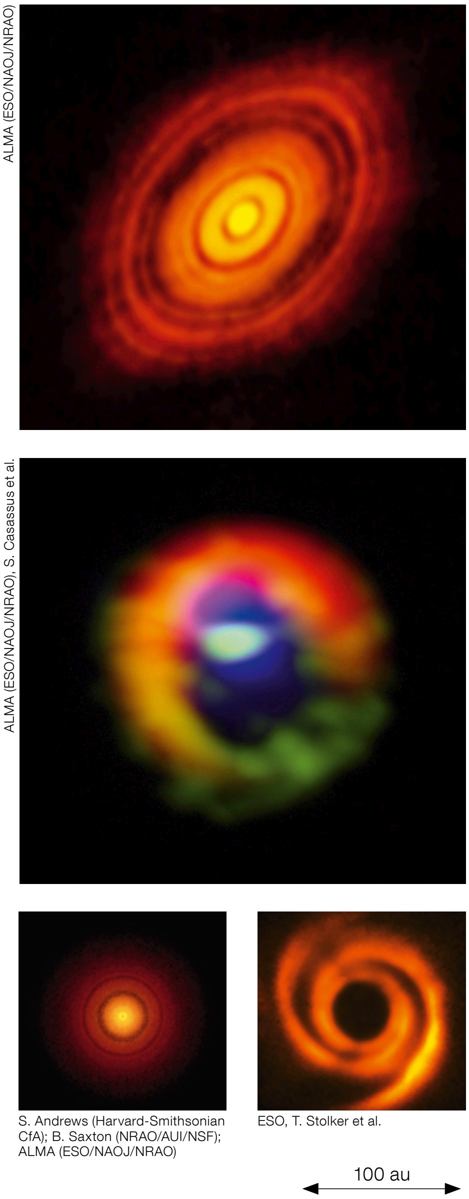

Figure 2. A few examples of protoplanetary discs shown during the meeting, illustrating the wide variety of structures found. Top: HL Tau (ALMA Partnership, 2015); middle: HD 142527 (Casassus et al., 2013; Boehler et al., in prep. using ALMA); lower left: TW Hya (Andrews et al, 2016, using ALMA); lower right: HD 135344B (from Stolker et al., in prep. using SPHERE XAO). All are shown on the same linear scale, except HD 142527, which is compressed by a factor of two.

pointed out, these superb new results clearly illustrated the fact that protoplanetary discs do not have the simple power-law radial density structures so beloved of theoreticians for the last 20 years or more (see the presentation by Giuseppe Lodato). In reality all discs have complex — and often very different — structures. The examples in Figure 2 illustrate both their similarity and their diversity. Some, such as HL Tau and TW Hya, have smooth, axisymmetric, concentric rings (presentations by Takashi Tsugakoshi and Andrea Isella). Others such as HD 135344 show low-order spiral arms (see the presentations by Henning Avenhaus, Elsa Huby and Matias Montesinos). Yet others, like HD 142527, have extreme asymmetries in their mm distributions, along with large central holes (Yann Boehler).

Continuum observations of these systems tend to trace dust of a size comparable with the wavelength, meaning there is a factor of ~ 1000 difference between the grain sizes traced by XAO and those traced by ALMA. Comparison images were shown which revealed interesting similarities and differences, promising a better understanding of the dust dynamics (Francois Menard). For example, grain size segregation can result from dust trapping induced by embedded planets or radiation pressure from the star (Paola Pinilla). The challenge now is to account for the multi-wavelength data available by combining the results in a self-consistent model.

A point emphasised during the meeting was that care must be taken in interpreting the images. For example, emission from dust can become optically thick in some discs, even at sub-mm wavelengths. Polarisation — often regarded as the way to measure the magnetic field from aligned grains in discs — is also affected by self-scattering of radiation at wavelengths even as long as 1 mm (Akimasa Kataoka, Adriana Pohl and Gesa Bertrang). Moreover XAO scattered light images tend to show the disc surface layers, which may not reflect the structure in the mid-plane. Finally, images were shown which indicated apparent changes in the outer disc structure on timescales of about one year, and these were interpreted as shadows projected from the inner region, and not part of the main disc structure itself (Tomas Stolker).

Gas in discs

Gas mass estimates in discs are still uncertain and, although self-consistent chemical models have improved, deciphering the physical conditions from molecular gas lines is clearly still a complex problem (Michiel Hogerheijde). Nevertheless, evidence is now being found of chemical abundance changes in discs, including global depletion (Megan Ansdell), as well as local depletion, including radial abundance changes, freeze-out in the disc mid-plane, and photodissociation on the surface (Mo Yu, Hideko Nomura and Stephane Guilloteau). Other exciting new results were the images of snow lines, where different molecules freeze out at different radii in the disc. These are regions thought to have enhanced core and planet formation rates — and some real examples were shown (Kamber Schwarz and Dominika Boneberg). As well as the ubiquitous ^{12}CO, instrumental sensitivities now allow imaging of complex molecules, including deuterated or isotopic species and simple organics (Viviana Guzman Veloso). Gone are the days semi-resolved CO blobs! However, it was recognised that spectral line observations of discs are always likely to be more difficult than those for dust continuum.

Transition discs

It was realised early on, from spectral energy distributions, that there exists a somewhat different class of disc with a large central hole, thought to be evolving from a disc to a planetary system. Resolved images presented at the meeting showed that such transition discs have a ring of millimetre-sized grains, with a large central cavity containing predominantly micron-sized dust and gas. This was explained by the trapping and growth of dust in the ring, along with dust filtration — a mechanism allowing small grains and gas through to the centre (for example by Sebastian Perez and Nicolás Cuello). This mechanism can maintain gas accretion onto the star, even with a central hole. Several presentations showed images of these systems in excellent detail, revealing not only the central cavity, but also detailed structures such as spirals, and warps in the ring (see Figure 2, and the presentations by Nienke van der Marel, Gerrit van der Plas, Clément Perrot and Matthias Schreiber).

Young planets

Catching planets in the process of formation is clearly an interesting topic and there is a concerted effort to find protoplanets, particularly around the central holes of transition discs. Although proof of a planet is not always straightforward, some candidates were shown during the meeting, along with several interesting predictions of the observational effects of planets on discs (Claudio Cáceres, Anne-Lisa Maire, Stephanie Sallum, Kazuhiro Kanagawa, Elena Sissa and Matías Gárate). At some point or other, planets were blamed for almost all of the structural complexities now being discovered, but it was clear that there were other possible explanations (as suggested, for example, by Sascha Quanz and Munetake Momose). Several authors are starting to use the observed disc structure to estimate planet masses and orbital parameters (Giovanni Rosotti, Judit Szulagyi, Hauyu Baobab Liu, Ilse Cleeves and Valentin Christiaens). Related to this was some discussion of binary systems and their effect on discs (Joel Kastner, Jorge Cuadra and Meredith MacGregor), one example being disc warping and shadowing.

