ESO

European Organisation
for Astronomical
Research in the
Southern Hemisphere

Annual Report 2021

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Presented to the Council
by the Director General
Xavier Barcons

The European Southern Observatory

ESO/P. Horálek

The four 8.2-metre Unit Telescopes of ESO's VLT on the 2600-metre-altitude site of Paranal. Also visible are three of the four 1.8-metre Auxiliary Telescopes, and the VLT Survey Telescope.

ESO, the European Southern Observatory, enables scientists worldwide to discover the secrets of the Universe for the benefit of all. ESO designs, builds and operates world-class observatories on the ground — which astronomers use to tackle exciting questions and spread the fascination of astronomy — and promotes international collaboration in astronomy.

Established as an intergovernmental organisation in 1962, today ESO is supported by 16 Member States (Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and the United Kingdom), along with the host state of Chile and with Australia as a Strategic Partner.

ESO operates La Silla, Paranal and Chajnantor, three observing sites in the Chilean Atacama Desert, a place with unique conditions ideally suited to observing the sky. La Silla was ESO's first observatory and remains productive today, particularly in time-domain astronomy. The site is also home to a number of hosted telescope projects operated by institutes in ESO Member States.

At Paranal, ESO operates the VLT (Very Large Telescope) and the VLTI (VLT Interferometer), as well as two survey telescopes, VISTA (the Visible and Infrared Survey Telescope for Astronomy) working in the infrared and the visible-light VLT Survey Telescope. Paranal is also home to a number of smaller telescopes. In the future, ESO will host and operate CTA-S, the southern site of the Cherenkov Telescope Array, the world's largest and most sensitive gamma-ray observatory, at Paranal.

D. Kordan/ESO

The Atacama Large Millimeter/submillimeter Array (ALMA) on the 5000-metre-altitude Chajnantor plateau.

Gerhard Hüdepohl/ESO

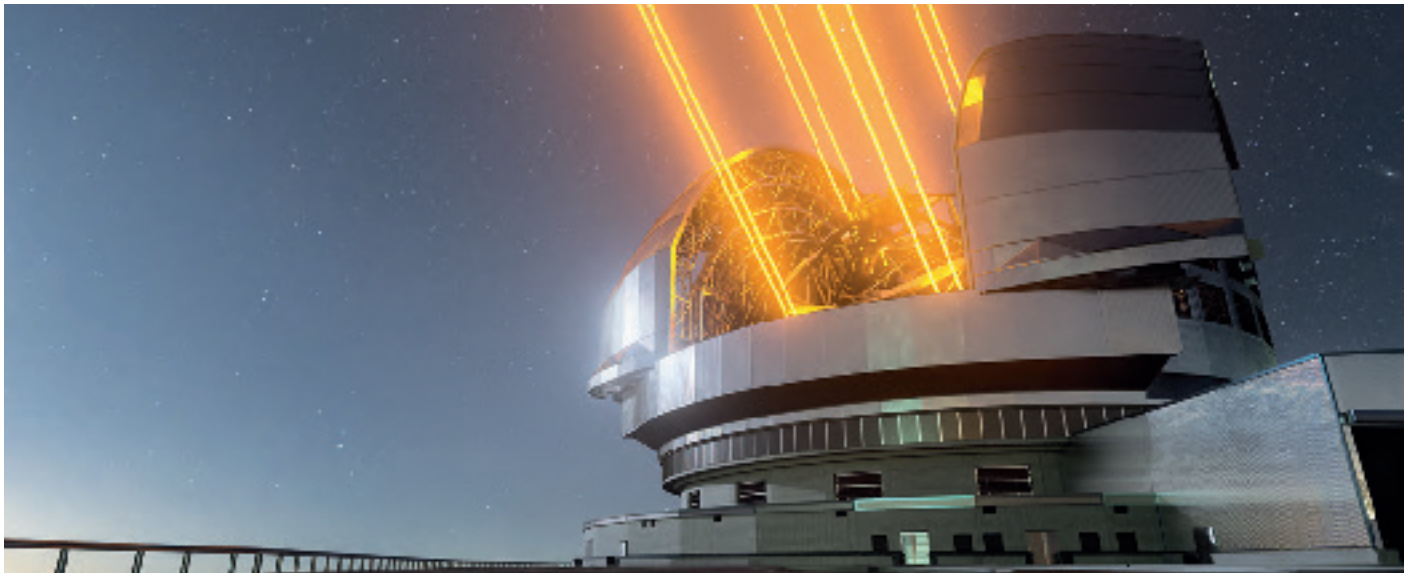
ESO's first observatory, La Silla, is home to the ESO 3.6-metre telescope and the New Technology Telescope, both operated by ESO, as well as a number of hosted telescopes operated by institutes in ESO Member States.

On Chajnantor, at 5000 metres above sea level, ESO operates APEX (the Atacama Pathfinder EXperiment) and ALMA (the Atacama Large Millimeter/submillimeter Array). These two facilities observe the skies in the millimetre and submillimetre range. ALMA is a partnership with East Asia and North America, in cooperation with the Republic of Chile. APEX is operated by ESO on behalf of the Max Planck Institute for Radio Astronomy, the Onsala Space Observatory and ESO itself.

At Cerro Armazones near Paranal, ESO is building "the world's biggest eye on the sky" — ESO's ELT (Extremely Large Telescope). The ELT will be the largest optical/near-infrared telescope in the world and will address many of the most pressing unsolved questions in astronomy.
In a typical year, more than 1700 proposals are submitted for the use of ESO telescopes excluding ALMA, requesting up to six times as many hours as are available. For ALMA, astronomers from the regions represented by ESO typically submit over 700 proposals every year. ESO is the most productive ground-based observatory in the world and its operation yields many peer-reviewed publications, with over 1000 refereed papers based on ESO data published each year.

ESO's headquarters and its visitor centre and planetarium, the ESO Supernova, are located in Garching, close to Munich, in Germany. This is the scientific, technical and administrative centre, where development programmes are carried out to provide the observatories with advanced technologies. From its offices in Vitacura, Santiago ESO supports its operations in Chile and engages with Chilean partners and society. The ESO Vitacura site also hosts the ALMA Santiago Central Offices.

The total Member State financial contributions to ESO in 2021 were approximately 214 million euros and ESO employs over 700 staff from more than 30 different countries.



Artist's impression of ESO's Extremely Large Telescope (ELT), at Cerro Armazones near Paranal. The ELT will be the largest optical/near-infrared telescope in the world.

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Foreword by the President of Council

ESO/M. Zamani

Linda Tacconi, ESO Council President.

The year 2021 was one of delicate balancing. The organisation has been on a steady path of recovery from the effects of the COVID-19 pandemic, but continued to endure the effects of the multiple waves in both hemispheres. There have been many advances towards ESO's major strategic goals, yet there are new pandemic- and technical-induced delays and risks. Despite the ongoing challenges, ESO managed to deliver the majority of its objectives in 2021. These remarkable achievements are attributable to the combined efforts of many across the organisation.

Major highlights of 2021 were the safe restart of operations at the La Silla Paranal Observatory and ALMA, exciting new data deliveries to the astronomical community, and the restart of ELT construction on Armazones. The webcam at the ELT site demonstrates to the entire ESO community the significant progress on what will be the world's largest and most powerful ground-based optical/near-infrared telescope.

During 2021 the ESO Council met twice, as did the Committee of Council. The March Committee of Council and June Council meetings took place via video-conference because of pandemic. Some members of Council were able to meet in person once again for the hybrid September Committee of Council and the December Council meetings at Headquarters in Garching. Safety regulations and continued travel restrictions meant that it was not possible to have the full complement of Council on site. Those who could travel were pleased to meet once again with the other delegates. The meeting at Headquarters afforded those Council members present the welcome opportunity for informal exchanges with ESO Garching personnel.

Among other matters, Council approved the set of ESO Values at an extraordinary Council meeting in September. The core values of excellence through innovation, service to the ESO communities, and an emphasis on diversity, inclusion, and sustainability are key to maintaining ESO's world-leading role in ground-based astronomy.

During an extremely busy December meeting, Council approved the agreements with the GRAVITY+ and CUBES (Cassegrain *U*-Band Efficient Spectrograph) consortia, providing the astronomical community with two powerful new capabilities for the VLT/I. GRAVITY+ will extend the capabilities of GRAVITY to faint targets, opening the extragalactic sky to a wide range of milliarcsecond interferometric imaging science, and enabling sensitive spectroscopy of exoplanets. CUBES will provide sensitive spectroscopy in the ultraviolet. Council also approved the way forward for the fourth and fifth ELT instruments, HIRES (the HIgh REsolution Spectrograph, renamed ANDES in early 2022) and MOSAIC (the Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology), and noted the progress on the first three instruments as they undergo their Final Design Reviews. Council noted with pleasure two anniversaries, marking 20 years since the start of the VLTI and 10 years of ALMA science operations. These decisions and highlights demonstrate the significant progress made in the ESO programmes in this second difficult year of the pandemic.

Committee of Council meetings serve the purpose of discussing issues and preparing decisions to be taken at regular Council meetings. They are extraordinarily important as they provide delegations the opportunity to share and discuss their concerns and ideas in an open and informal way. They play a central role in ensuring governance of the organisation based on mutual understanding and trust. The two meetings in 2021 were no exception and the discussions were very focused and productive, paving the way for smooth decision making at the successive Council meetings.

In closing, I want to express Council's sincere thanks to the entire ESO staff and management for their continued dedication and endurance, which has resulted in many successes in 2021 despite the ongoing challenges. As ESO approaches its 60th birthday, the ESO community should look back at the last year with pride, and look forward to the next successes and great discoveries at ESO!

Introduction by the Director General

Xavier Barcons, ESO Director General.

In this, the second year of the COVID-19 pandemic, ESO delivered remarkably close to its objectives. Scientific data from ESO's observatories flowed to the community throughout the year and all projects progressed, not to 100%, but to a remarkably high level under the circumstances. This speaks highly of the commitment and dedication of ESO's staff, and those of the community, through particularly harsh times. Engagement and support from the Member States, in particular via the delegations, were crucial for maintaining momentum.

The La Silla Paranal observatory continued operating to various degrees, as pandemic restrictions allowed, and reached close to full operation by the end of the year. Priority was given to obtaining science data and to critical technical interventions (such as mirror re-coatings). Designated Visitor Mode enabled remote observers to participate in observing runs in real time. Given its added value, we look forward to re-opening actual Visitor Mode observations when conditions allow.

Two Paranal Instrumentation Projects — CRIRES$^+$ (the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph) and the IRLOS (the InfraRed Low Order Sensor) — were successfully commissioned remotely, with the support of the available observatory staff, using the Garching Remote Access Facility (G-RAF). ERIS (the Enhanced Resolution Imager and Spectrograph) arrived in Paranal and when the Chilean borders opened in late 2021 the team travelled to the observatory to prepare its installation at the VLT. The CONCERTO (CarbON CII line in post-rEionisation and ReionisaTiOn epoch) instrument was installed at APEX, whilst the NIRPS (Near Infra Red Planet Searcher) team also made progress with its installation at La Silla.

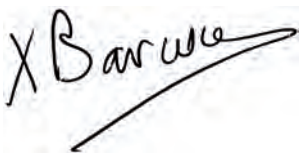
ALMA restarted observations in March and completed Cycle 7 to around 80%, the priority being to start Cycle 8 observations in October. ALMA Development activities continued; in particular, Band 1 started its observatory integration, Band 2 progressed through pre-production, and the development of a new Band 6 prototype was approved.

The ELT saw significant progress in 2021, both in design and manufacturing in Europe and at the construction site. Civil work at Armazones resumed in May — under strict COVID-19 safety conditions — and ramped up through the rest of the year. By the end of the year Armazones was again a busy construction site, with many components ready for installation. Building commenced of the walls on which the dome bogies will rest, and the ELT dome and auxiliary building are expected to take shape early in 2022. The telescope main structure successfully passed its Final Design Review, thanks to a massive effort from the contractor and ESO's engineers. More than 50% of the glass of the 39.3-metre-diameter primary mirror has now been cast, and polishing will begin soon. The rest of the optomechanics, in line with the entire project, is also making progress, although technical difficulties remain in some areas. Work on the very complex and challenging ELT instruments is also progressing. The ELT baseline schedule now forecasts first science light in 2027.

ESO's mission of fostering cooperation in astronomical matters continued in several fronts, e.g. through science and engineering studentships and fellowships, and (mostly online) workshops. ESO continued to assess and raise awareness in several forums of the impact of satellite megaconstellations. Education and outreach continued with the restricted operation of the Supernova Planetarium & Visitor Centre in Garching, alongside virtual observatory visits. Once again, science enabled by ESO's facilities resulted in more than 1000 refereed papers in 2021. That included some important breakthroughs, some highlighted with ESO's support in the general media.

Council approved an updated formulation of ESO's Values, which will underpin all organisational activities. Striving for excellence through innovation, serving the communities, diversity and inclusion and sustainability all feature prominently. These underpin the present and are essential to guaranteeing the future of ESO. Sustainability in all its facets (financial, environmental and social — which also links to diversity and inclusion) percolates through ESO's plans. The Integrated Operations Programme, for example, aims to achieve a lean, remote and high-performance operations concept for the VLT/I and the ELT — and to some extent CTA-S, the southern site of the Cherenkov Telescope Array (CTA) — in Paranal, sustainability being a key driver.

Now on the verge of turning 60, ESO has consolidated its international standing as an experienced and world-leading organisation. ESO's ELT is not only en route to being the most powerful telescope of its class, but is also the most advanced in its construction and the only one fully funded. With the VLT/I, ALMA, the ELT and CTA, ESO will offer a unique set of facilities to enable its community to maintain leadership in ground-based astronomy.



The Seagull Nebula, observed with the VLT Survey Telescope. Made up of dust, hydrogen, helium and traces of heavier elements, this nebula is the hot and energetic birthplace of new stars.

ESO/VPHAS+ team/N. J. Wright (Keele University)

Science

The Directorate for Science (DSC) provides scientific guidance to all science-related projects at ESO, and is responsible for nurturing ESO's scientific vision. It hosts the brilliant young scientists — the Fellows and Students — entrusted to ESO's care by the Member States. DSC contains ESO's Project Scientists, the Programme Scientists of ALMA (the Atacama Large Millimeter/submillimeter Array), the VLT (Very Large Telescope), the VLTI (VLT Interferometer) and the ELT (Extremely Large Telescope), and the Observing Programmes Office, which organises the allocation of time on ESO's telescopes and drives improvements to the processes by which that time is distributed, ensuring that the most important and exciting science is done. These scientists interact closely with the scientific community through joint personal research projects, committees, workshops, seminars, and individual contacts, such that ESO can best serve the needs of its community. DSC is also home to the ESO Supernova Planetarium & Visitor Centre, which engages closely with educators and the public to promote the discoveries made using ESO facilities. Lastly, the Offices for Science in Garching and Vitacura, and the Library and Information Centre therein, are tasked with providing a robust, exciting science environment, not just for ESO astronomers, but also for those in our Member States, especially the early-career scientists, who have struggled throughout the COVID-19 pandemic. Their extensive use of virtual platforms throughout 2021 has been instrumental in bringing people together to talk science.

The Tarantula Nebula — in the Large Magellanic Cloud, a satellite galaxy to our Milky Way — as observed by the VLT Survey Telescope.

The largest main-belt asteroids

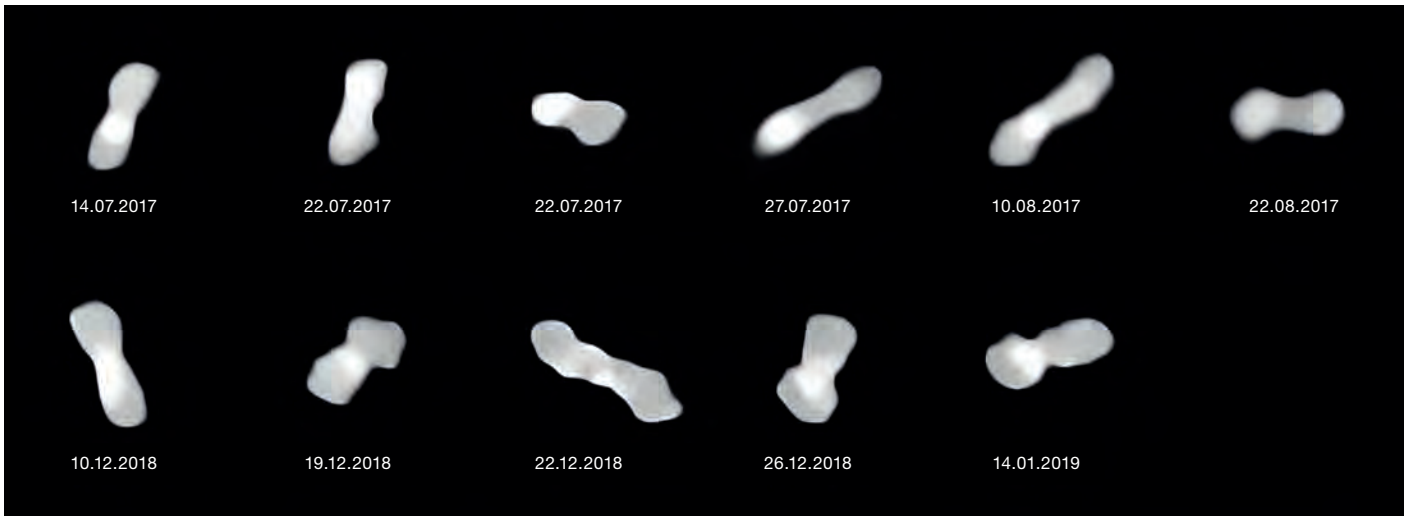
A major constituent of the Solar System — by number, not mass — are the hundreds of thousands of asteroids in orbits between Mars and Jupiter. These main-belt asteroids come in many different sizes, but little was known about their shapes and densities beyond the very few objects observed by satellite flybys. The objects are typically too small to be spatially resolved by ground-based telescopes. SPHERE (the Spectro-Polarimetric High-contrast Exoplanet Research instrument), with its adaptive optics capabilities, overcomes the imaging constraints set by the atmosphere and has enabled a detailed study of most of the largest main-belt asteroids (Vernazza et al., 2021). This large, uniform dataset enables questions about the formation and evolution of asteroids to be addressed, such as their 3-dimensional shapes, their rotation properties and their densities. The sample can be split into two families, with objects of mostly spherical shapes in one and those with strongly elongated bodies in the other. Elongated asteroids tend to have smaller rotation periods and be less massive than more spherical objects. The densities range from 1.3 g cm^{-3} to 4.3 g cm^{-3} and the sample can be divided into a low-density group which typically also has a smaller geometric albedo and a high-density group which reflects more light.

One particular asteroid was investigated in more detail. The dumbbell-shaped object (216) Kleopatra is one of the few asteroids with known moons. It has a very unusual shape and had a very high mass density estimate. Combining the SPHERE observations with previous adaptive optics data from the Keck Observatory, light curves from smaller telescopes and observations of stellar occultations by (216) Kleopatra allowed a more accurate determination of the mass density and the formation scenarios of the asteroid and its moons (Marchis et al., 2021; Brož et al., 2021). The orbits of the two moons lead to a very good estimate of the mass of (216) Kleopatra and the derived density is 3.38±0.50 g cm^{-3}, significantly lower than previously thought. The high reflectivity measured from radio delay Doppler images with the Arecibo telescope indicates a large metal content. The combination of these two

ESO/M. Kornmesser/Vernazza et al./MISTRAL algorithm (ONERA/CNRS)

Gallery of the largest asteroids in the Solar System.

facts leads to a picture of the asteroid as a very porous body, like a rubble pile. The equilibrium dumbbell shape hints at its formation by a giant impact followed by re-accumulation. (216) Kleopatra rotates near its breakup velocity, which also hints at a violent formation scenario. The equatorial orbits of the moons could be due to a mass-shedding event.

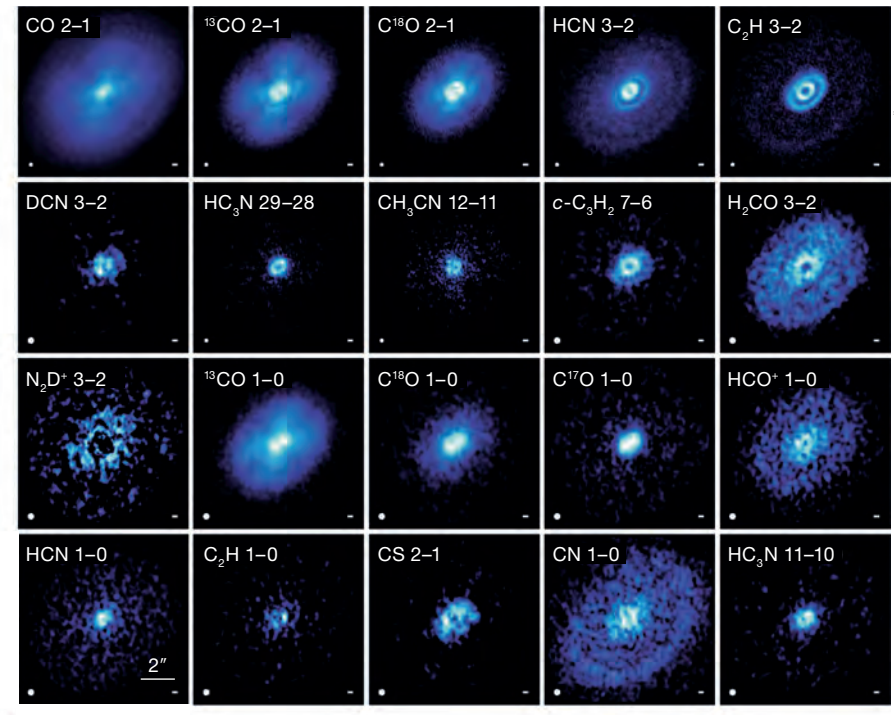


ESO/Vernazza, Marchis et al./MISTRAL algorithm (ONERA/CNRS)

Various views of the asteroid (216) Kleopatra with SPHERE. The rotation is clearly visible.

MAPS: mapping the distribution of molecules on planet-forming scales

The ALMA Large Programme MAPS (Molecules with ALMA at Planet-forming Scales), the most extensive molecular line survey to date of five protoplanetary discs, captured the chemical composition of discs at a time when planets are in their formation process (Öberg et al., 2021). The project targeted more than 20 different molecules in around 50 different lines, on scales of 10 astronomical units (au). The results revealed that the disc gas properties and chemical composition show significant spatial variations across the disc, suggesting that planets form in distinct chemical environments.



Öberg et al. (2021)

Maps in 20 different spectral lines of the protoplanetary disc surrounding HD 163296, providing a sample of the data obtained in the MAPS survey, whilst at the same time displaying the enormous variety in the spatial distribution of the line emission in the disc.

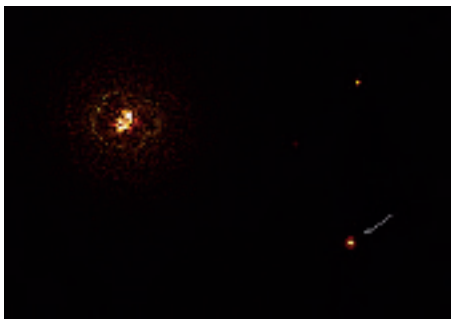
Exoplanet Extremes

The plethora of exoplanets shows a plethora of phenomena. More accurate and detailed observations allow us to better characterise individual planets and find more planetary systems. ESO facilities continue to find exotic planets and systems that enhance our understanding of the formation and existence of exoplanets. The search for Earth-like planets in the habitable zone continues. NASA's TESS (Transiting Exoplanet Survey Satellite) has discovered many interesting systems. Many of them are now being followed-up with radial velocity measurements from the ground. The M-dwarf star L98-59 shows evidence for three transiting planets with periods of 2.3, 3.7 and 7.5 days. Radial velocity measurements with HARPS (the High Accuracy Radial velocity Planet Searcher) at the ESO 3.6-metre telescope and ESPRESSO (the Échelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) at the VLT have provided evidence for a fourth planet, which is not detected in transits and has a period of 12.8 days (Demangeon et al., 2021). A planet candidate with a tentative period of 23.2 days has yet to be confirmed. The combination of transit and radial velocity observations allows astronomers to derive the masses and mean densities of the planets and hence they can infer their most likely composition. The masses of the planets around L98-59 are 0.4, 2.2 and 1.9 times the Earth's mass ($M_\oplus$). These are amongst the lowest-mass exoplanets so far observed and the innermost planet is the lowest-mass exoplanet found with radial velocity data to date. The masses of the fourth and the potential fifth planets depend on their orbital inclination angles; the derived upper limits are 3.1 $M_\oplus$ and 2.5 $M_\oplus$, respectively. All these planets are likely to be rocky or mostly covered with water. With the star's parameters, in particular its luminosity, the irradiation of the planets can be determined, and the candidate fifth planet would lie in the habitable zone around the M star.

ESO/N. Risinger (skysurvey.org)

Candidate free-floating planets in the upper Scorpius and Ophiuchus region.

Most planets have been found around stars less than three times the mass of the Sun (<3 $M_\odot$). Whether this is due to the conditions required for star formation or to an observational bias is currently unclear. One way to detect planets around massive stars is to search for common proper motion, i.e. the star and the planet move together relative to distant background stars. SPHERE is being used to target high-mass stars to check whether planet formation is suppressed for more massive stars. A massive planet has been discovered around the young, massive stellar system b Centauri (not to be confused with β Centauri). On SPHERE images obtained in 2019 and 2021 a planet on a wide orbit could be identified (Janson et al., 2021). The host star is a binary with a system mass of at least 6 $M_\odot$. The primary star itself has a mass of 5 to 6 $M_\odot$. The distance of the planet from the star is 560 au. From the observed colours and the age of the system the mass of the planet is determined to be 11 times the mass of Jupiter.



ESO/Janson et al.

Image of the planet around b Centauri. The bright object in the top left is b Centauri, the bright and dark rings around it being optical artefacts. The planet, b Cen(AB)b, is in the lower right, marked with an arrow. The bright dot in the top right is a background star.

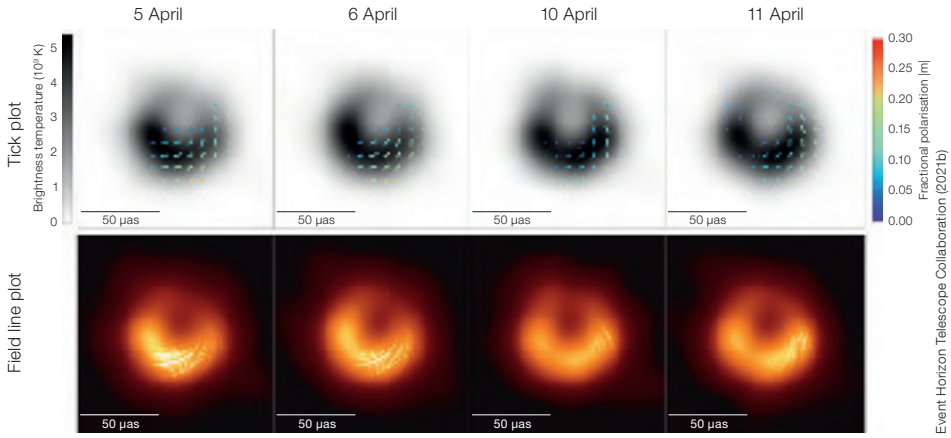
Possible orbital periods are currently rather unclear and range from 2500 to 7000 years. How this planet formed so far from the host star is also unclear. Most likely, the planet is the result of an instability in the protoplanetary disc.

Planets can also be found that are not bound to stars. These are objects whose mass is too small to initiate nuclear burning, the mass limit being around 13 Jupiter masses (M_{Jup}). Searching for small objects without a nuclear energy source is difficult, particularly so if they are not bound to a star. A project to search the archives of all major observatories examining images spanning 20 years has generated a new large sample of free-floating planets (Miret-Roig et al., 2021). The upper Scorpius and Ophiuchus region hosts the closest (130 parsec) and youngest (1–10 Myr) OB (massive) stars. A region of 171 square degrees has been surveyed with optical and near-infrared imaging from many different archives supplemented by observations with VISTA (the Visible and Infrared Survey Telescope for Astronomy) and the VST (VLT Survey Telescope) as well as many other telescopes. More than 80 000 individual images from 18 different instruments were analysed. Proper motions could be measured thanks to the long timespan covered. The search resulted in the detection of between 70 and 170 candidate free-floating planets with masses from 4 to 13 M_{Jup}. The uncertainty stems from not knowing the exact ages of the sources. Since young planets rapidly cool and fade, their luminosity is a strong function of their age. This is the largest homogeneous sample of nearly coeval free-floating planets to date. The number detected is more than would be predicted if the planets form, like stars, by the contraction of cool gas. Other formation channels must contribute to the population of observed planets, the most promising being the early ejection of planets formed in a disc around stars.

Polarisation observations of the supermassive black hole in M87

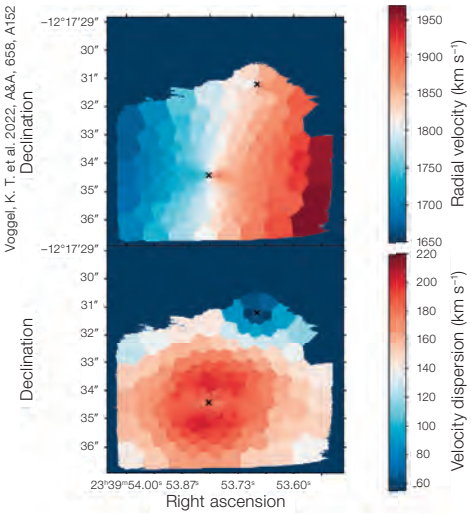
The magnetic field structure in the direct vicinity of the supermassive black hole (SMBH) in M87 has been probed with VLBI (very long baseline interferometry) measurements in polarisation mode (Event Horizon Telescope Collaboration, 2021a, 2021b). The measurements were obtained by the Event Horizon Telescope Collaboration in April 2017 using simultaneous observations with a VLBI network of millimetre and submillimetre facilities, including ALMA and APEX (the Atacama Pathfinder EXperiment). A fractional polarisation level of ~15% has been measured in the southern part of the ring-shaped continuum emission pattern surrounding the SMBH. The overall observed polarisation level is low, which may indicate that the magnetic field is scrambled on spatial scales smaller than the resolution of the observations.

Different image reconstruction pipelines result in very similar polarisation maps. These maps have been compared to a library of simulated polarimetric images resulting from general relativistic magnetohydrodynamic modelling, from which more detailed properties of the central black hole have been derived. It is found that the SMBH is accreting gas from its surroundings at a rate of 3–20 × 10^{-4} $M_{\odot}$/year. The magnetic field strength is somewhere between 1 and 30 Gauss (for comparison: the magnetic field of Earth is around 0.5 Gauss), and the electron temperature of the radiating plasma is on the order of 10–120 × 10^9 K. By determining these parameters for this SMBH, fundamental physics is being tested at an unprecedented level.



Resulting images averaged from the different image reconstruction pipelines utilised by the Event Horizon Telescope Collaboration for different observing dates. Variations in the magnetic field line pattern (bottom) and polarisation direction and strength can be seen on timescales as short as a day.

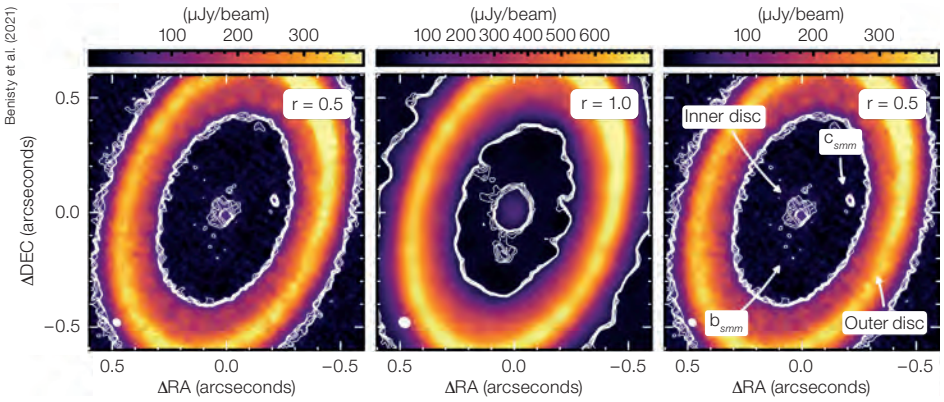
A pair of supermassive black holes



Stellar velocities in the centre of NGC 7727. The upper panel shows the radial velocity and indicates that both nuclei are part of the same galaxy. The lower panel displays the velocity dispersion, which depends on the central mass. The kinematically separated second nucleus is clearly visible and displays a much smaller velocity dispersion.

Galaxy evolution includes major mergers. Since most galaxies host a SMBH, such mergers must lead to the inspiral of the black holes. However, all possible candidates of binary black holes so far have been observed in distant galaxies and inferred indirectly from their signatures as active nuclei. MUSE (the Multi Unit Spectroscopic Explorer) with its adaptive optics capabilities has now observed the double nucleus of the peculiar galaxy NGC 7727 at a distance of 27 Mpc to obtain the velocity distributions near the two nuclei, yielding estimates of the central masses (Voggel et al., 2022). The MUSE observations show two black holes with masses of $1.5 \times 10^8\ M_\odot$ and $6.3 \times 10^6\ M_\odot$. They are separated by a projected distance of 480 pc, which makes them the closest known binary black hole pair. Simulations have indicated that the two black holes will merge in about 250 million years. The less massive nucleus is most likely the stripped core of a smaller galaxy, a conclusion supported by the disturbed morphology of NGC 7727.

An exomoon forming



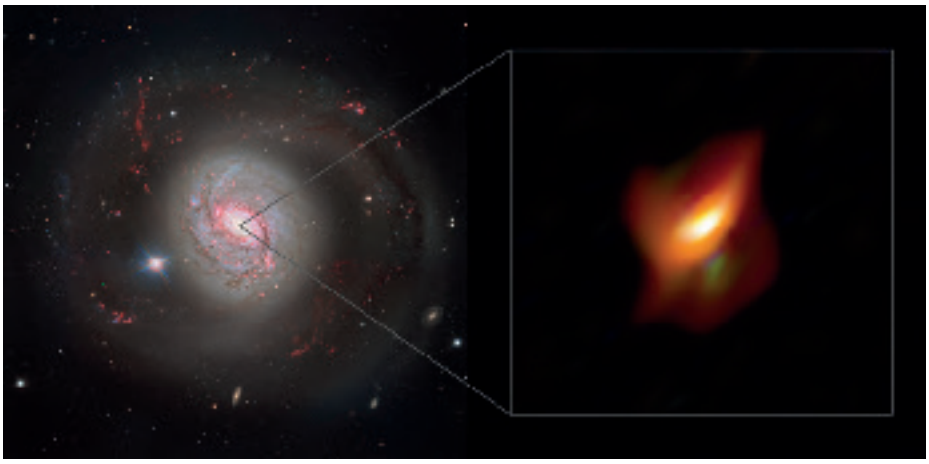
Continuum images of the circumstellar environment of PDS 70, processed with two different robust parameters (left two panels). The right-hand panel is a repeat of the first panel, labelled with the different components. The circumplanetary disc around component c is clearly visible in the continuum emission.

High-resolution continuum observations of the young star PDS 70 have provided the first unambiguous detection of a disc around a planet (Benisty et al., 2021). Previous VLT observations discovered two planets around the star, and the new ALMA observations clearly detected dust emission coincident with the planet PDS 70c. The dust mass contained in the circumplanetary disc is between 0.007 and 0.031 times the mass of Earth. This is enough material, if it accumulated, to form a moon. For comparison, the Moon itself, one of the largest satellites in the Solar System, has a mass of 0.012 times the mass of Earth.

VLTI images of NGC 1068 challenge the unified models of active galactic nuclei

According to unified models of active galactic nuclei (AGNs), a central accreting SMBH is surrounded by a an optically thick torus which, when viewed at high inclination (Type 2), obscures the accreting central engine which is normally seen (Type 1). These unified models started to be developed in the 1980s, based on global observations (spectroscopic and photometric) to sort AGNs into two broad categories, arguing that AGN diversity can be explained by the inclination of the viewing angle, rather than any intrinsic differences in the physics of the objects. It has been long expected that resolving the surroundings of the central engine, in particular the torus, would confirm the unified theory of AGNs. Only interferometry allows such resolution in the infrared, and the VLTI is uniquely equipped to observe AGNs, since it has large apertures, adaptive optics and sensitive instrumentation. Although pioneering VLTI observations with VINCI (the VLTI Commissioning Instrument), AMBER (the Astronomical Multi-BEam combineR) and MIDI (the MID-infrared Interferometric instrument) resolved AGNs, only combining simultaneously the signals from all four VLT Unit Telescopes (UTs) provides enough spatial information to address the complex morphologies of AGNs.

GRAVITY observations of NGC 1068 led to reconstructed images at the sub-parsec level of this archetypical Type 2 AGN (GRAVITY Collaboration, 2020). These observations have triggered modellers to explain in detail what the surroundings of NGC 1068's central engine look like, in particular the expected highly inclined dust torus that obscures the central engine. Whereas the original GRAVITY article (presenting the image) models the dust as a thin disc similar in morphology to the gas disc seen by its submillimetre maser emissions, a subsequent paper (Vermot et al., 2021) argues that the disc's inclination is more shallow, and it is not as thin and uniform. A third paper (Nikutta et al., 2021) argues for a highly inclined, thin but flared disc structure for the dust. Recent observations with MATISSE (the Multi-



ESO/Jaffe, Gámez-Rosas et al.

Active galaxy NGC 1068, captured with FORS2 on the VLT. Right: a blow-up view of the very inner region of this galaxy, its active galactic nucleus, as seen with MATISSE on the VLTI.

AperTure mid-Infrared SpectroScopic Experiment) (Gámez Rosas et al., 2022) have also led to reconstructed images and the modelling leans towards a disc that is thinner and not inclined enough to obscure the accreting SMBH, as well as the presence of a prominent polar flow. Interestingly, the spectral resolution of MATISSE also indicates that the mineralogy of the light-obscuring dust in NGC 1068 is different from that seen towards the centre of our Milky Way.

