VLT Science Products Produced by Pipelines: A Status Report

Using the Data Flow System, ESO is producing calibrated science data products for all VLT and VLTI instruments. For many users, these products can be used directly for scientific analysis without further processing. In the end, the scientific usefulness of these products depends strongly on the needs of the individual investigators.

David R. Silva and Michèle Peron (ESO)

One of the goals for the VLT Data Flow System (Quinn 1996) is to provide calibrated data products ready for science analysis for the instrument modes used most heavily during service observing. Achieving this goal depends on a complex interaction between the science goals of the astronomer, the operational model of the observatory, and the implementation of **instrument calibration pipelines**. The VLT Science Policy document establishes the following guidelines for instrument calibration and data products:

> *ESO will execute and maintain a calibration plan for all VLT/VLTI instruments. The calibration data resulting from this plan shall be made available to the ESO community. ESO will also use these data to monitor the long-term evolution of instruments and to produce data products. These data products will result from pipeline processing using the VLT/VLTI Data Flow System. Data products will consist of data with the instrumental signature removed as well as data calibrated into physical units. The accuracy of the instrumentation and physical unit calibration will be monitored and maintained by ESO.*
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> *In order to allow the ESO community to reproduce and modify the output of instrument calibration pipelines, ESO will make the pipeline reduction recipes and code available to the ESO community for all supported instrument modes. Over time, the number of supported modes for each instrument will be increased to ensure that the most actively used modes have calibrated data products available.*
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> *The accuracy of ESO pipelines should be such to satisfy a major fraction of the scientific needs of the users and ESO will attempt to increase their accuracy over time following the guidance of its community and in-house scientists.*

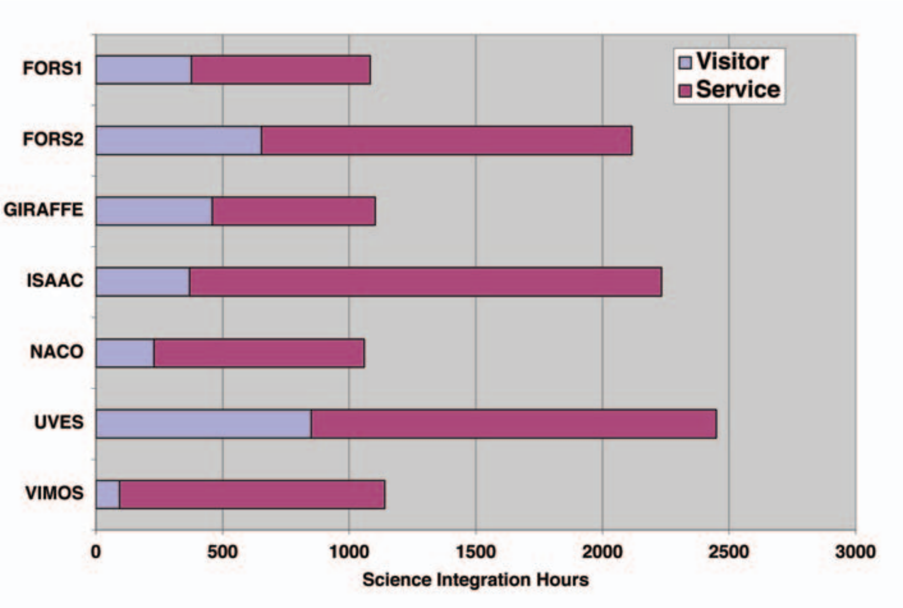


Figure 1: Science integration hours per VLT instrument, Period 70 – 73. The FORS1, FORS2, ISAAC, and UVES instruments were operational during this entire two-year period. VIMOS and GIRAFFE operations did not start until February 2003. Exact dates are 2002 October 1 to 2004 September 30. Guaranteed Time Observations (GTO) data have been excluded.

