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Very Large Telescope

Paranal Science Operations

SINFONI data reduction cookbook

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1 Introduction

In this document you will find necessary information to guide you through the various steps of reduction of SINFONI data, which ultimately produce the reconstructed 3D cube needed to extract the spectral information corresponding to the region of interest of the SINFONI field-of-view.

1.1 Purpose

The purpose of this document is to provide a brief introduction and quick help to the reduction of SINFONI data. A more detailed explanation of the data reduction process and use of the pipeline can be found in the SINFONI Pipeline User Manual (VLT-MAN-ESO-19500-3600), whose latest version can be downloaded from the ESO-VLT instrument pipelines webpage: http://www.eso.org/projects/dfs/dfs-shared/web/vlt/vlt-instrument-pipelines.html

It is also important to keep in mind that, as all reduction software aiming at processing a wide variety of astronomical data, the tools described in this document will certainly be found of limited use in certain complex cases, either due to the observing strategy adopted, or simply to the nature of the science target.

This document is an updated version of the SINFONI reduction cookbook, however, it is expected to evolve considerably over time, particularly while the users, including myself, are gaining experience with the subtleties of SINFONI data reduction. For this reason, all users are welcomed to send useful comments and suggestions regarding improved ways to reduce SINFONI data to the instrument user account: sinfoni@eso.org".

1.2 Reference documents

Please refer to the documents listed below to best optimize both the use of SINFONI to carry-out your research program, and the use the ESO pipeline to reduce your data:

1.2.1 Main documents

1 SINFONI Pipeline User Manual - VLT-MAN-ESO-19500-3600
http://www.eso.org/projects/dfs/dfs-shared/web/vlt/vlt-instrument-pipelines.html
2 SINFONI User Manual - VLT-MAN-ESO-14700-3517
http://www.eso.org/instruments/sinfoni/doc

1.2.2 Additional reading:

3 Common Pipeline Library (CPL)
http://www.eso.org/sci/data-processing/software/cpl
4 Gasgano File Organizer
http://www.eso.org/observing/gasgano
5 ESORex command line tool
http://www.eso.org/sci/data-processing/software/cpl/esorex.html
6 QFITSView datacube viewer
http://www.mpe.mpg.de/∼ott/QFitsView

7 Euro3D cube viewer
http://www.aip.de/Euro3D/E3D
8 SINFONI quality control and data flow operations web pages
http://www.eso.org/observing/dfo/quality/indexsinfoni.html
9 Euro3D data format
http://www.aip.de/Euro3D/E3D/E3Ddistrfiles/Documentation/Euro3Dformat.pdf
10 Pipeline recipes, download links, installation instructions
http://www.eso.org/projects/dfs/dfs-shared/web/sinfoni/sinfo-pipe-recipes.html

1.3 Abbreviations and acronyms

The following abbreviations and acronyms are used in this document:

SciOp	Science Operations
ESO	European Southern Observatory
Dec	Declination
eclipse	ESO C Library Image Processing Software Environment
ESO-MIDAS	ESO's Munich Image Data Analysis System
FITS	Flexible Image Transport System
IRAF	Image Reduction and Analysis Facility
PAF	PArameter File
RA	Right Ascension
UT	Unit Telecope
VLT	Very Large Telescope

1.4 Stylistic conventions

The following styles are used:

bold	in the text, for commands, etc., as they have to be typed.
italic	for parts that have to be substituted with real content.
$\boxed{\text{box}}$	for buttons to click on.
`teletype`	for examples and filenames with path in the text.

Bold and *italic* are also used to highlight words.

2 An overview of the SINFONI data product

SINFONI is an Integral Field Spectrograph in conjunction with the MACAO Adaptive Optics (AO) Module. Observations can be done either using AO in Natural Guide Star (NGS) or Laser Guide Star (LGS) modes, or in seeing limited conditions (i.e. no AO correction). SINFONI uses an image slicer to sample a square patch of the focal plane, cut it into 32 stripes. These stripes are dispersed spectrally and reimaged on a 2048×2048 detector. The instrument operates in the J, H, K and H+K bands (i.e. from 1 to 2.5 microns) with average resolutions between 2000-4000 depending on the setting. SINFONI has plate scales of 0.25″, 0.1″ and 0.025″ per pixel, which correspond to 8, 3 and 0.8 arcsec^2 FOVs (large, medium and small). An Integral Field Spectrograph such as SINFONI, produces 2-dimensional raw image files that contain both spatial and spectral information. It is therefore possible to reconstruct the science frame into a 3D data cube. Conventionally the X and Y represent the spatial directions on sky, while the corresponding spectrum is along the Z axis.

2.1 File viewers

Regular fits files are best viewed with the usual suites of tools such as saoimage, ds9, fv, skycat, the two later allowing also to display the content of fits tables. Links to download these tools can be found at: http://tdc-www.harvard.edu/software/saoimage.html.

