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Paranal Instrumentation Plan Lessons Learned 2023

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The 2023 Paranal Instrumentation Programme Lessons Learned exercise assessed the recent major projects delivered to Paranal. The goal was to identify good practices and improvements for the future by examining cost, schedule, and performance against targets. The review also considered ESO's response to the previous exercise and lessons learned from interactions with partner institutes in Europe. This article summarises the overall findings and key recommendations for ESO.

Introduction

The 2023 Paranal Instrumentation Programme (PIP) Lessons Learned exercise was scoped by ESO as a review of the lessons learned for the future from the major projects delivered recently to Paranal, namely the GRAVITY instrument, the Multi-AperTure mid-Infrared Spectro-Scopic Experiment (MATISSE), the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO), the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+), the Adaptive Optics Facility (AOF) and the Very Large Telescope Interferometer (VLTI). Instruments still under construction will be covered in a future exercise. The goal of the exercise was to explore the lessons learned to identify good practice and improvements for the future. Specifically, the panel was tasked with:

- examining the overall cost, schedule, and performance of each project against its targets;
- reviewing and commenting on the response by ESO to the last exercise; and
- examining the lessons learned in interacting and partner institutes in Europe.

In this article we present the overall findings of the 2023 Lessons Learned review and the key recommendations made to ESO, including some suggestions for potential actions. The review panel consisted of Matthew Colless (Chair), Michele Cirasuolo (Vice-chair), Anja C. Andersen (La Silla Paranal Committee), Vanessa Hill (Scientific Technical Committee), Rebecca Bernstein and John Monnier (external members), Sebastian Egner (internal member) and Antoine Mérand (secretary).

Overall lessons learned

The lessons learned summarised below are the consensus conclusions drawn by the panel from information provided in the course of the review (the documentation and presentations provided by the representatives of the consortia, the ESO-Garching follow-up teams, and the ESO-Paranal operations teams) together with the subsequent discussions.

Previous lessons learned

The timeframe covered by the projects in this review is important, given that a goal of this Lessons Learned exercise is to "review and comment on the response by ESO to the last exercise". All these projects started prior to the previous review (see Figure 1), and so only benefitted from any changes that ESO implemented in response during the latter stages of each project. This makes it difficult to judge the effectiveness of ESO's response to the previous exercise based on these particular instruments and facilities.

It is therefore not surprising that many issues noted in the previous exercise were also apparent in these projects. On the other hand, some positive changes were seen, most notably in improved relations between the ESO-Paranal operations teams and the consortia and ESO-Garching follow-up teams during the very intense commissioning phases of these instruments and facilities, which generally occurred after the previous Lessons Learned exercise.

Infrastructure implications

One of the notable features of the instruments/facilities covered by this Lessons Learned review is that they mostly involve

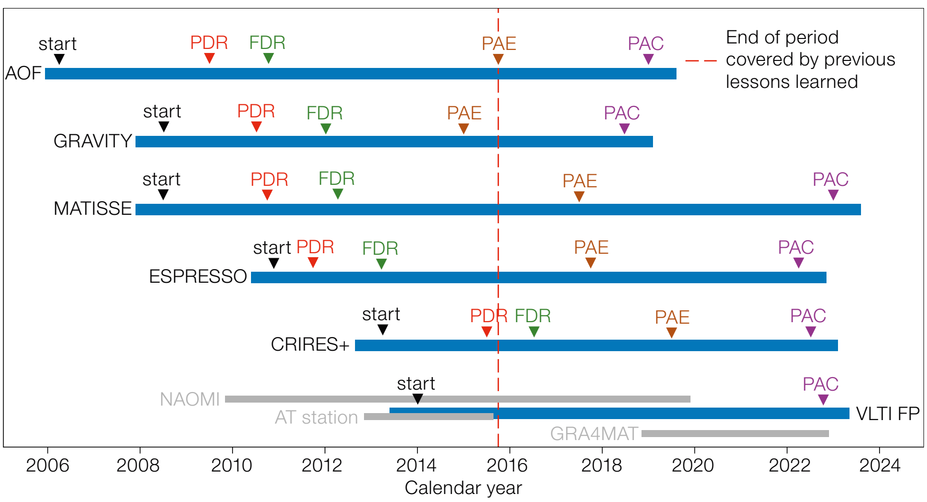

Figure 1. Timelines of instrument/facility projects covered by this review, showing key milestones for each project and the previous Lessons Learned exercise (red dashed line). 'Start' means the beginning of the project at ESO (i.e., after phase A); PDR = Preliminary Design Review; FDR = Final Design Review; PAE = Preliminary Acceptance Europe; and PAC = Preliminary Acceptance Chile.