In this article, the current status of VLT/VLTI science products delivered by instrument calibration pipelines is presented with an emphasis towards science readiness, i.e. whether the currently delivered science products can be used for science analysis without further processing. For the most heavily used instrument modes over the last two years, we believe the answer is "yes", depending on the science objective and the required calibration precision. In the end, however, the usefulness and quality of any given science data product is in the eye of the beholder, i.e. it strongly depends on the technical needs and science objectives of the end-user astronomer or data analysis team. We hope this article will not only provide information to the ESO user community but also elicit feedback to help us improve our service.

In the following article, VLT is used as a metaphor for all science instruments operated on Cerro Paranal. Messenger articles by Comerón et al. (2003) and Mathys (2004) provide recent overviews of the VLT service observing operational model. Discussion of instrument calibration pipelines and science products for La Silla instruments are outside the scope of this article.

Instrument Calibration Pipelines

Operational fundamentals

All VLT science observations are executed using Observation Blocks (OBs) that are in turn composed of observation templates. Automatic instrument calibration pipelines have been implemented for the most heavily used instrument modes. These pipelines produce master calibration products used to monitor instantaneous and long-term instrument performance. Using the master calibration products, the pipelines also process raw science data into science products. Data are processed on a template-by-template basis. Data from different templates (or different OBs) are not processed together. In general, only so-called standard instrument configurations are supported.

The *automatic* production of science products using instrument calibration pipelines requires an electro-mechanically stable instrument (including detector), the acquisition of sufficient calibration data, and the implementation of proper software algorithms, where proper is defined as an algorithm that does not degrade scientific usefulness. How is ESO doing in these areas?

• **Stability:** at present, most of our instruments are stable (FORS1, FORS2, UVES, GIRAFFE), some are semi-stable (ISAAC, NACO) and one is (mechanically) unstable (VIMOS). Despite various mechanical problems, high quality VIMOS science products are often produced in automatic mode if sufficient night-time calibrations are available.

• **Calibration data:** calibration plans exist for all instruments and calibration data are obtained on a regular basis. These data are used to monitor instrument health and process science data. The target photometric calibration accuracy is 5–10% in magnitude for imaging and in the relative flux calibration for spectroscopy. The achieved photometric accuracy is often much better in both cases. Nevertheless, the achieved accuracy may not be sufficient for all science programmes.

• **Proper algorithms:** for imaging, essentially no problems exist today. For spectroscopy, the situation is more complex. While UVES pipeline results are universally proclaimed as science-ready for most users, this is not necessarily true for other instruments.

Instrument usage for science observations during the last two years is summarized in Figure 1. During this interval, more science data was produced in Service Mode than in Visitor Mode for all instruments. This information is broken down by instrument mode in Figure 2. Modes without pipeline support are indicated by vertical stripes. The vast majority of science data obtained during this period came from instrument modes with pipeline support. The most glaring exception is FORS2-MXU. Unfortunately, it was necessary in the last two years to shift pipeline development resources originally scheduled for FORS2-MXU to VIMOS.

Recipe development and availability

At the core of each instrument calibration pipeline are a set of instrument-specific software data processing engines known as **pipeline recipes**. For FORS1, FORS2, VIMOS, GIRAFFE, and MIDI, the instrument consortia that built and commissioned those instruments developed the original pipeline recipes. Since their delivery, these recipes have been maintained by ESO and modified to meet ESO operational goals. Recipes for the other currently operational instruments (VIMOS-IFU, ISAAC, UVES, and NACO) were developed within ESO where they are still actively maintained and extended as needed.

Recipes are released to the community as soon as possible after instrument operations begin, but not before their performance has been verified using data from the as-built, as-operated instrument in all standard configurations. In the past, this verification process has taken as long as a year but has recently accelerated. Recipe upgrades are released as needed. For information about how to download available recipes, see http://www.eso.org/pipelines/.

All released pipeline recipes come with technical documentation – some good and some not so good. More useful for astronomers are the science reduction discussions maintained for each of the VLT instruments on the ESO QC Web pages (http://www.eso.org/qc). But astronomer-oriented cookbooks are really needed, preferably written by experienced astronomers familiar with the pipeline recipes. Such a guidebook exists for ISAAC. ESO is trying to find ways to facilitate the creation of such cookbooks for other instruments, but unfortunately no direct resources for this activity exist right now.