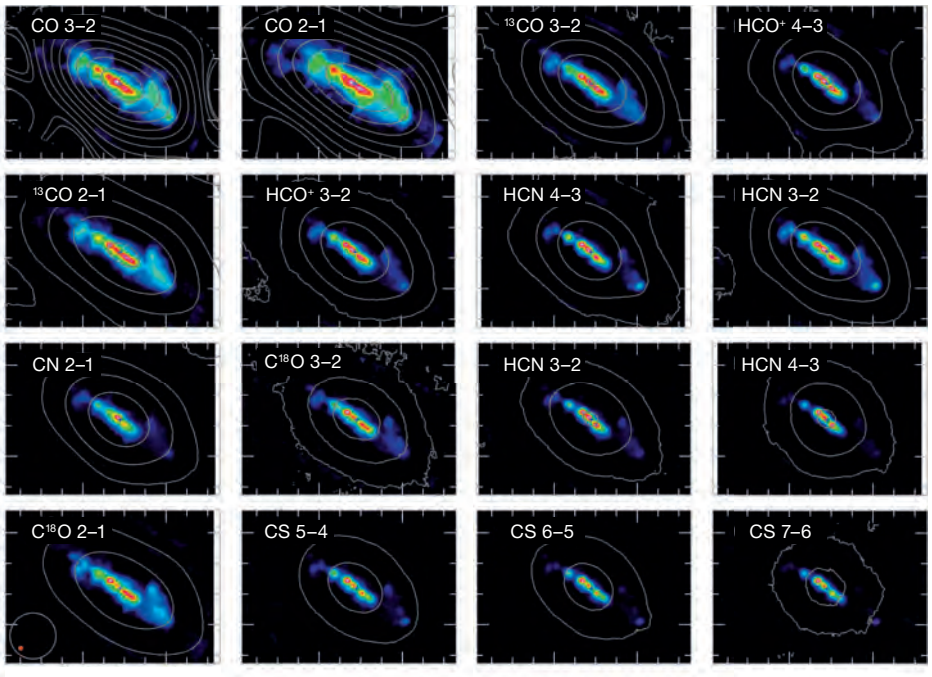
Interferometric observations of NGC 1068 in the infrared seem to challenge the unified model of AGNs. The angular resolution of the VLTI allows the obscuring dust to be directly imaged, hinting that its morphology and orientation may not match the expected geometry from the unified model — a highly inclined, thick torus. Upcoming VLTI observations of other AGNs will reveal whether and how the unified model may need to be amended.

P. Hrobárik/ESO/MATISSE consortium

Part of the complex optics of the VLTI instrument MATISSE during installation. Many components occur four times, one for each beam of light entering the instrument from a different telescope.

ALCHEMI: an 84–373-GHz spectral scan of the star-forming galaxy NGC 253

One of the fundamental science drivers for ALMA is understanding the origin of chemical complexity. For this, spectral line surveys are indispensable. The ALCHEMI project (Martín et al., 2021) has completed a spectral line survey of NGC 253 covering ALMA bands 3, 4, 5, 6 and 7, using both the 12-metre array and the Atacama Compact Array (ACA). It is the most extensive spectral survey ever undertaken with ALMA of a single source. NGC 253 is a nearby, highly inclined, star-forming galaxy. The star-forming activity gives rise to a wealth of spectral lines, whilst the high inclination means that many star-forming regions are visible on a single line of sight, thus enhancing the signal. The ACA part of the survey has already detected about 10, mostly complex organic, molecular species for the first time outside the Milky Way. In total, a spectacular 78 molecular species, including isotopomers, are detected in the ACA data. Maps showing the distribution of these species over the galaxy have also been constructed. Comparing this dataset with chemical models will contribute to the understanding of the star-formation processes in NGC 253.

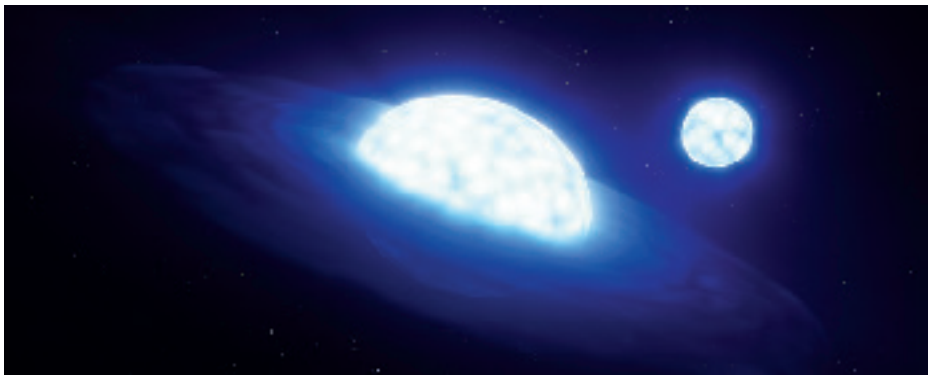


Martín, S. et al. 2021, A&A, 656, A46

Maps taken with the ACA (contours) in 16 of the brightest lines observed in the context of the ALCHEMI survey, superposed on the colour scale maps of the emission in the same lines obtained with the 12-metre array.

“Stellar-mass black hole” system found to contain no black hole

The Annual Report 2020 referred to the controversy over a possible stellar-mass black hole nearby. New VLTI observations (Frost et al., 2022) have now resolved the dispute in favour of a binary star system and no black hole. The search for stellar-mass black holes continues.



ESO/L. Calçada

HR 6819, previously believed to be a triple system with a black hole, is in fact a binary star system with no black hole. This artist’s impression shows what the system might look like.

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The first rays of the morning Sun shine down upon Cerro Paranal, the home of the VLT. What looks like a 'sea' in the distance is in fact a layer of cloud at lower elevation.

Gerhard Hüdepohl/ESO

ESO/K. Muzic

Observations of the star cluster RCW 38 made with HAWK-I and the GRAAL adaptive optics system on the VLT.

The Offices for Science and the ESO Faculty

Scientific activities

The efforts made by the Offices for Science to maintain a stimulating science research environment and engage the community were extended during the second year of the pandemic. Virtual platforms were used extensively to enable scientific interactions and foster scientific collaborations with the community. When the pandemic situation allowed, hybrid-mode activities (partly in person and partly virtual) were promoted within ESO to increase social interaction and as a benchmark to inform a new format for future workshops. Most of the new ESO Students and Fellows started on the planned dates on both sides of the Atlantic, and science internships took place in remote mode. The Scientific Visitor Programme was restructured to allow early-career scientists to apply.

ESO/Itziar de Gregorio-Monsalvo

ESO Chile Science Days 2022 (hybrid mode format).

Early-Career Scientific Visitor Programme

The new programme allows early-career scientists (PhD students and postdocs up to three years post-PhD) to spend one to four months working on their science projects at ESO and to enrich their professional profiles with the unique experience of working in the vibrant scientific environment of one of the world's leading observatories. The programme aims to promote scientific interaction with the ESO community and research institutions worldwide and to enhance ESO's role as an astronomical centre of excellence.

Science Workshops

Drawing on last year's experience of organising international conferences online, and in light of the pandemic situation, ESO continued to organise virtual meetings and workshops, which helped to maintain the interaction with the astronomical community. High -lights were "Atmo 2021: Atmospheres, Atmospheres! Do I look like I care about atmospheres?" and "GCF 2021: Galaxy Cluster Formation II" in Garching, and "The Star-Planet Connection" and "GALSPEC 2021: Extragalactic Spectroscopic Surveys: Past, Present and Future of Galaxy Evolution" in Chile. These events hosted 204, 211, 261, and 256 participants, respectively. To foster new scientific collaborations between the Vitacura campus and the Chilean community in the middle of the pandemic a virtual "ALMA Cycle 8 Proposals Preparation Workshop" was organised. As a test of hybrid-mode meetings, the "ESO Chile Science Days" were organised at the end of the year on the Vitacura campus.

Summer Research Programme in Garching

2021 marked the third year of the ESO Summer Research Programme. For six weeks this summer, six talented university students from across the globe got to work on research projects supervised by ESO Fellows and staff astronomers. The programme was held virtually.

Faculty Science Highlights

ESO's scientific excellence is illustrated by the achievements of its astronomers. We showcase here some particularly impressive highlights from the work of ESO astronomers (including staff, Fellows and Students) in Chile and Germany.

Avinash Chaturvedi, 3rd year, International Max Planck Research Schools PhD Student

Avinash comes from Varanasi, India, and completed his master's in astrophysics at the Laboratoire d'Astrophysique de Marseille in France. He is currently working with Michael Hilker, exploring the mass assembly of nearby Fornax galaxy clusters. He was awarded, as Principal Investigator, a total of 90 hours of observing time with FLAMES (the Fibre Large Array Multi Element Spectrograph) and FORS2 (the FOcal Reducer and low dispersion Spectrograph) to study the globular clusters in the Fornax galaxy cluster. He was awarded a prestigious grant by the Flatiron Institute (New York) pre-doc programme to understand galaxy cluster environments using cosmological simulations alongside Meerkat radio observations. He presented his work at several conferences and he is a very engaged organiser of ESO scientific activities.

Carlo Felice Manara, User Support Department Astronomer

Carlo joined ESO as a Fellow in Garching, where he played a major part in implementing the first ESO Summer Research Programme, now a regular fixture in the ESO calendar. He was awarded the European Research Council starting grant "WANDA – Winds ANd Disk

structures near and Afar", which aims to explain the rings and spirals observed in protoplanetary discs, determining what fraction is due to planets, and what fraction to other mechanisms, such as the effect of magnetically driven disc winds, and looking at more massive, more distant, more representative star-forming regions than have been studied to date. To achieve these goals, the project will exploit ESPRESSO, UVES (the Ultraviolet and Visual Echelle Spectrograph), MUSE, X-shooter and SPHERE (the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument) on the VLT, along with ALMA. In this quest, new advanced data analysis techniques for the VLT and ELT will be explored and developed. The grant will be used to build a team of postdocs and students, hosted within the Office for Science. This will allow at least five more early-stage researchers from our community to experience ESO first-hand, and enable collaborations, visits and workshops involving Member State scientists.

Claudia Paladini, Paranal Science Operations Astronomer

Claudia is a staff astronomer and chair of the ESO Chile Fellowship Committee. This year she was elected Vice-President of the European Interferometry Initiative (Eii), an open association of institutes and laboratories for the exploitation and development of optical long baseline interferometry. The Eii brings together the activities included in the European Commission instruments of the 6th, 7th and H2020 R&D programmes, including the most recent OPTICON-RadioNet Pilot programme. Claudia was recently appointed as chair of the Fizeau exchange visitor programme, allocating travel funding to support VLTI collaborations. She was recently allocated a VLTI/MATISSE Large Programme to image the dusty environment of evolved stars and understand the impact of binaries on the mass-loss process.

Marie-Lou Gendron Marsolais, ESO ALMA Fellow

Marie-Lou is an ESO Chile Fellow with duties at ALMA. As part of those duties she acted as ALMA VLBI Fellow, on the preparatory work and quality analysis of the ALMA VLBI observing campaign in 2021. Marie-Lou has also contributed to ALMA data quality, calibration assessment and software testing.

Marie-Lou studies groups and clusters of galaxies, focusing on the interaction between supermassive black holes in galaxies and their surrounding dense environments. To achieve a better understanding of this interplay, she analyses multi-wavelength observations of these objects. In particular, the combination of optical Integral Field Units (such as MUSE on the VLT) and millimetre facilities (such as ALMA) provides spectroscopically and spatially resolved information about the warm ionised and molecular components surrounding the elliptical galaxies sitting in the cores of clusters. Such measurements are essential to our understanding of the multiphase gas interplay in the centres of clusters.

Marie-Lou is very committed to diversity matters and passionate about science communication. She is spending the fourth year of her fellowship at the Instituto de Astrofísica de Andalucía, CSIC, in Granada (Spain).

Priscila Pessi, ESO Student

Priscila is working on the characterisation of supernovae (SNe) under the supervision of Joseph Anderson. She has defined a parameter to characterise SNe Ia *i*-band light curves which could have important implications in the field of cosmology by reducing the scatter in Hubble residuals. She has observed over 25 nights with the NTT (New Technology Telescope) at La Silla and the Helen Sawyer Hogg telescope at the Complejo Astronómico El Leoncito in Argentina to classify and follow up hundreds of SNe. She recently presented her work at the Supervirtual 2021 conference. Priscila is an active member of our ESO community, organising the Vitacura lecture series, and is deeply involved in outreach activities.

Library and Information Centre

In 2021 the Library and Information Centre operated mostly online while still maintaining essential activities on-site in order to make sure that all user requests for access to material were fulfilled in a timely manner. Open Science and Open Access (OA) were particularly important topics this year as the first astronomy core journals — Astronomy & Astrophysics, the Astrophysical Journal, and the Astronomical Journal — announced their move to OA. As members of the OA Working Group of Astronomy & Astrophysics, a "Diamond" Open Access model, which avoids direct publishing costs for authors as well as readers, was


Avinash Chaturvedi


Carlo Felice Manara


Claudia Paladini


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Priscila Pessi

strongly promoted by the ESO Head Librarian and the Head of the Garching Office for Science; a slightly modified version will be implemented by the journal as of 2022. Further developments also occurred in other areas of scholarly communication, such as the increasingly widespread use of the ORCID (Open Researcher and Contributor ID) author identifier. The Library provided guidance and advice on these topics to researchers at ESO and beyond through a variety of presentations.

The ESO Library maintains an infrastructure to make presentation slides and posters of ESO-hosted conferences available via the Zenodo platform. A Creative Commons Attribution licence (CC-BY) allows re-distribution and re-use of the content on the condition that the creator is appropriately credited. In this way, ESO's "Conference Proceedings 2.0" apply the widely used principles of making research content Findable, Accessible, Interoperable, and Re-usable (FAIR). In accordance with legislation such as the European Union's General Data Protection Regulation, the Conference Proceedings workflow was amended, offering a stronger involvement and more autonomy to conference participants during the file upload process.

The organisation-wide rollout of ESO's Information Repository system progressed well. Policies and procedures were established in order to ensure that consortia, contractors, and partner organisations can use the PDM (Product and Document Management) system to exchange documentation with ESO. The database of refereed articles that use ESO's observational data — the ESO telescope bibliography (telbib) — is developed and curated by the Library and Information Centre. Entries in the database are facet-rich and provide an essential tool for the organisation's management to evaluate research output and its impact among the research community. Information about telbib, including statistics derived from it, can be found in the Publication Digest section of this report.

Star cluster NGC 1850, as seen in overlaid observations made by ESO's VLT (of the wide field and the reddish filaments of hydrogen gas) and the NASA/ESA Hubble Space Telescope (of the central cluster).

ESO, NASA/ESA/R. Gilmozzi/S. Casertano, J. Schmidt

Allocation of Telescope Time

The VLT's Unit Telescope 4, with its laser guide stars, observing under the Milky Way at Paranal.

The table shows the requested and scheduled observational resources allocated for Periods 108 (1 October 2021 to 31 March 2022) and 109 (1 April to 30 September 2022) for the La Silla Paranal Observatory and APEX. These are specified as the length of the run in nights, the usual allocation unit for the La Silla Paranal Observatory and APEX. Current Large Programme runs approved in previous periods, Guaranteed Time runs and Public Survey runs are not included. The pressure is computed as the ratio of requested time to allocated time. The last two columns present the total telescope time allocations and the fractions per instrument.

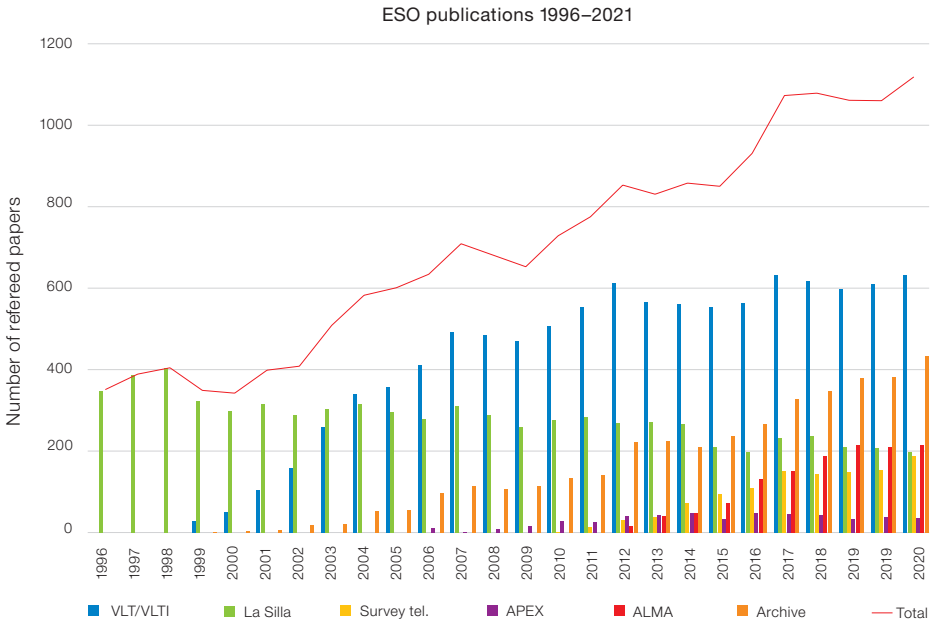
The Incoherent Combined Coudé Focus (ICCF) is listed separately and presents the statistics for ESPRESSO in the 4UT mode. The time fractions are computed relative to the total allocated time on the four VLT UTs. In the request, the ESPRESSO-1UT proposals are randomly distributed across the four UTs, while the allocated time reflects the final schedule, which is constructed taking into account the loads on the different UTs.

The proposal review process for ALMA Cycle 8 (covering the period from October 2021 to September 2022) utilised Distributed Peer Review for proposals requesting less than 25 hours on the 12-metre array, and traditional panel review for proposals requesting more than 25 hours. Dual-anonymous reviewing was employed, independent of proposal size. The table shows the requested and scheduled resources for the ALMA observatory in Cycle 8 listed by scheduling priority (A or B) and ALMA frequency band, for the community in the ESO Member States, and the rest of the world (including North America, East Asia, the ESO community and the Host State Chile). The scheduling unit for ALMA is an hour of 12-metre array time. Note that the total number of ALMA proposals is less than the sum of the numbers in the table, as proposals can request more than one band.

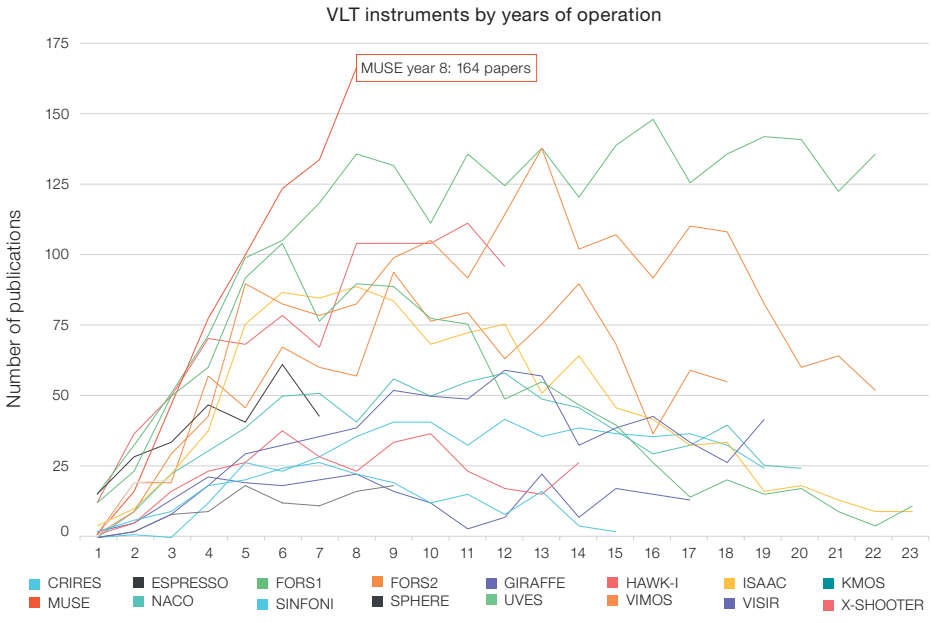
Telescope	Instrument	Requested runs	Scheduled runs	Requested time	%	Scheduled time	%	Pressure	Total allocation	%
UT1	FORS2	252	96	295	54.7%	89	50.7%	3.32	93	40.5%
	KMOS	79	17	135	25.0%	31	17.6%	4.37	31	13.4%
	VISIR	53	33	23	4.2%	14	8.0%	1.63	17	7.2%
	ESPRESSO1	75	22	87	16.1%	42	23.7%	2.09	90	39.0%
Total		**459**	**168**	**540**	**100.0%**	**176**	**100.0%**	**3.08**	**231**	**100.0%**
UT2	FLAMES	51	18	87	16.7%	35	20.6%	2.50	35	16.8%
	UVES	199	48	362	69.5%	97	57.8%	3.72	106	51.1%
	ESPRESSO2	65	32	72	13.8%	36	21.6%	1.98	67	32.2%
Total		**315**	**98**	**520**	**100.0%**	**168**	**100.0%**	**3.09**	**207**	**100.0%**
UT3	SPHERE	163	37	136	17.1%	29	19.8%	4.72	34	20.6%
	XSHOOTER	483	112	596	75.1%	117	80.2%	5.10	130	79.4%
	ESPRESSO3	55	0	62	7.8%	0	0.0%	-	0	0.0%
Total		**701**	**149**	**794**	**100.0%**	**146**	**100.0%**	**5.45**	**164**	**100.0%**
UT4	HAWK-I	82	16	135	14.6%	22	21.3%	6.10	26	19.9%
	MUSE	657	102	696	75.1%	82	78.7%	8.51	103	80.1%
	ESPRESSO4	58	0	96	10.3%	0	0.0%	-	0	0.0%
Total		**797**	**118**	**926**	**100.0%**	**104**	**100.0%**	**8.92**	**129**	**100.0%**
ICCF	ESPRESSO-4UT	1	0	0	0.1%	0	0.0%		0	0.0%
VLTI	GRAVITY	171	61	107	44.9%	48	48.2%	2.22	97	48.5%
	MATISSE	136	26	86	36.3%	35	34.8%	2.48	85	42.4%
	PIONIER	35	14	45	18.8%	17	16.9%	2.64	18	9.0%
Total		**342**	**101**	**238**	**100.0%**	**100**	**100.0%**	**2.38**	**200**	**100.0%**
3.6-metre	HARPS	72	42	399	100.0%	142	100.0%	2.82	310	100.0%
Total		**72**	**42**	**399**		**142**		**2.82**	**310**	
NTT	EFOSC2	80	45	232	67. 7%	140	63.1%	1.66	174	68.0%
	SOFI	33	27	110	32.3%	82	36.9%	1.35	82	32.0%
	SpecialNTT	0	0	0	0.0%	0	0.0%	-	0	0.0%
Total		**113**	**72**	**342**	**100.0%**	**221**	**100.0%**	**1.55**	**255**	**100.0%**
APEX	ARTEMIS	1	0	1	0.5%	0	0.0%	-	8	8.0%
	LABOCA	2	1	7	3.3%	5	6.8%	1.42	5	4.9%
	SEPIA	32	3	37	17.1%	9	11.9%	4.26	9	8.6%
	nFLASH	29	6	121	55.3%	21	29.0%	5.65	21	21.0%
	CONCERTO	8	4	52	23.8%	39	52.3%	1.35	59	57.5%
Total		**72**	**14**	**218**	**100.0%**	**74**	**100.0%**	**2.96**	**102**	**100.0%**

	Band	Requested proposals		Scheduled (A+B) proposals		Requested 12-metre time		Scheduled (A+B) 12-metre time		Pressure (time)	
		All	ESO	All	ESO	All	ESO	All	ESO	All	ESO
ALMA	3	461	197	58	27	5496.23	2377.69	845.09	439.69	6.50	5.41
	4	183	85	22	7	1471.92	764.63	158.27	29.37	9.30	26.03
	5	155	73	17	6	1127.11	481.11	118.59	56.35	9.50	8.54
	6	754	324	120	39	8882.07	3847.63	1330.37	494.24	6.68	7.78
	7	630	263	91	19	7305.13	3278.31	1144.57	181.04	6.38	18.11
	8	158	68	28	6	1157.1	496.32	208.97	32.1	5.54	15.46
	9	84	36	12	3	554.02	268.04	57.96	7.62	9.56	35.18
	10	45	16	10	3	210.93	61.11	51.26	17.35	4.11	3.52
Total						**26205**	**11574.84**	**3915.08**	**1258**	**6.69**	**9.20**

Publication Digest



Refereed papers using ESO data, 1996–2021. Some papers use data from more than one facility. VLT/VLTI: papers using data generated by VLT and VLTI instruments, including visitor instruments for which observing time is recommended by ESO. La Silla: papers using data from La Silla facilities, including visitor instruments (see VLT/VLTI). Papers based on data from non-ESO telescopes or observations obtained during reserved periods (for example, national time allocations) are not included. Survey telescopes: papers using data from ESO's survey telescopes VISTA and VST. APEX: papers using APEX data, including visitor instruments (see VLT/VLTI). ALMA: papers using data generated by ALMA. For APEX and ALMA, only papers based (entirely or partly) on data obtained during ESO time are included. Archive data papers are those without overlap between authors and observers.



Number of papers using data generated by VLT instruments by year since the start of operations.

The ESO community published more than 1100 data papers in 2021, the highest number ever. The total number of data papers included in the ESO Telescope Bibliography (telbib), published between 1996 and 2021, has surpassed 18 400.

Publications from different sites

As in previous years, VLT/VLTI data led to more than 600 refereed papers in 2021. The number of data papers has been stable at this high level for the past five years. The number of papers using data from MUSE has continued to rise, amounting to over 160 articles in 2021. At the VLTI, the steep increase in the number of papers using GRAVITY data since 2019 has continued.

With almost 190 papers using data obtained at ESO's survey telescopes, VISTA and the VST, a new level was reached in 2021. Approximately half of these papers (46%) used data obtained from the ESO Science Archive, emphasising the value of ESO's public surveys to the astronomy community.

As in previous years, observations obtained at the La Silla facilities led to approximately 200 papers. Even instruments that were decommissioned years ago still contribute to the pool of data papers. An increasing number of telescopes, for instance the Max-Planck-Gesellschaft/ESO 2.2-metre telescope, the Swiss 1.2-metre Leonhard Euler Telescope, and the Danish 1.54-metre telescope, are hosted but not run by ESO, and their papers are not included in the ESO statistics.

The number of papers that use partly or exclusively archival data, i.e., observations without any overlap between the authors and the team of observers, has increased continuously during recent years, reaching 38% in 2021. Almost a quarter of all data papers published in 2021 (23%) deployed only archival observational data, without any ESO observations obtained by the authors; these papers would not have been in telbib without the existence of the ESO Science Archive.

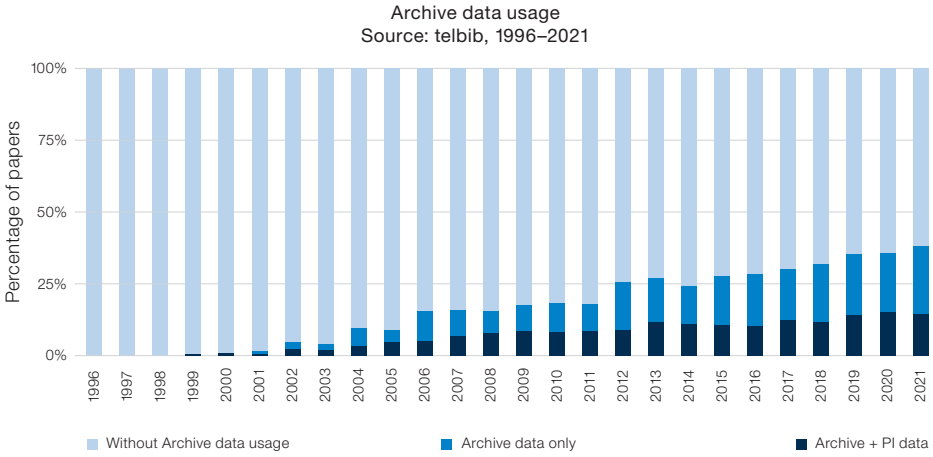
APEX, after over 15 years of operation, led to more than 60 papers in 2021 from all APEX partners combined, i.e., the Max Planck Institute for Radio Astronomy, the Onsala Space Observatory, and ESO. Observations obtained during ESO observing time at APEX contributed to more than half (57%) of them. The total number of APEX papers since the first science publication in 2006 has surpassed 870.

In 2021 the ALMA user community published more data papers than ever before, using observations from all ALMA partners. Once again, almost half of them (45%) made use of at least some data obtained during ESO ALMA time. The ALMA bibliography is maintained jointly by the librarians at ESO and the National Radio Astronomy Observatory in the USA as well as by the National Astronomical Observatory of Japan. Publications based on data from all ALMA partners are recorded in telbib, but only those based on ESO observing time are counted in the ESO statistics, unless otherwise noted.

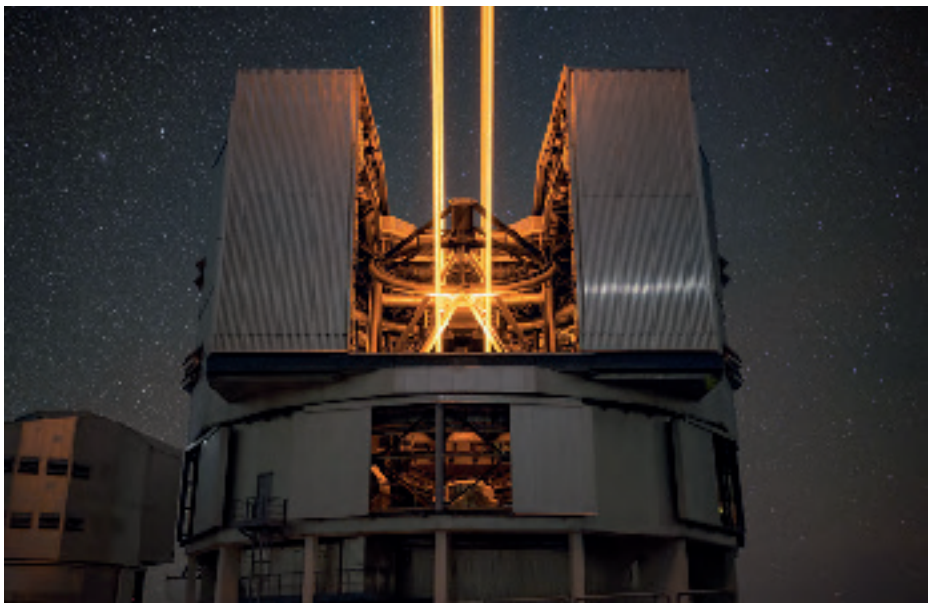
The ESO Telescope Bibliography (telbib)

The statistics presented here are derived from telbib, a database of refereed papers published by the ESO user community. Telbib links publications with the data in the ESO Science Archive and assists the ESO management with evaluating the organisation's productivity and impact. Telbib is curated and developed by the ESO Library and Information Centre. Whilst text-mining scripts are applied when screening the literature for ESO data papers, articles are carefully examined by the curators before they are added to the database to ensure that all telbib papers use partly or exclusively data from facilities for which observing time was recommended by ESO. The public telbib interface (telbib.eso.org) provides visualisations of search results including on-the-fly graphs and predefined charts.

Records of all 2021 papers using ESO data can be accessed at https://telbib.eso.org/ESODataPapers2021.php. A separate listing of refereed publications by authors with an ESO affiliation, with or without the use of ESO data, can be found at https://www.eso.org/sci/libraries/telbib_ info/AR/ESOStaffPapers2021.pdf. Details about telbib, including information about the methodology used to screen and classify papers, can be found on the web at https://www.eso.org/sci/libraries/telbib_info.html.



Percentage of papers 1996–2021 using ESO data obtained by the team of authors ("without Archive data usage"), obtained from the ESO or ALMA Archive ("Archive data only"), and obtained partly by the team of authors as well as from the ESO or ALMA Archive ("Archive + PI data"), respectively. For APEX and ALMA, only papers based (entirely or partly) on ESO time are included.



ESO/A. Ghizzi Panizza

The four beams of the Adaptive Optics Facility laser guide stars emerge from the VLT's Unit Telescope 4 at Paranal.

ESO/P. Horálek

A view of Saturn in the planetarium at the ESO Supernova Planetarium & Visitor Centre.

The ESO Supernova Planetarium & Visitor Centre

Owing to the continuing pandemic, the ESO Supernova remained closed until mid-May 2021. During this time, focus was shifted to online activities and improving existing social media channels. Several virtual tours were delivered — each with 50–100 people watching live, around 200 school students in Brazil and Italy participated in online education sessions (which, thanks to the support of ESO staff, were offered in Portuguese and Italian respectively), and the annual Max Planck Institute for Extraterrestrial Physics "Women in Astronomy" talk — normally hosted in the planetarium — was streamed live on the ESO Supernova YouTube Channel. 18 ESO Students and Fellows, in both Garching and Chile, participated in a modified online version of the communication training session offered in previous years, and the ESO Supernova volunteers were engaged with monthly online presentations.

During the closure, the opportunity was taken to upgrade the planetarium projectors. The old light-bulb-based technology was replaced with a new state-of-the-art LED version. Not only do the new projectors have an extended lifespan but they are quieter and deliver better image quality, brightness and sharpness. They also consume less energy and require less warm-up time, and hence have lower running costs. Pending minor adjustments, this was a highly successful upgrade.

From January to June, a University of Leiden Science Communication master's student, Ulrika Ferner, undertook a 6-month internship, the focus of which was visitor analysis. She produced an online survey and gathered responses from 186 people. In addition, she conducted 12 interviews on-site with groups of visitors. This project served well as a pilot for conducting more evaluation in the future and helping to understand the needs and expectations of visitors.

In May the facility reopened to the public, initially offering access only to the exhibition. Planetarium shows were reintroduced to the programme shortly after and the centre remained open, albeit with varying levels of restrictions, until the end of the year. During the 7.5 months the ESO Supernova was open to the public, over 16 100 people visited, over 9800 of those watching one of the 266 planetarium shows, and an additional 6330 people explored the exhibition. A stargazing event was hosted together with TEDxTUM and a programme of short planetarium shows named Art and Science under the Dome was part of the new regional art and research Hi!A Festival supported by the Bavarian government.

Team members presented the ESO Supernova at various important conferences, including the annual meeting of the Society of German-speaking planetariums, the conference of the European Network of Science Centres and Museums and the 3rd IAU-Shaw Workshop on Astronomy for Education.

Education

A total of 75 school groups (more than 2300 pupils and 311 accompanying teachers) took part in the on-site education programme. School classes were able to enjoy planetarium shows and the exhibition, with or without a guide. The reach of the ESO Supernova education programme was wider during 2021 than ever before, with 40% of classes travelling more than 100 kilometres (compared to around 25% in 2020) and 77% of the schools visiting us for the first time.

Girls' Day 2021 was held as a virtual event and attracted 50 female school students from all over Germany. Thanks to ESO colleagues, a rich and exciting mix of astronomy and engineering was offered, and the feedback was overwhelmingly positive.

Over 370 teachers from across Germany were engaged in a variety of activities, both on-site and virtually, during 2021. Approximately 230 teachers participated in a selection of online teacher training events, including four 2.5-hour workshops on ESO's involvement in the Nobel Prizes of 2019 & 2020 (in collaboration with the district subsidiary of the Ministry of Education) and a two-day workshop about infrared astronomy delivered alongside the German Stratospheric Observatory For Infrared Astronomy (SOFIA) Institute at the University of Stuttgart.

A cooperation agreement was signed with Forscherstation, Heidelberg, to foster early childhood science education. A proposal was submitted to the Klaus Tschira Stiftung to request funding for the project, including a full-time staff position. The proposal was approved and the recruitment process for the Education Specialist role, responsible partly for the collaboration with Forscherstation and partly for the education programme (age 4–12 years), was completed. A well suited candidate has been selected, who will join the ESO Supernova team in February 2022.

TEDxTUM/Florian Bodlée

Visitors in the planetarium of the ESO Supernova Planetarium & Visitor Centre, during the stargazing event hosted together with TEDxTUM in August 2021.

ALMA antennas on the Chajnantor plateau under the Milky Way. The white glow of zodiacal light is visible in the sky above the person in the foreground.

ESO/P. Horálek

Operations

Gideon Yoffe/ESO

La Silla Paranal Observatory

The Directorate of Operations is responsible for all activities related to science operations, including the preparation and execution of observing programmes, the operation of the La Silla Paranal Observatory with its La Silla, Paranal and Chajnantor sites, and the delivery of raw and calibrated data. This involves user support, data flow management, operational technical support and the development and maintenance of a science archive as provided by the Data Management and Operations (DMO) Division. The Science Archive Facility holds all of the data obtained using ESO and hosted telescopes, as well as highly processed, advanced products derived from those data. Operations also include ESO's contribution to the operation and development of ALMA (the Atacama Large Millimeter/submillimeter Array) through the ESO ALMA Support Centre (EASC) and the construction support and future operation of CTA-S (the southern site of the Cherenkov Telescope Array).

The Coalsack Nebula, a dark cloud of interstellar dust, is seen here above one of the VLT's Auxiliary Telescopes on Paranal.

Operations

ESO's VLT (Very Large Telescope) at Paranal operates with four 8.2-metre Unit Telescopes (UTs) and includes an instrumentation suite comprising three remaining first-generation instruments, two upgraded first-generation instruments, and all six second-generation instruments. The Adaptive Optics Facility (AOF), with four laser guide stars and a deformable secondary mirror, has converted UT4 into an AO telescope that provides atmosphere-corrected images to its instruments. The VLTI (VLT Interferometer) combines the light from either the four UTs or the four Auxiliary Telescopes (ATs) to feed one of the three interferometric instruments with a coherent wavefront. VISTA (the Visible and Infrared Survey Telescope for Astronomy) and the VST (VLT Survey Telescope) are also in regular survey operation.

At La Silla the NTT (New Technology Telescope) and the ESO 3.6-metre telescope operate with an instrumentation suite of three instruments. The La Silla and Paranal sites further support 13 hosted telescope projects, of which ten are currently operating.

The observatory provides operational support for APEX (the Atacama Pathfinder EXperiment), a 12-metre submillimetre radio antenna on the Chajnantor plateau at an altitude of 5100 metres; it has a suite of heterodyne and bolometer facility instruments, as well as visitor instruments.

CTA-S will be hosted in the valley between Paranal and Armazones and will be operated by ESO on behalf of the CTA Observatory (CTAO). Paranal Observatory provides administrative, logistics, and technical support to the construction of CTA-S.

Operational statistics

The scientific community submitted 1064 and 950 Phase 1 observing proposals for the La Silla Paranal Observatory (including APEX) in Periods 107 and 108, respectively. This underlines the continuing high demand for ESO's observing facilities. About 89% of the proposals received were for the Paranal site (including the VLT, VLTI, VST and VISTA).

The observatory continued its efficient operation, marked by the high availability of its telescopes and instruments and low technical downtime — key elements for productive scientific observations — although availability for science was reduced by the pandemic. In 2021 (2020), a total of 1764 (973) nights were scheduled for scientific observations with the four UTs at the VLT and with the two major telescopes at La Silla. This is equivalent to 81% (44%) of the total number of nights theoretically available over the whole year and close to pre-pandemic values of typically 90%.

Of the available science time on the VLT, only 2.9% (2.7%) was lost to technical problems and about 10.5% (8.9%) to adverse weather conditions. At La Silla bad weather accounted for losses of about 14.6% (6.8%) and technical problems for about 0.3% (0.8%). VISTA delivered 166 (72) nights of survey observations out of 198 (94) scheduled nights or 84% (77%) and the VST delivered 180 (105) nights of survey observations out of 205 (127) scheduled or 88% (83%). VISTA and the VST were affected by weather losses of 8.0% (19.1%) and 10.3% (15.1%), respectively. The technical losses of VISTA and the VST were 8.2% (3.9%) and 1.9% (1.8%), respectively.

