

The SINFONI pipeline

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Abstract

The SINFONI data reduction pipeline, as part of the ESO-VLT Data Flow System, provides recipes for Paranal Science Operations, and for Data Flow Operations at Garching headquarters. At Paranal, it is used for the quick-look data evaluation. For Data Flow Operations, it fulfills several functions: creating master calibrations; monitoring instrument health and data quality; and reducing science data for delivery to service mode users. The pipeline is available to the science community for reprocessing data with personalised reduction strategies and parameters. The pipeline recipes can be executed either with EsoRex at the command line level or through the Gasgano graphical user interface. The recipes are implemented with the ESO Common Pipeline Library (CPL).

SINFONI is the Spectrograph for INtegral Field Observations in the Near Infrared (1.1-2.45 μm) at the ESO-VLT. SINFONI was developed and built by ESO and MPE in collaboration with NOVA. It consists of the SPIFFI integral field spectrograph and an adaptive optics module which allows diffraction limited and seeing limited observations. The image slicer of SPIFFI chops the SINFONI field of view on the sky in 32 slices which are re-arranged to a pseudo slit. The latter is dispersed by one of the four possible gratings (J, H, K, H+K). The detector thus sees a spatial dimension (along the pseudo-slit) and a spectral dimension.

We describe in this paper the main data reduction procedures of the SINFONI pipeline, which is based on SPRED - the SPIFFI data reduction software developed by MPE, and the most recent developments after more than a year of SINFONI operations.

Key words: Integral Field Spectroscopy; ESO; pipelines

1. Introduction

SINFONI is the Spectrograph for Integral Field Observations in the Near Infra Red (NIR). It is attached to the Cassegrain focus of Yepun, the fourth Unit Telescope (UT4) on Cerro Paranal in northern Chile. It allows diffraction and seeing limited integral field observations in the near infrared (1.1-2.45 μm) at 3 spatial resolutions: 250, 100 and 25 mas/pixel.

We will provide a general introduction to instrument pipelines, then present the features of the Common Pipeline Library (CPL) and its front end applications Gasgano and EsoRex. These will be followed by an overview of the instrument and an introduction to the principle of integral field spectroscopy. Next we will describe the data reduction cascade and the main data reduction challenges. Finally we will highlight some scientific results based on pipeline reduced data products which were obtained during the science verification phase.

2. Instrument Pipelines Objectives

Today twelve instruments are operational at Paranal. They cover the observational domain over a wide range of spectral and spatial resolutions. ESO uses instrument data reduction pipelines to support the complex end to end data flow operation model. The main objectives of the pipeline are to:

- Support the Garching Data Flow Operation (DFO) department in the:
 - Processing of raw calibration frames into master calibrations.
 - Generation of quality control (QC1) parameters to monitor telescope, instrument and detector performance, so that the quality of calibration and science data can be assessed in due time.
 - Reduction of sets of raw science data files to science data products.
- Support the Paranal Science Operations (PSO) with a quick-look tool to assess the instrument health and the quality of the science and calibration data in due time.
- Allow users to perform a personalised data reduction with user selected reduction strategies and parameter settings.

The VLT instrument pipeline releases are publicly available at www.eso.org/pipelines. More details are given in [Ballester et al.(2006)] and [Silva D. & Peron M. (2004)].

3. The Common Pipeline Library

The Common Pipeline Library (CPL) has been produced by ESO to aid in the development of VLT pipelines with standardised implementations and lower maintenance costs. CPL is offered to instrument consortia and the user community to build instrument data reduction software. It is distributed as a development kit together with documentation and recipe front-ends. It is available on the web at www.eso.org/cpl.

