For Recommendation

SCIENTIFIC TECHNICAL COMMITTEE

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Science Priorities at ESO
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1. **Prologue**

This report presents the findings of a working group established by the ESO Director for Science to prioritise the ESO programme on the basis of its scientific promise and to probe the changes that ESO should make to address the likely astronomical landscape in the 2020s.

The working group met seventeen times by teleconference between April 2014 and April 2015, with face-to-face meetings in Garching on 4-5 September 2014 and 1-2 December 2014. During these meetings the ESO Programme Scientists presented their views of the priorities of the various elements constituting their respective facilities, the La Silla Paranal Observatory (LSP, including the Very Large Telescope, VLT), the VLT Interferometer (VLTI), the European Extremely Large Telescope (E-ELT) and the Atacama Large Millimetre/Submm Array (ALMA). Francesca Primas, at that time the Head of ESO’s User Support department, presented the current status and plans in the DMO (Operations) area. The activities of the Directorate for Science were also discussed. With the exception of the Directorate of Administration and the Cabinet of the Director General, all aspects of the ESO programme were debated, with nothing considered ‘off the table’.

The process comprised four parts, which are captured in this report:

First, the ESO Programme Scientists prepared discussion documents, identifying strengths, weaknesses, risks and opportunities in their respective areas of expertise – ALMA, E-ELT, LSP/VLT and VLTI. The panel’s thoughts relating to data archiving were also captured. These documents were then subject to criticism and debate until consensus was achieved across the panel, noting where consensus was not possible.

Second, steps were taken to determine the needs and opinions of the ESO community, beginning with the careful orchestration of a Community Poll, designed to elicit from the community clear choices, while acknowledging that the ESO budget is finite. The Poll was sent to all users registered with ESO or the European portion of ALMA. The Poll was also designed to provide context for a workshop organised by the working group: ‘ESO in the 2020s’. This was held at ESO’s Garching HQ on 2015 January 19-22. Its goals were to explore the likely astronomical landscape in the 2020s and ESO’s place within that landscape, and to provide the community with an opportunity to feed its thoughts directly to the ESO executive (the ESO DG and ESO Council President were present throughout), and to our working group.

Third, an attempt to quantify how well the various elements of ESO’s current and planned programmes allow the ESO community to address science cases connected with a list of eleven compelling science topics thought likely to remain compelling for some considerable time (these same eleven topics were also the basis for science-related questions in the Community Poll).

Fourth, the report reflects upon how ESO should respond to the changing astronomical environment, e.g. the imminent arrival of the James Webb Space Telescope (JWST) and the Large Synoptic Survey Telescope (LSST).


For reference, the most recent version of the La Silla Paranal Instrumentation Plan at the time of writing, is available here: [http://www.eso.org/sci/facilities/develop.html](http://www.eso.org/sci/facilities/develop.html).
2. Executive summary

We recommend that the roadmaps and highest priorities with regard to the VLT, VLTI, ALMA and E-ELT programmes, on timescales ranging from a few years to a few decades, should be as follows. We have prioritised across the individual programmes in the case of the La Silla Paranal Observatory, combining recommendations for La Silla, VLT and VLTI. Some further recommendations are italicised in bold in the remaining sections of the report.

LPO priorities and roadmap

**Epoch 1: 2016-2020**
- a) Deliver GRAVITY by 2017 to observe the periapsis of S2, providing reliable, high-performance VLTI infrastructure and robust fringe tracking;
- b) Deliver AOF, ESPRESSO and CRIRES+ by 2018;
- c) Complete the ongoing public surveys;
- d) Establish development plan for the VLTI (VLTI White Book, mid-2016);
- e) Deliver MATISSE, ERIS and MOONS;
- f) Deliver new instrument for the NTT;
- g) Start second round of VISTA public surveys;
- h) Revise operational model for a more flexible time allocation and execution process;
- i) Expand VLTI user base by improving access to the facility to non-experts through dedicated expertise centre(s);
- j) Develop upgrade and replacement plan (VLT and VLTI);
- k) Select and design AO instrument.

**Epoch 2: 2021-2025**
- a) Fully exploit the by-now existing VLTI infrastructure by expanding its instrumentation;
- b) Upgrade and replace VLT science capabilities, as defined in the upgrade plan;
- c) Deliver 4MOST to VISTA;
- d) Design and deliver AO instrument to VLT;
- e) Encourage visiting instruments for VLT and VLTI.

**Epoch 3: Beyond 2025**
Operate the ESO optical/NIR telescope system making best use of the synergies. With the E-ELT starting operations, the support role of the VLT, VLTI and the 4-m telescopes needs to be defined. Support capabilities for other ESO observatories, e.g. ALMA.

E-ELT priorities and roadmap

**Epoch 1: 2015-2024**
- a) Deliver/commission E-ELT and its first-light instrumentation (MICADO/MAORY, HARMONI);
  - a) Begin planning for 2nd generation of instruments.

**Epoch 2: 2025-2030**
- a) Full exploitation of first-light instrumentation;
- b) Deliver and commission METIS;
- c) Select 2nd generation instruments; begin development;
- d) Complete the first generation of instruments (in no particular order): HIRES, MOS, ELT-6, EPICS.

ALMA priorities and roadmap

**Epoch 1: 2015-2020**
- a) Complete the commissioning of the baseline trilateral ALMA and deliver efficient science operations to the community;
- b) Deliver the first set of upgrades focusing on expanding the parameter space for science capabilities: e.g. new receiver bands, Phased Array modes, Solar observing;
c) Develop further upgrades option focusing on significant improvements of the existing capabilities: e.g. receiver bandwidths, data rates, pipelines and archive services;

d) Continue to exploit the competitive advantage offered to the ESO community by APEX as a survey/pathfinder instrument for ALMA; explore the long-term evolution of this opportunity.

**Epoch 2: 2020-2025**

a) Upgrade receivers and signal chain to allow, at least, 16 GHz/polarisation bandwidth;

b) Implement the plans for next generation survey instruments (single dish or panoramic detectors for interferometry);

c) Approve and start development for a transformational upgrade of ALMA (e.g. longer baselines, larger collective area, full bandwidth receivers and signal chain).

**Epoch 3: 2025-2030**

Deliver the transformational upgrade.

**Community input**

The ensemble of opinions received as a result of our Community Poll represents the largest feedback ever collected by ESO from its users in a systematic manner. It provides a clear picture of our astronomical community, in terms of its current scientific interests, future research goals and expectations. Although our poll suffers from some intrinsic biases and caveats, as is common for this type of approach, the results are sufficiently solid to guide and support future implementations. In particular, we believe that the responses about science vision and instrumental capabilities provide a clear picture of which scientific quests will dominate the 2020–2030 astronomical scene and which facilities will be needed. Some of the other results are more difficult to interpret and to prioritise based purely on scientific grounds.

The user community has clearly endorsed the need for normal programmes and for condition-adapting queue observing (service mode) at all ESO facilities. The latter can be clearly connected to science-driven observing strategy optimisations and efficiency. Our pool of respondents also recognises the importance of Public Surveys and Large Programmes. We recommend keeping these facts in mind when discussing future evolutions of the operational model and evaluating changes to the science policy.

Regarding data processing, archiving and exploitation, it proved difficult to arrive at firm conclusions and recommendations. A detailed breakdown of possible correlations between different levels of data products and the suite of instruments that will become operational in the next decade is missing. We believe it is important to reflect further on some of the figures that have emerged from this poll, inside and outside ESO, keeping science as the top driver for any future decisions. ESO should involve the community even more, via a much more detailed science-driven poll on all data-related aspects, followed by a formal review.

**Working groups**

During the course of our deliberations several topics merited more consideration than could realistically be devoted, and in one case (data archiving) consensus was not possible. We therefore recommend that working groups be established to look in more detail at the issues surrounding: 1) data archiving; 2) the case for a large, wide-field sub-millimetre dish; 3) the case for a 10–15-m optical/IR spectroscopic survey telescope; 4) the needs of the laboratory astrophysics community; 5) time allocation. These working groups should involve the community, and should include voices that do not resonate with the status quo.

With regard to the last of these, ESO should consider the implementation of coherent programmes, i.e. the allocation of sufficient observing time across its facilities, possibly in coordination with other organisations, to solve major scientific problems. These could take various forms, e.g. block allocation of time, long-term monitoring or synoptic observations with other facilities over an extended period.
3. **ESO's primary facilities: Programme Scientists' perspectives on the future**

In this section, we present discussion documents prepared by the ESO Programme Scientists, identifying strengths, weaknesses, risks and opportunities in their respective areas of expertise, LSP/VLT and VLTI, ALMA and E-ELT. This section also contains the group’s thoughts on the evolution of the ESO Science Archive Facility.

3.1 **La Silla Paranal Observatory (excluding VLTI)**

The VLT should remain the leading optical/infrared ground-based telescope system until the start of operations of the ELTs. Its success is based on modern instrumentation and an operations model that is flexible. The four 8-m unit telescopes offer 12 focal stations that cover a large range of observational capabilities, unmatched by any other observatory. Together with the 4-m telescopes, La Silla as a science platform for the community, and the survey telescopes, VST and VISTA, the LSP Observatory is unique worldwide in providing many opportunities to match facilities to the observing needs of the ESO community.

The landscape that the VLT will be operating in includes complementarity with the operating ALMA, X-ray and γ-ray observatories, and HST until the end of the decade, the scientific results of the satellites Kepler, Planck and Gaia, and the early operations of the ELTs. It is expected that the next decade will see surveys by LSST, Euclid, TESS, PLATO and JWST.

**Challenges**

Existing plans for instrument deployment will bring new capabilities to the VLT. New instruments need to adopt new technologies to be competitive. The existing VLT instrumentation is aging and many instruments will have to be operated beyond the originally planned operational dates. Maintaining and upgrading the current instrumentation will require increasing levels of effort.

The development time of VLT instruments has increased continuously – typically a decade for recent deliveries – resulting in reduced flexibility. In the past, the large number of available focal stations provided flexibility, and the VLT could offer a large instrumentation complement. It has become difficult for ESO to react to new technological developments. This is exacerbated by the loss of a focus for visiting instruments, which provided an opportunity for experimental setups.

Scientific exploitation of the large investment in the Adaptive Optics Facility (AOF, on UT4) requires new instrumentation on a timescale competitive with and complementary to the ELTs.

*Adapting the operational model to the best scientific usage will require changes in how the telescope time is allocated and how the data are disseminated in the community.* The public surveys undertaken with ESO telescopes are examples of new modes of operation. Completing the surveys in a timely manner is a separate operational challenge to which ESO needs to rise.

In the next decade, the effect of JWST and the ELTs on the VLT will be significant. All near- and thermal-infrared observations made by the VLT will be outclassed. The image quality on the VLT will be inferior to the new space- and ground-based telescopes. Wide-field science (relative to all but LSST and Subaru), optical imaging and spectroscopy and high-resolution spectroscopy are likely to remain important VLT science capabilities. The VLT will provide the optical complement to new facilities operating at other wavelengths or making use of different messengers (e.g. gravitational waves, neutrinos). The existing plan for VLT instrumentation ([http://www.eso.org/sci/facilities/develop.html](http://www.eso.org/sci/facilities/develop.html)) – with AOF, ESPRESSO, TMT and GMT will have comparable fields of view to VLT.
4MOST, MOONS, CRIRES+, KMOS, MUSE, SPHERE and ERIS all in the pipeline or recently deployed – already takes this into account.

**Priorities**
The highest priority should be to maintain VLT as the world’s leading optical/infrared observatory until the E-ELT arrives. **To this end, all operating instruments need to be maintained at a competitive level.** An upgrade and replacement plan for instruments covering the most important capabilities needs to be established. Operating instruments with compromised capabilities represent a loss to the community; such capabilities need to be fixed unless the mode is regarded to be no longer interesting or competitive.

The best use of the Adaptive Optics Facility needs to be explored. **ERIS will replace NaCo; its scope must be commensurate with delivery on the quickest possible timescale. Planning for the next AO instrument – to replace HAWK-I at the beginning of the next decade – needs to begin immediately.**

Flexibility should be one of the main advantages of the VLT, given the number of telescopes and foci. **The possibility to quickly accommodate a visiting instrument, if a promising science case is presented, needs to be encouraged.** In the case of VLTI, PIONIER is a good example. Flexibility should also be achieved through a faster development cycle and quicker implementation of new technologies. This will be a virtue of the VLT in the E-ELT era.

**Planning the continuation of surveys with VISTA needs to start soon.** While there appear to be no really strong science cases for VST, given the competition from LSST, VISTA will host 4MOST and will remain competitive as a survey telescope into the next decade. The operational model for 4MOST will need to be investigated carefully and the lessons learned potentially applied to VLT operations. In general, all of ESO’s 4-m telescopes may be run in survey mode in the next decade with full-time allocation to special observing programmes over long periods.

**Roadmap**

**Epoch 1: 2016-2020**

a) Implement the instrumentation plan with the upgrade of VISIR and the delivery of AOF, ESPRESSO, CRIRES+, MOONS and ERIS;
b) Develop upgrade and replacement plan for existing instruments;
c) Complete the ongoing public surveys (imaging and spectroscopic);
d) Deliver new instrument for the NTT;
e) Start a second round of VISTA public surveys;
f) Revise the operational model for a more flexible time allocation and execution process.

**Epoch 2: 2021-2025**

a) Deliver 4MOST for VISTA;
b) Design and deliver AO instrument;
c) Upgrade and replace science capabilities as defined in the upgrade plan;
d) Encourage visiting instruments for exploration of specific science cases.

**Epoch 3: Beyond 2025**

Operate the ESO optical/NIR telescope system making best use of the synergies. With the E-ELT starting operations, the support role of the VLT, VLTI and the 4-m telescopes needs to be defined. Support capabilities for other ESO observatories, e.g. ALMA.
3.2 VLT Interferometer

The VLTI will remain, even in the ELT and ALMA era, the European astronomical facility with the highest angular resolution. The last decade has seen ESO mastering the difficulties of coherently combining the array of four unit or auxiliary telescopes. These successes have paved the way for ambitious second-generation instruments, GRAVITY and MATISSE. With VLTI and ALMA, the ESO user has now gained access to milli-arcsecond astronomy from the near-infrared to the millimetre-wave regime.

Since its conception, VLTI has pursued two goals: delivering an imaging capability at the milli-arcsecond resolution level and providing precise relative astrometry with an ultimate goal of ten micro-arcseconds accuracy, the latter being technically much more challenging.

The scientific production of VLTI has been heavily dominated by simple but important morphological (i.e. imaging) measurements of the near- and mid-infrared emission of bright sources and the rise of spectroscopy with milli-arcsecond angular resolution. While this has challenged a number of established theories in the field of stellar physics and AGN, the VLTI must now enter a time when the true complexity of objects is revealed. **VLTI must offer the possibility to spatially and spectroscopically resolve a wealth of time-variable astrophysical processes that will never be accessible via other techniques.** It will be the tool that will allow us to challenge our indirect understanding of stars, exploring rotation, turbulence, shocks, winds, accretion and ejection phenomena as they happen, revealing the complex interplay between a star and its environment throughout its lifetime. The VLTI capability of resolving the complexity of AGN nuclei, measuring precisely the central black-hole mass and pinpointing their distance with unmatched accuracy has barely been exploited so far.

