Twenty Years of FORS Science Operations on the VLT

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Celebrating the double jubilee of ten years in operation of FORS1 and FORS2, this article summarises, from an insider's point of view, the history of the FORS instruments, arguably the most prolific on ESO's Very Large Telescope. The FORS story began in the early 1990s and FORS1 was the first VLT user instrument to be commissioned. Both FORS instruments have undergone considerable evolution and quickly parted from the original concept of being identical twins. They have both made major contributions to scientific research and have helped shape VLT operations. In 2009, FORS1 was retired, but FORS2 continues, fusing the best of both.

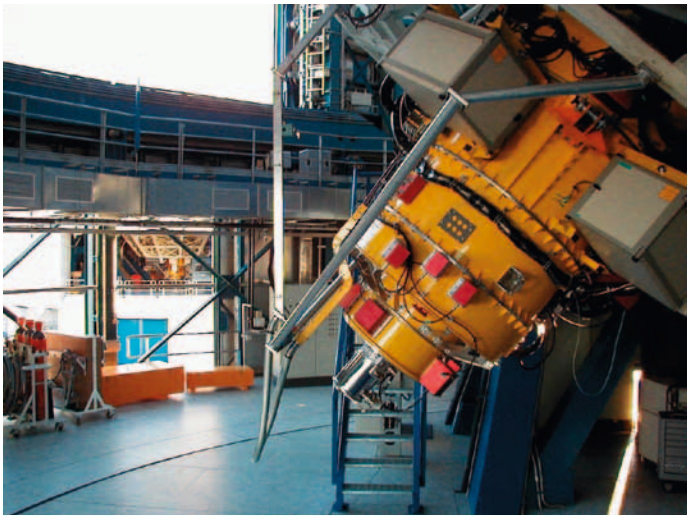

Figure 1. The FORS twins, in separate UTs.

The first of April 1999 marks the day science operations started on the Very Large Telescope (VLT), with Unit Telescope 1 (UT1, Antu) only. Two instruments were installed on Antu: ISAAC, (the Infrared Spectrometer And Array Camera) designed and built by ESO, and FORS1, (the first FOcal Reducer/low dispersion Spectrograph) created by VIC, the VLT Instrument Consortium, composed of the observatories of Heidelberg, Göttingen and Munich (Germany). Exactly one year later, FORS2 took up duty on Paranal on UT2 Kueyen. Since then the FORS twins (Figure 1) have provided astronomers with a wealth of observational data of excellent quality. The successful teamwork of the two FORS instruments came to an end on 1 April 2009 with the retirement of FORS1 after exactly ten years of operations. FORS2 reached the ten-year mark one year later, so on 1 April of this year, the two FORS instruments together had racked up a total of 20 years of successful science operations.

Some pre-history

The origins of what became FORS date back a long way. The report of the Working Group on Imaging and Low Resolution Spectroscopy (VLT Report No. 52) in July 1986 recommended building *"a set of general purpose focal reducers at one Nasmyth focus on each of the (four) array elements"* (that is, the UTs). The only direct legacy of this far-reaching recommendation are the twin FORS instruments. In June 1989 ESO issued the VLT Instrumentation Plan asking for comments and expressions of interest from European institutes. In response to the ESO call, a consortium was formed by Immo Appenzeller of the Landessternwarte in Heidelberg as Principal Investigator, with Rolf Kudritzki of the University of Munich and Klaus Fricke of the University of Göttingen as co-Investigators. This consortium intended to submit a proposal for the medium-high resolution spectrograph, now known as UVES. ESO, however, finally decided to build this instrument internally, so the consortium changed course at short notice and entered the competitive tender with a bid for the focal reducer/low dispersion spectrograph instead! The bid was successful, against one competing proposal, and after lengthy contract negotiations involving the project institutes, their host universities and, by the end, three different German federal states as well as several federal ministries, the contract with ESO was signed in December 1991. The contract foresaw ESO paying for the FORS hardware and the provision of the detector systems; in addition the consortium invested substantially in its infrastructure in support of the FORS project and about 130-person years of work until the completion of the project. At the final acceptance of the FORS instruments by ESO, the FORS consortium even stayed under budget. In return for its effort, the consortium was granted 66 nights of guaranteed observing time to be spent on science programmes using the two FORS instruments in visitor mode.

