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# Scientific Return from VLT instruments

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**A statistical analysis of metrics probing the use of VLT instruments yields a perspective on the demand, productivity and impact of individual instruments. The trends in the usage of these instruments provide information that may be useful in determining the timing of potential future instrument upgrades and replacements. We look at the evolution of observing time requests on VLT instruments; this is measured using the number of proposals submitted each semester as well as the requested time. We also look at the publication statistics on all VLT instruments and find that the older workhorse instruments have produced over 1000 publications to date. The most successful VLT instruments produce over 80 publications per year. After an initial increase as they enter operation, most instruments reach a constant rate of publications after between four and eight years and the number of publications and citations only starts to decline after decommissioning. We find that all instruments currently operating show increasing citation counts every year. ESO has regularly upgraded instruments to strengthen their scientific impact.**

## Introduction

Assessing the scientific impact of scientific institutes, observatories, telescopes and their instrumentation has a long history. Several different methods have been employed in the past (Abt, 1994; Trimble, 1995; Bergeron & Grothkopf, 1999; Benn & Sanchez, 2001; Meylan, Madrid & Macchetto, 2003; Madrid & Macchetto, 2007). The advent of electronic bibliographies has greatly increased the power of statistical analyses. The ESO telescope bibliography telbib[1] (see Grothkopf & Meakins, 2012, 2015 for recent descriptions) has been used in several analyses (for example, Leibundgut, Grothkopf & Treumann, 2003; Grothkopf et al., 2005, 2007) and can be compared to other observatories (Crabtree, 2014, 2016). Sterzik et al. (2015) recently presented a detailed analysis of the science return from VLT observing programmes, identifying connections to operational modes.

Recently, Kulkarni (2016) proposed a new metric to investigate the scientific return of individual instruments. In addition to the publication statistics, he proposes investigating the citations every (calendar) year collected by publications based on a specific instrument. He refers to this as the "citation flux". A further criterion for the success of an instrument is its capability to provide landmark results universally accepted by a large fraction of the community as yielding new insights; such publications are typically cited very often. The demand by the community is another factor that can be used to describe the popularity and science potential of instruments. The number of proposals and the requested time are good indicators of whether an instrument caters for the scientific needs of the community.

In this analysis we focus on Very Large Telescope (VLT) instruments only. The VLT has been operating since April 1999. There are currently 12 instruments in operation (see Table 1), two have been decommissioned (FORS1 and ISAAC) and one is currently being upgraded (CRIRES).

Our analysis encompasses statistics of the instrument demand (popularity), publications (science return), citations (science impact) and most-cited publications (landmark contributions). We focus on results up to the end of 2016. The proposal statistics therefore include Period 99 (deadline October 2016; observations from 1 April until 30 September 2017) and the citation statistics are also until the end of 2016 (from statistics gathered in July 2017). The proposal database at ESO and telbib[1] were used. Citations are drawn from the SAO/NASA Astrophysics Data System (ADS). The ESO telescope bibliography collects refereed publications based on ESO instruments. We note that several instruments canbe associated with a single proposal or publication.

## Overview of the demand for VLT instruments

Figure 1a presents the evolution of the demand per instrument over the past 12 years (i.e., 24 observing periods since April 2005) as indicated by the number of proposals submitted. In 2005, all four Unit Telescopes (UTs) were fully operational and nine instruments were offered. The graph shows that some instruments are extremely popular and remain so for many years. The most frequently demanded instruments are FORS2, X-shooter and MUSE. These are multi-purpose instruments suitable for many astrophysical applications. X-shooter and MUSE are unique among the instruments available at 8- to 10-metre telescopes.

New instruments display a strong start in demand and exhibit a strong increase in the number of proposals and requested time within a couple of periods to at least 50 proposals per semester (for example, VISIR, CRIRES, HAWK-I, KMOS) and in some cases significantly more (X-shooter, MUSE, SPHERE). The strong increase in the demand for FORS2 after Period 82 is due to the decommissioning of FORS1. We note that some instruments were not offered during specific semesters (ISAAC in Period 91, which was followed with a last call for proposals in Period 92; VISIR between Period 92 and Period 94 during the upgrade; HAWK-I in Period 93).

With a few exceptions, a general trend towards fewer submitted proposals over the years can be observed. This shows the early science interest in new capabilities — sometimes in competition with instruments at other facilities — and the move to newer instruments as they become available. In some cases, the decrease is probably connected to the ageing of instruments (for example, NACO).

