Impact of calibration on performances with IRDIS, the infrared imager and spectrograph for SPHERE

M. Langlois[a], A. Vigan[b], K. Dohlen[b], C. Moutou[b], D. Mouillet[c], F. Wildi[d], A. Boccaletti[e]

[a] CNRS, Centre de Recherche Astrophysique de Lyon , Université Lyon 1, Observatoire de Lyon, 9 avenue Charles André, Saint-Genis Laval, F-69230, France ;
[b] Laboratoire d'Astrophysique de Marseille UMR 6110, CNRS/Université de Provence, 38 rue Frédéric Joliot-Curie, 13388 Marseille cedex 13, France
[c] Laboratoire d'Astrophysique de l'Observatoire de Grenoble UMR 5571, Université Joseph Fourier/CNRS, B.P. 53, F-38041 Grenoble Cedex 9, France
[d] Observatoire de Genève, Université de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland
[e] LESIA Observatoire de Paris, Section de Meudon 5, place Jules Janssen 92195 Meudon Cedex

ABSTRACT

The detection and characterization of extrasolar planets by direct imaging is becoming more and more promising with the preparation of dedicated high-contrast instruments and the help of new data analysis techniques. SPHERE (Spectro-Polarimetric High-contrast imager for Exoplanets REsearch) is currently being developed as part of the second generation instruments of the ESO-VLT. IRDIS, one of the SPHERE subsystems, will provide dual-band imaging with several filter pairs covering the near-infrared from 0.95 to 2.3 microns, among with other observing modes such as long slit spectroscopy and infrared polarimetry. This paper describes the instrument performances and the impact of instrumental calibrations on finding and characterizing extrasolar planets, and on observing strategies. It discusses constraints to achieve the required contrast of $\sim 10^6$ within few hours of exposure time.
Keywords: extrasolar planets, extreme AO, coronagraphy, dual imaging, polarimetry, long-slit spectroscopy

1. INTRODUCTION

The SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) instrument[1],[2] is being built by a wide consortium of European countries. It is based on an extreme AO system (SAXO)[3] and employs coronagraphic devices[4] and differential imaging techniques for stellar diffraction suppression. It is equipped with three science channels: a differential imaging camera (IRDIS), an integral field spectrograph (IFS)[5], and a rapid switching polarimeter (ZIMPOL)[6]. The IRDIS differential imaging camera provides imaging in two parallel channels over a wide FOV (11"). A beam splitter plate associated with a mirror separates the beam in two parallel beams. Two parallel beams are spectrally filtered before reaching the detector, by dual band filters with adjacent bandpasses corresponding to sharp features in the expected planetary spectra. Differential aberrations between the two beams are critical for achieving 5s contrast of $5\ 10^{-5}$ at 0.1" and $5\ 10^{-6}$ at 0.5" from the star in 1 hour integration. For the achievement of such High contrast performances, it is mandatory to keep errors due to instrumental effects at very low level. This can be achieved by optimizing the instrument design, by providing suitable tools to calibrate such effects and by developing adequate data reduction procedures. After a brief presentation of the science case and the instrument, we describe the expected performances for various observation modes in section 4 and the instrumental calibration issues in section 5. Sect. 6 summarize the calibration plan of SPHERE-IRDIS.

2. SCIENCE CASE

The prime objective of SPHERE is the discovery and study of new planets orbiting stars by direct imaging of the circumstellar environment. The challenge consists in the very large contrast of luminosity between the star and the planet (larger than ~12.5 magnitudes or ~10^5 flux ratio), at very small angular separations, typically inside the seeing halo. The whole design of SPHERE is therefore optimized towards high contrast performance in a limited field of view and at short distances from the central star. With such a prime objective, it is obvious that many other research fields will benefit from the large contrast performance of SPHERE: proto-planetary disks, brown dwarfs, evolved massive stars. These domains will nicely enrich the scientific impact of the instrument. The science cases are described elsewhere[1].

The main observing mode, which, will be used for 80% of the observing time, combines IRDIS dual imaging in H band with imaging spectroscopy using the IFS in the Y-J bands. This configuration permits to benefit simultaneously from the optimal capacities of both dual imaging over a large field (out to ~5" radius) and spectral imaging in the inner region (out to at least 0.7") and allows to reduce the number of false alarms and to confirm potential detections obtained in one channel by data from the other channel, a definitive advantage in case of detections very close to the limits of the system.