Recent pipeline recipes (VIMOS, GIRAFFE) were built partially or in whole using the Common Pipeline Library (CPL) developed by ESO. All future recipes will be based on CPL (http://www.eso.org/cpl). This has two benefits for end-user astronomers. First, all CPL-based recipes will have common Unix shell behavior, creating a more unified and stable user interface. Such behavior allows rapid development of user-specific processing scripts using the Unix shell or such common scripting languages as Perl or Python. The tools *dfits* and *fitsort* (see http://archive.eso.org/saft) can be used to extract and organize FITS header information within such scripts. Second, CPL-based recipes can be executed within the **Gasgano** data organization and management tool developed by ESO (available from http://www.eso.org/gasgano/). Gasgano provides a user-friendly Java-based environment for data organization and processing within a single graphical user interface.

At ESO, the pipeline recipes are embedded in an infrastructure that automatically classifies raw data frames, associates them with appropriate master calibration products, and then executes the appropriate

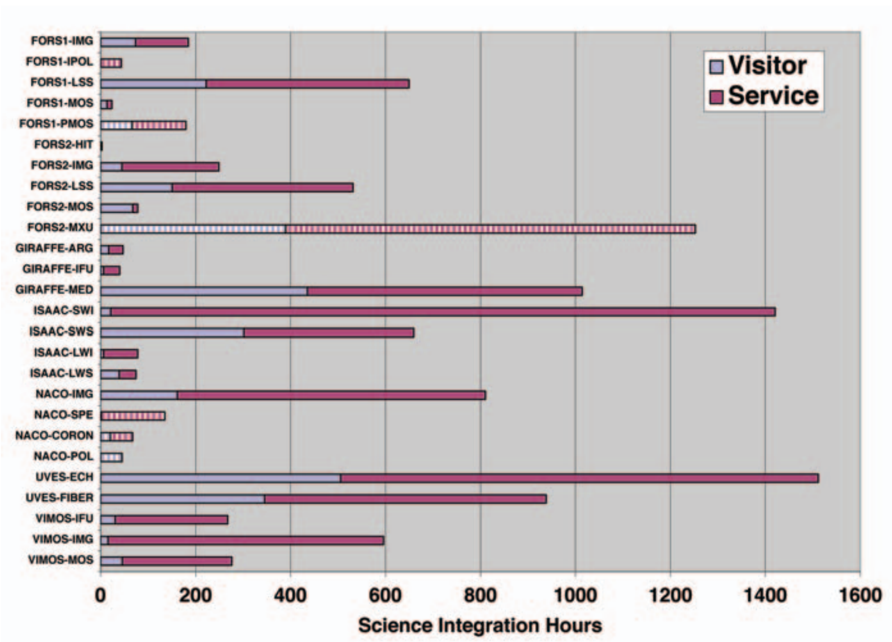


Figure 2: Science integration time per VLT instrument mode, Period 70 – 73. Modes with active instrument calibration pipelines are shown with solid colors, while modes without pipelines are indicated by vertical stripes. Exact dates are 2002 October 1 to 2004 September 30. Guaranteed Time Observations (GTO) data have been excluded.

pipeline procedure. This infrastructure is tuned to the ESO operational environment and cannot be easily exported to external sites. As our pipeline infrastructure evolves this situation may change, and ESO will explore ways of providing more automatic data organization tools to the community.

Science products

Creation of science products

For instrument modes with pipeline support (see Figure 2), science products can be produced automatically on Paranal, if appropriate calibration data are available. Immediately after an OB template is completed, the Paranal-based pipelines attempt to create science products using pre-loaded calibration data. These pre-loaded data are not necessarily the best possible and are typically updated only at 1 – 3 month intervals. On a best effort basis, Paranal Science Operations can sometimes pre-load more appropriate calibration data for specific programmes. If appropriate calibration data are not available (e.g. mask-specific flats for multi-object spectroscopy reductions obtained in morning after science observations or non-standard instrument configuration used), no science products are created. If created, science products are made available to visiting astronomers at the appropriate off-line workstation. Visitors also have the option of using the off-line workstations to process (or re-process) their science data.