Complementing regular VLT operations, the VLTI was scheduled for 201 (89) additional nights to execute scientific observations using baselines with either the UTs or the ATs. Of the scheduled VLTI science time, 6.6% (8.7%) was lost to technical problems and 16.3% (8.0%) to bad weather. In 2021 (2020), 55 (11) engineering nights but only 7 (22) commissioning nights were invested in the continued installation and commissioning of the VLTI infrastructure. Despite these continued technical activities, the availability of the VLTI for scientific observations increased from 56% in 2019 and 73% in 2020 to 77% in 2021.

In 2021 (2020), a total of 197 (61) days and nights were scheduled for science observations with APEX, of which 162 (59) could be used, resulting in more than 3420 (1287) hours of on-sky science time.

ESO/P. Horálek

Dusk at Paranal, with the crescent Moon visible in the sky on the left.

The combination of high operational efficiency, system reliability and availability for scientific observations at the La Silla and Paranal facilities continues to result in high scientific productivity. In 2021 (2020), 636 (612) peer-reviewed papers were published which were at least partly based on data collected with VLT and VLTI instruments at Paranal. In addition, 189 (155) referred papers were published referring to observations with VISTA and the VST at Paranal, and 199 (209) referring to ESO-operated telescopes at La Silla. Regarding papers using APEX observations, 35 (38) made use of data gathered during ESO's share of the observing time in 2021 (2020). In 22 years of operation, the VLT and VLTI have produced a total of 10 209 publications and add about a dozen every week. The second-generation instrument MUSE (Multi Unit Spectroscopic Explorer) leads the annual publication statistics of all ESO instruments with 164 (132) publications in 2021 (2020). The veteran instrument UVES (Ultraviolet and Visual Echelle Spectrograph) still produced 134 (121) publications followed by the second-generation instrument X-shooter with 95 (110) publications.

COVID-19 — observatory ramp-up

Observatory operation continued to be strongly affected by the COVID-19 pandemic in 2021.

By the beginning of the year all sites had reached the Restricted Operation phase, allowing basic science and technical operation with selected telescopes, instruments and modes only and with a much reduced on-site operation team as defined in the ramp-up plan. Restricted Operation allowed most of the scientific observations planned for observing Period 106 to be secured, operationally critical technical and maintenance activities to resume, and (remote) commissioning of some new instruments like CRIRES$^+$ (the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph) to be enabled.

However, owing to the third wave of the pandemic in Chile, on-site presence and science capabilities had to be reduced again in the period from mid-March to mid-August 2021 and the sites remained in an intermediate stage between Minimal and Restricted Operation. Between April and the end of July Paranal science operations were restricted to between two and four UTs and the VLTI to four UTs. Neither the survey telescopes VISTA and VST nor the VLTI with the ATs could be operated during this period. Only by mid-August had operation of all Paranal telescopes resumed. At La Silla the 3.6-metre telescope was not operated during April but gradually returned to full operation by August, whilst the NTT was operated without interruption. From April to September APEX reduced science operation to 8 to 16 hours per day instead of the nominal 24 and remained in 16-hour operation per day until the end of the year.

During the last quarter of the year all observatory sites moved through three preparatory stages towards Full Operation. On 23 November Stage 3 was reached which introduced a number of major changes, including breaking the “closed bubble” concept of the ramp-up plan; all sites resumed commercial flights and close to pre-pandemic commuting arrangements. Flexibility for shift planning was gradually increased. Room alternation

in the Paranal Residence stopped, since cleaning between shifts could be ensured, and car and office sharing was increased according to need and following defined safety procedures. Stage 3 allowed larger missions to Paranal, e.g. to start the assembly, integration and verification of ERIS (the Enhanced Resolution Imager and Spectrograph) and to commission GRAVITY Wide. However, since the start of Stage 3 coincided with the peak of the fourth wave of the pandemic in Chile — dominated by the spread of the Delta variant — all observatory sites remained in Stage 3 until the end of the year.

Paranal Observatory

Infrastructure

The construction of the new modular two-floor office building in the Paranal basecamp was completed in late 2021. Relocation of the Director's Office and the Information Technology Team from the VLT Control Building and the Warehouse Building started. The space gained in the VLT Control Building will be used to provide more office space to several groups, to create a proper meeting and video conference room, a larger kitchenette and additional bathrooms, and will provide additional laboratory space close to the VLT telescopes and instruments. Several rooms in the Residence that are currently used as offices will be converted into additional bedrooms.

Telescopes and instrumentation

Restricted Operation and the ramp-up towards Full Operation during the year allowed operationally critical technical activities to be resumed despite continued pandemic restrictions.

CRIRES$^+$ was successfully commissioned during Restricted Operation by a mixed team of on-site observatory staff, remote Garching staff and instrument consortium members and was offered to the scientific community as of Period 108, starting in October following Science Verification in September. The successful upgrade of IRLOS (the InfraRed Low-Order wavefront Sensor) of MUSE allows the use of reference stars some two magnitudes fainter for AO corrections at even higher correction frequencies. The commissioning of the GRAVITY fringe tracker for MATISSE (the Multi-AperTure mid-Infrared SpectroScopic Experiment), a mode known as GRA4MAT, was completed, as well as the commissioning of MATISSE itself on the UTs. The relocation of VISIR (the VLT Imager and Spectrometer for mid-Infrared) from UT4 to UT2 was eventually completed and it was available again for science operations in Period 108.

The increasing on-site staffing complement during Stage 1 towards Full Operation allowed the recoating of the M1 and M3 mirrors of UT1 in September, and during Stage 2 in October two Garching engineering staff members were able to visit Paranal — the first since the beginning of the pandemic — to carry out some critical laser splitting tests for the future MAVIS (MCAO Assisted Visible Imager and Spectrograph). The three-laser-guide-star mode of HAWK-I (the High Acuity Wide-field *K*-band Imager) was commissioned in November. Between October and December, the M4 and M6 mirrors of all four UTs were recoated for the first time since their initial installation for the VLTI some 20 years ago, followed by the installation and commissioning of the Delay Line Stroke Extension system for the VLTI.

Stage 3 towards Full Operations was initiated in early December and eventually allowed missions of larger external teams onto the Paranal site. This enabled the start of the assembly, integration and verification of ERIS in the New Integration Hall before it was moved to UT4 in early 2022, and the commissioning of the GRAVITY Wide mode for the VLTI.

Operation development

The observatory continued the development of an operation model for the future integrated operation of the VLT and the ELT (Extremely Large Telescope). The integration of VLT and ELT operation is expected to maximise the synergies between the existing Paranal facilities, infrastructure and resources and the ELT at Armazones. Moreover, it forces the indispensable evolution of the observatory's operations model for the coming decades in the context of not only the fourth industrial revolution and global digital transformation but also the response to climate change; a simple scaling of the current conventional operation model would otherwise not be sustainable for one of the largest ground-based astronomical observatories at such a remote site in the Atacama Desert.

After the review of the development of the Integrated Operation programme in 2020 the work breakdown of the programme was revised and restructured into a more sequential order. This new work breakdown structure emphasises first delivering an evaluation of the operation processes and a consistent baseline operations model before formulating any implementation projects, and defines the deliverables of the programme Phase A more clearly. The Top-Level Requirements and the Phase A proposal were reviewed by the Directors Team in May and the programme was presented to the ESO Council later in the year. The programme closed the year with the presentation of the Phase A plan in December, outlining the work to be delivered in 2022.

Hosted telescopes at Paranal

Both hosted telescope projects at Paranal, SPECULOOS (the Search for habitable Planets EClipsing ULtra-cOOl Stars) and NGTS (Next-Generation Transit Survey), continued regular operation during the year.

As of this year, the Observatory Cerro Armazones — on Cerro Murphy next to Cerro Armazones — is operated and maintained by the Nicolaus Copernicus Astronomical Centre in Warsaw, Poland, according to the recently renewed hosting agreement with the Ruhr-Universität Bochum, Germany. During the year, planning started for the installation of the new 0.6-metre, 0.8-metre, and 1.5-metre telescopes in addition to the existing 0.8-metre IRIS (InfraRed Imaging System) telescope. The assessment of the proposed installation of an additional 2.5-metre telescope is ongoing and would require an amendment to the existing hosting agreement.

CTA-South Observatory

During its 141st meeting in 2016 the ESO Council unanimously approved the participation of ESO in the CTA project as a new Supplementary Programme. During its 149th meeting in December 2018 Council expressed its intention to become a founding member of the CTAO European Research Infrastructure Consortium (ERIC) and approved the CTA Hosting Agreement.

The CTA Hosting Agreement between ESO and the CTAO gGmbH and the agreement between the Republic of Chile and ESO to host, construct, commission and operate the CTA-S Project were signed in December 2018.

During 2021 the first large procurement for the site infrastructure of CTA-S was carried out by ESO in close coordination with the CTAO. A Call for Tender for the construction of the access road to the site was successfully concluded and a contract for the construction work was awarded before the end of the year. In addition, preparation work for the connection of CTA-S to the electrical grid has begun. Different options, including the connection to the Paranal 4-MW photovoltaic plant, are being considered to maximise the use of renewable energies by the observatory.

ESO continued to support the establishment of the CTAO ERIC. During 2021 the Board of Government Representatives (BGR) led a reconfiguration exercise to establish a so-called Alpha Configuration that could be affordable and that meets the national interests of the CTAO members. The resulting Alpha Configuration has fewer telescopes than the initially presented baseline configuration but was approved by the CTAO Council in June. In September the BGR approved all relevant documents for the submission of Step 2 of the application to the European Commission and in December the ESO Council authorised the ESO Director General to co-sign the formal request to the European Commission for the establishment of the CTAO ERIC, now expected by the end of 2022.

La Silla Observatory

Many technical activities planned for this year at La Silla had to be postponed because they could not be supported during Restricted Operation. However, Stage 2 and 3 towards Full Operation allowed the M1 coating of the 3.6-metre telescope in November and the commissioning of the AO module of NIRPS (the Near Infra Red Planet Searcher) in December. All hosted telescope projects at La Silla continued in operation during the year.

Despite the pandemic, La Silla continued to implement its revised technical operation scheme according to its LS2020+ plan. A Call for Tender to industry for the technical operation and maintenance of the site, including its infrastructure, the telescopes and instruments, and the commitments towards the hosted telescope projects, was successfully concluded. The corresponding service contract was signed with OHB Chile SpA and came into operation in July.

APEX Observatory

APEX currently operates under a partnership agreement between the Max Planck Institute for Radio Astronomy (MPIfR, Bonn, Germany; 55% share), ESO (32% share) and the Onsala Space Observatory (OSO, Sweden; 13% share). The current APEX agreement further establishes an additional investment of 18.5 million euros in the antenna, instruments and infrastructure for the period 2018–2022.

As part of these investments, SEPIA (the Swedish ESO PI receiver for APEX) had already been equipped with Band 9 (at 660 GHz) and Band 5 (at 180 GHz). The last two receivers completing the planned upgrade of the suite of heterodyne facility instruments are SEPIA345 (Band 7 at 345 GHz) from OSO and the nFLASH (new FaciLity APEX Submillimeter Heterodyne) instrument — Band 6 at 230 GHz and Band 8 at 460 GHz — from MPIfR. They successfully completed their commissioning this year.

APEX supported the installation and commissioning of the CONCERTO (CarbON CII line in post-rEionisation and ReionisaTiOn epoch) visitor instrument from the Laboratoire d'Astrophysique de Marseille, France. CONCERTO is an imaging spectrometer based on lumped-element kinetic inductance detector technology with a large field of view and operating in the frequency range between 130 and 310 GHz. The instrument saw first light at APEX in July and was ready for regular science operations at the beginning of Period 108 in October. In December APEX also welcomed the second-generation ZEUS-2 (Z [Redshift] and Early Universe Spectrometer) as a visitor instrument from Cornell University, USA. APEX further successfully participated in the April campaign of the EHT (Event Horizon Telescope).

In 2021 the three APEX partners agreed on the closeout of their current agreement at the end of 2022. ESO and MPIfR prepared a new agreement for the operation of APEX in the period 2023–2025, when APEX will be operated as a hosted telescope under a new operation model that includes operational support by, but is cost neutral to, ESO.

A. Ghizzi Panizza/ESO

The Milky Way over La Silla.

APEX on a starry night on the Chajnantor plateau. The first-quarter Moon glows brightly in this exposure, outshining the surrounding stars in the sky.

ESO/B. Tafreshi (twanight.org)

Data Management and Operations

The DMO Division ensures offsite operations and user support for the La Silla Paranal Observatory. Data obtained from ESO instruments are a valuable scientific resource, and the ESO Science Archive Facility enables seamless access to the large volume and high quality of its holdings. An integrated Data Flow System for combined VLT and ELT science operations is being developed. During the last year many improvements, welcomed by our user community, were introduced that cover the entire observing chain.

User support

The User Support Department (USD) provides support to users of the Paranal Observatory facilities, assists the Paranal Science Operations Team with executing the observations, defines user requirements for observation preparation tools and oversees their development. The USD acts as an important interface between the community and the observatory, including operating a helpdesk system, organising travel for astronomers visiting the observatories and being the contact for the ESO Users Committee.

Preparation and follow-up support were provided for nearly 1000 Service Mode observing runs during 2021. Many of the runs scheduled in the first part of the year were carried over from early 2020, requiring modest updates, and a further 78 runs were added through a special Period 107 call and Director's Discretionary Time channels. In the second part of the year 481 new runs were reviewed before the start of Period 108 in October. Support for the newly commissioned instrument CRIRES$^+$ has been added following a successful Science Verification in August. USD carried out the Science Verification observations through the Garching Remote Access Facility. Throughout the year the evolution of operations was closely followed, keeping users informed and ensuring well populated queues and smooth operations after quite frequent schedule changes. The Deskpro helpdesk software was deployed in July to support communication with users.

The USD implemented a dedicated support scheme for users with observations scheduled in designated Visitor Mode (dVM). Because of the travel restrictions during 2021, all Visitor Mode observations were scheduled in dVM, amounting to 262 dVM runs on Paranal and 211 on La Silla. These observations are scheduled on predefined nights when staff at the observatory execute observations in remote contact with the users. The reminders about forthcoming dVM runs and reviews by USD ensure timely preparation of observations and complete contact information, and enable observers to clarify doubts before the start of their first observing night.

Two online community workshops were organised in 2021, the first dedicated to observing proposals in March and the second focused on observation preparation in July.

Back-end operations

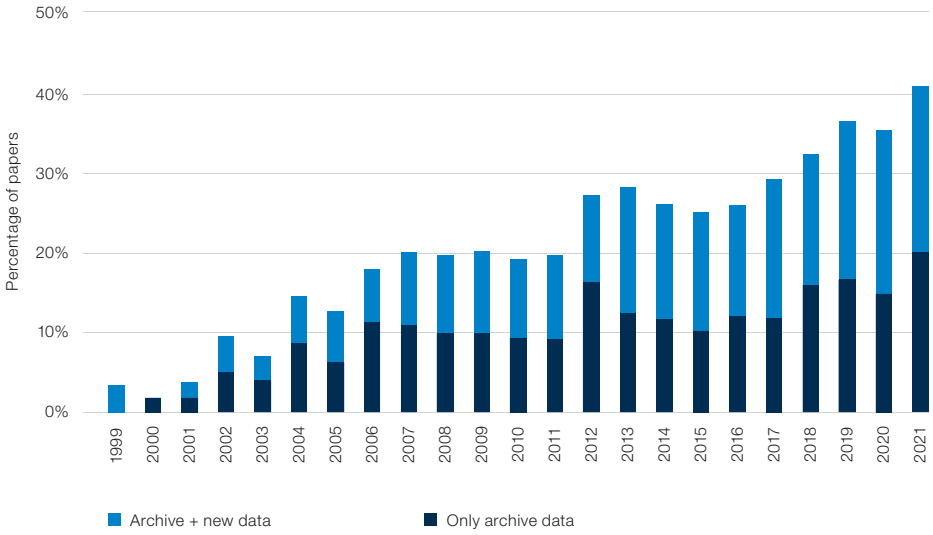
ESO's telescopes and instruments provide state-of-the-art data to the astronomical community. The steady increase in the volume and complexity of these data poses a continuous challenge for their scientific exploitation. ESO addresses this challenge in two ways: by providing users with tools to process raw data so that science information can then be extracted; and by publishing data in the ESO Science Archive that are already processed, calibrated and ready for scientific exploitation. Data calibration and signal extraction are performed using dedicated software tools that implement sophisticated signal processing algorithms, often specifically tailored to a given data type. For this reason, they are typically developed by the consortia that build the instruments. They are crucial to an instrument's success because they are usually the only way to meaningfully process its data. ESO then takes over the maintenance and evolution of the data processing tools, often called pipelines, and makes them available to the astronomical community. However, the pipelines alone are not enough. A framework around them is needed to run them, including organising the input data, scheduling the processing, analysis of various interconnections and dependencies, and visualisation of the different steps to check the progress and quality of the results so that appropriate actions can be taken. In 2021 we began to develop such a framework, the ESO Data Processing System (EDPS). Within one tool it will unify all the different use cases for data processing, both internal in support of science operations and external towards science users. The first release focuses on the former and is scheduled for 2022. A user-facing version will follow about a year later.

The ESO Science Archive provides access to a wide variety of data. In addition to all raw data, selected processed data are made available, either generated at ESO or provided by teams in the astronomical community for the benefit of their fellow scientists. Its contribution to ESO's science output has increased over time, reaching about 40% for the VLT in 2021.

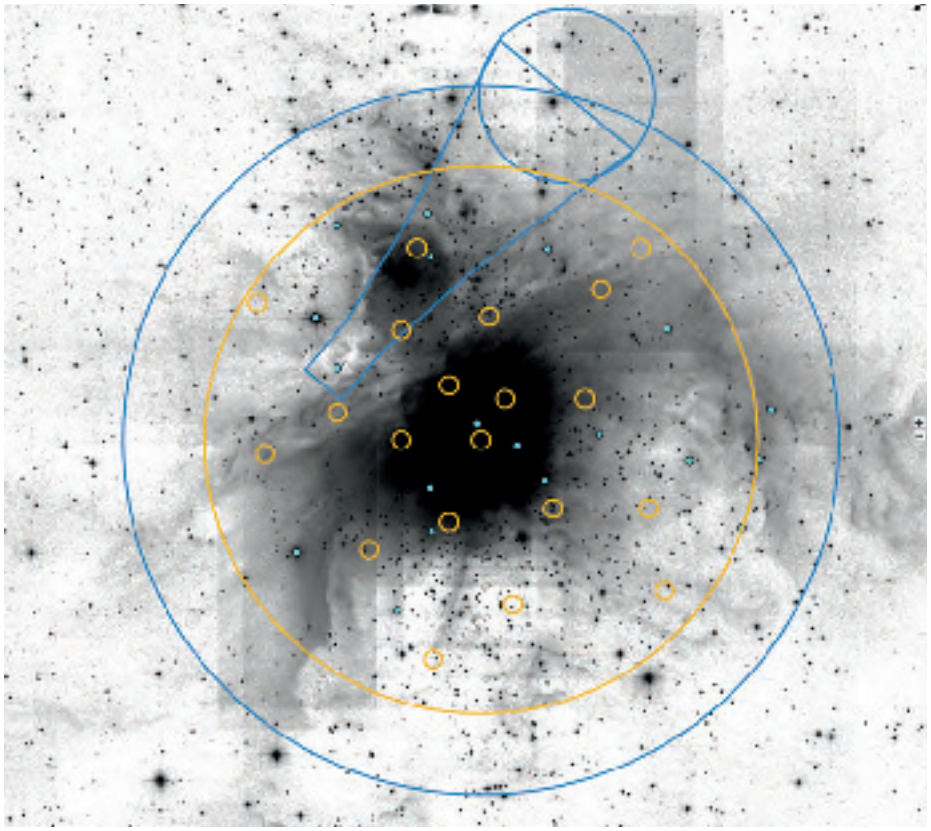
Data flow projects

Data flow applications and services ensuring end-to-operation cover the proposal submission system (Phase 1), observation specification and execution (Phase 2), archiving and retrieval of raw frames, data reduction, the ingestion of data products including catalogues (Phase 3) and their publication and exploration. These services ensure the scientific value delivered to the ESO user community and a high operational efficiency both in Garching and at the observatory. New developments address additional functionalities, obsolescence management and requirements from the ELT and new systems.

For Phase 1 a new web-based Proposal Evaluation Interface was realised, supporting the off-site pre-grading and grading of proposals during the evaluation panel meetings. Developments were begun to enable Distributed Peer Review of proposals. The Phase 2 project has been completed after the final delivery of tools that support the definition, review and execution of complex observing strategies. The last release also includes visualisation of uv-plane coverage for efficient interferometry observations. The ObsPrep project integrates instrument-specific observation preparation into the Phase 2 tool. Support for CRIRES$^+$, FORS2 (the FOcal Reducer and low dis-



The contribution of the ESO Science Archive to the science output of the VLT, characterised here in terms of the percentage of all the papers using VLT data published in peer-reviewed astronomical journals.



Field of view of MOONS with acquisition cameras (yellow circles) and candidate VLT guide stars (blue), as visualised in ObsPrep.

persion Spectrograph) (non-FORS Instrument Mask Simulator based modes) was fully implemented, and support for ERIS was begun. In collaboration with the consortium, the first prototype for MOONS (the Multi-Object Optical and Near-infrared Spectrograph) observation preparation was completed.

A new project for a unified observing tool, OTTO, completed its inception phase. It addresses technical obsolescence, supports the evolving operations model on Paranal as we move towards the ELT and is a prerequisite for a new International Celestial Reference System-compliant target definition throughout the entire dataflow.

All interfaces to the ELT control software were specified and reviewed, including a new instrument package format, and its implementation was started.

A new set of tools (known as qcFlow) will optimise our data Quality Control (QC) processes. Based on EDPS, its initial release will support QC (level 1) for calibrations at the observatory sites. Throughout 2021, requirements were analysed and implemented, aiming for a first release in 2022.

An ALMA antenna on the Chajnantor plateau. The Large Magellanic Cloud peeks out from behind the antenna on the left.

ESO/P. Horálek

ALMA and the ESO ALMA Support Centre

ALMA is a large interferometer for radio wavelengths ranging from 0.3 to 9.6 millimetres. ALMA was constructed between 1999 and 2014 through an international collaboration involving Europe, North America and East Asia in cooperation with the Republic of Chile. The ALMA observatory comprises 66 high-precision antennas with state-of-the-art receivers located on the Chajnantor Plateau at 5000 metres above sea level in the district of San Pedro de Atacama, in the Chilean Andes. The 12-metre- and 7-metre-diameter antennas can be placed in various configurations with baselines ranging from 15 metres to 16 kilometres. Resolutions as fine as 0.005 arcseconds can be achieved at the highest frequencies, a factor of ten better than the NASA/ESA Hubble Space Telescope achieves at optical wavelengths.

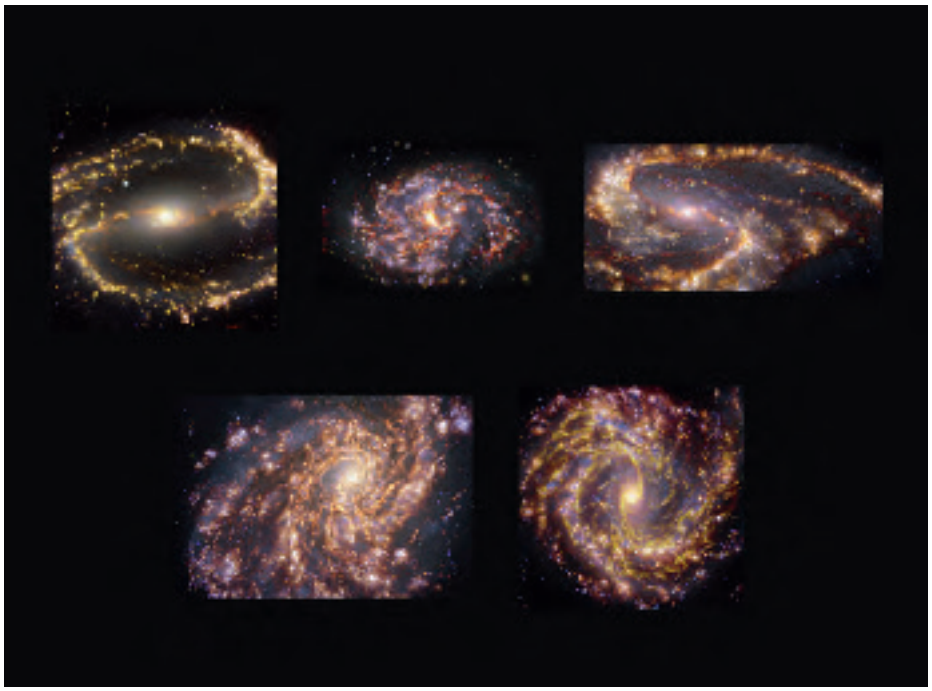
ALMA operations and science

After a six-month complete suspension, followed by a painstaking ramp-up process, ALMA resumed scientific operations in March 2021, almost a year to the day after the site was closed. This achievement was the result of extensive efforts by staff in Chile and the ALMA Regional Centres in Europe (ESO), East Asia (the National Astronomical Observatory of Japan, NAOJ) and North America (the National Radio Astronomy Observatory) to return the observatory to operation while navigating the challenges presented by the COVID-19 pandemic.

With only a limited number of staff on site, Cycle 7 data were obtained and processed on a best-efforts basis with all science operations being run from Santiago using a new control room that had been installed prior to the pandemic — a demanding and rigorous test of this new facility. ALMA delivered 3220 observing hours out of an offered 4300 hours with the 12-metre array in Cycle 7. With the 7-metre array, 2578 hours were completed out of the 3750 hours offered. Eight Large Programmes were completed. Even with reduced staffing levels and challenging winter conditions, 5 different configurations were provided, ranging from intermediate to extended and back to a relatively compact configuration by the end of the year, and antenna overhaul activities were restarted.

For Cycle 8, which started in October 2021, the science community submitted 1735 proposals requesting over 26 000 hours on the 12-metre array, exceeding the available time by more than a factor of six. For this cycle, a number of changes to the proposal review process were introduced, including dual-anonymous proposal review and, most significantly, Distributed Peer Review, in which Principal Investigators (or co-Investigators) of submitted proposals were asked to assess a small number of other proposals. This was the first time this approach had been used on such a large scale, with 1497 proposals receiving 14 970 reviews in total. The remaining proposals were reviewed by panels, including a record number of 40 Large Programs. Despite the changes, the review process was a success, with few requests for support from the Proposal Handling Team and very few proposals that did not follow the dual-anonymous guidelines. This required a major effort from across the ALMA partnership, with significant contributions from the integrated teams in Computing, Science and Science Operations. The teams also tested and delivered a very robust production software system to support Cycle 8 observations, leading to perhaps the smoothest and most trouble-free start to a new observing cycle at the observatory. In addition to the successful return to science operations, ALMA made many outstanding discoveries in 2021, leading to 478 refereed publications.

Looking to the future, the ALMA Management Team and Integrated Teams have prioritised development of the Wideband Sensitivity Upgrade (WSU), which will increase the instantaneous bandwidth by at least a factor of two (with a target goal of four) and improve receiver sensitivity. The WSU will require upgrading the receivers (front-end detectors) and most of the digital electronics, including the correlator, as well as the ALMA software that drives the system and processes and stores the output. When completed, the WSU will afford significant improvements to all ALMA observations. A major milestone for the WSU was achieved in November 2021, when the ALMA



ALMA (ESO/NAOJ/NRAO)/PHANGS, S. Dagnello (NRAO

Images of five nearby galaxies observed by the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) project, combining data from ALMA (in brownish-orange) and the Multi-Unit Spectroscopic Explorer (MUSE) on ESO's Very Large Telescope (in gold and blue). The galaxies are NGC 1300, NGC 1087, NGC 3627 (top, from left to right), NGC 4254 and NGC 4303 (bottom, from left to right).

Board approved the upgrade to Band 6, which will be the first upgraded receiver designed to meet the WSU requirements. Other major pieces of the current ALMA Development Programme have continued making progress, with Band 1 integration in Chile restarted after a year of suspension because of the pandemic, and Band 2 prototype development advancing throughout the year.

Throughout the year, ALMA has maintained its close relationship with the local communities around the observatory and whilst the approach had to change with the pandemic-related restrictions, it was possible to continue and support some joint initiatives.

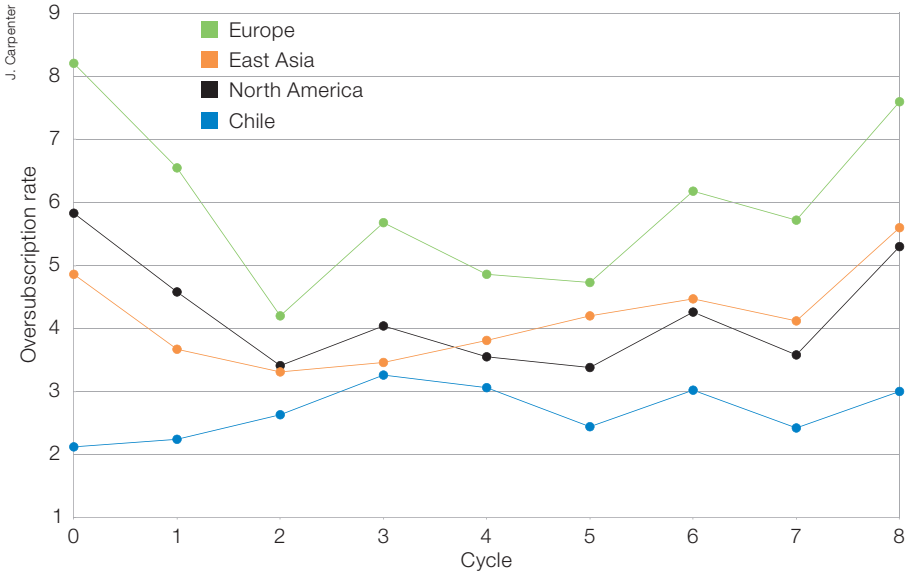
ESO ALMA Support Centre

The EASC is ESO's offsite operations unit for ALMA and a division in the Directorate of Operations. It is one of three ALMA Support Centres, based at the three ALMA Executives in Europe, North America and East Asia to support the Joint ALMA Observatory and ALMA onsite and offsite operations. The EASC comprises the ALMA Regional Centre (ARC), ALMA offsite technical maintenance and development support, and ALMA science. The EASC is the face of ALMA for the European scientific and technical community and for the international ALMA partners in respect of ALMA operations. It is an important component of the success of ALMA, both for its performance as a scientific observatory and for ESO as a partner in the ALMA project.

2021 was an intense year for the EASC, marked by the support for the Restart to Operation, extraordinary maintenance activities on site, and a very active ALMA development programme. The activities were carried out in light of restrictions due to the pandemic, which included travel restrictions and limited access to equipment on site. The execution of critical activities requiring access to sites and laboratories was achieved by careful and opportunistic planning, e.g. the onsite overhaul activities for the ESO-provided antennas and the collaborations in Europe with institutes and companies to carry out the laboratory measurements necessary for the analysis of the cryostat windows anti-reflection coating and the tests of the critical components for Band 2. Major successes in 2021 include: the deployment of the Distributed Peer Review software tools to review about 1500 Cycle 8 observing proposals; progress with the definition and implementation of the ALMA2030 Roadmap Development Projects including the initial study for a new optical fibre connection between the Array Operations Site and the Operations Support Facility; the new digitisers and associated signal processing; the preproduction of the wide-radio-frequency and wide-intermediate-frequency Band-2 receiver and the development of advanced studies for upgrading Bands 7 and 9; and the increased operational synergy with optical observatories as part of the OPTICON-RadioNet Pilot EC-H2020 project and through the ALMA Advanced Data Products initiative, which completed the first definition phase and is entering the advanced study and prototype phase in 2022.

ALMA (ESO/NAOJ/NRAO)

The ESO-provided ALMA antenna DA-42 undergoing overhaul procedures at the Operations Support Facility in 2021.

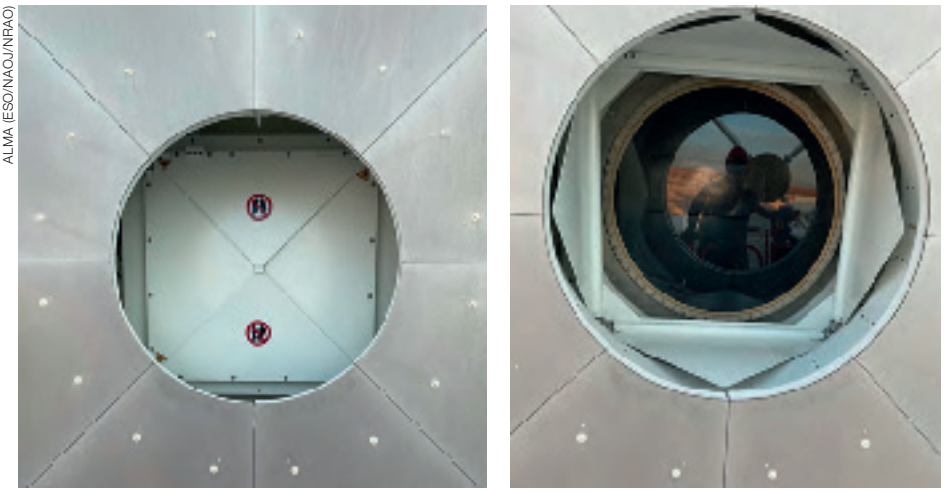


ALMA 12-metre array oversubscription in the different regions as a function of science operations cycle.

ALMA Regional Centre

The ARC department operates at the crossroads of ALMA science operations and user support. It provides support to the development and implementation of science operations policies and together with the European ARC network it supports the European user community. This network has seven nodes, located in Onsala, Manchester, Leiden, Bonn/Cologne, Grenoble, and Bologna,

ALMA (ESO/NAOJ/NRAO)



Feed Shutter Prototype installed on the ESO-provided antenna DA44 (shutter closed on the left, open on the right).

all locations with a history in radio and millimetre astronomy.

During 2021 the ARC supported the call for Cycle 8 observing proposals, issued on 17 March. Despite the challenging work conditions imposed by the pandemic, the community submitted 1735 proposals that requested over 26 000 hours on the 12-metre array, far exceeding the time requested in previous cycles. With 4300 hours available on the 12-metre array, Cycle 8 was one of the most competitive cycles to date.

The European ARC continued to provide virtual support to European ALMA users. Regular communications about the status of ALMA were circulated and virtual community assemblies were held. The ARC network also launched several new activities to engage the community, including the ALMA Recounts of Cosmic Conundrums talk series and a set of three-minute ALMA Explained videos.

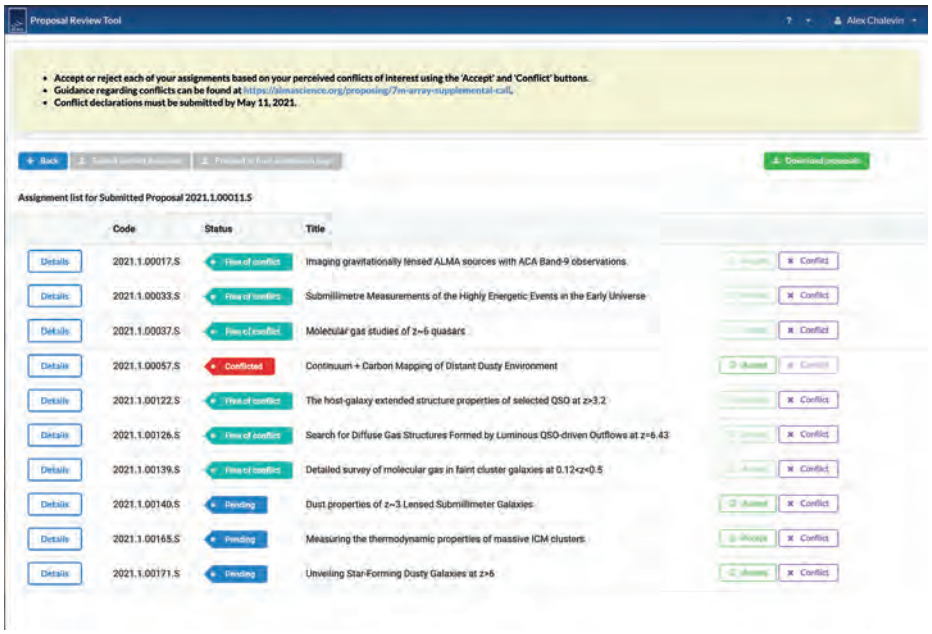
The ARC continues to provide science operations guidance to the development of several key components of the ALMA software system, such as the observing tool, the archive, the quality assurance tool AQUA, scheduling and the Snooping Project Interface (SnooPI).

ALMA Technical Team

The ALMA Technical Team (ATT) in the EASC is responsible for off-site technical support and hardware development projects and is providing the European contribution to the ALMA Integrated Engineering Team. In 2021 the ATT provided support off and on site, specific knowledge, and assistance to the ALMA observatory in the areas of antennas (including the in-kind contribution to on-site maintenance and on-site supervision of the overhaul activities), antenna transporters, front ends, calibration devices, water vapour radiometers, back end, correlator, and site infrastructure.

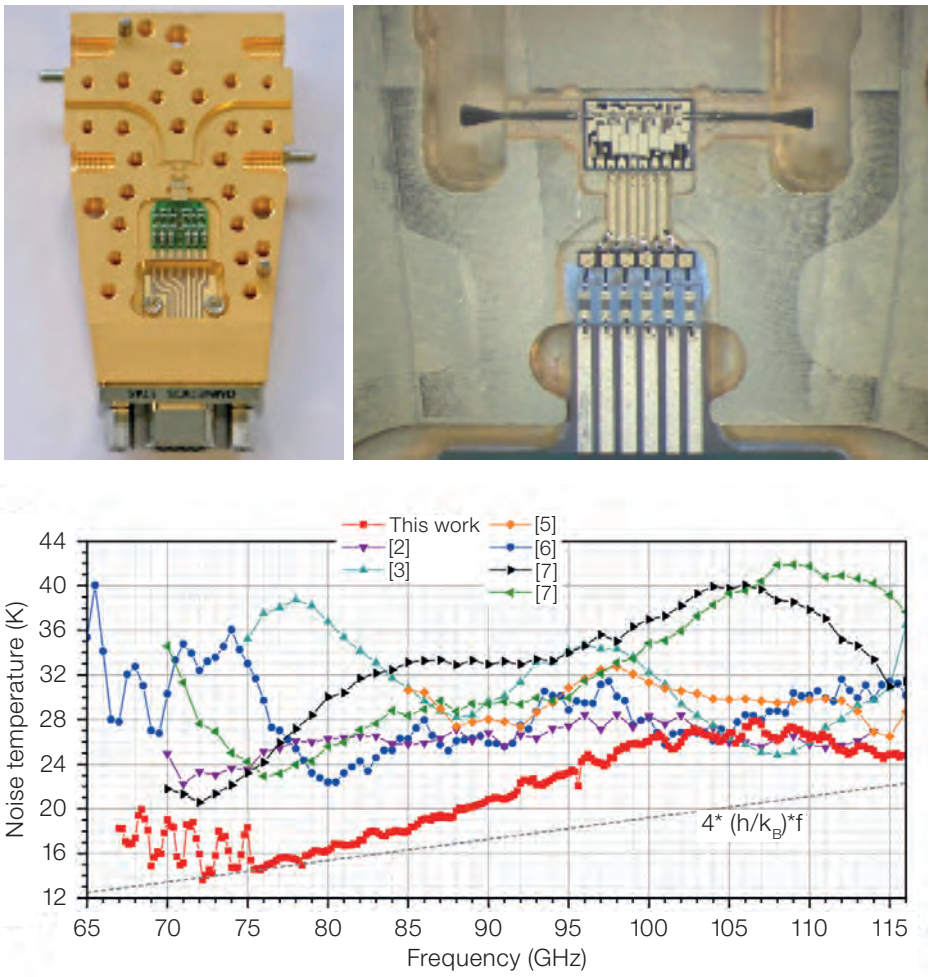
All relevant antenna, back-end and front-end maintenance tasks were taken care of. Specific support was provided when the equipment was restarted after the prolonged shutdown. In June 2021 the Critical Design Review (CDR) of the new Antenna Feed-Shutter was passed. The feed-shutter prototype, having passed all off-site qualification tests, was shipped to Chile, and installed on one ESO-provided antenna in December 2021. A possible issue with the azimuth and elevation antenna bearing was constantly monitored, and actions reviewed with JAO and the manufacturer. The porting of the Antenna Control Software to a new central processing unit passed Phase 2 of the Antenna Control Unit obsolescence mitigation project. All the Antenna Maintenance scripts have been updated to Python version 3 and delivered to JAO. The second release of the new Antenna Maintenance Manual was issued and transmitted to the ALMA observatory.