IRDIS used alone in its various modes will furthermore allow obtaining observations in the full FOV in all bands from Y to short-K, either in differential imaging, polarimetry or in broad and narrow-band imaging. The observing modes and main characteristics and performances are summarized in Table 1. This will be especially interesting in order to obtain complementary information on already detected and relatively bright targets (follow-up and/or characterization). Spectroscopic characterization at low or medium resolution will be possible in long-slit mode. The main specifications for IRDIS include a spectral range from 950-2320 nm and an image scale of 12.25mas/pixel consistent with Nyquist sampling at 950nm. A FOV of 11" is provided for both direct and dual imaging using two "quadrants" of a 2kx2k Hawaii 2-RG detector.

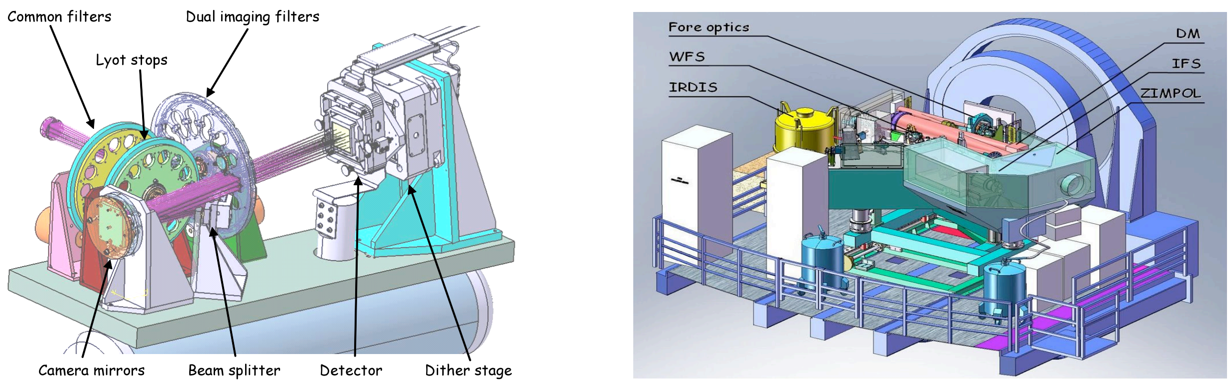
Table 1: Summary of IRDIS observing modes and main characteristics.

Mode	Use Science case	Wavelength Bands	Rotator mode	Filters, Resolution	Contrast Performance (1h, SNR=5, H<6)
Dual Band Imaging	Survey mode (H only) Characterization of cool outer companions	Y,J,H,Ks bands	Pupil or field stabilized	6 pairs R=20-30	~ 10^{-5} at 0.1” ~10^{-6} at 0.5”

Dual Polarimetry Imaging	Reflected light on extended environment	Y,J,H,Ks bands	Pupil or field stabilized	4 Broad 10 Narrow bands	~ 10^{-4} at 0.1” ~ 10^{-5} at 0.5” 30% circumstellar source
Slit Spectroscopy	Characterization of not too faint companions	LRS : Y-Ks MRS: Y-H	Pupil stabilized	LRS : R=50 MRS : R=500	~ 3.10^{-4} at 0.3” ~ 10^{-5} at 0.5”
Classical Imaging	Environment with no spectral features	Y,J,H,Ks bands	Pupil or field stabilized	4 Broad 10 Narrow bands	~ 10^{-3} at 0.1” ~ 3.10^{-4} at 0.5

3. INSTRUMENTAL SETUP

The opto-mechanical implementation of IRDIS is shown in Figure 1 (a). Three wheels are provided within the cryogenic environment. For more details please refer to paper [6] in this proceeding. The Lyot Stop Wheel also contains a prism and a grism for long-slit spectroscopy. It is preceded by a common filter wheel carrying wide band (WBF), broad-band (BBF) and narrow band (NBF) filters for classical imaging. A second filter wheel carrying dual imaging filter pairs and polarizersis located down-stream of the beam-separation unit. The detector is mounted on a two axis piezo motor translation stage to allow dithering for flat-field improvement.