In Garching, all Service Mode science data are processed (or re-processed) using the same pipeline recipes, although sometimes with different control parameters (e.g. average vs. median combination, block-average vs. optimal spectral extraction). Furthermore, the best available and most appropriate calibration data are used, even if they were obtained after the science observation. Service Mode science products are delivered in due time to the principal investigator. At this time, Visitor Mode data are not re-processed and delivered due to staffing limitations, but such a service may be provided in the future. In general, the quality of the science products produced in Garching are higher than the products produced on Paranal because better calibration data are used and the pipelines are more closely monitored by ESO staff for output quality.

Table 1: Summary of Science Product Status By Instrument Mode

Instrument	Mode	Science Ready?	Product Remarks
FORS1/2	IMG	Yes	No jitter combination
FORS1/2	LSS	Maybe	Polynomial correction for distortion and dispersion too low (?), no correction for slit response or sensitivity, not all grisms supported. Spectrophotometric standards observed but not applied by pipeline.
FORS1/2	MOS	Maybe	Same comment as FORS/LSS.
FORS1	PMOS/IPOL	No	Not supported yet
FORS2	MXU	No	Not supported yet
FORS2	HIT	No	Not supported yet
GIRAFFE	All	Maybe	Science pipeline still under development. Products produced with flat-field correction or optimal extraction. Not all setups supported.
ISAAC	SWI/LWI	Yes	For data before April 2003, image stacks should be reprocessed with the latest recipe.
ISAAC	SWS/LWS	Maybe	Polynomial correction for distortion and dispersion too low (?), no correction for slit response or sensitivity. Telluric standards can be used to determine sensitivity function.
ISAAC	SW-POL	No	Not supported yet
NACO	IMG	Yes	
NACO	Other	No	No pipeline support
MIDI	HIGH_SENS	Yes	Dispersed modes not yet supported. See Ballester et al. (2004)
UVES	ECH	Yes	
UVES	SLICER	Yes	
UVES	FIBRE	Yes	Fibre-to-fibre correction but no sensitivity correction. No automatic background correction, since no dedicated sky monitoring fibre.
VIMOS	IMG	Yes	No jitter combination.
VIMOS	MOS	Maybe	Flat-field not applied, pending further investigation of internal reflections and fringing. No sensitivity correction. Dispersion correction quality variable due to problems related to mask insertion and mechanical flexure. If present, more than one object extracted per slit.
VIMOS	IFU	Maybe	See VIMOS-MOS comments as well as Izzo et al. (2004)

Science data product quality: what is it?

The VLT Science Policy guidelines indicate that pipelines should remove the instrument signature and calibrate the data into physical units to an accuracy that is satisfactory for a major fraction of users. What is the current general situation?

For **imaging**, the current goal is to produce photometrically flat images with astrometrically accurate World Coordinate System (WCS) coefficients and a nightly zeropoint with 5 – 10% accuracy if a standard filter was used. Zeropoint accuracy is limited by the number of standard field observations per night (typically, 2). Nightly reports from the Paranal Astronomical Site Monitor (available from http://archive.eso.org/asm/ambient-server) can be used to constrain whether or not the night was photometric. Color terms and extinction coefficients are measured several times a year but not in all filters. Values are published on the ESO Quality Control Web pages (http://www.eso.org/qc). If a non-standard filter is used or higher photometric transformation accuracy is required, the user must obtain additional calibration observations. However, ESO leaves the responsibility for building object catalogs in the hands of the user. So, strictly speaking, the objects on delivered images have not been calibrated into physical flux units – roaming over an image with a WCS aware image browser will show the celestial coordinates of each object but not their magnitudes. But ESO provides the information necessary to convert instrumental flux measurements into physical units once (project specific) object identification and extraction is complete.

