Performance of FLAMES at the VLT: 1 year of Operations

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ABSTRACT

Four years after its announcement at SPIE, FLAMES, the VLT fibre facility, has been completed, integrated into the VLT observatory and commissioned. It has been in operation since February 2003. More than 250000 scientific (single) spectra have been obtained, which have enabled the on-sky performance of the instrument to be compared to the predictions. We show that in several relevant aspects the real instrument significantly outperforms the specified astronomical performance. Some of the early scientific results are finally presented

Keywords: : Wide field Multi-Object Spectroscopy, Optical Fibres, Intermediate and high resolution spectroscopy

1. INTRODUCTION:

FLAMES is the fibre facility of the VLT. In 1998 the first FLAMES concept was presented at SPIE [1] predicting that the facility would have first light at the end of 2001, or about 3.5 years after the recommendation of the ESO Scientific Technical Committee. At the time of the SPIE conference in 2000, the concept was already fairly consolidated and at an advanced stage[2] ; two years later we were able to announce its successful installation and commissioning[3], which was completed with a delay of less than 1 year with respect to the first, very ambitious planning. FLAMES was developed by many institutions, across several continents, and its main milestones are summarized in Table 1. A more complete description of FLAMES can be found in [2,3, 4], in the web page of the instrument (www.eso.org/instruments/FLAMES) and in the FLAMES User's Manual. We note that FLAMES operates with a corrected field of 25 arcminutes, and that it is linked to both the Giraffe and the UVES-Red spectrographs, which can also be used simultaneously. FLAMES is equipped with two plates, so that while one plate is observing, the next observation can be prepared on the other plate. The connection to UVES hosts 8 one arcsecond fibres, while the connection to Giraffe hosts 3 fibre systems: Medusa (132 single objects), IFU (15 deployable Integral Filed Units), and Argus (a single, larger fixed IFU in the middle of one plate). Giraffe is an intermediate and high resolution spectrograph, equipped with two gratings: an echelle for the high resolution mode and a normal grating for the low resolution applications. UVES is a stand alone instrument, pre-existingo FLAMES, and it has been possible to add a fibre link to its red arm by using its 12 arcseconds long slit[5].

1998	Apr: ESO STC Recommendation	Jul: Kickoff	Oct: PDR Optics Giraffe
1999	Apr: Giraffe PDR, Oz Poz PDR	Aug: Software PDR	Oct: Oz Poz FDR
2000	Jan: Giraffe FDR	July: Software FDR	
2001	Sep: Corrector Commissioning	Dec: PAA Oz Poz	Dec: Giraffe First light Europe
2002	Feb: Oz Poz integration at Paranal	Spring: Commissioning	Sep: Call for Proposal P71
2003	Jan: Science Verification	Feb: First visiting astronomer	Apr: Standard P71 operations

Table 1: Summary of the main FLAMES milestones. PDR: Preliminary Design Review. FDR: Final Design Review. PAA: Provisional Acceptance Australia.

A picture of FLAMES on the Nasmyth A platform of the VLT unit Kueyen is given in Figure 1, which shows the Oz Poz and the Giraffe enclosures, with the fibre trail between them.

2. PERFORMANCE

In its first year of operation (April 2003-April 2004), FLAMES was used for about 1500 hours, with an open shutter time of 1100 hours, producing about 2200 GIRAFFE scientific frames as well as about 1200 UVES-FLAMES frames. So far, MEDUSA has been the most widely used observing mode with Giraffe, being used for ~85% of the time. We can therefore estimate that about 250000 single spectra have been produced to date. The instrument has received between 60 and 90 proposal/period with a success rate slightly above 50% (including, however, several runs of GTO time). As for every other VLT instrument, FLAMES has been offered in visitor and service modes, with all the observing runs being fully supported by the ESO operations system, through the different phases of the proposal; from Phase1 to the observation, data distribution and archiving. This implies also the distribution and maintenance of the fibre assignation software, developed at AAO for FLAMES, which allows users to prepare their observations. For service mode observers, the assignation file is attached to the Observation blocks prepared by the Phase 2 proposal tool, and transmitted to the observatory. The UVES-fibre on-line pipeline has been installed since November 2002 and it has produced fully-reduced spectra since, passing through several upgrades.