Disc theory

Dust evolution in discs was discussed in terms of grain collisions and their outcomes, and dust transport — including turbulence, settling, and radial drift. Particle trapping was considered as an important and ubiquitous effect, and the contributors described how this could be caused by relatively small pressure bumps, by embedded planets or by rotational instabilities (for example, Paola Panilla, Laura Perez and Giuseppe Lodato). Many images showed evidence of these particle traps, which operate both radially (giving rise to rings and gaps) and azimuthally (resulting in non-axisymmetric clumps). This was something not appreciated until the new images actually showed the evidence. Some examples are shown in Figure 2.

Moreover, with the high dynamic range imaging now possible, spiral structures are also being found (Figure 2). There were presentations of methods to distinguish between spirals induced by planets and those resulting from gravitational instabilities, and the new images are providing the "ground truth" for these debates.

One issue which is still unclear is gas accretion. Observations indicate accretion rates can be ~ 10^{-7} $M_{\odot}$/yr, yet the observations so far are suggesting that discs are not particularly turbulent, implying that models of viscous disc accretion may need to be revised (Phil Armitage, Jacob Simon and Christophe Pinte).

Statistics and disc evolution

It was pointed out that the spectacular resolved images only represent 1 % of all discs. So what about more typical systems? Instrument sensitivities now enable disc statistics to be measured over whole star-forming regions, and the first results of some of these studies were presented, providing estimates of disc lifetimes as a function of stellar mass and binarity (Lucas Cieza, Scott Barenfeld and Megan Ansdell). Disc dissipation and evolution are not yet fully understood, but gas removal mechanisms, including photoevaporation and planet interaction, were discussed (Uma Gorti, Cathie Clarke and Olja Panic). At least one example of a disc caught in the act of dissipating was shown (Emmanuel Di Folco).

Debris discs & planets

Debris discs are somewhat different from protoplanetary discs, in that they are normally dust-dominated and found around older main-sequence stars. It has long been assumed that they are composed of secondary dust released in collisional cascades of larger bodies. Systems were described which may be hybrid between protoplanetary and debris discs, containing mostly dust but with some traces of gas. The origin of their gas is presently unclear; some contributors presented evidence that some disc systems could contain remnant primordial material, and others that they could contain gas released from secondary collisions (Andreas Moór, Luca Matrà, Sebastian Marino and Daniela Iglesias).

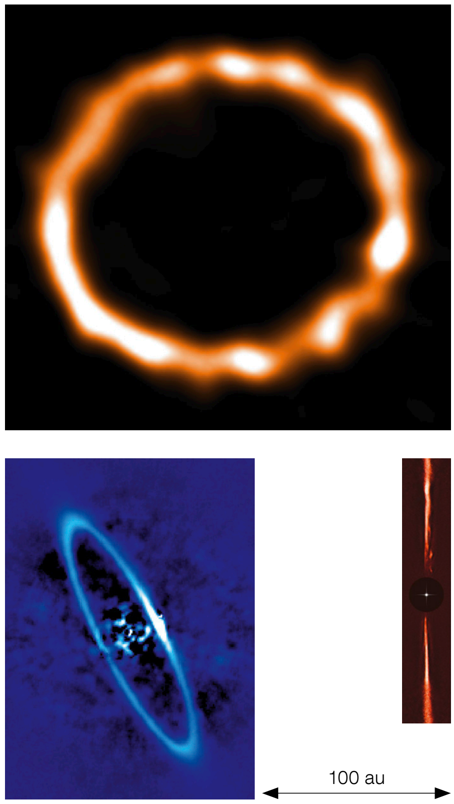

Figure 3. Some examples of high resolution images of debris discs, shown on the same spatial scale. Clockwise from top: the face-on system HD 181327 with ALMA (from Marino et al., 2016); the edge-on disc AU Mic (from Boccaletti et al., 2015) with SPHERE; and HR 4796A with SPHERE-IRDIS (from Milli et al. in prep.).

Several spectacular new images, both from the ground and from space, of debris systems were shown during the meeting (some examples are shown in Figure 3 and see also Anne-Marie Lagrange, Katherine Follette, Thayne Currie and Mark Booth). These high-resolution data commonly show rather narrow rings of dust — sometimes eccentric, warped, or asymmetric. Such structures are thought to be caused by secular perturbations, resonances and/or scattering by unseen planets (Mark Wyatt and Virginie Faramaz). Encouragingly, the number of scattered light discs detected (and resolved) with new XAO systems (as well as with improved data reduction of archived Hubble Space Telescope data) is now providing a first look at the statistics of their morphology (Markus Kasper, Elodie Choquet and Maud Langlois).

The big picture

Interspersed throughout the conference were summary reviews of the established planet formation mechanisms invoked to describe the formation of the Solar System and known exoplanets, and how they are both challenged and supported by the new results (Hilke Schlichting, Ruth Murray-Clay and Benjamin Bromley). Overall, it was clear from the superb images, the models, and the discussions held during the meeting that the new high-resolution facilities are transforming our understanding of the field. An audience vote on the newly discovered disc structures favoured their being caused by a combination of protoplanets as well as complex disc physics and chemistry. We can expect many more fascinating high-resolution results in the next few years. The challenge is to link these results with planet formation models as well as with the zoo of exoplanets now being discovered.

Most of the talks and posters are available on the conference website[1]. They are also available through Zenodo[2] and linked through the Astrophysics Data System (ADS[3]).

References

ALMA Partnership: Brogan, C. L. et al. 2015, ApJ, 808L, 3
Andrews, S. M. et al. 2016, ApJ, 820, L40
Boccaletti, A. et al. 2015, Nature, 526, 230
Casassus, S. et al. 2013, A&A, 553, 64
Marino, A. et al. 2016, MNRAS, 460, 2933

Links

[1] Workshop website: http://www.eso.org/sci/meetings/2016/Planet-Formation2016/
[2] Zenodo: http://zenodo.org/
[3] ADS: http://adsabs.harvard.edu/

Report on the ESO Workshop

Very Large Telescope Adaptive Optics Community Days

held at ESO Headquarters, Garching, Germany, 20–21 September 2016

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The future of adaptive optics (AO) instruments at the VLT was discussed during a two-day workshop. Three major directions emerged from these discussions: adaptive optics in the optical; multi-object adaptive optics (MOAO); and extreme adaptive optics (XAO). The science cases for these three options were presented and the discussions are summarised. ESO is now planning to provide detailed science cases for an optical AO system and to prepare upgrade plans for XAO and MOAO.