substantial coordination with (or major upgrades to) the infrastructure of the VLT/I facility and its operations. This contrasts with most instruments covered in previous reviews, which tended to have (relatively) simpler interfaces to the telescopes and their infrastructure. It was clear that the degree of coordination with existing infrastructure was underappreciated in the initial stages of these projects and consequently projects were inadequately scoped and costed; this was broadly true for both ESO-led projects and consortia-led projects.

Overview of cost and schedule

Depending on the project, the hardware cost was provided by some combination of ESO and consortia, and the latter were compensated with nights of guaranteed time observations (GTO). While for GRAVITY and MATISSE the consortia contributed most of the hardware cost, for ESPRESSO and CRIRES+ the contributions were more balanced between ESO and the consortia. The costs of the VLTI and AOF facilities were covered almost entirely by ESO.

In terms of effort (FTE = person-years) used for the projects, there is no traceability nor visibility of the FTEs spent by the consortia, but only those spent by ESO for the follow-up team and the specific work packages delivered by ESO, such as detectors. For the VLTI and the AOF the FTEs also account for all the work done in-house at ESO, to upgrade infrastructure and to deliver the project. Comparing the planned FTEs at kick-off to the actual FTEs spent, the ESO effort over-run ranged from a factor of 1.3 to 2.9, with a mean of 1.9.

For estimating the delays to schedule (planned versus actual), the time from kick-off to Preliminary Acceptance Europe (PAE) is considered the fairest and most reliable measure of project duration. The schedule over-run in reaching PAE is similar for the various projects, ranging from a factor of 1.3 to 2.5, with a mean of 1.8. For all projects, most of the delays happen in the manufacturing, assembly and integration (MAIT) phase, between Final Design Review and PAE.

Integration of project teams

The consortia, ESO-Garching and ESO-Paranal teams for almost all the projects reviewed here reported benefits from better project integration as a result of members of each of these teams embedding/visiting/interacting more with the other teams on the same project. Specific examples from the ESPRESSO and AOF projects were given, where these benefits were clearly realised and positively recognised by all parties. But these actions were taken in response to crises, while it seems likely that increased interactivity would help to avert not only crises but also some of the misunderstandings and errors in instrument design or implementation that appeared in most of these projects during commissioning or in operation. Benefits were felt to be greatest when interactions occurred earlier and over longer timescales; leaving interactions until a formal review was as likely to cause problems as to solve them. All the externally led projects indicated they would have appreciated better integration with ESO and a more continuous contribution of ESO technical experts so as to bring in experience and to communicate and ensure the implementation of ESO standards (rather than just checking their compliance at the reviews).

There was a call on all sides for more engagement by the ESO-Paranal operations team in earlier phases of instrument development, as expressed by the consortia, by the ESO-Garching follow-up teams, and by the ESO-Paranal operations team. This engagement should be over the life of the project and not just at reviews, although there is real value in having active Paranal involvement in reviews if this can provide some assurance to the consortia and ESO-Garching teams that design decisions are in some sense approved by Paranal. Engagement needs to be through interaction of personnel as well as through formal procedures and documentation. Several groups mentioned problems and delays with the change control process at Paranal.

On the other hand, increased engagement was a real concern for Paranal operations team members and management, who did not feel they had sufficient capacity to supply effort to support instrument projects prior to commissioning because existing resources were wholly consumed by the demands of operations. The review panel could clearly see this tension and the strains imposed on operations staff by such 'additional' workload. Nonetheless, the panel considered there to be a plausible case that extra time spent by ESO-Paranal staff on instrument development (if intelligently directed) could potentially reduce the amount of time spent on instrument commissioning, 'Paranalisation', maintenance and repairs, leading to a reduced overall load on consortia, on ESO-Garching follow-up teams, and on ESO-Paranal operations staff themselves. To make the handover and operation of the instrument to LPO smoother, a more systematic transfer of the knowledge gained about the behaviour of the instrument during MAIT could be useful. This would include engineering data such as logbooks, solutions to encountered problems, and sensor readings.