An efficient tool to display SINFONI 3-D cube has been developed by our colleagues at MPE and can be accessed at : http://www.mpe.mpg.de/∼ott/QFitsView.
More information can be found in the user manual, as well as on the instrument webpages:
- http://www.eso.org/instruments/sinfoni/overview.html
- http://www.eso.org/instruments/sinfoni/inst

2.2 Calibration and science raw files

The science and calibration files for SINFONI consist of the following frames below. ESO uses custom FITS keywords for file classifications. Every raw frame produced by the instrument is uniquely classified by means of the DPR.CATG, DPR.TYPE and DPR.TECH keywords. The table below lists al the available combinations for SINFONIs calibration frames. When retrieve science data from the ESO Science Archive Facility, the user needs to choose "Selected files + associated raw calibrations (if available)" option to download necessary calibration files. Darks, flats and arcs are taken daily. The linearity calibrations are taken about once per week in each of the four gratings. The distortion calibrations are taken once per month in each of the four gratings.
A complete description can be found at:
http://www.eso.org/observing/dfo/quality/SINFONI/pipeline/recipe_calib.html

2.3 Calibration products

The ESO pipeline recipes produce files which can be classified according to their PRO.CATG keywords. In the table below we list some of those files. Again, more information about

DPR.CATG	DPR.TYPE	DPR.TECH	Type of frame
CALIB	LINEARITY, LAMP	IFU	Detector Linearity
CALIB	DARK	IMAGE	Dark
CALIB	FLAT,LAMP	IFU	Flat
CALIB	DISTORTION,FIBER,NS	IFU	Distortion North-South
CALIB	DISTORTION,FLAT,NS	IFU	Distortion Flats
CALIB	DISTORTION,WAVE,NS	IFU	Distortion Wave
CALIB	WAVE,LAMP	IFU	Wave
CALIB	PSF-CALIBRATOR	IFU	PSF Star
CALIB	SKY,PSF-CALIBRATOR	IFU	Sky for PSF Star
CALIB	STD	IFU	Telluric Standard
CALIB	SKY,STD	IFU	Sky for Telluric
SCIENCE	OBJECT	IFU,NODDING	Science
SCIENCE	SKY	IFU,NODDING	Sky for Science

the pipeline recipe outputs files can be found in the Pipeline User Manual, as well as at: http://www.eso.org/observing/dfo/quality/SINFONI/pipeline/recipe_calib.html

PRO.CATG	Type of frame
BP MAP NL	Non linear bad pixels map
BP MAP HP	Hot pixels map
MASTER BP MAP	Map of all bad pixels
MASTER DARK	Reduced dark frame
MASTER FLAT LAMP	Reduced lamp at field
DISTORTION	Distortion coecients
SLITLETS DISTANCE	Table with relative slitlets distances
WAVE MAP	Wavelength calibration map
SLIT POS	Pixel position for start/end of each slitlet (static also provided)
DRS SETUP WAVE	Static wavelength calibration
FIRST COL	Static: table with initial guess of pixel position of first slitlet
REF LINE ARC	Static: table with wavelength and line intensity
REF BP MAP	Static bad pixel map
ATM REF CORR	reference atmospheric refraction correction catalog
STD STAR SPECTRUM	Extracted spectrum 1D image
COADD STD	Coadd cube for standard
COADD OBJ	Coadd cube for science object

3 Reducing SINFONI data

Please, for more information, refer to the "Reduction cascade" description, available in the Chapter "Data reduction" of the Pipeline User Manual. This Chapter guides you though the main steps of data reduction, which are summarized below.

3.1 Bad Pixel Mask, Master Dark and Master Flat

The first step of the reduction consists to build the mask of badpixels, which is made of the dead, hot, and non-linear pixels. The following will guide you through the reduction steps to identify bad pixels, and create the "master dark" and "master flat" frames. The outputs are:

3.1.1 Checking the detector linearity with sinfo_rec_detlin

The recipe **sinfo_rec_detlin** computes the detector responsivity as a function of the pixel intensity and determines when it becomes non linear. Input is a set of 24 Linearity frames (DPR.TYPE=LINEARITY_LAMP), which are provided as part of the SINFONI calibration.

The main output file is a map of non-linear pixels (PRO.CATG=BP_ MAP_ NL). Non-linear pixels are identified by fitting a set of linearity frames taken with various exposure time (1, 9, 18, 27, 36, 45s). Linearity frames are taken with the 25mas/pix scale and with the same grism and filter setting as that of the science observations. The most sensitive parameter is *sinfoni.bp_lin.nlin_threshold*, which defines the criterion of identifying bad pixels.