Introduction

ESO is planning the future of adaptive optics with the Very Large Telescope (VLT). With the Adaptive Optics Facility (AOF; Arsenault et al., 2010, 2014, 2016), the VLT will deploy a powerful tool for correcting the distorting effects of the Earth's atmosphere. As part of the AOF, the GRound layer Adaptive optics Assisted by Lasers module (GRAAL) will provide a wide-field (7 × 7 arcminute) ground-layer adaptive optics imaging system for the High Acuity Wide field *K*-band Imager (HAWK-I). Also part of the AOF, the Ground Atmospheric Layer Adaptive optiCs for Spectroscopic Imaging module (GALACSI) will provide two modes of optical corrections for the Multi Unit Spectroscopic Explorer (MUSE), one providing a doubling of the encircled energy over the 1 × 1 arcminute field-of-view of MUSE, and the other with a narrow field (7.5 × 7.5 arcseconds) with at least 5 % Strehl ratio at 650 nm for the MUSE narrow field mode. The Enhanced Resolution Imaging Spectrograph (ERIS) will complement the instrument suite on Unit Telescope 4 (UT4) offering *J*-, *H*- and *K*-band integral field spectroscopy and *J*- to *M*-band imaging with a single-conjugate AO (SCAO) system with high Strehl ratio.

The VLT AO Community Days provided an opportunity to discuss the future of AO at the VLT. The aim was to explore the scientific goals of a new instrument to make good use of the AOF, ideally while complementing the European Extremely Large Telescope (ELT) capabilities. There were 54 registered participants at the Community Days and the programme, with links to the presentations, is online[1].

The VLT AO Community Days started with an overview of the existing and planned AO instrumentation on the VLT (see Table 1). Major development paths for multi-conjugate adaptive optics (MCAO), multi-object adaptive optics (MOAO) and extreme adaptive optics (XAO) were presented. MCAO corrects more than one turbulent layer in the atmosphere and can achieve corrections over a larger field-of-view than single-conjugate adaptive optics systems, like NAOS-CONICA (NACO) and ERIS, are able to. ESO deployed an MCAO test instrument in 2007 (the Multi-conjugate Adaptive optics Demonstrator — MAD; Marchetti et al., 2007). In MOAO several non-contiguous fields are corrected individually so as to permit observing over a wider area. XAO reaches the highest density of correction over a small

Name	Year starting operation	Instrument modes	Field of view	Comments
NACO	2002	Imaging: *JHKsL′M′* Spectroscopy: 0.9–2.6 μm Coronagraphy Polarimetry	14 × 14″ 28 × 28″	NIR wavefront sensor; to be decommissioned in 2019
SINFONI	2004	Integral field spectroscopy: 1.1–2.45 μm	3 × 3″ 0.8 × 0.8″	To be upgraded for use with AOF as part of ERIS
SPHERE	2015	Imaging: 0.95–2.3 μm Spectroscopy: 0.95–2.3 μm Coronagraphy Imaging & polarimetry: 500–900 nm	11 × 11″ 3.5 × 3.5″	On-axis correction only
HAWK-I	2018	Imaging: *JHK*	7 × 7′	Ground-layer AO
MUSE	2018	Integral-field spectroscopy: 480–930 nm	1 × 1′ 7.5 × 7.5″	Optical ground-layer AO Optical laser tomography
ERIS	2020	Imaging: *J*–*M′* Integral-field spectroscopy Coronagraphy: *L*-, *M*-bands	27 × 27″ 54 × 54″ 8 × 8″	

Table 1. VLT AO instruments and AO-assisted instrument modes.

field-of-view and the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) is currently the VLT instrument serving this need.

A discussion session at the end of the first day of the meeting was used to clarify several issues connected to adaptive optics. The importance of astrometry, the potential of new noiseless detectors, and different metrics for image quality were part of this discussion. The distinctions between Strehl ratio, full width at half maximum, encircled energy and image stability can be of particular importance to individual science cases. The definition of a new instrument will have to clearly specify the important parameters in terms of image quality. The second day began with a general introduction to future directions of adaptive optics, which was followed by several presentations on specific science cases for the AO modes described above. An open discussion at the end of the second day was used to collect opinions on the different science cases and the scientific promise they provide.

Science with adaptive optics

The science cases for new adaptive optics instrumentation cover several broad topics. Adaptive optics has opened up the study of the close environments of stars (circumstellar discs and exoplanets) and this is clearly the realm of XAO. Other science topics addressed by such instruments are star formation and evolution as well as the formation of planets and planetary systems. SPHERE is currently proving very effective for such observations in the near-infrared and at optical wavelengths, producing a stream of publications (16 publications in 2015 and 22 already in 2016 at the time of writing). A second case is the study of stellar populations in nearby resolved objects — stellar clusters and (dwarf) galaxies in the Local Group and beyond. The important parameter for this research is the concentration of the stellar light into stable point spread functions (PSFs) which ensure accurate photometry and astrometry. Since the spectral energy distribution of most stars peaks in the optical, short wavelengths are important for this science case. The example of MAD near-infrared observations combined with optical Hubble Space Telescope (HST) imaging shows the power of a wide wavelength range (for example, Ferraro et al., 2009; Fiorentino et al., 2011). This is a typical MCAO application.

The third science case deals with resolved objects, typically at large distances, where the improved image quality allows one to analyse individual regions in galaxies rather than only the global parameters (for example, Förster Schreiber et al., 2014; Genzel et al., 2014; Troncoso et al., 2014). The galaxies are, however, sparsely distributed on the sky and a non-contiguous corrected field must be considered. Important clues to the history of star formation are provided by the morphologies of galaxies observed in the local Universe, in particular their discs. An instrument like the *K*-band Multi Object Spectrograph (KMOS) could be supported through an AO module in such a case (MOAO). Other emerging AO applications discussed at the Community Days were: astrometry, for example to measure proper motions of individual stars or to search for stellar-mass black holes in nearby stellar systems; time domain observations in crowded fields (comparing variable stars in the field and in clusters; unique events like the flares around the massive black hole at the Galactic Centre); and the use of adaptive optics to push the limiting magnitude for point sources.