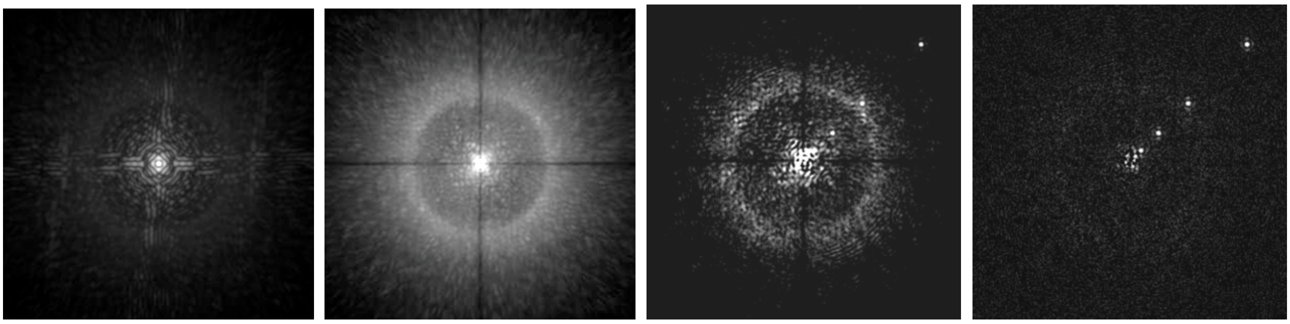


(a) (b)

Figure 1: IRDIS opto-mechanical implementation (a) Global view of the SPHERE instrument (b)

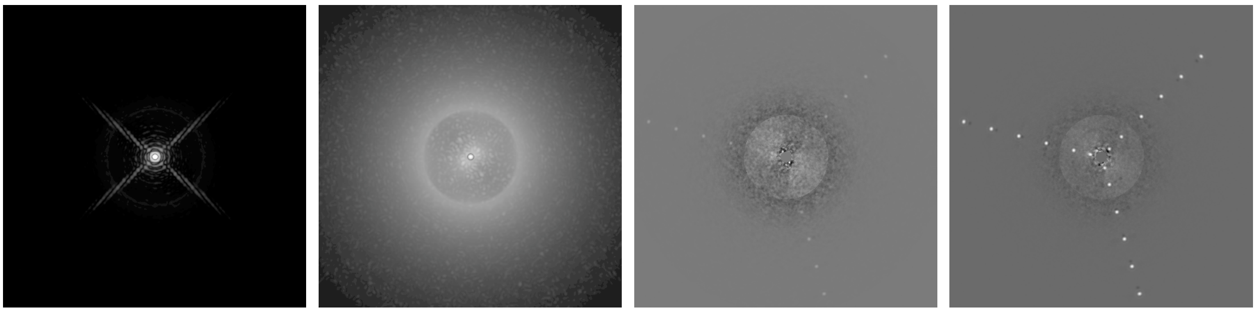
4. PERFORMANCES FOR THE DETECTION AND CHARACTERIZATION OF EXOPLANETS

The dual-band imaging (DBI) mode achieves high contrast by simultaneous imaging at both sides of the H methane absorption band, allowing to remove most of the systematic speckles due to instrumental defects. Further contrast improvements has to deal with two main components (as illustrated on Fig. 2 and 3): a speckled halo which is averaging over time from adaptive optics residuals over atmospheric correction and a quasi-static speckle pattern originating from time evolving instrumental aberrations with longer lifetime. IRDIS DBI mode will allow the use of different data analysis methods to remove the speckle residuals, in particular simultaneous Spectral Differential Imaging (SDI), for which the main limitation are the quasi-static aberrations upstream the coronagraph and the spectral shift between the DBI filters, and Angular Differential Imaging (ADI) using field rotation and for which the main limitations are the field rotation rate and the temporal evolution of the aberration [6] The achievable level of contrast in DBI is 5 10^{-5} at 0.1" and 5 10^{-6} at 0.5" from the star at 5σ in 1 hour integration time.