**As an astrometric machine, with GRAVITY, the VLTI will offer a unique way to observe strong gravity in action and explore physical conditions close to the horizon of the Galactic Centre black hole. As such it offers a rare opportunity to probe the nature of strong gravity.** The technology required to enable such an ambitious goal will most probably open the way for science projects exploiting micro-arcsecond astrometric capabilities from the ground. This unique combination of a fascinating science case and instrumental innovation is a strong incentive to support the development of VLTI.

The evolution of VLTI infrastructure – and the associated increase in performance – should bring trust in ESO’s ability to continue developing milli-arcsecond astronomy from the ground. Whether this will be achieved by expanding VLTI or by developing other facilities is still to be explored.

**Challenges**

ESO has mastered the difficult technique of coherent optical beam combination. The next challenge to be met is to combine increases in sensitivity and precision. Phasing (the so-called ‘fringe tracking’) of the array of telescopes on-axis (and later off-axis) is therefore the next essential step. This will considerably increase the size of samples that can be observed and will enable spectroscopic observations to be made at medium and high spectral resolution, ultimately with off-axis interferometric guiding. As learned through the difficulties with AMBER and MIDI, efficient fringe tracking requires a number of sub-system implementations or upgrades and particular attention must be paid to global performance. ESO has acquired sufficient expertise to tackle this difficulty but will have to dedicate the required resources. Without fringe tracking, neither GRAVITY nor MATISSE will deliver.

The second challenge is to deliver the final astrometric performance promised by GRAVITY. The remarkable scientific outcome will be delivered only at a price – significant technological and system effort. GRAVITY’s success will require patience and commitment from all its partners.

The third challenge is to democratisate access to the VLTI by providing user assistance for observation preparation, data reduction and image reconstruction. Considerable progress
has been made by the VLTI community to develop reliable software, dedicated training schools, etc., yet VLTI data continues to be perceived as an ‘experts-only’ process, as mentioned by ESO’s User Committee. VLTI benefits from an active and dedicated community. **Both ESO and the VLTI community must establish a proper interface to provide users with easier access to data reduction and image reconstruction.** The subsequent broadening of the community will then inevitably bring new ideas for the scientific exploitation of VLTI. In addition to that, the development of synergies with ALMA and diffraction-limited telescopes, and the expansion of VLTI Large Programmes should be pursued.

**The VLTI beyond GRAVITY and MATISSE**
The need for milli-arcsecond-resolution observations will not disappear with the advent of GRAVITY and MATISSE. Moreover we can already anticipate that both instruments will open new avenues. We can anticipate critical areas where VLTI could evolve from the routine delivery of useful information to the delivery of conclusive information:

- Expand milli-arcsecond astronomy towards the visible;
- Enable high spectral resolution ($R > 30,000$) and polarimetry;
- Combine both the previous items and find the synergy with asteroseismology, with a possible link to space missions (e.g. PLATO);
- Make it possible to image complex environments (by increasing the number of telescopes) and therefore the ability to catch the complexity of time-variable events on short timescales;
- Develop a high-dynamic-range capability (similar to extreme adaptive optics for interferometry) in order to probe planet-forming regions that escape other direct-detection techniques;
- Explore whether VLTI imaging and astrometric capabilities for cosmological applications can be developed (e.g. strong lensing);
- Develop synergies with ground-/space-based facilities providing similar angular resolution, requiring high-angular-resolution complementarity, or connecting different spatial scales (e.g. ALMA, SPHERE, PLATO, LSST).

This prospective exercise will be carried under joint ESO and European Interferometry initiative leadership and should lead to a VLTI White Book around mid-2016.

**Priorities and roadmap**

**Epoch 1: 2016-2020**

a) Make GRAVITY and MATISSE a success by providing reliable, high-performance VLTI infrastructure. Demonstrate robust fringe tracking.
b) Expand VLTI user base by improving access to the facility to non-experts through dedicated expertise centre(s);
c) Establish development plan for the VLTI (VLTI White Book, mid-2016).

**Epoch 2: 2021-2030**

a) Fully exploit the by-now existing infrastructure by expanding its instrumentation, for example to the visible and to very high spectral resolution and/or by providing ‘wide-field’ astrometric capability.
b) Encourage visiting instruments, pushing the technique in new directions (e.g. high dynamic range; polarimetry).

**Epoch 3: Beyond 2030**

This later epoch will depend on the funding situation in the ELT-era and the ability of the community to propose strong science-driven projects that could justify the expansion of the infrastructure (e.g. more telescopes).
3.3 E-ELT

ESO is currently engaged in the design and construction of the world’s largest optical and infrared telescope, the 39-m European E-ELT, on Cerro Armazones in Chile. With construction having started in December 2014, first light is currently planned for 2024.

Building on the success of the VLT, the strategic aim of the E-ELT programme is to maintain ESO’s leadership in the area of ground-based optical and infrared observational facilities into the 2020s and beyond. The E-ELT will provide ESO’s community with the optical and infrared capabilities necessary to achieve major breakthroughs in many areas of present-day astrophysics. The E-ELT undoubtedly represents one of the scientifically most exciting (and technically most challenging) projects in the history of astronomy.

Description of the E-ELT

As a future facility, in what follows we provide more detail about E-ELT than we have about the existing ESO facilities. The E-ELT is a 39-m, fully steerable telescope with a 10-arcmin (5-arcmin unobstructed) field of view, integrated wavefront control, two Nasmyth and a Coudé focal stations, operating in the wavelength range 0.35–20 µm, designed to achieve diffraction-limited performance at wavelengths >1 µm, equipped with a wide range of instruments as well as six laser guide stars, and located at a dry, dark, mid-latitude, high-altitude (3000-m) site under a highly transparent and stable atmosphere. Being located just ~22 km from Paranal will enable the E-ELT to be operated as an integral part of the Paranal Observatory.

In principle, the telescope can host at least eight instruments simultaneously: three on either Nasmyth platform; two at the Coudé focal station. The E-ELT instrumentation plan comprises seven first-generation instruments (plus MAORY, an MCAO relay system) and their associated adaptive optics modules:

- a diffraction-limited, SCAO and MCAO-assisted near-infrared imager with a ~1-arcmin science field of view (MICADO, first-light instrument);
- a single-field, SCAO and LTAO-assisted, wide-band, medium resolution, visible and near-infrared IFU with a range of spaxel scales and fields of view suitable for diffraction-limited as well as seeing-limited operations (HARMONI, first-light instrument);
- a mid-infrared, SCAO and LTAO-assisted imager, medium-resolution spectrograph and high resolution integral field unit (IFU), METIS;
- a high-resolution spectrograph (ELT-HIRES);
- a multi-object spectrograph (ELT-MOS);
- an XAO-assisted planetary camera and spectrograph;
- one as-yet-unspecified instrument.

The last was included to retain some flexibility within the programme.

Current status

In December 2014 ESO Council approved the construction of the E-ELT in two phases, and authorised spending of up to 1012.5 M€ on Phase 1. The split of the construction into two phases had become necessary because of the continuing day-by-day delay of the project caused by Brazil not yet having completed the ratification process of its accession agreement. To allow the project to move forward, while still respecting Council’s funding principles, required moving some 106.5 M€ of scope to Phase 2 and delaying first-light of Phase 1 from 2024 to 2026. The items moved to Phase 2 include the five inner rings of segments of the primary mirror, the entire seventh sector of the primary mirror as well as the LTAO module. However, future approval of Phase 2 is only contingent on the availability of funding. Individual Phase 2 items will be reinstated (and/or first light brought back to 2024) as soon as the required additional funding becomes available. In particular, as soon as
Brazil completes its ratification process, Phase 2 will be reinstated in its entirety. Note that the procurement schedules of the baseline construction plan and of the two-phase plan only start to diverge in 2017. This is the earliest time at which any Phase 2 item would have to be deferred. If Brazil completes its ratification process before this time then the two-phase plan is identical to the original baseline. Given recent developments in Brazil, the current assumption is that no items will actually have to be deferred, and that the full E-ELT will see first light in 2024.

The E-ELT thus fully entered its construction phase in December 2014. Since then, excellent progress has been made on a number of critical items, including work on the access road and the platform on Cerro Armazones (which began in March 2014), the Dome and Main Structure, and the M4 unit and shells.

Regarding instrumentation, the aim is to sign the agreements for the construction of MICADO, HARMONI, METIS and the MCAO module MAORY in 2015. Design studies for the LTAO module, as well as for ELT-HIRES and ELT-MOS are also to be commissioned this year. Note that the construction of the LTAO module is a Phase 2 item, while the construction of ELT-HIRES, ELT-MOS, ELT-PCS and the as-yet-unspecified instrument is to be covered by the operations budget. When these instruments might become available is thus difficult to estimate at present.

**Science with the E-ELT**

It has long been acknowledged that there are (at least) three broad sub-topics that should be considered when discussing ‘E-ELT science’: (i) the potential of the E-ELT to achieve major breakthroughs in ‘contemporary astrophysics’, i.e. its ability to answer the questions we can already pose today; (ii) the synergies that arise from combining the capabilities of the E-ELT with those of other major facilities of the coming decades; (iii) the new, unforeseen, and unexpected science that will arise from exploiting currently inaccessible parts of observational parameter space.

Regarding item (i) we must first of all note that the E-ELT is not being built to answer a single scientific question. Rather, it is a multi-purpose facility and as such it will address a wide range of topics across the whole breadth of astrophysics: from our own solar system to extra-solar planets, from nearby galaxies to the furthest observable objects at the edge of the visible Universe, from fundamental physics to cosmology. Nevertheless, a number of science cases have played a particularly prominent role in developing the E-ELT, including:

- Detection and characterisation of exo-planets down to super-Earth masses in the habitable zones of nearby stars;
- Formation of planetary systems: structure, kinematics and physical processes in proto-planetary disks;
- Probing gravity in the strong-field regime in the vicinity of the supermassive black hole in the centre of the Milky Way;
- Assembly history of (elliptical) galaxies from the resolved stellar populations of galaxies out to the Virgo cluster;
- Physics of high-redshift galaxies: comprehensive and detailed surveys of the physical properties of galaxies out to redshifts of six;
- Detection and characterisation of the structures containing the first generation of stars driving the reionisation of the Universe.

In many science cases the E-ELT will profit from synergies with other facilities that will be operating concurrently. These include existing facilities such as VLT/VLTI and ALMA, as well as planned facilities such as JWST, LSST, Euclid, PLATO, SKA, TMT and GMT. In this context we first of all point out the obvious: namely that the choice of a southern hemisphere site for the E-ELT was critical, since many of the facilities for which particularly symbiotic relationships with the E-ELT are predicted are also located in the south, in particular the
VLT, ALMA, and LSST. Second, it is similarly obvious that one would like to renew the successful partnership between the Hubble Space Telescope and ground-based 8–10-m telescopes in the JWST and ELT era (albeit with reversed roles, where the ground-based facility will have the highest spatial and spectral resolution). **Clearly, the synergy between the E-ELT and JWST is best exploited if at least some overlap in their operational lifetimes can be achieved.** This requires that JWST outlives its design lifetime of 5 years and that first light of the E-ELT is not delayed beyond 2024. Preserving a minimum operational overlap between what are destined to become the most influential astronomical facilities of the next 20 years should have the highest priority for ESO.

In the past, the unlocking of previously inaccessible observational parameter space has led us to entirely unpredicted discoveries. This thesis has held true for many facilities in the past, and is simply a consequence of the fact that – as a science – astronomy has not yet completed its exploratory phase. We have no reason to believe that this situation will have fundamentally changed by the time of the E-ELT’s first light, and thus we can safely assume that the E-ELT’s most important discoveries will be those we cannot foresee today.

The fundamental observational parameters in which the E-ELT will excel are of course spatial resolution and sensitivity. However, these will in turn unlock, both individually and in combination, uncharted territory in a host of other parameters, such as e.g. time resolution, spectral resolution, astrometric precision and radial velocity precision.

The high spatial resolution of the E-ELT and its astrometric precision (potentially as low as 10 µas) will combine to provide us access to the environment of the supermassive black hole at the centre of the Milky Way at distances of just ~100 Schwarzschild radii. This is the only place in the Universe where we can study the effects of strong field gravity in detail, and the E-ELT will thus provide unique tests of our understanding of gravity in this regime. At the other end of the scale, the potential ability of the E-ELT to achieve a radial velocity precision at the level of ~1 cm s\(^{-1}\) provides direct access to gravitational potentials (by measuring accelerations) in the extreme weak-field regime. It is in this regime that we are forced to introduce both dark matter and dark energy (or, alternatively, a modified theory of gravity), and where arguably significant discovery potential awaits, alongside the exo-planet work.

E-ELT thus promises the combination of two vistas – one, a clear, sharp picture of what lies ahead on a well-defined path, the other, a blurry vision of possibility. **Achieving first light with E-ELT by 2024, ahead of the other ELTs and contemporaneously with JWST, with a full complement of instrumentation, should be ESO’s highest priority.**

**Priorities and roadmap**

**Epoch 1: 2015-2024**

b) Deliver the E-ELT and its first-light instrumentation (MICADO/MAORY and HARMONI);

c) Begin planning for 2nd generation of instruments.

**Epoch 2: 2025-2030**

a) Full exploitation of first-light instrumentation;

b) Commission METIS;

c) Select 2nd generation instruments; begin development

d) Complete the first generation of instruments (in no particular order): HIRES, MOS, ELT-6, EPICS.
3.4 ALMA

ALMA is a unique, transformational observatory, providing an improvement in the parameter space of angular resolution, sensitivity and image fidelity of up to two orders of magnitudes in the classical millimetre windows (1-4mm) and significantly more in the submillimetre domain. We predict that this will enable ALMA to make many scientific breakthroughs in the 2015-2025 era. The design goals have always been for a long-lifetime (at least 30 yr), upgradable facility for general users, i.e. not limited solely for the traditional small community of mm/radio astronomers. The key philosophy from the beginning was to deliver a versatile and user-friendly observatory with expert users able to fully stretch its capabilities and novice users also able to harvest the scientific potential by making use of the user support and science-grade data products.

ALMA has completed the construction phase and is now carrying out Early Science observations in parallel to the extension and optimisation of capabilities (i.e. completing the commissioning of the construction project).

Two key features of the ALMA programme have been drawn and extended from the successful VLT experience: the end-to-end data flow concept and the long-term development programme. With respect to the VLT, ALMA has raised the bar of the data-flow concept to a higher level: the off-site segment of the observatory has been extended beyond ESO, comprising a distributed network of nodes in the Member States community that is committed to providing the users with science-grade reduced data. This choice was made with two goals in mind: use and extend the expertise in European institutes; and ensure that a much broader community would be able to make an efficient scientific use of the ALMA data, i.e. not only the small community of traditional interferometrists.

ALMA is a modern general-user ground-based observatory; its raison d’être is to deliver unique, transformational science for the broader community. The lack of competition and the excellent data delivered by the observatory provide significant challenges, as the focus on excellence needs to be maintained. If no other observatory can provide μJy-level sensitivity in the submillimetre wavelength regime, then is a data-delivery timescale of several months acceptable? In this regard, we believe the onus is on ESO to lead the world, continuing to provide its ALMA users with an advantage in terms of user support (data delivery – speed and quality assurance, and support of subsequent data analysis).