The evolution of the demand for observing time is displayed in Figure 1b. Strong fluctuations in demand for time can be due to Large Programme and Public Survey proposals. A sawtooth distribution between even and odd periods is also observed. More time is requested in even periods as they offer access to the Northern Galactic Cap. The separation between very highly demanded instruments and the bulk of regularly requested instruments remains. Like the number of proposals, the time requested tends to decrease over time for ageing instruments.

A further indication of the popularity of instruments is the number of approved Large Programmes (LPs). This is a strong function of the duration of operation of an instrument. By far the largest number of LPs have been approved on FORS2: 28 programmes in total, covering a wide range of scientific topics from Solar System objects to cosmology. Most other early instruments (FORS1, ISAAC, UVES) and the survey instruments (FLAMES and VIMOS) had allocations of between 14 and 16 LPs. FLAMES and VIMOS are also used in Public Spectroscopic Surveys (Gaia-ESO, LEGA-C and VANDELS). The more recent instruments (HAWK-I, X-shooter, KMOS, MUSE and SPHERE) had smaller LP allocations simply because they have not been offered for the same length of time.

## Science return of VLT instruments

Data on the number of publications and citation counts per year have been analysed statistically for all instruments, partially following the methodology presented by Kulkarni (2016). We also looked at the ten most cited publications for each instrument to assess their impact.

The total numbers of publications and citations give a global view of the impact of an instrument. A direct comparison between the instruments is difficult for several reasons. The time between data collection and publication is typically from months

Table 1. VLT Instruments

| Instrument Name | Instrument Acronym | First offered Period | First offered Date | Comments |
|---|---|---|---|---|
| FOcal Reducer/low dispersion Spectrograph 1 | FORS1 | 63 | April 1999 | Decommissioned April 2009 |
| Infrared Spectrometer And Array Camera | ISAAC | 63 | April 1999 | Decommissioned December 2013 |
| FOcal Reducer/low dispersion Spectrograph 2 | FORS2 | 65 | April 2000 | – |
| UV-Visual Echelle Spectrograph | UVES | 65 | April 2000 | – |
| Nasmyth Adaptive Optics System (NAOS-CONICA) | NACO | 70 | October 2002 | – |
| Fibre Large Array Multi Element Spectrograph | FLAMES | 71 | April 2003 | – |
| VIsible Multi-Object Spectrograph | VIMOS | 71 | April 2003 | Decommissioning planned for 2018 |
| Spectrograph for INtegral Field Observations in the Near-Infrared | SINFONI | 74 | October 2004 | Upgraded in 2016; upgrade as part of ERIS project |
| VLT Imager and Spectrometer for mid-InfraRed | VISIR | 75 | April 2005 | Upgraded in 2015 |
| CRyogenic InfraRed Echelle Spectrometer | CRIRES | 79 | April 2007 | Dismounted in Period 93; to return to the VLT in Q1 2018 |
| High Acuity Wide field *K*-band Imager | HAWK-I | 81 | April 2008 | Commissioning instrument for the Adaptive Optics Facility (AOF) |
| X-shooter | – | 84 | October 2009 | Atmospheric Dispersion Corrector refurbished in 2017 |
| *K*-band Multi-Object Spectrograph | KMOS | 92 | October 2013 | – |
| Multi Unit Spectroscopic Explorer | MUSE | 94 | October 2014 | – |
| Spectro-Polarimetric High-contrast Exoplanet REsearch | SPHERE | 95 | April 2015 | – |

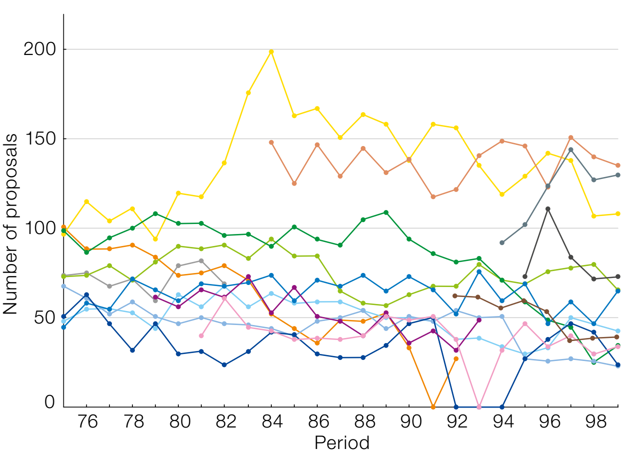


Figure 1a. (Below left) Demand per VLT instrument (number of proposals) over the past 12 years (24 observing periods). The colour assigned to each instrument is the same in the subsequent figures.