There was general agreement that SPHERE represents an ideal basis for future upgrades. Several potential upgrades were mentioned, such as a pyramid wavefront sensor to reach fainter reference stars; higher correction frequency; fibre coupling to the CRyogenic InfraRed Echelle Spectrometer [CRIRES]. A fibre link to the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations [ESPRESSO] has also been proposed recently as well. These options would push the contrast sensitivity of SPHERE towards reflected-light planets, and the high-resolution spectroscopy would enhance the capability to characterise exoplanet atmospheres. These items should be discussed as part of an upgrade planning of VLT instruments.

The galaxy-formation MOAO science case is an extension of the (large) programmes currently running with KMOS, targeting spatially resolved star formation in high-redshift galaxies and the kinematics of stars and gas in the precursors of present-day galaxies. With improved angular resolution, the individual parts of galaxies, such as giant HII regions, discs, in/outflows and their kinematics, could be resolved and investigated. The number density of these objects is fairly small, expected to be about five objects per 3 × 3 arcminute field with $K_{AB} < 20.0$ mag, which makes the multiplex gain rather small. Upgrading KMOS with a corresponding AO module is difficult, as the current spaxel size (0.2 arcseconds) is too coarse for AO-supported images, while reimaging may lead to integrated field unit (IFU) fields of view that are too small for the typical galaxy sizes (< 2 arcseconds). At the moment it is unclear whether a sufficient multiplex could be reached to give a significant advantage over single-object observations with SINFONI. MOAO should be discussed in the context of future instrument upgrades.

Resolving stellar populations implies observing individual stars in other galaxies in two or more filters and placing the measurements in a colour-magnitude diagram (CMD). This requires a combination of high angular resolution and high flux sensitivity. Adaptive optics can extend the reach to larger distances and also into denser regions. Contiguous fields with good, but not necessarily excellent, correction can provide the necessary statistics. A useful field-of-view is defined as one which provides measurements of a sufficient number of stars to populate a CMD, corresponding to roughly the diameter of the half-light radius in globular clusters in the Milky Way, i.e. about 1 arcminute. A wide wavelength range clearly benefits the interpretation of a CMD and in particular access to optical wavelengths would make a big difference. Pushing to wavelengths as blue as 500 nm would include observations of some important emission lines (for example [O III]) and also cover the peak of the blackbody curve of common G type stars. An important issue is the photometric accuracy that the system should deliver. A typical uncertainty that can be accepted is ~ 0.03 magnitudes. The magnitude difference for multiple main sequences in globular clusters is < 0.02 magnitudes. The field-of-view of existing and planned optical AO systems at the VLT is very limited: SPHERE with ZIMPOL (the Zurich IMaging POLarimeter) offers 3.5 × 3.5 arcseconds and the narrow-field mode of GALACSI with MUSE provides 7.5 × 7.5 arcseconds.

Additional considerations

The AO applications at the VLT should be seen in the wider context of imaging and spectroscopy with high image quality. Table 1 gives a flavour of the AO-supported instrumentation at the VLT in the next decade. Only NACO is scheduled to be retired by then and its capabilities will be superseded by ERIS. The ELT will provide superior image quality at near-infrared wavelengths with the first-light instruments MAORY (the Multi-conjugate Adaptive Optics RelaY), MICADO, and HARMONI. It is noteworthy that the diffraction limit of an 8-metre telescope at 500 nm corresponds to the diffraction limit of a 40-metre telescope at 2.2 μm.

HST will continue in operation until the scientific return diminishes, or it can no longer be maintained. It can be assumed that a few years into the operation of the James Webb Space Telescope (JWST), HST will cease to offer observing time. This will end over two decades of high-angular-resolution imaging in the ultraviolet and optical. JWST will cover the near- and mid-infrared wavelengths with improved image quality once it starts operating in 2019. By 2025, Gaia will have provided an astrometric coordinate frame covering the whole sky and Euclid and LSST will have mapped large fractions of the sky (to about 25th magnitude).

Some technical developments are also changing the landscape. In particular, new infrared detectors for wavefront sensing with exquisite noise performance will allow reference stars to be pushed to fainter magnitudes. The functionality of MEMS (micro-electro-mechanical systems) opens up new possibilities. They could be used to dissect the field-of-view into individually corrected sub-fields by an innovative use of the lasers, to replace the deformable mirror for atmospheric correction — potentially also in open loop — and as configurable slit masks.

Summary

There was general consensus at the VLT AO Community Days that an upgrade path for SPHERE should be defined to further develop XAO at the VLT. Clearly, the next-generation XAO instrument needs to be on the ELT. The science cases for reduced inner working angle and higher-contrast imaging are based on exoplanet characterisation and star formation research. The MOAO case is mostly focused on galaxy formation and evolution. The exact multiplex needed for this latter science case is unclear. Statistically significant samples (several hundred galaxies, if possible) are required for a detailed mapping of the star formation history and the dynamical changes of galaxies over cosmic time. The MCAO case for optical and infrared wavelengths appears to offer the biggest gain for future AO on the VLT. Optical AO has only recently started, but is already providing interesting results (for example, SPHERE/ZIMPOL, MagAO at Magellan and the recent tests with the Gemini Multi Object Spectrograph [GMOS] and the Gemini Multi-conjugate adaptive optics System [GeMS]).

The outcome of the VLT AO Community Days was presented to the La Silla Paranal subcommittee of the Scientific Technical Committee (STC). The STC recommends pursuing the studies for a new optical/near-infrared MCAO system and upgrade paths for SPHERE and KMOS. These studies should be presented to the STC in the coming year so that it can issue recommendations on the respective scientific merits.

References

Arsenault, R. et al. 2010, The Messenger, 142, 12
Arsenault, R. et al. 2014, The Messenger, 156, 2
Arsenault, R. et al. 2016, The Messenger, 164, 2
Ferraro, F. R. et al. 2009, Nature, 462, 483
Fiorentino, G. et al. 2011, A&A, 535, A63
Förster Schreiber, N. M. et al. 2014, ApJ, 787, 38
Genzel, R. et al. 2014, ApJ, 785, 75
Marchetti, E. et al. 2007, The Messenger, 129, 8
Troncoso, P. et al. 2014, A&A, 563, A58

Links

[1] Programme of VLT AO Community Days: http://www.eso.org/sci/meetings/2016/VLTAO2016/program.html

Claus Madsen Retires

Tim de Zeeuw[1]
Jeremy Walsh[1]

[1] ESO

Claus Madsen began at ESO as a photographer in 1980 and recently retired as senior advisor on international relations. During his career he authored several books, the most notable being a history of ESO from the late 1980s to the 50th anniversary in 2012. A brief appreciation of his career is presented.

Figure 1. Claus Madsen (left) discussing the history of ESO with the second Director General, Adriaan Blaauw, at his home in Groningen, the Netherlands.