Challenges

Unique among the major ESO observatories, ALMA is a partnership with North America and East Asia. This poses significant differences in culture, expectations and administrative procedures. ESO is not able to directly apply its normal, well-understood rules of engagement. All the partners face similar challenges: all need to understand the true meaning of a shared decisions/priorities/commitments process; all have difficulties coping with this. There is scope for critically considering the pros and cons of the ALMA governance scheme and possible adjustments (or revolutions). This is also reflected in the competitive (as opposed to visionary) way the ALMA Development has so far been handled by the ALMA Executives.

The extreme end-to-end concept adopted by ALMA – including full-service observing and the release of reduced, scientifically qualified data for all observing modes – was designed to boost the productivity of the observatory, and has been successful so far. Nevertheless, it has two major drawbacks: no external astronomers interact directly with the observatory, the full load of training staff astronomers and the running of the end-to-end system is on ESO, with a very significant cost and risk of losing expertise in the community. Note that this process is already materialising in the fast-reacting North American system, with university (sub)mm facilities being shut down – a process mimicking the effect the Very Large Array had on the classical radio astronomy university groups in the US. In Europe this effect has not yet kicked in, in fact the Member States are investing significantly in the ARC network (including training and full community support) effectively supporting the Joint ALMA
Observatory and ESO in executing the end-to-end model. Nevertheless, this is a risk that requires constant monitoring and mitigation. Connected to this risk, expert, competitive users are often frustrated by the delay in accessing data taken by the observatory for their programme. Procedures to release raw data for 'stale' projects represent a first step in addressing this problem.

Being a unique facility also poses a significant challenge: as there is no competitor offering similar capabilities, the pressure to deliver them efficiently and on time is reduced. After the first three years of Early Science operations, the overall number of projects executed and the timescales for completing projects and delivering data to the users is still considerably lower than had been originally hoped.

Priorities

**In the short term, the priority for ALMA has to be to increase the overall efficiency of Science Operations and enter into routine Full Science Operations, offering a significantly larger amount of time and overall system reliability.** Any activity that distracts effort from this goal should have lower priority. In particular, the delivery of development items should be re-prioritised to occur after the constructed system is fully operational.

In the medium term, ALMA is re-assessing the scientific priority of the items that were deferred beyond the construction phase as part of the 2005 re-baselining exercise. Completion of the missing frequency bands, mmVLBI, sub-array capabilities, and advanced archiving and data analysis software systems all fall in this category. All these should not be blindly implemented as originally envisaged 15 years ago, but should be reviewed in the context of the evolving major scientific questions, the availability of new and more advanced technologies, and the development of other ground- and space-based facilities.

Also in the medium term, an obvious area of development that would significantly improve the scientific capabilities of ALMA is the doubling of the bandwidth of the receivers, with a concurrent upgrade of the digital processing chain (digitisers and correlator). Another aspect that should be investigated, following our consultation with the ESO community through our Poll, is the possible scientific requirement(s) for single-dish survey capabilities in the next 10-20 years.

There are several ambitious upgrade paths that would enable ALMA to deliver transformational science on a long-term timescale: increasing the collective area, providing wide-field survey capabilities (through panoramic detectors), extending the maximum baselines, etc. As ALMA is in the initial phases of delivering science with the current capabilities, it is perhaps too early to decide now which, if any, of these avenues should be pursued. **We believe that over the next 5 years, ESO should consolidate a science case and technical plan, pushing hard for a major upgrade of the Joint ALMA Observatory.**

To identify the scientifically most promising avenues for upgrades and to make the best use of the limited development resources, a scientific vision for the ALMA Development Plan and a careful handling of the implementation in the various regions is also urgently required. We can thus avoid a random flow of sub-ideal upgrades to the observatory, as the regions compete among themselves in order to support their own technical groups with ALMA development funds. In this regard, we note and applaud the ASAC-led ‘ALMA2030’ process (Annex 4), which has defined the long-term scientific vision for ALMA development.

The costs and benefits of the service offered to the community, and more generally the whole end-to-end system, should also be carefully monitored. We note at this point that following a few more years of experience and scrutiny, the ALMA model of user support might be worth exploring for other ESO facilities, e.g. one could imagine community-based support via centres similar to the ARC nodes in the area of VLTI generally, as well as for
instruments such as MOONS and 4MOST. We note that the ARC review in Europe was a useful step in this direction, and postulate that a similar ALMA-wide exercise could be considered.

**Roadmap**

**Epoch 1: 2015-2020**

- a) Complete the commissioning of the baseline trilateral ALMA and deliver efficient science operations to the community;
- b) Deliver the first set of upgrades focusing on expanding the parameter space for science capabilities: e.g. new receiver bands, Phased Array modes, Solar observing;
- c) Develop further upgrades option focusing on significant improves of the existing capabilities: e.g. receiver bandwidths, data rates, pipelines and archive services;
- d) Continue to exploit the competitive advantage offered to the ESO community by APEX as a survey/pathfinder instrument for ALMA; explore the long-term evolution of this opportunity.

**Epoch 2: 2020-2025**

- a) Upgrade receivers and signal chain to allow, at least, 16 GHz/polarisation bandwidth;
- b) Implement the plans for next generation survey instruments (single dish or panoramic detectors for interferometry);
- c) Approve and start development for a transformational upgrade of ALMA (e.g. longer baselines, larger collective area, full bandwidth receivers and signal chain).

**Epoch 3: 2025-2030**

Deliver the transformational upgrade.
3.5 Data archiving at ESO

Scientific trends
Science archives are playing an increasingly important role in maximising the scientific return of astronomical observatories. We note four major trends in astronomy and science operations that are directly related to data archiving and that will develop into challenges for the future:

The increasing need for science grade data products. An increasing fraction of the scientific workflow, from observing through data reduction and even scientific analysis, is undertaken by observatories. This allows scientists to concentrate more on physical interpretation, to use the free energy to exploit data sets from different provenance or simply to increase the overall scientific productivity. Service-mode observing, automatic science-grade data-reduction pipelines and archives of trustable final products are becoming available. Amongst many other examples, the Hubble Space Telescope (HST), Spitzer Space Telescope, Herschel Space Observatory and XMM and ESO for the public surveys and selected instruments provide source catalogues and extracted spectra. ESO has been one of the first ground-based observatories to pioneer these services. At ESO, including ALMA with its partners, a number of development activities are ongoing with the goal of providing automatic source extraction, line identification and source classification for all science products. In particular ESO has started producing as many science-grade pipeline-reduced products as possible for the existing data holdings (currently UVES, Xshooter and HARPS, with other instruments in preparation). If science-grade data products are available, these are more popular and downloaded more often than the corresponding raw data. This effect can be observed at established observatories like ESO and HST. At ESO, the fraction of publications from archival data has already reached 25%.

The increasing use of multi-wavelength and multi-technique observations. The need to consider celestial objects through different observing techniques or wavelengths is becoming a prime requirement if one is to capture the essence of astrophysical phenomena. Over the past decade, many observatories have worked towards homogenising their holdings, standardising the product metadata and developing into large data centres. The standardised and homogenised archives, together with programmatic access to a wealth of science-grade data, will facilitate multi-wavelength research, bulk data analysis and data mining. It will also enable more astronomers to pursue purely archival careers.

The advent of massive datasets. Surveys have a need for high-quality, automatic data-reduction standards with well-defined workflows and advanced archive services. This trend will no doubt accentuate as the support for survey missions such as LSST, PLATO or Euclid and all future steradian projects appear more clearly.

The spread of data-reduction expertise. The development of sophisticated instrumentation and surveys puts a considerable strain on observatory capabilities to provide perfect end-to-end expertise for all its scientific observations. Offloading expertise to the community is proving to be a promising route. Obvious cases are reduced data and catalogues for cosmological deep fields or stellar libraries. ESO Public Surveys follow this philosophy, where the data products are the essential results rather than the individual observations. Future dedicated facilities or instruments (e.g. 4MOST) will be operated under this premise. The question of how to organise and/or delegate the archive and pipeline services, perhaps to one or more community-based centre(s), perhaps connected with the instrument providers, is a central one.

Challenges
We extract from these trends a number of challenges that ESO will have to face:

• The production of science-grade data products may eventually turn astronomers into consumers instead of co-producers of the data. Much of the responsibility for the quality of the results will shift from the users to the observatories. As such there is a
risk that ESO’s community of users may become detached from the observing process, failing to understand the technical limitations of the observations. Observatories will need to mitigate this risk by meticulously analysing and documenting the limitations of their data and workflows and providing incentives to continue the development, at the telescope, of young astronomers.

- It is highly probable that the global need for surveys to tackle astrophysical problems in a systematic way will not remove the need for detailed, handful-of-object studies, with different archiving requirements.
- It is clear that there will always be users with special observing needs and skills that will allow them to extract additional information from the data. Observatories such as ESO, in addition to their support for visitor-style observations, should remain open to that prospect and offer possibilities to integrate this expertise through the archiving of user-generated science data products.
- A serious concern, related to the previous concern, is that observatories may not fully exploit the expertise and talent of expert users eventually leading to quantity (as opposed to quality) science. The key difficulty, which should be analysed in more detail than was possible for this working group, is how to strike the correct balance between PI-driven data processing and standardised data processing and archiving.
- Observatories will have to shift from providing excellent data alone, towards providing an ever-better end-to-end user experience. In order to remain competitive in the 2020s, the ESO Science Archive Facility may need to develop into a science data centre. The development of the advanced data products (Phase 3) process is leading in this direction: standardising the data and metadata holdings, describing them with more physical parameters and producing science-grade data products for the Public Surveys.
- The possibility of re-processing the data holdings with improved pipelines could be a generic feature of such a data centre.
- In order to continue maximising the exploitation of its archive, ESO should provide a single, user-friendly entry point into the archive for all data from ESO facilities, allowing the discovery of data via searches based on physical parameters. We note that this goal is also achievable with a distributed network of data and recipe repositories, and does not necessarily require the creation and maintenance at ESO of a potentially huge infrastructure and expertise. It also seems appropriate to lower the hurdles for data download, e.g. to require authentication only for the download of proprietary data. The question of how to properly coordinate such an activity between institutions and maintain high data-quality standards is not a trivial one.
- ESO may also want to examine how it will retain ownership for data produced by ESO facilities but stored elsewhere, at one of what may be many data centres worldwide.
- As a final challenge, we note that the art of exploiting the ESO archive could probably spread, with proper user support such as that provided now for, e.g., proposal preparation.

Striking the right balance and making the correct strategic choices for the long-term future of ESO in the area of archiving is a complex matter that could not be fully addressed by this group, and it was one of the few areas where the group could not reach a consensus view. We note that ESO is already well advanced in some domains and is well placed to influence the data-archiving paradigm. We note also that the community has grown tremendously in expertise and the archiving challenge may prove an excellent way to increase the bond between ESO and its community. Having failed to achieve an adequate consensus in this area, we suggest that this analysis should continue via a dedicated working group comprising experts from ESO and the community.
4. **Messages from the ESO Community**

To tension the current and planned ESO programme against new possibilities, the working group launched a Community Poll and organised a conference, aiming to collect the scientific priorities of the ESO users' community. The poll was launched on 19 December 2014 with a deadline of 9 January 2015. It was designed to provide context for the ESO workshop, ‘ESO in the 2020s’, described briefly later in this section.

4.1 **Community Poll**

The community poll was anonymous and organised in four main sections, as follows:

I. Tell us about yourself and your scientific interests;
II. Present and future observing facilities;
III. Time scheduling and observing modes;
IV. Data management and services.

Section I was meant to collect basic demographic and professional aspects of the targeted audience: current position, country of present affiliation, type of home institution, main research interests (mainly, scientific area and wavelength domain), science vision for the 2020–2030 period. Section II followed up on the research interests and paired them to the facilities that will enable the users to achieve their science goals, inside and outside ESO. Sections III and IV focused mostly on ESO's science policy aspects and their implementation, in terms of observing, data reduction and data archive capabilities. A preview of the results was presented at the start of the ESO2020 conference in January 2015, to provide context for the later discussion.

All professional astronomers (students, postdocs and tenured astronomers) registered in the ESO User Portal and in the ALMA Science Portal were invited to share their scientific views. Out of the 9,350 astronomers thus targeted, a total of 2,541 responses were received, 1,775 of which were complete (i.e. all questions were answered). These numbers thus offer a solid basis for the analysis of the results, corresponding to 27% and 19% response rates, respectively. Notwithstanding this positive outcome, we are aware of the weaknesses that polls have in terms of biases and caveats and we spell them out whenever applicable.

**Sections I and II**

The poll did very well in sampling the targeted audience, both in terms of geographical and professional distribution. All ESO Member States achieved similar response rates (20–25%). Of the 1,775 complete responses, slightly more than half came from tenured professionals, a third from young astronomers at post-doctoral level and the remainder from students. Not surprisingly, the large majority of the respondents work in observation-related research fields (82%).

Section I also aimed to collect the main scientific drivers of the community, now and in the future. The users were presented with a list of research topics (Table 1) and asked to select those best describing their current research interests and their science vision in the 2020–2030 timeframe. While *Structure/evolution of galaxies, Stars and Planetary systems* are currently the most populated research fields of the sampled community, our users foresee a clear dominance of the future astrophysical scene by *Planetary systems, Cosmology/Fundamental physics, Search for life* and *Structure/Evolution of galaxies*. These claims reflect the absolute number of preferences expressed by the respondents.

A direct comparison between current research areas and science vision is presented in Figure 1. Note that the top four research areas that received preferences only as 'Scientific areas' did not appear in the list of science vision topics. It was decided to keep them in Figure 1 for completeness, and because they represent a non-negligible fraction of preferences.
It is worth noting that except for the *Structure/evolution of galaxies* area, the other three ‘visionary’ fields are expected to increase significantly in popularity, especially the *Search for life* area. Other areas of research are also expected to double in popularity, but they overall represent a smaller fraction of the respondents (*Extremes states of matter, Pre-biotic chemistry*).

The research fields affected by the largest decrease in number of preferences for the 2020-2030 decades are instead the more classical fields, like *Stars and Interstellar matter*. The outcome on *Stars* is especially puzzling considering that one of the main science cases for the E-ELT is indeed resolving individual stars in external galaxies (for kinematics and chemical tagging purposes). One possible explanation could be tied to the basic logic and implementation of these two questions in the poll: the one about current personal research interests allowing as many choices as necessary, the one about the science vision, allowing a maximum of three choices only.

**Table 1:** Science areas deemed likely to remain compelling in the 2020s, as identified by the working group.

<table>
<thead>
<tr>
<th>Cosmology and/or fundamental physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-scale structure of the Universe</td>
</tr>
<tr>
<td>Structure and evolution of galaxies (incl. AGN)</td>
</tr>
<tr>
<td>Milky Way dynamics and evolution</td>
</tr>
<tr>
<td>Life cycle of interstellar matter</td>
</tr>
<tr>
<td>Life cycle of stars</td>
</tr>
<tr>
<td>Planetary system formation and evolution</td>
</tr>
<tr>
<td>Search for life outside Earth</td>
</tr>
<tr>
<td>Pre-biotic chemistry</td>
</tr>
<tr>
<td>Extreme states of matter</td>
</tr>
<tr>
<td>The Sun and the solar system</td>
</tr>
</tbody>
</table>

This significant decrease also contrasts with the future capabilities and facilities the community has identified as the most important for the 2020–2030 period. The future capabilities are strongly dominated by high-multiplex, high-/moderate-resolution spectroscopy, single/IFU spectroscopy and wide-field imaging/continuum and spectroscopic surveys (Figure 2). The top four requested facilities are optical/IR, of any size (from 4m/8–10m, including a dedicated 10-m spectroscopic telescope, to E-ELT; Figure 3). With the sole exception of *Long-Baseline Interferometry*, the wavelength ranges 0.4–1 µm and 1–2.4 µm have the highest priorities for all other observing capabilities listed in Figure 2, followed by the 2.4–20 µm interval. Noteworthy here is the rather constant (20%) response that the 0.3–0.4 µm waveband received across capabilities, a need for blue coverage that emerged also at the ESO2020 conference (see later).