A CPL based pipeline is structured as a set of recipe plug-ins which are called by front-end applications (EsoRex or Gasgano). The recipes of the Data Reduction Software

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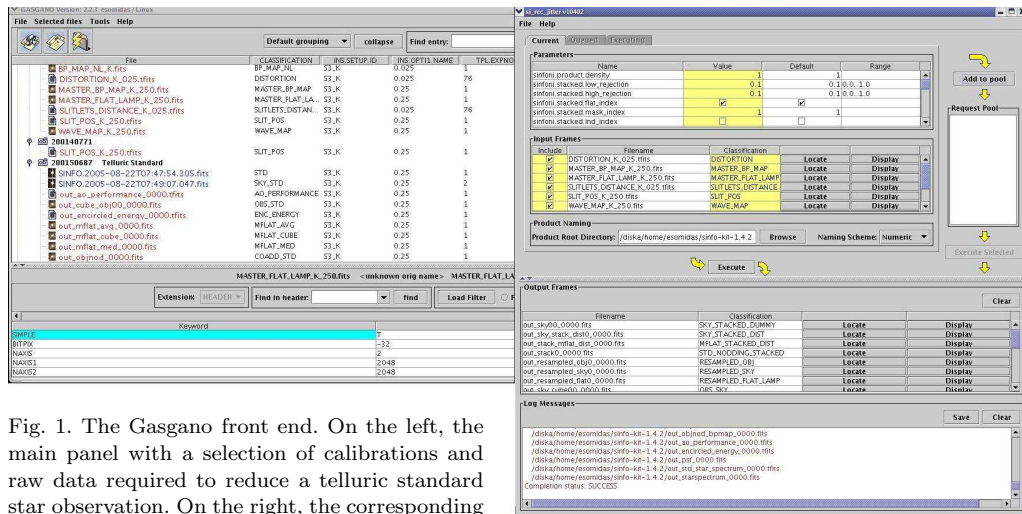


Fig. 1. The GAsgano front end. On the left, the main panel with a selection of calibrations and raw data required to reduce a telluric standard star observation. On the right, the corresponding recipe execution control panel.

(DRS) are implemented as CPL plug-ins - units of code which are dynamically loaded into a host application at run time. The parent application is shielded from the recipe plug-in's implementation details by the CPL plug-in interface. This interface consists of three functions, to initialize, execute and destroy the recipe plug-in. These functions need to be provided by the recipe implementation.

The SINFONI pipeline is the CPL implementation of the Python based **SPRED** package, the SPIFFI data reduction software developed by the Max-Planck-Institut für extraterrestrische Physik (MPE, see also [Abuter et al.(2006)] and [Schreiber et al.(2004)]).

4. Pipeline Front-End Applications

GAsgano is a data management tool that simplifies the data organisation process. It offers automatic data classification and association (Fig. 1). GAsgano classifies the raw and reduced data files based on their FITS keyword content by applying instrument specific rules. It allows users to execute recipes directly from a GUI with flexible data reduction strategies. GAsgano is available from the ESO web pages at www.eso.org/gasgano.

EsoRex, the ESO Recipe executor, allows the execution of recipes from the command line. It does not offer the high level functionalities of GAsgano, but it can easily be embedded in scripts.

5. Integral Field Spectroscopy

For SINFONI, the instrument's two dimensional field of view (FOV) is sliced into a one dimensional pseudo long-slit, which is then dispersed by a spectrometer onto the two dimensional detector array (see Fig. 2 for a simplified overview of the principle). The recorded data contains the spatially resolved image slices (in one direction) and the spectra (in the other). The data reduction software has the task of removing the instrument signature, in this case reconstructing the full spatial and spectral information

into a 3D data cube. Here, the FOV is mapped into the first and second dimensions, with the wavelength in the third dimension.

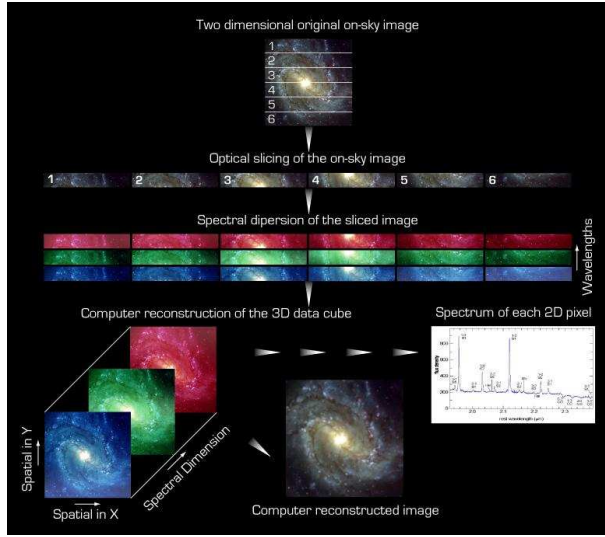


Fig. 2. This figure describes the Integral Field Spectroscopy concept: a two dimensional image on the sky is sliced, dispersed and imaged on the detector. The data reduction software then reconstructs a cube containing the full spatial and spectral information.