Similarly, it was noted that the best outcomes for ESO and the user community were obtained when the teams were constructively engaged well after Preliminary Acceptance Chile (PAC), and there were positive examples of that amongst the instruments/facilities reviewed here. Effective management and good relations with the consortia during the instrument support phase after delivery and the GTO period, together with continuing access to the ESO follow-up team, are the critical ingredients. It was particularly mentioned that it is necessary to update the data-reduction software based on commissioning results and the feedback by users after early open observations with the instrument, and to include revised and improved algorithms. To further optimise the outcome, a more flexible scheme for GTO, perhaps allocating half-nights where appropriate and providing compensating time for bad weather, might be beneficial.

Reviews and documentation

As expected, reviews were a recurring theme. The Lessons Learned panel heard sufficient concerns from all parties to justify the planned ESO 'review of reviews'.

While the panel will leave specific recommendations to that process, we can report the key concerns expressed by those involved in the projects reviewed here. These included: excessive documentation that was not in fact much used or much use; reviews of instruments being used to drive wider political agendas within ESO; related to that, insufficient independence of the review panels from ESO, especially where ESO was itself a significant element of the project; and insufficient expertise on the review panels, so they degenerate into tick-the-box checks of low-level requirements, rather than incisive investigations into whether instruments meet top-level science requirements effectively and efficiently, and their long term operability. The consortium representatives for one project suggested that the top-level requirements should be the sole focus of reviews at all review stages. The panel was not convinced by that suggestion, believing that reviews need to work down the chain of requirements as the project advances. However, reviews must always keep a close eye on the top-level requirements (particularly the top-level science requirements) and not get hung up on lower-level technical requirements if they do not have significant implications for the top-level requirements. The opinion of most of the consortia (and even of some ESO staff involved in the projects) is that the pendulum may have swung towards micro-management and even 'micro-design', the imposition by ESO of specific design solutions based on taste rather than clear benefits to the top-level requirements, operability, or maintainability. This seems to be due in part to the complexity of the projects (particularly projects with a complicated infrastructure interface), which makes it harder to have a top-level view, and in part to increasing formalisation of the contractual relationship (see below).

Several consortia, ESO-Garching follow-up teams and ESO-Paranal staff recognised the importance of adequate testing in Europe prior to PAE and shipping to Chile, since fixing problems at Paranal is generally (though not invariably) much more complex and expensive.

Communication

As is almost always the case in large, complicated organisations and projects, a common complaint was a failure to communicate information in a clear and timely fashion to all relevant parties within a project. In most cases, this could be put down to a failure (on all sides) to follow the policies and procedures already in place. However, there was also an apparent lack of communication about broader, context-setting information (for example, that GRAVITY was prioritised over other projects, or that the Paranal operations team would have more constrained resources). Such information, if appropriately shared, can be used by all parties to make more realistic plans and can also reduce misunderstanding based on differing assumptions or knowledge. More generally still, the panel recognised that future instrument Principal Investigators, Project Managers and others in key roles (both external and internal to ESO) could potentially benefit greatly from exposure to the information and accumulated knowledge on display in this review that is held by past PIs/PMs and the highly experienced ESO staff at both Garching and Paranal.

Contractual relations

Another broad issue, raised in various forms by most of the projects, is that of contractual relations between ESO and external consortia and the non-contractual relations between different parts of ESO itself. There was a repeatedly expressed desire for the relationship between ESO and the consortia to be more collaborative and less contractual. The consortia reported an increased formalisation of the client-contractor relationship by ESO, with a tendency for this to lead to more adversarial interactions. Obviously, there is a tension between the desire of all parties to have a more effective collaborative partnership and the need for ESO (and sometimes the consortia!) to have a more formal and explicit statement of responsibilities. This is further complicated when (as in most of the projects reviewed here) ESO is delivering significant components of the instrument or facility, and so is simultaneously in a client-contractor relationship and a collaborative partnership. These unavoidable issues are exacerbated when ESO, as internal contractor as well as client, does not live up to the standards it demands of external contractors; there were sufficient examples of this amongst these projects to make this a real grievance for some of the consortia.