R. Kurowski



ALMA's Distributed Peer Review tool showing proposal assignments being accepted or rejected by a reviewer.

Thome et al.



Photographs and noise temperature performance of the Band 2 low noise amplifier being developed by MPIfR and the Fraunhofer Institute.

Delamination of the anti-reflection coating of some of the cryostat windows was discovered during the Restart to Operation inspections. A problem with the front-end quartz windows was investigated with the support of the manufacturer and the root cause identified as a previously unnoticed progressive degradation induced by exposure to ultraviolet sunlight. A plan to progressively retrofit all the windows and spares is in place.

The 14 axles of the Lore transporter were replaced in February 2021 with the units dismounted from the Otto transporter and retrofitted in Europe. Seven of Lore's axles were transferred to Europe and completely overhauled by the manufacturer, and they are ready for shipment to Chile. The two new Portable Controllers were commissioned and delivered to JAO in March 2021.

ALMA Computing

The ALMA Computing Team at the EASC, including partner institutes in Europe, develops and maintains ALMA software subsystems in collaboration with similarly sized teams in East Asia, North America, and Chile.

ALMA proposal review software for 2021

The EASC ALMA Computing Team developed and deployed the software system that was used for the Distributed Peer Review of ALMA observing proposals in 2021. The introduction of this new system was an overwhelming success, with an exceptionally good reception from the users and observatory staff.

ALMA Development

To keep ALMA at the forefront of science and technology, all ALMA partners participate in an ambitious development programme. At ESO we achieve this through calls for development studies involving Member State institutes. The studies range from fundamental research in submillimetre receiver technology, new operation modes, new software systems to improved archive use. Some of these studies lead to actual implementations as ALMA development projects.

ALMA development projects

In 2021 the EASC continued the execution of the projects: Additional Representative Images for Legacy (ARI-L), the Band-2 cartridge preproduction, the redesign of the ALMA observing tool and the ALMA Science Archive acceleration. Key preparations for implementing the ALMA2030 Roadmap included the execution of a virtual receiver workshop, the analysis of the possibility of a new fibre connection from the Array Operations Site to the Operations Support Facility, the completion of an initial concept for new digitisers and digital signal processing in connection with the new correlator being proposed by North America, and the investigation of upgrade paths for the Band 7 and 9 receivers.

ARI-L

The ARI-L project passed the Second Year Review in 2021 and will likely meet the original project's stretch goals by June 2022. The Italian National Institute for Astrophysics is currently discussing with ESO an extension of this project to evaluate the possibility of extending the processing to further datasets.

ALMA band 2

In 2021 the Band 2 preproduction project made steady progress towards the CDR,

planned for May 2022. Three separate paths for procuring the most critical element of the system (the Low Noise Amplifier) are being actively pursued in collaboration with institutes and industries in ESO Member States. Passive optical components with excellent performance over the full 67–116-GHz band have been designed and manufactured by NAOJ, a partner in this development project.

ALMA observing tool redesign

The ALMA observing tool redesign project, led by the UK Astronomy Technology Centre (UK ATC), passed the mid-project milestone in July 2021 and is currently undergoing an internal progress assessment review at the UK ATC to confirm the tight timescale for delivery of the final software package.

ALMA Science Archive acceleration

Following up on one of the ALMA Archive Review recommendations, the ALMA Director approved the ESO proposal to deploy more resources to accelerate the development of the ALMA Science Archive. As part of this project, an additional developer was hired at ESO for a period of two years.

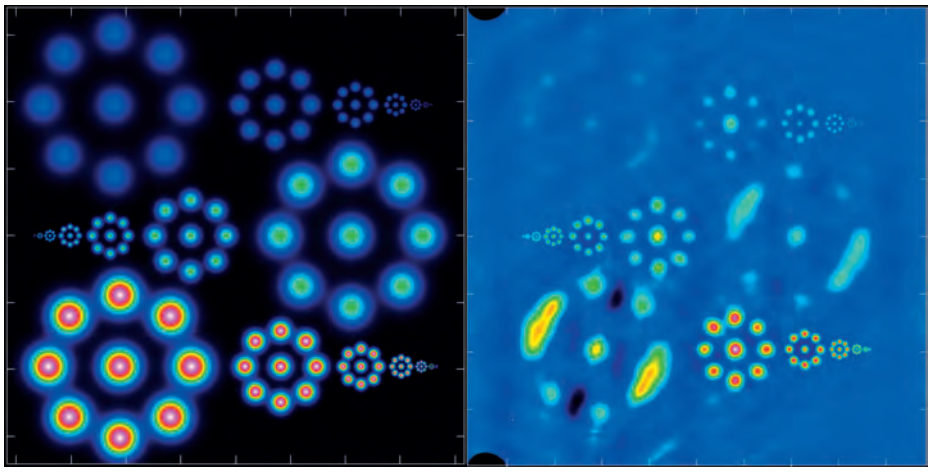
ALMA development studies

Upgrading the ALMA digital system

In 2021 a series of studies led by the Université de Bordeaux was successfully completed. A new digitiser prototype was successfully tested and will be fully compatible with the ambitious goals of the ALMA 2030 roadmap.

SIS wideband development

In two parallel studies, the Group for Advanced Receiver Development (GARD) at Gothenborg is developing new superconductor-insulator-superconductor (SIS) junctions with sizes down to 1 μm^2 or smaller. Such small sizes are critical to reaching broader IF bandwidths, one of the main goals of the ALMA 2030 development roadmap.



D. Petry

An input test pattern (left) with its simulated shape assuming the baseline distribution of the ALMA C43-5 configuration.

Band 7 upgrade feasibility study

The Institut de RadioAstronomie Millimétrique in Grenoble has begun a feasibility study to upgrade the original ALMA Band 7 receivers to make them compatible with the ALMA 2030 roadmap.

Band 9 upgrade to 2SB

The Nederlandse Onderzoekschool Voor Astronomie in Groningen is investigating the possibility of converting the ALMA Band 9 cartridges from double-sideband to sideband-separated and make them compliant with the ALMA2030 roadmap specifications.

High-cadence solar imaging

OSO collaborates with the University of Oslo to model the impact of high-cadence imaging of the Solar surface with ALMA.

Testing an improved atmospheric model beyond 300 GHz

The Instituto de Física Fundamental in Madrid is leading a study to verify the atmospheric transmission model used at ALMA at a spectral resolution of a few tens of kilohertz instead of hundreds of megahertz.

Internal development studies

In addition to the above studies by institutes in ESO Member States, the EASC also supports a small number of internal development studies on topics closely related to improving the ALMA observatory operations. One such study was completed in 2021 and investigated the beam shaping by comparing the observed and requested baseline distribution. Two other studies began in 2021, looking into setting up the phase rms database and a new Bayesian imaging technique.

Telescopes at La Silla, ESO's first observatory site.

ESO/A. Ghizzi Panizza (www.albertoghizzipanizza.com)

Programmes

G. Hüdepohl (atacamaphoto.com)/ESO

Instrumentation for the La Silla Paranal Observatory

The year was again dominated by the impact of COVID-19. Despite this, surprisingly good progress was made.

Within the Paranal Instrumentation Programme, thanks to the use of the Garching Remote Access Facility (G-RAF) and the excellent support of colleagues at the observatory, CRIRES+ (the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph) and IRLOS (the InfraRed Low Order Sensor) were fully commissioned remotely. ERIS (the Enhanced Resolution Imager and Spectrograph) passed Preliminary Acceptance Europe (PAE) and was integrated at Paranal, and both CUBES (the Cassegrain *U*-Band Efficient Spectrograph) and the GRAVITY+ instrument were approved by Council.

Despite the delays, the Armazones site of the ELT (Extremely Large Telescope) is open again and work on the Dome and Main Structure (DMS) has restarted, whilst in Europe the Main Structure passed its Final Design Review (FDR). In Europe progress on contracts is good, especially considering the situation.

Council approved both MOSAIC (the Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology) and HIRES (the HIgh REsolution Spectrograph, renamed ANDES in early 2022) with strong stage gates after Preliminary Design Review (PDR) to confirm overall funding and scope and Guaranteed Time Observing allocations.

Progress has also been good on the Technology Development programme, with the main barrier being availability of ESO effort rather than COVID-related delays.

A camera zoom during a long exposure produces a dramatic view of the VLT's laser guide stars and the starry sky above on Paranal.

This year too the Paranal Instrumentation Programme has been heavily affected by the COVID-19 pandemic. Thanks to the excellent support of colleagues at the observatory, several instruments were commissioned remotely. Despite the pandemic, progress was made on projects that are being integrated in Europe. MAVIS (the Multi Conjugate Adaptive Optics Visible Imager and Spectrograph) began its design and construction phase, whilst CUBES and GRAVITY+ are ready to start the design and construction phase after the Scientific Technical Committee (STC) recommendation and Council approval.

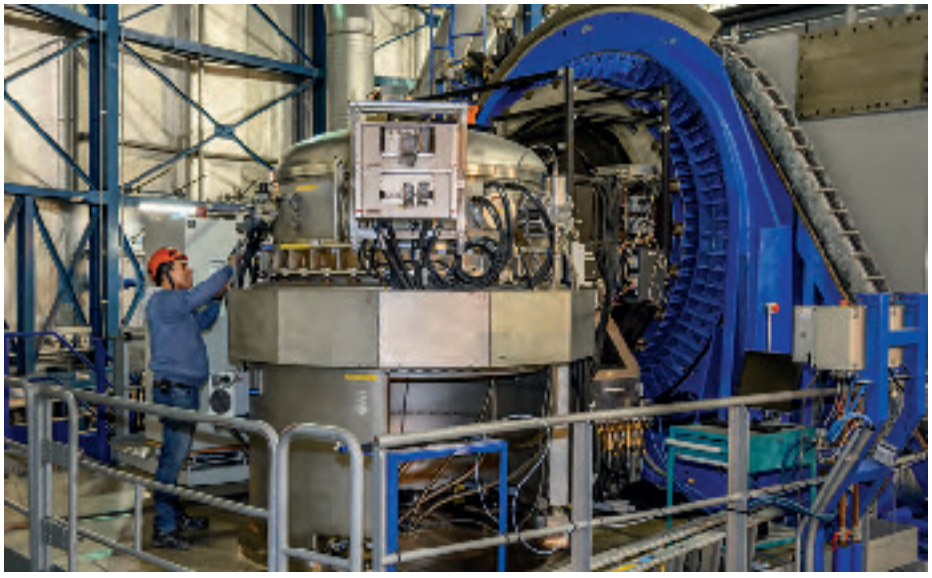
Paranal Instrument Commissioning

The use of the enlarged and more powerful G-RAF has been key for the Integration of new instruments at Paranal and commissioning activities in 2021.

The CRIRES upgrade project, CRIRES+, has transformed this VLT (Very Large Telescope) instrument into a cross-dispersed spectrograph, increasing the wavelength range covered in a single observation by a factor of ten. CRIRES+ underwent commissioning in the first half of 2021, and science verification in August, led by ESO astronomers at Paranal supported by the teams in Europe. The instrument behaves as expected and delivers a 10% gain in throughput compared to the old CRIRES. The polarimetric modes have been added. The radial velocity precision obtained with the absorption cell is below 10 m s^{-1} and improving. CRIRES+ is now offered in all observing modes and has received many observing proposals, reflecting the ESO community's high expectations of it.

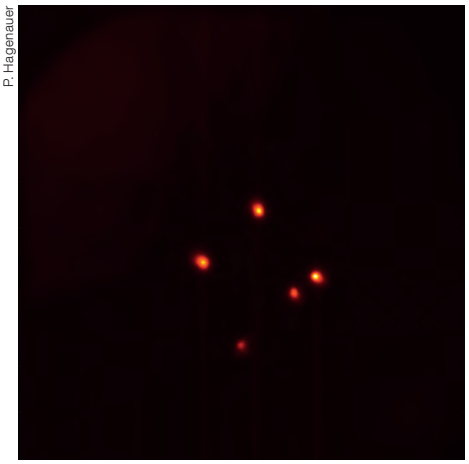
The VLTI (VLT Interferometer) Facility Project, begun in the summer of 2014, was planned to be completed in 2020. The remaining stage is the implementation of the fringe tracker for MATISSE (the Multi-AperTure mid-Infrared SpectroScopic Experiment), which uses the GRAVITY fringe tracker, GRA4MAT. GRA4MAT commissioning runs could not be carried out because of a malfunction of the MATISSE grism wheel, and have been postponed to 2022. The thermal control of the deformable mirrors of NAOMI (the New Adaptive Optics Module for Interferometry) has been fully implemented and successfully commissioned, and together with other software modifications it has produced a notable reduction in the Auxiliary Telescope acquisition time.

The limiting magnitudes of the IRLOS system for the narrow-field mode of MUSE (the Multi Unit Spectroscopic Explorer) were set by the noise of the old detector, and an upgrade was designed to gain several additional magnitudes by using a low-noise SAPHIRA detector, significantly



The CRIRES+ instrument installed on the VLT.

P. Hagenauer



All four lasers of the Laser Guide Star (LGS) Facility on UT4 propagated on sky in the asterism configuration corresponding to MUSE, with the laser from LGS Unit 4 split in two. The flux of each split laser guide star (the lower two dots) is half the flux of the non-split ones.

enlarging the narrow-field-mode sky coverage and the number of potential extragalactic targets. The new IRLOS system was shipped to Chile in January 2021, and it was commissioned at the UT4 telescope by the Paranal technical staff with remote support from the team in Garching. The upgraded system performs beyond expectations: it goes four magnitudes fainter, is less sensitive to atmospheric conditions and allows a larger distance between target and natural guide star than the old one.

ERIS is a new adaptive optics (AO)-supported infrared instrument for the *J-M* bands (1–5 µm) at the Cassegrain focus of UT4. The AO bonnette feeds both NIX, a near-infrared imager, and the upgraded SPIFFI (SPectrometer for Infrared Faint Field Imaging) of SINFONI (the Spectrograph for INtegral Field Observations in the Near Infrared). ERIS uses the Adaptive Optics Facility (AOF) deformable mirror and one of its lasers to improve both spatial resolution and sky coverage compared to previous VLT instruments. Following successful testing and PAE at the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, Germany, ERIS was shipped to the observatory in Q3 2021, and moved to the UT4 telescope in the first days of 2022. Commissioning runs will be in the first semester of 2022.

Upgrades

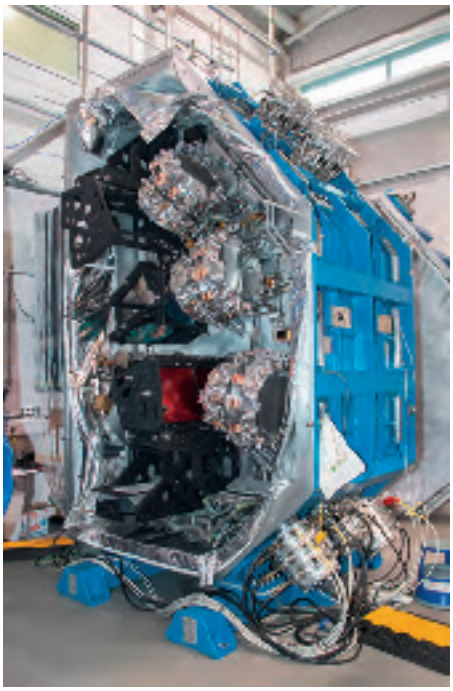
FORS2 (the FOcal Reducer and low-dispersion Spectrograph 2) is over 20 years old and requires an upgrade. The use of a 4K × 4K-pixel CCD detector will bring significant benefits. To ensure FORS's effectiveness for another 15 years its electronics and instrument software must be updated. In addition to the change of detector and new gratings and calibration unit, the project will use ELT standard software and electronics. After many months' delay because of the limited access to the observatory, FORS1 was shipped from La Silla (where it was stored) to Europe to be refurbished. After inspection and some maintenance, it is being used to test the new functions. It will then be shipped to Paranal, where the Mask Exchange Unit, now on FORS2, will be installed, and the upgraded FORS1 will return to the telescope. This strategy has been chosen to minimise the downtime of this highly requested VLT instrument. The new detector has been ordered and the FDR took place in November 2021, to be followed by a Delta review in the second half of 2022.

Instruments in design and under construction

MOONS (the Multi-Object Optical and Near-infrared Spectrograph) is a 0.8–1.8-µm multi-object spectrometer designed to work at the Nasmyth focus of the VLT. It will have 1000 fibres patrolling a field 25 arcminutes in diameter. There will be two modes: one with a spectroscopic resolving power R ~ 4000 spanning the full near-infrared wavelength range, and another with R ~ 9000 in the I band and R ~ 20 000 in the H band. MOONS has two main sub-components, the rotating front end (which is at the focal plane and houses the fibre positioners, the acquisition system and the metrology system for the fibres) and the cryogenic spectrographs. MOONS is in an advanced phase of manufacturing, assembly, integration and testing (MAIT) at the UK Astronomy Technology Centre. The delivery of the hardware is almost complete; in particular, all optical components have been delivered to the consortium. The optical corrector has been shipped from Europe to Paranal and the front end hosts several hundred fully armed fibre positioners. Perhaps the biggest achievement of the year has been that the big vessel hosting the two spectrographs has one spectrograph fully populated, and went through the first cooldown cycle, producing near-infrared test spectra fulfilling the requirements of spectral quality, resolving power and throughput.

4MOST (the 4-metre Multi-Object Spectroscopic Telescope), to be installed on VISTA (the Visible and Infrared Survey Telescope for Astronomy), will be a world-class facility for multi-object spectroscopy in the visible. Its unique capabilities result from the combination of a large field of view, very high multiplex, and simultaneous observations at medium and high spectral resolution for both Galactic and extragalactic astrophysics. 2436 fibres are available simultaneously — 1624 dedicated to low-resolution and 812 to high-resolution spectroscopy. 4MOST is composed of many subsystems that are internally accepted and shipped to the Leibnitz Institute for Astrophysics Postdam (AIP; Germany) for the final MAIT phase. It requires significant

UK Astronomy Technology Centre

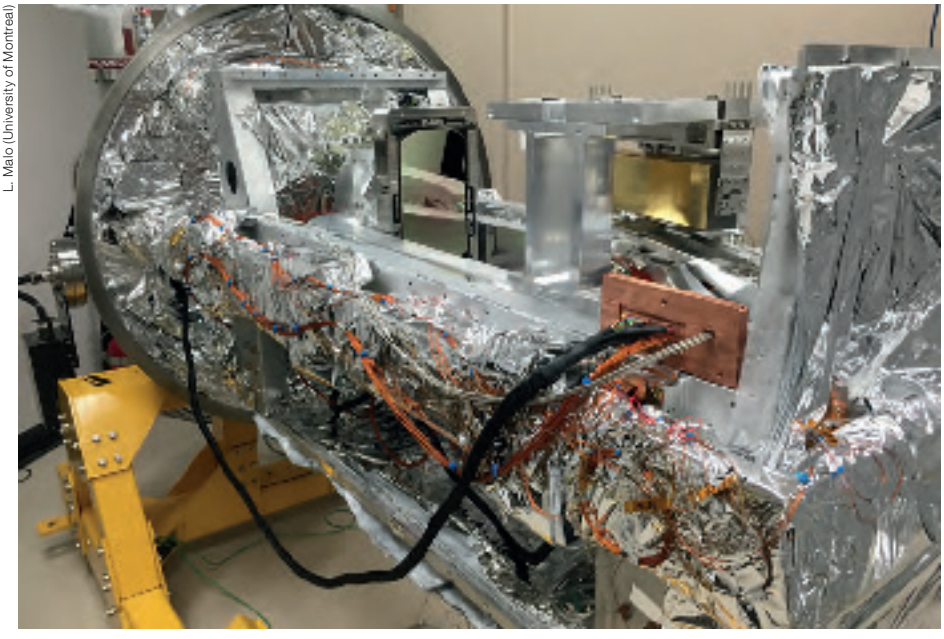


The MOONS cryostat showing the slit, colimator, dichroics and three cameras. The picture was taken prior to cooling for the first test with two detectors mounted and full optics on one side (the second spectrograph will be mounted on the reverse side).

modifications to the VISTA telescope, including a new large-field corrector. Several subsystems have been successfully completed and tested. AESOP (the Australian–ESO [fibre] Positioner) was sent to Europe, where it has been re-integrated. This process, originally planned to be performed together with the Australian team, was instead supported remotely because of the travel limitations imposed by the pandemic. The first of the low-resolution spectrographs has reached its final configuration, has been tested at CRAL (Centre de Recherche Astrophysique de Lyon), and will soon be shipped to AIP, whilst the high-resolution spectrograph has been fully integrated (although a lens had to be shipped back to the optics vendor to change the coating, causing several months of delay to the internal acceptance). The large wide-field corrector remains on the critical path, but all the six big lenses have been manufactured and delivered to University College London, where the wide-field corrector integration is taking place. All fibre-cables for LRS-A (the first Low-Resolution Spectrograph) and HRS (the High-Resolution Spectrograph) have been received at AIP. Completion of the assembly and acceptance testing are under way. On the operations side, the planning of the surveys is progressing and ESO has recently selected the surveys from the community that are going to join the ones led by the 4MOST consortium. The new 4MOST Data Processing Center has been launched.

ESO has defined an ambitious new instrument to exploit the full potential of the AOF: an imager and spectrograph to provide corrected AO images over a large field of view at visible wavelengths. The MAVIS concept, led by a consortium of Australian institutes with partners from Italy and France, started in 2021. MAVIS will be a multi-conjugate adaptive optics system in the visible for the VLT and will eventually replace GRAAL/HAWK-I on UT4. The specifications require a Strehl ratio greater than 10% at 500 nm in a 30-arcsecond field of view. Most science cases will benefit from an integral field unit (IFU), so MAVIS will host an IFU with 3.6 × 2.5-arcsecond field of view, a wavelength coverage of 370–950 nm and two spectral resolutions. MAVIS will require the use of eight laser guide stars, and a fundamental test for this instrument was carried out in 2021 by splitting the light of one of the existing UT4 lasers into two equally powerful beams.

L. Malo (University of Montreal)



The NIRPS instrument in the Center for Optics, Photonics and Lasers (COPL, Canada) laboratory.

The CUBES consortium, led by INAF–Trieste and including institutes from Australia, Germany, Poland, UK and Brazil, successfully concluded the Phase A study in mid-2021. They delivered the concept of a very efficient, two-arm, intermediate-resolution (R ~ 20 000) UV spectrograph, operating in the ~ 300–400-nm wavelength range. In a scientific workshop in February 2021 the impact of ground-based UV spectroscopy was discussed. After the STC's positive recommendation and Council approval, the project will start design and construction phase in early 2022.

The transformational new facility for the VLTI, GRAVITY+, will start its design and construction phase in January 2022. Recommended after the 2019 VLT2030+ workshop, GRAVITY+ went through a six-month Phase A study and all subsequent steps for approval. GRAVITY+ is a very demanding project that will upgrade the GRAVITY instrument and the VLTI infrastructure to provide milliarcsecond-resolution interferometric imaging and give access to targets as faint as K = 22 mag. GRAVITY+ will, amongst other things, measure the black hole masses of active galactic nuclei across cosmic time, and obtain high-quality exoplanet spectra and orbits. It will serve all present and future VLTI instruments and their communities. GRAVITY+ will introduce wide-field, off-axis fringe tracking and improve sensitivity and contrast of GRAVITY observations via new coudé adaptive optics at all four Unit Telescopes (UTs), new laser guide star adaptive optics at UTs 1, 2 and 3, and targeted infrastructure and instrument optimisation.

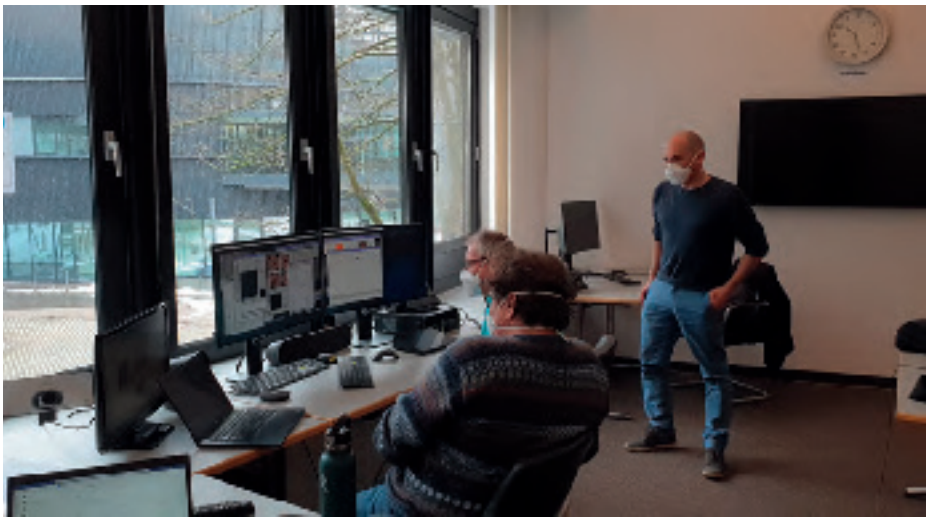
La Silla instruments

Two new spectrographs are under development for La Silla, one for the ESO 3.6-metre telescope and one for the NTT (New Technology Telescope).

NIRPS (the Near Infra Red Planet Searcher) on the ESO 3.6-metre telescope will complement HARPS (the High Accuracy Radial velocity Planet Searcher) by providing spectroscopy at 1 m s^{-1} precision over the Y, J and H infrared bands. NIRPS has two main subsystems: a front end, which includes

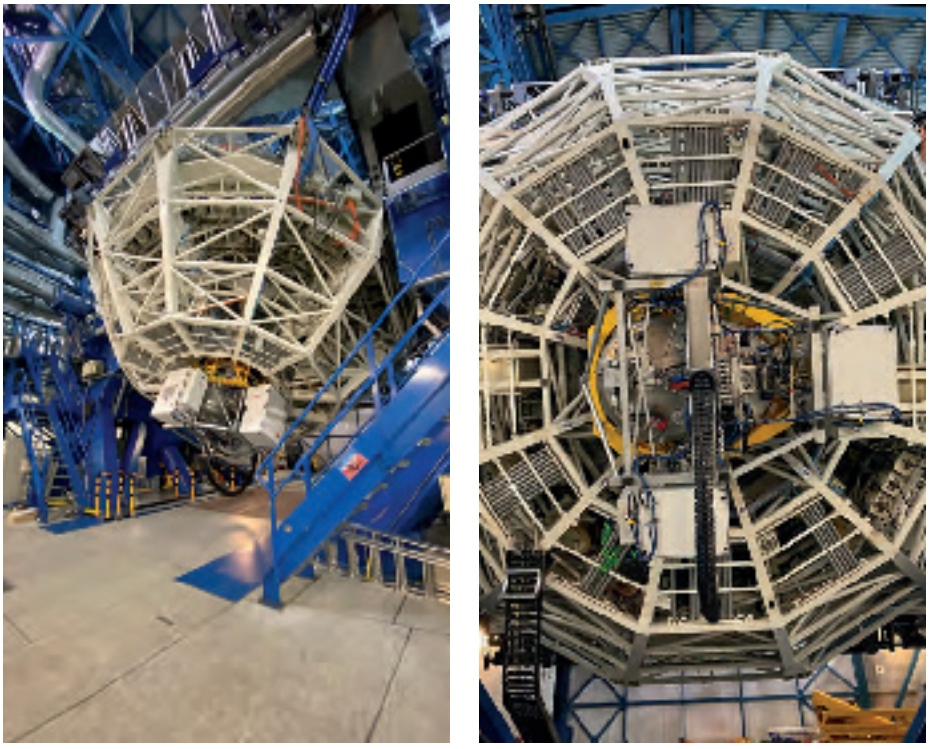
an AO module, acquisition and guiding and fibre systems, and a back end — mainly the spectrograph complemented by a Fabry–Pérot calibration unit. The front end has been mounted at the Cassegrain focus, replacing the HARPS front end. The commissioning was completed in 2021 using the G-RAF facility. The back end went through final integration and tests in Canada, and it has been accepted for shipment to the observatory. It is travelling to La Silla, where it will be integrated in the old Coudé Echelle Spectrometer room in the 3.6-metre telescope building.

The NTT will be dedicated to the study of transient objects using the new instrument, SoXS (Son of X-Shooter). SoXS will provide instantaneous spectroscopy from 350 to 1750 nm. SoXS is composed of many subsystems, developed by a dozen institutes. The common path structure has been aligned at the INAF-Padua Observatory (where the final integration is taking place) and is awaiting the shipment of the flange that will allow the tests with the NTT simulator. The ultraviolet–visible spectrograph opto-mechanics are almost ready and after final assembly and testing in Israel, it is expected to be shipped to Italy in February 2022. The near-infrared spectrograph is on the critical path; all the optical elements and the mechanics are ready and preliminary cryo-vacuum characterisation tests are ongoing (with the empty vessel).



S. Oberti/ESO

The end of the first IRLOS upgrade commissioning night in the G-RAF room in Garching. From near to far: System Engineer Stefan Ströbele, Software Engineer Gerard Zins and the Project Manager Sylvain Oberti.



ESO/A. Glindemann

Two views of the ERIS instrument mounted on the VLT.

A spectacular lunar halo — known as a 22° halo — appears in the sky above La Silla. The optical phenomenon is a result of moonlight interacting with millions of ice crystals suspended in the atmosphere, forming a ring with an apparent radius of approximately 22° around the moon.

ESO/Y. Beletsky (LCO)

The spectacular star-forming Carina Nebula, captured in great detail by the VLT Survey Telescope at Paranal.

ESO. Acknowledgement: VPHAS+ Consortium/Cambridge Astronomical Survey Unit

Technology Development

The ESO Technology Development programme aims to develop and secure the technologies that will enable ESO to successfully conduct its future scientific programme. It plays a key role in initiating new technologies for ESO's instruments and telescopes. In addition to working closely with industry, ESO acts in partnership with different Member State institutes to enable advances in key areas.

The Phase 2 contract with ALPAO (France) was launched for the design and prototyping of high-stability deformable mirrors and the test facility to validate their performance. MAVIS will be the first customer for this development. The new GRAVITY+ instrument from MPE will make use of the test facility.

For infrared wavefront sensing, the development of the large 512 × 512 SAPHIRA detector at 2000 frames per second from Leonardo (UK) has made good progress: the readout integrated circuit and the avalanche photodiode (APD) arrays were delivered to ESO and our partners MPE and the National Research Council (NRC; Canada) and testing of the APD arrays at ESO, AIP (Germany) and MPE will proceed in 2022. The new, larger format will increase the range of applications in AO and interferometry.

The development of curved detectors could allow simpler and more compact optical design of cameras at large telescopes. The collaboration agreement with the European Space Agency (ESA) to secure the manufacturability and reproducibility of curved scientific CCD detectors has allowed us to award a co-funded development contract to Teledyne-E2V (UK) in 2021.

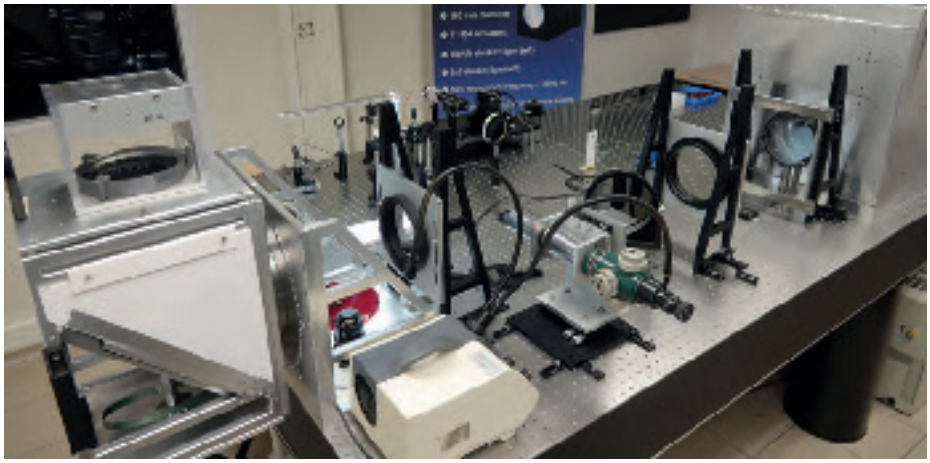
The development of intermediate-frequency (IF) cryogenic low-noise amplifiers by Yebes Observatory (Spain) was achieved, with improvements in the characterisation of both passive and active components used in the amplifiers. Two ultra-wideband (4–20 GHz) prototype cryogenic IF amplifiers were delivered to NOVA (the Netherlands) to be used in an experimental sideband-separating superconductor-insulator-superconductor mixer covering the ALMA (Atacama Large Millimeter/submillimeter Array) Band 9 frequency range.

Fraunhofer-IOF in Jena (contracted late in 2020) have designed and manufactured the first round of improved recipes for multiplayer protected silver coatings; they have improved performance in the ultraviolet whilst maintaining very high reflectivity out to the mid-infrared. A second iteration is foreseen which should also improve the durability of the proposed recipes in 2022.

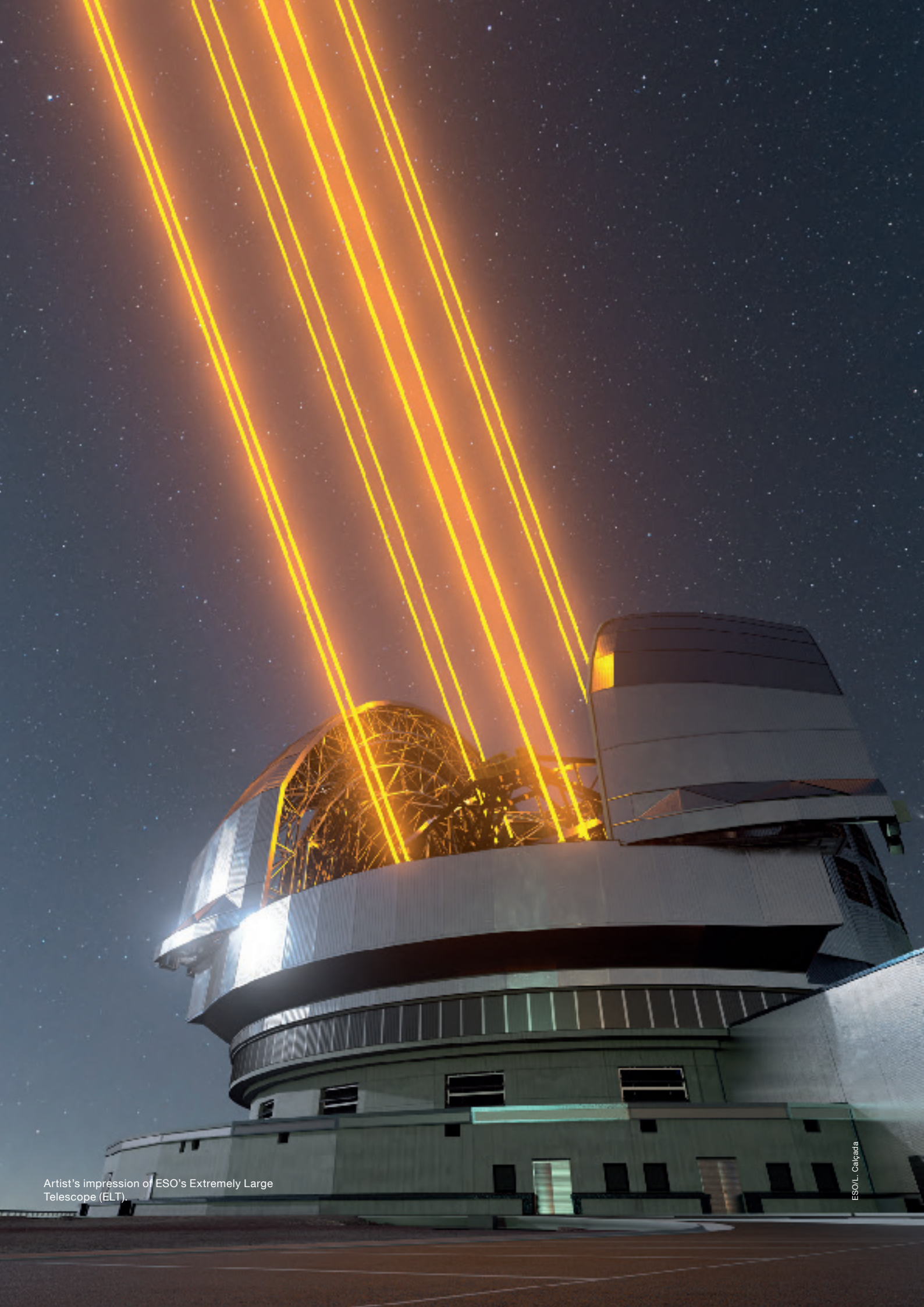
The design and prototyping of the new Next Generation Controller (NGCII) made good progress in 2021. Testing of the first NGCII controller prototype infrared science device is expected in late 2022/early 2023. NGCII will equip all instruments for the ELT and the new instruments for the VLT, including MAVIS, CUBES and the FORS upgrade project.

A collaboration agreement was signed between ESO and ESA in 2021 to develop a new concept of Laser Guide Star Adaptive Optics applied to Astronomy and to satellite communications. To that end a 64-W sodium laser was developed in collaboration with TOPTICA (Germany) and MPB Communications (Canada).

ALPAO



Deformable-mirror test facility developed at ALPAO (France) under ESO Technology Development contract.



Artist's impression of ESO's Extremely Large Telescope (ELT).

ESO/L. Calçada

The Extremely Large Telescope

Another year of resilience against the pandemic

At the start of 2021 Europe was in the middle of its second lockdown due to COVID-19 and the ELT construction site at Armazones had been closed since July 2020, although the pandemic in Chile was more controlled than it had been a year before.