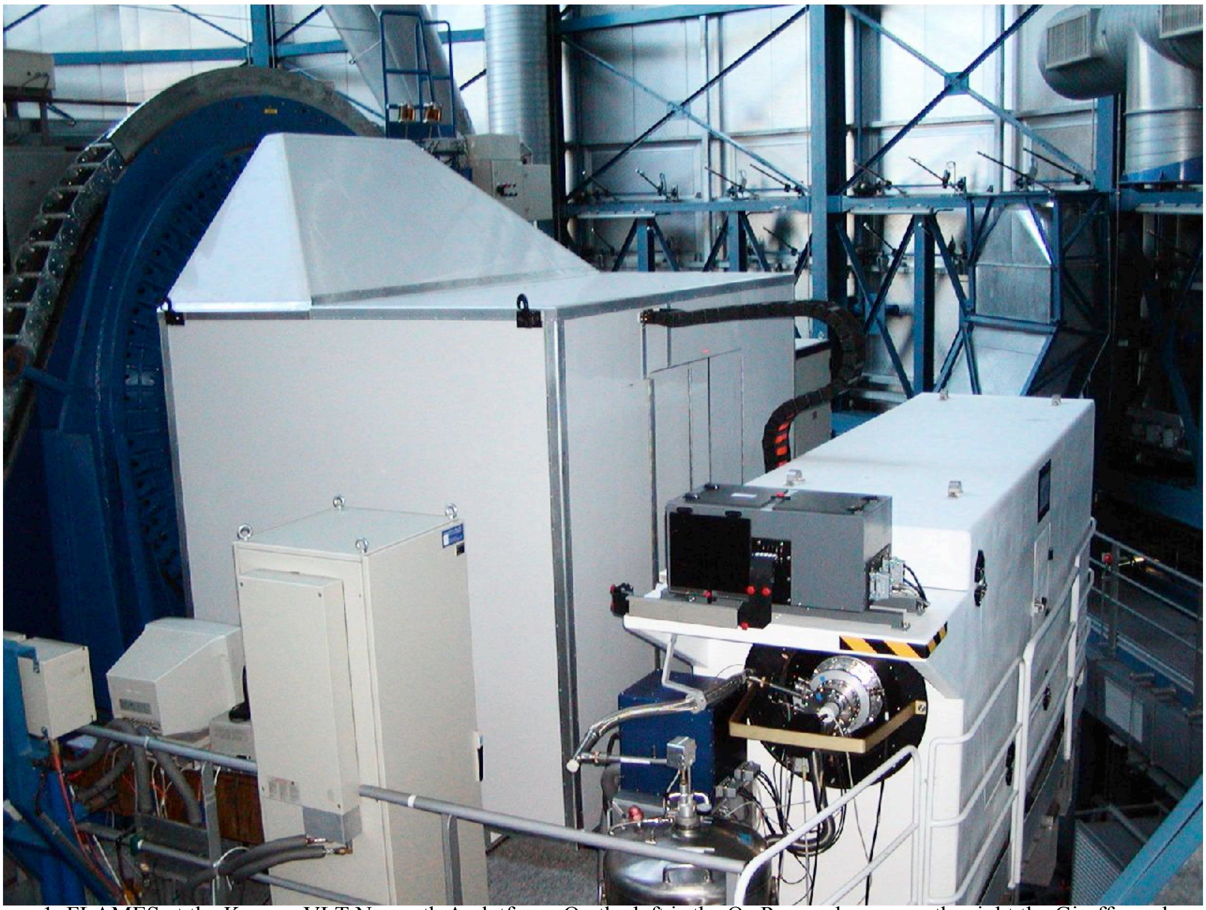

Figure 1: FLAMES at the Kueyen VLT Nasmyth A platform. On the left is the Oz Poz enclosure, on the right the Giraffe enclosure. The Fibre trail connects the two enclosures, and the Giraffe CCD dewar and continuous nitrogen cryostat is well visible

A baseline version of the Giraffe pipeline has been available on Paranal since April 2004, producing extracted science spectra for all observational modes, including reconstructed images for IFU and Argus. Additional features (scattered light removal, sky subtraction) needed to complete the pipeline will be added in the course of 2004. Although the Giraffe pipeline became available only recently, several quality control parameters have been successfully implemented. These are routinely applied and their outcomes will be widely used in this presentation.

From the beginning, FLAMES has been proven itself to be reliable and, thanks to the exchange plate mechanism inherited by 2df[6], it has a high duty cycle. This avoids the need for calibrations during the night and makes it possible to observe and prepare for the next observation simultaneously. This last function implies, in particular a) high fibre transmission stability, b) high spectrograph stability, c) development of a safe operational scheme and observing software.

2.1. Some Astronomical Performances

FLAMES has quite a remarkably high duty cycle, with an open shutter time of about 76%. This is a fraction of the total time effectively available for the acquisition of scientific exposures; the missing 24% excludes, therefore, weather losses and technical or operational problems of any nature. While this high open-shutter time is partially due to the relatively long exposure time required by each observation, a feature common to high and intermediate resolution spectrographs, it also implies that we have been rather successful in minimizing the overheads.