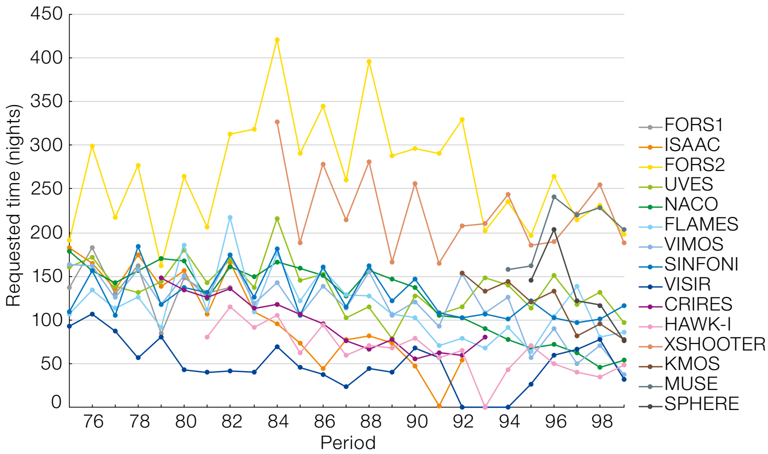


Figure 1b. (Below right) Requested time per VLT instrument over the past 12 years.

Table 2. Total publications and citations

| Instrument | Publications | Citations |
|---|---|---|
| FORS1 | 1000 | 57265 |
| ISAAC | 978 | 51839 |
| FORS2 | 1365 | 62499 |
| UVES | 1781 | 69754 |
| NACO | 598 | 23121 |
| FLAMES | 567 | 22001 |
| VIMOS | 715 | 32807 |
| SINFONI | 365 | 16075 |
| VISIR | 167 | 4225 |
| CRIRES | 168 | 4251 |
| HAWK-I | 199 | 6794 |
| X-shooter | 383 | 8072 |
| KMOS | 23 | 363 |
| MUSE | 66 | 391 |
| SPHERE | 45 | 344 |

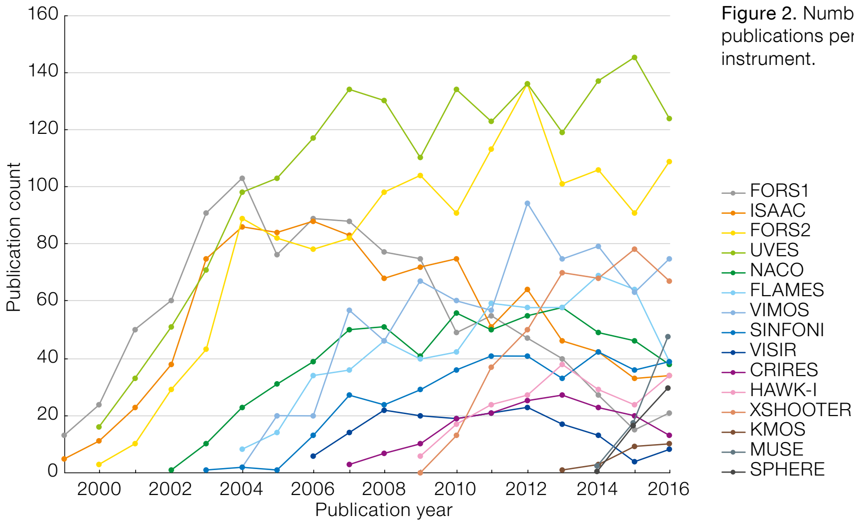


Figure 2. Number of publications per VLT instrument.

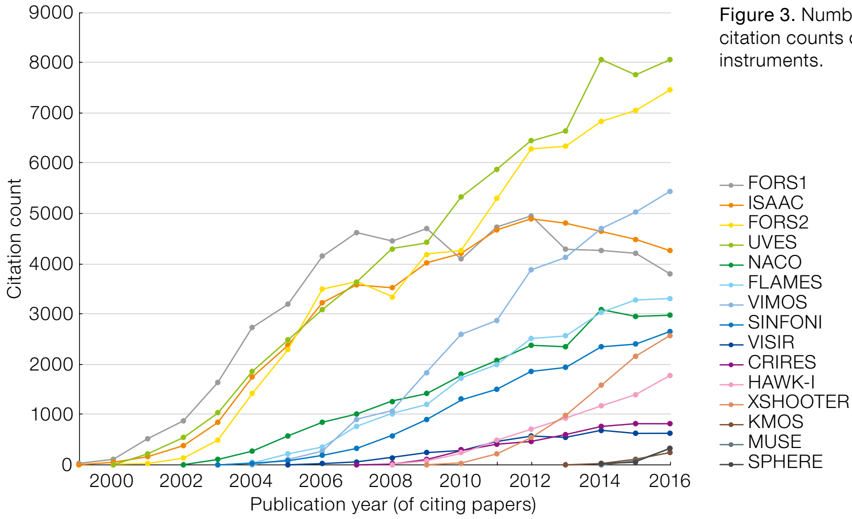


Figure 3. Number of citation counts of VLT instruments.