Nevertheless, the experience gained during 2020, and the new ways of working in ESO and with our contractors and consortia, enabled good progress overall. Items still in the design phase were less affected, progress meetings and project reviews being held remotely, although qualification tests and inspections, usually part of the final design phase, were much hindered by travel restrictions. But a mix of remote inspections via video, the involvement of local consultants or staff working in their home country, and travel restricted to the most critical cases worked reasonably well. Projects having passed FDR and therefore in the procurement and manufacturing phase were more affected, both by restrictions on attendance at the workplace and by the increasing supply chain difficulties. The materials shortage (e.g. electronic components, and also raw materials such as steel, wood etc.) led to increased delivery times and cost for the contractors. The skyrocketing cost of transport also impacted the programme at various levels. As an example, the 800 fixed frames, a component of the M1 Segment Supports built by VDL (the Netherlands), were not sent to Chile after acceptance as originally planned but were instead stored in Europe waiting for better times.

Throughout the year the impact of the pandemic on the various contracts was closely monitored and discussed between ESO and its partners to find case-by-case mitigations to limit the impact on cost and schedule.

Reopening the Armazones construction site

One of the major impacts on the ELT programme was the complete closure of the construction site at Armazones in July 2020 by ACe, the consortium in charge of the design and construction of the DMS. This was an unavoidable consequence of the deteriorating pandemic situation in Chile during the southern hemisphere winter. The original hope was to reopen in January/February 2021 but various factors, related to the pandemics in Europe and Chile and the time needed by ACe to establish a completely new team of subcontractors, contributed to the re-opening not happening until May 2021. A new schedule baseline for the ELT programme could then be established, albeit with remaining uncertainties due to the still evolving situation. This was endorsed by Council in June 2021, with a Science Verification First Light in September 2027 and the Telescope Technical First Light 6 months earlier.

Construction has since resumed, at slightly slower pace than expected but with visible progress. By the end of 2021, the floor slab of the Auxiliary Building (including its embedded seismic isolators) had been completed and the first elevated scaffolding for the dome wall foundation was emerging from the ground. About 120 workers were on site by December 2021.

Science and instrumentation

2021 was a very fruitful year for ELT science and instrumentation and many important reviews took place. MICADO (the Multi-AO Imaging CAmera for Deep Observations) instrument completed two of the four FDR sessions, the third one beginning at the end of 2021. MAORY (the Multi-conjugate Adaptive Optics RelaY) completed its PDR, significantly reducing the risk on the MICADO-MAORY interface. HARMONI (the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph) experienced some managerial and technical problems that triggered a red flag from ESO; a series of task forces have been jointly created and agreed between ESO and the consortium to address these issues. METIS (the Mid-infrared ELT Imager and Spectrograph) successfully completed the review for long-lead items and is now preparing for FDR.

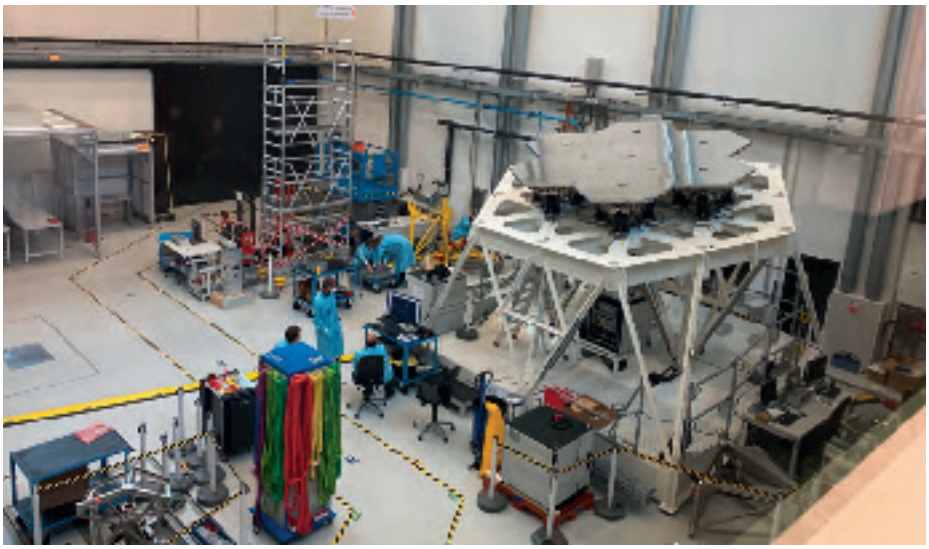
The HIRES (renamed ANDES in early 2022) and MOSAIC instruments, part of the Armazones Instrumentation Programme, have been approved by the STC and Council for the construction phase.

The ELT Working Groups have made significant progress with developing new

ESO/ACe

The ELT construction site at Armazones was closed in June 2020 because of the COVID-19 pandemic situation in Chile and re-opened in May 2021. By the end of 2021 the contractor was preparing for the pouring of the reinforced concrete for the Dome pier.

tools for improving operational aspects, including AO performance, astroweather, calibrations and the exposure time calculator (interested scientists can visit our website elt.eso.org to join these working groups).



The M1 Test Bench in ESO's Garching technical building, where a subset of seven M1 segment assemblies has been integrated to test the M1 control system and to optimise the various integration procedures and specifically-designed handling tools.

Progress with running contracts

Three new large contracts (> 500 000 euros) were signed in 2021. In January, the contract for the M1 Segment Manipulator, a robotic handler to move the segments of the primary mirror (M1) for recoating or repair, was signed with SENER (Spain). In May, the contract for the M1 Segment Local Coherencer, which precisely measures the relative position of the M1 segments after their installation, was signed with IDOM (Spain). Also in May, the contract for the Large Mirrors (M2, M3, M4, M5, M6) Coating Plant was signed with AGC Europe (Belgium), the company that is already manufacturing the two M1 Segment Coating Units. By the end of 2021 a total of 33 large industrial contracts were running, 11 had been completed (for example the delivery by SCHOTT (Germany) of the two 4-metre-diameter blanks for the M2 and M3 mirrors, and several types of high-performance detectors for wavefront sensors or scientific instrument focal planes) and the four agreements with consortia producing scientific instruments were progressing towards their final design and manufacturing phases.

The largest ELT industrial contract (the largest in the history of ground-based astronomy), signed with the ACe consortium led by Cimolai, is for the construction of the dome and the telescope structure. It completed its design phase and the FDR for the telescope structure was held in September 2021 (the dome FDR was in February 2020). An impressive number of qualification tests for critical components, such as louvres, the slit doors mechanism, and the hydrostatic bearing of the telescope, have been completed, opening the way for their manufacture. In total more than 100 standard transport containers were shipped from Europe to Chile in 2021.

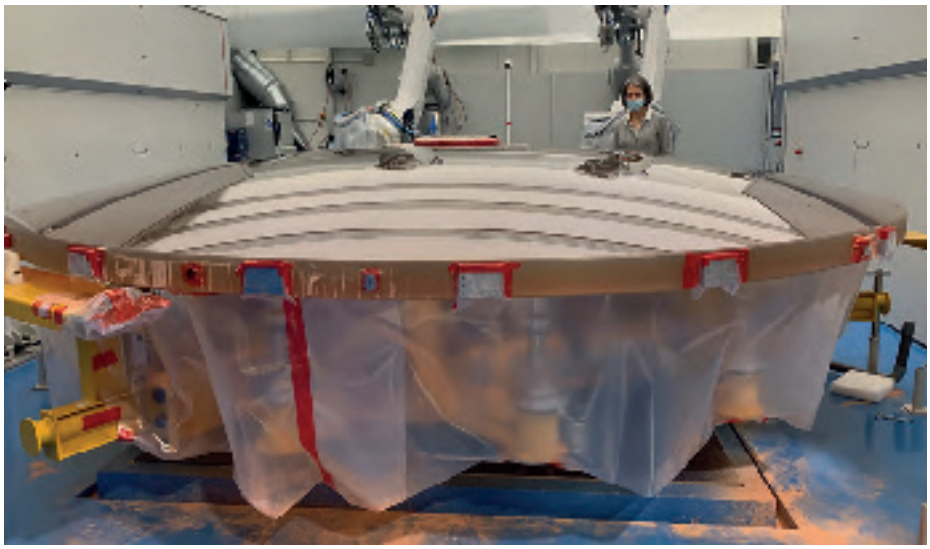
The second-largest clutch of industrial contracts concerns the telescope optomechanics. A total of 17 large running contracts (three of them already closed) aim at designing and fabricating the suite of telescope mirrors (M1 through M5) and their supports. Most of the running contracts have passed the design phase and are either preparing for series production or already in full production.

The production of the M1 segment blanks at SCHOTT has progressed according to plan. So far 360 M1 blanks have been delivered to Safran Reosc (France) for polishing, almost 40% of the total of 949. The production of the M1 Segment Supports at VDL also progressed well, albeit with some minor technical issues in the series production and the packaging that were resolved during 2021. This generated a few months' delay but it is not impacting the rest of the segment production line — 239 Segment Supports (about 30% of the total) have already been delivered by VDL to Safran Reosc. Regarding M1 polishing, Safran Reosc has completed the design phase. The production facilities became fully operational with the delivery of all production machines and tooling. Most of the dozen manufacturing processes were qualified during 2021; some work still remains on the machining and cutting, and the final stage of ion-beam figuring. A total of 31 segments were in production by the end of 2021. A number of technical difficulties, notably in the automated bonding process for the supporting pads and hex-cutting, created some delays and the first Segment Assemblies are expected to leave the factory in the first half of 2023.

Several other contracts are producing key components of the giant 39-metre segmented primary mirror. The Edge Sensors, which measure the relative position of the segments to nanometric accuracy, are now in series production at FAMES, the consortium formed by Micro-Epsilon and Fogale nanotech. More than 4500 units will be produced in total. The Position Actuators also completed their design phase and are in series production. Close to 200 actuator heads and more than 400 Control Modules have been produced. The latter have been delivered to PROCON, the company contracted by ESO to integrate the M1 field electronics into the 132 Segment Concentrator Cabinets located just beneath M1 and therefore specially designed for low thermal dissipation.

Following delivery of the two 4-metre-class blanks by SCHOTT and the closing of the related contracts, three contracts are still running for the design and manufacture of the M2 and M3 units. The first two are with Safran Reosc for polishing of the M2 and M3 mirrors. After some delays due to technical issues in the initial

ESO/Safran Reosc



The 4.2-metre-diameter ELT secondary mirror (M2) went through its pre-polishing phase at Safran Reosc in 2021, reaching a surface accuracy of about 2 µm rms.

SENER

The M2 and M3 cells developed by SENER completed their final design phase and underwent manufacturing during 2021. Here, the M2 cell structure is seen during its integration.

phases, the M2 polishing made very good progress in 2021. The grinding was completed and the pre-polishing started, reaching about 2 microns of surface accuracy by the end of 2021. M3 is next, sharing the same facilities. The bonding of the interface pads was completed, and the mirror has been transferred to the M2/M3 polishing facilities, waiting for its first grinding early in 2022. The last M2/M3 contract is with SENER for the design and production of the M2 and M3 Cells. The design phase has been completed and the various components are in procurement and manufacturing. Assembly of the M2 Cell has begun, and should be completed in the first quarter of 2022 when verification activities can start. The M3 Cell integration began at the end of 2021. The M4 unit also reached a significant milestone with the delivery by Safran Reosc to AdOptica of the 5th and 6th thin shells in March 2021. This marked the completion of the first ELT mirror. The M4 adaptive mirror consists of 6 very thin (1.95 millimetres) sectors made of Zerodur® glass ceramic produced by SCHOTT and later polished, thinned and cut by Safran Reosc. Two more shells, part of a spare mirror, were also completed and delivered to AdOptica in September and November respectively. The manufacturing of the M4 adaptive support by AdOptica continued during 2021, completing the procurement of the thousands of components and starting the assembly of sub-assemblies such as the main structures and drives, actuators mechanics and electronics (the so-called “bricks” modules), the hexapods supporting the unit in the telescope and also large handling and test equipment such as the 8-metre-high optical test tower that will enable full optical testing of the integrated unit (including at Armazones later on). Unfortunately, a persisting difficulty with lapping the so-called Reference Body at AdOptica’s subcontractor prevented, until the end of 2021, starting the integration of the full M4 unit. The Reference Body is a state-of-the-art, light, rigid, high-accuracy, 2.4-metre-diameter item made of silicon carbide (SiC), against which the adaptive mirror will be precisely controlled by acting on the more than 5000 voice-coil adaptive optics actuators.

Another very important technical challenge, also related to the use of SiC as an ultra-light and rigid material, is represented by the manufacturing of the M5 mirror, the 2.7 × 2.2-metre fast tip-tilt mirror acting hand in hand with M4 to correct atmospheric and other disturbances. After manufacturing of a dozen SiC sectors for the M5 mirror blank, part of 2021 was spent on qualifying the chemical vapour deposition process of each sector before they can be brazed together. After a number of unsuccessful attempts, the 6 petals that will form the mirror blanks were coated and the manufacturing process continues with another delicate operation: brazing the sectors together. The mirror will then be polished by Safran Reosc. The design of the M5 cell, under contract with SENER, is progressing well towards its FDR, planned for early 2022.

Mersen Boostec/Safran Reosc

The ELT's fifth mirror (M5) is a true technological challenge. The 2.7 × 2.2-metre flat mirror needs to be very light and stiff as it is designed to compensate for the fast pointing errors of the telescope (for example, due to wind buffeting). It is made of six SiC (silicon carbide) sectors coated with a special chemical vapour deposition coating before being brazed together and finally polished.

Moving further down the light path, the contract with IDOM (Spain) for the pre-focal station (PFS) has concluded its final design phase and is currently in the procurement and manufacturing phase. The M6 mirrors are in production at the subcontractor Glyndŵr Innovations (UK). The M6C mirror, that will redirect the light towards the coudé foci, has completed pre-polishing down to a level of 50 nm rms wavefront error.

Steady progress was also made in 2021 on many other less prominent but very important contracts, such as the Laser Guide Star System, for which the 6 laser sources developed by TOPTICA (Germany) are gradually being delivered to ESO (two in 2021) and for which the Laser Projection Subunit developed by TNO (the Netherlands) passed its PDR in June. The M1 segment coating units are also nearing completion; the first unit is in storage at Paranal, waiting for COVID-19 restrictions to allow its integration, and the second unit has been accepted. Both should be installed in the first half of 2022.

In terms of ESO internal activities, detailed planning of the assembly, integration and verification phase has made further progress with all activities defined and detailed staffing plan under discussion. The Phasing and Diagnostic Station, designed and built at ESO to be integrated into the PFS and serve as a commissioning tool and to perform diagnostics during operation, has passed its PDR.

The control system aspects have progressed well with the development of the ELT Control Model, the Instruments Control System Framework, the Data Display and preparation of the various networks. Very good progress was also made with the delivery of the CCD-220 and on the development of large wavefront sensor detectors. The wavefront sensor cameras, designed and developed internally at ESO, are now ready for the manufacturing readiness review.

All-in-all, 2021 has been a difficult year with many additional difficulties due to the pandemic. However, overall progress during 2021 has been very satisfactory.

The star cluster NGC 6604 and its surroundings, captured by the Wide Field Imager attached to the MPG/ESO 2.2-metre telescope at La Silla.

Panorama of the VLT under the Milky Way at Paranal. The bright object next to the person on the platform is the planet Jupiter.

ESO/P. Horálek

Engineering

The Directorate of Engineering (DoE) provides engineering resources and services to all ESO programmes and to the operations teams at the observatories and at ESO Headquarters. In addition, the DoE provides Information Technology (IT) services to the whole Organisation.

In 2021, despite the challenges brought by the COVID-19 crisis, the engineers and technicians of the DoE provided the required support to the ELT (Extremely Large Telescope), Paranal Instrumentation, Technology Development, and La Silla Paranal Observatory Programmes as well as to ALMA (the Atacama Large Millimeter/submillimeter Array). Working from home, they participated in project reviews, implemented and tested software and designed instruments and ELT subsystems. They travelled to ELT contractors to inspect hardware and came to ESO's Headquarters to work in the integration hall, optical laboratories, mechanical workshops and detector laboratories.

Beyond working on projects, the DoE finalised and released several engineering standards, including standards related to Real-Time Control, Technical and Wavefront Sensing Cameras, Instrument Control Software Architecture as well as Vacuum and Cryogenics Standard components.

The VLT Survey Telescope (VST) at Paranal is a 2.6-metre telescope equipped with OmegaCAM, a 268-megapixel camera with a field of view four times the area of the full Moon.

Mechanical Engineering Department

The Mechanical Engineering Department (MEC) provides mechanical engineering expertise to all ESO programmes.

The follow-up and management of external contracts, for example for ELT mirror units and instrument development, continued to require a lot of attention. It included participation in design reviews (instruments and the ELT Dome and Main Structure), developing conceptual designs and analyses, writing technical specifications and carrying out independent cross-check analyses. Mechanical support was provided for the design, risk assessment and certification of customised tools (the gripper, transportation cart, flipping tool, health check tool) that will be required to handle the main mirror (M1) segments in the ELT Technical Facility (ETF) on Paranal. The tools were tested on the M1 test stand located in the Large Integration Hall.

The mechanical engineers progressed the mechanical design of the ELT Phasing Diagnostic Station (PDS), completing the preliminary design phase. Considerable effort was put into management and development of the ELT instrumentation infrastructure and ELT cryogenic distribution system. With MEC's support a series of assembly, integration and verification (AIV) workflows were developed for the on-site installations of ELT subsystems. MEC staff are responsible for maintaining the overall as-designed ELT configuration in computer-aided design (CAD) and Building Information Modelling. This is a very challenging exercise because of the ever-increasing complexity and level of detail, the need to coordinate the various sources of the models, and the actual size of the models.

CAD design of M1 segment gripper and transportation cart for handling activities in the ETF.

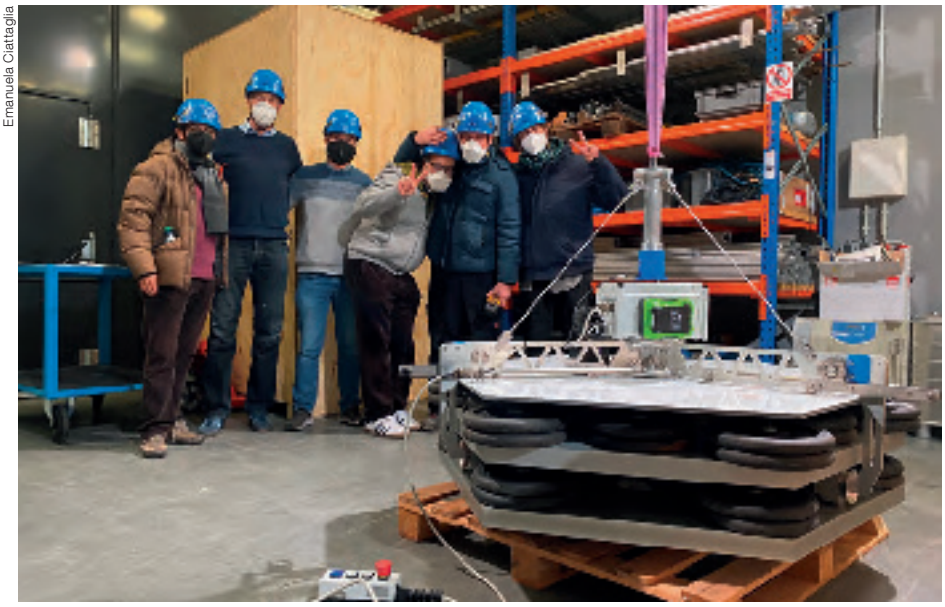
In a joint effort with other engineering departments, MEC led the verification and acceptance of the Facility for Infrared Array Testing (FIAT), a dedicated test bench for ELT-size detectors that was developed in-house.

VLT (Very Large Telescope) instrumentation also kept the department busy. Its staff helped the ERIS (Enhanced Resolution Imager and Spectrograph) project in closing the Preliminary Acceptance Europe phase by providing expertise in design verification, vibration characterisation and implementing vibration mitigations. A new sensor arm enabling the back focal length extension was fabricated and shipped to Chile as required before the arrival of ERIS at the VLT.

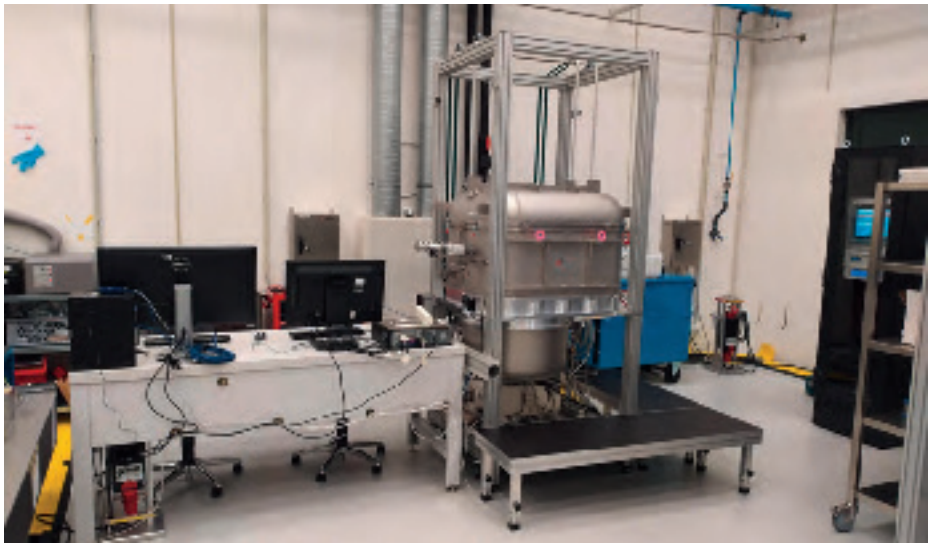
Efforts were made to identify the potential source of instability of the radial velocity measurements made by ESPRESSO (the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations) at the VLT. A spare detector cryostat was assembled and equipped with a newly designed thermal connection structure in order to improve the stability performance.

A newly developed feed shutter mechanism for the ESO-provided ALMA antennas was long-term tested inside and outdoors during the winter at ESO Headquarters in order to simulate the harsh ALMA high-site environment. A first prototype was delivered to ALMA for integration and testing at one of the antennas.

Emanuela Ciattaglia



An interdisciplinary team from mechanical, control and system engineering briefly gather for a photo while performing the load test of the ELT M1 segment gripper in the MEC laboratories as part of the certification process.



FIAT in its final configuration in ESO's Large Integration Hall.

Electronics Engineering Department

The Electronics Engineering Department provides electrical and electronic engineering support to all ESO programmes.

The development of the ELT adaptive optics (AO) cameras made a huge step toward to its finalisation in 2021. All final major board revisions were made and the camera testbench readied, and both ALICE (the smALl visible CamEra) and LISA (the Large vISible cAmera) were assembled and tested successfully on the testbench. ALICE and LISA are both in their final qualification run to confirm that both cameras meet their target specifications.

The development of the second Next Generation Controller, the ESO future readout electronics for all scientific detectors, commenced in 2021. Requirements were collected from the instrument consortia, consolidated by ESO detector experts and derived into subsystem specifications. Several of the printed circuit boards have been already designed and manufactured.

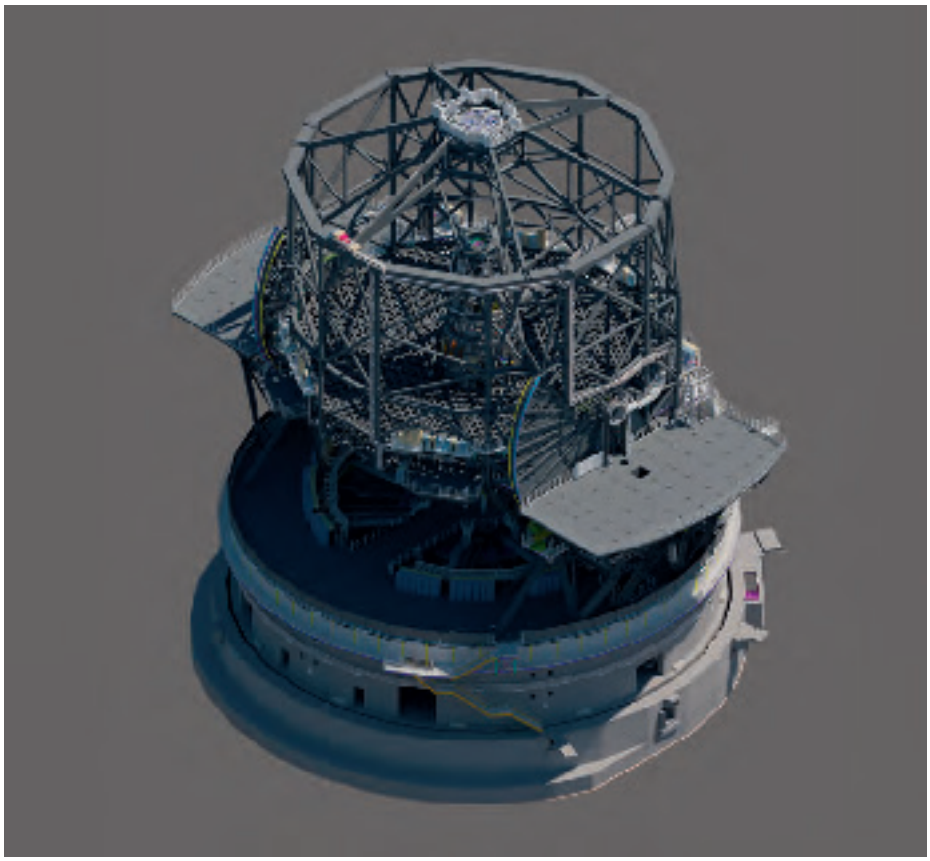
The ELT M1 electronics cabinets house the control electronics to shape the ELT M1 mirror and to distribute the power to the different loads. Substantial progress has been made on both the M1 Segment Concentrator Cabinets and the M1 Sector Distribution Cabinets. The production of the Segment Concentrator Cabinets at Procon Systems in Spain began with the manufacturing of one engineering model. This model was delivered to ESO Headquarters for final tests.

The Sector Distribution Cabinets are built entirely in-house. Six of them have been delivered and manufacturing is continuing.

Norm compliance is always a concern for ESO, as it offers security and provides proven design baselines. In this regard, the department offered support for ALMA in respect of the retrofit of the residencia lightning protection system, obsolescence management, and changing the fuel for the gas turbines from liquefied petroleum gas to liquefied natural gas. Options were evaluated for the connection of the future Cherenkov Telescope Array South observatory to the Chilean electricity network.

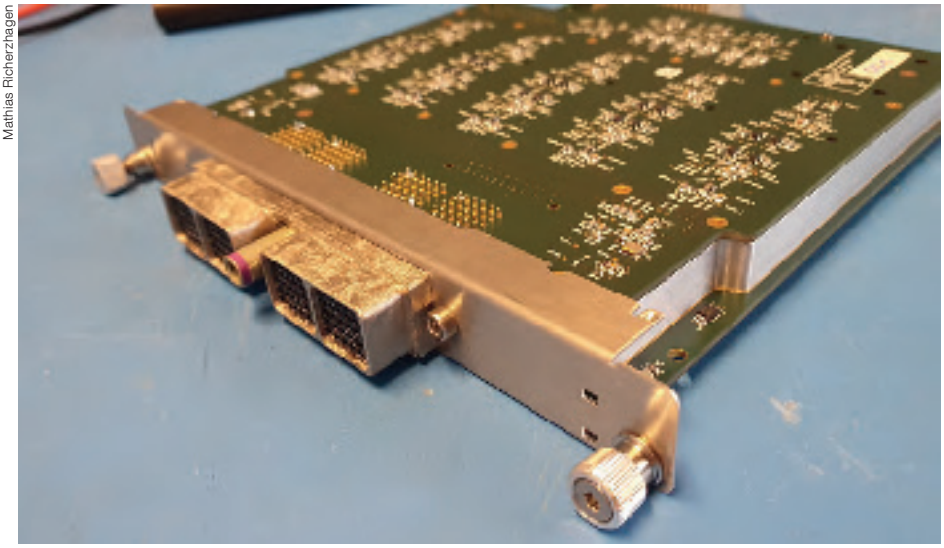
As in every year, efforts were made to maintain and develop our laboratory infrastructure. As an example, a Centralised Cooling Distribution Network (CCDN) was deployed and is supplying several of our detector labs. FIAT, the cryostat work horse for detector qualification for the ELT instruments, is close to its acceptance by the Electronic Detector Systems Group. The InfraRed Array Test Electronics Cryostat (IRATEC), another instrument test cryostat, has received new control electronics based on programmable logic controller technology and is ready to accept the first detector. The Cryogenic Electronics Assembly Test facility (CEAT), a cryostat specifically made for electronic

ACe consortium



CAD model of the final design of the ELT Main Structure, including the M2, M3 and M4 optomechanical units.

Mathias Richerzhagen



A C20B20 (CMOS clock and bias) printed circuit board developed in-house for the new NGCII detector controller.

tests in a cryogenic environment, started full operation in 2021. Our lab equipment was also updated with several new measurement tools, e.g. a new microscope in the workshop.

Systems Engineering Department

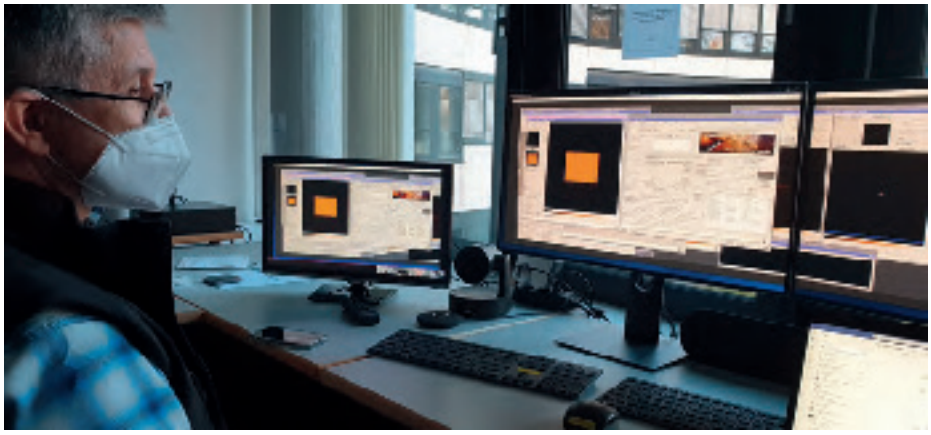
The Systems Engineering Department (SEN) provides all functions of Systems Engineering, such as requirements management, system architecture, technical coordination, analysis, and verification, as well as interface and technical performance management, for the ESO programmes.

One of the highlights in 2021 for in-house projects led by members of SEN was the completion of the commissioning of CRIRES$^+$ (the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph) in August and its being offered to the community in October. Another highlight was the remote AIV and commissioning of the IRLOS (InfraRed Low Order Sensor) upgrade. For the first time, such an intense activity was executed entirely remotely, requiring finding novel ways to transfer knowledge from Garching to Paranal, and to train and actively support colleagues remotely, as well as integrating the support to the commissioning runs into the usual daily activities.

A significant effort within SEN was the follow-up of contracts with industrial partners or scientific consortia. Many design reviews were held in 2021, with significant contributions by staff from SEN, ensuring compliance with ESO standards, requirements, and interfaces, providing experience from previous projects, and cross-checking critical engineering analyses, as well as coordinating the technical solutions amongst the various consortia and performing simulations of AO systems for independent performance assessment.

The Observatory Systems Group holds crucial Systems Engineering knowledge for developing large ground-based observatories. The group's main activities are providing multi-disciplinary Systems Engineering for ESO programmes, mostly for the ELT, and improving coordination amongst the engineering disciplines.

The ERIS AIV team in front of the assembled instrument in the Paranal New Integration Hall.



Remote commissioning of the SAPHIRA detector in IRLOS.

The Instrument Systems Group provides Systems Engineering and project management for both internal and external instrumentation projects for the VLT and ELT programmes. Members of the group supported eight instrumentation projects for the Paranal Observatory, the four first-generation instruments for the ELT, and the ELT PDS and managed the development of the ESO Wavefront Sensor Cameras. The Adaptive Optics System Group provides AO competences to develop and optimise AO systems. Members of the group were involved in developing AO systems for the second-generation VLT instruments, participated in the ELT programme on telescope- and instrumentation-related activities, and developed technologies required by the next generation of AO systems.

Optical Engineering Department

The Optical Engineering Department continued to provide engineering expertise across the whole suite of ESO projects, in the areas of optical design and analysis (including straylight, structural, thermal, and optical performance [STOP] and coating analyses), active optics using maximum likelihood methods and sensitivity matrices generated by our internal optical tool SENSITIZER, phasing, metrology for telescope alignment, laser guide stars, photonics technology and finally assembly, integration and testing of optical systems and instruments.

This included in particular the technical follow-up of the industrial contracts for polishing the ELT mirrors and for the prefocal station, the preliminary design of the overall ELT PDS (including the Final Design Review [FDR] of its optics), the definition of the ELT mirror alignment strategy, and the design of a pyramid sensor for the Minuscule ELT. The first laser of the ELT Laser Guide Star (LGS) system was tested in our integration facility, in addition to managing all ELT LGS industrial contracts. The Local Coherencer project, a daytime phasing tool for the ELT primary mirror, was kicked-off with industry. The department was also heavily involved in following up the ELT instrumentation, including the specification phase of MOSAIC (the Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology) and HIRES (the High REsolution Spectrograph, renamed ANDES in early 2022). The new Telescope State Inversion Module active optics algorithm for VISTA (the Visible and InfraRed Survey Telescope for Astronomy) was completed for the 4MOST (4-metre Multi-Object Spectroscopic Telescope) project.

The retrofit of our integration facilities has progressed with the help of an external planner, and the support of the Mechanical Engineering & Facility Departments. This activity is essential for preparing the assembly, integration and testing phase of the ELT PDS, the ELT LGS and MICADO (the Multi-AO Imaging CAmera for Deep Observations).

R&D activities were maintained, despite the heavy workload on ESO programmes. Field tests were conducted to validate the use of laser trackers for advanced optical metrology applications, which were then applied to ease the metrology of the ELT M4 reference body contracted to industry. Experimental tests were pursued of using a spatial light modulator, to emulate a pyramid phasing

View of the Large Integration Hall with areas currently allocated to the ELT and Technology Development Programmes.

sensor and a programmable computer-generated hologram, for optical surface testing. The department kicked off with industry the iterative design and fabrication of a photonic integrated circuit for the Photonics Spectrograph demonstrator. An internal STOP analysis working group submitted a referred paper to present ESO's approach and recent achievements in this field.

The department was also instrumental in solving stray light issues with FIAT.

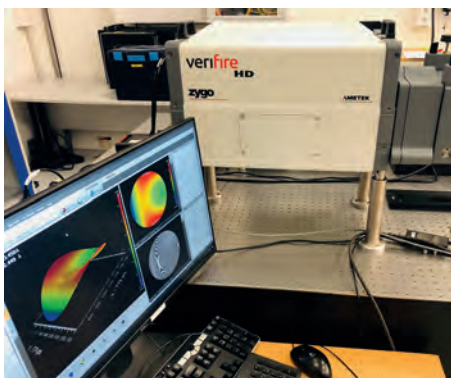
The department contributed to ESO's technology development programme in the area of advanced reflective coatings, including studies on the durability of coatings. Another field covers LGS R&D; it is aiming at improving LGS-based AO performance, and applying it to ground-to-satellite optical communication, in collaboration with the European Space Agency (ESA). The world record of available LGS power was broken by reaching an unpreceded 63 W.

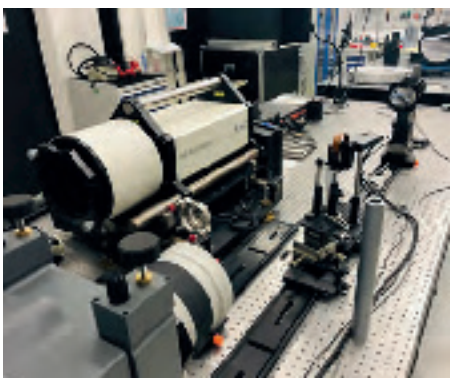
Control Software and Engineering Department

The Control Software and Engineering Department provides control engineering as well as control software expertise to all ESO programmes and to operations. The control engineering group within the Control Software and Engineering Department leads activities related to characterising potential sources of vibration, envisaging mitigation strategies, and verifying the ELT subunit requirements as well as overall telescope performance. This is multidisciplinary work which is done in close collaboration with MEC.

Together with MEC, the vibration measurements and characterisation continued this year with testing and verifying the efficiency of anti-vibration mounts for the equipment which is planned to be installed on the telescope structure. Excellent progress has been achieved in developing and characterising vibration isolating systems for standardised equipment like mechanical cryo-coolers and electrical cabinets, both considered main contributors in terms of vibration generation.

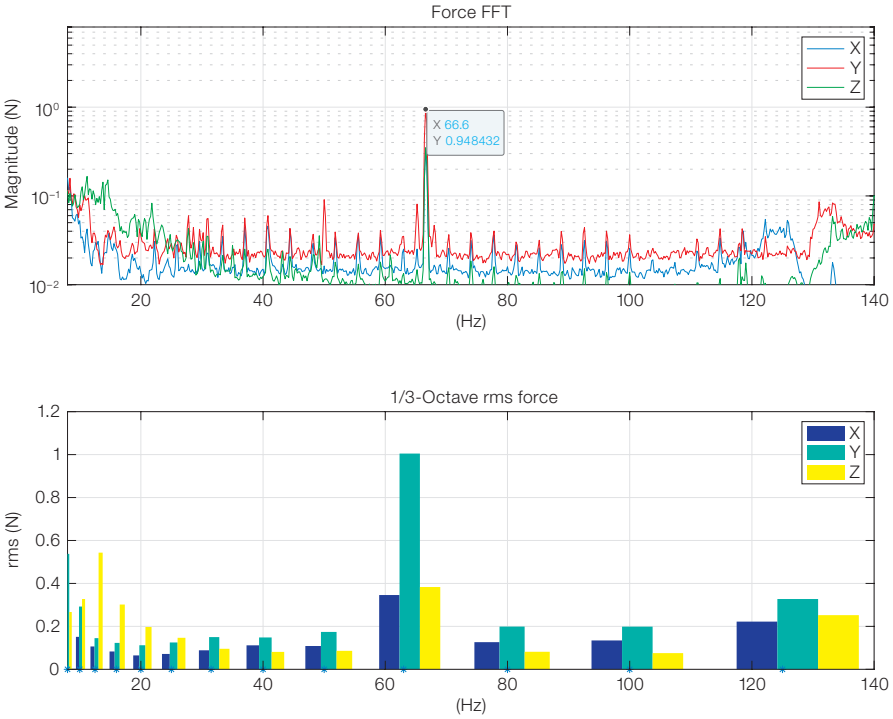
The measured exported forces of equipment together with their anti-vibration mounts are verified against specifications. The tight vibration budget led the team to only be satisfied when the measured exported forces were smaller than the specified values.