VLTI strategy

The VLTI was a focus for three of the six instruments reviewed here (GRAVITY, MATISSE and the VLTI facility itself). ESO's goals of recovering from the slow start of the VLTI and fully exploiting a capability that will remain world-leading even in the Extremely Large Telescope (ELT) era were clearly on display. The enormous scientific impact of GRAVITY and the more modest but still successful applications of MATISSE demonstrate that ESO is turning the corner with the VLTI, making it more scientifically productive and more interesting and usable by a wider (though still specialist) community. Set against this, however, the ESO people most involved still perceive the VLTI to be substantially under-appreciated internally, despite the high priority given to GRAVITY (and now GRAVITY+). There appear to be a few reasons for this perception, including a long-standing bias against the VLTI (considered an unwished-for encumbrance by earlier generations of ESO staff), the failure and cancellation of the Phase-Referenced Imaging and Microarcsecond Astrometry (PRIMA) project, and — more currently — issues with the way that ESO is (or appears to be) outsourcing the VLTI increasingly to some institutes. Some of the ESO staff working on the VLTI feel disenfranchised by the degree of control exercised by the Max Planck Institute for Extraterrestrial Physics (MPE) first in GRAVITY and now in GRAVITY+, which does appear greater than that found in other VLT/I (or ELT) projects. While it was clearly appreciated that without MPE neither GRAVITY nor GRAVITY+ could be realised, there was nonetheless a desire for ESO to maintain some control and engagement, at least at the same level as for other instrument projects. There is the distinct possibility that ESO will lose its most capable people in this field if it does not invest more and exercise more control over VLTI development.

Technology standards

There are clear benefits to having standards in instrumentation technology, software architecture and so on, and these benefits accrue both to ESO and to the consortia in a variety of ways. The two main challenges are: (i) balancing standardisation with quick uptake of powerful new technologies (when is standardisation appropriate in rapidly evolving areas?); and (ii) not imposing standards on projects so late in their development that this has a substantial impact on project cost and schedule (what should the policy be in this regard?). With software standards in particular, there seems to be an opportunity for ESO to provide considerable efficiency savings to consortia by supplying its in-house expertise (see below). There was a widespread view that ESO should also invest more in developing innovative technologies (either in-house or via external contracts) that could be useful or transformative for multiple instruments (for example, gratings, real-time computing, detector controllers, curved detectors, etc.).

In-house capabilities

ESO's instrumentation programmes have benefitted from considerable in-house capabilities and expertise. In earlier times this was generated naturally, because ESO was playing a leading role in a range of instrument projects. Now, however, the instrumentation programme is larger and broader, while in-house capabilities are focussed on the challenge of building the ELT and are constrained by tighter financial circumstances. This means ESO is finding it more difficult to maintain the breadth of expertise needed to be a well-informed client/manager of the instrument programme while simultaneously nurturing the deep expertise in key fields that has been crucial to solving major problems that have arisen within instrument projects. The external consortia emphasised that successful instruments required motivated, competent, and experienced ESO staff with strong technical skills and field experience, who were essential to a productive relationship between the consortia and ESO based on mutual respect.

ESO will only have a pool of such staff if it keeps developing at least one instrument (or equivalent) in-house at any time. This might also be partially addressed by embedding some ESO staff in external instrument consortia, but that does not necessarily foster deep expertise in leading instrument projects or critical skills/technologies. Another partial solution may be to delegate some areas of expertise to ESO's closest industry partners. While a lack of in-house expertise has not unequivocally led to issues in the set of instruments and facilities reviewed here, both consortia and ESO participants flagged this as a serious problem that is likely to grow as key experts retire. Moreover, ESO's VLTI experts indicated that key competencies in that area could be lost unless ESO is able to take a greater and more leading role in future VLTI projects. The significant number of retirements of senior managers and technical staff from the 'VLT generation' over the next few years is an added challenge that should be taken as an opportunity for renewal. ESO will need to find ways to attract junior staff and graduate students who are willing and able to be involved in instrumentation projects (both on the science and engineering sides).

