Scientific Planning for the VLT and VLTI

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ABSTRACT

An observatory system like the VLT/I requires careful scientific planning for operations and future instruments. Currently the ESO optical/near-infrared facilities include four 8m telescopes, four (movable) 1.8m telescopes used exclusively for interferometry, two 4m telescopes and two survey telescopes. This system offers a large range of scientific capabilities and setting the corresponding priorities depends good community interactions. Coordinating the existing and planned instrumentation is an important aspect for strong scientific return. The current scientific priorities for the VLT and VLTI are pushing for the development of the highest angular resolution imaging and astrometry, integral field spectroscopy and multi-object spectroscopy. The ESO 4m telescopes on La Silla will be dedicated to time domain spectroscopy and exo-planet searches with highly specialized instruments. The next decade will also see a significant rise in the scientific importance of massive ground and space-based surveys. We discuss how future developments in astronomical research could shape the VLT/I evolution.

Keywords: VLT, VLTI, Science Planning

1. INTRODUCTION

The VLT/I facility is offering a many different observing capabilities and serves a large community. The ESO community has access to 12 optical telescopes (VLT, VLTI, VST, VISTA, 3.6m, NTT) with 20 instruments. In addition, several hosted telescopes are operated at ESO observatory sites providing research groups access to the southern sky through telescopes dedicated to special science cases. The ESO community can be sized by the number of applicants for observing time: a typical semi-annual call for proposals is answered by about 700 principle investigators submitting around 900 proposals. Overall, there are of order 3000 individual co-investigators per semester[1]. The observations with ESO facilities are used for essentially all scientific topics of current astronomical research. ESO is also a partner in the global ALMA observatory and provides access to the mm and sub-mm wavelength range. The E-ELT is under construction. All these factors have to be taken into account when the future of the VLT and VLTI are considered.

The instrument planning for the VLT has proceeded for many years through dedicated workshops. The science cases for the second generation instrumentation was discussed in 2001 during a conference entitled *Scientific Drivers for ESO Future VLT/VLTI instrumentation*[2] and the instrument concepts defined in 2007 at the workshop *Science with the VLT in the ELT Era*[3]. Similarly, the VLTI science and future instrumentation were elaborated in 2005 exploring *The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation Instrumentation*[4]. Many conferences and workshops with titles as *Science with …* were organized at ESO and published within the ESO Astrophysics Symposia Series[5].

The VLTI community organized itself through the European Interferometry Initiative[6], an open association of European Institutes. The EII supervises a large number of activities ranging from European Joint Research activities to VLTI schools. The EII is also actively participating in the definition of future developments of interferometry and has taken special interest in the further development of the VLTI. It is therefore a natural interlocutor to the VLTI programme scientist as it provides ESO with a strong discussion channel with the community.

ESO continues to organize conferences to discuss future developments. The last such conference was *ESO in the 2020s*[7] in 2015. With the new facilities the science coordination at ESO has obtained a new quality. The goal is to provide an overall science guidance for all ESO facilities and break the top priorities down to individual topics relevant for the specific observatories and telescopes and define the instrumentation such that complementarity is provided. Following the conference and a specific online poll the overall science priorities for the next 10 years of ESO have been presented in a document entitled *Scientific Priorities at ESO*[8] to the ESO Science and Technology Committee (STC) in April 2015. This report was prepared by the ESO Director for Science, Rob Ivison, with a team composed of members of the ESO oversight committees, members of the ESO community and ESO Personnel. Science areas deemed likely to remain compelling in the next decade identified by this working group were:

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

All aspects of the telescope usage were included in this evaluation and in particular also operational modes of the facilities. An important aspect is how telescope time is allocated, scheduled and executed. ESO offers a range of different proposal types and observation modes. Operational priorities are also discussed as part of the overall facility priorities.

2. PLANNING FOR THE VLT/VLTI FOR 2016-2020

The coordination of these many telescopes and instruments is a constant challenge and, if not planned carefully, can lead to confusion and mismatches in the program. Instrument failures and delayed deliveries lead to 'gaps' within the available parameter space and also limitations of observing capabilities. The ESO process is not set up to quickly react to emerging scientific possibilities and suffers from the long implementation time scales. For example, the VLT instrumentation was set up in the early 1990s before the start of operations for a first suite of instruments and then with the 2nd generation instruments for the VLT and then VLTI. With the start of operations of SPHERE, the VLT 2nd generation instrumentation has been completed. VLTI instrumentation was also planned and the last VLTI second generation VLTI instrument, MATISSE, should enter in operation in 2018.

