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Abstract

The SPHERE instrument is a high-contrast imager and spectrograph on Unit Telescope 3 of the Very Large Telescope. It was commissioned in 2014, had its science verification in December 2014 and started regular operations in April 2015. More information can be found here: https://www.eso.org/sci/facilities/paranal/instruments/sphere.html

This document describes the SPHERE science data products, which have been processed by the SPHERE Data Center (SPHERE DC) and released via the ESO Science Archive Facility. The SPHERE Data Centre is jointly operated by OSUG/IPAG (Grenoble), PYTHEAS/LAM/CESAM (Marseille), OCA/Lagrange (Nice, France), Observatoire de Paris/LESIA (Paris), and Observatoire de Lyon. A full description of the SPHERE DC is available here: https://sphere.osug.fr/spip.php?rubrique16&lang=en

SPHERE-DC is a support service provided by the French community that targets users of the ESO instrument SPHERE. It implements a data base and data reduction workflows based on the SPHERE ESO pipeline, complemented by additional recipes to systematically process public data, which are then made available to the community. Reduced public data are made available through the SPHERE DC, through the DIVA+ database and as of now through the ESO archive.

The first data products published in December 2022 in the ESO Science Archive Facility include imaging data from the IRDIS sub-system, observed during the ESO period P103 and P104 acquired between April 2019 and March 2020. Users interested in more advanced data products (application of various high-contrast data reduction techniques, or intermediate data products to apply their own algorithm) can download them from the SPHERE DC or DIVA+ database.

List of acronyms

Acronym	Definition
ADI	Angular Differential Imaging
AO	Adaptive Optics
cADI	Classical ADI
CI	Classical Imaging (one observing mode of IRDIS)
DBI	Dual Band Imaging (one observing mode of IRDIS)
DIVA	Direct Imaging Virtual Archive
DPI	Dual Polarimetric Imaging (one observing mode of IRDIS)
DRH	Data Reduction and Handling
HDU	Header / Data Units
IRDIS	InfraRed Dual Imager and Spectrograph
OB	Observation Block
OSUG	Observatoire des Sciences de l'Univers de Grenoble
PSF	Point-Spread Function
RTC	Real-Time Calculator
SPHERE	Spectro-Polarimetric High-Contrast Exoplanet REsearch
SPHERE-DC	SPHERE Data Center
WFS	WaveFront Sensor

Overview of Observations

The science data products released in the SPHERE data collection are SPHERE IRDIS data. IRDIS is a dual-band imager and polarimeter. The release contains data observed in Classical Imaging (CI), Dual-Band Imaging (DBI) or Dual Polarimetric Imaging (DPI), but the polarimetric data reduction is currently not included.
The first steps of the data reduction consist in background- or sky-subtraction (whichever is available, sky being preferred over background), flat-field correction and bad-pixel correction, along with the separation of the two images from each of the two IRDIS channels. These steps are performed with the ESO DRH (Pavlov et al. 2008) version 0.15. Then the frames are corrected for the optical distortion, which is a small anamorphism along the horizontal direction of the detector (see Maire et al. 2021 for details). Frames are then re-centered, by finding the star position (possibly by using the echoes of the PSF called the waffle spots, if a coronagraph is used), and by shifting the star position to the central pixel of coordinate (512,512) using 0-based indexing. This is done using the *specal* pipeline (Galicher et al. 2018). The recentered frames from the same observation are assembled in a data cube called a master cube. The master cube is then processed to produce one final image per channel.

In high-contrast imaging with IRDIS, observations can either be done in pupil- or field-stabilization mode. In the former case, the field of view rotates during the observations, but the pupil and diffraction pattern remain fixed on the detector, allowing the use of Angular Differential Imaging (ADI) techniques to subtract the Point Spread Function and reveal the circumstellar environment. The standard ADI post-processing applied to the data in this release is Classical ADI (cADI, Marois et al. 2006). In the latter case, the field is fixed but the pupil rotates, and a simple stacking of the images is applied as the standard post-processing (referred to as non-ADI in this document). Depending on the observations, we provide either cADI or non-ADI reduced data.

Release Content

The current data collection contains SPHERE IRDIS data observed in the ESO semester P103 and P104. It includes 90% of the SPHERE IRDIS data acquired between April 2019 and March 2020.
Additional data products obtained with the above instrument mode will be added in future data publications. As the number of data products increases while SPHERE IRDIS is in operation, new data are planned to be processed and published with a yearly cadence and added to the SPHERE data collection. Data processing is automatic and thus may not include non-standard observing modes.

Release Notes

The science products in the SPHERE data collection are single reduced image files (one per observation) processed either using cADI or non-ADI. For users interested in getting either more aggressive reductions that reach better contrast (at the cost of a reduced sensitivity to extended signal such as circumstellar disk signals), or for users interested in getting the master cubes (pre-processed data cubes of images, centered, bad-pixel corrected, flat-field corrected, anamorphism-corrected and background subtracted) to perform their own post-processing, the data are available from the SPHERE DC interface: https://sphere.osug.fr/spip.php?rubrique16&lang=en
We therefore recommend users to check the data available on the ESO archive, and if they find their target of interest and need more aggressive reductions or master cubes to access the data products from the SPHERE DC interface.