(a) (b) (c) (d)

Figure 2: M0V star 10pc image with DBI (H2H3), the detected planets are located at 0.1", 0.2", 0.5", 1", 2" from the star and correspond to : 1MJ at 10My - 3MJ at 100My - 11MJ at 1Gy - 25MJ at 5Gy. The illustrations show the star PSF (a), the 4QPM raw image (b), the 4QPM single subtraction of 2 wavelengths H2H3 (c), the double subtraction image including calibration of differential aberrations and chromatic residual (d). Gray scales are arbitrary. The simulations are performed using CAOS- SPHERE [6].

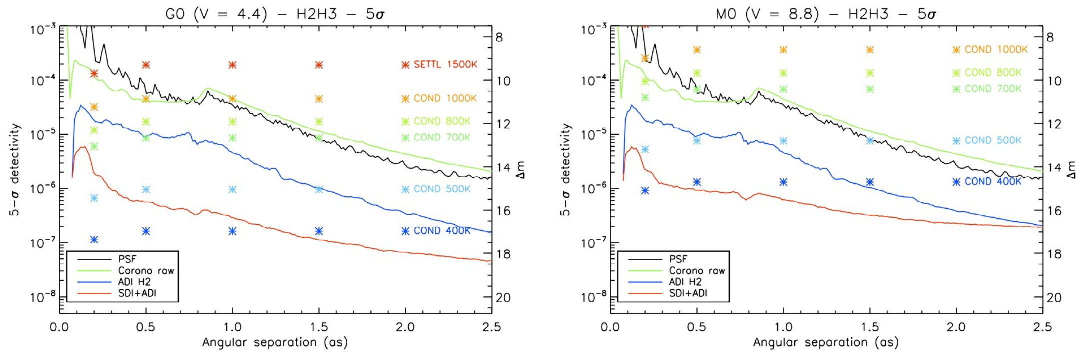


(a) (b) (c) (d)

Figure 3: G0V star 10pc image with DBI (H2H3), the detected planets are located at 0.2", 0.5", 01.0", 1.5", 2.0", and 2.5'' from the star and correspond to : 1.9MJ at 10My – 6.5MJ at 100My – 118.5MJ at 1Gy – 37.9MJ at 5Gy. The illustrations show the star PSF (a), the Apodized Lyot Coronagraph raw image (b), the analyzed imaged after using Angular Differential Imaging in filter H2 (c), and the combination of Spectral Differential Imaging (H2-H3) and Angular Differential Imaging (d). Gray scales are arbitrary.

Figure 3 (c) and (d) show the result of applying these data analysis methods on simulated data representing a G0 star at 10 pc with three series of planets at various angular separations. In very young systems, these planets would represent a mass of ~2 M_{Jup} according to current evolutionary models. Figure 4 represents the 5σ detection limits that can be reached for a 4-hours observation of G0 and M0 stars with H2H3 filter pairs. Combining SDI and ADI techniques we expect to reach a contrast of ~2 10^{-5} at a separation of 0.2'', which would result in the detection of ~1 M_{Jup} planets. A detailed comparison of the performances of different data analysis methods is presented by Vigan et *al.* at this conference.

The Long Slit Spectroscopy (LSS) mode, combined with an efficient data analysis method [6] offers the possibility of spectral characterization of detected objects at low (R = 60) and medium (R = 420) resolutions. In low-resolution spectroscopy (LRS), we will be able to characterize both objects detected by SPHERE in the NIR survey mode, providing they are within the field of view of IRDIS. With a simple Lyot occulting mask in the centre of the field, and limited contrast in the vicinity of the star, the angular separations (>0.5'') will be within access to this mode. The simulations show that we should obtain a signal-to-noise ratio of 20 or larger for a 700K-1000K companion around a typical target of SPHERE (e.g. around a H=6 magnitude star at less than 50 pc) allowing characterization of the J-Ks color of cool planets. The MRS Medium Resolution mode also allows observations in the full 11 arcseconds field-of view, except the central part, which is occulted by the coronograph. The scientific exploitation of these data is based on the observation of molecular and atomic bands that are sensitive to the temperature and gravity, and require a resolution of at least 400. The performed simulation show that the gravity-sensitive KI feature is clearly resolved for moderate companions temperature (> 900K) and separation larger than 0.5" with signal to noise ratio > 20 for both G0 and M0 star at 10pc.