to years, which means that a lag time from when an instrument is first offered would have to be applied. Similarly, citations build up after publication, and a corresponding lag time would need to be considered. The data in Table 2 should therefore be interpreted with caution.

As might be expected, the earliest instruments have also resulted in the most papers and citations (Figures 2 and 3). UVES has resulted in the most publications and the highest number of citations, while FORS1 and FORS2 have contributed more than 1000 papers each. ISAAC is the fourth VLT instrument with over 50 000 citations to nearly 1000 papers. VIMOS stands out with a large number of papers considering its late arrival and has a high number of citations. On the other hand, SINFONI has produced about half as many publications as VIMOS but joins FORS1, ISAAC, FORS2, and VIMOS as one of the instruments with more than 40 citations per publication on average.

The first VLT instruments (FORS1, ISAAC, FORS2, UVES) showed an early steep rise in publications and citations. It should be noted that not all foci of the available UTs were initially occupied, so the first instruments had a larger fraction of observing time available. While the numbers of papers for FORS1 and ISAAC started to decline after they were decommissioned, FORS2 and UVES have reached a stable level of about 120 (UVES) and 100 (FORS2) papers per year for the past ten years.

The increase in the number of papers for the instruments that came into operation later is more modest (NACO, FLAMES, VIMOS, SINFONI, VISIR and CRIRES). However, these instruments did have smaller shares of telescope time as the UT foci filled up. Specific situations for some instruments apply. As FLAMES and VIMOS are survey instruments, publications often require large samples collected over several semesters. In particular, the early rise in publications for VIMOS is not as steep as those for the FORSs, ISAAC and UVES, but VIMOS publications now match the same level (about 80 publications per year) as the plateau of ISAAC and FORS1 (both decommissioned). NACO and FLAMES had a slower evolution to reach a plateau of about 60 publications every year. SINFONI has contributed to about 40 papers per year for the past 6 years. HAWK-I, VISIR and CRIRES peak below 30 papers per year, but all three instruments were not offered for some time because of upgrades. The second-generation instruments have begun operating too recently to have reached a peak in their paper evolution. X-shooter displays an increase comparable to the most successful instruments, but has levelled at about 70 papers per year for the past three years, while KMOS, MUSE and SPHERE will need several more years to reach equilibrium.

## Science impact of VLT instruments

All VLT instruments show rising citation counts, which means that their impact continues to grow. The citation counts seem to separate the VLT instruments into three groups (Figure 3). Obviously, the citation counts strongly correlate with the length of time an instrument has been offered to the community. FORS2 and UVES, the two instruments in operation for the longest time show the highest citation counts. FORS1 and ISAAC levelled off after decommissioning. VIMOS shows a very steep rise in the past years and is now the third most cited VLT instrument. While still showing a steady increase, NACO, FLAMES and SINFONI are on a less accelerated path than the first instruments. This can clearly be seen when comparing the citation counts relative to the start of operations for all instruments (Figure 4).

Here the top group for the first decade of operation includes FORS1, FORS2, ISAAC, UVES, VIMOS and X-shooter. They each reached about 4500 citations per year after a decade. X-shooter has of course not reached the 10-year mark yet, but it is fully on track to match the evolution of the other instruments. A second group of instruments reaches about 2000 to 2500 citations after ten years and includes NACO, FLAMES, SINFONI and HAWK-I. Finally, VISIR and CRIRES had fewer than 1000 citations per year after their first decade; but CRIRES was only in operation for seven years.

Lower demand for an instrument naturally results in fewer observations, leading to fewer publications and citations. This causality can be roughly followed from Figures 1 to 4. A direct comparison of the total number of citations per instrument is not meaningful given the different operating times of the individual instruments. One should also be careful as overall statistics only tell part of the story and some instruments may have an important scientific impact in specific fields while not excelling in the global averages. For example, we note NACO's key role in the measurement of the mass of the supermassive black hole at the centre of the Milky Way.