A highly motivated team of astronomers and engineers jumped to the task of designing the first VLT science instrument, and the Preliminary Design Review took place in April 1992. Originally it was planned to build two identical copies of FORS and equip them with identical sets of filters and grisms. During the Final Design Phase it was, however, decided to purchase only one set of the expensive polarisation optics; the Wollaston prism and the linear and circular retarder plate mosaics being among the largest ever made, at least for astronomical applications. The money saved was instead invested in high-resolution collimator optics, which avoided vignetting out to the corners of the CCD and, in addition, also paid for the Mask Exchange Unit (MXU), later incorporated in FORS2.

The Final Design Review was passed at the end of 1994. In 1996 system integration and tests started in an assembly hall rented at DLR (Deutsches Zentrum für

Figure 2. Provisional Acceptance in Europe of FORS1 at DLR Oberpfaffenhofen in June 1998. From left to right: front row Heinz Kotzlowski, Immo Appenzeller, Sandro D'Odorico, Bernard Muschielok, Walter Seifert, Wolfgang Hummel. Middle row: Guy Monnet, Roberto Gilmozzi, Thomas Szeifert. Back row: Harald Nicklas, Rolf Kudritzki, Gerd Wieland, Gero Rupprecht, Reinhold Häfner, Wolfgang Meisl, Achim Hess. *Tempus fugit …*

Luft- und Raumfahrt) in Oberpfaffenhofen. It was here that an accident happened during a handling operation, and the fully equipped collimator section of FORS1, in total about 600 kg of mechanics, optics and electronics, fell from the crane. Rumours spread quickly that someone had been killed, which fortunately turned out not to be true. Nobody had been hurt, not even the optics, the only damage was to the metal housing and the floor of the DLR integration hall. Now ordering all major instrument parts twice paid off: within three weeks the damaged part had been replaced by the corresponding piece from FORS2 and a replacement ordered, which arrived by the time it was needed for the assembly of FORS2! After extensive tests, Preliminary Acceptance of FORS1 in Europe was declared by ESO in July 1998 (see Figure 2) and the instrument was shipped to Paranal for installation at the VLT.

Commissioning

Upon arrival of FORS1 and the integration team on site in August 1998, Paranal was still a full-blown construction site. You could only enter the Control Building wearing a hard hat — there were no proper ceilings, the rooms that later became offices had no windows, there were no sanitary facilities available, etc.! UT1 was still undergoing commissioning — first light (see Tarenghi et al., 1998) had occurred just weeks before. In September, on-site assembly and testing in the Auxiliary Telescope Hall (which was itself still under construction) was finished and FORS1 was attached to the Antu Cassegrain focus. In the hours preceding what was supposed to become the FORS1 first light on the night sky, one of us discovered, to everybody's horror, that there was water inside the instrument! FORS1 was quickly but carefully dismounted again, disassembled and painstakingly dried and cleaned using huge amounts of optical paper! The reason for this "flood" was a burst cooling hose inside the telescope adapter/rotator. After replacement of the hose, FORS1 was remounted and saw its true first light during the night of 15 to 16 September 1998 (Appenzeller et al., 1998).

It turned out that the instrument was in optimum focus when mounted, and the stars showed an image quality of 0.6 arcseconds in the very first image taken with the instrument on sky! The first exposures of an interesting celestial object resulted in the famous image of spiral galaxy NGC 1232, which, one year later, the readers of *Sky and Telescope* magazine voted to be among the ten most inspiring astronomical images of the 20th century (Figure 3)!

Figure 3. Named one of the most inspiring astronomical images of the 20th century: the FORS1 first light image of the galaxy NGC 1232.

A further (and final!) water incident during the second commissioning run, again due to a hose in the telescope adapter, earned FORS1 the nickname "Yellow Submarine" among the mountain crew. This had no effect, however, on the excellent relationship between the FORS consortium team and the colleagues on Paranal who gave superb support to the commissioning activities. One important commissioning task involved the verification on the telescope of the specified image motion due to telescope tilt and instrument rotation. To accomplish the task, the mechanics specialist from the instrument team spent several nights laboriously driving FORS through endless measurement cycles that confirmed the finite element prediction and first assessments at a telescope simulator in Europe: image motion is so small, below a quarter of a CCD pixel in two hours for the standard collimator, that FORS is known to be the only focal reducer type instrument to allow the image distortion by weak lensing around remote galaxy clusters to be measured. After two weeks of Science Verification in January 1999, FORS1 was finally handed over to ESO for operation at the VLT. As a last step, now performed by ESO, the instrument was "Paranalised", i.e. its operation and control scheme were tuned to fully match the observatory operation environment and science operations concept. During the VLT inauguration ceremony in March 1999, a few weeks before science operations began, FORS1 delivered some of the sharpest ground-based images ever taken without special techniques, such as adaptive optics or speckle imaging: 0.25 arcseconds full width at half maximum in *I*-band — a very promising start indeed!