(a) (b)

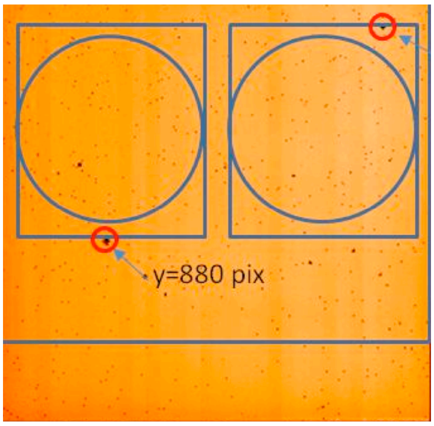
Figure 4: Some results of an extensive simulation of test cases involving various stellar ages and distances. Planetary companions intensities (crosses) are compared with radial variance profiles in the processed images with ADI and SDI+ADI data analysis methods, assuming a G0V (a) and a M0V (b) star at 10pc observed in the H2-H3 filter couple. COND refers to models for a condensed atmosphere free of dust, while SETTL refers to atmosphere models with rainout of refractory material.

5. CALIBRATION ISSUES

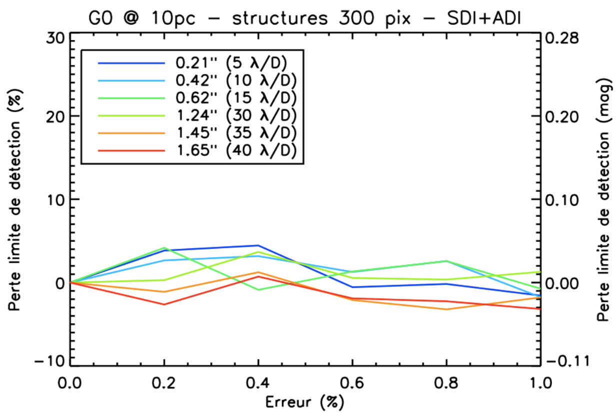
It is mandatory to keep instrumental effects at very low level. This can be achieved by optimizing the instrument design (WFE), by providing suitable means to calibrate such effects and by developing adequate data reduction procedures. Calibration is of paramount importance to reach the expected high contrast of the instrument: Whether it is the non-common path aberrations to reduce the static speckles, or more classically the detectors response, a maximal number of instrumental effects are measured to minimize their influence on the final performance. The number of calibration modes of SPHERE is almost tenfold larger than the operation modes.

High contrast imagery depends very much on the ability of the adaptive optics to reach the highest possible correction on the coronagraphic focal mask. The residual error after correction is composed of a dynamic part due to atmospheric turbulence and a static part due to the presence of static aberrations. Static Aberrations will be measured and pre-compensated to reduce the persistent speckle contribution. Common path aberrations are estimated with IRDIS by phase diversity and taking the difference between two measurements using a double source at coronagraphic focal plane and at the SPHERE input focal plane. These aberrations are then subtracted out by the addition of offsets onto the deformable Mirror.

5.1. Flat Field



(a)



(b)

Figure 2: IRDIS opto-mechanical implementation (a) Global view of the SPHERE instrument (b).

An important limitation in high contrast imaging with IRDIS apart from speckle noise (Table 2) is the accuracy of flat fielding calibration with Hawaii-II-RG detectors (Figure 2a). In principle, pixel-to-pixel division by the flat field image allows to reduce significantly the noise related to pixel-to-pixel response non-uniformity. The accuracy of this procedure was evaluated on images representing the flat field observation, and a simulated object images. After this simulated flat field calibration, the average value for the flat field Noise was 1.3×10^{-3}. The residual small scale Flat Field Noise obtained by a simple flat fielding procedure will be further reduced by using different detector pixels to observe the same sky area in different exposures (dithering). In such case, the flat field noise is expected to scale down roughly with the square root of the number of different pixels (exposures) considered. In simulation a level of noise of 2.6×10^{-4} is achievable when 10x10 pixel dithering pattern is applied. The effect of the small-scale flat field noise on the detection limit is the greatest at small separation due to the high level of photon from the star host. Such calibration must be performed with a very homogenous (99%) and high radiance incandescent lamp linked to an integrating sphere through an optical fiber. Dithering of images on the Detector is performed in practice by moving the detector on a fixed dithering pattern with 100 steps that shifts the image on the detector over a10x10 pixel grid. Such a strategy applies mainly to bright stars characterized by short integration time.