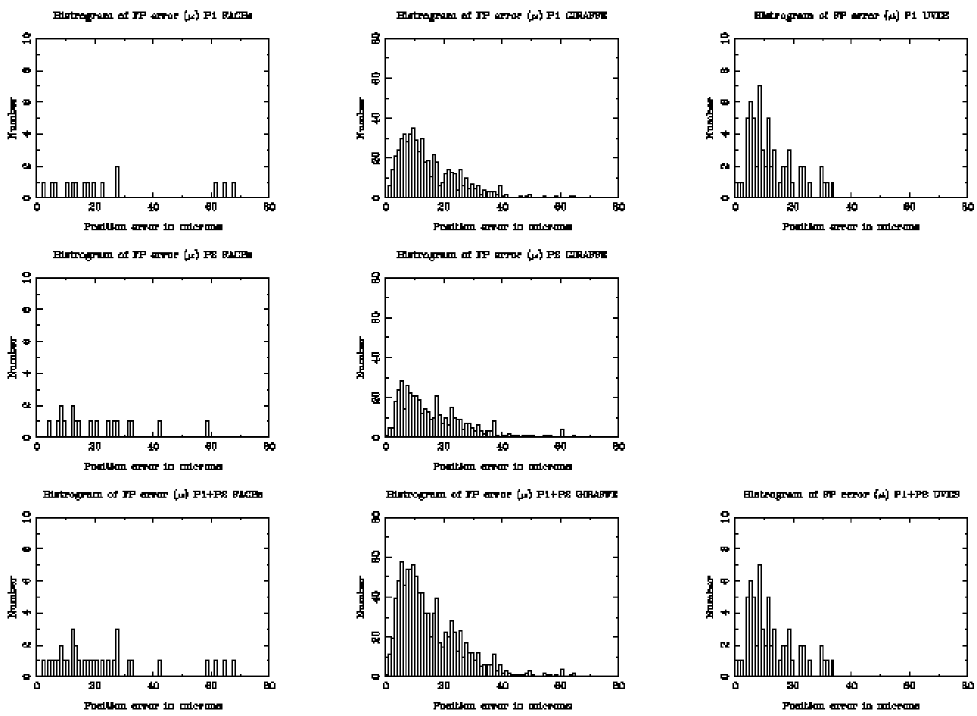

Figure 2: Example of FLAMES buttons positioning accuracy. Each panel shows the distribution of the obtained theoretical position (in microns; 60 microns correspond to ~0.1 arcseconds) for different types of fibres. Each number is automatically logged in the telescope log and can be constantly monitored by the users.

An average positioning of the 130 Giraffe fibres takes 15 minutes, which is typically done while observing with the other plate. The time needed to swap the plates is less than 3 minutes (specifications were 5 minutes, see [7] for details), and the typical time needed to point the telescope, apply active optics and acquire the acquisition Fiducial Bundles (coherent fibre bundles which point to 4 fiducial stars in the field) lasts less than 12 minutes, so that the full operation of exchanging between two fields takes less than 15 minutes.

The fibre pointing accuracy is not easy to assess. It is monitored by checking the mechanical accuracy of the positioning and through the observation of astrometric fields. The fibre positioning mechanical accuracy is well within 60 microns (0.1 arcseconds at the VLT Nasmyth focus) with a median value of between 10 and 20 microns. This can be seen from Figure 2, which shows the distribution of the fibre positioning error (fibre effective position – fibre theoretical position) for the different types of fibres, taken from the telescope log on a randomly chosen night. Fast tests on the sky can be made by placing the four FACBs (fiducial bundles) on four objects with accurate astrometry, and reading the RMS of the FACBs centre residuals. These tests, regularly performed, show that the fibres are well placed within 0.15 arcseconds. These measurements include all other effects, in addition to the mechanical positioning accuracy, which can affect the accuracy of positioning, such as determination of the plate scale, correct treatment of the atmospheric effects, plate metrics calibration. In this first year of experience, only one case emerged where doubt was cast on the accuracy of the positioning. In practice, the accuracy is so good that the FLAMES results are used to assess the coordinates provided by the users, rather than the other way around.

The resolving power obtained with a UVES-Fibre is of 47000, in perfect agreement with the predictions. With Giraffe, the resolving power is highly variable between the setups. Due to the need to use the gratings at different angles (cfr. www.eso.org/instruments/FLAMES/specs1.html) the average resolving power with Medusa is in the order of 19000 and 7000, with the high and low resolution gratings respectively, also in line with the theoretical predictions. The effects of the system's optical quality start to be noticeable only for ARGUS and IFUs which, with apertures of only 0.52 in the sky, are just properly sampled. For ARGUS and IFUs, the above spectral resolution should be multiplied by a factor of 1.6. The average UVES and Giraffe resolving power is slightly higher than that originally specified (due to the increase in resolution caused by the fact that the specifications considered the long slit approximation, without considering the circular aperture of the fibres). Nevertheless, several setups with even higher resolution are offered, although their efficiency is somewhat reduced by the quest for high-resolving power, in particular with regard to the detailed analysis of the spectra of cool stars.

The overall throughput of the system (including the telescope) is quite remarkable, particularly considering the fairly complex train of optics involved: with Giraffe in the V band it reaches 10.6% (setup HR10) and the 8.5% (setup LR4) with the high and low resolution mode respectively; it is of the order of 8.3% at 600 nm with UVES-fibres using the 580nm setup (see www.eso.org/instruments/FLAMES/etc) . This translates into 1 electron/sec/Angstrom at magnitude ~18.7 and ~19 for UVES-fibres (and Giraffe L-R), and Giraffe H-R respectively. Translating this efficiency into on-sky performance, assuming a seeing of 0.8 arcseconds and an object-decentering of 0.2 arcseconds, we obtain with a one-hour exposure a S/N of 12-14 per resolution element for an object of V=20.5 with the low resolution mode of Giraffe (LR4 setup with a resolving power of 6000) and of 40-44 for 1 hour observation of a 18 magnitude star in the high resolution mode (setup HR10, R=20000); a point source has been considered. These numbers accord extremely well the predictions made in the year 2000 (cfr. Figure 6 of reference [2]), in particular when considering that these performances are obtained for a resolution element which is now 20 to 30% smaller than what was accounted for in the early computations.

2.2. Calibrations and Stability

One of the operational concepts for FLAMES was that it should be possible to calibrate the instrument without using precious telescope time; i.e. during the day following the observations. The successful achievement of this requirement has had far-reaching consequences, one of which is that the fibres must not appreciably change their transmission when moved, and that the night setup must be highly reproducible after several hours. This requires very good spectrograph and grating position reproducibility, so that the science and calibration spectra fall on the same detector pixels.