## Most cited papers of VLT instruments

Citation counts can also depend on the specific research topics and communities. When comparing absolute numbers, the time for which an instrument has been in operation is also a deciding factor. The most cited VLT publications (more than 750 citations as at the end of 2016) come from FORS1, FORS2 ISAAC, VIMOS, NACO and SINFONI. The topics include supernova cosmology, deep galaxy surveys (GOODS, COSMOS), supernova–gamma-ray burst connection, dark matter searches, galaxy evolution at high redshifts, a massive pulsar in a compact binary and the Galactic Centre. Most of these publications use data from several major observatories and have large co-author lists (typically more than 20); for example, only five of the 25 most cited VLT papers have fewer than ten co-authors. Table 3 lists the most cited publications per instrument until 2016 based on ESO Publication Statistics[2].

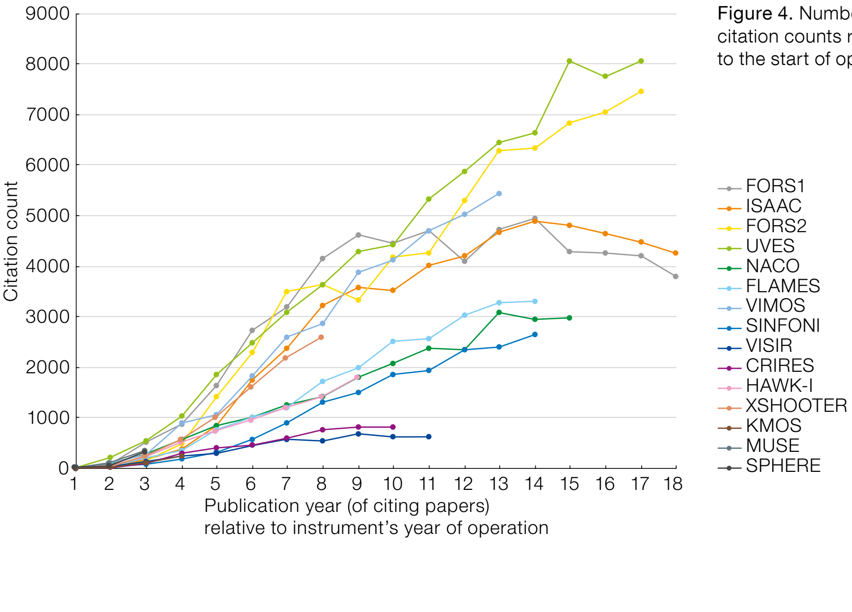


**Figure 4.** Number of citation counts relative to the start of operation.

## Conclusions and outlook

All VLT instruments are in constant demand, display a good scientific return and show significant scientific impact as measured by the proposal statistics, number of publications and citation counts, respectively. According to the criteria set out by Kulkarni (2016), the operational VLT instruments are all delivering. Instruments in operation for a few years show a nearly constant publication rate. Publications from new instruments increase substantially during their first years of operation. Instruments that were not offered for a period, or have been decommissioned, show a decrease in the number of publications after some years. The citation counts continue to increase for all operational instruments, which means that their scientific impact is maintained. A reduction in citation counts would indicate a loss of scientific edge and point toward necessary instrument upgrades or replacements (Kulkarni, 2016). This does not apply to any of the operational VLT instruments at the moment.

The oldest currently operated VLT instruments (FORS2 and UVES) have not received any major upgrades. They are among the VLT instruments with the highest scientific impact and their future operation must be ensured. As workhorse instruments they are the most versatile tools for astrophysics at the VLT and they will remain relevant for the foreseeable future.

ESO has upgraded instruments with low overall impact to improve their science capabilities in recent years (VISIR, CRIRES, HAWK-I). It remains to be seen how these upgrades increase their scientific impact. VISIR will be used for an experiment with the Breakthrough Initiatives (Kasper et al., p. 16). The new CRIRES capabilities will be extremely important in the characterisation of exoplanet atmospheres and HAWK-I will operate with a ground-layer adaptive optics system that will deliver supreme image quality for most of the time.