Table 2: Summary of IRDIS noise sources affecting the achievable contrast

Star magnitude	Dominant Noise Sources after speckle noise
H = 4	**Flat field (close to star S < 0.3”) PSF wing Photon noise (S > 0.3”)**
H = 6	**PSF wing Photon noise**
H = 8	**RON**

In addition to this constraint, large spatial scale flat field errors also have an impact on the achievable contrast. The impact is dependant on the data processing strategy. While the impact is negligible when using angular differential Imaging (ADI), spectral differential Imaging processing (alone or combined with ADI) leads to 0.1 magnitude loss in contrast. ADI processing allows some averaging of the large spatial scales residuals but cannot be used for all observing cases.

5.2. Readout Noise

The very high dynamic range between the central star and a planetary companion requires individual integration time to be rather short (several seconds for a J < 5 star) to avoid detector saturation. On the other hand for faint stars (J ~ 8) for which saturation is less critical, integration time can not exceed ~ 1 minute (depending on position on the sky) to avoid significant image smearing on the detector because of field rotation. Readout noise for single-read out mode has been measured to 8 e- in double correlated read. As a consequence, the readout noise is a significant source of error for single readout for faint stars at larger separations.

5.3. Reducing PSF wing photon noise

The achievable contrast is also determined by the coronograph efficiency, which is very sensitive to the centering of the star and the quality of the PSF but also the alignment of its Lyot stop. The precision required in centering (star centering < 0.5 mas, pupil shift < 0.2%, pupil rotation < 0.1º) imposes both pupil and star image stabilization optics and self-calibration control loops. On coronograph PSF quality is optimized by phase diversity using measurements with IRDIS and by adaptive optics.

Although the use of a coronograph is mandatory, its drawback comes from the difficulty of locating the star center in the image plane. This information is required to be know with 0.3 mas accuracy in order to process images to the required level of contrast in particular when using ADI technique.

A dedicated calibration is foreseen using a waffle pattern on the DM and simulations have shown the feasibility of such measurement.

5.4. Calibrations for long slit spectroscopy

The requirement on the accuracy on wavelength calibration (shift) of the spectra is not highly demanding. Using dedicated simulations, we estimated that errors larger 10 nm accuracy in LRS and 1 nm accuracy in MRS would cause a significant degradation of performances. The wavelength slope also has to be measured to 2% accuracy not to cause significant degradation.

This requirement can be satisfied without highly sophisticated devices for wavelength calibration and/or performing the wavelength calibration frequently during the night. The constraints here come from the wavelength range on one side and the low resolution on the other side. Traditional spectral lamps have a much too dense set of lines that cannot be resolved by the low-resolution spectroscopy.

The planet spectral resolution is independent of the slit size and defined by the planet PSF inside the slit. Any decentering of the planet in the slit will lead to a decrease in resolution. We have shown that realistic static accuracy of 17 mas and pointing jitter of 13 mas will both lead to 5% decrease in resolution. The centering procedures implemented within SPHERE satisfy these requirements.

5.5. Calibrations devices

The instrument design was performed taking into account the requirements for a proper calibration of the instrument. A calibration arm is foreseen on the SPHERE common path [6] that will also allow to simultaneously calibrate both infrared instruments, saving a significant amount of time. The following calibration devices are located in the common path to serve IRDIS calibrations:

- FF lamp
- Point source lamp
- Laser diodes sources for wavelength calibration
- Grid of holes for the calibration of astrometric distortions
- Laser source for the measurement of the spectral resolution

The calibration of the distortion also requires a wide spectrum source for the characterization of the field distortion. This source must have an accuracy of 0.5 mas. The calibration of the ghosts requires an unresolved source covering the wavelength range, with a fluoride fiber covering the K-band. The measurement of non-common path aberrations by phase diversity requires a double source paced in the vicinity of the coronagraphic focal planes. These sources are made of photonic crystal fibers (PCF) fed by the incandescent lamp to guarantee a diffraction limited monomode spot throughout the wavelength range. The solution chosen to produce the spectral features required for the spectral calibration of the LRS and MRS modes is to use single mode distributed fiber Bragg grating laser diode. A set of 6 lines with approximately equal spectral separation has been selected.