While the science priorities were being defined, we decided to set specific priorities in the VLT and VLTI instrumentation development for the next years to allow constraints on the instrumentation program resources to be taken into account. Several instruments are being built (the Adaptive Optics Facility – an upgrade of one 8m VLT unit telescope (UT4) with a deformable secondary mirror, laser guide stars and AO modules for two instruments; CRIRES+ – an upgrade of the existing CRIRES instrument; ESPRESSO – a new high-stability, high spectral-resolution spectrograph; ERIS – a near-infrared, adaptive optics supported camera; GRAVITY – a K-band camera and astrometric instrument for VLTI; MATISSE – a mid-IR spectrograph for VLTI; MOONS – an optical/infrared multi-object spectrograph; 4MOST – an optical massively multi-object spectrograph for VISTA). The new VLTI instrumentation requested a major upgrade in the infrastructure of both the Unit Telescope and Auxiliary telescope array. In addition, ESO has been seeking community offers to operate the La Silla 3.6m telescope and the NTT with new instrumentation.

The *Science Priorities at ESO*[8] list the following items for the period between 2016 and 2020:

- Deliver GRAVITY for the observations of the passage of the star S2 near the supermassive black hole at the center of the Milky Way providing reliable and high-performance VLTI infrastructure and robust fringe tracking
- Deliver the next set of instruments: AOF, ESPRESSO and CRIRES+ by 2018
- Complete the public surveys and start a second round of VISTA surveys
- Establish a development plan for the VLTI
- Deliver MATISSE, ERIS and MOONS
- Deliver the new NTT and 3.6m instruments
- Revise the operational model to increase the flexibility in time allocation and execution
- Expand the VLTI user base by improving access to the facility to non-experts
- Develop an upgrade and replacement plan for the existing instrumentation
- Select and design a new AO instrument

This list is based on a scientific evaluation of the most pressing instrument capabilities and was provided by the VLT and VLTI Programme Scientists to decide on the top priority to focus the available resources. GRAVITY is being constructed to observe the passage of star S2 near the supermassive black hole at the center of the Milky Way occurring around 2018. The exact astrometry of this star will reveal post-Newtonian effects of General Relativity in a strong gravity field. This is a unique opportunity, which will not arise for another 16 years after 2018. As a VLTI instrument GRAVITY depends on a fully functioning interferometer and a number of facility improvements have to be implemented before GRAVITY could be commissioned such as dual feed operation or adaptive optics infrared wavefront sensors. Due to the limited resources – in this case access to the telescopes and key personnel for adaptive optics – ESO decided to slightly postpone the introduction of the AOF. While the scientific value and promise of the AOF is undisputed, the unique possibilities offered by the periapsis of S2 took scientific preference. At the same time, the move of the adaptive optics camera NACO from UT4 to UT1 led to a series of technical problems, which normally would have resulted in the retirement of the instrument. Since it is of vital importance for the support of the GRAVITY and SINFONI observations of S2, ESO decided to maintain NACO at all possible costs until 2019, when the event at the Galactic Centre has passed and it will be replaced by the next AO imager, ERIS. In the meantime, ESPRESSO and CRIRES+ will bring more high-resolution optical and infrared spectrographs to the VLT in 2017, respectively. The priorities have helped focus the resources and activities onto the development of instruments with the highest scientific impact.

As a consequence of the continuation of the NACO operations until 2019 a decision had to be taken to decommission a productive VLT instrument. This is a short-term measure outside the regular planning exercise. It resulted in an evaluation of the scientific productivity and impact of several VLT instruments and the presentation of the results to the STC. In addition, principles for the decommissioning of VLT instruments in the future were developed. They are based on a combination of scientific value, operations and maintenance costs. Typically, instruments whose capabilities are superseded by new facilities should be decommissioned. Similarly, instruments that become too expensive to operate or to maintain should be slated for upgrades or be decommissioned.

The selection of the new instrumentation for the La Silla telescopes offered a chance to discuss the value of 4m-class telescopes in the next decade. Dedicating such telescopes to data intensive project appears opportune now. Such small aperture telescopes can no longer compete with the 8m-class telescopes, which also outnumber them. However, there remain interesting science projects, which require long observational timescales or specialization on specific science topics. The choice for the 3.6m telescope is a near-infrared high-resolution stable spectrograph, NIRPS, to complement the existing HARPS ultra-stable spectrograph. The targeted science is the discovery of Earth-mass planets around low-mass M stars making use of the higher radial velocity signal and the shorter periods. The NTT will be dedicated to time-domain science focusing on transient events. A new instrument should be developed to replace the aging optical and infrared camera/spectrographs to specifically focus on transient objects. With the dedication of its 4m telescopes (NTT – transients; 3.6m telescope – exo-planets; VISTA – survey science) ESO has clear scientific prospects for these facilities for the next decade.