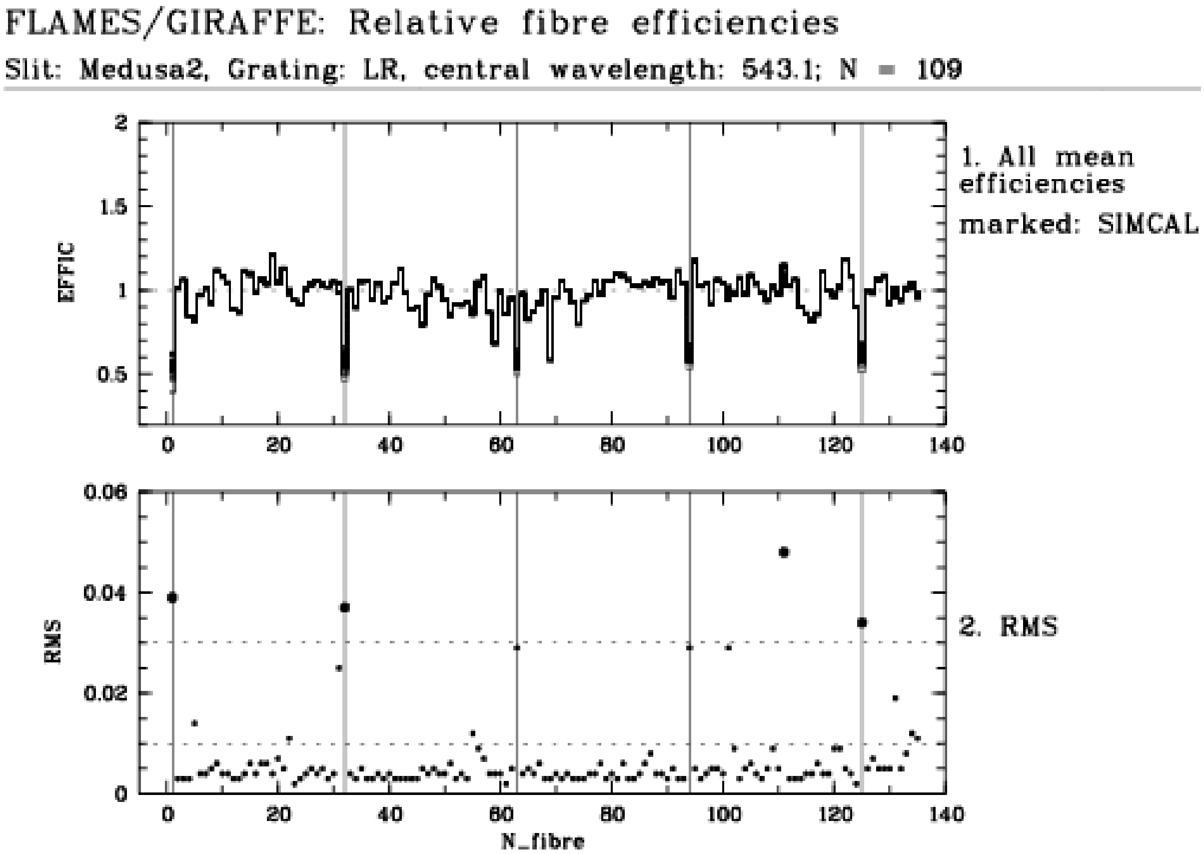

Figure 3: Fibre-to-fibre relative transmission (upper panel) after 54 tests, carried out regularly with the gripper, over a period of three months. The lower panel shows the measurements' RMS, or the relative transmission stability. The 5 simultaneous calibration fibres are clearly identified (they are not illuminated by the gripper unit, so should not be considered). Only one fibre shows variations above 3% and 3 additional above 1%.; the typical RMS is of 0.3%.

The FLAMES standard calibrations are obtained using a novel concept: the fibres are placed on the plate in a spiral shape; the Oz Poz gripper is equipped with a calibration unit which illuminates homogeneously the fibre entrance and the gripper sweeps over the spiral several times, the number of sweeps depending on the spectrograph setups. Since the accuracy of the gripper-moving mechanism is very high, a constant illumination of each fibre button to better than 0.3% is ensured. By using this method, quality control over the fibre-to-fibre transmission is obtained and, as shown in Figure 3, most fibres have a fibre-to-fibre transmission stable within 0.3% over several months. Giraffe is also equipped with 5 simultaneous calibration fibres, which are used to obtain very high radial velocity accuracy; the spectra of these fibres and of the calibrations can be used to monitor the accuracy of the grating repositioning and its shifts with temperature. Figure 4 (http://www.hq.eso.org./observing/dfo/quality/GIRAFFE/qc/qc1.html) shows that these two effects (repositioning and drifts) are extremely small, of the order of 0.2 Pixels/K in both the direction of the dispersion and perpendicular to it. Considering that the maximum excursion between night and day in the Giraffe enclosure is of less than 1 degree, this implies that, indeed, calibrations can be safely obtained the next day. Actual experience confirms this and, additionally, shows that they often do not appreciably vary, even after several days.

Although we do not yet have firm results concerning the sky subtraction capability of FLAMES, this very good overall stability shows that FLAMES has optimal characteristics for this critical task.