Petr Janout

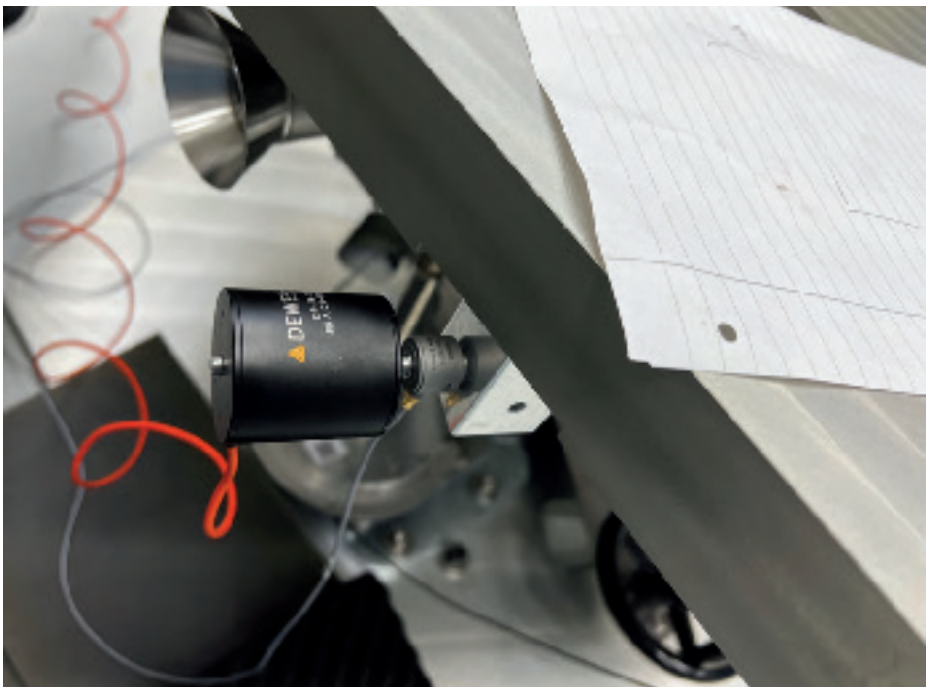
R&D in optical surface testing, using a spatial light modulator as a programmable computer-generated hologram.



Babak Sedghi

Large Integration Hall vibration testing facility: Measuring exported forces of a cryo-compressor (variable speed) isolated by a double stage anti-vibration mount (rubber isolator and swinging mechanism), magnitude spectra and measured exported force.

During the activities related to M1 segment assembly in the Large Integration Hall, the team realised the importance of the modal tests to identify and discover flaws in the installation and assembly of the segment support unit. The AIV team decided to use this approach for a systematic health check of the segment assembly after the reception in the ETF building at Paranal and before installation on the telescope structure. The aim of the testing is to detect loosening of assembled parts, flaws, voids, or cracks, caused during manufacturing or transportation or improper assembly of parts. The approach is planned for a semi-automated procedure that is easy to follow and repeat for hundreds of segments.



Babak Sedghi

Inertial exciter together with a force sensor connected to an ELT M1 segment, for performing modal tests.

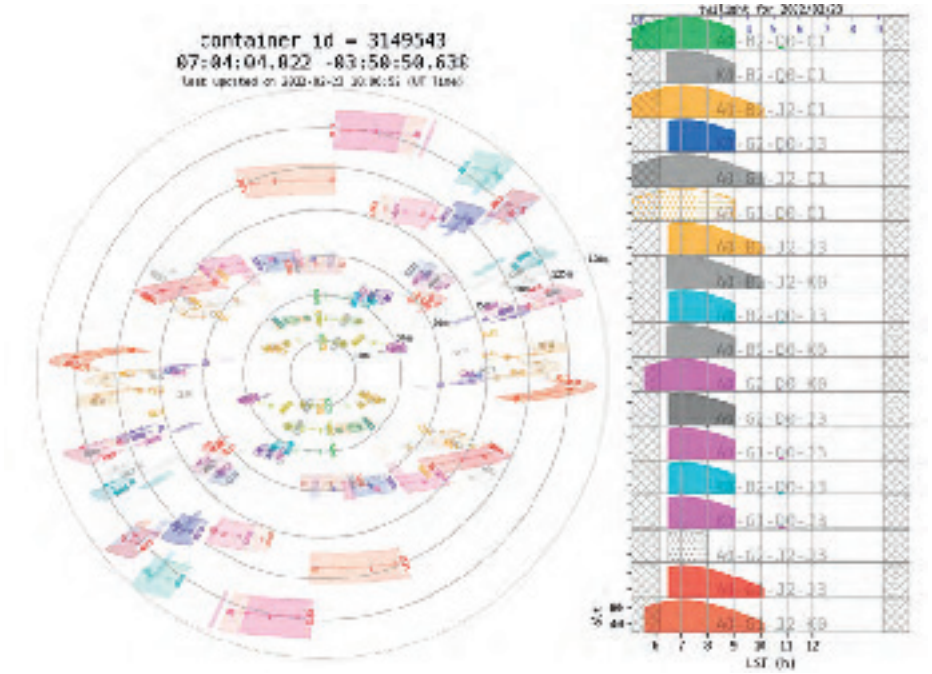
Science Operation Software Department

The Science Operation Software Department is responsible for all science operation software for the end-to-end operations of ESO observatories: La Silla-Paranal, ALMA, and the ELT. The devel-

opment of science operation software proceeded in all areas in 2021, with several major releases of ELT/VLT and ALMA dataflow components.

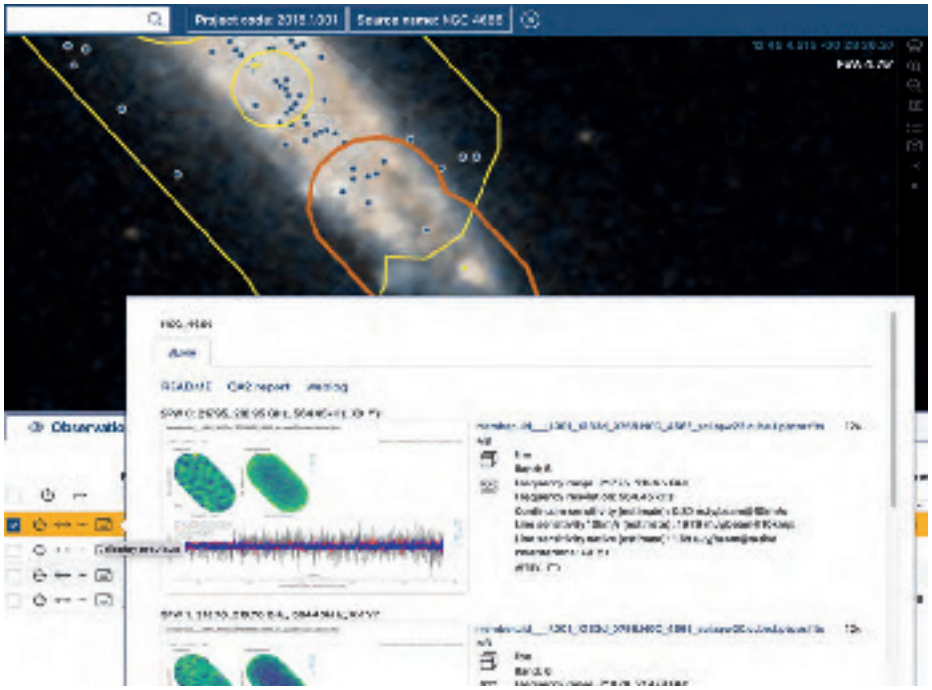
Highlights of 2021 in the area of observation proposal handling included the release of the new Proposal Evaluation Interface as part of the Phase 1 project for the VLT, and the release of the Distributed Peer Review system for ALMA proposal preparation. In the domain of data processing and quality control, major progress was made with the new VLT/ELT data processing and quality control infrastructure. The ESO Data Processing System is a new project with the goals to unify the data reduction infrastructure at the observatory and at the headquarters, to provide a platform for the new data quality control process, to support new ELT requirements, and to provide the community with a data reduction solution based on the same infrastructure and on the same data reduction cascades as used for internal scientific operations. Several releases of dataflow tools took place, including *uv* plots in the Observing Tool to be used at the VLT Interferometer, and an enhanced ALMA Science Archive interface with data previews. Observation preparation tools for on-going instrumentation projects were prepared including support for MOONS (the Multi-Object Optical and Near-infrared Spectrograph) and exposure time calculators.

A major milestone in the area of data reduction was the FDR for MICADO, the first ELT instrument, which included a review of the Point Spread Function Reconstruction dataflow, as well as a review of the data reduction software and observation preparation tools. Moreover, VLT pipelines were released for scientific operation at the observatory and for use by the user community. The pipeline group also contributed to the preparation of the ALMA/CASA (Common Astronomy Software Applications) data reduction software releases. Releases of CASA 6.1 to 6.4 were issued during the year, as well as a deployment branch to be used by the ALMA pipeline for the development of the pipeline's 2022 release. The CASA Test and Validation activity is now part of the ESO contribution, and the testing infrastructure was enhanced to include extended validation workflows



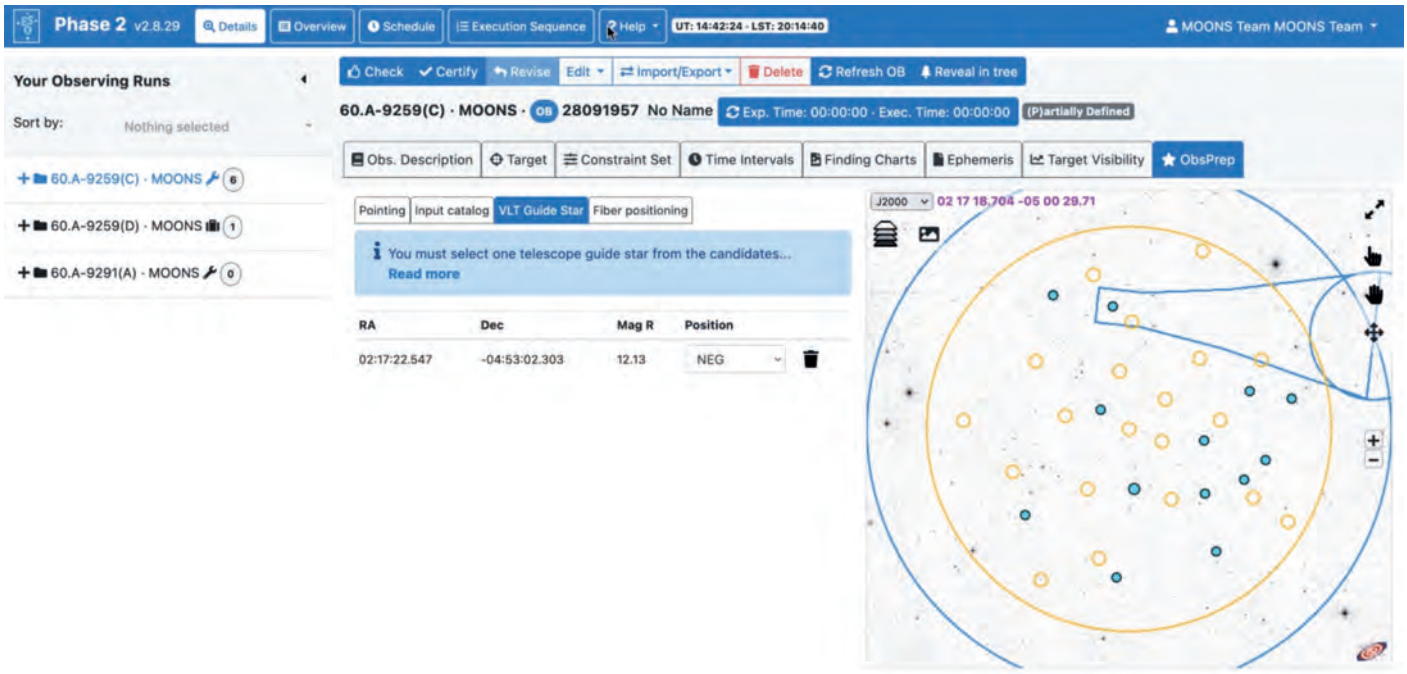
Paula Santos (ESO)

uv-plane coverage plots for GRAVITY imaging observations with the VLT/VLTI Observing Tool.



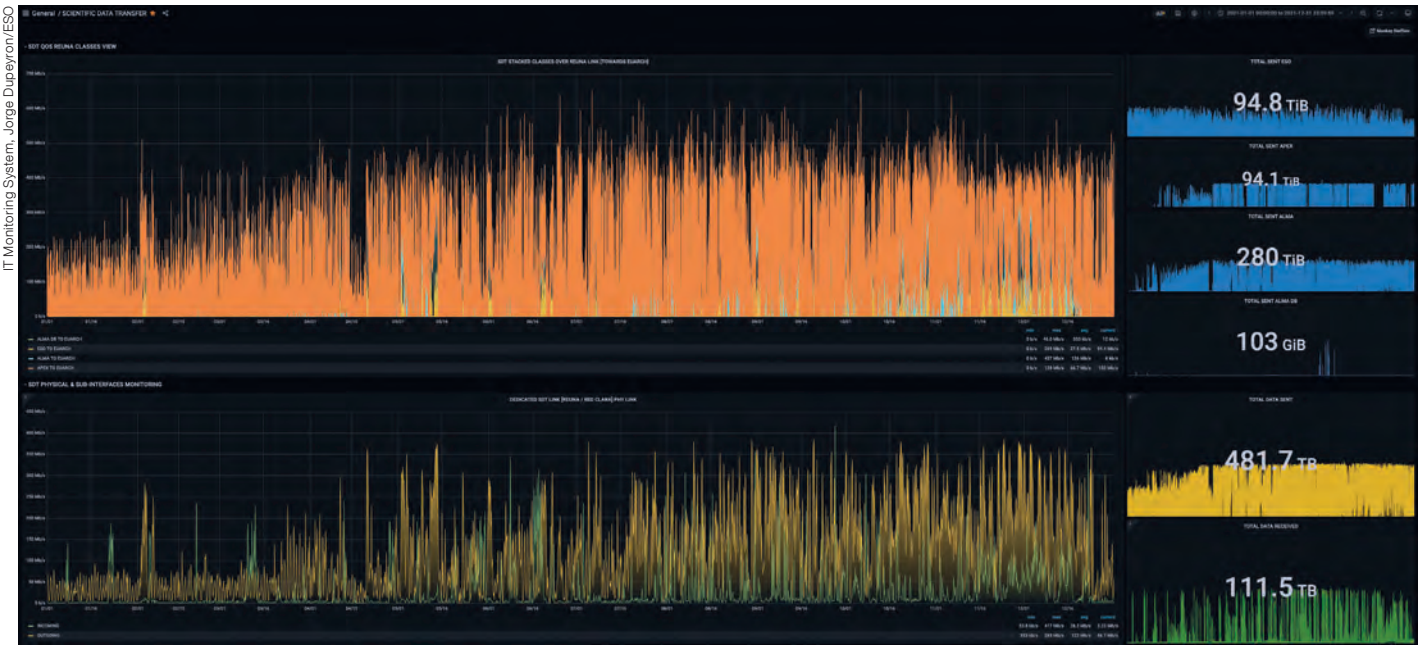
Interactive previews in the ALMA Science Archive. Selecting a dataset displays a preview of the scientific data and an information summary.

ESO/Vincenzo Forchi



Selection of VLT guide stars in the MOONS field of view with the p2 observation preparation tool.

IT Monitoring System, Jorge Dupeyron/ESO



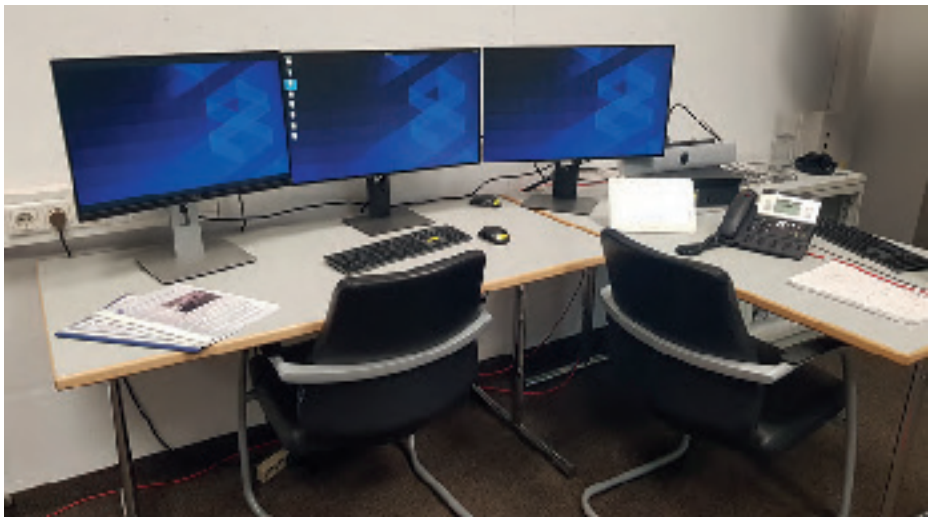
Scientific data transfer in 2021, showing the individual amounts of data sent from LPO, APEX and ALMA to the Scientific Archive at HQ, and the total data sent between Chile and the Scientific Archive at ESO HQ, through the Academic Network (DFN and REUNA) links.

and performance testing. Moreover, the Telescope Calibration subsystem (TelCal) release has been successfully verified and released in 2021 for the Cycle-8 science validation. All these software tools, both for VLT and for ALMA software releases, went through thorough integration and testing before being deployed in the operation environment or delivered to the users.

Information Technology Department

The ESO IT Department delivers services and supports users and science operations. During 2021 IT continued to provide integrated services to the organisation, and harmonised the IT monitoring infrastructure across all sites. Software and hardware were deployed to allow for "hybrid meetings", meetings with a subset of the participants on-site and others connecting to the meeting room via Microsoft Teams. IT augmented the infrastructure for remote commissioning and thus allowed for a successful commissioning of CRIRES$^+$ and IRLOS. The ramp-up of Paranal and La Silla into operation would not have been possible without dedicated support from IT. The IT specialists also implemented Azure Cloud services, decommissioned the ESO Data Centre at the site of a neighbouring institute and continued to address obsolescence on all sites.

Cyber security threats are taken very seriously by ESO and required increased attention from IT in 2021. The department started a long-term phishing awareness campaign and deployed an enhanced security analysis system correlating many log sources. The engineers followed up swiftly several critical system vulnerabilities, including the immediate update of software and configurations in order to mitigate the risks.



Sandor Horvath/Terma

IT utilised a former meeting room as the Garching Remote Access Facility extension to support parallel remote instrument commissioning runs.

Dieter Suchar/ESO

The ESO Data Centre was located at the Max Planck Institute for Plasma Physics, a neighbouring institute to the ESO HQ, and was decommissioned after the IT infrastructure was moved back to the ESO premises.

Aerial photograph of the ESO Headquarters in Garching, including the ESO Supernova Planetarium & Visitor Centre to the upper-left of centre.

E. Grafi/ESO

Administration

Roland Halbe/ESO

The Directorate of Administration (DoA) comprises ESO's administration in Garching and in Chile, in charge of all administrative matters across the organisation. Its functions include human resources, financial services, contracts and procurement, facility management (including the supervision of civil construction works), logistics and transport, safety coordination, Enterprise Resource Planning services, insurance and the operation of the ESO Guesthouse in Santiago. The Director of Administration is responsible for site safety in Garching, in Vitacura and at the Santiago Guesthouse, and represents ESO at the ALMA (Atacama Large Millimeter/submillimeter Array) Head of Administration meetings and in CERN Pension Fund matters. The Administration Office organises Finance Committee meetings.

Highlights

2021 was again a challenging year for the DoA, having to cope with changing local safety regulations in response to the COVID-19 pandemic. Despite the lockdown in the first months, some staff members had to work on site for operational reasons. In regular Emergency Team and gate review meetings, the best solutions were discussed with the internal stakeholders at all the sites in Germany and Chile. Together with the Human Resources (HR) department, options to travel for important review meetings were explored so as to ensure the best possible safety for staff members. The Contracts and Procurement (CP) department stayed in close contact with ESO's suppliers to find mutual agreements and the best way forward. As the construction of the ELT (Extremely Large Telescope) and some of the instruments and instrument upgrades did not progress as originally expected, the Finance Department undertook a greater than usual level of proactive cash management to mitigate effects on ESO. The safety and facility management teams were heavily involved in providing the conditions for safe on-site meetings once these were again possible to a limited extent. HR organised vaccination campaigns against COVID-19 and seasonal flu and there was a significant uptake amongst staff.

After an intensive internal consultation process and the rollout of an updated policy, a revised performance appraisal system including a new online tool was successfully launched by HR. An ESO-wide comprehensive staff engagement survey was performed in November, following a mini survey about COVID-19 earlier in the year. These yielded valuable feedback from staff.

A more formal governance and regular review process for the ESO Health Insurance Scheme was developed by a working group consisting of stakeholders within the organisation and was successfully implemented. After a review of the fund status, the contributions and the coverage, the newly established EHIS board proposed some recommendations to the ESO management.

In 2021 the ERP team implemented a revised leave module, allowing more flexibility for staff working part-time.

P. Horálek/ESO

Looking up at the ESO Headquarters in Garching, Germany.

Windows at the ESO Headquarters in Garching, Germany.

Finance and Budget

Financial Statements 2021

Accounting Statements 2021
(in €1000)

Statement of Financial Position	31.12.2021	31.12.2020
Assets		
Cash and cash equivalents	178 811	139 763
Inventories, receivables, advances and other current assets	83 956	62 273
Non-current assets	1 257 218	1 257 569
Total Assets	**1 519 985**	**1 459 605**
Liabilities		
Short-term borrowing	–	–
Payables, advances received and other current liabilities	191 745	166 496
Non-current liabilities	948 050	933 406
Total Liabilities	**1 139 795**	**1 099 902**
Accumulated surpluses/deficits	359 703	366 620
Other changes in net assets	23 469	–12 065
Net surplus/deficit for the year	–2 982	5 148
Total Net Assets	380 190	359 703
Total Liabilities and Net Assets	**1 519 985**	**1 459 605**

Statement of Financial Performance	2021	2020
Operating Revenue		
Contributions from Member States	213 672	225 075
Contributions to special projects	10 443	10 660
In-kind contributions	4 682	3 336
Sales and service charges	2 320	2 755
Other revenue	2 657	2 922
Total Operating Revenue	**233 774**	**244 748**
Operating Expenses		
Installations and equipment	2 119	1 616
Supplies and services	40 729	35 305
Personnel expenses	102 459	98 194
Depreciation of fixed assets	87 810	100 066
Other operating expenses	5 715	4 783
Total Operating Expenses	**238 832**	**239 964**
Net Surplus/Deficit from Operating Activities	**–5 058**	4 784
Financial revenue	3 365	2 787
Financial expenses	1 532	2 710
Net Surplus/Deficit from Financial Activities	**1 833**	77
Non-periodic and extraordinary revenue	243	287
Non-periodic and extraordinary expenses	–	–
Net Surplus/Deficit from Non-periodic and Extraordinary Activities	**243**	**287**
Net Surplus/Deficit for the Period	**–2 982**	**5 148**

Cash Flow Statement	2021	2020
Cash Flow		
Net surplus for the year	–2 982	5 148
Non cash relevant transactions	127 660	135 725
Changes in current assets and liabilities	–1 750	–2 272
Net Cash Flow from Operating Activities	**122 928**	**138 601**
Net Cash Flow from Investment Activities	**–84 187**	**–148 827**
Net Cash Flow from Financing Activities	**307**	**–771**
Net Cash Flow = Net Increase/Decrease in Cash and Cash Equivalents	**39 048**	**–10 997**

Budgetary Reports 2021
(in €1000)

Income Budget	Actual	Budget
Contributions from Member States	226 822	219 648
Income from partnerships	11 300	14 283
Income from third parties	852	1 333
Other income	1 613	2 313
Consolidated entities	3 042	2 775
Total Income Budget	243 629	240 352

Expenditure Budget	Actual	Budget
Programme	94 268	200 560
Technical infrastructure and production	5 997	8 677
Operations	66 326	85 865
Science support	6 988	10 966
General activities	29 650	36 830
Cherenkov Telescope Array	1 113	4 486
Financing cost	14	30
Consolidated entities	2 151	2 532
Total Expenditure Budget	206 507	349 946

Budget for 2022
(in €1000)

Income Budget	2022 (Approved)
Contributions from Member States	223 087
Income from partnerships	14 336
Income from third parties	1 274
Other income	2 294
Consolidated entities	2 587
Total Income Budget	243 578

Expenditure Budget	2022 (Approved)
Programme	208 569
Technical infrastructure and production	8 591
Operations	76 710
Science support	9 325
General activities	37 125
Cherenkov Telescope Array	6 041
Financing cost	26
Savings/delays	5 000
Consolidated entities	2 453
Total Expenditure Budget	353 840

The External Auditors from the National Audit Office of Finland* have expressed their opinion that the financial statements for 2021 give a true and fair view of the affairs of ESO.

The accounting statements for 2021 show a negative result of 3.0 million euros. While operating income decreased by 11.0 million euros — mainly due to a lower rate of conversion into income of previously received advances for the ELT, caused by lower project spending — operating expenses stayed rather stable. Personnel expenses increased owing to higher costs for post-employment benefits, but this was offset by lower depreciation cost.

The deficit from operating activities was 5.1 million euros. From financial activities a net surplus of 1.8 million euros could be generated, thanks mainly to favourable exchange rates of the euro to the Chilean peso. Furthermore, 0.3 million euros from non-periodic and extraordinary income added to the overall result.

ESO's net assets have increased by 20.5 million euros. A positive impact from the re-valuation of post-employment benefits, mainly caused by the actuarial gain and the return on fund assets for the CERN Pension Fund, more than compensated for the loss on the pension liability from the euro-Swiss franc exchange rate, the loss due to the re-valuation of the Chilean peso hedging agreements, and the negative result of the 2021 accounting statements.

The total cash flow turned positive again in 2021, caused by reduced payments. The operational cash flow was 15.7 million euros lower than in the previous year, partly reflecting the pandemic situation, the and cash demand for investments decreased by 64.6 million euros. With some minor positive cash flow from financing activities, the overall cash flow amounted to 39.0 million euros. The closing cash position at 31.12.2021 stood at 178.8 million euros.

The ESO Council approved the budget for 2022 in December 2021. The approved 2022 expenditure budget amounts to 353.8 million euros, remaining at a considerably high level with a large fraction dedicated to the ELT programme.

The 2022 approved income budget amounted to 243.6 million euros. It comprised the regular contributions from the ESO Member States including their additional contributions for the ELT, income from third parties and partners, and other income.

* Pontus Londen (Principal Financial Auditor, Financial Audit), Pauliina Taavitsainen (Principal Financial Auditor, Financial Audit), Jonna Carlson (Senior Auditor, Financial Audit).

Contracts and Procurement

The influence of the COVID-19 pandemic on daily work has remained significant and this is expected to continue during 2022.

Owing to the reduced level of operations on the ESO sites in Chile, fewer procurements were executed by the Chilean CP team in Santiago. On the other hand, a lot of time was spent coordinating, together with the operational management, the changing requirements for support during the ramp-up phases with the different suppliers.

The CP team in Garching needed to spend more time on dealing with changed market conditions, such as shortages, long delivery times, price increases and suppliers being affected by the pandemic.

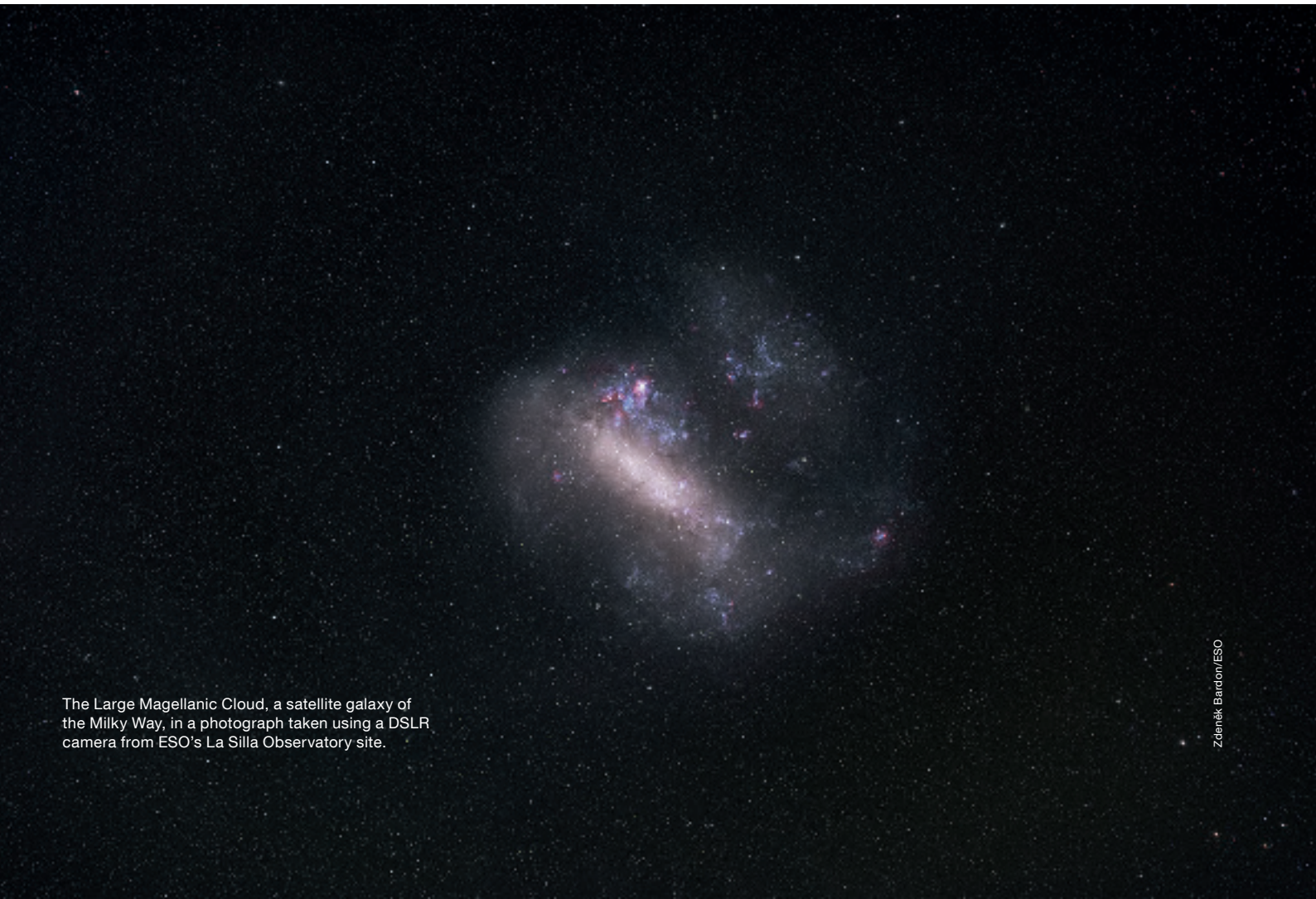
Overall 2195 orders were placed by the CP team, for a total of 116.3 million euros.

During 2021 an electronic tendering tool was sourced and contracted. The implementation of the selected tool, Intend, began in the last trimester of 2021 and its use is expected to begin in the second quarter of 2022. With this tool ESO aims to facilitate further the electronic exchange of procurement documentation and information with the supplier market and to build up more management information in order to further improve the process.

The Finance Committee approved three new contracts for the ELT programme. This brings the total number of contracts placed for the ELT following Finance Committee approval to 47, amounting to 875 million euros. Only a few remaining contracts are planned for the coming years.

The main external focus of the CP Department has again been on improving relations with industry in the ESO Member States.

ESO participated in several webinars, organised by some of its Industrial Liaison Officers and by the International Organisation Committee of the Big Science Business Forum under the leadership of the event host, the Centre for the Development of Industrial Technology (Spain). Besides the usual interactions with the Industrial Liaison Officers, the CP Department has welcomed new representatives from Germany, Denmark and the United Kingdom.



The Large Magellanic Cloud, a satellite galaxy of the Milky Way, in a photograph taken using a DSLR camera from ESO's La Silla Observatory site.

Zdeněk Bardon/ESO

Facility Management, Logistics and Transport

Garching Headquarters

The work priorities of the Garching Facilities, Logistics, Transport team were once again dominated by the COVID-19 pandemic and the implementation of safety measures. Staff presence on site was constantly adjusted, depending on the health authorities' regulations and the outcome of the regular ESO gate review meetings for the Garching site. The installation of air purifiers improved the situation in various building areas and meeting rooms. Vaccination campaigns for employees were offered and carried out at ESO Headquarters, and self-tests were provided on an ongoing basis.

The team started to prepare a major upgrade of the Technical Building, needed to meet the technical requirements of new projects. Stable temperatures and humidity conditions in the Large Integration Hall have to be guaranteed and a technical upgrade of various laboratories is planned. As a result, extensive retrofits and exchanges of house technique equipment have to be organised with the help of external planners and companies.

The lighting in staircases and corridors was converted to LED lamps in order to reduce power consumption and greenhouse gas emissions.

Santiago facilities

As at the Garching Headquarters, contingency plans at the Santiago office had to be continuously adapted to the local conditions and to the COVID-19 measures put in place by the health authorities. Office presence ceilings changed from minimal presence to generalised part-time on-site working. After several interruptions during the peaks of infections, the works that started in 2020 to expand office space were completed in July. Twelve offices and a new reception area were added to the main office building. With the Chilean borders re-opening to foreigners, albeit under strict conditions, some duty travel could take place and since November the ESO Santiago Guesthouse has been receiving visitors again.

Transport and Logistics

As foreseen, the transport and logistics activities in both Garching and Santiago ramped up in 2021, particularly in relation to the construction of the ELT. In Europe, the logistics team arranged the special transport of the large and heavy M2 and M3 (ELT mirror) containers from France to Spain. In Chile, the recommencement of ELT construction works on Cerro Armazones came with a significant increase in the number of received shipments.

ESO/Christoph Haupt

The M2 and M3 ELT mirror transport containers departing from Safran Reosc in France.

ESO/Christoph Haupt

The M2 and M3 ELT mirror transport containers arriving at the SENER integration and test facility close to Barcelona.

Human Resources

Located in both Garching and Vitacura, the HR Department manages all services connected with employment at ESO, including hiring, pay, benefits, training and development, travel, health, social security and wellbeing.

Recruitment

Hiring activities increased steadily in 2021 as operations resumed. Recruitment continued to be done mainly online in 2021, combined with remote on-boarding and initial remote working where still necessary.

During 2021 eight senior and middle management positions were advertised. In addition, 27 other notices for International Staff Members were published, and nine vacancy notices for Local Staff Members. A total of 1849 applications were received, compared to 2348 in 2020 for 35 vacancies, which reflects increased competition for science, technology, engineering and mathematics skills and conditions in the global labour market. The proportion of female candidates applying for international and local positions increased from 26.6% in 2020 to 32.4% in 2021, following a concerted effort to increase outreach activities and web/social media presence.

Staff departures in 2021

The annual turnover ratio remained consistent at 3.1% for International Staff Members and was lower at 3.6% for Local Staff Members (7.4% in 2020). Female staff members (both international and local) represent 25% of all departures, a decrease of 2% year on year.

Long service remains a feature at ESO, reflecting a passion for what we do. In 2021 twenty staff celebrated between 25 and 40 years of service. With some modifications to arrangements for safety, it was possible to celebrate these achievements at in-person events hosted by the Director General in Garching in October and Vitacura in December.

Employee relations

During 2021 the agenda for projects and policy initiatives re-gained momentum as working practices during pandemic conditions stabilised somewhat, becoming more familiar, if still not easy, and enabled by regular joint update meetings with staff representatives.

Despite the constraints there were some notable activities and achievements. In the first half of the year, HR conducted interviews with a wide cross-section of staff to inform the proposals for the new ESO Values, approved by Council in December. In September a revised performance appraisal system was successfully launched, following the rollout of an updated policy, a new online tool, and associated training for all staff and managers. Linked to this was the formalisation of a new policy to help manage significant under-performance, called a Capability Procedure.

During the year reforms to the governance of health insurance were introduced to formalise participation and oversight, and a mechanism to allow Member States to partially offset a fraction of their contributions by seconding expert staff was also agreed. In November the first Staff Engagement Survey since 2015 was run, with a participation rate of 77%, which is considered good (71% in 2015). Following presentations to staff, the analysed results will be presented to Council in March 2022 with associated work plans to tackle key issues arising.

Following a recommendation from the 2020 Regular Review report, a change to the Staff Rules to introduce unemployment benefits and a re-installation grant for Fellows, was approved by Council in December. Other changes to the Staff Rules were adopted so as to update texts concerning the application of the differential cost of living mechanism for International Staff Members in Chile. Internally, a policy on the handling of restructuring when more than two departments are concerned was approved by the Director General.

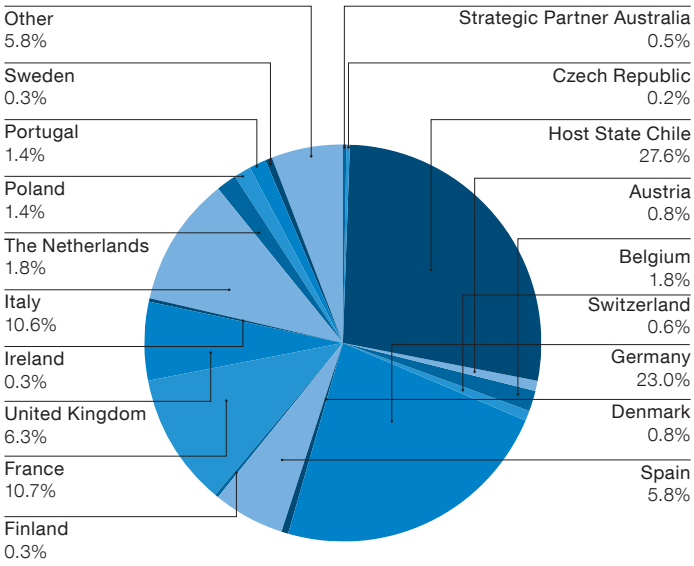
A proposal to allow the spouses of International Staff Members to work in Chile without losing their visa status, similar to the conditions accorded to other recognised international organisations, was presented to the Government of Chile early in 2021. The updated Regulations for Local Staff Members presented to the Government of Chile in 2020 are also still under consideration.

Within the framework of the Memorandum of Understanding signed in 2020 with UN Women in Chile, in the second half of 2021 ESO worked on an initiative under the UN's Second Chance programme to provide technical training to selected female applicants, to help increase the supply of future female candidates for upcoming ELT-related roles in the north of Chile. A number of female staff have also been participating in a mentoring programme for female engineering students at universities in the area.