3.1.2 Making master dark with sinfo_rec_mdark

The recipe **sinfo_rec_mdark** generates a master dark by stacking a set of raw darks (DPR.TYPE=DARK) and rejecting outliers. It also generates a bad pixel map flagging the hot-current pixels. The main output files are a map of hot pixels (PRO.CATG=BP_ MAP_ HP) and a master dark image (PRO.CATG=MASTER_ DARK). It is recommended to check the raw dark frames and discard the frames that are contaminated with cosmic rays. The contaminated darks would degrade the quality of the master dark frame and hot pixel frame. Three parameters, *sinfoni.bp_noise.thresh_sigma_factor*, *sinfoni.dark.low_rejection* and *sinfoni.dark.high_rejection*, can be adjusted to improve the output quality.

3.1.3 Making master flat with sinfo_rec_mflat

The recipe **sinfo_rec_mflat** generates a master flat field frame and a bad pixel map. Input files needed for this recipe are:

Input File	PRO.CATG	Short Description
SINFO.2015-02-28TNNN.fits	FLAT, LAMP	a set of raw flat field images
out_bp_lin.fits	BP_MAP_NL	a non-linear pixels map, output by sinfo_rec_mdark
out_bp_noise.fits	BP_MAP_HP	a hot pixel map, output by sinfo_rec_mdark *
REF_BP_MAP.fits	REF_BP_MAP	a reference bad pixel map, supplied by the pipeline package

* It is recommended to use the hot pixel map that is created using darks taken with low DITs.

The main output file are a master bad pixel map (PRO.CATG=MASTER_ BP_ MAP) and master flat field image (PRO.CATG=MASTER_FLAT_LAMP).

3.2 Computing the optical distortion with sinfo_rec_distortion

The recipe **sinfo_rec _distortion** computes a table of the distortion coefficients and the distance between the individual slitlets. Input files needed for this recipe are:

Input File	DPR.TYPE	Short Description
SINFO.2015-02-26TNNN.fits	FIBRE_NS	a set of 75 distortion frames, used to generate an uniformly illuminated synthetic fibre flat
SINFO.2015-02-28T*.fits	FLAT_NS	a set of 2 distortion flat frames with the flat lamp ON and OFF
SINFO.2015-02-28T*.fits	WAVE_NS	a set of 2 calibration arc frames with the lamp ON and OFF
xenonHK.fits	REF_LINE_ARC	the reference line list of the appropriate band (e.g. H+K), supplied by the pipeline package
drs_setup_wave.fits	DRS_SETUP_WAVE	the static parameters table, supplied by the pipeline package

The main output files is a FITS table containing the coefficients of the optical distortion polynomial. The second output is a SLITLET_DISTANCE table stores the computed slitlets distances from the left edge of the first slitlet. These output files will be used to create the wavelength map (i.e. to assign a wavelength value to each pixel on your detector), as well as to reconstruct the final 3D cubes.

3.3 Wavelength calibration with sinfo_rec_wavecal

The **sinfo_rec_wavecal** recipe is used to determine the wavelength dispersion coefficients and construct a wavelength calibration map. It also determines the positions of the edges of each slitlet. Input files needed for this recipe are:

Input File	DPR.TYPE	Short Description
SINFO.2015-02-28TNN.fits	WAVE_LAMP	a set of 2 calibration arc frames with the lamp ON and OFF
xenonHK.fits	REF_LINE_ARC	the reference line list, supplied by the pipeline package
out_flat.fits	MASTER_FLAT_LAMP	a master flat, output by sinfo_rec_mflat
out_bpmap_sum.fits	MASTER_BP_MAP	a bad pixels map, output by sinfo_rec_mflat
out_ distortion.fits	DISTORTION	a distortion table, output by sinfo_rec_distortion
drs_setup_wave.fits	DRS_SETUP_WAVE	the static parameters table
M.SINFONI.NNN.fits	SLIT_POS	the slitlet edge position table

The slitlet position table (PRO.CATG=SLIT_POS) is required if the parameter *wcal-slitpos_bootstrap* is set to **FALSE**, which is the default setting for robustness. Note that SLIT_POS table is also the output of the **sinfo_rec_wavecal** recipe. The input slitlet position file, M.SINFONI.NNN.fits, is usually downloaded as part of the calibration files together with the science data. The other main output file is the wavelength map of the detector (PRO.CATG=WAVE_MAP).