6. SINFONI

SINFONI is composed of two subsystems: the Multi-Application Curvature Adaptive Optics (MACAO) unit, which allows diffraction and seeing limited observations, and SPIFFI, the SPectrometer for Infrared Faint Field Imaging, an integral field spectrograph which is shown in Fig. 3. It is described with more details in [Bonnet et al.(2004)] and [Eisenhauer et al. (2003)].

Following the optical path, the light coming from the MACAO module is collimated by a doubled lens onto a cold stop to suppress the thermal background from the telescope secondary mirror. Then the light path continues through a broadband filter (to suppress unwanted diffraction orders of the grating) and the optics wheel hosting the camera lens systems for the three different image scales (250, 100, 25 mas/pixel). The images are focused on the small image slicer, a stack of 32 plane mirrors which slice the image into slitlets and separates the light from each slitlet into different directions. A second set of 32 mirrors, the big slicer, collects the light and forms a pseudo-slit which is then dispersed by the selected grating (J, H, K and HK bands) and finally imaged by the camera to the 2D NIR detector array.

The instrument FOV is rearranged on the detector into 32 vertical strips, (slices) each 64 pixels wide and 2048 pixels long, according to a given sequence in a brick-wall pattern. For SINFONI, the wavelength increases from the top to the bottom of the detector array. Sky lines appear as small horizontal stripes, whilst cosmic rays and hot pixels manifest

themselves as bright random spots (pixel aggregates). Dead pixels appear as black spots. Fig. 4 displays many of these features.

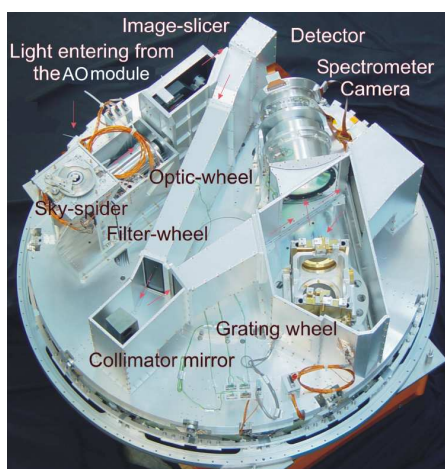


Fig. 3. The SPIFFI spectrograph.

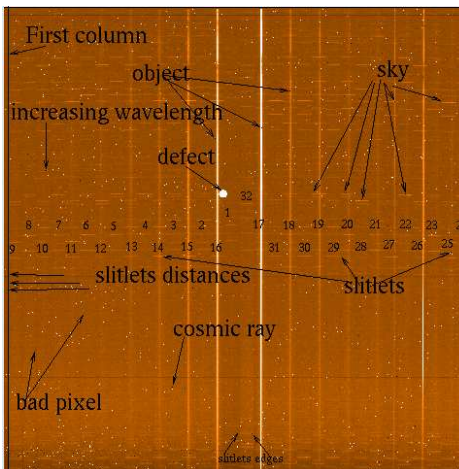


Fig. 4. Typical data features.