Conflict management

Both ESO staff and consortia raised the issue of improving ESO's conflict management skills and procedures in light of the perceived increase in friction between ESO and consortia. Suggestions included: closer, earlier, and more intimate integration of ESO staff with consortia (as discussed above) to make them collaborators and to avoid ESO's just being seen as the 'review police'; better training for ESO staff in managing conflicts; and more rapid escalation of problems to appropriate management levels before they cause damage.

Short-term hirings

The benefits and difficulties of short-term hirings were raised by some of the project teams. Given the unpredictable demand for staff resulting from the uncertainties associated with multiple simultaneous projects, there are clearly potential benefits to ESO if it can access skilled technical staff on a short-term, temporary basis when needed. The panel understands that legal restrictions, and perhaps internal concerns, have made such short-term hirings difficult or impossible, removing an important and effective lever from ESO's toolbox for managing the demands of its instrumentation programme.

Fragmentation and churn

Two other staffing issues raised in multiple contexts were the impact of fragmentation (the slicing of effort into smaller and smaller units) and churn (the rapid turnover of staff). Fragmentation is common in matrix-managed organisations. In theory it appears to be the efficient use of resources, but in practice it is highly inefficient because it atomises attention and imposes overheads, leading to staff stress and low morale. The VLTI facility supplied the clearest example of the cost to ESO of an overly fragmented technical workforce, but other projects also raised the issue. Churn can have various origins but is often a sign of lack of job satisfaction or precarity of employment. It too is highly inefficient, for similar reasons to fragmentation — personnel changes waste accumulated knowledge and impose overheads in the form of retraining requirements and re-establishing relationships. The seven project scientists involved in the CRIRES+ project supply the prime example of churn in this review, but there were other examples.

Finally, there were concerns that ESO staffing requirements were being underestimated because people were (either of their own accord or by direction) only requesting roughly the number of FTEs available, rather than the number of FTEs they really needed. For ESO to understand its true resourcing situation, it is essential that the real FTEs needed for each project are accurately estimated and recorded, reflecting the actual project needs and not just what it is reasonable to request given the constraints of available resources. The panel recognised that a modest level of over-requests (for example, 10–20%) above the available FTEs should be considered normal and appropriate for a large, matrix-managed organisation like ESO, but higher levels indicate over-commitment and signal workload stress. It was also noted that the requests for key experts must be managed carefully to avoid overloading specific individuals.

Software pipelines

The consortia provide data reduction pipeline software for their instruments, which ESO then maintains over the instrument lifetime. In some cases this pipeline software is sufficient for the needs of most users; in others, particularly where the full reduction and analysis are complex and delicate, the pipeline is suitable for basic reduction of the data, but not adequate for full scientific analysis. Some of these issues are considered to be due to a lack of integration of the pipeline development group with the rest of the project team. In some cases, instrument teams have developed their own alternative pipeline software (or valuable add-ons) that are not supported by ESO or available to other users. The panel believes there may be opportunities for ESO to negotiate access to such valuable resources for its user community without owning, paying for, or guaranteeing the software.

Several consortia mentioned that ESO's standard programming language (CPL) is not appropriate anymore, and that it also impedes software development because it is hard to find programmers for it and it excludes the use of software developed in the community (mostly Python-based).

Remote access

The Garching Remote Access Facility (G-RAF) has already proved its value by allowing instruments to be commissioned and operated remotely and should be integrated into future instrumentation project plans (although clearly some things can be efficiently accomplished remotely while others really require hands-on access). More broadly, however, ESO appears to lag behind other leading observatories in providing remote access and observing capabilities. Although the panel understands some of the reasons for this (large and complex facilities with a wide user base, plus cyber-security concerns), we believe that improved remote access capabilities (including solutions for logistics issues and responsibilities) will allow ESO to provide more flexible services to observers and instrument teams, and to save money on operations and maintenance, while reducing climate impact due to air travel.