Data Reduction and Calibration

The images have been corrected for bad pixels, sky- or background- subtracted, corrected by the flat-field illumination, and corrected for geometric distortion. The WCS was computed using the coordinate of the central star as retrieved from Simbad in the J2000 ICRS coordinate system, and using the pixel scale and true north derived from the astrometric calibrations regularly observed by the observatory (see Maire et al. 2021 for details on the astrometric calibration). For moving-objects, such as asteroids, the WCS is updated using the telescope coordinate, the absolute astrometric uncertainty is therefore larger[1].
Images are expressed in contrast, i.e. a pixel value of 1e-3 indicates a flux a thousand times fainter than the peak brightness of the central star (potentially hidden behind the coronagraph if such a device was used). The zero-point indicated in the header reflects this convention.

Data Quality

A manual check of the data quality was performed and a few data with poor image quality were removed from the data release.
For each data, an automatic frame selection is implemented in the reduction pipeline to discard bad or deviant frames from the master cubes (e.g. open loops, star out of the coronagraph…). The data quality can be assessed using the contrast at 500 milli-arcsec from the central star. This contrast is displayed in the header in AB magnitude (keyword ABMAGLIM). Other quality metrics include the average Strehl as measured from the RTC (keyword STREHL in each fits extension) when available.

[1] *For users who need a more accurate WCS of moving objects, we recommend to recompute the WCS using the moving object ephemeris and the date of observation*

Known issues

No issues have been reported so far.

Data Format

Files Types

General format

IRDIS being a dual-channel imager, two images are produced, for the left and right channel. In CI, those two channels contain the same astrophysical signal. In DBI each channel corresponds to a specific dual-band filter. In DPI, each channel contains the same spectral information but a different polarization information, but as the polarimetric reduction is not offered yet, the 2 channels can be considered identical.
The data are stored in FITS format with a primary HDU containing just header keywords, no data, and two Image HDU in the extensions for the two IRDIS channels. The extension name of those two HDUs are IRDIS_CHANNEL1 and IRDIS_CHANNEL2 respectively.
The general format follows the ESO Science Data Product Standard, described in https://www.eso.org/sci/observing/phase3/p3sdpstd.pdf
In particular, the provenance keywords, (PROVi, i being an integer starting at 1) give the name of the raw SPHERE science frames used to build the master cube

The keywords contained in the primary HDU are mostly propagated from the raw FITS files used in the data reduction, complemented by a few specific ones.

Keywords inherited from the raw files:
All keywords starting with HIERARCH ESO are inherited from the raw SPHERE science files used in the data reduction. A few specific ones are updated to reflect the average values over the length of the observation. This is the case for

- ESO TEL AIRM START: the airmass of the first frame used in the data reduction
- ESO TEL AIRM END: the airmass of the last frame used in the data reduction
- ESO TEL AMBI FWHM START: the DIMM seeing of the first frame used in the data reduction
- ESO TEL AMBI FWHM END: the DIMM seeing of the last frame used in the data reduction
- ESO TEL AMBI PRES START: the ambient pressure of the first frame used in the data reduction
- ESO TEL AMBI PRES END: the ambient pressure of the last frame used in the data reduction
- ESO TEL IA FWHM, ESO TEL IA FWHMLIN and ESO TEL IA FWHMLINOBS: the FWHM from the active optics (image analyser, using various algorithms) averaged over frames used in the data reduction
- ESO TEL PARANG START: the parallactic angle of the first frame used in the data reduction
- ESO TEL PARANG END: the parallactic angle of the last frame used in the data reduction

Specific keywords

In addition to those inherited keywords, some specific ones are added during the data reduction process. The table below provides the definition and examples of these keywords.

TN_CORR	-1.75 / deg True North correction: Astrometric calibration applied

TN_ERROR	0.0420000 / Error on TN_CORR in deg
PIXTOARC	12.25000 / mas per pixel
PIX_ERR	0.200000 / Error on PIXTOARC in mas
CALPIXTN	'NA ' / date of calibration for pix scale
CALTN	'2017-06-02' / date of calibration for TN
STREHL _MIN	0.606077 / Strehl ratio from SPARTA WFS, min of full dataset
STREHL _MAX	0.654006 / Strehl ratio from SPARTA WFS, max of full dataset
STREHL	0.621446 / Strehl ratio from SPARTA WFS, average of the full dataset
SEEI_MIN	1.28428 / Seeing from SPARTA WFS, min of full dataset Not as accurate in absolute as DIMM values below
SEEI_MAX	1.45104 / Seeing from SPARTA WFS, max of full dataset Not as accurate in absolute as DIMM values below
SEEI_AVG	1.37323 / Seeing from SPARTA WFS, avg of full dataset Not as accurate in absolute as DIMM values below
WIND_MIN	11.8809 / Effective wind velocity (m.s-1) from SPARTA WFS, min of full dataset
WIND_MAX	14.2776 / Effective wind velocity (m.s-1) from SPARTA WFS, max of full dataset
WIND_AVG	13.1817 / Effective wind velocity (m.s-1) from SPARTA WFS, avg of full dataset
OBS_STA	'2017-06-13T01:26:16.56' / Starting date of observation
OBS_END	'2017-06-13T01:45:53.45' / End date of observation
LEVELSEL	2 /Agressiveness of selection vector used when removing bad frames: 0: NO selection, 1: soft selection applied, 2: more aggressive selection