One side effect of being the first instrument on the VLT was the need to record all night activities, so the FORS team invented the structure of the night logs, which is still basically the same today, although the night astronomer can now rely on software tools to fill them, which the team did not have at their disposal back in 1999.

On 1 April 1999 Massimo Tarenghi, the first director of the VLT, declared that from now on Paranal was no longer a construction site, but a working observatory and FORS1, together with ISAAC, opened the science operations period at the VLT. In September 1999 its twin, FORS2 arrived on Paranal and entered regular service on UT2 Kueyen in April 2000 (without the embarrassment that FORS1 had to go through). Although this had not been foreseen, both FORS instruments changed telescopes several times in the following years to optimise the use of the UTs as telescopes came online one after the other. Every Cassegrain focus of the VLT has by now successfully hosted at least one FORS at some time, a testimony to the precision with which the UTs were built to be identical, and to the robustness of the FORS instruments at the VLT!

Upgrades and the FORS merger

Earlier than originally expected, new CCDs with a better red sensitivity became available, so work on the replacement of one of the original TEK 2k × 2k detectors started when FORS2 was barely on the telescope. The Garching Optical Detector Team provided a CCD mosaic with two MIT 2k × 4k (15 µm pixel) chips complete with a new FIERA controller, and the system was successfully commissioned in October 2001. It has been in continuous science operations on FORS2 since April 2002, only recently interrupted sometimes when the blue–sensitive FORS1 CCD is mounted. Upgrading FORS1 with a blue-sensitive CCD mosaic took much longer: a mosaic of blue sensitive e2v CCDs with the same format as the red system on FORS2 was ready for commissioning only in early 2007. Since the retirement of FORS1 in 2009 it has been offered in visitor mode on FORS2.

In addition to the replacement of the detectors, ESO improved the efficiency of both FORS instruments by acquiring a number of highly efficient Volume Phased Holographic Grisms (VPHG) as well as various high throughput broad- and medium-band filters.

The need to free a VLT Cassegrain focus for X-shooter (Vernet et al., 2009), the first of the second generation VLT instruments, sealed the fate of FORS1.The decision was to keep FORS2 operational since it is younger and is operationally more versatile due to the MXU. From the electro-mechanical point of view both FORS instruments are almost identical, so it was possible, with only a small effort, to transfer the polarimetry optics (Wollaston prism and the two retarder plate mosaics) from FORS1 to FORS2, to calibrate and commission this important mode and to offer it from Period 83 onwards with FORS2.

FORS: popular, productive and highly cited

From the very first period on the VLT, FORS1 was the most popular instrument in terms of requested observing time, and it was only surpassed in popularity by UVES at the time FORS2 came online and the demand for FORS time could be divided between the two instruments (Figure 4). The demand for both FORS instruments remained high until the day of FORS1 decommissioning. This is also reflected in their productivity. In Figure 5 we plot the number of refereed publications per year as a function of the time after the instrument came into operation. It is clearly seen that FORS1 and UVES were the two most productive instruments for the first five years of their careers, while FORS2 takes third position. Both FORS instruments together had produced 1161 refereed papers by the end of 2009 with a total of 40 783 citations.

Only after FORS2 was upgraded did FORS1 drop in popularity, as many users moved to FORS2 instead. The publication rate is, to some extent, a result of how much time was allocated. Looking instead at the publication efficiency, i.e. publication rate per allocated night, ISAAC and FORS2 currently produce roughly 0.75 refereed papers per observing night, UVES produces 0.9, while FORS1, during its last few periods, produced about 1.0 paper per night and was the most publication-efficient VLT instrument so far.

If we look at the number of citations of VLT papers, it is symptomatic that at least one of the two FORS instruments was involved in eight of the ten most cited VLT papers. The most-cited papers are those of large collaborations that include all major telescopes — the Hubble

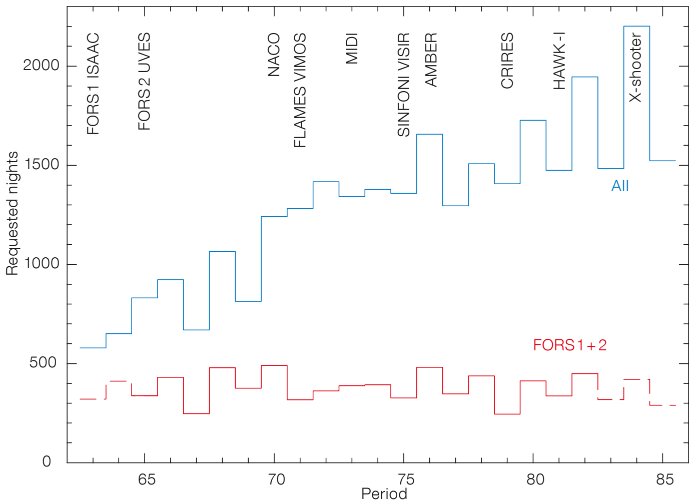

Figure 4. Breakdown of nights requested for all VLT and VLTI instruments (blue) and FORS (red — solid line both FORS instruments, dashed line for only one FORS).