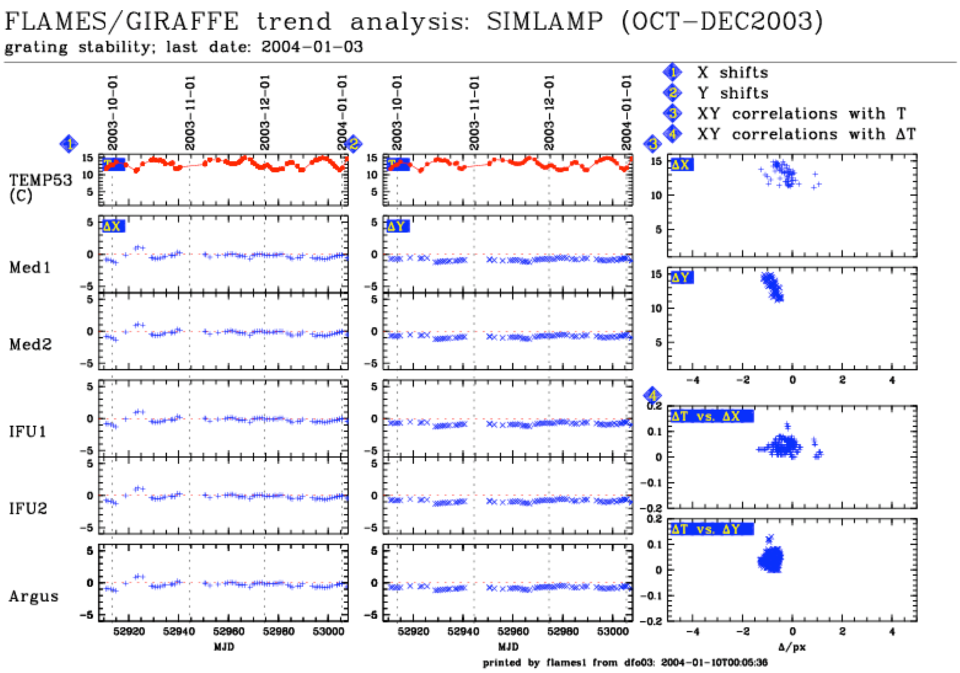

Figure 4: GIRAFFE Grating stability measurements, shown together with the temperature of the Giraffe optical table. These measurements are usually taken after a new setup is done, which includes repositioning of the slit and of the grating. The very good stability shown includes, therefore, also the effects induced by these movements.

2.3. Reliability

Experience with previous multi-fibre instruments has shown that reliability might be a potential issue, in particular in the first period of operation, and a great effort has been made at system level to ensure a system which is reliable and easy to maintain. The overall downtime of FLAMES has steadily decreased with time, from a rather high 10%-15% in the first 3 months of operations, to the actual 1-3% , in the last 6 months. The usage of FLAMES and its technical downtime is summarized in Table 2.

Month	Total Time (min)	Technical Downtime (min)	Downtime/Total Time
April 2003	2535	477	0.19
May 2003	8138	751	0.09
June 2003	7611	1261	0.16
Juky 2003	9041	579	0.06
August 2003	6881	237	0.03
September 2003	4656	505	0.11
October 2003	8298	927	0.11
November 2003	7836	407	0.05
December 2003	8777	99	0.01
January 2004	7687	269	0.04
February 2004	7497	184	0.02
March 2004	6820	251	0.04
April 2004	4293	45	0.01
TOTAL	90070	5992	0.065

Table 2: Total FLAMES scientific exposure time and instrument technical downtime per month, during the first year of operation. A clear decrease in downtime is evident after the November intervention.

Broadly speaking, we can divide the causes of time-loss into three main groups:

- Occasional failure of the gripper in picking or placing a fibre
- Occasional SW failure (most notably missing correct merging of the FITS headers, or CCD reading)
- Occasional inappropriate operation

The first problem was mostly due to the fact that, although remaining within a given range, the magnetic force of the buttons varies from button to button, and the force produced by the different types of fibres is also different (e.g. the thick and somewhat rigid IFU or FACB bundles exert a much higher force than the thin, flexible IFU sky or UVES). This problem was solved in October 2003, after a careful intervention on Oz Poz, by tuning the gripper distance to the plate and its strength.

The second problem was quite annoying because, as it affected the observations only during or upon completion of the detector reading, it could potentially lead to the loss of a full exposure. The problem was solved in January by upgrading both the controller hardware and the FLAMES software.

Finally, concerning operations, great progress has been made by improving the operational software and the instrument exchange procedures. One noteworthy point in this respect is that, from the outset, FLAMES observations were regularly interchanged with UVES stand-alone observations (UVES is sitting on the Nas. B platform of the same telescope) during the same night, if required by service operations. This means that, on almost every night dedicated to service observing, one change of instrument occurs.

We consider it a tremendous achievement that, during the whole two years spanned by commissioning and operations, with more than 1200 single fibres in the system, only two fibres (one sky IFU and one Medusa) have been damaged beyond repair. All other fibres are healthy, with no sign of transmission degradation. This was made possible by a number of up-front choices, including the (painful) decision to opt for a protective jacket up to the magnetic button on all fibres, so that no segment of 'bare' fibre is present, and to use a prism internal to the magnetic button to deviate the light into the fibre (cfr [8] for a detailed description of the fibre system). In addition, it is important to acknowledge the very careful job done by the positioner-software developers, who inserted a large number of software safety checks. It is worth recalling that no hardware mechanism or interlock is in place to prevent fibre collisions or stretch.