Future projects

The panel believes there are lessons to be learned from the experiences of the projects reviewed here in relation to selecting, timing, and managing future projects. None of these lessons is new or surprising, and ESO is well aware of all these issues — nonetheless, they are worth emphasising:
- All projects must have clearly specified science drivers, even those primarily providing technology or infrastructure. Project leaders need to regularly re-evaluate their plans in light of the scientific returns, which can be positively or negatively affected by changes in technology, schedule, and external circumstances.
- There is a necessary and healthy tension between the desire to start new projects and the need to finish existing projects to free resources. With both a burgeoning ELT programme and an increasingly constrained financial environment, ESO needs to manage community expectations and new project starts even more carefully: a new project should only start when ESO is reasonably assured it has the necessary resources to support the project over its lifetime.
- ESO also needs to be willing to make hard decisions to cut projects that are failing, that are overtaken by competitors, or that for any other reason are no longer able to deliver value for money to the ESO community. Such hard decisions need to be made as quickly as possible, to minimise pain and maximise gain.
- Given the lengthening timescales and greater resources demanded by innovative instrumentation projects, ESO needs to find ways to encourage the community to initiate visionary concepts while ensuring that only the best, most valuable, projects are accepted for adoption by ESO when it has the resources available to deliver them.
- While ground-based astronomy instrumentation is easier in several respects than space-based instrumentation, in terms of timescale, cost and complexity there is increasing convergence. Consequently, there may be lessons ESO can usefully learn from the competitive approaches used by ESA and NASA for managing their programmes.
- The AOF and VLTI facility projects provide lessons on the advantages and challenges of structuring groups of related smaller projects into overarching larger projects. The main lesson is that applying such structure early can be extremely valuable, particularly for infrastructure-related projects with complex dependencies that may be able to run in parallel or may require careful staging.

PIP resourcing

ESO has many instrumentation programmes, with separate management and budget lines. At present, the PIP is independent of the programmes for ELT first-generation instruments, subsequent ELT instruments, and Technology Development. Given that ESO's strategic plan requires the VLT/I to be maintained as a cutting-edge facility into the ELT era, it is essential that the PIP is sufficiently well resourced to achieve that goal. At present the nominal cap on the PIP is 26.5 FTE and ~ 3.8 million euros (2023) per year capital, which (based on ESO's experience and estimates of the required resources) is intended to allow one new instrument project to be started (or come online) every 1–1.5 years. As there are 13 VLT foci plus the VLTI (16 instruments in all) this would imply that the PIP can replace the full Paranal instrument suite every 16–24 years, which is consistent with the effective scientific lifetimes of 15 to 30+ years for VLT instruments. However, the increasing costs, staff effort, and development times for new instruments are concerns. The delays and extra effort evidenced in the analysis of the recent VLT/I instrument projects strongly suggest that the actual (as opposed to budgeted) ESO staff effort required to support delivery of a new instrument every 1–1.5 years is already at, or beyond, the limit set by the currently available ESO staff effort for the PIP. One way of seeing this is to note that the four consortia-led projects (i.e., setting aside the much more effort-intensive ESO-led projects) required a total ESO staff effort corresponding to six years of the nominal PIP budget. Moreover, the average time to reach PAE for these projects was 6.7 years, with PAC and a science-ready instrument taking significantly longer. The key lesson learned is that, to achieve its stated goal of maintaining a full and competitive instrumentation suite on the VLT/I, ESO will need to become significantly more efficient in the support it provides for future VLT/I instruments and significantly increase the staff effort committed to the PIP, or (more likely) some combination of both.

Given the challenges of completing the ELT and its first-generation instruments, compounded by the tightening of the wider financial environment, it seems likely that the PIP will come under even greater pressure in future. ESO will clearly have some difficult decisions to make regarding future VLT/I instruments, but the panel strongly believes that adequate investment in the PIP is crucial to ESO's long-term scientific impact.

Recommendations and Suggestions

The following key recommendations from the review panel to ESO are goals for follow-up actions that the panel believes would help realise benefits from the lessons learned in this review and previous exercises. In some cases, we also offer suggestions (distinguished by being in italics) for potential ways of implementing these recommendations. Related recommendations are grouped by topic, but the order is not significant.

