

# ***VLT/SPHERE Data Processed by the High-Contrast Data Center ESO Science Archive Facility Phase 3 Data Release Description***

Data Collection: SPHERE

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Document Author: Julien MILLI (IPAG)

## **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 [High-Contrast Data Center](#) (HC-DC) and released via the ESO Science Archive Facility. The High-Contrast 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 HC-DC is available here: <https://sphere.osug.fr/spip.php?rubrique16&lang=en>

HC-DC is a support service provided by the French community that targets users of the ESO instrument SPHERE. It implements a database 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 HC-DC (with a java-based application), but also through the [DIVA+ portal](#), and since December 2022 through the ESO Science Archive Facility.

The data products published in the ESO Science Archive Facility include imaging data from the IRDIS sub-system, observed during the ESO period P95 to P109 acquired between April 2015 and September 2022. 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 HC-DC or DIVA+ portal.

## 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
HC-DC	High-Contrast Data Center
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
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 of 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-centred, 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 recentred 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-stabilisation 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 when available or non-ADI reduced data.

## Release Content

The data release contains all SPHERE IRDIS data observed between the ESO Period P95 to P109 (acquired between April 2015 and September 2022), including the SPHERE consortium Guaranteed Time Observations. Frames from P103 and P104 that were already available in the ESO science archive were reprocessed to refine the information provided in the FITS keywords (target identification and contrast assessment) and to deprecate low-quality frames obtained under poor observing conditions. The pixel values themselves were not altered.

The only missing data concern the IRDIS observations from P106 to P109 obtained in the K band (broad-band filter BB\_K or dual-band filter DB\_K12), as an on-going improvement in the background subtraction is being performed. These missing datasets will be uploaded in a future update.

Additional data products obtained with the above instrument mode after September 2022 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.

Data products obtained in the polarimetric observing mode of IRDIS will also be made available in a next data release.

## 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, centred, bad-pixel corrected, flat-field corrected, anamorphism-corrected and background subtracted) to perform their own post-processing, the data are available from the HC-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 HC-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 at the epoch of observation, 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). More details about how the central star is identified are detailed in the appendix “astrometric calibration”. For moving-objects, such as asteroids, the WCS is updated using the telescope coordinate, the absolute astrometric uncertainty is therefore larger<sup>1</sup>.

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<sup>1</sup> 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.

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.

## 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>

Maire, A.-L., Langlois, M., Delorme, P., et al. (2021) "Lessons learned from SPHERE for the astrometric strategy of the next generation of exoplanet imaging instruments," JATIS, 7, 035004 - 2021JATIS...7c5004M

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. If the observations use a coronagraph, the master cube is made of coronagraphic frames and the raw frames used for the flux calibration (with the DPR TYPE "OBJECT,FLUX") are also listed in the header with the keyword HCDC PSF PROVi.

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 /Aggressiveness 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
PSF_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. Additional details are provided in the decisional tree in the Appendix below.

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 always 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  $G \sim 10$ , 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. Any publication making use of these data, whether obtained from the ESO archive or via third parties, therefore must include the following acknowledgments:

- *Based on data obtained from the ESO Science Archive Facility with DOI: <https://doi.org/10.18727/archive/79>*
- *This work has made use of the High-Contrast 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](#): to credit the High-Contrast Data Centre infrastructure and service.
- [Galicher et al. 2018](#): to credit the reduction pipeline called *SpeCal*.
- [Maire et al. 2016](#): to credit the astrometric and plate scale calibration of SPHERE.

Science data products from the ESO archive may be distributed by third parties, and disseminated via other services, according to the terms of the [Creative Commons Attribution 4.0 International license](#). Credit to the ESO provenance of the data must be acknowledged, and the file headers preserved.

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## Appendix: Astrometric registration

The images produced by the pipeline automatically have the astrophysical object used for correction by the AO system centred in the middle of the pixel with coordinates (512,512), using 0-based indexing (the convention used in Python, for instance). The WCS information in the header reflects this convention, assuming the North is up and East to the left.

If this astrophysical object is a moving object (keyword ESO TEL TRAK STATUS set to MOVING), then the telescope pointing coordinate at the start of the observation (keyword RA/DEC of the first original file) is assumed to be the coordinate of the object. If the target is not a moving object (keyword ESO TEL TRAK STATUS set to NORMAL, which is the most common case) a decisional tree is implemented to identify the star from the telescope pointing coordinate (keyword RA/DEC of the first original file). The target name as defined by the user in the OB (keyword OBJECT) is not 100% reliable or may contain typos, therefore this information is not used in the first place. This decision tree is detailed below in Figure 1.