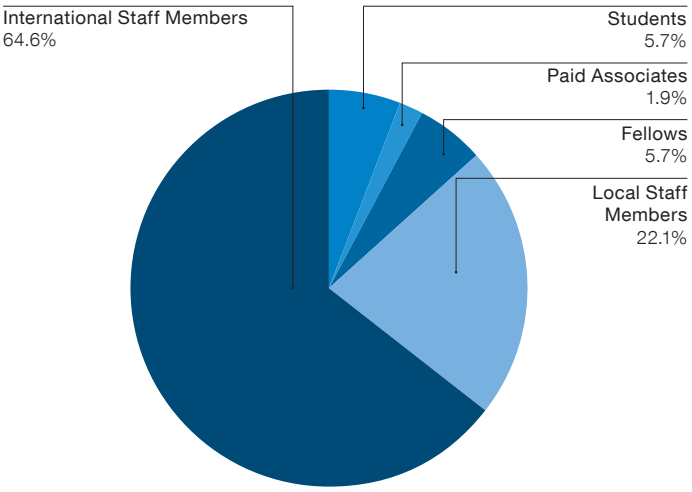
Finally, in 2021 the HR Department was reorganised to group HR Operations under a newly created Deputy Head of HR post located In Vitacura, and HR Business Partnering activities, which includes employee relations, policy and expert support, under the management of the Head of HR In Garching. An important idea and ethos underpinning the change was HR One, meaning one department covering both duty stations, to focus the approach on morale, teamwork and service consistency.

Learning, Development and Support

The focus of training activities and delivery in 2021 was on performance management, with additional ongoing work on remote management and teamworking, and support for scientific staff, mostly delivered fully online. In July a small focused survey on staff experiences during the pandemic prompted staff support services to be reinforced, including special workshops to help the return to the workplace, a health and wellbeing event in October in Garching, and increased services and offerings from the confidential Employee Assistance Service in Germany and Chile.



Distribution of International Staff Members and Local Staff Members by nationality (December 2021).



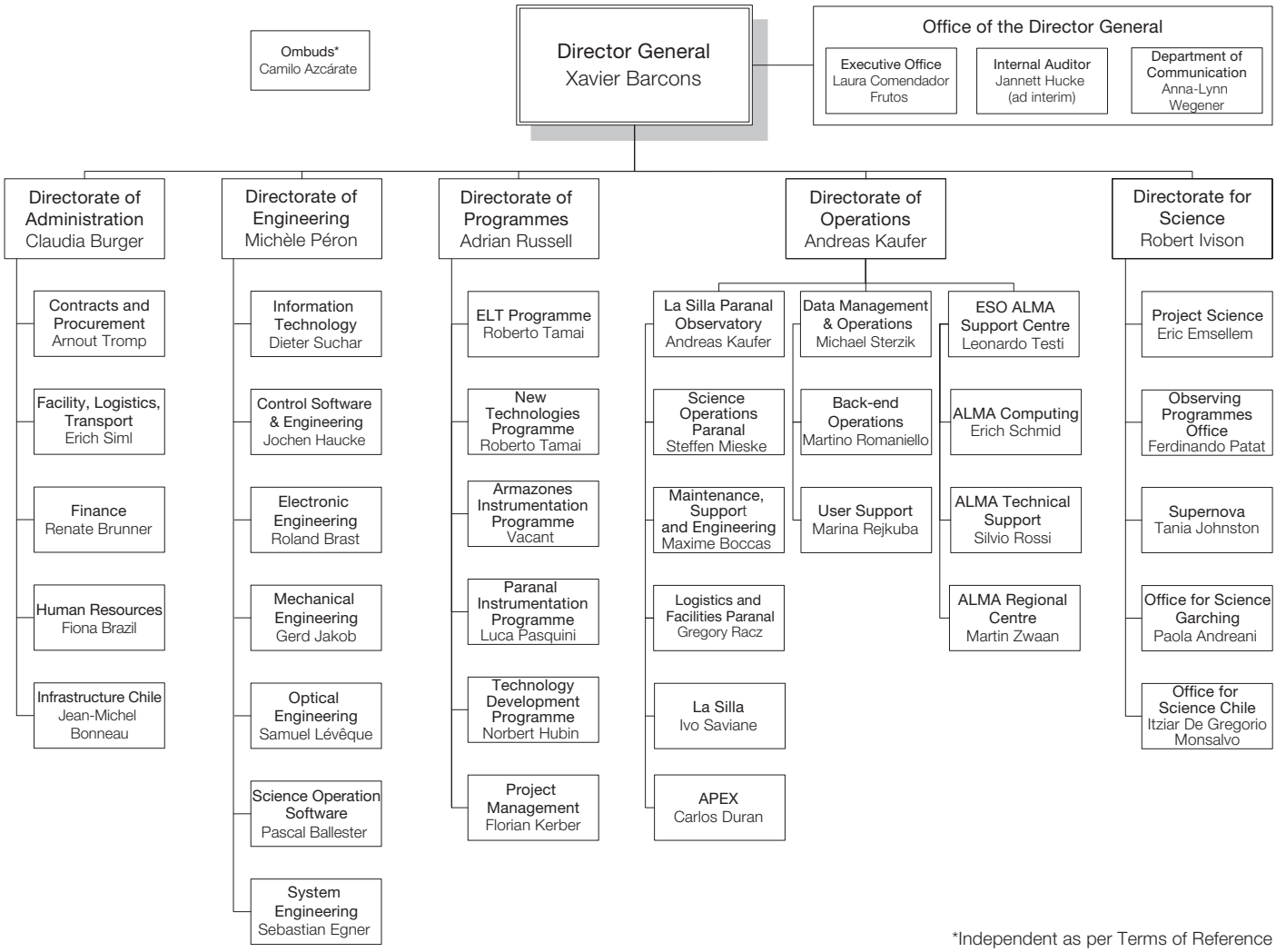
Distribution of ESO personnel by staff category (December 2021).

Twilight bathes the Chajnantor plateau in a fiery red glow. The skyline is dominated by the Purico complex of volcanic peaks. APEX (the Atacama Pathfinder EXperiment) is visible on the left.

ESP/Y. Beletsky (LCO)

Organigram

Organisational Structure December 2021

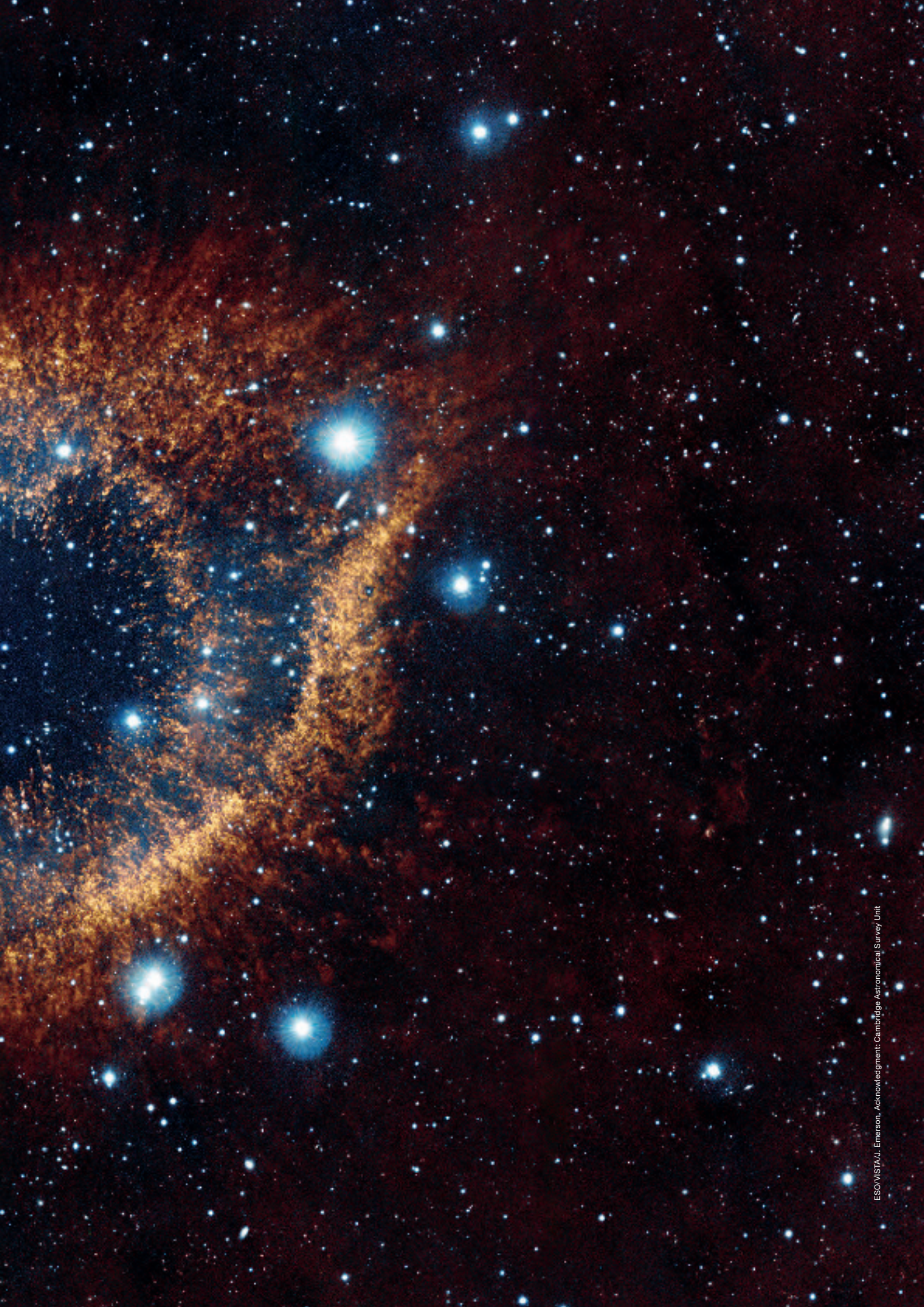


*Independent as per Terms of Reference

La Silla, ESO's first observatory site. In the foreground is the Danish 1.54-metre telescope, one of the hosted telescopes on the site. Dim lights that mark the road look brighter in this extended exposure.

ESO/P. Horálek

An infrared view of the Helix Nebula, a planetary nebula located 700 light-years away, captured by ESO's Visible and Infrared Survey Telescope for Astronomy (VISTA) at Paranal.



ESO/VISTA/J. Emerson. Acknowledgment: Cambridge Astronomical Survey Unit

Office of the Director General

An Auxiliary Telescope of the Very Large Telescope Interferometer at Paranal, under the band of the Milky Way. In the sky on the right are Canopus, the brightest star in this image, and the Large and Small Magellanic Clouds.

ESO/P. Horálek

The Office of the Director General (ODG) has three departments.

The Executive Office (ODG-X) supports ESO's governance and facilitates collaboration with key scientific and governmental stakeholders in areas including Legal and Institutional Affairs, Corporate Policies and Risk Management, and Representation in Chile.

The Department of Communication is responsible for ESO's external communication with a broad range of audiences from the astronomy community, through decision-makers and industry, to journalists and the public. It is also in charge of the internal communication of matters of general interest to the organisation.

Internal Audit (ODG-A) evaluates processes for risk management, control and governance, and provides independent, objective assurance and consulting to support ESO's operations and objectives.

Prevention and Safety are also included in the ODG section of the Annual Report as the Director General has overall responsibility for safety at ESO, and chairs the Safety Commission, which is composed of representatives from all areas and sites.

ESO/G. Beccari

The star cluster NGC 3572 and its spectacular surroundings, captured by the Wide Field Imager on the MPG/ESO 2.2-metre telescope at ESO's La Silla Observatory.

Legal and Institutional Affairs

Legal Affairs

The major focus for the Office of Legal and Institutional Affairs in 2021 was on the design of the legal framework of two projects ESO is involved in together with external partners. The APEX (Atacama Pathfinder EXperiment) Agreement in its current form will come to an end on 31 December 2022 and both the close-out agreement with the current partners, the Onsala Space Observatory and the Max Planck Institute for Radio Astronomy (MPIfR), and the new agreement between ESO and MPIfR for the continued operation of APEX in the years 2023 to 2025 had to be prepared and agreed.

In the Cherenkov Telescope Array (CTA) project, work concluded on the preparation of the second step of the application to the European Commission for the establishment of the CTA Observatory (CTAO) European Research Infrastructure Consortium (ERIC) with the approval of the ERIC statutes by the CTA Board of Government Representatives. This followed an extensive reconfiguration exercise which led to an affordable yet scientifically competitive configuration for the CTA.

At its December 2021 meeting the ESO Council approved the two APEX agreements and authorised the Director General to (co-)sign the formal request to the European Commission for the establishment of the CTAO ERIC, putting ESO's future involvement in both APEX and CTA — the latter subject to the decision of the European Commission — on a firm footing.

Despite the obstacles caused by the pandemic, regular legal support was provided continuously, both in Chile and in Garching.

International Relations

Whilst COVID-19 prevented much of the usual official engagement and visits from diplomatic and government representatives, ODG-X's work supporting ESO's Member States did not cease. ODG-X staff supported several Member States conducting formal evaluations of their involvement in ESO and maintained close contacts with Member State representatives. Despite the pandemic restrictions, ODG-X and the Director General hosted several high-level visits, both virtual and in-person:

– On 26 April the Deputy Director for UK Research Infrastructures, James Parrington, and other UK representatives took part in a virtual tour of Paranal to highlight the UK's involvement in ESO.
– On 28 July the Chilean Minister of Science, Technology, Knowledge and Innovation, Andrés Couve, visited — under COVID-19 safety measures — Armazones and Paranal, marking the first official visit to sites since the beginning of the pandemic in March 2020.
– On 21 September the Director General presented in Vienna at the workshop "Austria and the ELT" at the Observatory of the University of Vienna, arranged by the Austrian Academy of Science.

A long-exposure photograph captures star trails over La Silla.

Zdeněk Bardon (bardon.cz)/ESO

A waterless riverbed in the Atacama Desert near Paranal contrasts with the “river” of the Milky Way in the night sky above.

P. Horálek/ESO

– On 18 November the Bavarian Minister of State for Science and Arts, Bernd Sibler, visited ESO Headquarters.

ODG-X represented ESO at meetings of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) in February, April and August, and supported activities related to the International Asteroid Warning Network and the Space Missions Planning Advisory Group. ESO took a leading role in Europe in responding to the issue of the impact of satellite constellations on astronomy. In addition to providing technical and policy expertise to several national working groups studying the issue, ODG-X staff supported engagement with ESO Member State representatives to ensure that the topic of dark and quiet skies was adequately addressed at COPUOS, including the presentation of a Conference Room Paper (CRP) on Recommendations to Keep Dark and Quiet Skies for Science and Society led by the International Astronomical Union (IAU). The CRP made recommendations for the protection of optical and radio astronomical observatories and for mitigating the impacts of satellite constellations. ESO also supported the IAU together with the UN Office of Outer Space Affairs and other observatories in hosting the Dark and Quiet Skies for Science and Society Conference in October and producing a formal Working Paper to be presented to COPUOS in 2022.

ODG-X staff and the Director for Science participated in ASTRONET, a strategic coordination mechanism preparing to develop the next European Science Vision and Infrastructure Roadmap for Astronomy. ESO is also an observer on the Astroparticle Physics European Consortium and continued to monitor developments. ESO staff participated in the International Conference on Research Infrastructures, held virtually in June, at which the Director General gave a presentation.

ODG-X staff also supported the May biannual EIROforum (European Intergovernmental Research Organisation forum) DG Assembly, which took place online on 17–18 May 2021, at which the Directors General, or equivalent, of the eight EIROforum organisations convened to discuss areas of shared interest and common challenges. Also in attendance was Jean-Eric Paquet, Director General of Research and Innovation in the European Commission. The assembly highlighted the essential role of EIROforum in European science and emphasised the responses of major facilities to the challenges posed by COVID-19. A further EIROforum DG Assembly took place on 15–16 November.

Several developments were made in ESO’s relations with the European Union (EU). ESO continued its participation in the ATTRACT consortium, which was successful in securing a further 35 million euros from Horizon 2020 to continue the project in 2021 and guide the development of the most promising projects from Phase 1. ESO continued participation in the ESCAPE project, which was awarded 16 million euros in funding from Horizon 2020 to develop solutions for the large datasets handled by the European Strategy Forum on Research Infrastructures (ESFRI) facilities, and also joined the AtLAST (Atacama Large Aperture Submillimetre Telescope) consortium, which was awarded 3.6 million euros for a research infrastructure design. ESO also joined the combined OPTICON-RadioNet Pilot project, which is a merger of the separate optical and radio strands after almost two decades of funding from the EU Framework Programmes. ESO participated as observer at the Physical Sciences and Engineering Working Group of ESFRI and supported the development of a landscape analysis of European research infrastructures in the domain, which appeared in the ESFRI Roadmap document released in December 2021. ESO’s ELT (Extremely Large Telescope) is represented on the roadmap as landmark research infrastructure of strategic importance to Europe.

Corporate Policies and Risks Management

The work of the Corporate Policies and Risks Manager focused on the implementation of ESO's Personal Data Protection Policy in 2021. Besides the pandemic-related data collection and processing, ESO's standard processes also required attention from a data protection point of view.

The Directors Team updated the Corporate Risk Register on a regular basis, still focusing on the potential impact of the pandemic on the corporate matters of the organisation, in particular the financial impact.

In the area of corporate policies, the draft Anti-Fraud Policy and the draft Fraud Investigation Procedure were launched into the internal approval process, which starts with consultations with the International Staff Association. Further consultations will follow with the Local Staff Representatives in 2022.

In the area of intellectual property and technology transfer, as in 2021 there were no developments worth reporting.

The quartet of galaxies known as Hickson Compact Group 86, observed with ESO's VLT Survey Telescope (VST).

ESO/Ragusa, Spavone et al.

Representation in Chile

Luis Chavarria Garrido was appointed as the new ESO Representative in Chile on 1 October 2021.

Claudio Melo, ESO Representative in Chile, left the organisation in July 2021. During the last three years of his long and fruitful career at ESO, Claudio supported ESO's interests and promoted a very constructive relationship with Chile. From 1 June to 30 September, Jean-Michel Bonneau, ESO Deputy Director of Administration, acted as interim Representative in particularly difficult times. On 1 October 2021 Luis Chavarria Garrido was appointed as the new ESO Representative in Chile, the first Chilean national to hold this position.

Following Luis Chavarria's appointment, he and the Director General held discussions with Andrés Couve, Minister of Science, Technology, Knowledge and Innovation, and Undersecretary Carolina Valdivia from the Ministry of Foreign Affairs. The main topics discussed with Minister Couve were progress on the new light pollution regulation to protect the Chilean skies against the growing issue of light pollution close to the observatories, and the creation of a Ministerial Astronomy Advisory Council, which will advise Minister Couve on the mid- and long-term strategies needed to strengthen the impact of astronomy in Chilean society. The main topic of the meeting with Undersecretary Valdivia was to reaffirm the good collaborative relations between the institutions and to continue with the drive to generate initiatives that maximise the benefits and impact of ESO's work in Chile.

The ESO-Chile Agreement for Scientific and Technological Collaboration in the Construction and Operation of the ELT was signed in December 2021. This milestone in the collaboration between Chile and ESO will bring together ESO staff and young Chilean engineers to work on technological aspects of the development of the ELT and the VLT (Very Large Telescope). The agreement expresses the parties' mutual motivation to learn, develop and incorporate aspects related to Industry 4.0 — the application of artificial intelligence to monitoring of systems and hardware — at ESO sites in Chile.

On 30 January 2020 ESO and UN Women signed a Memorandum of Understanding at ESO's Vitacura Office, under which ESO stresses its commitment to advancing gender equality, diversity and inclusion. In that context, in the course of 2021 ESO took part in the UN Women's Second Chance programme (Tu Oportunidad) in Chile. This programme trained seven women in key astronomical technical skills, which will allow them to expand their job opportunities and gain the skills needed to work in top astronomical observatories. The process envisages hiring one of the trainees for a position at Paranal Observatory.

The ESO–Government of Chile Joint Committee issued its first call for proposals for regional funds, with the aim of financing projects in the Coquimbo and Antofagasta regions. These funds will foster the role of astronomy as a development tool for communities in both regions, where all ESO's observatories are located. The funds will finance projects that use astronomy as a tool to address challenges related to sustainable development, including proofs of concept, feasibility studies, and educational, social and outreach projects, amongst other things. A total amount of 165 000 euros was allocated for the 2021 call. In the coming years, this fund will reach up to 230 000 euros per year. The funds will be distributed in the regions based on a calculation of ESO's investment in each locality; from 2022, 70% of the funds will go to the Antofagasta Region and 30% to Coquimbo.

Among the broader events that took place during 2021 in Chile were a second and a third wave of COVID-19 infections which led to the introduction of measures to prevent and reduce infections. The vaccination scheme started in March and by the end of 2021 almost 90% of the total population had had at least one dose and 60% of the population a third dose. This allowed mobility restrictions to be relaxed, helping to return, little by little, to operations at the observatories at a capacity close to that before the pandemic.

A process was held in May to elect the Constituent Convention whose mission will be to draft a new Constitution for Chile, as expressed by the citizens in the National Plebiscite of 25 October 2020. The process to write the document proceeds according to the stipulated deadlines and the new proposed constitution will be approved or rejected in a plebiscite during 2022. In addition, presidential elections were held during December; President Sebastian Piñera will hand over his post to Mr. Gabriel Boric in March 2022.

The signature of the ESO-Chile Agreement for Scientific and Technological Collaboration in the Construction and Operation of the ELT, in December 2021.

Communication

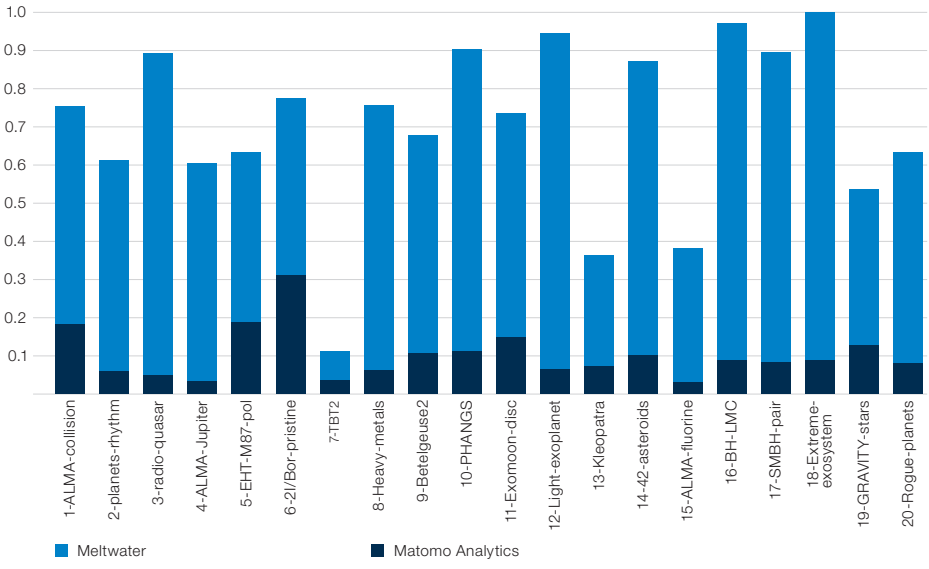
ESO's communication activities in 2021 were shaped by a combination of short-term adjustments to pandemic conditions and long-term planning to gear up for the future. The Department of Communication developed and launched new formats to engage audiences, inspire them about astronomy and help them to feel connected to the organisation during the pandemic. In parallel, the department finalised ESO's new communications strategy for the next five years.

ESO communication strategy 2022–2027

The ESO communication strategy 2022–2027 outlines directions, objectives and guiding principles for the next five years. The new strategy aims at building long-term engagement with key audiences in the ESO Member States and Strategic Partners as well as host country Chile and raising ESO's visibility as a reliable partner that enables astronomers worldwide to answer exciting questions about the Universe. Amongst the communication objectives for the next five years are: raising ESO's profile with decision-makers, scientists and the public; sharing the science, engineering and technology enabled and developed by ESO; informing and inspiring lay audiences; highlighting ESO's impact on society; and promoting the visibility of the ELT. To implement the new strategy the Department of Communication is pursuing a two-fold approach of developing new strategic projects and redirecting and aligning many of its well established and successful initiatives with the new strategy.

Visual identity revamp

Hand in hand with the new strategy the Department of Communication delivered a revamped visual identity for ESO, which gives the organisation a more consistent, approachable and memorable look and feel and reflects the guiding principles of the new communication strategy. The visual identity defines elements such as logos, colours, fonts, graphical elements, layout, and an infographic and photography style and it will gradually be applied to ESO's portfolio of communication products and channels.



Relative popularity of the 20 ESO press releases in 2021, normalised to the most popular release. Matomo Analytics measures the number of visitors to the English-language news release webpage at www.eso.org. Meltwater is an electronic press clippings service that measures the number of online newspaper articles mentioning ESO published about a particular news release. Meltwater counts have been scaled by a factor of 100 to better match the range of Matomo Analytics.

New social media strategy

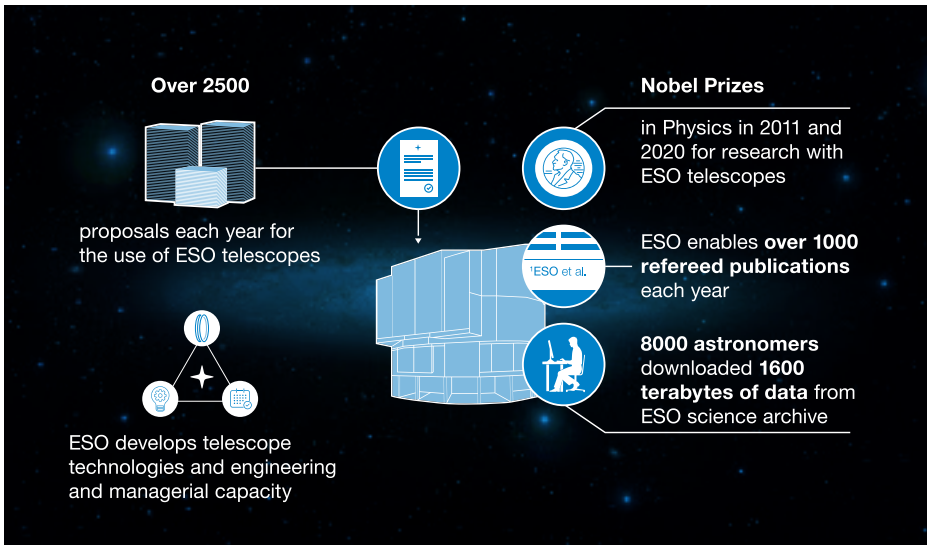
ESO's new social media strategy is aimed at building more engagement with key audiences, pursuing distinct objectives with audience groups across different channels. 2021 saw the implementation of new social media formats and an increased level of engagement with followers. In 2021 ESO's social media channels had 17.2 million impressions and reached 113 million people. Twitter was the fastest-growing channel (+18% in English, +17% in Spanish), while Instagram ranked second (+10%). On YouTube we earned 14.8 million views. Engagement rates in the second half of the year were well above benchmarks — by a factor of 10 or more.

Communicating ESO's impact on society in Member States and Chile

In early 2021 the Department of Communication ran multi-channel campaigns to raise awareness of ESO's impact on society in the areas of science and engineering, economy and innovation, talent development, education and outreach and international collaboration and policy. Central to the campaigns were a report summarising ESO's societal benefits for the Member States, as identified by an extensive study in 2020, and Astronomy and Society, a summary of the cooperation between ESO and Chile. The Twitter and Facebook accounts reached almost 10 million people. In addition, ESO representatives presented the main messages at a number of conferences and events, including the International Conference on Research Infrastructures (ICRI), the annual meeting of the European Astronomical Society and the IAU conference Communicating Astronomy to the Public.

New ELT website

To raise awareness of the ELT as ESO's telescope of the future, and to inform diverse audiences about progress with its construction, its leading technology and the way it will shape astronomy research in future, a new ELT website was launched early in 2021. elt.eso.org, a one-stop-shop of information about the ELT for a variety of audiences, saw over 80 000 visits in its first year.



Infographics communicate the impact ESO has on society in different areas in a dedicated social media campaign.

Virtual tours of ESO's observatory sites

In 2020 ESO launched virtual guided tours of its observatory sites for public audiences. Initially driven by restrictions imposed by the pandemic, these virtual tours have become a regular outreach format and in 2021 were complemented by special virtual educational tours for school classes. Since their launch in September 2021, initially exclusively in Spanish, over 90 guided tours took place for teachers and pupils of Chilean schools.

In addition to these new and strategic projects, the Department of Communication continued its well established and successful initiatives, within the limitations imposed by the pandemic.

Activity in the media

ESO issued 20 press releases, 22 announcements and 27 blog posts in 2021. As a result, ESO was mentioned in close to 21 000 news reports around the world, which makes an average of around 57 mentions in the media each day. ESO's social media channels saw greatly increased engagement following the new social media strategy, as described above.

Exhibitions and events

Owing to the pandemic, meetings and exhibitions again adopted virtual formats in 2021. ESO took part in the virtual exhibition of the European Astronomical Society Annual Meeting and the ICRI.

Communication in Chile

As visitor tours to ESO's observatory sites remained suspended in 2021, ESO's Communication Chile team focused its efforts on virtual public and educational tours, running 296 of these digital events in total and engaging several thousand people with ESO, many of whom might not have been reached by traditional in-person formats.

ESO participated in the National Week of Science in Chile and the first National Congress of Astronomy Education, which both took place as virtual events, and also contributed to the programme offered by the Chilean pavilion at the Dubai EXPO 2021–2022. The highlight in-person event supported by the Communication Chile team was the signing ceremony of the ELT collaboration agreement at ESO's Vitacura premises on 15 December in the presence of Chilean Minister of Science, Technology, Knowledge and Innovation Andrés Couve and other distinguished guests and journalists.

Internal Communication

Keeping ESO staff informed, safe and connected in pandemic times was the main driver for the Internal Communication team in 2021. Making use of digital communication formats, the team kept ESO staff informed about the evolving pandemic as ESO's response measures were continuously adjusted. Apart from regular all-staff assemblies featuring updates from the Director General, these included three sessions of a revamped overview event, called ESO Perspectives, discussing topics such as the organisation's resilience, societal impact and future direction.

Creative Team

In addition to producing ESO's most visible print products, the Annual Report and the quarterly journal The Messenger, and ESO merchandise, the team also produced a large variety of graphics, video formats and animations in support of ESO press releases, announcements and social media campaigns.

Web support

As well as providing regular support and maintenance to all websites hosted by ESO's Department of Communication, including those of the ESO Supernova and the IAU, the Web Team ran a web content audit of eso.org.

Internal Audit

From left to right: ESO Internal Auditor Jannett Hucke; External Auditors Pauliina Taavitsainen, Pontus Londen, and Jonna Carlson (National Audit Office of Finland).

The objectives and scope of the work of ODG-A are to evaluate whether processes for risk management, control and governance are adequate and functioning sufficiently well to achieve ESO's objectives. In 2021 an audit of Safety Governance and an audit of the allocation of observing time via the Director's Discretionary Time channel were concluded. A fraud risk assessment and some fraud related checks in the Enterprise Resource Planning system were also carried out. Additionally, seven certificates were issued, three consultancies performed, and one investigation of alleged wrongdoing conducted.

ODG-A is also in charge of coordinating the work of ESO's external auditors, which entails maintaining regular contact with the external auditors to coordinate audit work and avoid overlap in coverage. ODG-A provides copies of internal audit reports to the external auditor. It also maintains regular contact with other units of ESO, such as Corporate Policies and Risk Management, and Legal and Institutional Affairs.

Prevention and Safety

In 2021 work activities in Safety were once again dominated by the COVID-19 pandemic situation, and ESO Safety Engineers were part of the ESO Emergency Team. They were also involved in the Gate Reviews for the different sites to define safety requirements according to the situation.

The need to deal with the prolonged pandemic situation required a significant update of the Safety Standards for COVID-19 prevention. For the operational sites new guidelines had to be established for the staged re-opening of operational activities to achieve the primary goal of keeping all staff and contractors safe and preventing the spread of infection. The main challenges were maintaining requirements for distancing on site during shifts and also practical issues such as ensuring a sufficient stock of masks etc. In addition to measures to minimise the risk of contact infection, air purifiers were installed at all sites in meeting rooms, the cafeterias and some open-plan offices. To comply with local regulations in Bavaria at the end of 2021 that allowed only vaccinated, recovered or negatively tested staff in the workplace, access to Headquarters was limited accordingly. Apart from that the team was able to implement a tailored risk assessment process for operations and started training sessions.

Special focus this year was on the three mirror coatings undertaken at La Silla and Paranal. Safety was present during the preparation and also involved during the coating activities to support the teams in the field.

ESO Safety continued to support the ELT project in 2021. While support activities at Armazones were limited, many activities at the ELT Technical Facility had to be planned and reviewed.

ESO actively participated in the ALMA (Atacama Large Millimeter/submillimeter Array) Safety Advisory Group (ASAG) to review measures that allowed staff to work safely under the pandemic conditions on the sites. ASAG advises the ALMA Director and the ALMA Director's Council on prevention and safety, security and environment-related issues and improvements.

The incident and accident figures for all sites in 2021 are very small, largely owing to the fact that only a limited number of staff were allowed on the sites.

G. Hüdepohl (atacamaphoto.com)/ESO

In this photograph from the enclosure of the Visible and Infrared Survey Telescope for Astronomy (VISTA), ESO's VLT can also be seen on the adjacent peak of Paranal.

The Orion Nebula star-formation region, seen with the HAWK-I infrared camera on the VLT.

ESO/H. Drass et al.

Organisational Matters

The spectacular spiral galaxy NGC 1964, observed with the Wide Field Imager on the MPG/ESO 2.2-metre telescope at ESO's La Silla Observatory.

ESO/Jean-Christophe Lambry

Council

As its main governing body, the ESO Council determines the Organisation's policies in regard to scientific, technical and administrative matters. Both Council and the Committee of Council — the informal body of Council — normally meet twice a year. However, in 2021 an extraordinary Council meeting was required and this took place in tandem with the Committee of Council meeting in September. Owing to the COVID-19 situation, the Committee of Council meeting on 3–4 March and the Council meeting on 8–9 June were held via video-conferencing. The Committee of Council meeting on 27–28 September and the Council on 7–8 December took place in hybrid mode. All meetings were chaired by the Council President, Linda Tacconi.

At the June meeting, the Council President and the ESO Director General provided an update on a range of ongoing events and actions on all aspects of ESO's programme. As presented by the external auditors, the Financial Statements for 2020 and the External Audit Report 2020 were approved, with discharge being granted to the Director General. A presentation on the status of the CERN Pension Fund was provided by the ESO Council appointee to the fund's Governing Board. Council also approved the ESO Annual Report and the Scale of Contributions for 2022.

At the September meeting, the ESO Values document was approved, in which ESO describes what the organisation believes in and how ESO and the people working at ESO behave to achieve ESO's goals.

The December Council meeting included the regular programme updates and committee reports, as well as a presentation from the Chair of the ELT (Extremely Large Telescope) Management Advisory Committee. In this meeting, Council authorised the Director General to sign the submission of the second step of the European Research Infrastructure Consortium (ERIC) application to the European Commission for ESO to become a founding member of the CTA (Cherenkov Telescope Array) ERIC. In written procedure, Council had already authorised ESO to confirm the favourable vote to the updated CTA Cost Book in CTA Council. The Director General was also authorised to sign an agreement with the Max Planck Institute for Radio Astronomy for the extension of APEX (the Atacama Pathfinder EXperiment) from 2023 to 2025, such that it will be cost-neutral to ESO and there will be no further calls for proposals to the ESO community in that period. Council also approved a policy that regulates the granting to consortia of Guaranteed Time Observations on the ESO share of ALMA (the Atacama Large Millimeter/submillimeter Array) in return for additional contributions to ALMA Development Projects. The Director General was further authorised to sign agreements for the construction and delivery of the instruments GRAVITY+ and CUBES (the Cassegrain *U*-Band Efficient Spectrograph) for the VLT/I (Very Large Telescope/Interferometer) and for the construction and delivery of the ELT instruments HIRES (the High REsolution Spectrograph, renamed ANDES in early 2022) and MOSAIC (the Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology). Council also approved a scheme for the Member States to provide in-kind contributions via the temporary secondment of specialist staff from Member State institutions to work on the ELT. Council also authorised the Director General to sign an Amendment to the Australian-ESO Partnership Arrangement which will further strengthen the partnership by allowing Australia to participate in ESO's Technology Development Programme. Council approved the budget for 2022 and several amendments to the Staff Rules and Regulations, including updates of the unemployment benefits and relocation allowances for Fellows. Council also received a report on ESO's science priorities as approved by the Scientific Technical Committee (STC) and on the statistics of telescope time distribution at the La Silla Paranal Observatory (LPO) and ALMA. Elections were held for the appointment of personnel to the various ESO Committees. Delegates also took the opportunity to meet with their national staff members.

Council and Committee of Council 2021

President	Linda Tacconi
Austria	João Alves Daniel Weselka (Vice President)
Belgium	Sophie Pireaux Christoffel Waelkens (until February 2021) Emmanuël Jehin (from February 2021)
Czech Republic	Jan Buriánek Soňa Ehlerová
Denmark	Allan Hornstrup René Michelsen
Finland	Anna Kalliomäki Seppo Mattila
France	Guy Perrin Laurent Vigroux
Germany	Matthias Steinmetz Martin Thomé
Ireland	Joseph Moore Tom Ray
Italy	Vincenzo Fiorentini Marco Tavani
The Netherlands	Amina Helmi Patricia Vogel
Poland	Dariusz Drewniak Marek Sarna
Portugal	Ricardo Conde Paulo Garcia
Spain	Rafael Bachiller Inmaculada Figueroa
Sweden	Sofia Feltzing Camilla Jakobsson
Switzerland	Xavier Reymond (January 2021) Martin Steinacher (February–September 2021) Xavier Reymond (from November 2021) Stéphane Udry
United Kingdom	Isobel Hook Colin Vincent

Observers

Australia	Matthew Colless Janean Richards

Finance Committee

The ESO Finance Committee has overall responsibility for advising Council on all matters of administrative and financial management. Owing to the COVID-19 restrictions, the ordinary meeting in May and the extraordinary meeting in September were held by video conference and the ordinary meeting in November in hybrid mode with some participants travelling to Garching and others attending online.

In 2021 the Finance Committee approved ten contracts exceeding 500 000 euros, eight amendments to existing contracts and six single-source procurements exceeding 250 000 euros for the construction of the ELT, for ESO's programmes and instruments and for site logistics.

The Finance Committee delegates recommended that Council approve, amongst other things, the Financial Statements, the Scale of Contributions, the Budget for 2022 and some personnel-related matters, as well as an in-kind contribution scheme to provide staff support for the ELT. They also received updated information on the ELT Project, the Paranal Instrumentation Programme, the CERN Pension Fund and procurement statistics.

At the meeting in November, the delegates had the opportunity to meet ESO staff from their respective nationalities for informal discussions.

Finance Committee 2021

Chair	Sirpa Nummila
Austria	Sabine Hertgen (until November 2021) Daniel Weselka (as of November 2021)
Belgium	Alain Heynen
Czech Republic	Pavel Křeček
Denmark	René Michelsen
Finland	Peter Salo
France	Guilhem de Robillard
Germany	Harald Haakh
Ireland	Oisín McManus (until September 2021) Peter Healy (as of September 2021)
Italy	Salvatore Vizzini (Vice-Chair)
The Netherlands	Ellen Ipenburg-Tomesen
Poland	Dariusz Drewniak
Portugal	Filipa Batista Coelho
Spain	José Juan Sánchez Serrano
Sweden	Katrin Brandt
Switzerland	Astrid Vassella
United Kingdom	Chris Woolford
Observer	
Australia	Janean Richards (until February 2021) Robert Hanlon (as of February 2021)

SPECULOOS Team/E. Jehin/ESO

The well-known Horsehead Nebula, as seen by the Callisto telescope of the SPECULOOS Southern Observatory, hosted by ESO at Paranal.

