Infrared Differential Imager and Spectrograph for SPHERE: Performance Status with Extreme Adaptive Optics before shipment to ESO/VLT

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Abstract.

SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) is a second-generation instrument for the VLT optimized for very high-contrast imaging around bright stars. Its primary goal is the detection and characterization of new giant planets around nearby stars, together with the observation of early planetary systems and disks. The Infrared Dual Imager and Spectrograph (IRDIS), one of the SPHERE subsystems, will provide dual-band imaging in the near-infrared, among with other observing modes such as long slit spectroscopy, classical imaging and infrared polarimetry. IRDIS is able to achieve very high contrast with the help of extreme-AO turbulence compensation, coronography, exceptional image quality (including non-common-path aberrations compensation), very accurate calibration strategies (including star centring with waffle mode) and very advanced data processing. We will describe the results of performances validations performed with SPHERE. In particular we present the achievable level of contrast based on the latest experimental validations at IPAG.

Keywords: extrasolar planets, extreme AO, Coronography, High-contrast imaging, Dual-band imaging, polarimetry, long-slit spectroscopy

1. Introduction

The SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) instrument \cite{1} is being built by a wide consortium of European countries to directly detect young exoplanets down to the Jupiter mass (MJup) by reaching contrast values of $10^6$ to $10^7$ at angular separations as small as 0.15''. Similar instruments are currently being built for other telescopes, such as GPI \cite{2}(Gemini Planet Imager) for Gemini South, HiCIAO \cite{3} (High-contrast Coronographic Imager for Adaptive Optics) for Subaru. The SPHERE instrument is based on an extreme adaptive optics (AO) system (SAXO) \cite{4} and employs coronographic devices \cite{5} and differential imaging techniques for stellar diffraction suppression. It is equipped with three science channels: a differential imaging camera (IRDIS) \cite{6} an integral field spectrograph (IFS) \cite{7}, and a rapid switching polarimeter (ZIMPOL) \cite{8}. 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 \(5 \sigma\) contrast of at least \(5 \times 10^{-5}\) at 0.1" and \(5 \times 10^{-6}\) at 0.5" from the star in 1 hour integration. In such case, it is mandatory to keep errors due to instrumental effects at very low level. This has been achieved by optimizing the instrument design, by defining 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 performances achieved during the testing phases with adaptive optics. In particular, we show the achievable level of contrast in spectral differential imaging, a technique used to attenuate the speckle noise induced by the instrumental aberrations and we compare these results to end-to-end simulations of the instrument.

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 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 NIR survey mode, which, will be used for 80% of the guaranteed 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 with IRDIS (11"x11") and spectral imaging in the inner region with IFS. This allows to reduce the number of false alarms and to confirm potential detections obtained in one channel by data from the other channel, a definite 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 and medium resolution will be done in long-slit mode. Test results are also available for this mode in Vigan et al [9].

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Use Science case</th>
<th>Wavelength Bands</th>
<th>Rotator mode</th>
<th>Filters, Resolution</th>
<th>Contrast Performance (1h, SNR=3, H=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Band Imaging</td>
<td>Survey mode (H only)</td>
<td>Y,J,H,Ks bands</td>
<td>Pupil or field stabilized</td>
<td>6 pairs, R=20-30</td>
<td>(\sim 10^{-5}) at 0.1&quot; (\sim 10^{-6}) at 0.5&quot;</td>
</tr>
<tr>
<td></td>
<td>Characterization of cool outer companions</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Dual Polarimetry Imaging</td>
<td>Reflected light on extended environment</td>
<td>Y,J,H,Ks bands</td>
<td>Pupil or field stabilized</td>
<td>4 Broad 10 Narrow bands</td>
<td>(\sim 10^{-5}) at 0.1&quot; (\sim 10^{-5}) at 0.5&quot; 30% circumstellar source</td>
</tr>
<tr>
<td>Slit Spectroscopy</td>
<td>Characterization of not too faint companions</td>
<td>LRS: Y-Ks</td>
<td>Pupil stabilized</td>
<td>LRS: R=35 MRS: R=350</td>
<td>(3 \times 10^{-4}) at 0.3&quot; (10^{-5}) at 0.5&quot;</td>
</tr>
<tr>
<td>Classical Imaging</td>
<td>Environment with no spectral features</td>
<td>Y,J,H,Ks bands</td>
<td>Pupil or field stabilized</td>
<td>4 Broad 10 Narrow bands</td>
<td>(10^{-3}) at 0.1&quot; (3 \times 10^{-3}) at 0.5&quot;</td>
</tr>
</tbody>
</table>
3. IRDIS Characteristics