5.6. Calibrations Procedures

A detailed calibration plan has been prepared, including the definition of the various calibration procedures, the accuracy required, the frequency, the duration, the instrument set-up, and the related software (for instrument control and data acquisition, and data reduction handling). Three classes of calibrations are considered: science calibration, technical calibration and instrument monitoring
The classification is done according to the following guidelines:

- Science and technical calibrations are taken in due time and cover the instrument setup relevant for the corresponding science observation. Such calibrations should be available on the day following the science observation in order to allow data reduction to proceed.
- Instrument monitoring calibrations are carried out routinely at a lower rate (weekly to yearly) and are concerned individual instrumental parts (e.g. detectors) whose performance is monitored over long periods of time.
- While science calibrations are generally taken at night and cover a parameter range close or

restricted to the one used in actual science observations, technical calibrations are generally (or as far as possible) carried out in daytime and cover a large or complete range of the offered instrument setups and parameters.

Table 3: Summary of calibration procedures

Science calibrations	Technical calibrations	Instrument monitoring
Astrometry	Bias/Dark	Detector readout noise
Flux calibration	Instrument Flat field	Detector gain and non-linearity
Instrument throughput	*Wavelength calibration*	Detector persistence
Atmospheric calibration	star center	Instrumental background
PSF Calibration		Dithering
Sky background		Distortion map
Zero point		*Spectral resolution*
Instrumental & telescope Polarization		Instrumental Polarization Efficiency
DBI calibrations, *extra LSS calibrations*, extra DPI calibrations		Instrumental Polarization Offsets

The science calibrations as listed in Table 3 are not the only source for astrometric and photometric calibration of the instrument. In fact, we also plan to exploit the AO data (e.g. images of differential tip tilt sensor) and a dedicated calibration device to determine the astrometric distortions. Observations of photometric standard will provide absolute photometry of the targets and a measurement of the instrument throughput. Atmospheric calibration, PSF calibration, and sky calibration are not foreseen during the standard operations (search for faint companions around bright stars) but they can be useful for selected science goals (e.g. study of spatially extended features). We also include in Table 3, calibrations dedicated to infrared polarimetry for extended object such as disks polarimetry. These procedures are described in details in [6].

The technical calibrations: Dark/bias frames will be obtained for several integration time in the range range allowed for the instrument (1.3 to 60 s). Detector FF will be obtained using the set of narrow and broadband sources to properly take into account the wavelength dependences of FF. On weekly timescales a longer procedure considering also different flux level is foreseen (neutral density filter are included in the design of the internal calibration arm for this goal) to obtain a full reconstruction of the behaviour of the detector. A subset of the FF procedure is also planned to be performed in night-time during telescope pointing, allowing us to take into account the short term (about 1 hour) temporal variations of detector FF. The wavelength calibration will be obtained at beginning and end of the night to allow taking into account thermal and mechanical variations. The field center calibration has the goal of calibrate the detector field center with respect to the CP optical axis.

The instrument monitoring calibrations are performed on regular basis (typical monthly) to check proper working of the instrument and/or update suitable parameters (expected to change slowly with time) to be used in the data reduction pipeline.

6. CONCLUSION

We have described the main instrumental calibration challenges to be addressed to reach high contrast using IRDIS coupled with an extreme AO system at the ESO VLT observatory, the solutions selected to properly handle calibration issues, and the calibration procedures. Following this calibration strategy, SPHERE-IRDIS should be able to achieve the extreme contrast required for the detection and first physical characterization of giant planets around nearby stars (At 1600 nm IRDIS is expected to reach a 5sigma contrast of ~10^{-5} at its inner working angle of 100 mas, and ~ 10^{-6} at 500 mas). The large number of required calibrations implies an effective calibration plan including the three instruments in SPHERE in order to take reasonable time in comparison with acquisition overheads. In the future ELT instruments, the added instrumental complexity will increase the calibration time and dedicated studies will need to perform to balance calibration time with scientific return.

ACKNOWLEDGEMENTS

SPHERE is an instrument designed and built by a consortium of French, German, Italian, Swiss and Dutch institutes in collaboration with ESO.

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