Claus Madsen began working at ESO just as the newly built Headquarters was being occupied by staff in 1980. He began as a photographer (which fitted well with his hobby) and worked closely with his fellow countryman Richard West in the ESO Sky Atlas Laboratory. This involved both photography at the telescope, curation and duplication work on the ESO-Schmidt Southern Sky Survey (later combined with the plates from the UK Science Research Council 1.2-metre Schmidt at Siding Spring, Australia as the ESO/AAO Southern Sky Survey) and development of photographic techniques, such as masking to enhance the contrast range of prints (Madsen, 1981) and wide-field sky photography. He was a co-author of the pictorial atlas of the southern skies (Laustsen et al., 1987), whose publication coincided with ESO's 25th anniversary. This book proved very popular and was subsequently translated into Spanish, German, and Danish.

The increasing importance of information dissemination led to the ESO Information and Photographic Service which was set up in 1986 under Richard West's leadership. Claus was a key member and he broadened his skillset. In the time before the web, exhibitions were an important part of the promulgation of ESO's activities and Claus was involved in the organisation of many of these, such as at Expo 92 in Seville, Spain and also several in Chile. Claus also assisted the former Director General (DG), Adriaan Blaauw, in the preparation of his book on the early history of ESO (Blaauw, 1991).

Outreach and policy

As photography gave way to digital (mostly CCD) imaging as an observational technique, so Claus moved his focus towards outreach and into policy on a wider stage. He was editor, with André Heck, of *Astronomy Communication* in 2003. The ESO DG at that time, Catherine Cesarsky, promoted ESO's entry into the European science arena through ESO membership of EIROforum and Claus was a key member of ESO's EIROforum Team (Madsen, 2004). In 2005 he became Head of the Educational and Public Relations Department. During this time he was closely involved in the planning for the International Year of Astronomy, which was declared by the United Nations (UN) in 2007 and celebrated in 2009, as the 400th anniversary of Galileo's telescope. By 2008 his work in international relations had increased and he was appointed Senior Advisor for International Relations.

Claus continued to be closely involved with EIROforum and from September 2010 to August 2011 he was seconded to the European Fusion Development Agreement Joint European Torus (EFDA/JET) based at Culham, United Kingdom to support EIROforum activities. Then from September 2011 to August 2012 he was seconded to CERN as Chair of the Coordination Group of EIROforum. The fruits of his learning in these corridors were transmitted in the well-received *Scientific Europe: policies and politics of the European research area*, which explains the maze of research funding (Madsen, 2010). In 2011, at the request of the current DG, Claus worked intensively on the recent history of ESO, to follow on from Adriaan Blaauw's book on the early history (Blaauw, 1991). The resulting tome, *The Jewel on the Mountaintop*, was published for ESO's 50th anniversary in 2012 and showed Claus's flair for writing that is both engaging, historically informed and highly communicative. Most recently he also represented ESO on the UN Committee on the Peaceful Uses of Outer Space, specifically in the area of alerts for Near Earth Asteroids (NEA's). By reporting accurate ephemerides of asteroids, he could several times save the Earth from a catastrophic collision!

Retirement

Claus retired from ESO in August 2016 but returned for a farewell party on 22 November 2016 attended by many ESO colleagues and accompanied by his wife and one of his sons. The Director General presented him with a liquid souvenir of his many evenings in the ESO

Guest House in Santiago. Claus said he could recommend retirement for opening up new avenues and he has enthusiastically taken up his old love of photography once more. He emphasised that the history of ESO is bound up with advances in European astronomy and he is a strong advocate that ESO should engage in astronomy across the electromagnetic spectrum — a trend that is beginning to happen with the hosting of the southern Cherenkov Telescope Array at Paranal.

References

Blaauw, A. 1991, *ESO's Early History — The European Southern Observatory from Concept to Reality*, (Garching, Germany: ESO)
Heck, A. & Madsen, C. (ed.) 2003, *Astronomy Communication*, Astrophysics and Space Science Library, 290
Laustsen, S., Madsen, C. & West, R. M. 1987, *Exploring the Southern Sky: a pictorial atlas from the European Southern Observatory* (ESO), (Springer)
Madsen, C. 1981, The Messenger, 25, 16
Madsen, C. 2004, The Messenger, 116, 42
Madsen, C. 2010, *Scientific Europe: policies and politics of the European research area*, (Brentwood, UK: Multi-Science Publishing)
Madsen, C. 2012, *The Jewel on the Mountaintop*, (London: Wiley-VCH)

Retirement of Dietrich Baade

Jeremy Walsh[1]

[1] ESO

After 35 years as an astronomer at ESO, Dietrich Baade has retired. He held many different scientific positions in ESO during his career and a brief appreciation is presented, together with a glimpse of his astronomical research interests. A retirement party was held in September 2016.

Dietrich Baade

Dietrich Baade retired from ESO at the end of September 2016 with 35 years service, after a highly varied career within the Organisation. He joined ESO as a Fellow in February 1981, having received his PhD from the Astronomisches Institut, Universität Münster in 1979. After his Fellowship he joined the Space Telescope European Co-ordinating Facility (ST-ECF) when it was set up at ESO Garching in 1984, long before the actual launch of the Hubble Space Telescope (HST) in 1990. There he worked in the area of instrument calibration, particularly for the High Resolution Spectrograph (HRS), and was involved in the development of an exposure time simulator for HST instruments. When HST was subsequently launched he worked with Leon Lucy on restoration and deconvolution of the aberrated images with increased sampling, and also applied these methods to imaging with the New Technology Telescope (NTT).

On leaving the ST-ECF he worked in the Visiting Astronomers Section providing support for data reduction visitors and use of the remote observing facility, by which visitors could use the NTT, and the Coudé Echelle Spectrometer (CES) at the Coudé Auxiliary Telescope (CAT), in remote mode. He was a long-time user of MIDAS (Munich Image Data Analysis System) and contributed to the development of the data reduction system and the Data Organiser. He was a member of the working group (headed by Preben Grosbol) that conceived the Very Large Telescope (VLT) Science Data Flow and edited the first version of the VLT Science Operations Plan that has subsequently matured to the standard of today.

Telescopes, instruments and detectors

A few years after the opening of the NTT, with its outstanding image quality (Wilson, 1989), a team was set up within ESO, headed by Dietrich, to determine why the initial promise could not be sustained (Baade et al., 1994). Claus Madsen refers to this in his book (Madsen, 2012) as the "Dream Team". The team found that the operations and the control software required improvement and this was seen as an opportunity to install and test the VLT Control Software, which was in advanced development, and thus to provide an opportunity to test and develop the VLT operations model. It was decided to take the telescope out of commission for a year to refurbish it. Lead of this project was continued by Jason Spyromilio and culminated in the "NTT Big Bang" which was completed in 1997 (Mathys, 1997).