IRDIS spectral range runs from 950-2320 nm with an image scale of 12.25 mas per pixel consistent with Nyquist sampling at 950nm (18µm detector pixels). A FOV greater than 11" square is obtained by using two 1kx1k quadrants of a 2kx2k Hawaii 2-RG detector. The main mode of IRDIS is the dual imaging mode providing images in two neighbouring spectral channels with minimized differential aberrations. Different filter couples are used corresponding to different spectral features in exo-planet spectra. In addition to dual band imaging, long-slit spectroscopy at resolving powers of 50 and 370 is provided thanks to a zero-deviation prism and a grism, as well as a dual polarimetric imaging mode. The dual polarimetric Imaging mode provides simultaneous imaging in two orthogonal polarizations within any of the broad and narrow-band filters [10]. The instrumental polarization is greatly removed for this mode by using a rotating half wave plate near the entrance of the SPHERE instrument. A pupil-imaging mode for system diagnosis is also implemented. The detector is mounted on a two-axis translation stage to allow dithering for flat-field improvement to $10^{-3}$ accuracy and temporal interpolation of bad pixels. In the classical imaging mode, four broadband filters corresponding to the atmospheric bands Y, J, H, and K_s are provided, as well as 10 narrow-band filters corresponding to molecular features and continua. The IRDIS opto-mechanical implementation is shown on Figure 1.

Figure 1: IRDIS opto-mechanical implementation from drawings (a) and as pictured. Global view of the SPHERE instrument system from drawings (b) and as pictured without the cold tent showing IRDIS cryostat on the front outside of the enclosure.
4. Limitations for the detections and characterization of exoplanets

The mode used in survey for the detection of exoplanets is the dual-band imaging (DBI) mode, where two images are acquired simultaneously in close narrow-band filters allowing to remove most of the halo speckles. High-contrast imaging is limited by the presence of these speckles attributed to two main components: 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 (from minutes to hours) not corrected by the AO system. Different data analysis methods are used to remove the speckle residuals. The first one is simultaneous Spectral Differential Imaging (SDI) [11] for which the main limitation is the amount of differential aberrations between the two wavelength paths. Recent laboratory measurements obtained with IRDIS have shown a level of differential aberrations of 6 nm RMS making it compatible with very high contrast imaging to \(~10^{-6}\) at 0.5”. Practically, the speckle noise, in the science images, is reduced by constructing a reference stellar point spread function (PSF) in order to subtract it from the data. This reference PSF is obtained by introducing spectral diversity when acquiring simultaneous images at two close wavelengths in order to perform spectral differential imaging. The technique relies on the fact that planetary objects have large molecular absorption features in their spectrum, while the host star has a relatively flat spectrum. By taking simultaneously two images of a system at two close wavelengths located around one of these sharp features and subtracting them, the star contribution is largely attenuated, and the planet signal is revealed. SDI is most effective when used for detecting cool companions that show deep molecular absorption bands caused by H2O, CH4 and NH3 at low effective temperature. With carefully selected filter pairs, a contrast of several magnitudes on the planet flux between the two filters can be obtained.

The reference PSF can also be obtained by introducing angular diversity into the data. This technique, called angular differential imaging (ADI) [12] is performed on data acquired with a stabilized telescope pupil to increases the stability of the PSF, and to achieve higher AO performances, leading to field rotation with time as function of star elevation. This allows construct a reference PSF not including signal from planetary companions instead of getting one from off axis observations. The main limitations of this technique are the field rotation rate and the temporal evolution of the aberrations. The field rotation rate during telescope observations will range typically from 20 to 50 degrees per night. Concerning the temporal evolution of the aberration, it is expected that the derotator, which is responsible for stabilizing the telescope pupil during on sky observations, is a major contributor. We have measured during the laboratory validations that its contribution is within specifications, allowing to achieve coronographic speckle residuals smaller than \(3.10^{-3}\) when using adaptive optics and non-common path (NCPA) aberration correction.