7. Data Reduction Cascade

The SINFONI data reduction is described in more detail in the SINFONI Pipeline User Manual, available on the web (www.eso.org/pipelines). An overview of the data reduction cascade is shown in Fig. 5. The following recipes are used in the data reduction process:

- The linearity recipe derives a map of non-linear pixels from a set of flat fields with increasing intensity.
- The master dark recipe derives a master dark frame and a map of hot pixels from a set of dark frames.
- The master flat recipe derives a master flat field frame and a map of pixels whose intensity is above a given threshold from a set of flat field frames. It combines this map with the input non-linear pixel map and the reference bad pixel map to build the master bad pixel map.
- The distortion recipe determines the optical distortion coefficients for image reconstruction and the slitlets' distance tables from a set of (typically 75) fibre flats. Fibre flats are taken with the calibration fibre moved perpendicularly to the image slices. Additional inputs are a pair of on/off arc lamp frames, standard flats, a reference arc line list and a “setup” table.
- The wavelength calibration recipe determines the wavelength map and the slitlet position table from: a set of arc lamp frames, a master flat, a master bad pixel map, a distortion table, a reference arc line table, and a “setup” table.
- The jitter recipe reduces standard star calibrators and science target observations at the bottom end of the data reduction cascade. It requires as input a master bad pixel map, a master flat, a master dark of the proper detector DIT, a distortion table, a wavelength map, a slitlet distances table and a slitlet position table. The recipe extracts

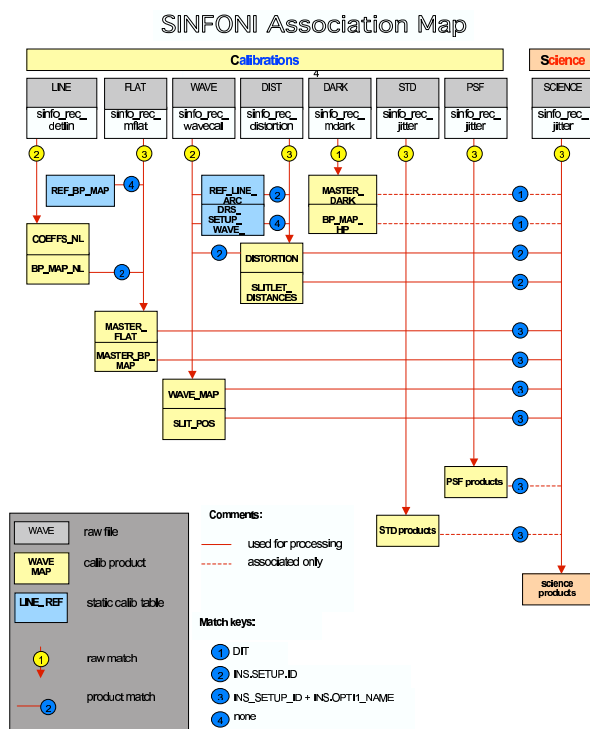


Fig. 5. Data reduction sequence with recipe and calibration product dependencies.

the object spectrum (for sources whose Point Spread Function is well approximated by a 2D Gaussian), computes the instrument's Strehl ratio, determines instrumental throughput and reconstructs a 3D cube. This cube is composed of a stack of planes, each of which contains the full spatial information of the instrument FOV. The wavelength information is mapped on the cube's third dimension. If the recipe is provided with several object frames - for example, a sequence of on/off-sky or jittered images - it will generate the sky subtracted mosaic data cube from the raw data frames (Fig. 9).

8. Pipeline challenges

The main tasks of the SINFONI pipeline are: the calculation of the optical distortion coefficients, the computation of a wavelength calibration solution, the reconstruction of the full spatial and spectral information on a 3D data cube, and the removal of the emission from the telescope, the instrument and the sky (dominant in the NIR). Additionally, the pipeline should generate the information needed to monitor the behavior of the instrument as atmospheric conditions change. These QC1 parameters are used by DFO to monitor the quality of master calibrations, and science products; they also give an indication of the instrument's health (see [Hummel et al.(2006)] for a more comprehensive overview).

8.1. Distortion Computation:

The distortion function, which characterises the curvature of the spectral traces of the 32 slices, is calculated from a series of continuous light fibre spectra taken with the fibre moved perpendicularly to the slices. For every position of the fibre a raw FITS data file is recorded. With an initial data reduction step the single fibre spectra are co-added to an all-fibers synthetic frame and the offset of the first slitlet is calculated as a reference position. The distortion is computed in three further steps:

- Detecting the fibres and tracing the curved fibre spectra.
 - Constructing two numerical grids on the distorted and the undistorted fibre positions.
 - Solving a 2D polynomial fit to transform positions from raw to undistorted coordinates.
- Finally, the recipe determines the position of the edges of the slitlets by fitting the edges of the brightest arc line of each slitlet with a linear step function or a Boltzmann function.