3. Upgrades

While in operation, a number of parallel activities were being carried out. The most noticeable of these was the completion of the instrument, through the commissioning of the central IFU[9] (Argus) and the upgrade of the high resolution grating. The original Giraffe high resolution echelle grating was coated with protected silver. It was below specification because it had received a non-uniform protective coating, which varied the thickness along the grating. The decrease in efficiency was strongest in the UV and at one end of the grating, while the other end was in accord with the specifications. We therefore mounted this grating as a temporary solution, waiting for the results of a better coating on a replica of the same master. It was indeed important that the overall spectral format be maintained, because of the presence of the order-selecting filters and because we wanted to guarantee as much continuity as possible to the users.

The newly coated grating arrived in 2003 and was mounted in October. In addition to the spectacular gain (in particular in the Blue range, where the transmission is almost 1.5 times higher), the new coating exhibited an interesting effect: the overall efficiency in the old grating is dominated by non-overlapping S and P polarization curves in the NIR, leading to a rather flat and low average efficiency curve. With the new coating, the S and P polarization curves also overlap in the NIR, and the effective blaze peaks moved towards the Blue; the effective blaze angle is wavelength-dependent and changes from about 60 degrees for orders 15-10 to 50 degrees in the lowest order 5, as shown in Figure 5.

While such behavior is generally well known, for most echelles, which have a coarse number of lines/mm, it happens in the IR, where it cannot easily be measured. The combination of a high blaze angle operating in low order numbers with such a high number of groves/mm produces this effect for Giraffe in the NIR, where it can be measured. In order to allow the full exploitation of the FLAMES potentialities, we have maintained as well the old (higher resolution, lower efficiency) NIR setups. Further future upgrades include the coating of the low resolution grating of Giraffe, and a new

CCD, much more RED sensitive than the one presently in use, but still maintaining an appropriate blue response. The UVES detector system will also be upgraded in the framework of the UVES project.

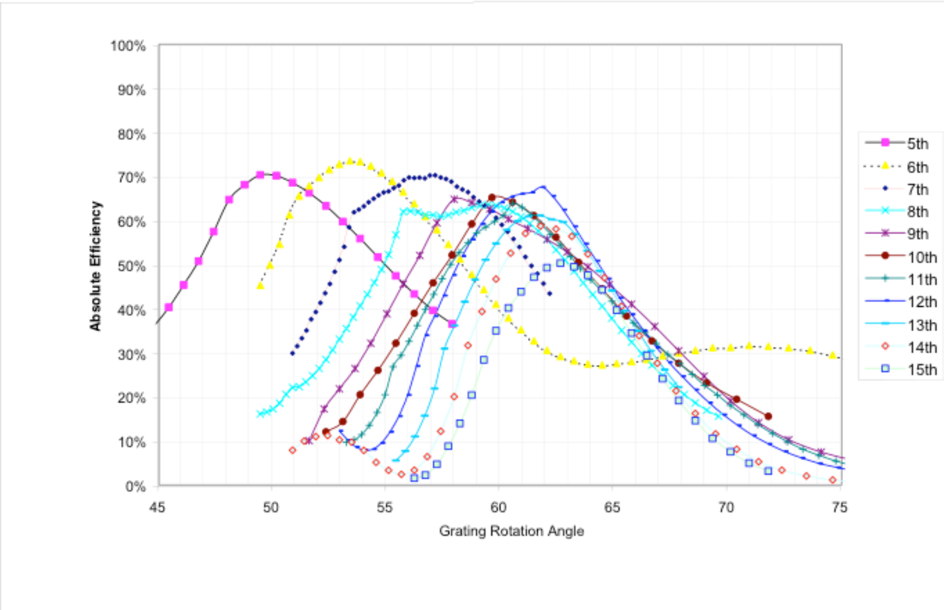

Figure 5: Change of the effective blaze angle at low order numbers for the Giraffe HR grating

4. Early Scientific Results

Among the science drivers of FLAMES we may recall that one of the main drivers, identified in the detailed study of different stellar populations in the Galaxy and in the local group, was to derive either their chemical or kinematical properties. A special effort has been made to guarantee the possibility to reach very good radial velocity accuracy, both with Giraffe and with UVES-fibre, by inserting simultaneous calibration fibres, following a technique developed by the Geneve group (see e.g. [10,11]). It does not come as a surprise, therefore, that precisely in these fields the first scientific FLAMES results have been obtained. In January 2003, a month before the first visiting astronomers arrived, the FLAMES science verification took place[12], assuring more than 5000 single spectra (see also http://www.eso.org/science/vltsv/flamessv). A few months afterwards, in April, the first release of the Giraffe data reduction software was made public by the Geneve-Lausanne group and the UVES-fibre pipeline was installed and distributed. This allowed the first exploitation of the science verification data, the first results of which were recently published. A detailed study of the globular cluster NGC2808 has been performed, to investigate mass motions and chromospheric activity in the red giant stars, and to understand how and when heavy mass losses are originated in the atmospheres of these stars [13]. Spectra of more than 100 RGB stars were secured in the chromospheric H and CaII H and Klines.