Some VLT instruments have been in operation for more than 15 years. A sound assessment of the scientific merit and competitiveness of the existing instrumentation will guide the way to an upgrade and replacement path. Technical obsolescence coupled with increased maintenance demands and decreased science value need to be evaluated. At the end of this process, the VLT instrumentation planning should be available indicating upgrades to existing instruments and the development of new capabilities.

ESO is also discussing a coherent planning for the future VLT adaptive optics instrumentation. NACO has been offered with single-conjugate infrared adaptive optics since 2002, SINFONI provides AO-supported near-infrared integral-field spectroscopy since 2004 and SPHERE offers extreme on-axis adaptive optics in several modes. The AOF will become fully functional in 2018 and will support ground-layer adaptive optics for HAWK-I and MUSE and narrow-field optical adaptive optics for MUSE. ERIS is being built to enhance single-conjugate AO replacing NACO. ESO identified a new AO instrument as the next step to improve image quality and contrast. A first informal meeting with AO experts in Europe took place in September 2015 and is followed by VLT AO Community Days in September 2016 to develop the science case for a new instrument. Such an instrument also needs to be seen in comparison with ELT capabilities likely to be offered when it will come into operations and probable lack of optical high angular-resolution imaging when HST will stop operations. The discussion hence focusses currently less on technical solutions, but more on the potential gains compared to today's capabilities and complementarity with E-ELT instruments.

Figure 1 shows a mapping of the existing and planned ESO optical/NIR instrumentation onto the broad science topics outlined in the *Science Priorities for ESO* document. With the exception of the pre-biotic chemistry, which is a realm of low-energy astrophysics, i.e. mm and sub-mm telescopes like ALMA and APEX, all science fields receive substantial support from VLT and VLTI instrumentation. This figure is not meant to be used to evaluate individual instruments, but rather to give an overview of the instrument complement and to identify weak spots in the overall scientific parameter space. It is an attempt to move away from the physical parameter space coverage (e.g. field of view, spectral coverage, spatial sampling) and to directly connect the instruments to the most interesting science fields. The VLT, VLTI and the La Silla telescopes already provide a very strong coverage of most science fields. Future instruments will strengthen the investigations of Cosmology, Large Scale Structure, the Milky Way dynamics and all stellar topics. No major instrumental capability will be lost in the future.

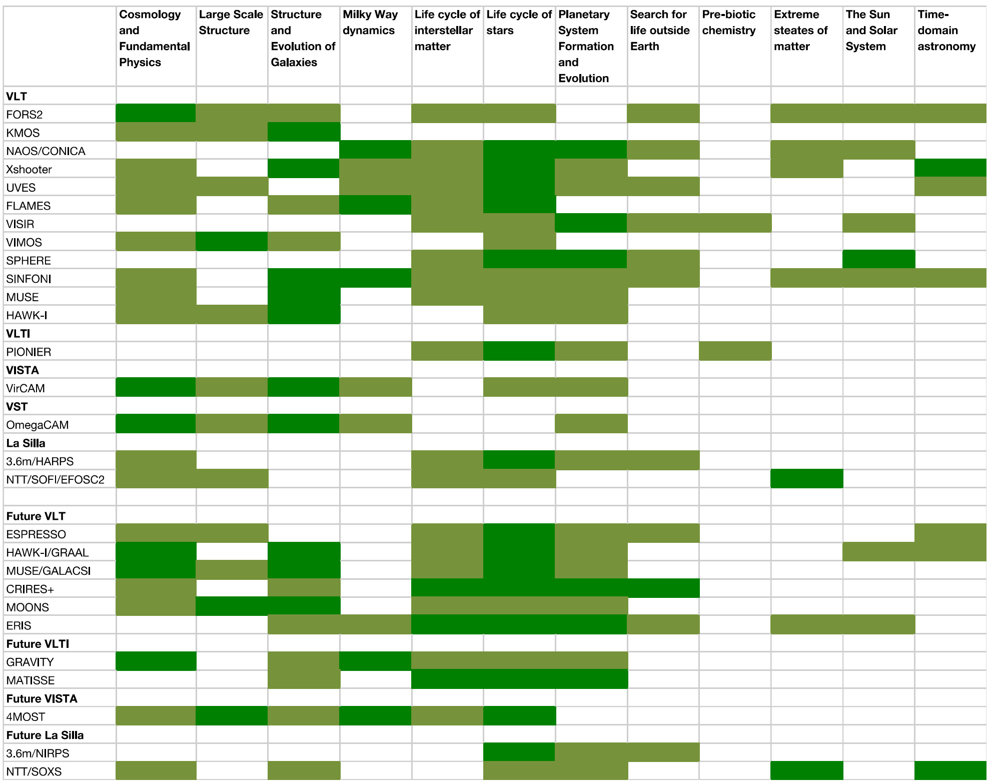

Figure 1: Mapping of the VLT/VLTI instrument capabilities to serve the major science topics. Dark green fields indicate a good match of the instrument capability to the science topic and light green some applicability. Empty fields show no strong suitability.