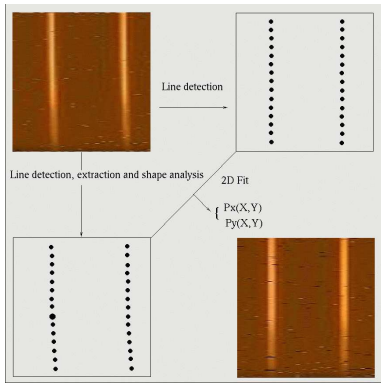


Fig. 6. This image describes the concept of the distortion computation algorithm. The spectra of the fibres are traced, two grids on the distorted and undistorted space are built, then a 2D polynomial transformation is performed. This figure displays only two of the 32 slitlets.

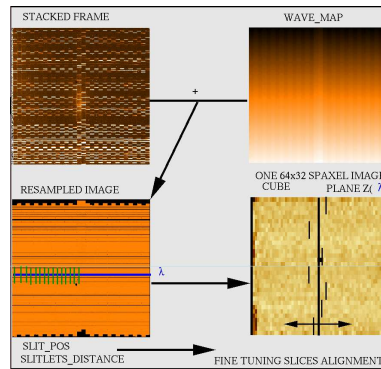


Fig. 7. Cube reconstruction: raw data are re-sampled using a wavelength map to remove the brick-wall pattern. The slitlets are then stacked into a cube taking slitlet distances and edge positions into account. Each plane of the cube is a monochromatic image of the instrument FOV.

8.2. Wavelength Calibration:

The wavelength calibration is based on a set of on/off arc lamp exposures. Initially, the arc lamp frames are stacked and the off-frames are subtracted from the on-frames to remove the thermal background. The resulting frame is flat fielded, the distortion correction is applied, and static bad pixels are corrected.

Using a polynomial model, guess values for the central wavelength λ_0 and the first and second order dispersion coefficients, it is possible to build a synthetic frame from the reference arc line list by associating at each catalog entry a delta-like function of proper wavelength and intensity. Then this spectrum is convolved with a Gaussian having a FWHM appropriate to the instrumental resolution. The synthetic frame thus has a well known wavelength and intensity. Cross correlation of the synthetic frame with the

observed spectrum provides an approximate wavelength and line intensity for each raw (and emission line).

Doing a non-linear least squares fit with a Gaussian to the synthetic frame, one can associate to each line an accurate intensity, position, FWHM and background. This permits the construction of line index triplets (x, y, λ) . After removal of false identifications, dispersion coefficients are derived by a polynomial fit along each detector's column. Finally the smoothed wavelength dispersion coefficients are obtained with a low order polynomial interpolation of each dispersion coefficient in the detector's spatial direction.

8.3. 3D Data Cube Reconstruction:

From the input set of frames object-sky pairs are defined by associating to each object frame the sky frame that is closest in time. For each object-sky pair a 3D data cube is constructed as follows. If a master dark is provided as input of the jitter recipe, this is subtracted from the object and the sky frames, then the corrected sky frame is subtracted from the corrected object frame, and the resulting frame is flat fielded and distortion corrected. The resulting image is re-sampled into the same wavelength steps, a process which aligns the different slitlets in wavelength. A 3D data cube is subsequently constructed using the information read from the slitlet position table and the slitlet edge distances table. As not all of the slitlets are exactly 64 pixels long and 64 pixels distant from the adjacent one, it is necessary to refine the slitlets' position alignment on the stacked cube. The jitter recipe then constructs a mosaic of the series of input data cubes (each aligned in the co-added space) by reading the cumulative offset information from the FITS headers of the raw input frames (Fig. 9). Finally, the recipe extracts the spectrum along the Z-axis.