For the record, Section II closed with a question about which non-ESO facilities users plan to use. The outcome here is quite undisputable, with JWST clearly at the top, followed by LSST and SKA.

At first sight, Figures 2 and 3 are heavily dominated by optical/IR facilities and a strong need for spectroscopic capabilities. With ALMA operations ramping up and a very stable and successful APEX facility already operational, the fact that the sum of all choices related to mm/sub-mm/radio domains (single-dish or array, Figure 3) is slightly less than one quarter of the total, may be surprising. However, the poll may suffer from some intrinsic biases. First, the answers provided by the community are not unique since the question allowed for (a maximum of) three choices to be specified. Second, this result may simply reflect the distribution among the targeted audience, in terms of scientific profile and interests of the respondents.

In fact, if one checks the distribution of the respondents according to the wavelength domain they usually work in, one reaches similar numbers, i.e. slightly more than one quarter of the
respondents selected the mm/sub-mm/radio ranges (Figure 4). It seems plausible that the apparent dominance of optical/IR facilities and spectroscopic capabilities reflects in part the pool of respondents.

Figure 1. A direct comparison between individuals’ research areas and the science vision for the 2020-2030s.

Figure 2. Users were asked to select the most important capabilities for their own research in the 2020–2030 timeframe. Responses are shown in absolute number of preferences expressed for each option. A total of 4,661 responses were received.
Users were asked to select which facilities will be required for their future research objectives. Responses are represented as in Figure 2. A total of 4,575 responses were received.

This is even more so, considering the bias in our initial targeted audience, namely the number of users drawn from the ALMA Science Portal is at most one-fifth of the total number of users who were contacted (if one considers users with a unique account in the ALMA Science Portal – around 900 – and users who have an account on both portals – another 990). Normalising the responses is not straightforward, because of the complicated logic behind some of the questions. This bias may possibly be reflected also in the distribution of wavelength domains among the respondents (Figure 4), with the further complication that users were allowed to select all wavelengths applicable to their science projects.

### Figure 3

![Future facilities](image)

**Figure 3.** Users were asked to select which facilities will be required for their future research objectives. Responses are represented as in Figure 2. A total of 4,575 responses were received.

### Figure 4

![Distribution of the wavelength domains](image)

**Figure 4.** Distribution of the wavelength domains in which respondents are mostly working. A total of 3,960 responses were received.

### Sections III and IV

The second half of the poll focused more on aspects related to science policies and to a range of services that ESO already provides or may/shall provide in the future. This part
probed the community’s needs and ideas about observing programmes, observing modes and how the data shall be returned to the community.

In section III, the community expressed a strong opinion on the need for Regular observing programmes, defined an essential and/or very important channel to fulfil their research objectives, followed by Large programmes and Public surveys. This point also emerged clearly at the ESO2020 conference, where the need for large allocations of telescope time – concentrated in time rather than spread over multiple years – was voiced. Another remark made at the conference was about ways to improve the connection between ESO facilities and space-based missions, in terms of time allocations.

The overall opinion about Filler and DDT (Director Discretionary Time) programmes is less clear: the responses distributed equally among all options, including the ‘Not important’ category. On the one hand, the resulting differences may be interpreted as significant because the question was mandatory and users were forced to express their opinion on each option; on the other hand, one has to reconcile this with the almost 40% that Filler queues to exploit poor weather scored in the following question about observing modes.

![Figure 5](image-url)

**Figure 5.** Overall user preferences regarding observing modes.

Among the other observing modes (Figure 5), a few remarks are merited: Condition-adapting queue observing is the mode that received the highest preference for both ALMA and E-ELT and is one of the two preferred modes for La Silla Paranal. This is a clear recognition of the importance of Service Mode for optimal exploitation of ESO facilities. Also noteworthy is the large number of votes for Classical observing (Visitor Mode) at La Silla Paranal, significantly more than what can be considered alternative options, like Designated VM or Remote observing. The correct interpretation of this distribution is challenging. It might have to do with being less familiar with such concepts and implementations (DVM is relatively new at ESO-Paranal and entirely assigned by ESO for very short and time critical observations, while Remote observing is not offered at all). On the other hand, astronomers are keen to observe at Paranal (La Silla is offered only in VM), in part because they recognise the hands-on experience, or because they may think that in VM they have a better chance of returning home with some data.
Section IV focussed on functions and services related to data management. Users were asked to express their opinion on a. the importance of different data-reduction software capabilities for their research objectives; b. on the importance of accessing different types of archived data products in order to maximize their scientific productivity; c. on the criticality of having specific functions and capabilities, both in terms of data exploitation tools and archive content. The last and more global question was about the level of data support (data reduction and data archiving) needed to maximise the scientific impact of ESO facilities.

Overall, approximately half (55%) of the respondents consider advanced data reduction tools and pipelines as critical for their own research projects and believe that ESO should routinely process and archive most or all of ESO science data in order to maximise the impact of ESO data (50%).

![Figure 6. A radar plot combining users’ reply to questions a. (right half of the plot) and b. (left half of the plot), where a. is about the importance of data-reduction software capabilities for the respondent’s own research objectives and b. focuses on access to different data products in the Archive to maximise the respondent’s own scientific productivity.](image)

While the vast majority of the respondents to the first two questions (listed as a. and b. above) chose 'Essential/Very important' for most of the proposed options (Figure 6), it is not straightforward to assess their significance. An illustrative example is how 'Essential/Very important' the access to different types of archived data products is judged for one's individual research: Raw data, Pipeline processed data (sub-set), Pipeline processed data (all) and Advanced data products created by the PIs all scored around 55% (60%, 56%, 55% and 51% respectively). On the other hand, one could argue that Reduced data products created by PIs and Custom/customizable data reduction achieved slightly lower numbers (46% and 43%). Similarly, some differences are noticeable also among the choices of different data products that the users would like to access from the ESO Science Archive Facility (left half of the radar plot, Figure 6), with some larger preferences to have the data pipeline-processed to remove the instrumental signatures. Again, it is very difficult to assess the significance of these differences. **It is clear that the community wants to have pipeline-processed data in the archive, but the respondents do not seem to have a strong preference between having subsets or all of the data available for prompt exploitation.** Also, one should note that among the 'Important/Somewhat important' votes, the preferences are different.
In the next question (c.), about the criticality of different functions/capabilities for one’s research, the differences among the proposed options are more significant. Here, for instance, 55% of the respondents consider it ‘Critical’ to have Advanced data reduction tools and pipelines available, but only 28% chose ‘Critical’ for Advanced archive facilities.

Figure 7. Overall preferences for data processing and archiving (in terms of who should take responsibility) in order to maximise the scientific impact of ESO facilities. Each option shows the distribution of the preferences it received, with the professional standing of the respondents indicated by colour.

With respect to the level of overall support that should be provided to ESO data (Figure 7), half of the community is of the opinion that most or all science data should be routinely processed and archived, whereas the other alternative options (selective processing of data-sets by ESO or PI data processing with commitment to return the data products to ESO) scored only 20% each. An interesting sociological remark is that the younger fraction of our respondents (students and in part also postdocs), i.e. our future user community, seems to be less interested in a fully-served system, probably showing their ‘hands-on attitude’ when it comes to data reduction and exploitation. This is partly captured in the diversification of the bars shown in Figure 7. The number of preferences expressed per available option by each professional group does reflect the professional standing distribution of the pool of respondents (~53% Faculty, ~32% Postdocs, ~13% Graduate students, ~2% Other). There are however some noticeable deviations from this distribution, if one looks option-by-option: 57% of the more senior astronomers (vs 8.7% of the graduate students) think that ESO should process and archive most or all ESO data, whereas only 40% of the more senior astronomers (vs 16% of the graduate students) are fine with the PI being in charge of the data processing without any further commitment. While the difference among the more senior respondents is not so large, the deviations from the original population of graduate students is certainly remarkable (they almost halved when it comes to fully-served data archive and they slightly increased when it comes to be in charge of the processing).
4.2 `ESO in the 2020s' workshop

The ESO workshop, `ESO in the 2020s', was organised by the working group at ESO Headquarters, over 19–22 January 2015. Annex 3 reproduces the workshop programme and the presentations can be found online at http://www.eso.org/sci/meetings/2015/eso-2020/program.html.

At the workshop, ten contributed talks were mingled with presentations about the ESA programme, LSST, CTA, SKA, and about the science priorities for VLT, VLTI, E-ELT and ALMA as viewed by the respective Programme Scientists. Review speakers covered exoplanets, the origin of the Solar System, astrobiology, high-mass star formation, stellar evolution, late-type stars, the Milky Way and Galactic Centre, the Magellanic Clouds, gas in galaxies and AGN, galaxy evolution, weak lensing, and large-scale structure. Finally, a considerable fraction of the time available was set aside for discussion led by trios of experts. The workshop was publicised as an opportunity for the community to advise the ESO Executive with regard to future facilities, including but not limited to the LSP and the Joint ALMA Observatory and this was very much the spirit in which ESO and its community behaved during the workshop.

In a closing talk, the Director for Science presented the workshop participants with `What did ESO hear at ESO in the 2020s?' – a presentation that is summarised below, in bullet form, and which can be found on the workshop website, above.

ESO’s community, as represented by the attendees of the workshop, made clear that they expect ESO to provide or explore the following, in no particular order:

- a world-class 8-m telescope facility at Paranal, with a competitive instrumentation programme;
- the full suite of E-ELT instruments;
- ESO should explore pushing instrumental response towards the blue, ~370 nm, where possible;
- more bandwidth for ALMA, along with longer baselines;
- the ALMA Phasing Project (mm-VLBI), particularly for the Event Horizon Telescope;
- a large submm/mm dish;
- a 10–15-m wide-field spectroscopic survey telescope;
- access to and/or synergies with CTA and SKA.

This list of community desires was tempered by realism – a clear brake on ambition in the absence of new funds – with strong demands to see the planned programme delivered on time, particularly GRAVITY, since the Galactic Centre periapsis event will not wait for ESO instrumentation to be made ready.

Probably the most regular topic of debate at the workshop was the issue of time allocation – in relation to potentially colossal allocations in support of space missions such as Gaia, PLATO and Euclid, and also in relation to the developing field of transients. One participant questioned whether ESO is exploiting the natural synergy between the La Silla Paranal Observatory and ALMA to the maximum level possible.

In response to the messages from the community, a series of working groups were proposed by the Director for Science to explore the science cases for a large submm dish and a 10–15-m wide-field spectroscopic survey telescope, to investigate ESO’s time allocation procedures, and to look at the needs of the laboratory astrophysics community.
4.3 Capturing input from the prioritisation working group

As a working group, we captured and quantified our own thoughts about the future scientific direction and priorities for ESO by developing some key science cases. These usually offer good pointers towards the facilities that are most crucial to answer those questions. Below, we describe each of the science case in broad strokes. This is not meant to be exhaustive but rather indicative of the area under discussion. Working group members assigned marks for each science case according to the following scheme, adapted from the recent effort to re-baseline SKA:

- How fundamental is the scientific impact of this result? 0 (none), 1 (incremental), 2 (incremental/significant), 3 (significant), 4 (significant/fundamental), 5 (fundamental)
- What is the importance of ESO’s contribution to this result? 0 (none), 1 (low), 2 (low/medium), 3 (medium), 4 (medium/high), 5 (high)
- To what degree does ESO contribution enable enhanced outcomes when combined with other data? 0 (no synergy), 1 (low synergy), 2 (low/medium), 3 (medium), 4 (medium high), 5 (high)
- Risk associated with instrumental technique (in achieving performance goals)? 0 (no risk), 1 (low risk: all relevant performance goals have been demonstrated to achieve necessary precision), 2 (low/mid risk), 3 (mid-risk), 4 (mid-high risk), 5 (high: key performance goals have not been demonstrated at the required precision)
- Risk associated with understanding observable attributes of the target/source population? 0 (no risk), 1 (low risk: target population well understood), 2 (low/mid risk), 3 (mid-risk: target population modelled), 4 (mid-high risk), 5 (high: target population unknown)

Within the science themes, sub-categories have been created and therefore, in most cases, the number of votes was in excess of 10 or 20 allowing for a meaningful standard deviation to be generated.

Cosmology and fundamental physics

ESO’s involvement in cosmology and fundamental physics lies in a number of areas. Wide-field spectroscopic surveys provide critical support to the photometric redshifts that are used in gravitational shear experiments and Baryon Acoustic Oscillations (Euclid/WFIRST). They are also critical for the measurement of redshift distortion maps. The supernova work remains critical but with space missions actively competing with ground-based observations, the ESO-based work supports the understanding of the supernovae and the search for population based systematics. It is likely that the cosmology will only be marginally affected by such work as in a large enough sample (e.g. many thousands of supernovae from Euclid/WFIRST/LSST) the creation of a coherent sub-sample that is useful for cosmology may be possible without reliance on follow-up observations. MOONS and 4MOST are supporting instruments for Euclid/LSST and need to be on sky around 2020. This field is extremely competitive and Subaru with PFS is the key competing facility, in terms of AOmega. However, if we include observing time as a parameter, the VLT becomes very competitive assuming Subaru can only allocate a quarter of its time to this science field. To compete in this field with Subaru in this field, a UT would need to be dedicated to a particular survey for a number of years (allowing, of course, for some time for VLTI).

Fundamental physics is an area where the ground-based facilities have critical roles to play. The detection of evolution, or lack thereof, in the fundamental constants is an ongoing experiment from multiple telescope facilities and a key science for all the ELTs. This experiment has only a positive result in the long term (there is no theoretical prediction for the value of the change, although there are strong theoretical predictions that there ought to be a change). Sensitivity in the blue is important for these science cases, as is improved calibration of the spectrographs. Assuming the E-ELT is not capable of working in the bluest
regions, it is important that at least one UT is equipped with an appropriate spectrograph and can be optimised with blue-sensitive coatings.

The detection of some manifestation of the event horizon of a black hole at the Galactic Centre has profound physical implications and is the closest that we can get to test general relativity in the strong-field regime. This is science where ESO is a key player with GRAVITY on the VLT and the Event Horizon Telescope of which ALMA is a critical component. The medium-term 2025 priority rests on the use of the 30-m class facilities at the diffraction limit. The orbits that 30-m class telescopes will be determining for the stellar objects surrounding the Galactic Centre will be completed within 1 year. Therefore, first come will absolutely be first served. The schedules of the events rather than the technical capabilities of TMT, GMT and E-ELT will dominate the discovery space.