EFF_NFRA	59.00 /UPDATED effective number of frames used in dataset, after selection
EFF_ETIM	944.0 / effective exposure time used in dataset, after selection
SCPIPE	'SpeCal ' / All "SC" keywords below refer to values used/determined by the reduction algorithm, usually Specal
SCVERS	'2020-09-09' / Version of the package
SCDATE	'Thu Feb 4 10:12:12 2021' / Date of the data reduction
SCFOVROT	9.63456 / Total fov rotation(deg)
SCPSFVAR	'Alert ' / Strong flux variation for >1 PSF
SC_FWHM	5.00000 / FWHM in pixels used by the algo
SC_FLRMS	0.0456585 / variation of the star flux (sequence + PSF)
SC_MODE	'NO ADI ' / algorithm
SC_ADI	'ADI ' / accounts for ADI only
SCRMIN	1.00000 / min radius, in FWHM,
SCRMAX	40.0000 / max radius in FWHM
SC_TYPE	'NOADI REDUCED MED' / algo applied, here Median of median images

The fits extensions contain information specific to each image.
In particular the images are astrometrically registered using the standard FK5 WCS. The photometric calibration is performed using the magnitude of the target as retrieved from Simbad. If a coronagraph is used and the star is observed outside the coronagraph (observations with a DPR TYPE of OBJECT,FLUX), the zero point is computed using this non-coronagraphic image taking into account the possible use of a neutral density filter to avoid saturation.
SPHERE is not an instrument designed to provide accurate photometry, with zero points measured accurately on photometric standard stars. The PSF can change during an observation due to the variable level of correction of the adaptive optics, and most SPHERE observations are carried out under thin conditions. We therefore provide an uncertainty of 1 magnitude on the zero point, which is reflected in the PHOTZPER keyword.

In case the magnitude of the target could not be retrieved on Simbad (for instance in case of moving or variable targets), a rough guess is provided from the flux observed on the WFS, and the uncertainty is then larger than 1 mag.
The saturation limit (keyword ABMAGSAT) is not accurately known because the saturation threshold in the raw frames was until recently not currently propagated until the final reduced images by the pipeline. Therefore, the keyword ABMAGSAT provides the best possible estimate of the saturation limit but has a large uncertainty of 2.5 mag.
The keyword PSF_FWHM currently represents the diffraction limit at the wavelength of observation. While the SPHERE adaptive optics system provides diffraction-limited observations for bright stars, this is no longer the case for stars fainter than G=12.5 (see Jones et al. 2022).
The STREHL keyword provides the Strehl value as estimated by the SPARTA RTC. This is not a measurement done on the image. It can be biased if the star is faint, because the WFS flux is too faint for a proper Strehl estimation. It can also be biased in case of low-wind effect which is invisible for the WFS but which degrades significantly the image quality, thus the Strehl (Milli et al. 2018). For stars brighter than G~10, deviations between the Strehl estimated by the RTC and measured on the image can reach more than 10% (see Milli et al. 2017 for a comparison).

Acknowledgements

According to the Data Access Policy for ESO Data held in the ESO Science Archive Facility, all users are required to acknowledge the source of the data with an appropriate citation in their publications.

Processed data downloaded from the ESO Archive are assigned a Digital Object Identifier (DOI). The following statement must be included in any publications making use of them:

Based on data obtained from the ESO Science Archive Facility with DOI(s): https://doi.org/10.18727/archive/79

Any publication making use of these data, whether obtained from the ESO archive or via third parties, must include the following acknowledgment:

- *Based on data products created from observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme(s) TPPP.C-NNNN(R)*
- *This work has made use of the SPHERE Data Centre, jointly operated by OSUG/IPAG (Grenoble), PYTHEAS/LAM/CESAM (Marseille), OCA/Lagrange (Nice), Observatoire de Paris/LESIA (Paris), and Observatoire de Lyon.*

Finally when using these data please cite to the following publications:

- Delorme et al. 2017: http://cdsads.u-strasbg.fr/abs/2017sf2a.conf..347D to credit the SPHERE Data Center infrastructure and service.
- Galicher et al. 2018 : http://cdsads.u-strasbg.fr/abs/2018A%26A...615A..92G to credit the reduction pipeline called *Specal*.
- Maire et al. 2016 : https://ui.adsabs.harvard.edu/abs/2016SPIE.9908E..34M/abstract to credit the astrometric and plate scale calibration of SPHERE.

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