Dietrich then moved as instrument scientist to the development of the Wide Field Imager (WFI) to be installed on the 2.2-metre MPG/ESO telescope at La Silla. This 67 megapixel camera, with a field of 34 by 33 arcminutes (using eight charge-coupled device [CCD] chips) and a large suite of filters, was built by ESO (Baade et al., 1995). The WFI was successfully commissioned in 2002 (after the camera head was carried in Dietrich's hand luggage from Garching to La Silla) and was in service as ESO's large area camera for a decade before the Survey Telescopes (Visible and Infrared Survey Telescope for Astronomy [VISTA] and VLT Survey Telescope [VST]) came into operation. Following this experience with instrumentation, he became head of the Optical Detectors Team (ODT) in 2002 and was involved in the development of the 16 × 16K CCD detector system for the VST camera, OmegaCam.

During his time in the ODT the New General detector Controller (NGC; Baade et al., 2009) based on high-speed serial link technology was developed and implemented jointly with the Infrared Detectors Department; it has become the standard detector controller for all VLT instruments. The ODT was also involved in adaptive optics wavefront-sensing detector developments. Dietrich continued to head this group of engineers and earned a reputation as an astronomer with a real understanding for the engineering, which was highly appreciated by his engineering colleagues. He encouraged the engineers to deepen their analysis in order to better understand the instruments and their performance, often with "Gedankenexperimenten". Dietrich was the head of the Optical Detectors Department from 2009 until 2013, when he became head of the Instrument Science Department, now the Project Science Department, in the Science Directorate. From 2009–2012 Dietrich was also Chair of the ESO Astronomy Faculty. He was finally elevated to Deputy Director for Science for his last two years before retirement.

Be stars, non-radial pulsations and supernovae

Throughout his astronomical research career Dietrich has been energised by Be stars, whose periodic and non-periodic photometric and spectroscopic variations have been subject to deepening study and understanding. He was twice chair of the IAU Working Group on Be and active B stars. He has also participated in surveys for Be stars in the Magellanic Clouds. Thomas Rivinius from ESO and Stanislav Štefl (deceased 2014) were among his closest collaborators in this field.

Around 2000, he started to study supernovae in nearby galaxies with Lifan Wang (then at Lawrence Berkeley National Laboratory and subsequently at Texas A. & M. University) and became interested in the investigation of the asymmetry of the SN explosion as revealed by spectropolarimetry, for which the FOcal Reducer low dispersion Spectrographs, FORS1 and FORS2, are ideally suited. He has continued this collaboration and has also studied SN 1987a and the light echoes around SNe. His concentration on Be stars and long-period photometry has now found its forte in observations with the BRITE-Constellation Nanosatellite mission[1]. Its 3 cm telescope in orbit allows milli-magnitude photometry over periods of many months, suitable for the investigation of periodicities in variable stars of all types, though of course confined to the brightest examples.

Retirement

In the weeks before he retired Dietrich gave two very well-received talks in the lunch-time "Astronomy for non-astronomers" series, reminiscing, in 76 anecdotes, about tough (and sometimes very comfortable) times observing at La Silla in the 1970s and early 1980s. The talks came with the warranty that the speaker's observations are absolutely authentic, and incomplete. His first observing trip to La Silla was in 1976 during his PhD. Unusually for modern talks he presented no slides, but kept his audience's attention, and received many questions.

A retirement party was held at ESO Headquarters on 16 September 2016 and Dietrich gave a farewell speech in several chapters, interspersed with some heartfelt tributes from those he had worked with, led by the Director for Science, Rob Ivison. His zeal was well known at ESO Headquarters and his famous yellow Smart car was typically seen to be one of the first to arrive in the car park in the morning and among the last to leave in the evening, even on his last official day at ESO. Dietrich is still seen around the Headquarters building as he begins his retirement, devoting himself to the ESO Supernova Planetarium & Visitor Centre and more intensively than ever to hot star studies and semi-infinite photometry with BRITE-Constellation, interspersed with non-periodic travels to remote parts of the globe.

Acknowledgements

I would like to thank Pauline Conlon, Olaf Iwert, Jean-Louis Lizon, Claus Madsen and Rob Ivison for providing information and reminiscences.

References

Baade, D. et al. 1994, The Messenger, 75, 1
Baade, D. et al. 1995, The Messenger, 95, 15
Baade, D. et al. 2009, The Messenger, 136, 20
Madsen, C. 2012, *The Jewel on the Mountaintop*, (London: Wiley-VCH)
Mathys, G. 1997, The Messenger, 89, 11
Wilson, R. N. 1989, The Messenger, 56, 1

Links

[1] BRITE-Constellation Nanosatellite Mission: http://www.brite-constellation.at/

Fellows at ESO

Yara Jaffé

I grew up in Venezuela, a tropical country next to the Caribbean sea where astronomy is not really something people do. I was raised in a family of biologists and poets, and as a child I had interests in both the arts and the sciences. I was not the kind of kid who knew all the constellations by heart (I still do not). In fact, after high-school I was not sure what to study so I applied for all kinds of things like literature, arts, physics and mathematics. I chose physics at the Universidad Simón Bolívar (USB), a very prestigious and beautiful public university on the outskirts of Caracas. By then I had realised I wanted to study the cosmos, but there was not a single astronomer at USB, so during my fifth (and final) year of undergraduate studies, I went to Mérida to do a research thesis at Centro de Investigaciones de Astronomía (CIDA) with A. Katherina Vivas.

Yara Jaffé

I loved meeting astronomers and working at the National Observatory, which, despite having limited resources, was used effectively by the few (now fewer than five!) resident astronomers. At CIDA I did actual research for the first time and loved it. Using RR Lyrae stars, we searched for small galaxies cannibalised by the Milky Way and actually found some! I left that place with a strong desire to go back as a professional astronomer one day. Owing to the increasingly complex political situation in Venezuela over recent years, that has never happened.

After my undergraduate degree in physics (2007) I was encouraged to do a short internship at Goddard Space Flight Center (US National Aeronautics and Space Administration, NASA) to study the outflows of Seyfert galaxies. I was really excited. Despite getting (and paying for) the appropriate visa, when I got there I learned that because Venezuela had become a "designated country", I could not enter NASA until I got special clearance. My boss there did everything he could to get that clearance, and after one month working remotely at the Catholic University of America I finally got in to Goddard, but only to non-restricted areas, and I had to be escorted at all times. Although being escorted was not much fun, NASA was impressive, with hundreds of people working in space sciences, including a Nobel prize laureate. The work I did there, although brief, was fruitful: we wrote a paper, and my grandma got to tell all her friends that I went to NASA.