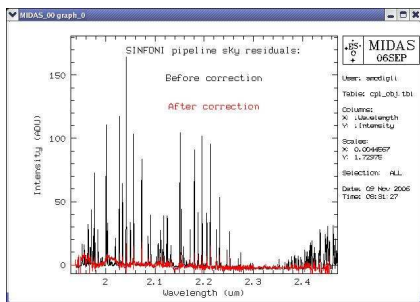


Fig. 8. Comparison between un-corrected (black) and corrected (red) sky subtracted object spectra.

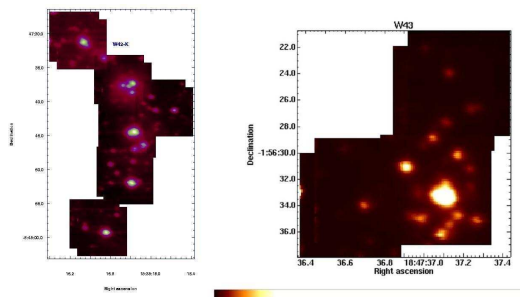


Fig. 9. Observations of stars embedded in the giant HII regions W42 (left) and W43 (right). SINFONI allows to resolve the cluster and extract the spectra of many stars.

8.4. Sky subtraction

In its most recent release the pipeline corrects for improper sky subtraction; in older releases this caused residuals in on-off sky-subtracted frames. The sky emission is removed from the object observation by subtracting the sky frame from the object frame. This assumes that the two frames have a stable spectral format. However, it has been found that

in on-off, object-sky sequences the instrument setting can occasionally have instabilities up to a significant fraction of a pixel. The residual sky features (resembling a P-Cygni profile) can be significantly reduced by using an improved data reduction procedure developed in collaboration with Ric Davies from MPE (Fig. 8 and [Davies R., (2007)]).

9. Science Results

SINFONI started science operations on April 1, 2005, and has since then obtained science data for over 1000 hours of science integration time - not including acquisition overheads, calibrations or standard star observations. The scientific observations discussed below were taken within the science verification runs before the start of operations and reduced with the SINFONI pipeline. The results are given as examples for the performance of the instrument and the pipeline data reduction.

[Messineo et al. (2006)] have observed stars embedded in the stellar clusters of the giant HII regions W42 and W43 (Fig. 9). In W42 they have resolved the cluster and extracted the spectra of 7 stars with high S/N of >30 in H and K bands. This has doubled the number of spectral detections with respect to what was available in the literature. In W43 the cluster centre has been resolved, and they have detected the photospheric lines of several of the 13 brightest stars (9 stars in K and 4 in H band).

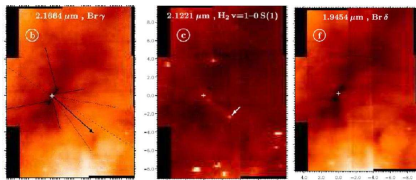


Fig. 10. The discovery of a collimated H_2 jet in M17 (center) is an indication of on-going accretion processes. On the left side is indicated a possible geometry of the jet. On the right it is shown the Br_δ map.

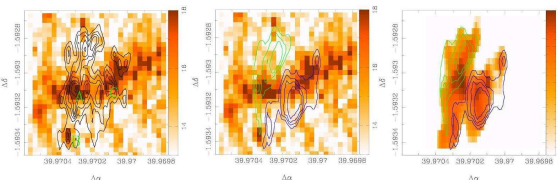


Fig. 11. Star formation in a high-red shift galaxy (A370-A5). Observations suggest that it is not a rotating disk, and that it is probably characterised by a bipolar outflow.

[Nürnberg et al.(2007)] were studying the formation of massive proto-stars through disk accretion of gas in M17. From the SINFONI H_2 maps they report the discovery of an H_2 jet which apparently arises from the suspected proto-stellar source(s) located at the very center of the disk. They can infer the diameter and sub-structure of the innermost part of the flared disk from the Br_γ , Br_δ and HeI maps. As the ejection of material through a jet and/or the outflow is always linked to accretion of gas and dust onto the circumstellar disk or onto the central proto-stellar source(s), the presence of a collimated H_2 jet provides direct and unquestionable evidence for ongoing accretion processes in the case of this disk.