In the most general sense, the current goal for **spectroscopy** is to produce background corrected one or two-dimensional spectra with linear scales in the spatial and dispersion direction and their true relative continuum shapes. WCS coefficients should be set to relevant wavelength units (e.g. Ångstroms or microns) in the dispersion direction and arc seconds in the spatial direction. In the future, the spatial WCS coordinates may be updated to support true celestial coordinates. The flux units are relative counts. If users require a conversion to absolute flux units (e.g. ergs s^{-1} cm^{-2} $Å^{-1}$), they must request additional observations of flux standards with appropriate slit sizes and at appropriate time intervals. For all instruments that produce two-dimensional spectra, ESO provides the processed 2D spectra and an extracted 1D spectrum for the brightest object in each slit. If spectra are extracted, signal-to-noise should be optimized. Of course, details of spectral extraction (or even deciding what to extract) are usually science-driven, so many users may choose to re-extract their objects.

Nevertheless, the usefulness of any given science product for a specific programme may be limited by the quality of the available calibration data and the choice of parameters used when running the recipes (e.g. type of spectral extraction, order of polynomial used for spatial correction). By design, these automatic pipelines process science type of similar type in a similar way in all cases. In the end, astronomers need to decide for themselves and for every project if the science products produced by ESO are right for them or if they need to reprocess their raw data.

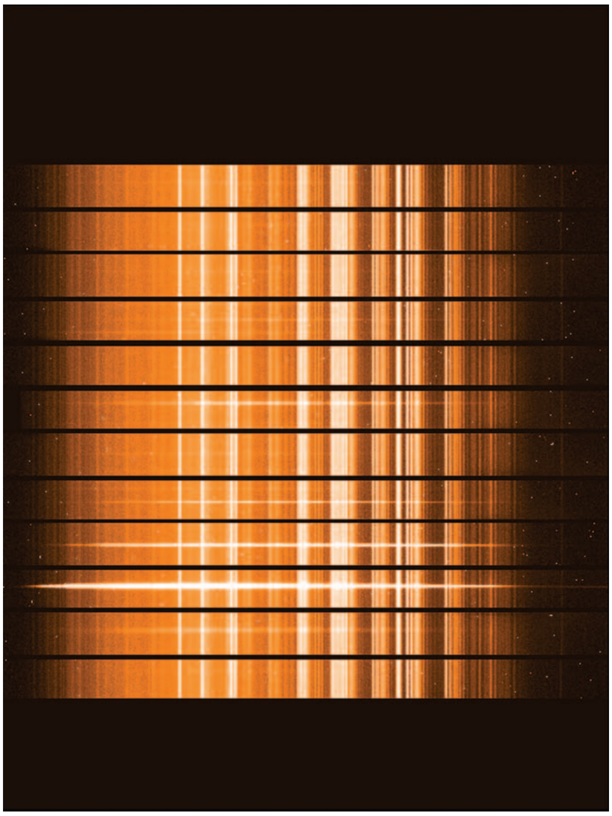


Figure 3: Example FORS MOS Science Product. From FORS1 MOS using 150I grism at λ_{cen} = 7100 Å. Notice alignment of skylines. Courtesy of R. Mignani.

Specific goals

Over time, the following goals for science product creation have emerged:

• **All instrument modes:** as appropriate for the specific instrument and detector, corrections for bias, dark, small scale pixel-to-pixel sensitivity variations and large scale illumination variations are applied. WCS coefficients are updated appropriately for instrument mode and situation. Instrument specific quality control parameters are provided.

• **Imaging (IMG):** all frames acquired through the same filter within a single OB template are combined. If the image group is a jitter stack, they are co-aligned and co-added using average with some form of outlier rejection; a byproduct weight map is produced. For mosaic imagers (WFI, OmegaCam), the entire field-of-view is placed on a common astrometric grid; this requires geometric rectification of images from the individual detectors. For imaging polarimetry, images are grouped by relevant optical element, and processed; but Stokes parameters are not computed. *Final product*: single corrected image. *Instruments*: FORS1/FORS2 IMG, ISAAC SWI/LWI, NACO, VIMOS IMG, WFI, OmegaCam.

• **Spectroscopy (general):** corrections are applied for optical distortion, wavelength dispersion, slit response function (only long-slit spectroscopy), fibre response function (fibre-fed instruments only), spectral cross-talk (for densely packed spectra, e.g. IFUs), and relative sensitivity (flux). No corrections are made for fringing, atmospheric differential refraction, telluric absorption, or airmass. For instrument modes with slits, the background is subtracted; the derived background spectrum used for correction is provided to the user. The brightest object (or objects in some cases) within each slit are extracted into 1D spectra.