- How fundamental is the scientific impact of this result? 4.7+/−0.5
- What is the importance of ESO contribution to this result? 4.8+/−0.4
- To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.3+/−0.8
- Risk associated with instrumental technique (in achieving performance goals)? 3.4+/−1.3
- Risk associated with understanding observable attributes of the target/source population? 3.4+/−1.5

Large-scale structure of the Universe

In the context of redshift surveys, there is significant cross talk between the Large-scale structure of the Universe and the Cosmology sections.

For the purposes of this document we re-iterate the need for wide band spectroscopic redshifts (to catch more than one line) to support the photometric redshifts from imaging surveys and also to support/cross calibrate missions such as Euclid. The ESO survey telescopes are participating in this work through KIDS and the various VISTA surveys. The good image quality provided by the VST appears unfortunately not to be delivered at high enough efficiency to bring that survey to conclusion in an expedient manner. ESO will not be competitive in wide-field work unless a large amount of observing time is allocated, e.g. on the VLT. MOONS and 4MOST are the relevant facilities. The heavily dust-obscured Universe should not be ignored here, and is perhaps best accessed via wide confusion-limited submm/mm imaging surveys with a wide-field single-dish telescope.

In the longer term E-ELT MOS will push the redshift limit of such work. The limited field of view of the E-ELT will by necessity restrict such work to KMOS-style surveys rather than wide-field work. Both GMT and TMT provide significantly higher AOmega and the option of allocating hundreds of nights on the E-ELT is unrealistic in the early years of operation.

The use of ESPRESSO to extend the UVES quasar work is considered relevant but the magnitude limit of the VLT even in the combined mode is the dominant factor. E-ELT with HIRES is the critical facility in this case. IGM tomography is a key science case of HIRES.

- How fundamental is the scientific impact of this result? 4.5+/−0.7
- What is the importance of ESO contribution to this result? 4.5+/−0.7
- To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.0+/−1.3
- Risk associated with instrumental technique (in achieving performance goals)? 2.5+/−1.2
- Risk associated with understanding observable attributes of the target/source population? 2.4+/−1.1
**Structure and evolution of galaxies (including AGN)**

The UTs with IFUs on SINFONI, FLAMES and KMOS are strong participants in this study of the Structure and evolution of galaxies. MUSE at moderate to low redshifts will significantly enhance our capabilities, in particular with the advent of laser-assisted adaptive optics, albeit with a narrow field of view. Follow-up of the eROSITA survey will provide an excellent census of the black holes/AGNs at the redshifts were the star formation peaks. The combination of these data with powerful imaging surveys should provide an excellent target list for extensive KMOS spectroscopy at a redshift of a few. MOONS and 4MOST are key components of the ESO strategy of supporting this work. Future facilities such as ELT MOS in the longer term will play a key role in observing the high redshift galaxies. In the E-ELT era, HARMONI will be critical for observations of selected systems at unprecedented sensitivity and resolution. The study of “normal” galaxies at high redshift will become the norm. ALMA will provide the information on the cold gas and dust in the galaxies and the excitation mechanism of star formation and galaxy evolution. Due to the inverse K-correction ALMA can observe the high-redshift objects much more easily than optical/NIR telescopes.

The study of emission from cold molecular and atomic gas traces the star formation (and the potential for star formation) in galaxies at a large range of redshifts. Of particular interest is the strong [C II] cooling line at 158 µm. This is a key science case for ALMA and, as efficiency of operations improves, the field will rapidly expand. ALMA has already moved the field forwards, using rapid continuum measurements of optically thin dust emission as a proxy for gas mass.

The absence of an MCAO IR camera affects the ability of the VLT to complement HST and JWST photometry in crowded regions to study the stellar populations in nearby galaxies. On E-ELT timescales, MICADO/MAORY will provide deep crowded field photometry. This is likely to be a breakthrough science case, strongly reliant on the multi-conjugate capabilities of the E-ELT.

The satellites of the Milky Way, their distribution and stellar content are an active area of research as they current represent a discrepancy between the simulations of structure formation and the observations. Deep surveys will reveal the stellar content of the Local Group.

The study of the AGNs requires exquisite spatial resolution at long wavelengths to peer through the dust. The drawback of filled-aperture telescopes is that they are limited in resolution to that of the primary mirror and at the longer wavelengths of the mid-IR the beam becomes relatively large. Interferometry is much better suited to this task. In the mid-IR it is somewhat easier to find the photon that coherently interferes and the baselines at Paranal provide the appropriate resolution. The combination of VLTI probing the dust and ALMA the atomic/molecular gas promises great advances in the study of nearby AGNs.

- How fundamental is the scientific impact of this result? 4.1+/−0.6
- What is the importance of ESO contribution to this result? 4.4+/−0.9
- To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.3+/−0.9
- Risk associated with instrumental technique (in achieving performance goals)? 2.5+/−1.4
- Risk associated with understanding observable attributes of the target/source population? 2.1+/−1.4

**Milky Way dynamics and evolution**

The current execution of the *Gaia*-ESO survey is a key component of this work. The output of *Gaia* will dominate this field and it can be expected that stellar spectroscopy will receive a huge boost from the *Gaia*-ESO survey, with multiple new questions arising. This is linked to the 'life cycle of stars' item, below, but the connections of stellar populations with stellar
dynamics will need to be supported by further work with FLAMES and MUSE on the VLT. The follow up of VISTA surveys, as well as LSST, Pan-STARRS, etc., to study the bulge and disc of the Galaxy, streams and clusters, is a key component of the MOONS and 4MOST instruments programme.

The satellites of the Milky Way, their distribution and stellar populations are of great relevance to the galaxy formation and large-scale structure fields. This is an overlapping science case where largely the same dataset will serve to explain both the Milky Way’s dynamical history and to constrain general galaxy-formation scenarios. Massive surveys of the stellar populations of near or near-by systems are necessary to separate the wheat from the chaff. MOONS/4MOST are key players in the mid term and FLAMES in the near term.

- How fundamental is the scientific impact of this result? 4.3+/-0.8
- What is the importance of ESO contribution to this result? 4.5+/-0.5
- To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.4+/-0.5
- Risk associated with instrumental technique (in achieving performance goals)? 2.4+/-1.1
- Risk associated with understanding observable attributes of the target/source population? 2.5+/-1.1

**Life cycle of interstellar matter**

The properties of the interstellar medium are extensively studied from measurements of quasar absorption lines to measurements of circumstellar material. Many of these studies rely on absorption lines where high-resolution spectroscopy enables the weaker lines to be resolved from the continuum. ESO instrumentation such as UVES, ESPRESSO and CUBES are key players in this work. Wide wavelength coverage is important here.

The absorption-line work is critical for the earliest epochs through observations of the Lyman alpha lines which probe the structure of the ISM around the epoch of re-ionisation, to the tomography of the IGM, to structure formation (probes of low-density neutral gas along the line of sight), etc. The tomography will benefit from a degree of multiplexing and wide fields of view. The evolution of the metallicity in the IGM is an on-going study for which high-resolution observations are needed.

The life cycle of dust in the ISM from the solar neighborhood to high redshift will be/is being probed in the sub-mm regime by ALMA, which is and will remain the leading instrument for these studies for at least a decade. In the thermal infrared spectral region ground-based telescopes are not competitive with space missions with the exception of high-resolution spectroscopy. The high angular resolution of the E-ELT is not coupled with the sensitivity necessary for extragalactic work at the limit that JWST will establish. On the other hand, dust within our Galaxy, the studies of pollution of the ISM by stars and the studies of embedded regions will benefit from the high angular resolution of the E-ELT.

The expansion of the ALMA bandwidth and receiver bands will allow a qualitative change of the studies undertaken both in the Galaxy and at high redshift allowing spectral surveys and a variety of tracers. ALMA, together with the VLT and E-ELT in supporting roles, will remain the premier facility for these studies for the foreseeable future. In the context of the Galaxy and nearby galaxies, surveys of the dense molecular gas phase require wide-field sensitive mapping from a large, single-dish, sub-mm telescope.

- How fundamental is the scientific impact of this result? 4.1+/-0.9
- What is the importance of ESO contribution to this result? 3.8+/-1.0
- To what degree does ESO contribution enable enhanced outcomes when combined with other data? 3.7+/-1.2
- Risk associated with instrumental technique (in achieving performance goals)? 1.7+/-1.1
Life cycle of stars
The studies of star formation in different Galactic and extragalactic environments are critically dependent on the study of cool gas. ALMA is transforming this field. The high angular resolution and sensitivity of the JWST in the thermal infrared will also be revolutionary. Optical/IR ground-based facilities in the 2020 timescale will be limited to high-spectral-resolution work, complementary to ALMA. There is a good coincidence between the thermal velocities of the gas to be observed and the spectral resolution, where the ground-based facilities are competitive with space.

‘Normal’ work on stellar populations will be/is being profoundly affected by Gaia and the Gaia-ESO survey. Accurate distances to a very large number of stars will place strong constraints on their parameters and the combination with stellar spectroscopy is likely to create a renaissance in stellar astrophysics. MOONS and 4MOST will be critical facilities in the follow-up of Gaia. VLTI measurements of stellar parameters will also be a key factor in this work, directly measuring diameters at different wavelengths. Imaging of the nearest stars is on the horizon. MATISSE and GRAVITY will be key players.

PLATO/CHEOPS will provide many targets for astro-seismology studies. The ground-based follow-up will be spectroscopic characterisation of these stars. This field has been monopolised and much-expanded by Kepler. However, as the Kepler fields are not accessible from the south, ESO has not been a major player in support of this community. We can expect a renewal of interest following PLATO/CHEOPS.

The explosive death of stars has had the attention of the community for some time. It is likely that the interest will subside as the cosmological toolkit expands and the usefulness of many less precise distance indicators also declines. The interest in the death of stars will shift to a more detailed understanding of the explosion physics, the timescales and their interaction with the ISM and their contributions to galaxy evolution. The structure of the ISM is very-much influenced by supernovae and they remain the main chemical pollutants. The detailed study of supernovae is likely to continue to be of interest but unlikely to be a strong driver for instrumentation.

• How fundamental is the scientific impact of this result? 4.5+/-0.5
• What is the importance of ESO contribution to this result? 4.1+/-1.0
• To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.3+/-0.9
• Risk associated with instrumental technique (in achieving performance goals)? 2.2+/-1.2
• Risk associated with understanding observable attributes of the target/source population? 2.6+/-1.2

Planetary system evolution
The formation of planets is already a field being transformed by ALMA. The observations are comparable, or better, in fidelity than the simulations and the promised, and hinted at by VLTI, gaps in proto-planetary disks have been detected. The formation of planets will need to be pushed to cover a broader wavelength range probing the proto-planetary disks in the mid-infrared. Until the ELTs, the IR will be dominated by JWST, but the angular resolution of a 6.5-m telescope will be a limiting factor for this type of research. SPHERE/ERIS are going to be the primary VLT contributors in this area. E-ELT with METIS will play a key role in this field, together with an expanded ALMA that will provide high sensitivity at high frequencies and on long baselines.
The number of available planetary systems for follow-up will rapidly expand to easily saturate the available observing facilities. ESPRESSO observing time will be in high demand for this work. There are key roles to be played by smaller telescopes equipped with stable spectrographs in support of this science case. In most of these cases we are observing the parent star and surmising properties of the planets. The 3.6-m with HARPS or a new facility at that or another La Silla telescope, a re-purposing of the VST in the post-LSST era are all options.

The study of the planets themselves through transmission spectroscopy is a field of great interest. ESO is relatively ill equipped for this work, with CRIRES+ being ESO’s strongest card. SPHERE and ERIS will increase the profile but in the intermediate future we have little on the table. HARMONI on the E-ELT will provide the highest angular resolution combined with spectroscopy to further elaborate the studies undertaken by SPHERE. E-ELT/HIRES and METIS will complement this work in the mid-term by replicating CRIRES+, but on a bigger telescope. This field will be driven forwards by TESS and JWST.

Search for life outside Earth
ESO facilities are unlikely to be involved in Solar System exploration of life, with the exception of the detection of methane or other species at a variety of expected and unexpected locations.

On the other hand, observations of planetary atmospheres, using transmission spectroscopy, are likely to provide the first hints of systems that are capable of hosting life. JWST will move this field forwards and while the ECHO mission was not selected by ESA it is likely that cheaper/faster more focused missions will appear on the horizon. The signatures of ozone, methane, sulphur dioxide, etc., could be found in extreme cases by E-ELT instruments. This science is part of the EPICS instrument on the E-ELT. EPICS is approved but in the ‘in the future’ category, awaiting the results from SPHERE to provide a technical and scientific focus. Characterisation of planets is a key science case for E-ELT.

Pre-biotic chemistry
Hundreds of interstellar molecules have been detected in the Milky Way and external galaxies. Most of the observed molecules are organic in nature and constitute the building blocks of pre-biotic molecules, copiously present in primitive Solar System bodies such as carbonaceous chondrites and interplanetary dust particles. More than 70 amino acids have been found in meteorites and their isotopic fractionations are similar to those measured in nascent stellar systems as well as on our Earth. The study of complex organic molecules
(precursors of amino acids, building blocks of proteins, and precursors of nucleic acids, such as RNA and DNA) in different stages of evolution of star/planetary systems is needed to shed light on our origins. ALMA and its upgrades will help us tremendously in this endeavour.

• How fundamental is the scientific impact of this result? 4.5+/−0.6
• What is the importance of ESO contribution to this result? 4.5+/−0.6
• To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.3+/−1.0
• Risk associated with instrumental technique (in achieving performance goals)? 3.7+/−0.6
• Risk associated with understanding observable attributes of the target/source population? 3.7+/−0.6

Extreme states of matter
The observations of the black hole in the centre of the Milky Way have been addressed earlier. This is a field where ESO has the potential to move dramatically into the lead using GRAVITY on the VLTI and by being a provider of ALMA to the Event Horizon Telescope.

High-mass X-ray binaries are the signposts of stellar mass black holes. Other dense states of matter are neutron stars and their formation in supernovae. Gamma-ray bursts and other violent transients (radio bursts?) mark the dramatic change of matter from one state into another. Accretion disks can represent extremes temperatures and densities in a dynamic state.

Optical follow-up of X-ray binaries or other binary systems involving a black hole or neutron stars will always be needed to determine orbital parameters. This is a key contribution from ground-based facilities but in the absence of a particular system (e.g. a triple black hole, neutron star, Be-star system) to be further studied, and to provide specific orbital characteristics, the currently planned facilities appear well suited for this kind of work. The study of pulsars in the optical remains of interest, although the improvements in angular resolution of X-ray satellites provides strong competition.

The detailed studies of the kinematics of globular clusters may place constraints on the presence/absence of dark matter halos in such systems. Multi-object spectroscopy combined with proper motion studies using E-ELT MICADO will be a significant player in this area.