Some specific crowded fields, especially those used for the astrometric calibration of the instrument (e.g. 47 Tuc, theta Ori B1-B4, NGC3603 or NGC6380; see Maire et al. 2016), are treated as special case and the central star is hard-coded, as this is always the same star used as the AO star in this astrometric calibration.

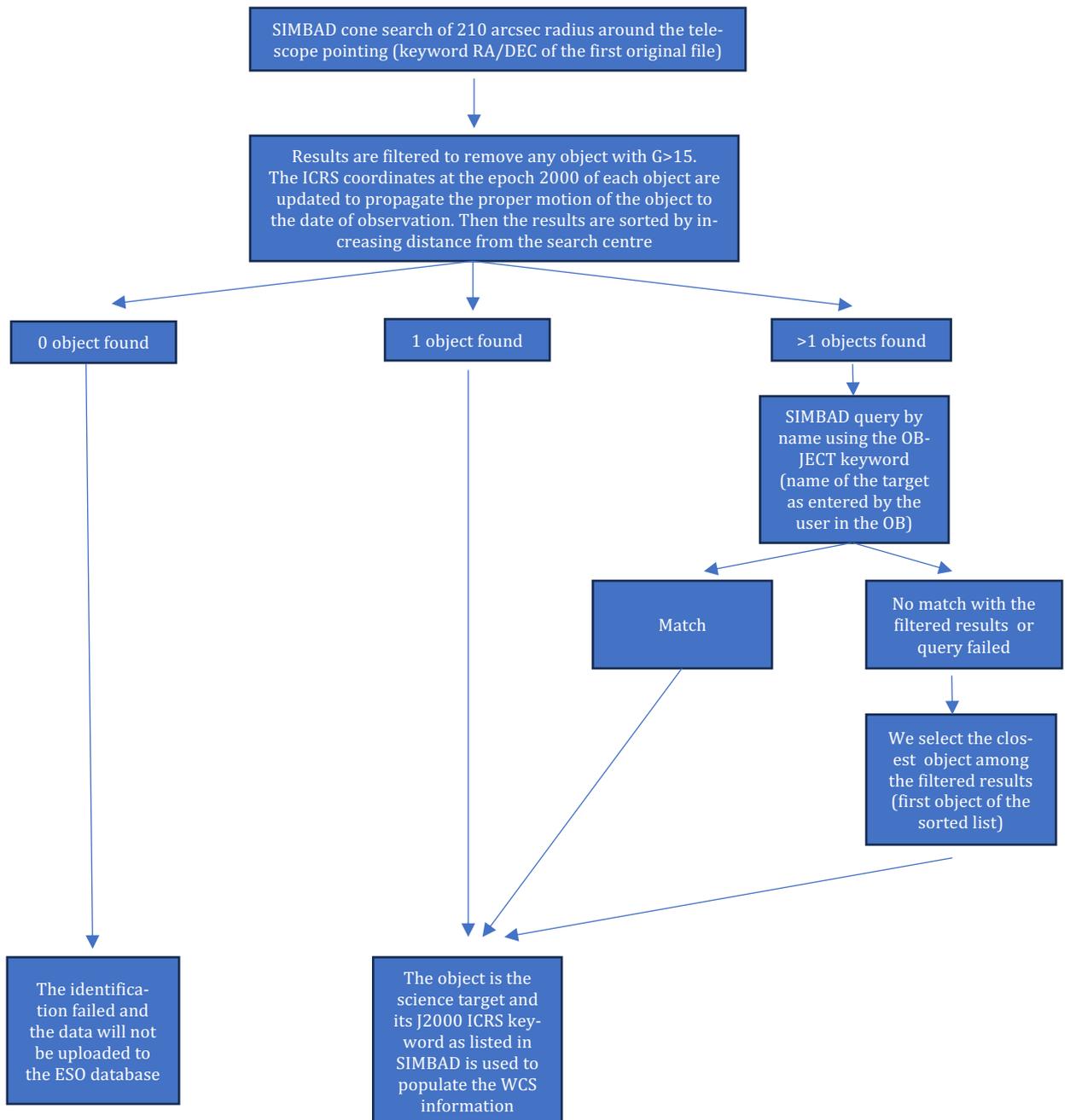


Figure 1 Decision tree to populate the WCS information of the FITS header