After that experience, I went back home to pack again and say goodbye to my country and loved ones. This time I was going to the United Kingdom, to do a PhD on galaxy evolution with Alfonso Aragón-Salamanca at the University of Nottingham. The department there was a good match for me because it has strong groups in extragalactic astronomy and cosmology, which is what I wanted to do. The UK was certainly very different from what I had known so far. Basically it was much colder and more expensive, and to my surprise people's accents were not at all like the Queen's. It took some adjustment, but I ended up calling it home, and even marrying a British man. Despite having two scholarships, the tuition fees in the UK were so high for overseas students that I had to work on the side. During my first year I marked coursework, served hotdogs in football stadiums, and did loads of paid psychological tests. It was tough, but the situation improved after I got a studentship at ESO Garching to work with Harald Kuntshner and Piero Rosati for a year.

During the 3.5 years of my PhD I studied different galaxy populations across cosmic environments, mostly using data from the ESO Distant Cluster Survey (EDisCS). In particular, I studied the star formation histories of early-type galaxies in the cores of galaxy clusters, and the effect of environment on late-type galaxies falling into the clusters.

While I was writing up my thesis (2011) I got a job offer from Bianca Poggianti to work at the Astronomical Observatory of Padova on the optical side of the Blind Ultra Deep HI Environmental Survey (BUDHIES). It took almost eight months to get the visa, so I started working remotely and travelling back and forth from Padova to Exeter, where my husband was working at the time. The astronomers at the University of Exeter kindly hosted me during those months. My time in Padova, although intermittent, was very pleasant and inspiring. I enjoyed living in a place with so much (visible) history, and working in a new collaboration with very active researchers. My work with BUDHIES resulted in a series of papers revealing the effect of environment on the removal of HI gas from galaxies.

After almost five years in Europe I wanted to go back to Latin America. My husband and I applied to several places and we both got good offers in Concepción (Chile), so we moved there. The three-year fellowship at Universidad de Concepción (UdeC) was great because I had the freedom to develop my own research projects, and also the visa process was much friendlier. In addition, I had access to the 10 % of Chilean time allocation at all the observatories based in Chile, and I could do outreach in my mother tongue. One of the most important projects I developed at UdeC, together with other postdocs from the theory group, was an orbital study of ram-pressure stripping in clusters using observed and simulated phase-space diagrams. I also got involved in many collaborations, including GASP (GAs Stripping Phenomena), a large ongoing Multi Unit Spectroscopic Explorer (MUSE) programme to study "jellyfish" (notably stripped) galaxies covering a wide range of stellar mass and environment.

At the end of 2015 I moved to Santiago to start an ESO Fellowship with duties in Paranal. At ESO I am a support astronomer for Unit Telescope 4 and a MUSE fellow. I am also involved in the organisation of "Astronomy for everyone" talks in Vitacura and am co-supervising a very bright student who is working on the first GASP results. Working in Paranal has been a unique experience and I find the desert very inspiring. In the past year I have supported a diverse body of observing programmes, and been exposed to cutting-edge astronomical instruments, as well as scientists from all over the world. Although spending 80 nights per year in Paranal can be physically and mentally challenging, it is rewarding to be part of new discoveries in all areas of astronomy. Overall, the experience is helping me become a more complete scientist, for which I am very grateful.

Andra Stroe

I have always been fascinated by the cosmos and for as long as I can remember I wanted to become an astronaut when I grew up. In high school, upon realising that my chances of becoming an astronaut were very slim, I decided to work towards moving people into space, so I participated in a series of space settlement design competitions organised by NASA. For these, I designed habitable space settlements orbiting around the Earth and Mars, and also settlements located on the Moon and Mars.

Andra Stroe

Having a great role model and supporter in my engineer mother, I knew I wanted to become a scientist. My strong interest in all things space-related led me to study physics and astronomy at Jacobs University in Bremen, Germany. During my undergraduate degree, I had the opportunity to gain teaching and research experience, catching a glimpse of what academic life entails. Through my internships, I dabbled in spacecraft design, the physics of the Earth's magnetosphere and optical interferometry. After going observing for an undergraduate course, I was sold on the idea of pursuing a career in observational astrophysics.

Originally wanting to pursue research in the field of black holes during my Master's at the University of Cambridge, I then discovered galaxy clusters. I found them to be great laboratories that brought together many of my interests: galaxies, black holes and diffuse gas. I realised that the best way to really understand the physics of galaxy clusters was by combining multiple types of observations and techniques. Hence I started my PhD at Leiden Observatory in 2011, working on multi-wavelength observations and modelling of merging galaxy clusters.

At Leiden I worked on the physics of shock waves and how they interact with the diffuse intra-cluster medium, and with the star-forming galaxies and active galactic nuclei (AGN) in the clusters, complementing this work with studies of field galaxies. I was fortunate enough to pursue my own research and lead my own projects, which meant travelling a lot to meet collaborators or go to conferences. I had amazing opportunities to visit some of the world's largest, most advanced telescopes, such as the Jansky Very Large Array (VLA), the La Palma Observatories and Mauna Kea. One of the highlights of my trips was being able to walk on one of the 25-metre dishes of the VLA and enjoy the beautiful scenery from an amazing vantage point.

Towards the end of my PhD I became really interested in the evolution of the star formation and gas content of active galaxies. With the advent of the Atacama Millimeter/submillimeter Array (ALMA), and the new instruments on the Very Large Telescope (VLT), this was a perfect time to pursue these topics. Upon finishing my PhD, I was very fortunate to be able to follow this dream at ESO, where I started as a Fellow in 2015. At ESO, I am pursuing research into star formation and AGN activity though large surveys. One of my goals is to find the driver for the enhanced number of spiral galaxies in disturbed and merging clusters. I am also extending my work to high-redshift twins of local merging clusters: high-redshift protoclusters. I am one of the organisers of the first regular Garching campus meetings on galaxy clusters, as well as of the Wine & Cheese informal seminar series at ESO.

With the amazing support of ESO, and in line with my research interests, I am also organising a conference in 2017 which will bring together, for the first time, experts working on early stages of cluster formation throughout the range of redshifts. Through my duties, I regularly travel to one of the few observatories I had never visited before: the VLT at Paranal. I get to be part of an amazing team of more than 100 people working together to ensure the smooth operations of no fewer than seven telescopes. I am trained to operate the instruments on the Antu telescope (Unit Telescope 1). Adding to my previous observing experience, I have now became acquainted with new observing modes, such as adaptive optics and integral field spectroscopy.