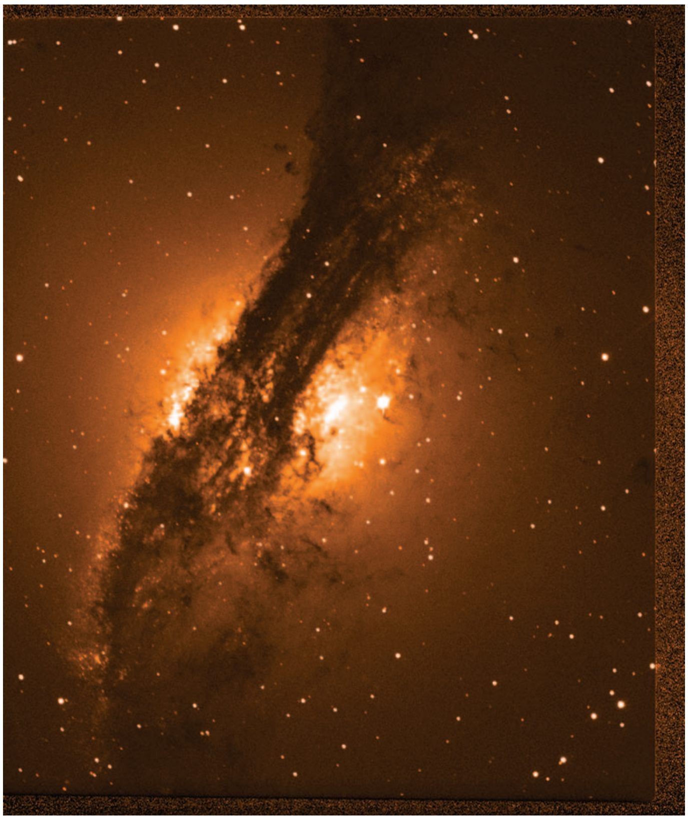
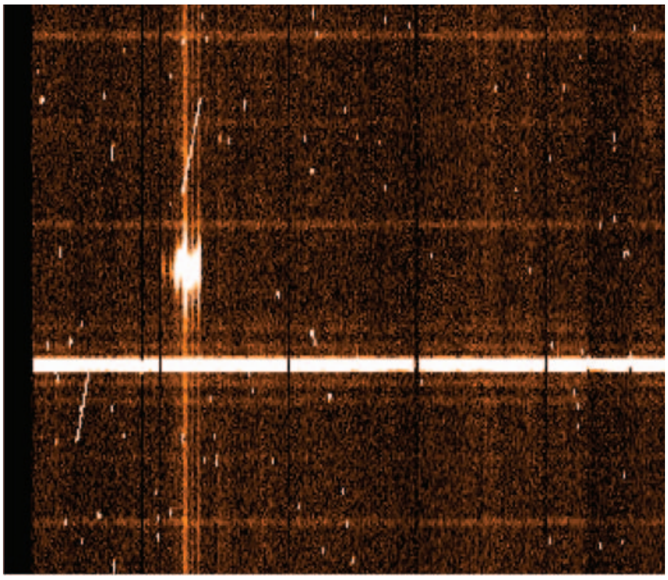
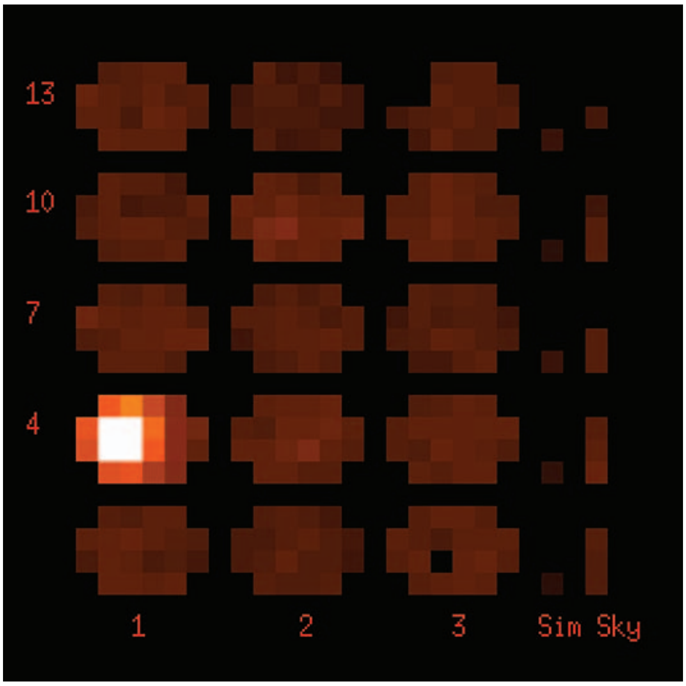