Table 3. Most cited paper for each instrument (as at end 2016)

| Instrument | Bibcode | Publication Title | Authors | Citations |
|---|---|---|---|---|
| FORS1 | 2006A&A...447...31A | The Supernova Legacy Survey: Measurement of $\Omega_M$, $\Omega_\Lambda$ and *w* from the First Year Dataset | Astier et al. | 1873 |
| ISAAC | 2003ApJ...594....1T | Cosmological Results from High-*z* Supernovae | Tonry et al. | 1450 |
| FORS2 | 2004ApJ...607..665R | Type Ia Supernova Discoveries at $z > 1$ from the Hubble Space Telescope: Evidence for Past Deceleration and Constraints on Dark Energy Evolution | Riess et al. | 3009 |
| UVES | 2004A&A...416.1117C | First stars V — Abundance Patterns from C to Zn and Supernova Yields in the Early Galaxy | Cayrel et al. | 710 |
| NACO | 2009ApJ...692.1075G | Monitoring Stellar Orbits Around the Massive Black Hole in the Galactic Centre | Gillessen et al. | 781 |
| FLAMES | 2009ARA&A..47..371T | Star-Formation Histories, Abundances, and Kinematics of Dwarf Galaxies in the Local Group | Tolstoy, Hill & Tosi | 496 |
| VIMOS | 2007ApJS..172....1S | The Cosmic Evolution Survey (COSMOS): Overview | Scoville et al. | 823 |
| SINFONI | 2009ApJ...692.1075G | Monitoring Stellar Orbits Around the Massive Black Hole in the Galactic Centre | Gillessen et al. | 781 |
| VISIR | 2010ApJ...716...30A | The Spectral Energy Distribution of Fermi Bright Blazars | Abdo et al. | 331 |
| CRIRES | 2009A&A...506..287L | Transiting Exoplanets from the CoRoT Space Mission. VIII. CoRoT-7b: the First Super-Earth with Measured Radius | Léger et al. | 361 |
| HAWK-I | 2009Natur.461.1254T | A $\gamma$-ray Burst at a Redshift of $z \sim 8.2$ | Tanvir et al. | 410 |
| X-shooter | 2011A&A...536A.105V | X-shooter, the New Wide Band Intermediate Resolution Spectrograph at the ESO Very Large Telescope | Vernet et al. | 285 |
| KMOS | 2015ApJ...799..209W | The KMOS 3D Survey: Design, First Results, and the Evolution of Galaxy Kinematics from $0.7 \le z \le 2.7$ | Wisnioski et al. | 74 |
| MUSE | 2015MNRAS.449.3393M | The Behaviour of Dark Matter Associated with Four Bright Cluster Galaxies in the 10 kpc Core of Abell 3827 | Massey et al. | 58 |
| SPHERE | 2015A&A...578L...6B | Asymmetric Features in the Protoplanetary Disk MWC 758 | Benisty et al. | 51 |

Two VLT instruments have been decommissioned (FORS1 and ISAAC) and VIMOS will follow next year. Instruments under development are either complementary to the current instrument capabilities or will enhance them (such as the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations [ESPRESSO], the Multi Object Optical and Near-infrared Spectrograph [MOONS] and the Enhanced Resolution Imager and Spectrograph [ERIS]). Several instruments have seen extensive interventions to maintain their operability (VIMOS, NACO, X-shooter, KMOS). Others have either recently been upgraded or will be upgraded (for example, VISIR, CRIRES, and SINFONI as part of ERIS).

The second-generation instruments (KMOS, MUSE and SPHERE) began operating within the past three years and will need to fulfil their scientific promise in the coming years. New instruments will replace and improve the capabilities of existing instrumentation: ERIS will replace NACO and SINFONI with improved adaptive optics, ESPRESSO complements UVES as a high-resolution spectrograph while MOONS and 4MOST will massively expand the multiplex capabilities of FLAMES and VIMOS (after 2021). Of course, the Extremely Large Telescope (ELT) will supersede many of the current VLT capabilities (particularly in contrast and depth in the infrared). At the VLT Adaptive Optics (AO) Community Days in 2016, upgrade paths for extreme AO (XAO; upgrade of SPHERE) and Multi-Object AO (MOAO; potentially KMOS) were discussed (Leibundgut, Kasper & Kuntschner, 2016) and a pre-Phase A study for an optical AO imager is currently underway.

Finally, an observatory like the VLT also needs to cover parameter space that will not necessarily yield the highest impact in terms of publications and citations. For example, it has been seen as necessary to offer mid-infrared capabilities to the community to enable research that otherwise would not be possible. In this context, the lower impact of some instruments is expected and acceptable.

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## Links

[1] ESO telescope bibliography telbib: http://telbib.eso.org/
[2] ESO Publication Statistics: http://www.eso.org/sci/libraries/edocs/ESO/ESOstats.pdf