In the future, I am excited about the scientific opportunities provided by the new multiplex spectroscopic instruments coming to Paranal, and the European Extremely Large Telescope and the Square Kilometre Array which will enable us to study galaxies and AGN across time and environment.

Siyi Xu

Siyi Xu

I grew up in a small town called Kunshan near Shanghai in China. The population is about one million but it is still considered a small town by Chinese standards. I was always quite interested in mathematics and physics — I particularly liked the simple and objective language they use to describe the rules governing the world around us. My first real astronomy experience was seeing the Leonid meteor shower in 2001. That was a spectacular year — I even managed to catch sight of a few shooting stars while staying in the middle of the slightly polluted city.

Then my parents got me a small (~ 20 cm) amateur telescope so I could use it to observe the Moon, Jupiter and Saturn. I had a lot of fun playing with the telescope. I remember that one time, in order to find to a good spot to observe the Moon, I climbed up to the top of the roof. My neighbours thought I was a burglar and they almost called the police.

In China, we are required to decide on a major before going to college. I remember going through the list of majors and astronomy stood out. I thought to myself, "I like physics. I like maths. Astronomy sounds like a cool major!" I decided this without much hesitation. My friends and relatives were all quite shocked about this decision. They did not know what I would do with a degree in astronomy, a major that they had barely heard about; they thought I should go for something more practical like business or accounting instead. To this day, I am still very grateful for my parents' support. They told me to "choose what I love and love what I choose". They were always very supportive of my decision.

I ended up majoring in astronomy at Nanjing University. Astronomy is a small department there and we were ~ 30 students in total, roughly one from each province of China. It was fun for me to meet students from all over China. My favourite class was observational astronomy. We had a 1-metre telescope and we used it to measure the atmospheric extinction curve and the period of a variable star, or just to take pretty pictures of other galaxies.

My first real research experience was in the summer of 2009, when I was selected to be part of an exchange programme called CSST (Cross-disciplinary Scholars in Science and Technology). It is a 10-week summer programme run between the University of California, Los Angeles (UCLA) and several Chinese universities. The idea is to bring some junior-year students from China to work on a research project at UCLA. I had a fun time working with Mike Jura, who was an extremely caring advisor and an inspiring scientist. My summer research experience prompted me to continue my studies in the USA and apply to graduate schools there. Another plus was that all PhD programmes in the USA offer both tuition and a stipend. As a result, I would be able to live in a foreign country for a few years and be financially independent as well — I loved that idea!

The graduate school application was rather smooth and I was accepted by a few places. I was very lucky to have the chance to visit a few of them. I was amazed by the interesting experiences that my fellow prospective students had encountered. I remember I asked one prospective student why he decided to do a PhD in astronomy. His answer was something like "I worked in a physics lab for the first year, a chemistry lab the second year, and an astronomy lab the third year. I loved the astronomy lab the most! That is why I am here!" That was very different from my experience.

In the end, I decided to go to UCLA for graduate school, mostly because I really enjoyed working with Mike. There were so many interesting projects to work on! I think that was one the best decisions I ever made in my life. Plus, Los Angeles had a lot of good Chinese restaurants in case I got homesick.

My main research topic was planetary systems beyond the main sequence stage, particularly around white dwarfs. For my PhD studies, I worked on data from a lot of telescopes, including the Keck Telescope, the Hubble Space Telescope, and the Spitzer Space Telescope. Mike was a superb advisor and he trained me in many aspects of research, from writing proposals, planning the observations (always have a backup plan — or several!) and reducing the data, to publishing the results and presenting them at conferences. I still remember my very first paper: we kept revising the manuscript and the final submitted version ended up being version u (i.e., the 21st version). The accepted version was version z (26). I was seriously concerned about what would happen if we used up all 26 letters! I feel extremely grateful that I had a chance to work with Mike so closely. He is always a source of inspiration and a role model for me. Whenever I encountered a problem, I would ask myself "What would Mike do in this situation?"

I joined ESO in Garching as a fellow in September 2014. I very much enjoy the freedom that I have and the diversity of research done at ESO. There are interesting talks and discussions happening every day. On account of my passion for observational astronomy, I decided to work as a support astronomer at Paranal for my functional duty. So I have the chance to travel to Chile, meet many interesting people, and operate one of the world's best telescopes. The sky there is amazing! Looking into deep space, it constantly reminds me why I am here and why I decided to pursue astronomy in the first place. Most importantly, it has been a really fun journey. I cannot wait to see what the future has in store for me!

Personnel Movements

Arrivals (1 October–31 December 2016)

Europe	
Augustin, Ramona (DE)	Student
Brucalassi, Anna (IT)	Astronomer/CRIRES+ Project Scientist
Chen, Chian-Chou (TW)	Fellow
Darré, Pascaline (FR)	Applied Physicist in Interferometry
Nedelchev, Borislav (BG)	Student
Querejeta, Miguel (ES)	Fellow
Seidel, Matthias (DE)	Electronic Engineer
Zanella, Anita (IT)	Fellow

Chile	
Anderson, Joseph (UK)	Operation Staff Astronomer
Corral Santana, Jesus (ES)	Fellow
Jones, Matias (CL)	Fellow
Leftley, James (UK)	Student
Milli, Julien (FR)	Operation Staff Astronomer
Nurzia, Vittorio (IT)	Telescope System Engineer
Opitom, Cyrielle (BE)	Fellow
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The Messenger is published, in hardcopy and electronic form, four times a year: in March, June, September and December. ESO produces and distributes a wide variety of media connected to its activities. For further information, including postal subscription to The Messenger, contact the ESO education and Public Outreach Department at:

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Printed by FIBO Druck und Verlags GmbH, Fichtenstraße 8, 82061 Neuried, Germany

ISSN 0722-6691

Contents

Front cover: Visible and Infrared Survey Telescope (VISTA) composite near-infrared image (from *Z*-, *Y*-, *J*-, *H*- and *Ks*-band images) of the star-forming region Messier 78 (NGC 2064, 2067 and 2068) and to the north-east NGC 2071, located in the Lynds 1630 dark cloud in the Orion molecular cloud complex at a distance of around 400 pc. NGC 2068 is predominantly ionised by two blue supergiant stars, HD 38563A and B, while HD 290861 ionises NGC 2071. These embedded active star-forming regions also contain many low-mass young stars. The blue comet-shaped nebula to the south-west is McNeil's Nebula which was discovered in 2004 when it underwent a strong brightening. See Release eso1635 for more information.