• How fundamental is the scientific impact of this result? 4.1+/−0.9
• What is the importance of ESO contribution to this result? 3.9+/−0.7
• To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.1+/−1.0
• Risk associated with instrumental technique (in achieving performance goals)? 2.9+/−1.3
• Risk associated with understanding observable attributes of the target/source population? 3.4+/−1.1

The Sun and the solar system
Solar system observations of comets, asteroids, planets and dwarf planets are all key areas for E-ELT and ALMA. VLT (in particular SPHERE) and La Silla continue to play roles in these fields. A specific technique is the occultation of a star by a solar system object. ESO with its several sites can contribute to ‘stereoscopic’ observations. Space missions such as JUICE may require support. With in-situ measurements close or around many of the planets, ESO will need to focus on spectroscopic observations. The E-ELT with high angular resolution and immense collecting area promises to expand the study of various rocks in space. Much of this may be done in narrow-band imaging using MICADO. METIS
depending on sensitivity and wavelength coverage is also expected to be a contributor in this field. ALMA of course is designed to be able to observe the sun and this is a unique capability.

- How fundamental is the scientific impact of this result? 3.8+/−1.0
- What is the importance of ESO contribution to this result? 4.0+/−1.3
- To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.0+/−0.7
- Risk associated with instrumental technique (in achieving performance goals)? 2.4+/−0.9
- Risk associated with understanding observable attributes of the target/source population? 2.4+/−1.2

**Time-domain astronomy**

Time-domain astronomy will be split between relatively slow events that warrant target-of-opportunity follow-up, very much along the lines that ESO currently operates, and flash events that will need campaigns of monitoring, either the sky or the photons. The latter category may include experiments such as QUANTEYE. Visitor instrumentation will need to remain a high priority for ESO in order to support the possibility of a new and exciting capability.

Anything that can wait for 1 or 2 hours before we turn a telescope to it is covered by the current scheme of operations. The typical brightness of these sources would require integration times of tens of minutes and while timeliness is always an advantage, the sampling of the variation is smoothed by the integration time. More efficient switching to targets may be considered, but ESO is already one of the most productive ToO facilities thanks to the operational scenario employed and the high availability of the facilities (both in terms of weather and technical reliability). The community is already gearing up to seek the optical counterparts of gravitational-wave detections by advancedLIGO/VIRGO. While ESO cannot compete with LSST in terms of surveys, the relatively wide field of the VST may be useful in rapidly surveying to a plausible depth over a few hundred square degrees.

The flash events are likely to pose significant challenges to all of ground-based astronomy. The GRBs are a prime example. Until the afterglow detection at the William Herschel Telescope, 20 hours after the burst of 970228, there was not much ground-based facilities could provide. The next flash in the sky may not be so generous in the lag time. The discovery is likely to be serendipitous, in fields that are being observed repeatedly (e.g. deep Euclid fields) and therefore there is a case for shadowing such observations from the ground. Unfortunately, the field of view of ESO’s spectroscopic facilities is limited.

This science is virtually unexplored at millimetre and submillimetre wavelengths, due to the limited sensitivity of pre-ALMA facilities. ALMA opens this wavelength window to time-domain astronomy for the first time. At this stage it is unclear what the impact will be, high frequency pulsar studies and monitoring of variable phenomena at locations difficult or impossible to probe at other frequencies (e.g. the immediate surroundings of black holes in the centre of galaxies, including our own, and in multiple stellar systems) will be the first applications.

- How fundamental is the scientific impact of this result? 4.3+/−0.8
- What is the importance of ESO contribution to this result? 3.7+/−1.1
- To what degree does ESO contribution enable enhanced outcomes when combined with other data? 4.1+/−0.9
- Risk associated with instrumental technique (in achieving performance goals)? 2.5+/−1.5
- Risk associated with understanding observable attributes of the target/source population? 3.2+/−0.8
5. **Responding to the new global astronomical environment**

ESO offers its community a panoply of front-line ground-based facilities across the electromagnetic spectrum, from the atmospheric cut-off in the blue to mm-wave astronomy. Although the ESO facilities are at the forefront of astronomical research, the landscape is evolving in significant ways and it is incumbent on us to consider whether we are configuring the facilities to address this landscape. We consider a set of developments that are ongoing and examine what options are available. There are areas where ESO is part of the formation of this new landscape (e.g. ALMA, E-ELT) and others where we are examining how to best interact/interface/exploit the new challenges/opportunities.

It is important to note that the community reacts to the changing landscape. How ESO will react and follow-up on these developments is an issue of prioritisation (the nature of this report).

In discussing the proposed facilities it is important to note that they all have broad science cases affecting many aspect of astrophysics. For the purposes of generating an ESO response, it is not useful to cover all these cases. The main topics of each mission or telescope project need to be addressed and the discovery space opened in other areas remains in the opportunity category.

**Data-access science**

It is critical to consider the way the community is funded/supported when defining ESO’s role as a research infrastructure. ESO operates an egalitarian, community-based, observing time-allocation process. Allocation of time is based on scientific merit alone, irrespective of the wealth of ones institution\(^2\). The ability of any research group to exploit these datasets is, however, limited by the resources available to them to do so. Unlike the allocation of time, then, ESO is blind to the ability of the community to use its datasets. ESO generates a high-quality product and excuses itself from the feeding frenzy that may follow.

This landscape, which ESO has been helping to create, will only expand with the ever-increasing number of survey-driven projects. This is not accidental, but rather a deliberate science-driven shift by the community aiming to solve problems that can no longer be addressed with a few targets or a few nights. It must be noted that we have now had more than a decade of ‘few-night’ allocations on many 8-m class telescopes. We refer to this as the “**observing the data challenge**”.

ESO provides tools to reduce data (pipelines), to access data (the ESO Science Archive Facility) and generates coherent datasets (advanced data products). These tools and products require support for their full exploitation. Assuming large surveys require significant time resources at the VLT, a re-direction of the user support and pipeline resources at ESO to supporting the community in the usage of the data may be an option. The accumulation of user-community-proposed tools and algorithms then provides a basis for the exploitation of the data.

**Theoretical developments**

Simulations of galaxy formation over cosmologically relevant timescales and distances have created a new observational paradigm: **Observing the simulation and comparing to the telescope data**. We call this the “**steradian challenge**”. The steradian problem should not be confused with cosmic variance. The steradian challenge is best illustrated by the ‘missing satellite galaxies’ problem – the Lambda cold dark matter (CDM) model requires these to exist, but they are not observed in the numbers predicted (although this situation is evolving rapidly). More powerful computers and a proliferation of simulations have created a landscape that is comparable to the introduction of a powerful, new telescope. The

\(^2\) The ability of a particular collaboration to execute the programme and exploit the data are considered in the case of large-scale programmes; the *quid-pro-quo* for the community is the generation of large, coherent, public datasets.
Millennium Simulation is a dark-matter-only telescope. Large-scale surveys are necessary to match the simulations. The community has moved towards addressing the steradian challenge with LSST and Euclid.

A second area of advance in simulations is in stellar atmospheres and the 3-D treatment of convection and in general magneto-hydrodynamics. The standard excuse of astrophysicists that magnetic fields or rotation or binarity would explain the observations if only we knew how to treat these effects is losing traction. Our observations should be able to challenge these advances in meaningful ways. Interferometric imaging of nearby stellar surfaces, monitoring of the fluctuations of the stars, proto-stars and evolved stars are all necessary. Precise spectropolarimetry is a powerful diagnostic tool tying the simulations of magnetic fields to observations.

**JWST**

It is critical to consider that JWST longwards of 2 µm for isolated point sources is more sensitive than the E-ELT and all other ground-based telescopes. JWST will be working at the diffraction limit, with an exquisite Strehl ratio at all wavelengths longwards of 600 nm, and with access to the 5–8- and 13–18-µm bands that are not accessible from the ground. These performance figures imply that 8-m-class telescopes equipped with adaptive optics will no longer be discovery machines. We call this the “sensitivity challenge”.

The JWST landscape will include the faintest high-redshift galaxies at the very edge of the era of re-ionisation and characterisation through spectroscopy of the atmospheres of the nearest exo-planets. JWST photometry of crowded fields will push – through improved angular resolution – further into the centres of globular clusters and galaxies. Relative astrometric measurements will be powerful diagnostics of the stellar dynamics in the cores of clusters.

More innovation in the areas such as polarimetry may provide avenues for the VLT to carve a niche in the era of the JWST.

The other area of complementarity will come from higher spectral resolution work on targets that are brighter than the ones JWST observes. There is a straightforward conflict in that much of the discovery space will be at the limit of the sensitivity suggesting that the sources will be too faint to be studied in more detail.

![Photometric performance, point source, SNR=10 in 10^4 s](source: NASA)

**Figure 8.** Photometric sensitivity of JWST as a function of wavelength, compared to other facilities (source: NASA).
The visible AO (see for example the discussion paper by Ric Davies at ESO2020) would also push the VLT into a potentially powerful niche. The field of view would be very limited but until the arrival of visible AO on the E-ELT it would be a most powerful facility.

![Spectroscopic sensitivity of JWST as a function of wavelength, compared to other facilities (source: NASA).](image)

**Figure 9.** Spectroscopic sensitivity of JWST as a function of wavelength, compared to other facilities (source: NASA).

### LSST

LSST is a 8.4-m 7-degree² field-of-view imaging survey telescope located in Chile which will image the entire sky in six bands (0.3–1.1 µm) with a declination <34.5 degrees repeatedly over a decade creating new, deep sky maps. First light is planned for 2021, with the decade-long survey beginning in 2022. The LSST plan is to dedicate 90% of the observing time to 18,000 deg² to be observed uniformly with approximately 800 visits to r ~ 27.5 (AB mag). Approximately 20 billion galaxies and approximately the same number of stars will comprise the catalogue and hundreds of thousands of transients per year.

Large parts of the ESO community are actively participating and contributing financially to the LSST project. As the primary source of observing facilities in the southern hemisphere, ESO needs to consider the LSST follow-up as a core mission of support to its community.

It is important to see LSST as more than just a cartographic mission. Having a deeper southern sky imaging survey will deliver spectacular results and provide new projects to an enormous variety of astronomical projects. This is the “new map of the skies problem”. However, it is also important to consider that the LSST will provide the temporal dimension of these maps. Relatively narrow field surveys looking for MACHOs in the LMC or the Galactic plane through gravitational lensing and supernova related surveys such as the Palomar Transit Factory, have occupied the transient community in the past. However, the LSST landscape is profoundly different in depth and field.

LSST will also provide a census of almost all decent sized moving objects in the solar system. ESO should consider whether committing resources to a systematic follow-up study of asteroids is warranted.

The LSST landscape obviously contains the photometric redshift of every decent sized galaxy out to a redshift of a few. These will need to be calibrated to extract the most out of them and this calibration is not latitude dependent. It is possible that Subaru with PFS or the Mauna Kea Spectroscopy Explorer (ngCFHT) will engage in this work. It is clear that there exists an enormous opportunity in engaging early and in a systematic way. Although Subaru
is more efficient, given that the VLT in principle could dedicate a telescope for a year or more to the task of providing redshifts, it is clear that ESO can provide a better service to the survey teams. It is likely that MOONS would suffice for this task given sufficient telescope time. The redshift calibration is not an open-ended task but it does need to take place as early in the LSST lifetime as possible.

![Figure 10. Map of the sky showing the number of visits by LSST (source: LSST).](image)

Following up and typing every supernova, nova, LBV or GRB that LSST discovers is going to be impossible. Critically, the sources will be found very soon after the start of their brightening. This is particularly interesting in a number of cases where the early evolution of the object informs us about the surrounding environment (e.g. companion) while at the same time it is most difficult as this is the time at which the sources are hardest to identify. The transient community will need a fast and flexible follow-up facility for this work, along the lines of the on-going PESSTO survey. Since LSST is coming on-line around 2025, this is also the timescale for the deployment of an appropriate facility. The community has raised the necessary resources to provide for follow-up on the NTT in the SOXS proposal for the NTT.

VISTA will move to 4MOST at the same time-frame as LSST will start operating. Clearly LSST will have a catastrophic impact on VST survey work. While a science case for a better seeing or narrow-band survey can always be made, the efficiency will be low (we already see this with KIDS). This would make operating the VST a rather expensive proposition.

**TMT and GMT**

E-ELT’s direct competitors are the Thirty Meter Telescope (TMT), which will use 1.4-m mirror segments and is targeting 2022 for first light, and the Giant Magellan Telescope (GMT), which will ultimately comprise seven 8.4-m mirrors, with the resolving power of a 24.5-m telescope, but which will begin operations with just four of those mirrors and which may therefore arrive even sooner.

**Euclid**

Euclid (a 1.2-m wide-field infrared/optical telescope at L2) is a self-contained space mission focused on weak gravitational lensing and baryonic acoustic oscillations. Thanks to the excellent image quality, photometry, grism spectroscopy and broad wavelength coverage, Euclid is to provide accurate photometric redshifts in an extragalactic 15,000 deg² survey.
Euclid should be able to constrain the equation of state parameters for dark energy with 1% accuracy. Additional tests of general relativity and CDM will come from the analysis of the Euclid survey.

Although Euclid does have grism low-resolution spectroscopy available, the wavelength range is limited and cross calibration using ground-based spectroscopic surveys will deliver more accurate redshifts. Deep MOS ($I_{AB}$ of 24.5 and $10^5$ galaxies) and an as-yet unspecified ultra-deep MOS sample have been discussed. The Euclid launch date of 2020 matches well with the date planned for the deployment of MOONS at Paranal, 2019.

Although Euclid is an ESA-led mission, NASA is providing the infrared detectors and a commensurate number of US-based scientists are part of the 1,200-strong Euclid consortium. NASA will establish a data centre at IPAC. The combination of facilities such as PFS at Subaru, which will be completing its 300-night survey at the launch of Euclid, and the 8-m-class telescopes available to the US community will create a significant pressure on ESO to provide support to the European community.

Euclid includes a very sensitive SN survey, DESIRE, that is largely self contained, pushes the redshift range of supernovae above unity and, critically, thanks to the broad wavelength coverage of Euclid, provides the same rest-frame wavelength coverage for the supernovae in the redshift range of interest. Host galaxy redshifts will be obtained from the ground. A need for follow-up of supernovae and other transients from ground-based facilities in a PESSTO style will be needed (see LSST discussion).

The Euclid deep survey will cover two fields of 20 deg$^2$ each. The higher cadence of the deep fields will generate more transients and these will also require follow-up.

**WFIRST-AFTA**

WFIRST is a NASA-led infrared 2.4-m telescope with a wide field of view, on schedule for a mid-2020s launch. The mission will be significantly later than Euclid and therefore will not compete directly. WFIRST is planned to deliver Hubble-quality imaging over a 200 times larger field of view. The follow-up of Euclid in terms of IR surveys will be dominated by WFIRST. With a much wider field of view than JWST, WFIRST will be a powerful tool for deep IR surveys, although the imaging survey is likely to cover ‘only’ 2,400 deg$^2$. The higher angular resolution of WFIRST will improve upon the surface density of galaxies compared to Euclid.

The capability of WFIRST to also use an IFU for spectroscopic characterisation makes it a self-sufficient observatory for many science cases (e.g. the detection and characterisation of thousands of type Ia supernovae).

Critically for the ESO landscape, WFIRST has a strong focus on coronography and monitoring of exo-planets, providing the ability to operate at exceptional contrast in the inner working angle of the telescope. The contrast that WFIRST is aiming for is of order $10^{-9}$, comparable to the best that is considered viable for the E-ELT/EPICS. The inner working angle of WFIRST is much larger than that of E-ELT but the discovery space for the ‘easy’ targets is likely to have been occupied if E-ELT/EPICS and WFIRST-AFTA arrive concurrently.