Figure 4: Example VIMOS IMG Science Product. *B*-band image of the center of Cen A (NGC 5128) – quadrant 3 only. Courtesy of P. Sartoretti.

• **Long-slit spectra (LSS) and echelle (ECH):** *Final product:* two-dimensional (2D) frame with linear spatial and dispersion scales, extracted 1D spectrum of brightest

Figure 5: Example GIRAFFE IFU Science Product. Left panel: reduced science spectra from 15 GIRAFFE IFU units. Right panel: reconstructed images for each IFU unit. For VIMOS IFU example, see Izzo et al. (2004). Courtesy of R. Hanuschik.





object, and various related spectra depending on instrument (e.g. background spectrum). *Instruments:* FORS1, FORS2, ISAAC SW/LW, UVES (2D spectra by request only).

- **Multi-object spectra (MOS) with slits:** *Final product:* corrected two-dimensional slit images with linear spatial and dispersion scales, aligned in wavelength space, and stacked into one plane of a FITS image. Also: 1D spectra for brightest objects in slits with various supporting spectra as appropriate for instrument (e.g. background spectra). *Instruments:* FORS1/FORS2 MOS, FORS2 MXU, VIMOS MOS.
- **Multi-object spectra (MOS) with fibres:** *Final product:* extracted, flux-corrected one-dimensional spectra with linear dispersion scales, aligned in wavelength space, and stacked into one plane of a FITS image. Various supporting spectra (e.g. error vector). *Instruments:* GIRAFFE MEDUSA, UVES FIBRE.
- **Integral-field spectroscopy (IFU):** *Final product:* same as fibre MOS plus reconstructed (broad-band) image corrected for fibre efficiencies. *Instruments:* VIMOS IFU, GIRAFFE ARGUS, GIRAFFE IFU, SINFONI.

At this time, none of our pipelines make specific corrections for fringing, an optical phenomena caused by interference between incident light and internal reflections between the thin layers in a detector. Internal discussions about this complex topic continue but are beyond the scope of the current article. Likewise, no corrections for telluric absorption lines in spectral regions beyond 7000 Å are made, although spectra of telluric absorption standard stars are obtained as part of the standard ISAAC and NACO calibration plans and delivered to users.

The goal of **VLT interferometry** is to deliver calibrated visibilities. For further details, see Ballester et al. (2004).

Status

Science products created by pipelines during the first years of Paranal operations had variable usefulness for science analysis. Within ESO, higher priority was given initially to producing quick-look data products necessary to confirm field acquisition and quality control parameters to monitor instrument health, rather than science-ready data products. The number one priority for ESO was (and remains) to assure that the raw science data stream is fundamentally sound and produced in a controlled manner. Nevertheless, the quality of pipeline-produced science products has steadily improved and today is quite good in many cases.

Table 1 summarizes current pipeline product status. In the *Remarks* column, deviations from the goals listed above are described. For a brief summary with more details, see Pipeline Status Web page (http://www.eso.org/qc/pipeline-status.html). For complete details, see the instrument-specific sections of the Quality Control Group Web site (http://www.eso.org/qc/). *In particular, readers are urged to read the Known Problems information provided for each instrument.*

A few example science products are shown in Figures 3 – 5. Examples for all supported instrument modes can be found on the QC Group Web pages.