Infrastructure implications

1. ESO should ensure tnat instrument and facility projects explicitly consider the associated requirements for changes to infrastructure and operations at every stage of their development, where possible with the direct involvement of the ESO-Paranal operations team. The cost and effort associated with infrastructure or operations changes should be carefully estimated at each project stage and assessed at each stage review.

Integration of project teams

2. ESO should consider how projects can best integrate the consortium, ESO-Garching, and ESO-Paranal teams over the project lifetime to ensure transparent communications between these teams and a comprehensive flow of knowledge and expertise throughout the project. *Various ways of integrating the teams are worth exploring, and might be employed in different circumstances, including embedding members of one team in another, sending staff on regular visits between teams, frequent face-to-face interactions (in person or by video link), and regular email updates. ESO might*

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

Sometimes dramatic events are needed to create something stunning. This beautiful structure of filaments and clouds in the southern constellation Vela is all that remains of a massive star that died in a powerful explosion known as supernova. This is a small section of a larger image taken using the wide-field camera OmegaCAM at the VLT Survey Telescope (VST). Hosted at ESO's Paranal Observatory in the Chilean desert, the VST is one of the best telescopes in the world to take large images of the sky in visible light.

consider ways to bring younger staff (both scientists and engineers) into instrumentation projects this way.

3. ESO should examine whether there are long-term benefits to be had from earlier and stronger engagement by the ESO-Paranal operations team in PIP projects. If so, ESO should consider how to facilitate such engagement without placing additional burdens on the operations team, either in the long term or during any transition phase before benefits are realised. It may be appropriate to trial such an approach on one or more PIP projects.
4. ESO should also consider how to engage the ESO-Paranal operations team more effectively in reviews, both so that operational requirements and implications are fully examined and so that reviews provide assurance to the consortium and ESO-Garching follow-up team that commissioning and operations plans are viable.
5. ESO should consider how to encourage constructive engagement and ongoing support for instruments and facilities well after PAC by both consortia and ESO-Garching.

Reviews and documentation

6. ESO should carry out a 'review of reviews' for all its instrumentation programmes, as is currently planned. This should consider, amongst other issues, the mixed experiences of the projects covered by this Lessons Learned exercise and the various concerns they have raised.

Communication

7. ESO should provide and share best-practice guidelines for ensuring effective and transparent communication between consortia, ESO-Garching and ESO-Paranal. *Amongst other things, these guidelines might cover the proper use of formal and informal communication channels, codes of conduct for professional communications, and appropriate processes for resolving conflicts. They might usefully draw on the experiences from previous projects of both ESO staff and external consortia, and be part of the reference material for new project teams.*
8. ESO should ensure that key personnel in the consortia, ESO-Garching, and ESO-Paranal teams are made aware of significant context-setting information (such budgetary or resourcing forecasts, or the relative prioritisation of projects) to allow informed project planning.
9. *ESO may consider providing a short training course for key personnel (both internal and external) involved in proposing or initiating projects. The course might introduce the basic functioning of ESO and the PIP programme, and share a distillation of accumulated 'project lore' from earlier projects (both the internal view from ESO and the external view from previous Consortia). ESO might also consider integrating this course with a wider effort to update and improve the processes and documentation for all projects, capturing 'lessons learned' as a continuing exercise within ESO.*

Contractual relations

10. ESO should explore a variety of approaches to fostering better collaborative partnerships with consortia for instrument projects and avoiding adversarial contractual relationships. *The panel recognises that this is a fundamentally difficult problem that requires careful hands-on management in every single instance. However, keeping contracts as simple and clear as possible and constructively managing the relationship are essential ingredients, along with a greater degree of interaction and better communication, as per recommendations above. Reforming or streamlining the Change Control Board (CCB) process at Paranal to make it more collaborative and efficient also has the potential to improve relations*.
11. ESO should be an exemplary partner in projects where it is providing significant components of the instrument or facility, delivering products and documentation that are at least of the standard demanded of consortia. This requires ESO to appropriately resource ESO-Garching staff delivering the components, ESO follow-up teams, and ESO-Paranal operations teams.