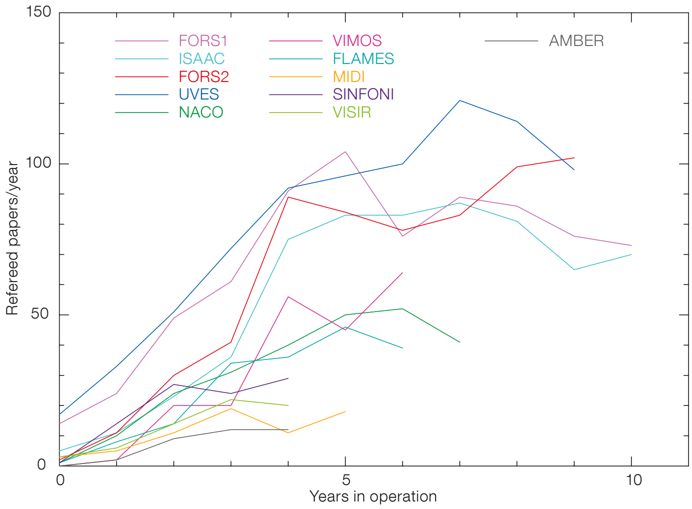

Figure 5. Number of refereed papers per year for all VLT and VLTI instruments in operation since 2005.

Space Telescope, Keck and the VLT. Typically those are produced by high-redshift supernova projects with up to almost 2000 citations. The most-cited paper exclusively involving the VLT currently has 643 citations and was based on data taken with both FORS1 and FORS2 (Hjorth et al., 2003; see also the science highlights below).

Science highlights

As befits a multi-mode instrument like FORS, it has contributed to a broad range of science topics, some of which will be briefly reported below. Considering the huge number of publications and citations, it is obvious that the papers discussed below present a very limited sample. We have tried to select publications that illustrate the wide variety of science topics addressed with FORS.

One of the first major scientific ventures by the FORS consortium was an imaging campaign for the FORS Deep Field (FDF; Appenzeller et al., 2004), with a sky coverage substantially larger than the Hubble Deep Field (HDF), see Figure 6. Across several semesters, many members of the three observatories of the FORS consortium spent several nights on Paranal, enjoying the desert life, since the Residencia had not yet been built. In the end, about 72 hours of integration time were spent on UBgRI images reaching limiting magnitudes similar to the Hubble Deep Field. The resulting catalogue of 8753 objects in this 7 × 7 arcminute region close to the South Galactic pole also contained a quasar at $z = 3.4$. Several papers exploited this deep field investigating for example evolving luminosity functions and star formation rates. However, the FDF project was, from the start, also a spectroscopic campaign obtaining about 700 spectra of high-redshift galaxies to study, for example, their metal enrichment and mass evolution.

As already mentioned the FORS instruments are the only focal reducers to allow measurements of weak gravitational lensing. Bradac et al. (2005) used FORS data of a very massive X-ray cluster to perform a combined analysis of both strong lensing (multiple images of background sources) and weak lensing (distortion of background sources) effects to determine the cluster's mass. They used the high resolution collimator of FORS1 to achieve an internal astrometric accuracy of 0.01 to 0.015 arcseconds.

Both FORS instruments were involved in the first conclusive demonstration that long-duration, energetic gamma-ray bursts (GRBs) are associated with the deaths of massive stars (also known as hypernovae). Hjorth et al. (2003) used long-slit spectra of GRB030329 obtained with FORS1 and FORS2 over a period of four weeks after the detection of this high-redshift GRB to fit the light curve of the underlying supernova. Analysis of these observations strongly favoured the collapsar model for typical GRBs.