A SPHERE upgrade may rationally complement developments for EPICS depending on the WFIRST timeline.

**PLATO**

PLATO, scheduled for launch in 2024 by ESA, will provide a large number of planetary candidates whose parent stars will require spectroscopic follow-up for radial velocity measurements and characterisation. Additionally, there is much to be done in the field of astro-seismology which received a boost from Kepler. The PLATO science case requires significant ground-based follow-up. The facilities are largely in place but what is required is the necessary co-ordination for the allocation of telescope time. While a solid case can be
made that these observations are a pre-requisite for the success of the mission, the de-facto assumption that this is a sufficient case is not commensurate with the culture of ground-based time allocation. This is the “too many planets problem”.

Figure 11. WFIRST performance simulation of planets placed in orbit around the nearest 200 stars based on statistics from Kepler. If WFIRST achieves its goals (dashed line), rather than just the specification, imaging water planets will be plausible (source: NASA).

**TESS**
TESS is an explorer-class NASA mission to observe the nearest 100,000 bright stars to detect transiting exo-planets. TESS is scheduled for launch in 2017; before PLATO flies, TESS will have observed the bulk of the nearby objects and created a very fruitful interaction with JWST. The US community has the resources for spectroscopic follow-up and it is possible that many of the most promising targets will have been observed as ESA/ESO ramp up. This landscape forces us to consider the more systematic approach that characterisation of larger samples requires, especially arriving after the ‘wow factor’ has subsided. This is very much a replay of the WMAP/Planck scenario. ESO’s support of the PLATO mission must take into account that it is likely that TESS/JWST will have created a ‘new normal’ in the field of planetary transits and spectroscopy of exo-planet atmospheres. The discovery space will be defined either by exception (niche) or in the larger scale, or higher precision, of the experiments that follow.

**Gaia**
Gaia will revolutionise our understanding of the Galaxy and its dynamics. Furthermore, accurate distances are likely to change much of our current framework of stellar structure and evolution. The large Gaia-ESO survey is underway and will not only provide critical support to the mission itself but also a key foothold in the Gaia science for the broader ESO community (the survey results are promptly public).

We can expect that new structures within the Galaxy will need to be studied and therefore we can expect ever-increasing pressure for stellar spectroscopy across the optical and near-infrared regime.

**CTA**
The Cherenkov Telescope Array is a very ambitious observatory-scale facility that will revolutionise astro-particle physics starting before 2020 with the early deployment of the prototype systems developed in the design phase. Some of the deployments will be in the
northern hemisphere. The first large telescope is planned to be located at La Palma, adjacent to the MAGIC telescopes. One flavour of the small telescopes is likely to be located at the southern site as soon as that is selected. In the first instance, CTA can be considered to have a fairly limited scientific interface with the normal ESO programme. There is no doubt that the science drivers of the facility have profound implications for the physics of the Universe (e.g. dark matter signatures) and for the physics of the most energetic sources that we observe (blazars, GRBs, SNe, etc). The CTA landscape is one where sources of the most energetic photons need to be matched with optical counterparts. A plausibly reactive 4-m telescope with a few arcseconds field of view IFU in ToO mode should suffice for some of the science cases.

SKA
The radio landscape is evolving rapidly. We group together all of LOFAR, PAPER, ASKAP, MeerKAT and other facilities that are in some way SKA precursors. These telescopes are taking advantage of technological developments in focal-plane technology and computing facilities to enormously expand the survey capabilities in the radio. While the full SKA2 may not materialise on the timescales that this paper discusses, SKA1 at least in some permutation of the proposed SKA-mid, SKA-low or SKA-survey should start operating within the 2020 framework. The SKA1 landscape will include a HI map of the Universe probing to the start of the re-ionisation as well as large samples of radio galaxies, AGNs, etc. The interaction with the optical facilities will rest on the broader multi-wavelength capabilities of ESO in the south. SKA is a southern telescope and although the declination limits for radio telescopes are very low, the bulk of the survey results will be in the south. There is a natural synergy between the SKA and ESO for spectroscopic follow-up of surveys. It is clear that SKA1 observations will probe many other areas of astrophysics (e.g. pulsar studies of gravitational waves).

LIGO - eLISA
It is reasonable to expect that Advanced LIGO/VIRGO will provide the first direct detection of gravitational waves within the 2020 timeframe, if not sooner. This discovery, which has been long awaited, will require prompt and effective follow-up. While every observatory will be seeking the astrophysical counterpart of the signal, ESO is well placed to react promptly and effectively to such a detection. While the first detection may take some time to propagate through the astrophysical community, it is likely that a rapid reaction will be needed for subsequent events. The positional accuracy of LIGO is of order 1 degree although improved angular resolution will be forthcoming after the first detections (assuming that new facilities come online).

eLISA is on a longer time horizon but its increased sensitivity will create a plethora of sources that will need to be localised and possibly studied.

The ability to rapidly point with very wide field-of-view telescopes of significant size to the approximate location of the source will prove critical. An improved (i.e. accelerated) VST may find a reasonable niche in the rapid follow-up of transients.

eROSITA
eROSITA is expected to launch soon. The initial 4-year survey will deliver a complete 4π steradian census of the X-ray Universe out to a redshift of 3. The observations will provide us with many thousands of galaxy clusters, active galaxies, black holes as well as plethora of Galactic sources. A large-scale spectroscopic survey is a necessary complement to eROSITA and forms part of the 4MOST consortium science case. The proprietary time for the German part of the survey is 2 years, after which the data become public. There is therefore an issue of timelines. eBOSS is already planning to work with the SPI DERS northern survey from the same spacecraft.

Additionally, LSST will also be discovering a large number of clusters. While the redshift of the X-ray clusters needs to be determined, LSST will automatically provide a photometric redshift.
ATHENA
ATHENA will start operations in 2028. This brings it into the post E-ELT first-light timeline. ATHENA will have a large collecting area and high angular resolution (~5 arcseconds) and will probe the earliest epochs of galaxy formation and black hole formation. There exists a history of collaborative science between ESO/ESA in the framework of the XMM mission and it is expected that this will be the framework for the future. The ground-based observational capabilities to support ATHENA will include the need for deep imaging and prompt follow-up of transients. The E-ELT will probably be the telescope of choice for the very-high-redshift objects discovered by ATHENA.

Addressing challenges brought about by the changing global environment
The changing landscape is dominated by large facilities with very focused scientific aims. To engage with these facilities, ESO will need to act in a similar fashion, providing telescopes and resources for focused scientific objectives through dedicated instrumentation and large allocations of observing time. The available time for smaller programmes on the VLT and other telescopes will be reduced and the pressure factors will increase, though the over-subscription rate arguably has some headroom before it reaches a prohibitive level. The large community of users will feel pain and push back, nevertheless.

Scientific prioritisation within this framework is more complex than simply selecting an instrument. We are concurrently selecting observing time and – by nature of prioritisation – also restricting the resources for the remaining community. This is not unlike the space mission conflict, where non-selected themes can languish for generations.

If ESO chooses to move towards enabling more and/or larger surveys, then the teams [consortia, collaborations] that will come to consume much of the observing time will need to be representative of the bulk of their community. These teams will present coherent/consensus programmes to OPC and/or STC in order to acquire the necessary broad-based support. This implies that prompt innovation will occur within the consortia where much of the expertise will rest. It is unlikely that simply making the data public will satisfy the bulk of the community. ESO will need to provide support to observers of the data so that new ideas can be tested.

There will be a fundamental shift in the needs of the community, illustrated here by an analogy: in the current scheme, the catalogue is in the sky and the query is performed using a telescope. Today, ESO’s role is to provide the telescope/instrumentation and the operational support such that the query is successfully answered (e.g. delivery of high-quality B- and V-band imaging of a globular cluster). By obtaining the data, ESO answers the query: “provide the catalogue entries for B- and V-band photometry of said globular cluster”. The future role of ESO may be to provide support for queries such as “provide the colour-magnitude diagram of said globular cluster”. The evolution of data curation at ESO may well prove key to the future health of the organisation.
Annex 1: Panel members

Almudena Alonso-Herrero
Spain
Scientific and Technical Committee / E-ELT sub-committee
Email: aalonso@ifca.unican.es
Scientific Interests/Expertise: AGN and star-forming galaxies both in the local and distant Universe; stellar populations in galaxies; luminous and ultraluminous infrared galaxies; the dusty torus of the AGN Unified Model.
Current participation in projects: JWST/MIRI, GTC/CanariCam, SPICA/SAFARI, possible future mid-infrared instrument, MICHI, for the TMT.

Paola Caselli
Germany
Visiting Committee 2013-14
Email: caselli@mpe.mpg.de
Scientific Interests/Expertise: Astrochemistry; (Extra-)Galactic star and planet formation; molecular astrophysics; astrobiology, interstellar dust, radiative transfer, millimetre and submillimetre observations

Kirsten Kraiberg Knudsen
Sweden
Users’ Committee
Email: kraiberg@chalmers.se
Scientific Interests/Expertise: galaxy formation and evolution, star-forming galaxies at cosmological distances, distant starburst galaxies, properties of redshift z=2-7 (lensed) submillimetre galaxies and quasar host galaxies

André Moitinho
Portugal
Scientific and Technical Committee / La Silla Paranal sub-committee
Email: andre@sim.ul.pt
Scientific Interests/Expertise: Galactic astrophysics (namely star and planet formation, stellar clusters, stellar variability and the structure and evolution of the Milky Way Galaxy), machine learning/statistical data analysis, data visualisation.
Current participation in projects: Gaia - DPAC, visual analysis of large multi-dimensional data sets; GRAVITY (participation in the science preparation).

Stephane Vennes
Czech Republic
Scientific and Technical Committee / La Silla Paranal sub-committee
Email: vennes@sunstel.asu.cas.cz
Scientific Interests/Expertise: physics of hot stars (winds, disks), white dwarfs (evolution, atmospheric properties, distribution of white dwarfs in the Galaxy); hot subdwarfs (atmospheric properties, evolution); close binary systems (evolution, orbital parameters and atmospheric properties); optical and ultraviolet observations (spectroscopy and photometry).
Jean-Philippe Berger
ESO – VLTI Programme Scientist
Email: jberger@eso.org
Scientific interests/Expertise: observational studies of star and planetary formation with an emphasis on high angular resolution observations of proto-planetary disks and the study of the accretion ejection connection, compact binaries at high angular resolution; expert in interferometric instrumentation and associated research and technology, aperture synthesis image reconstruction software, quantum optics for astrophysics.
Current participation in projects: PI of IONIC-3 and PIONIER, co-I of SMART, instrument scientist of VSI and co-I of GRAVITY for IPAG before joining ESO.

Itziar De Gregorio Monsalvo
ESO – Joint ALMA Observatory – ALMA Programme Manager
Email: idegrego@alma.cl
Scientific interests/Expertise: star formation, interstellar medium, protoplanetary disks, jets and molecular outflows, multiple young stellar systems, brown-dwarf formation, planetary system formation, astronomical masers, and evolved stars; expert in cm/mm/submm interferometry, cm/mm/submm single-dish techniques (heterodyne and bolometer), commissioning of interferometers and single-dish telescopes, spectroscopy, calibration, data reduction.

Rob Ivison
ESO – Director for Science
Email: rivison@eso.org
Scientific interests/Expertise: galaxy formation and evolution, with emphasis on FIR, submm and radio observations; dust and molecular gas; symbiotic stars and cataclysmic variables; masers; formation and evolution of disks and planets.
Current participation in projects: KMOS and MOONS science teams, JVLA (3-bit samplers), NGVLA galaxy assembly working group, UK LSST science team, Euclid consortium.

Bruno Leibundgut
ESO – VLT Programme Scientist
Email: bleibund@eso.org
Current participation in projects: Supernova Intensive Study (HST observing consortium), The Dark Universe (Collaborative Research Center in Germany), Origin and Structure of the Universe Excellence Cluster (Munich).

Francesca Primas
ESO – Faculty Chair, Observing Programmes Office (Head of User Support Department, previously)
Email: fprimas@eso.org
Scientific interests/Expertise: chemical evolution (origin and evolution of the chemical elements in (extra-)galactic environments, primordial and stellar nucleosynthesis, the light elements lithium, beryllium, boron (production and galactic evolution), stellar evolution,
stellar atmospheres, globular clusters, high resolution spectroscopy. Expert in data flow operations of modern observatories.

**Ivo Saviane**  
ESO – La Silla Site Manager  
Email: isaviane@eso.org  
Scientific interests/Expertise: (early) star formation in galaxies, resolved stellar populations of the Local Group (LG), in particular on Galactic globular clusters (GGCs) and dwarf galaxies; UV, optical and IR photometry, applied to star clusters and dwarf galaxies, mid-resolution spectroscopy; expert in science operations (Paranal and La Silla).

**Jason Spyromilio**  
ESO – Head of Project Science Department, 2015- (E-ELT Programme Scientist previously)  
Email: jspyromi@eso.org  
Scientific interests/Expertise: physics of supernova explosions.

**Leonardo Testi**  
ESO – European ALMA Programme Scientist  
Email: ltesti@eso.org  
Scientific interests/Expertise: high mass star formation and interaction with surrounding interstellar medium, young (proto-)stellar clusters, young brown dwarfs, circumstellar disks and their evolution; observational techniques from radio to near-IR.

**Contributions also made by:**

**Joe Liske**  
ESO – E-ELT Programme Scientist, from October 2014  
Email: jliske@eso.org

**Felix Stoehr**  
ESO – Subsystem Scientist of the ALMA Science Archive  
Email: fstoehr@eso.org
Annex 2: Terms of reference

- The panel will review and prioritise ESO’s scientific programme, evaluating all existing and planned projects above a nominal total cost threshold of €1M. Although the panel will generally take a bird’s-eye view, where it is deemed necessary it is free to investigate topics in detail – an “adaptive grid” approach.

- The panel will organize a major ESO workshop in 2015 January to look at the likely astronomical landscape in the 2020s, inviting the community to advise the ESO Executive with regard to future facilities, including but not limited to LSP and the Joint ALMA Observatory.

- The panel’s recommendations will be presented to the Scientific and Technical Committee (STC) of ESO Council.

- The review will take into account the views of the ESO community via an electronic poll, and via cross-membership in the Visiting Committee (VC), Users’ Committee (UC) and STC of five (of 13) panel members.

- The panel will quantify the scientific importance of each of a number of astronomical science topics deemed likely to remain compelling into the 2020s, thereby laying the framework for the prioritization of individual projects via their ability to increase our understanding of those topics.

- The report will include the ALMA2030 report, a link to the latest version of the Paranal Instrumentation Programme, and will supersede the so-called LPO White Paper.

- The onus is on individual panel members to declare any personal or institutional conflicts of interest.