[Lemoine-Busserolle et al.(2007)] (see also [Gillissen et al. (2006)]) used SINFONI to probe the star formation of the high-red shift galaxy A370-A5. The clumpy structure evidenced by the H_α contour plots are an indication of a stellar component and show two extended regions without continuum counterpart (Fig. 11, left). H_α velocity maps indicate the presence of a velocity gradient perpendicular to the stellar emission (Fig. 11, center). The H_α velocity dispersion map shows no indication of the central peak which would

characterise a rotating disk (Fig. 11, right). From these observations Lemoine-Busserolle et al. conclude that A370-A5 is not a rotating disk, and it is probably characterised by a bipolar outflow.

10. Summary

The SINFONI pipeline is an important part of the ESO-VLT Data Flow System to support SINFONI operations, monitor the instrument's health, generate master calibration and scientific products, and assess their quality. Applying the recently improved sky subtraction, the master dark, master flat and optical distortion corrections, and the wavelength calibration, a good quality 3D data cube is constructed, which contains the full spatial and spectral information of the SINFONI FOV for further science analysis.

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References

- [Abuter et al.(2006)] Abuter R., Schreiber J., Eisenhauer F., Ott T., Horrobin M., Gillesen S., *SINFONI data reduction software*, 2006, New Astronomy Reviews, **50**, Issue 4-5, 398, 2006.
- [Schreiber et al.(2004)] Schreiber J., Thatte N., Eisenhauer F., Tecza M., Abuter R. & Horrobin M., *Data Reduction Software for the VLT Integral Field Spectrometer SPIFFI 2004* in ASP Conf. Ser., Vol. 314, 380 - 383, Astronomical Data Analysis Software and Systems XIII, eds. Francois Ochsenbein, Mark G. Allen and Daniel Egret.
- [Ballester et al.(2006)] Ballester P. et al., *Data reduction pipelines for the Very Large Telescope*, 2006, Proceedings of the SPIE, 6270, 2006.
- [Bonnet et al.(2004)] Bonnet H. et al., *First Light of SINFONI at the VLT*, 2004, The Messenger, **117**, 17.
- [Davies R., (2007)] Davies R., *A method to remove residual OH emission from near infrared spectra*, 2007, Monthly Notices Reviews Astronomical Society, accepted.
- [Eisenhauer et al. (2003)] Eisenhauer F., et al. *SINFONI - Integral field spectroscopy at 50 milli-arcsecond resolution with the ESO VLT*, 2003, SPIE, **4841**, 1548.
- [Gillessen et al. (2006)] Gillessen S., et al., *First Science with SINFONI*, 2006, The Messenger, **120**, 26.
- [Hummel et al.(2006)] Hummel W., Modigliani A., Dumas C., Amico P., Szeifert T., Neeser M., *Quality Control of the 3D spectrograph SINFONI*, 2006, These Proceedings.
- [Lemoine-Busserolle et al.(2007)] Lemoine-Busserolle M., Sanchez S.F., Kissler-Patig M., Pelló R., Kneib J.-P., Bunker A., Contini T., 2007, A&A, submitted.
- [Messineo et al. (2006)] Messineo M., Petr-Gotzens M., Menten K.M., Sculler F. & Habing H.J. *Galactic structure and stellar clusters in obscured HII regions*, 2006, Proceedings of the Galactic Center Workshop "From the Center of the Milky Way to Nearby Low-Luminosity Galactic Nuclei". Eds Reiner Schoedel.
- [Nürnberger et al.(2007)] Nürnberger D.E.A., Chini R., Eisenhauer F., Kissler-Patig M., Modigliani A., Siebenmorgen R., Sterzik M.F., Szeifert T., *Formation of a massive protostar through disk accretion of gas*, 2007, A&A, submitted.
- [Silva D. & Peron M. (2004)] Silva D. & Peron M., *VLT Science Products Produced by Pipelines*, 2004, The Messenger **118**, 2.