FORS1 in particular contributed significantly to the study of asymmetry effects in Type Ia supernovae, employing its spectro-polarimetric (PMOS) mode. Electron scattering in the ejecta of a supernova polarises its light and polarimetry therefore allows information about possible asymmetries in the ejecta to be derived. Wang et al. (2007) presented observations of 17 Type Ia supernovae, twelve of which were observed with FORS1 in its PMOS mode. They clearly show significantly higher polarisation in some emission lines compared to the continuum. This points towards a chemically clumpy structure of the outermost ejecta. Such clumpiness introduces a certain amount of randomness into the modelling of supernovae and may thus affect their use as standard candles.

Figure 6. Colour-composite of the FORS Deep Field formed by combining *UBgR* filter images (Appenzeller et al., 2004).

Moving from extragalactic to closer targets, in 1999 FORS1 also obtained the first spectra of globular cluster white dwarfs, the brightest of which have typical *V* magnitudes of 24–25. The high background added by myriads of brighter stars close by, most of them on the main sequence, made these observations a real challenge. Using FORS1 multi-object spectroscopy data observed with the high resolution (HR) collimator from 1999–2001, Moehler et al. (2004) verified for the first time that the average mass of hot globular cluster white dwarfs differs significantly from the average mass of field white dwarfs. Their detection of only hydrogen-rich white dwarfs was the first indication that the number of hydrogen-rich *vs*. helium-rich white dwarfs differs between field and globular cluster stars, which raises questions about our understanding of white dwarf evolution.

Coming even closer to home the FORS instruments also pointed their optics to extrasolar planets, and more specifically to transiting planets. Moutou et al. (2004) used FORS2 with its HR collimator to achieve a spatial resolution of 0.125 arcseconds and observed OGLE-TR-132b during a transit. With these data they achieved an unprecedented relative photometric precision of 0.0012 mag, which allowed them to constrain the previously rather uncertain planetary parameters, despite the very shallow minimum of the light curve.

The outskirts of our own planetary system, the trans-Neptunian region, has also been explored with the FORS instruments. In fact most of the visible spectra of Trans-Neptunian Objects (TNOs) that exist in the astronomical archives were collected with one of the FORS instruments, and there are several indications for features attributable to alteration by water seen in these spectra: an intriguing detection indeed, since it may imply the existence of liquid or gaseous water in these objects for a couple of million years at a solar distance where it was not expected to exist.

Operations and future prospects

When the VLT started science operations in 1999, the way the VLT was operated differed in many aspects from the La Silla model. The concept of observation blocks (OBs) was quite new, as was the excellent pointing precision of the UTs and the fact that you never needed to worry about focusing the instrument or the telescope — it was all designed and built into the system! But it was necessary to gain experience in building efficient OBs, otherwise one could waste a lot of precious observing time (one second of telescope time on the VLT costs roughly one euro) with unnecessary instrument reconfiguration or telescope presets.

Although the optical concept of FORS looks quite simple, the technical realisation resulted in a complex instrument. Each FORS instrument contains more than 50 motors, most of them small precision motors driving, for instance, multislits with sub-arcsecond accuracy, but also some big ones used to turn heavy filter and grism wheels or to exchange collimators the size of a small telescope. Nevertheless both instruments hold top positions on Paranal regarding reliability, thanks to the careful design, engineering, manufacture and testing done by the FORS consortium more than a decade ago. As true multi-mode instruments with a large number of available filters and grisms, the FORS instruments also present a particular challenge to the operations team at Paranal — every evening the correct set of components must be inserted and the necessary sequence of calibration OBs executed in the morning. This is now supported by software tools whose development was triggered by the difficulties our first Paranal post-docs encountered when they tried to stitch together the calibration sequences from the entries in faulty paper log sheets written by tired astronomers during the night!

Considering the long way we have come since then and the huge success achieved by the FORS instruments, it is understandable that many users did not like the decision to mothball FORS1 to give way to the new X-shooter. But we are looking forward to many exciting FORS2 observations and results in the years to come — after all, what would the VLT be without a sturdy, reliable imaging/low resolution spectrograph like FORS?

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The authors are, or were at some time, members of the FORS Instrument Operations Team (IOT), and we would like to thank all the colleagues who contributed to the design, construction, commissioning and operation of these marvellous instruments.

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Last, but not least, we thank the staff in the ESO Garching library for providing the data for the citation statistics, and in OPO for providing the proposal statistics.

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Links

For technical details on FORS see http://www.eso.org/sci/facilities/paranal/instruments/fors/.

A recent FORS image showing the massive young Galactic star cluster NGC 3603. Located at about 8 kpc, NGC 3603 is the nearest giant H II region. This colour image (7 × 7 arcminutes) was formed from FORS2 exposures taken through *V*, *R* and *I* filters. See release eso1005 for more details.