Future Development

Although the current pipeline recipes receive maintenance as time permits, implementation of instrument calibration pipelines for new instruments using CPL-based recipes remains the highest priority. Thanks to early and fruitful collaboration with the instrument development teams during commissioning and science verification, the SINFONI and VISIR pipelines are close to completion and should be operational at the start of Period 75. Next will come OmegaCam, Hawk-I and CRIRES, followed by the various VLT 2nd generation instruments. As soon as possible, FORS1, FORS2 (including MXU), ISAAC, NACO and UVES pipelines will be re-implemented, using CPL-based modules written for other instruments. Realistically, it may take more than two years to complete this conversion work, given higher priority projects.

In parallel, ESO is investigating ways of providing science products produced from data with expired proprietary periods to the community. Possibilities include ingesting existing Service Mode science products kept on off-line archival media or re-created science products produced by re-processing raw science data with improved pipeline recipes. A pilot project involving UVES data is active. In the future, ESO will also ingest into the Science Archive Facility science products produced by ESO for Service Mode users immediately after their creation and then make them available to the community after the proprietary period is completed. If resources permit, it may also be possible to start created products from Visitor Mode data on a regular basis. Finally, as

Table 2: On-line Resources Related to Science Products

Resource	URL	Remarks
ESO Quality Control Group	http://www.eso.org/qc/	Instrument-specific information about quality control, data processing, and science products
Gasgano	http://www.eso.org/gasgano	Java-based tool for file organization and recipe execution
Common Pipeline Library (CPL)	http://www.eso.org/cpl	ISO-C libraries to build pipeline recipes
Pipeline recipes	http://www.eso.org/pipelines	Released recipes and documentation
Pipeline status	http://www.eso.org/qc/pipeline-status.html	Brief overview of pipeline status, updated before every ESO Period
Site Monitor	http://archive.eso.org/asm/ambient-server	Daily meteorological data for Paranal and La Silla
Standalone FITS Tools	http://archive.eso.org/saft/	Tools for working with FITS files

appropriate, on-the-fly recalibration systems will be activated for appropriate instruments modes. Many of these efforts will fall under the responsibility of the Virtual Observatory Systems department created recently within the Data Management and Operations Division.

Acknowledgments

The development of instrument calibration pipelines to produce science products has been a collaborative effort involving many people over many years. We thank everyone for their efforts on behalf of the ESO community. The original pipeline recipes for FORS1, FORS2, GIRAFFE, SINFONI, UVES-Fibre, and VIMOS were developed by their respective external instrument consortia. Of course, the consortia are not responsible for how these recipes have been maintained or revised over time by ESO to suit our operational needs. The DMD Data Flow Systems department developed all other pipeline recipes, as well as the associated infrastructure wrapped around all recipes, in close collaboration with astronomers from the Instrument Division, the Paranal Observatory, and the DMD Data Flow Operations group. In particular, we thank sincerely the various cross-divisional Instrument Operations Teams for their past and on-going efforts. Finally, we thank Fernando Comerón, Reinhard Hanuschik, Andreas Kaufer, Bruno Leibundgut, Chris Lidman, Peter Quinn, and the DFO/QC team for their comments on earlier drafts of this article.

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H. Heyer (ESO)

Signature in Copenhagen of the agreement for the construction of the *X-shooter*, a second generation VLT instrument scheduled to go into operation in 2008. From left to right, sitting: Jens Hjorth (Astronomy Professor, Copenhagen University Observatory), Henning Jørgensen (Astronomy Professor, Copenhagen University and Danish ESO Council Member), Jørgen Olsen (Vice-Chancellor, Copenhagen University), Catherine Cesarsky (Director General of ESO), Per Kjærgaard Rasmussen (P.I. for the *X-shooter*, Copenhagen University Observatory); standing: Nils O. Andersen (Director of the Niels Bohr Institute for Astronomy, Physics and Geophysics), Sandro D'Odorico (*X-shooter* P.I. at ESO) and Jens Viggo Clausen (Director of Copenhagen Observatory). (see Page 71)