In addition to the instrumentation planning, the priority list for 2016 to 2020 includes operational items, like the planning for the next round of surveys with the VISTA telescope before it will be converted for the operations of 4MOST. This call has in the meantime been issued and the selection of the new surveys completed. The mix of different observing program types (normal, large, surveys, target of opportunity, etc.) and operational modes (visitor and service modes) has been shown to enable new science endeavors at ESO. The dedication of large fractions of observing time to pursue specific science questions has been shown to be very successful. This has been confirmed through workshops and conferences[9] and statistical analyses[10]. Opening the VLT to surveys has been a logical consequence of the increased demand on experimental investigations which need large statistical samples. ESO operates VST and VISTA nearly exclusively for imaging surveys in the optical and infrared. The observations for the first surveys have now been completed and VISTA will start the next set of seven surveys in 2017. As an example, we show in Figure 1 an extra column on time-domain astronomy. The operational models offered by ESO have enabled certain time-domain projects. A prime example is the Public ESO Spectroscopic Survey of Transient Objects (PESSTO[11]) where a large fraction of time on the NTT was committed over 5 years for a systematic follow-up of transient sources, mostly supernovae and gamma-ray burst. The coordination of the surveys and the scientific guidance through the external survey panels are regularly provided.

In this period VLTI will have to maximise the scientific return of GRAVITY and MATISSE. This involves the consolidation of a robust infrastructure and the development of an efficient operation model suited for imaging requests and monitoring programs. Both improvements should enable a much wider use of large programs at VLTI. Moreover, in order to widen its community VLTI would considerably benefit from the development of community user support/expertise centres. These could clearly improve synergy with other high angular resolution communities such as e.g. SPHERE and ALMA. ESO is thus willing to facilitate their establishment.

3. PLANNING THE NEXT DECADE

The ESO science priorities had a list of recommendations for the next decade. They are:

- Fully exploit the by-now existing VLTI infrastructure by expanding its instrumentation
- Upgrade and replace VLT science capabilities as defined in the upgrade plan
- Deliver 4MOST to VISTA
- Design and deliver AO instrument
- Encourage visitor instruments for VLT and VLTI

The VLT upgrade plan as described in Section 2 will provide the directives for the instruments to be refurbished for another decade of operations. For the discussions of instrument replacements, we have defined a set of *core capabilities* for the VLT, which describe capabilities, which need to be always present at the VLT. The list includes the following items: seeing limited deep imaging, low-resolution spectroscopy, high-resolution spectroscopy, high-contrast imaging, wide-field imaging, wide-field spectroscopy and integral-field spectroscopy. We show the distribution of the current instruments in these categories in Figure 2. An evaluation on how a core capability will be maintained shall take place whenever an instrument should be retired.

Figure 2: Core capabilities of VLT instrumentation

Obviously, Figure 2 does not cover the full parameter space and other important capabilities need to be considered, like high angular resolution, astrometry, or the community demands on certain instrument means. High-resolution spectroscopy is such an example, where ESO offers a highly stable spectrograph for radial velocities (HARPS), wide-wavelength range spectrographs for stellar studies (UVES) and a multi-object spectrograph (FLAMES). These capabilities will be complemented in the future with infrared spectrographs (NIRPS and CRIRES+) and an ultra-stable spectrograph for radial velocities (ESPRESSO). The future multi-object spectrographs (MOONS and 4MOST) will also have a high-resolution mode. Figure 2 provides guidance to establish the important upgrade and replacement strategies.

After the VLTI consolidation phase where it is shown that the facility is robustly phased and efficient we will have a better idea of how its instrumentation can be expanded. Unlike in single telescope instrumentation there are still numerous capabilities that have not been explored such as the development of a large wavelength coverage instrumentation (an analog to X-Shooter), high contrast imaging, the extension to the visible or even very high spectral resolution and polarimetry (see **Figure 3**).