Scientific Technical Committee

The STC advises Council and the Director General on the scientific and technical priorities for ESO's projects and programmes. It comprises one member from each Member State and from Chile, plus up to six members-at-large who may be from non-member states. The composition of the STC aims to adequately cover the relevant astronomical disciplines and techniques.

The two customary biannual meetings of the STC and its subcommittees — the ALMA European Science Advisory Committee (ESAC), the La Silla Paranal subcommittee (LSP), and the ELT SubCommittee (ESC) — were conducted by video-conference owing to the restrictions imposed by the COVID-19 pandemic. Both STC meetings were chaired by Paul Callanan (University College Cork, Ireland).

98th STC meeting

The 98th meeting took place on 29 and 30 April 2021. It opened with a review of recent organisational developments and an update on the ESO programme by the Director General, with an emphasis on the impact of the pandemic. There were reports on the ELT by the Project Manager, Roberto Tamai, and updates on its HIRES and MOSAIC instruments by the Project Scientist, Michele Cirasuolo. The ELT section closed with a summary of the ESC meeting by its chair, Vanessa Hill.

La Silla Paranal was introduced by the Director of Operations, Andreas Kaufer, who detailed the measures taken over previous months to resume operations. He also discussed the proposal by the Italian National Institute of Astrophysics (INAF) to continue operation of the VST (VLT Survey Telescope) as a hosted telescope following the end of the present agreements. The Paranal Instrumentation Programme Manager, Luca Pasquini, gave a progress report, highlighting the commissioning of CRIRES$^+$ (the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph) and the upgrade of IRLOS (the InfraRed Low Order Sensor). A proposal for a new hosted telescope was presented by the VLT Programme Scientist, Bruno Leibundgut, who discussed its scientific and operational implications.

This section ended with a report on the LSP subcommittee by its chair, Hugues Sana.

A report on recent developments concerning satellite constellations was presented by the End-to-End Operations Scientist, Olivier Hainaut, and the External Relations Officer, Andrew Williams. Regulatory initiatives proposed by international organisations, including ESO, were discussed.

ALMA news opened with a presentation by Leonardo Testi on behalf of the ESO ALMA Support Centre describing the work on advanced data products and the implementation of the ALMA development plan. The ALMA Regional Centre (ARC) Manager, Martin Zwaan, focused on the preparations for the resumption of observations and other ongoing projects. The ALMA European Project Scientist, Franciska Kemper, presented recent science highlights and the European projects being carried out under the ALMA development plan. The ALMA section closed with a presentation on the outcome of the ESAC meeting by its Chair, Paul van der Werf.

The meeting ended with an open discussion that included matters such as the fellowship selection process, the selection of talks for the Hypatia Colloquium series, and the options under consideration to alleviate pressure in case the pandemic worsened.

99th STC meeting

The 99th STC meeting was held on 25–27 October. The overview by the Director General covered the entire programme, highlighting the ramp-up of activity to recover from the impact of the pandemic, and progress with previous STC recommendations was discussed. The Head of Finance, Renate Brunner, provided an overview of the 2022 budget, followed by a presentation by the Head of Systems Engineering, Sebastian Egner, on ESO's engineering standards strategy.

A report on the ELT was presented by the Project Manager, covering construction progress, status of major contracts, procurements, design activities, major deliveries and schedule. The ELT Project Scientist presented the options concerning the development of HIRES and MOSAIC and their impact on the guaranteed time. The ELT section concluded with the ESC Chair's report.

The Director of Operations reported on the ramp-up to full operations at La Silla Paranal, recent achievements, and ongoing

The Scientific Technical Committee 2021

Chair	Denis Mourard (STC 98) Paul Callanan (STC 99)
Austria	Stefan Kimeswenger
Belgium	Hugues Sana (LSP Chair, STC 99)
Czech Republic	Pavel Jáchym (ESAC, STC 98) Dušan Mandát (STC 99)
Denmark	Marianne Vestergaard
Finland	Talvikki Hovatta (ESAC Chair, STC 99)
France	Vanessa Hill (ESC Chair)
Germany	Jochen Liske (ESC)
Ireland	Paul Callanan (LSP)
Italy	Marcella Marconi (LSP)
The Netherlands	Paul van der Werf (ESAC Chair, STC 98)
Poland	Grzegorz Pietrzyński (STC 98) Tomasz Kamiński (LSP, STC 99)
Portugal	Sérgio Sousa (ESC)
Spain	Javier Cenarro
Sweden	Kirsten Kraiberg Knudsen (ESAC)
Switzerland	Francesco Pepe
United Kingdom	Ross McLure
Chile	Laura M. Pérez
Observer	
Australia	Michael Ireland (LSP Chair, STC 98) Michael Murphy (STC 99)

user support and data flow projects. The scientific capabilities of GRAVITY+ were presented by its Principal Investigator, Frank Eisenhauer (Max Planck Institute for Extraterrestrial Physics). The VLTI Programme Scientist, Antoine Mérand, reported on the completed Phase A and the subsequent proposal to proceed. A presentation on science with CUBES by Stefano Cristiani (INAF) on behalf of the consortium was followed by one on the proposal for design and construction by the VLT Programme Scientist. The progress and recent achievements of other instrumentation projects were reviewed by the Head of the Paranal Instrumentation Programme. A proposal for a technology demonstrator visitor instrument was discussed, with concerns expressed about the resources required from ESO. The Head of the Observing Programmes Office, Ferdinando Patat, reported on the Special Call for Period 107 and developments concerning proposal submission, handling and scheduling. The Chair of the LSP subpanel acknowledged the significant progress made on the many instrumentation projects and the handling of the pandemic crisis.

A summary of the science priorities reviewed by a working group established in 2019 was presented by its chair, Fernando Comerón, followed by a discussion on the future of the prioritisation process. Regarding CTA-South, the Director General expressed ESO's views on the rebaselining, construction proposal, and operations plan. A review of the project and its scientific capabilities was provided by the CTA Observatory (CTAO) Project Scientist, Roberta Zanin.

The session on ALMA began with a presentation by the Head of the ESO ALMA Support Centre on the progressive return to normality, onsite operations under the remaining restrictions, and progress on the ALMA development projects. The Head of the ARC summarised recent milestones, the impact of the pandemic on Cycle 7, and the very high demand for Cycle 8. Science highlights were presented by the European ALMA Programme Scientist who also reported on the current status of the foreseen joint ALMA/VLT(I) proposals. The Director for Science, Rob Ivison, presented a proposal for European contributions to the ALMA development plan, with their compensation in guaranteed time. The session concluded with the presentation of the ESAC report by its Chair, Talvikki Hovatta, and an open discussion ended the meeting.

Y. Beletsky (LCO)/ESO

The New Technology Telescope (left) and the ESO 3.6-metre telescope (right) at La Silla.

Observing Programmes Committee

During its meetings in May and November, the Observing Programmes Committee (OPC) evaluated the proposals submitted for observations to be executed in Periods 108 (1 October 2021–31 March 2022) and 109 (1 April–30 September 2022). The numbers of proposals for observations with ESO telescopes in these two periods were 952 and 880, respectively.

The proportions of submitted proposals (excluding Large Programmes and Calibration Programmes) were 16.5%, 21.0%, 36.5% and 26.0% for A, B, C and D categories, respectively. In terms of time requested, the corresponding proportions were 20.2%, 22.1%, 32.5% and 25.2%. The OPC categories are specified in full at https://www.eso.org/sci/observing/phase1/p109/opc-categories.html

In 2021 MUSE (the Multi Unit Spectroscopic Explorer) was the VLT instrument with the largest amount of requested observing time (696 nights), followed by X-shooter with 596 nights, UVES (the Ultraviolet and Visual Echelle Spectrograph) with 362 nights and ESPRESSO (the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations) on one Unit Telescope (UT) with 316 nights. The time allocated to ESPRESSO was distributed between UT1 and UT2 in an ad-hoc way, to level out the respective telescope loads. Given the large request for MUSE and X-shooter, no ESPRESSO time was allotted to UT3 or UT4.

The demand for the interferometric instruments GRAVITY (107 nights) and MATISSE (the Multi-AperTure mid-Infrared SpectroScopic Experiment) (86 nights) remained high. A total of about 50 nights was reserved for pre-allocated VLTI slots with the four UTs. This included Guaranteed Time Observing (GTO), Large Programmes and normal programmes.

On La Silla, HARPS (the High Accuracy Radial velocity Planet Searcher) continued to be in high demand (399 nights), whilst the pressure on EFOSC2 (the ESO Faint Object Spectrograph and Camera 2) (232 nights) and SOFI (Son of ISAAC) (110 nights) was more moderate.

In 2021 twelve applications were received within the framework of the continuing agreement between ESO and ESA (the European Space Agency) for a joint telescope time allocation scheme for coordinated observations with the VLT and XMM-Newton (nine were submitted to the XMM-Newton Observing Time Allocation Committee and three to the ESO OPC). Of these, four were approved (two by XMM-Newton and two by ESO).

Target of Opportunity Programmes

In 2021 108 proposals containing Target of Opportunity runs were submitted (1025 hours). Of these, 33 were scheduled, amounting to a total of about 330 hours. FORS2 (the FOcal Reducer and low-dispersion Spectrograph 2) and X-shooter were the most requested instruments for Target of Opportunity observations, with a total of 177 hours. These two instruments were allocated 53% of the total Target of Opportunity time.

Calibration Programmes

Calibration Programmes allow users to complement the existing calibration plans for ESO instruments. They are mostly evaluated by comparing the potential of the programme to enhance the outcome of future science against the immediate return from science proposals in the current period, which are directly competing for the same resources. In 2021 four Calibration Programmes were submitted and were all recommended for implementation by the OPC.

Large Programmes

Large Programmes are projects that require a minimum of 100 hours of observing time and that have the potential to lead to a major advance or breakthrough in the relevant field of study. Large Programme execution can be spread over several observing periods with a maximum duration of four years for observations to be carried out with the La Silla telescopes, and two years on the VLT/I and on APEX.

The Observing Programmes Committee 2021

Elaine Sadler (Chair)
Linda Smith (Vice Chair P10)
Serena Viti (Vice Chair P109)

Angela Bragaglia
Jarle Brinchmann
Francisco Javier Castander (P109)
Olga Cucciati (P108)
Christina Chiappini
Emanuele Daddi
Lilia Ferrario
Alexis Finoguenov
Jochen Heidt (P109)
Emmanuel Lellouch
Phil Lucas
Livia Origlia
Tom Oosterloo
Björn Malte Schäfer (P108)
Hans Martin Schmid
Linda Smith (P108)
Aldo Serenelli (P109)
Manuela Zoccali

As of Period 104, Large Programmes are invited once per year, in even semesters. In 2021 ESO received 37 Large Programme applications including one Large GTO proposal from the ESPRESSO instrument consortium. The total request was about 670 nights.

Following the OPC recommendations, 11 Large Programmes (four in science category A, one in B, three in C and three in D) were implemented. The long-running trend of Large Programmes using a large fraction of the science time on the La Silla telescopes continued in 2021. The total allocations to new and ongoing Large Programmes in Periods 108 and 109 at the ESO 3.6-metre telescope and at the NTT (New Technology Telescope) were 183 and 96 nights, respectively. This corresponds to 59.1% and 29.8% of the available science time at these two telescopes.

Director's Discretionary Time

Proposals asking for Director's Discretionary Time (DDT) may be submitted throughout the year for programmes that are urgent and incompatible with the reg-

ular biannual proposal cycles which are reviewed by the OPC. In 2021 the ESO user community submitted 48 DDT proposals, requesting about 224 hours. After taking advice from an internal committee of ESO staff astronomers, the Director for Science, delegated by the Director General, approved 19 DDT proposals for implementation, amounting to a total of 25 hours. The DDT requests and the allocation were smaller than usual because of the simultaneous presence of the Special Call for P107. During this semester the submission of DDT proposals was limited to transient events only.

Special Call for P107

To compensate for the suspension of the Call for Proposals for P107 caused by the pandemic, and to enable the submission of projects consisting of novel and urgent observations, a Special Call was opened between 1 April and 1 September 2021. The 62 proposals submitted through this channel were reviewed by four external panels. The total request was 470 hours, of which 214 were allocated.

The star-forming region Messier 17, captured by the Wide Field Imager on the MPG/ESO 2.2-metre telescope at La Silla.

Users Committee

Y. Beletsky (LCO)/ESO

An extraordinary photograph of a total lunar eclipse setting over the VLT on 26 May 2021, captured from a location nine kilometres to the east of Paranal.

The Users Committee (UC) is an advisory body to the ESO Director General providing community feedback and recommendations related to the operation and use of the LPO and ALMA. The UC met virtually for their annual meeting on 27 and 28 April 2021, chaired by Arjen van der Wel.

The UC received updates on the science operations, the status of observatories, and operations development plans. The UC reported that the community largely supported the decision not to issue a new call for observing proposals when observatories stopped operating because of the pandemic. It recommended making public the outcome of the first ALMA Distributed Peer Review and informing users about the roadmap for the Distributed Peer Review of the LPO proposals.

The UC was interested to hear about the plans for the new ESO Data Processing System and asked ESO to explore the possibility that users might reprocess large datasets remotely in a similar way as for ALMA. The UC also recommended further enhancing the scientific use of the archive by encouraging the submission of advanced data products by users and collaborating with data centres.

A special session focused on the VLTI. Ágnes Kóspál described how a new VLTI experts group was formed at Konkoly Observatory in Hungary through connections with scientists in different institutes. Paulo Garcia outlined the history of VLTI Expertise Centres founded through the European Interferometry Initiative, highlighting their successes and challenges. The OPTICON/RadioNet Pilot funding will further expand the VLTI support infrastructure and facilitate synergies between the ARC and VLTI networks. The UC encouraged ESO to continue broadening the VLTI user community, engaging ESO Member States with less historical involvement with VLTI exploitation, and to collaborate with VLTI Expertise Centres to further enhance science with the VLTI.

The Users Committee 2021

Chair	Arjen van der Wel (Belgium)
Austria	Miguel A. Urbaneja Perez
Czech Republic	Petr Kabáth
Denmark	Lise Bech Christensen
Finland	Rubina Kotak
France	Philippe Salomé
Germany	Peter Schilke
Ireland	Rebeca Garcia López
Italy	Maria Teresa Beltran
The Netherlands	Søren Schack Larsen
Poland	Łukasz Wyrzykowski
Portugal	Nuno Peixinho
Spain	Nicolas Lodieu
Sweden	Jouni Kainulainen
Switzerland	Miroslava Dessauges (co-Chair)
United Kingdom	Danny Steeghs
Chile	Amelia Bayo
Australia	Caroline Foster

International Staff Association

The International Staff Association (ISA) had a busy year in 2021, engaging in improving working conditions for staff, in protecting the interests of staff, both collectively and individually, and supporting progress on several issues through the various committees and working groups its representatives sit on. Productive monthly meetings were also held with the Head of Human Resources (HR) and Director for Administration.

The International Staff Committee (ISC) saw elections at both sites in September 2021. With participation at 82% in Europe and 79% in Chile, these elections demonstrated once more the extremely high interest in staff representation. Three representatives were elected to the committee in Chile, and four in Garching. The ISA is very pleased that the newly installed committees consist of a mix of staff with a range of experience at ESO.

ISA statutes

A major accomplishment in 2021 was the progress made on the new statutes of the ISA. This is the culmination of almost a decade of work by many people. The existing ISA statutes date back to the 1970s and a major revision was required to adjust to current and future situations. One major change to the statutes concerns membership categories; Fellows, Students and Paid Associates will now be eligible to be Ordinary Members of the ISA, and a new category of Retired Members has been introduced. Current members of the ISA were presented with the new draft statutes in March 2021 and given the opportunity to ask questions at the General Assembly of the ISA. A first vote was held, members being invited to vote for or against 14 key points. Approximately 70% of members took part in the first round of voting and the statutes were updated accordingly. Members were then asked in May 2021 to vote for or against the new ISA statutes. There was a 75% participation rate in the second round of voting, with 95% voting in favour of the new statutes. At this stage, the statutes were presented to the Director General for review, to ensure that they are compatible with the goals and objectives of the organisation. Feedback was received in September. Owing to the elections and handover to the new committees, as well as further consultation with the retirees, it was not possible to implement the new statutes by the end of 2021, but it is planned to implement them early in 2022.

Working groups

Another large item of work for 2021 was the development of the staff engagement survey. Staff representatives formed part of the working group, coordinated by HR, that identified the list of questions to be included. The questions were largely based on the questions which had been asked in 2015, but a large section of new questions was introduced on the topic of Diversity and Inclusion. The ISC was given access to the results of the survey at the end of 2021, with a view to providing feedback early in 2022.

The Working Group on Mobile Working, which had been put on hold because of the pandemic and the corresponding need for emergency remote working, was restarted. The purpose of this working group is to review the Mobile Working Policy at ESO. Staff representatives from across the organisation are contributing to the development of a survey, with the aim of capturing the level of interest among staff, identifying potential obstacles for particular staff, and understanding potential benefits to staff and the organisation. In the second half of 2021 the working group modified the original survey, which had been created pre-pandemic, such that the questions better reflect the changed situation.

Social activities

Owing to the pandemic, in-person social activities were limited. However, the ISA continued to make efforts to support colleagues during these challenging times. Online yoga lessons, which proved popular in 2020, were provided once more in the first half of the year. In Garching, in September, once it was again compulsory for staff to be in the office, the popular ice cream van was available again, offering free ice cream and an opportunity for staff to socialise safely outside. Additionally, online virtual coffee sessions were held approximately once per month.

Zdeněk Bardon/ESO

The Carina Nebula, as seen in a photograph taken from ESO's La Silla site with a DSLR camera.

Looking up at the New Technology Telescope at La Silla.

ESO/P. Horálek

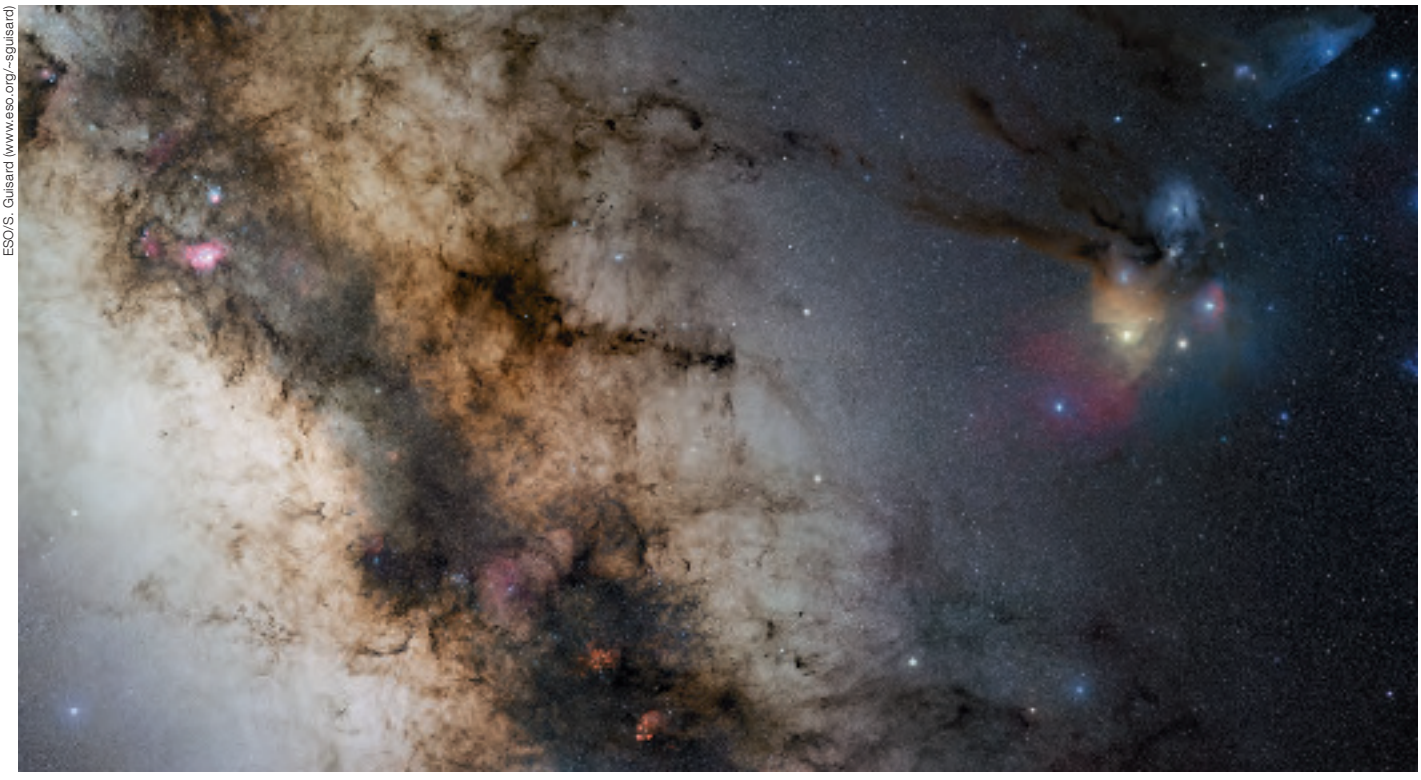
Local Staff Representatives

Local Staff Members are represented by two unions: the Sindicato del Personal Local del Observatorio La Silla – ESO and the Sindicato de Técnicos y Profesionales del Personal Local del Observatorio Paranal – ESO. Additionally, there is the Group of Non-Unionized Local Staff Members represented by one delegate. The representatives from the three groups represent their members in regular communication with the ESO Management. In December 2021, Carlos La Fuente, Marcelo Lopez, and Rodrigo Romero were re-elected as the directors of the La Silla Union, until December 2023.

With the continuing evolution of the COVID-19 pandemic during 2021, adjustments to working practices and conditions were still a matter of significant concern and necessary cooperation with all the representatives, which was fully in evidence throughout the year. Union directors and the delegates were closely involved in regular briefing meetings with the observatory management on operational and safety matters, and the Director of Administration also continued to chair weekly meetings to inform the representatives about changes to emergency measures and to seek feedback on applicable policy matters and areas of concern. The updated Regulations for Local Staff in Chile, submitted to the Chilean government at the end of 2020, were still under review by the government in 2021, as expected given the crisis conditions.

During 2021 local staff representatives participated in a number of cross-organisational working groups and activities to advance planned topics, for example the new ESO Values, the Performance Management and Personal Development implementation project group and the working group that proposed the format and content of the Staff Engagement survey and assisted with the selection of the supplier. Local staff representatives were also consulted on new policies concerning restructuring and a procedure for under-performance management.

Concerning activities connected to the Collective Contracts in place since 1 December 2019, the recommendations on health insurance coverage were implemented this year, and after a hiatus as a result of large changes and restrictions in travel possibilities in Chile, activities around adding flexibility to the commuting schemes for observatory staff have resumed.



ESO/S. Guisard (www.eso.org/~sguisard)

A dramatic wide-angle view of the central regions of our Milky Way galaxy, assembled from multiple astrophotographs taken from Cerro Paranal, demonstrates the quality of the site's night sky.

A fisheye-lens photograph taken from the entrance of the Paranal Residencia captures a unique view of the Milky Way in the night sky.

ESO/P. Horálek

Diversity and Inclusion

The Diversity and Inclusion Committee continued to meet once a month during 2021.

Some of the recommendations on diversity hiring that were finalised in 2019 were implemented in 2021. As an example, for each recruitment campaign, a diversity profile of the corresponding group and department is prepared by HR and distributed to the selection board. The purpose of this is to highlight the diversity status of the unit and identify potential improvements as another input to the recruitment process. Vacancy advertisements have also been reviewed, to make sure that the language and requirements encourage applications from diverse candidates. Even through the fraction of women in engineering jobs is still low, we have seen that our efforts to increase awareness of the importance of diversity, the attention given to the composition of selection boards and the deployment of diversity maps have all contributed to the recruitment of more female engineers than in past years.

The Diversity & Inclusion Committee prepared a number of questions related to diversity, inclusion and discrimination for inclusion in the engagement survey that ran in November 2021.

In October 2021, as part of the agreement between ESO and UN Women signed in 2020, ESO initiated a number of projects that promote gender diversity. The UN Second Chance Programme creates training opportunities for disadvantaged women in Chile who have struggled to complete their formal education. In partnership with UN Women, ESO began to train seven Chile-based women in key astronomical technical skills, such as coating large telescope mirrors, which will allow them to expand their job opportunities and gain the skills needed to work in top astronomical observatories. In addition to this, ESO's female staff are participating in a mentoring programme for female engineering students at the universities in the north of Chile. By supporting and accompanying them as role models through their professional careers, we are hoping to prepare potential female candidates for ESO positions.

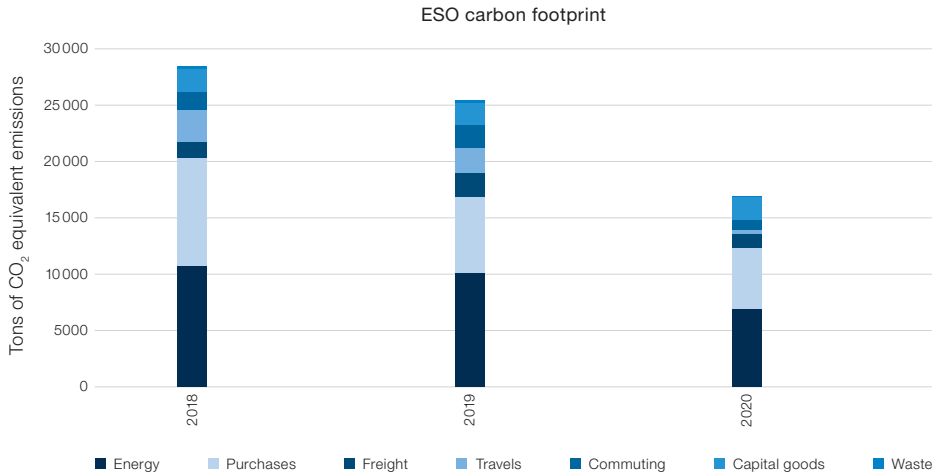
ESO has also continued its participation in international activities related to equity, diversity and inclusion.

As a member of GENERA Network (the successor to the H2020 project Gender Equality Network in the European Research Area), ESO has agreed to co-chair the management of the network for one more year. The network has been able to attract new members and has been active in the H2020 ACT project as one of the ACT Community of Practice. Members of the network are also members of at least one of the network's internal working groups, which focus on specific topics (e.g. career development, gender dimension in research, gender disaggregated statistics). The working group on career development has finalised a training module tailored to students and early career scientists which is now being reviewed by an expert panel before being rolled out. The working group on gender dimension has organised a dedicated conference on the subject, which was initially planned for the northern hemisphere autumn 2021, but owing to the pandemic it has been postponed to June 2022. It will take place at the University of Lund (Sweden).

Francesca Primas completed her term as the chairperson of the EIROforum (European Intergovernmental Research Organisation forum) ad-hoc Working Group on Diversity and Inclusiveness (AHG) and handed it over to her colleague at the European Synchrotron Research Facility. The leadership of the working group has now been aligned to the overall leadership schedule (by rotation) of the EIROforum. The main highlights of 2021 were:

– the completion of the gender disaggregated data collection, the results of which can now be compared to the results of a similar exercise that was done five years ago, for the Gender in Physics Day workshop. For both data collections, ESO was the main driver and organiser. The results have already been shared within the AHG and with the EIROforum Coordination Group. An infographic brochure is in preparation.
– the benchmarking analysis, announced last year, on policies concerning the area of impairments and disabilities has also been completed and the results shared within the AHG.
– ESO is now also represented on the AHG by an HR officer, as many discussion topics are relevant for HR policies. This is a development that is also being implemented by other EIROforum organisations.

Environment Committee



ESO carbon footprint data for 2018, 2019 and 2020, divided by category.

Sustainability is one of the five organisational ESO Values, as newly formulated last year and approved by Council: "ESO believes in the key role of sustainability for its future." For us this means, "Acting with a long-term environment, social, and economic perspective in mind. Actively pursuing the responsible management of natural, human and monetary resources."

In 2019 ESO carried out its first carbon footprint audit, which indicated total emissions for 2018 of 28.4 kT CO_2 equivalent for all ESO sites (Garching, Santiago and the LPO), including upstream activities (e.g. purchases, commuting). The main sources of CO_2 emission were energy (~ 38%), purchases (~ 34%) and transport (~ 21% for freight, professional travels and commuting).

Recently, the carbon footprint data were collected and updated for the years 2019 and 2020. For 2019 a reduction on the total CO_2 equivalent emissions of ~ 10% relative to 2018 can be observed, caused mainly by a reduction in purchases, energy consumption and travel, while on the other had the carbon footprint from the transport of goods and from commuting increased.

2020 was a special year as the COVID-19 pandemic started in early 2020. Most ESO staff worked in part from home and the observatories were put in safe state for almost six months from the second half of March to early September, then gradually ramping up operations again with a reduced staff complement on site. The reduced level of operations and mobility of staff is reflected in the 2020 carbon footprint figures: compared to 2019, the ESO CO_2 equivalent emissions decreased by another ~ 33% to an overall level of 16.9 kT CO_2 equivalent. Emissions caused by energy consumption decreased by ~ 30%, purchases by 20%, freight by more than 40%, travel by more than 80%.

It is expected that ESO's CO_2 emissions will increase again in the post-pandemic period as operations return to pre-pandemic levels. However, considerable efforts are being made to permanently reduce ESO's CO_2 footprint. An internal environmental sustainability project was established to define a way forward and the Environment Committee discussed proposals for the ESO Sustainability Action Plan which the Directors Team endorsed for implementation. The new measures build on the organisation's previous and ongoing environmental sustainability actions already adopted in the past. These include:

– Implementing a large 9-MW solar array serving the future Integrated Paranal Observatory in Chile, which will host the ELT and CTA-South, in addition to the existing facilities. This could save up to 1700 tonnes of CO_2 equivalent per year.

– Wherever operationally feasible, preferring sea freight over air freight for shipments of materials from Europe to Chile. This could save up to 1400 tonnes of CO_2 equivalent per year.

– Reducing business travel, especially flights, opting for virtual meetings over physical meetings whenever possible, resulting in a potential saving of up to 800 tonnes of CO_2 equivalent per year.

– Optimising the electricity consumption at ESO's Headquarters in Garching, Germany by regularly investigating and addressing sources of energy consumption, yielding a carbon footprint reduction of up to 250 tonnes of CO_2 equivalent per year.

– Finalising the ongoing transition to renewable energy of the Vitacura premises. The corresponding saving may reach up to 200 tonnes of CO_2 equivalent per year when completed in four years.

– Extending the lifetime of IT equipment and exploring ways to repair broken devices, only resorting to new purchases where necessary. These actions may save up to two tonnes of CO_2 equivalent per year.

– Taking sustainability into account during the design phase of new projects and procurement, working with contractors who share ESO's concerns on sustainability and acting together to minimise CO_2 emissions.

– Continuing to increase the use of electric vehicles at ESO sites.

– Monitoring ESO's emission sources on a periodic basis in the coming years and producing regularly updated roadmaps for the reduction of the organisation's carbon footprint.

These measures set an initial step within the organisation's commitment to monitor its emissions and to continue to contribute to a more sustainable future.

Aerial view of the construction site of ESO's Extremely Large Telescope (ELT), on Cerro Armazones, taken in January 2022.

G. Hüdepohl (atacamaphoto.com)/ESO

Glossary

4MOST	4-metre Multi-Object Spectroscopic Telescope (VISTA)
ACA	Atacama Compact Array
AESOP	Australian ESO [fibre] Positioner
AGN	active galasctic nucleus
AHG	EIROforum Workign Group on Diversity amd Inclusiveness
AIP	Leibnitz Institute for Astrophysics Potsdam
AIV	assembly, integration and verification
ALICE	smALl visible CamEra (ELT)
ALMA	Atacama Large Millimeter/ submillimeter Array
AMBER	Astronomical Multi-BEam combineR (VLTI)
AO	adaptive optics
AOF	Adaptive Optics Facility
APD	avalanche photodiode
APEX	Atacama Pathfinder EXperiment
ARC	ALMA Regional Centre
ARI-L	Additional Representative Images for Legacy
ASAG	ALMA Safety Advisory Group
AT	Auxiliary Telescope (VLT)
AtLAST	Atacama Large Aperture Submillimetre Telescope
ATT	ALMA Technical Team
au	astronomical unit
BGR	Board of Government Representatives (CTAO ERIC)
CAD	computer-aided design
CASA	Common Astronomy Software Applications
CDR	Critical Design Review
CEAT	Cryogenic Electronics Assembly Test facility
CERN	European Organization for Nuclear Research
CONCERTO	CarbON CII line in post-rEionisation and ReionisaTiOn epoch
COPUOS	(United Nations) Committee on the Peaceful Uses of Outer Space
CP	Contracts and Procurement
CRIRES$^+$	upgraded CRIRES (VLT)
CRP	Conference Room Paper
CTA	Cherenkov Telescope Array
CTA-S	Cherenkov Telescope Array South
CTAO	Cherenkov Telescope Array Observatory
CUBES	Cassegrain *U*-Band Efficient Spectrograph (VLT)
DDT	Director's Discretionary Time
DMO	Data Management and Operations
DMS	Dome and Main Structure (ELT)
DoA	Directorate of Administration
DoE	Directorate of Engineering
DSC	Directorate for Science
dVM	designated Visitor Mode
EASC	ESO ALMA Support Centre
EDPS	ESO Data Processing System
EFOSC2	ESO Faint Object Spectrograph and Camera 2 (NTT)
EHT	Event Horizon Telescope
Eii	European Interferometry Initiative
EIROforum	European Intergovernmental Research Organsiation forum
ELT	Extremely Large Telescope
ERIC	European Research Infrastructure Consortium
ERIS	Enhanced Resolution Imager and Spectrograph (VLT)
ESA	European Space Agency
ESAC	European Science Advisory Committee
ESC	ELT subcommittee
ESFRI	European Strategy Forum on Research Infrastructures
ESPRESSO	Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (VLT)
ETF	ELT Technical Facility
EU	European Union
FAIR	Findable, Accessible, Interoperable, and Re-usable
FDR	Final Design Review
FIAT	Facility for Infrared Array Testing
FLAMES	Fibre Large Array Multi Element Spectrograph (VLT)
FORS2	FOcal Reducer and low-dispersion Spectrograph 2 (VLT)
G-RAF	Garching Remote Access Facility
GARD	Group for Advanced Receiver Development (Chalmers University, Sweden)
GTO	Guaranteed Time Observing
HARMONI	High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (ELT)
HARPS	High Accuracy Radial velocity Planet Searcher (3.6-metre)
HIRES	HIgh REsolution Spectrograph (ELT)
HR	Human Resources
IAU	International Astronomical Union
ICCF	Incoherent Combined Coudé Focus
ICRI	International Conference on Research Infrastructures
IF	intermediate frequency
IFU	integral field unit
INAF	Italian National Institute for Astrophysics
IRATEC	InfraRed Array Test Electronics Cryostat
IRIS	InfraRed Imaging System
IRLOS	InfraRed Low Order Sensor
ISA	International Staff Association
ISC	International Staff Committee
IT	information technology
LGS	Laser Guide Star(s)
LISA	Large vISible cAmera (ELT)
LPO	La Silla Paranal Observatory
LSP	La Silla Paranal subcommittee
MACAO	Multi-Application Curvature Adaptive Optics (VLT)

MAIT	manufacturing, assembly, integration and testing
MAORY	Multi-conjugate Adaptive Optics RelaY (ELT)
MAPS	Molecules with ALMA at Planet-forming Scales
MATISSE	Multi-AperTure mid-Infrared SpectroScopic Experiment (VLTI)
MAVIS	Multi-conjugate-AO-assisted Visible Imager and Spectrograph (VLT)
MEC	Mechanical department
METIS	Mid-infrared ELT Imager and Spectrograph (ELT)
MICADO	Multi-AO Imaging CAmera for Deep Observations (ELT)
MIDI	MID-infrared Interferometric instrument (VLTI)
MOONS	Multi-Object Optical and Near-infrared Spectrograph (VLT)
MOSAIC	Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology (ELT)
MPE	Max Planck Institute for Extraterrestrial Physics
MPIfR	Max Planck Institute for Radioastronomy
MUSE	Multi Unit Spectroscopic Explorer (VLT)
NAOJ	National Astronomical Observatory of Japan
NAOMI	New Adaptive Optics Module for Interferometry (VLTI)
nFLASH	new FaciLity APEX Submillimetre Heterodyne instrument
NGC2	Next Generation Controller 2
NGTS	Next-Generation Transit Survey
NIRPS	Near InfraRed Planet Searcher (3.6-metre)
NTT	New Technology Telescope
OA	Open Access
ODG	Office of the Director General
ODG-A	Office of the Director General – Internal Audit Office
ODG-X	Office of the Director General – Executive Office
OPC	Observing Programmes Committee
ORCID	Open Researcher and Contributor ID
OSO	Onsala Space Observatory
PAE	Preliminary Acceptance Europe
PDR	Preliminary Design Review
PDS	Phasing Diagnostic Station
PFS	pre-focal station
QC	Quality Control
SEN	Systems Engineering department
SEPIA	Swedish ESO PI receiver for APEX
SINFONI	Spectrograph for INtegral Field Observations in the Near-Infrared (VLT)
SIS	superconductor-insulator-superconductor
SMBH	supermassive black hole
SNe	supernovae
SnooPI	Snooping Project Interface
SOFI	Son of ISAAC (NTT)
SOFIA	Stratospheric Observatory for Infrared Astronomy
SoXS	Son of X-Shooter (NTT)
SPECULOOS	Search for habitable Planets EClipsing ULtra-cOOl Stars
SPHERE	Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (VLT)
SPIFFI	SPectrometer for Infrared Faint Field Imaging (VLT)
STC	Scientific Technical Committee
STOP	straylight, structural, thermal and optical performance
telbib	ESO Telescope Bibliography
TESS	Transiting Exoplanet Survey Satellite
UC	Users Committee
UK ATC	UK Astronomy Technology Centre
USD	User Support Department
UT	Unit Telescope (VLT)
UVES	Ultraviolet and Visual Echelle Spectrograph (VLT)
VINCI	VLTI Commissioning Instrument
VISIR	VLT Imager and Spectrometer for mid-InfraRed
VISTA	Visible and Infrared Survey Telescope for Astronomy
VLBI	very long baseline interferometry
VLT	Very Large Telescope
VLTI	Very Large Telescope Interferometer
VST	VLT Survey Telescope
WSU	Wideband Sensitivity Upgrade (ALMA)
ZEUS-2	Z (Redshift) and Early Universe Spectrometer 2

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Cover: Aerial view of the construction site of ESO’s Extremely Large Telescope (ELT), on Cerro Armazones, taken in January 2022.

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