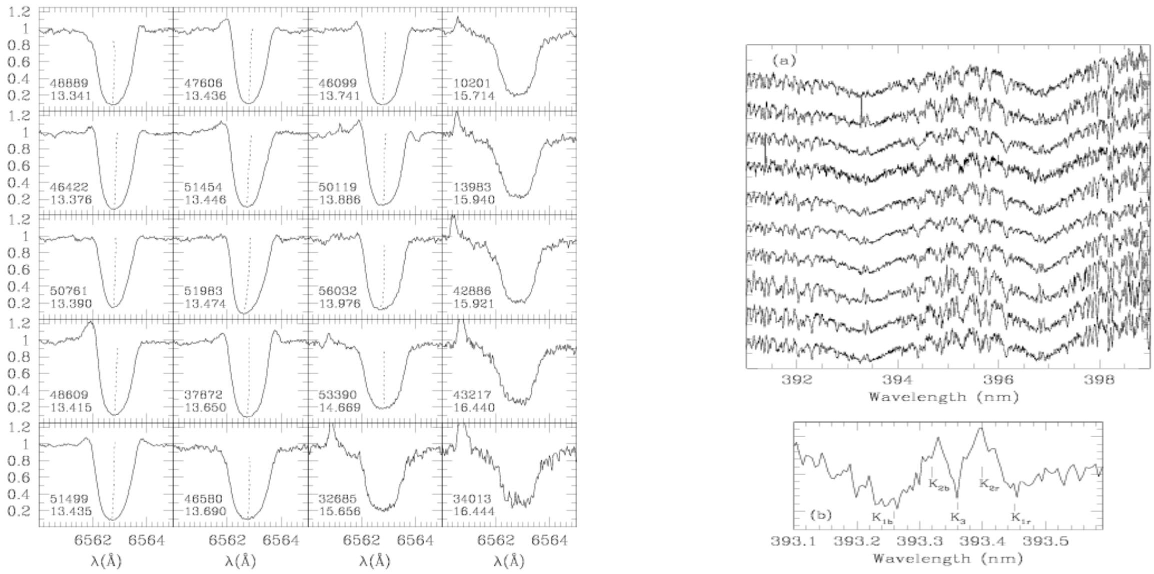

Figure 6: Ha and CaII spectra of Red Giant Branch stars in the globular cluster NGC2808, from [13]

Thanks to spectra similar to those presented in Figure 6, the detection limits of these phenomena have been pushed 1.5 magnitudes lower then previous studies. The quality of the spectra (both for S/N ratio and resolution) make it possible to study subtle features, such as Ha asymmetries and the details of the deep Ca II K line core.

By using similar data in the Na D lines it has been proven for the first time that the giants of this cluster show a scatter in their Na abundance. Since this is also observed in low luminosity giants, where deep mixing phenomena do not occur, it is very likely that this scatter is primordial, intrinsic to the gas which formed the stars [14].

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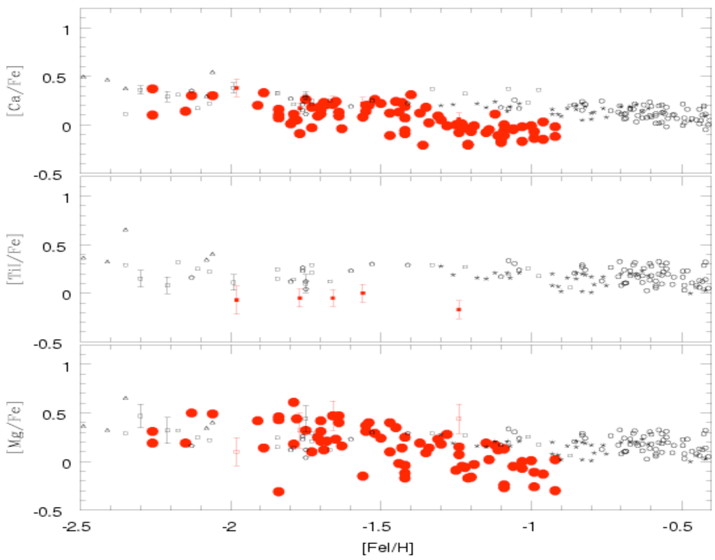

Figure 7: Elemental abundance ratios for about 100 stars in the LMC, from [16]. Data of this kind provides a much-needed basis for the study of the chemical evolution and star forming rate of the Magellanic Clouds and similar local group galaxies. Filled points are LMC stars; the other galactic stars.

Commissioning data has been used to study the dynamics of another, very peculiar Globular Cluster, Pal 12[15] The unprecedented accuracy obtained with Giraffe has shown that, contrary to previous claims, the cluster mass-to-light ratio is rather typical for globular clusters.

The Large Magellanic Cloud (LMC) is a natural target for FLAMES; and LMC science verification observations have been used to derive accurate abundances and abundance ratios in LMC giants.
In Figure 7 we show the abundance ratio of 100 stars in the LMC bar; this data will be of great importance for the study of star formation history and chemical evolution of our companion[16]. Similar data, acquired for other local group galaxies such as the Sculptor dwarf spheroidal, will provide a calibration for many lower quality Ca triplet spectra, making it possible to derive the metallicity distribution of this interesting object.[17]

Rotational velocity distribution in very low mass stars of the Orion Nebula have been obtained by[18], who have shown that these stars do not follow the bimodal period distribution expected of a classical disk-locking scenario; in addition, several PMS double-line spectroscopic binaries were found in this study. Figure 8 shows the cross-correlation profiles of one of them, taken at different phases. By studying in detail the radial velocity curve, it should be possible to determine the stellar parameters with a high level of accuracy.