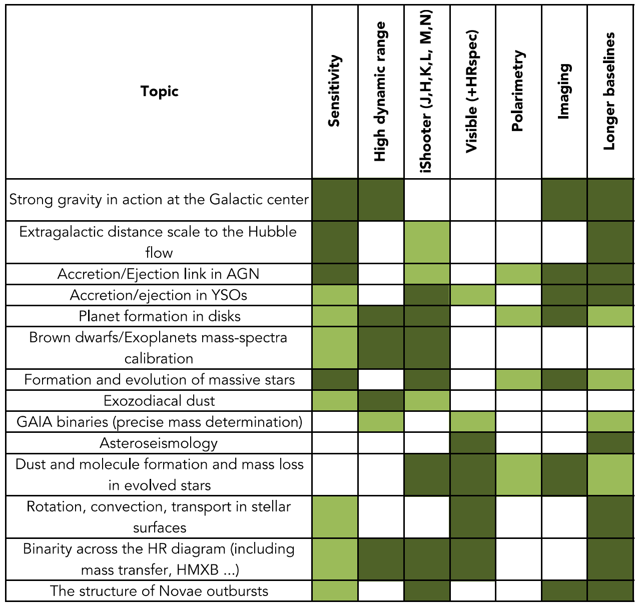

Figure 3: Selected scientific topics that would benefit from an expansion of VLTI capabilities.

The VLT and possible also VLTI should provide a focus for visitor instruments. The possibility to bring an instrument for a dedicated experiment to the VLT should be offered.

4. BEYOND 2025

Beyond the next decade the planning has to take into account that ESO will add the E-ELT to its optical/NIR system and should make best use of the synergies. With ALMA and the E-ELT in operation, the support role of the VLT, VLTI and the 4m telescopes needs to be defined. The VLT will no longer be the prime facility for most infrared observations and the angular resolution provided by VLTI will be approached by the filled-aperture E-ELT. The planning for the best synergies are already starting through discussions of the appropriate operations models and the instrument complements between the different facilities.

The scientific landscape will have changed considerably in 10 years. JWST will have opened the faint infrared sky and there will be many sources that need follow-up from the ground with the largest telescopes. HST may have stopped operations and the UV and optical high-angular resolution imaging lost with it. The optical and near-infrared sky will have been mapped to faint magnitudes by LSST and Euclid. Requests of follow-up time, mostly spectroscopy for individual objects and statistical samples can be expected and in many cases will be for large statistical samples. While the E-ELT will focus on the most interesting and faintest objects, the VLT will provide the main observational resource, in particular in the optical. With four individual telescopes and instruments covering a larger parameter space than the E-ELT, the VLT will serve a community presumably comparable in size to the E-ELT community.

VLTI will still provide an angular resolution unmatched even with the E-ELT and can provide information on brighter sources. A first obvious direction of development could be to increase its imaging capabilities through the use of additional telescopes. However, the natural limitation of baseline length given the size of the Paranal platform might affect the scientific scope. Currently, the VLTI advantage with respect to competing facilities is the access to the UTs and its newly implemented dual feed capability. Several years of exploitation of Gravity and Matisse might open new opportunities never thought of before including a better overlap with ALMA's increased angular resolution. In any case, it is expected that, by next decade, prospective exercises both in the Europe and the US will have defined what the next-generation interferometric facility could be[12]. The future of VLTI will have to be discussed with this context in mind.

Radical options should be explored for this time frame. The discussion for this future has already started with the poll of the community connected to the *ESO in the 2020s* conference. Scientific topics the community is expecting to significantly increase are the Search for life, Planetary Systems, and Cosmology/Fundamental Physics[13]. The largest request was for optical/infrared 8m telescopes, access to the E-ELT, followed by the 4m and dedicated 10m telescopes. The most interesting instrument capabilities from this community poll are high multiplex high-resolution spectroscopy, wide-field spectroscopic surveys, IFU spectroscopy, wide-field imaging surveys, high multiplex moderate-resolution spectroscopy to long-baseline interferometry. Interestingly, high contrast imaging and high-precision radial velocities were ranked comparably low, possibly because such facilities are already available.

5. CONCLUSIONS

The community process of optimizing existing observatories and providing new capabilities can be complicated. The initiative normally comes from the observatory although we have also experienced the community pushing for certain facilities. The changing scientific landscape and research interests demand a careful planning with a wide margin of flexibility built in. The VLT and VLTI observatory have a strong instrumentation covering a wide parameter space and employs an operational model that has enabled new observations and discovery. The planning for the next ten years is firmly in hand and the discussions for the ESO optical/NIR observing system after 2025 have started.

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