- The process will be transparent and the panel’s report will be freely available.
Annex 3: ‘ESO in the 2020s’ workshop programme

Workshop “ESO in the 2020s”
ESO Garching, 19-22 January 2015

Scientific Programme

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<th>Day 1: Monday, 19 January 2015</th>
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<td>12:00-13:00 REGISTRATION</td>
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<tr>
<td>13:00</td>
<td>T. de Zeeuw</td>
<td>Welcome</td>
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<tr>
<td>13:10</td>
<td>R. Ivison</td>
<td>Introduction</td>
</tr>
<tr>
<td>13:20</td>
<td>F. Primas</td>
<td>Community Poll</td>
</tr>
<tr>
<td>13:40</td>
<td>M. McCaughrean</td>
<td>ESA Programme (Invited Talk)</td>
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**Planets and planet formation**

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<tbody>
<tr>
<td>14:30</td>
<td>M. Bizzarro</td>
<td>Origin of the solar system (Invited Talk)</td>
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<tr>
<td>15:10</td>
<td>Y. Alibert</td>
<td>Exoplanets (Invited Talk)</td>
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<tr>
<td>15:50</td>
<td>I. Jimenez-Serra</td>
<td>Astrobiology (Invited Talk)</td>
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<tr>
<td>16:30</td>
<td><strong>Coffee Break</strong></td>
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<tr>
<td>16:50</td>
<td>T. Stallard</td>
<td>Giant planets in the solar system: Ongoing and upcoming observations and their implication for exoplanets and brown dwarfs</td>
</tr>
<tr>
<td>17:10</td>
<td>A. Fitzsimmons</td>
<td>Asteroids and comets in the coming decade</td>
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<tr>
<td>17:30</td>
<td>L. Testi, P. Caselli, S. Udry</td>
<td>Panel Discussion</td>
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<tr>
<td>18:30</td>
<td><strong>End of Day 1</strong></td>
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<tr>
<td>18:30</td>
<td><strong>Welcome Reception</strong> (Foyer of New Auditorium Eridanus, HQ.E-Foyer)</td>
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<thead>
<tr>
<th>Day 2: Tuesday, 20 January 2015</th>
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<tbody>
<tr>
<td><strong>Stars, formation and evolution</strong></td>
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<tr>
<td>08:30</td>
<td>S. Longmore</td>
<td>High-mass star formation/ clusters (Invited Talk)</td>
</tr>
<tr>
<td>09:15</td>
<td>G. Chabrier</td>
<td>Stellar evolution (Invited Talk)</td>
</tr>
<tr>
<td>10:00</td>
<td>E. Humphreys</td>
<td>Late-type stars (Invited Talk)</td>
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<tr>
<td>10:45</td>
<td><strong>Coffee Break</strong></td>
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<tr>
<td>Time</td>
<td>Speaker</td>
<td>Topic</td>
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<tr>
<td>11:00</td>
<td>A. Richards</td>
<td>Seeing into stars (and their clouds)</td>
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<tr>
<td>11:20</td>
<td>R. Smiljanic</td>
<td>Overview of <em>Gaia</em>-ESO Survey results based on high-resolution spectra of FGK-type stars</td>
</tr>
<tr>
<td>11:40</td>
<td>S. Feltzing, P. Roche</td>
<td>Panel Discussion</td>
</tr>
<tr>
<td>12:30</td>
<td>Lunch</td>
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<tr>
<td>13:30</td>
<td>R. Braun</td>
<td>SKA (Invited Talk)</td>
</tr>
<tr>
<td>14:00</td>
<td>M. Bremer</td>
<td>Do we need a wide-field 8-m spectroscopic survey telescope?</td>
</tr>
</tbody>
</table>

### Milky Way and Local Neighbourhood

- **14:20** F. Eisenhauer: The centre of the Milky Way (Invited Talk)
- **15:05** A. Helmi: The Milky Way as a galaxy (Invited Talk)
- **15:50** M.R. Cioni: Magellanic Clouds (Invited Talk)
- **16:35** Coffee Break
- **16:50** R. Davies: Resolved Stellar Populations with Visible Adaptive Optics on the VLT
- **17:10** F. Primas, I. Saviane, C. Evans, J. Knapen: Panel Discussion

### Day 3: Wednesday, 21 January 2015

#### Galaxies

- **08:30** R. Maiolino: Gas in galaxies (Invited Talk)
- **09:15** V. Mainieri: AGN and galaxies (Invited Talk)
- **10:00** N. Förster-Schreiber: Galaxy evolution (Invited Talk)
- **10:45** Coffee Break
- **11:00** S. Hoenig: AGN cosmology – a new perspective for VLTI in the E-ELT and LSST era
- **11:20** S. Smartt: Explosive transients in the next decade
- **11:40** A. Alonso-Herrero, L. Tacconi, F. Hammer: Panel Discussion
- **12:30** Lunch
### Cosmology

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<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
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<tbody>
<tr>
<td>14:00</td>
<td>S. Bridle</td>
<td>Weak lensing in the next decade (Invited Talk)</td>
</tr>
<tr>
<td>14:45</td>
<td>P. Noterdaeme</td>
<td>Gas at high redshift/ fundamental constants (Invited Talk)</td>
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<tr>
<td>15:30</td>
<td>J. Peacock</td>
<td>Large Scale Structure (Invited Talk)</td>
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<tr>
<td>16:15</td>
<td><strong>Coffee Break</strong></td>
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<tr>
<td>16:30</td>
<td>M. Haehnelt</td>
<td>The future of reionization</td>
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<tr>
<td>16:50</td>
<td>C. Cicone</td>
<td>ESO in the 2020s: the “bright” millimetre/ sub-millimetre future</td>
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<tr>
<td>17:10</td>
<td>B. Leibundgut, C. Lagos, Y. Mellier</td>
<td>Panel Discussion</td>
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<tr>
<td>18:00</td>
<td><strong>End of Day 3</strong></td>
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### Day 4: Thursday, 22 January 2015

#### Future facilities

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<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
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<tbody>
<tr>
<td>08:30</td>
<td>P. Antilogus</td>
<td>LSST (Invited Talk)</td>
</tr>
<tr>
<td>09:15</td>
<td>S. Wagner</td>
<td>Gamma-Ray Astronomy in the 2020s (Invited Talk)</td>
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<tr>
<td>10:00</td>
<td><strong>Coffee Break</strong></td>
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<tr>
<td>10:15</td>
<td>J.-P. Berger</td>
<td>VLTI</td>
</tr>
<tr>
<td>10:55</td>
<td>B. Leibundgut</td>
<td>VLT</td>
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<tr>
<td>11:35</td>
<td>L. Testi</td>
<td>ALMA</td>
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<tr>
<td>12:15</td>
<td>I. Hook</td>
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<td>14:00</td>
<td>R. Ivison</td>
<td>Concluding Remarks and Discussion</td>
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A ROAD MAP FOR DEVELOPING ALMA

ASAC recommendations for ALMA 2030


This document summarizes the recommendations emerging from the ALMA 2030 process. The findings are discussed in three documents: 1) the Major Science Themes in the 2020-2030 decade, 2) the landscape of Major Facilities by 2030, and 3) the Pathways to Developing ALMA, which describes a number of possible developments.

After compiling this information, the ALMA Science Advisory Committee discussed together with the Regional Program Scientists and the JAO at its February 2015 face-to-face meeting the best avenues for mid- and long-term improvement of the observatory, arriving at the conclusions presented here. The purpose of these recommendations is to guide the regional ALMA Development process in a coherent fruitful direction, by presenting a list of broad themes we foresee as the highest priority among the developments considered. It is important to keep in mind, however, that the development process also includes a creative, bottom-up element. Innovative technical ideas well grounded in astronomy should also have space in the future development of ALMA, and in that sense this is not an exclusive list. It also assumes that completion of the baseline capabilities of ALMA (adding bands 1 and 2) will proceed.
Separately from these developments, the ASAC notes that a large single-dish telescope equipped with cameras capable of fast large-scale mapping would be an important scientific complement to the interferometer. Such an instrument is outside the scope of the envisioned ALMA development projects, but if built, it would have large potential scientific synergies with ALMA (for example, surveying for sources, or providing the larger source context).

**Recommended development paths**

1. **Improvements to the ALMA Archive**: enabling gains in usability and impact for the observatory.
2. **Larger bandwidths and better receiver sensitivity**: enabling gains in speed.
3. **Longer baselines**: enabling qualitatively new science.
4. **Increasing wide field mapping speed**: enabling efficient mapping.

**Better usability and impact: ALMA Archive**

The archive is an integral piece of the observatory. An archive that is easy to use for the non-expert, and goes beyond being simply a repository for PI data is a great potential multiplier for the impact of ALMA. Analysis of the productivity of mature facilities shows that publications using archival data can rapidly overtake the publications from the original proposers acquiring the dataset, as is the case for the Hubble Space Telescope and other facilities. Thus the archive may be what ultimately determines the productivity of ALMA.

In order for the archive to be productive, it needs to be public, searchable, easy to mine, and it needs to contain fully reduced science-grade data products. In addition, the archive should contain value-added products either automatically generated (for example, lists of “detected lines” in the target), or user submitted post publication. Ideally the archive should be fully compliant with the Virtual Observatory standards, to be able to interface across wavelengths. It is also crucial that it can be fully exploited by users outside the community of interferometry and mm-wave experts.

With high sensitivity, position, frequency information, and large bandwidth, ALMA data are intrinsically very rich. A common feature is “involuntary” line surveys of sources, where lines beyond the targeted transitions are detected and mapped. The archive developers are already working on a few features to make it more user-friendly, with the introduction of quick visualizations of datasets, for example. Regional funding is being used to develop the first efforts into archive “enrichment” toolkits in EU, EA, and NA (e.g., ADMIT, the Japanese Virtual Observatory ALMA interface). Developing the ALMA archive into a fully-fledged science-grade minable archive, however, requires significant further development into pipelines and automated analysis. Because it will be unlikely that the quality of an automated pipeline reaches what is possible with experienced user reduction, we think the archive should be designed to accommodate user-submitted products (a version of this has been done for legacy- or treasury-class projects in facilities such as Spitzer, Herschel, and HST).

**Gains in speed: Larger Bandwidths and Improved Receivers**

The ability to provide and process wider instantaneous bandwidths, together with continuous improvements in receiver sensitivity, can bring scientifically significant increases in observation speed. The ultimate goal is to correlate an entire receiver band in one go, with
no loss of sensitivity. This requires improvements not just to the receivers themselves, but also to the digitizers, the IF transport, the correlator, and the archive.

Increasing the IF bandwidth of the receivers appears as eminently feasible technologically. ALMA currently features a 4 GHz bandwidth per sideband, except in Band 6 where it is 5 GHz. CARMA and NOEMA, by comparison, feature 1-9 GHz and 4-12 GHz IFs, providing 8 GHz of bandwidth per sideband (note that a bandwidth of at least 6 GHz would allow to fit simultaneously $^{12}\text{CO}$ and its common isotopologues in one sideband of Band 3, for example). Doubling the bandwidths of the digitizers, fiber-optics transmission, correlator, and archive seem, likewise, eminently possible with current technology. The expansion of the IF to include an entire band will require considerable research. Nonetheless, it looks like an achievable long-term goal that will bring gains of factors of ~4-6 in speed for many observations. Bandwidth expansions will, simultaneously, enormously increase the legacy value of the archive while increasing the likelihood of serendipitous discoveries.

Continuous improvement to receiver sensitivities will also result in significant gains in speed across all science. Besides improving receiver temperatures (through removal of warm optics, or improved devices), the dual sidebanding of the currently DSB Band 9 and Band 10 receivers would yield important gains in speed at the higher frequencies of ALMA operation. Long-term sustained research in better devices or new technologies (such as TKIP amplifiers) has the potential to yield significant breakthroughs that are equivalent to doubling or tripling the collecting area of the array with its present instrumentation.

**New Science: Longer Baselines**

ALMA just recently demonstrated the potential of 10-km baselines in millimetre-wave interferometry by producing breathtaking images of the HL Tau protostellar disk and the SDP81 gravitational lens, among other targets. The designed maximum baseline of ALMA is 16 km. Doubling it to 32 km will provide an angular resolution of ~8 mas at 230 GHz (reaching this resolution at optical wavelengths would necessitate a 16 m diameter telescope in space). This is the size of the photosphere of α Centaurus A, and it is equivalent to a resolution of 1 AU at the distance of the Taurus molecular cloud (140 pc), ~10 pc at 240 Mpc, or a resolution of ~60 pc in the high-z universe (the size of a large Giant Molecular Cloud in the Milky Way). With the current system the Rayleigh-Jeans 1-sigma noise equivalent in a 24-hour continuum integration would be ~1 K at that angular resolution. This means that it is certainly possible to image warm dust structures with a moderate optical depth (τ≥0.01), and it is easy to detect stellar photospheres, which have resolved brightness temperatures of several thousand degrees.

A further doubling of the baseline to ~60 km would lower the sensitivity to 4 K (assuming no improvements to the system), which means that a wide range of structures can still be imaged (from warm dust in protoplanetary disks to AGN tori). This angular resolution corresponds approximately to the diameter of the main sequence B7 star Regulus, 20 pc away. High signal-to-noise imaging of stellar photospheres at high-resolution opens up the possibility of measuring star-spots, temperature gradients, and stellar shapes in nearby stars.

Longer baselines will also allow for very accurate astrometry of nearby solar-type stars, enabling the search for planetary companions through their orbital effects. A Jupiter-like
companion of a solar mass star induces a wobble of ~0.01 AU (i.e., ~1 mas at 10 pc) on the primary: because high signal-to-noise measurements can centroid with very high precision, and because ALMA astrometry should be extremely stable over long periods of time, it is likely that ALMA can look for companion-induced wobbles in stars out to several tens of parsecs. The bottom line is that increasing the resolution of ALMA has the potential to lead to qualitatively new scientific insights about the universe, and even more so when coupled with the sensitivity/bandwidth increases that we recommend in the previous point.

An intrinsic advantage of an interferometer is that the increase in angular resolution can be done progressively, by adding new antenna stations at larger distances. It is possible to progressively increase the length of the maximum baseline over the designed 16 km to understand the technical and practical limits of the equipment (e.g., LO distribution noise, line-length correction, and ultimately correlator) and the normal coherent correlation technique.

Correlation on long baselines requires using atmospheric phase correction techniques, currently 183 GHz water vapor radiometry in combination with fast switching in ALMA. Devoting effort to perfecting the atmospheric phase correction is something that should proceed in parallel with the investigation of the longer baselines. This will likely pay off not only on long baselines, but also on the fraction of usable time at the highest frequencies.

**Wide Field Mapping Speed: Multi-beam Receivers**

One of the major limitations of ALMA is its relatively small field of view (~1 arcmin at Band 3 and inversely proportional to frequency), determined by the diameter of the antennas and their primary beam. There is considerable scientific interest in increasing the field of view to enable faster wide field mapping of extended objects. Survey and imaging science will benefit from this.

The primary way to attain potentially large gains in mapping speed is to develop multi-pixel array receivers for interferometry. Such receivers are likely to occupy a significant fraction of the (already tightly packed) available focal plane space, and are likely feasible for only one band at a time and with only modest pixel counts without major redesign of the antenna optics. Nonetheless, it makes a lot of sense to investigate the tradeoffs in replacing a high-demand band (e.g., band 6 or 7) single-element receiver with a multi-pixel receiver.

The technical and scientific tradeoffs involved in developing and using multi-pixel receivers in ALMA are complex and require investigation to evaluate feasibility. Upgrading even one band to a multi-pixel receiver requires a number of improvements in elements downstream (IF transport, correlator, archive), and possibly upstream (LO distribution). Some of these improvements may be parallel with improvements required by larger bandwidths. In particular, for many science projects that require mapping of one spectral line, it may be practical to share bandwidth among pixels (large scale mapping of continuum sources would not be practical with such a scheme).