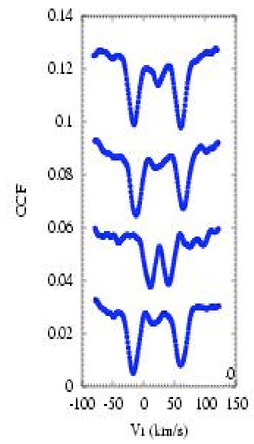

Figure 8: Cross-correlation profiles of a double line, very low mass main sequence binary in the Orion Nebula Cluster, from [18]

Finally, some results are already emerging from the 'normal' observing programs: the high radial velocity accuracy mode of the UVES-fibre has found a very spectacular application by confirming two hot Jupiter transit candidates proposed by the OGLE group[19]. Only 4 stars of this type are known and they may represent yet a new kind of exo-planet. In addition, the combination of eclipse and radial velocity observations allows unprecedented accuracy in the derivation of the planet characteristics. In the extra-galactic domain, it is worth mentioning the discovery of several intra-cluster planetary nebulae in the Virgo Cluster [20] Figure 9 shows one such spectrum. These nebulae are fundamental to the study of intra-cluster populations and cluster dynamics. Remaining in the extra-galactic planetary nebulae domain, a study of PN around the Centaurus A galaxy will allow the determination of the mass of this giant elliptical; the high resolution of FLAMES has allowed the recognition of line-of-sight coincidence of PN. [21] Moving towards higher redshifts, the large potential of the FLAMES IFUs for the study of the dynamics of intermediate redshift galaxies has been shown by the first application of this system to galaxies in the redshift range $0.45 < z < 0.65$ [22].

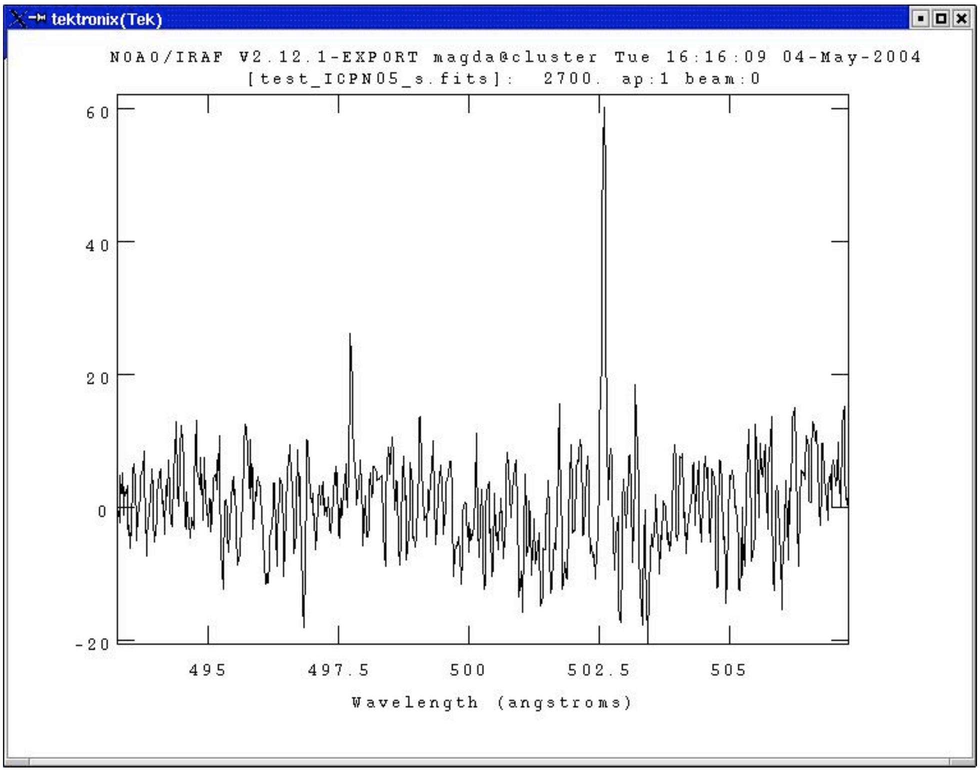

Figure 9: Portion of a Giraffe low resolution spectrum (R=7500) of an Intra-Cluster planetary nebula in the Virgo cluster. From[20] ; the exposure time was 2.5 hours and the integrated flux of the red shifted 5007 line is of 10^{-16} ergs cm^{-2} sec^{-1}.

5. Conclusions

After one year of operation at Paranal, FLAMES is a well-established instrument at the VLT observatory. All its basic performances meet and occasionally even exceed the specifications. In particular, there are two aspects of the project which we consider to be quite an achievement. The first is that FLAMES was developed within a reasonable timescale, given its complexity, providing the ESO potential users with a facility which is unique for an 8m telescope. The second is that such a complex system has demonstrated a level of reliability and operational efficiency which quickly reached the level of the other well-established VLT instruments. We welcome the first scientific publications and we look forward to many more exciting results in the future.

ACKNOWLEDGEMENTS

We would like to thank all the colleagues at ESO (Paranal and Garching) and at the different institutes (AAO, Meudon, Geneve, Lausanne, Cagliari, Trieste, Bologna, Palermo) which have contributed to the realization of FLAMES. We thank J. Eskdale for a careful reading of the manuscript.

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