VLTI strategy

12. ESO should more clearly define and socialise its development strategy for the VLTI, particularly regarding its own role and capacity to advance the VLTI relative to that of external consortia. *If ESO is to continue to play a leading role in developing the VLTI, then it will likely need to strengthen its in-house capabilities for both VLTI science and technology*.

Technology standards

13. ESO should continue to develop appropriate technology standards and require their use in instrument/facility projects, balancing the benefits of standardisation against the advantages of new technologies.
14. ESO should consider when in a project's lifecycle it is appropriate to impose standards, and how to fairly mitigate cost and schedule delays due to late imposition. *ESO may find it helpful to develop guidelines (or even policy) on this point*.
15. ESO should explore the opportunities for efficiency savings by making in-house expertise on ESO software standards more available to consortia.
16. ESO should continue to develop technical solutions in strategic areas that are required by, or could be transformative for, several instruments.

In-house capabilities

17. ESO should develop a strategy for its in-house technical capabilities that meets the needs of its longer-term instrumentation plans, retaining key expertise by continuing to develop instruments in-house. *ESO should consider in which areas it needs to retain deep expertise in-house and which it can delegate to the astronomy community or close industry partners.*
18. ESO should develop a succession plan, in line with this strategy, for the significant number of senior instrumentation managers and expert technical staff retiring in the next few years.

Short-term hirings

19. ESO should explore ways and means to provide additional flexibility in technical staffing to allow its instrumentation programme to respond more effectively to short-term demands.

Fragmentation and churn

20. ESO should consider measures to reduce the degree of fragmentation in technical staff effort and the churn of staff through projects. *ESO might explore the potential benefits and costs of imposing a minimum level of commitment of staff to projects, a maximum number of projects for each staff member, and a minimum duration for commitments to projects.*
21. ESO should encourage project managers to request the FTEs they really require, not just what is reasonable within extant constraints, to ensure ESO has a clear and accurate picture of its programme resourcing needs.

Software pipelines

22. ESO should explore the benefits and costs of enabling its user community to have access to software pipelines developed by consortia or specialised user communities, without ESO committing support or guaranteeing outcomes.

Remote access

23. ESO should develop and extend the remote access capabilities for its facilities and make such capabilities more widely available to observers and instrument developers. *ESO may need to assist with solutions to logistics issues experienced by users of its remote access facilities.*

Future projects

24. ESO should ensure all instrumentation and facility projects have clearly defined science drivers, and that these science drivers are re-assessed whenever a project descopes or changes are required for technical or financial reasons, or when external developments alter the scientific landscape.
25. ESO should explore ways to combine a disciplined approach to starting new projects with positive support for the development of new instrument/facility concepts in the community. *This may require a more competitive procedure for project selection at an early stage.*
26. *ESO might consider being more intentional about bundling small projects into larger projects and, conversely, splitting large projects into smaller projects (or stages)—particularly for internal infrastructure projects, but perhaps also for consortia-led projects.*

PIP resourcing

27. ESO should seek to increase efficiency in the staff effort it provides for VLT/I instruments and/or increase the amount of staff effort committed to the PIP in order to achieve its stated goal of maintaining a full, front-rank instrumentation suite on the VLT/I.
28. ESO should ensure strong and competitive instrumentation for the VLT/I despite pressure from the ELT and its instruments. ESO might consider merging the VLT/I and ELT instrument programmes to improve efficiency and coordination; however, any merged programme must guarantee a state-of-the art instrument suite for the VLT/I as well as for the ELT.

Acknowledgements

The 2023 Lessons Learned review panel wishes to thank all the ESO staff and members of the various instrument consortia who participated in this process, giving so generously of their time and sharing their hard-won experience in order to help ESO improve its already outstanding performance in providing world-class instruments and facilities to the ESO user community.

The BlackGEM array, consisting of three new telescopes located at ESO's La Silla Observatory, has begun operations. This photograph shows the three open domes of the BlackGEM telescopes under a stunning night sky a La Silla. Other telescopes at the observatory are visible in the background.