Alternatively, wavelength calibration can be performed using OH skylines instead of the arc lamps. In this case, the two on/off ac lamp frames need to be replaced with a sky frame (PRO.CATG= SKY_NODDING) and a dark frame (PRO.CATG= MASTER_DARK). Also the drs_setup_wave.fits needs to be replaced with drs_setup_wave_oh.fits The wavelength map obtained using the sky frame may grant a better calibration accuracy. However, input sky frames need to have high signal to noise ratio (SNR). Sky frames of 250 mas and often of 100 mas have sufficient SNR. In case of 25 mas observations, sky frames usually have too low SNR to be useful for wavelength calibration. For J and H bands, there are plenty of OH lines to ensure accurate wavelength calibration. In K-band, the accuracy of sky-based calibration may be less robust beyond 2.3 μm due to the lack of OH lines.

3.4 Cube reconstruction with sinfo_rec_jitter

The **sinfo_rec_jitter** recipe subtracts sky background, corrects for the flat-field and constructs a wavelength calibrated cube for each exposure. Finally, all the cubes of the same target are aligned and combined. This recipe can be used to reduce PSF standard (PRO.CATG=PSF, and SKY_PSF) , telluric standard (PRO.CATG=STD, and SKY_STD) and scientific targets data (PRO.CATG=OBJECT_NODDING, SKY_NODDING).

In case of reducing science data, input files needed for this recipe are:

Input File	DPR.TYPE	Short Description
SINFO.2015-02-28TNN.fits	OBJECT_NODDING & SKY_NODDING	object and sky frames
out_flat.fits	MASTER_FLAT_LAMP	a master flat
out_bpmap_sum.fits	MASTER_BP_MAP	a bad pixels map
out_wavemap_ima.fits	WAVE_MAP	output by sinfo_rec_wavecal
out_slitpos.fits	SLIT_POS	output by sinfo_rec_wavecal
out_distortion.fits	DISTORTION	output by sinfo_rec_distortion
out_distances.fits	SLITLETS_DISTANCE	output by sinfo_rec_distortion
SI_GATM_REF_CORR_HK_025.fits	ATM_REF_CORR	supplied by the pipeline package

The ATM_REF_CORR frame is optional, which is used to compute the correction due atmospheric refraction. The correction is applied only if this input frame is provided. The atmospheric correction is recommended, particularly when the object is observed at a high airmass.

The main output is the coadded reconstructed cube of the science target "out_objnod.fits" (PRO.CATG= COADD_OBJ). Individual reconstructed cubes "out_cube_obj_N.fits" (PRO.CATG=OBS_OBJ) of the science target are part of the output as well. For the full list of the output of **sinfo_rec_jitter**, refer to section (10.8.2) of the SINFONI Pipeline User manual.

NOTE: for pupil tracking mode, **sinfo_rec_pupil** should be used instead of **sinfo_rec_jitter**. The only difference is to replace OBJECT_NODDING and SKY_NODDING frames with PUPIL_LAMP frames.

3.5 Spectrum extraction with sinfo_utl_cube2spectrum

This is an optional recipe to perform cube to 1D spectrum image conversion.

Users need to change classification (PRO.CATG) of data cubes from OBS_OBJ or COADD_OBJ to CUBE. Extraction operations are: average, clean_mean, median, sum. Possible apertures are: rectangle, circle.

If rectangle is chosen, users need to define the corner coordinates by llx, lly, urx, ury (lower left x,y and upper right x,y). If circle is chosen, users need to define the center (centerx, centery) and the radius of the aperture.

Alternatively, a useful way to both visualize the 3D cube and extract the spectrum of any part of the cube, is to use QFitsView.

3.6 Tips to improve sky subtraction for faint targets

By default, the *objnod.autojitter_method* parameter in the **sinfo_rec_ jitter** recipe is set to "1", which means that the sky closest in time is subtracted from the corresponding object frames. If users prefer to subtract the sky in different manners, then set *objnod.autojitter_method* to "0" and no sky would be subtracted automatically. If no sky frames available and the science target is not extended, the sky background can be estimated by median combining all the science frames (as long as the object is jittered sufficiently within the FOV). In this case, *objnod.autojitter_method* needs to be set to "2".

If the target is faint and the optimal sky subtraction is required, it is recommended to activate the *objnod.scales_sky* parameter when running **sinfo_rec_jitter**. This parameter enables subtraction of the median value of each slice of the data cube (i.e. for each wavelength channel) in order to remove any sky subtraction residual. However, it is only useful for non-extended objects. Please refer to section (11.1.25) and (11.1.26) of the SINFONI Pipeline User manual for detailed description on how to optimize the sky subtraction.

3.7 Moving targets

In the case the science target has a significant proper motion, which is not compensated by the telescope tracking or AO system, the user needs to co-register individual object cubes using the **sinfo_ utl_cube combine** recipe. This is usually the case of observing faint solar system objects with AO, while the AO system use a different source (nearby bright source or other brighter moving target within the vicinity of the main science target) as the AO reference source.

The user needs to provide in an input ASCII file, which specify the x and y offsets for each science frame. For details, please refer section 10.16.1 of the SINFONI Pipeline User manual.

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