5. Calibration strategy and laboratory validations

It is mandatory to keep instrumental effects at very low level. This has been achieved by optimizing the instrument design, by providing suitable means to calibrate such effects and by developing adequate data reduction procedures. Whether it is the non-common path aberrations, or more classically the detectors response, a large number of instrumental defects are measured to minimize their influence on the final performance with IRDIS. In the following sections, we focus on two important calibrations performed in the laboratory with adaptive optics: the non-common path aberrations calibration and compensation, and the star centre registration using waffle mode.

5.1. Phase diversity combined with DM quasi-static aberrations compensation

High contrast imagery depends very much on the ability of the adaptive optics to reach the highest possible correction on the coronographic 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. Non-common path aberrations are estimated with IRDIS by phase diversity as described in [13] and taking the difference between two measurements using a double source at coronographic focal
plane and at the SPHERE input focal plane. These aberrations are then subtracted out by the addition of offsets onto the deformable Mirror. Figure 2 shows that the correction of the non-common path aberrations by the deformable mirror allows to achieve very high Strehl ratio (> 99%). These aberrations have been calibrated beforehand using phase diversity calibration using IRDIS with a point source located at the telescope focal plane. In this case the aberrations are compensated up to IRDIS focal plane while when using a coronograph, the highest possible aberration correction will be achieved on the coronagraph to maximize its efficiency.

![Figure 2: Both illustrations show the star PSF with and without non common path aberrations compensation](image)

**5.2. Star center estimation using the DM waffle mode**

The determination of the star center is mandatory to ensure final instrument performance in particular when applying ADI techniques. Because when using a coronograph, the star center is hidden, we developed a method, based on waffle pattern introduction on the DM in closed loop to address this issue. The amplitude of waffle mode is set to 0.05% of the DM dynamic corresponding to +185nm optical deformation. This generates four satellites spots created by the waffle, which are used to compute very accurately (~ 1/10 pixel) the star position.

![Figure 3: Both images show the star PSF with (left) and without (right) the apodized Lyot coronograph while adding waffle mode with ~ 400 nm amplitude on the deformable mirror.](image)

**6. Laboratory performances for the detection of exoplanets**

During the laboratory tests we also acquired images under various conditions to estimate the achievable contrast. These images were first corrected using standard data reduction procedures: a background was subtracted from each image and these images were divided by the corresponding flat field. Both process were done using the data reduction pipeline developed for the SPHERE instrument [14]. After these steps, the frames were aligned using the star centre estimation from waffle use. Finally, the frames were combined using a median for both filters H2 (1.593 microns) and H3 (1.667 microns). The image in the H3 filter is spatially rescaled and subtracted from the image in the H2 filter, with an amplitude rescaling factor to minimize the residuals in the subtracted image. A global minimization procedure has been implemented to optimise the amplitude scaling factor, the spatial rescaling, the x and y relative shift between the two images. Figure 4 presents the detection limits obtained on the data set with the H2H3 filters. The curves represent the 5-sigma noise contrast level measured in annuli of
width \( \lambda/D \) normalized to the maximum of the PSF (Black lines). The contrast reached with the SDI procedure is \( 10^4 \) at 0.1" and \( 10^6 \) at 0.5". The tests were also performed with simulated atmospheric turbulence with two seeing values (0.62" / 0.85") and various wind speeds (from 0 to 25 m/s). The loss between the case with and without turbulence is in general below 1 mag. The use of phase screens of finite size produce only 20 completely decorrelated realizations of atmospheric turbulence. In real observations, the system will see a much larger number of decorrelated realizations of atmospheric turbulence. We conclude that current measurements obtained with turbulence in laboratory are slightly pessimistic because of the small number of independent atmospheric turbulence realizations, and that we should observe a gain of a factor 1.5-2.5 on-sky. The comparison with end-to-end simulation [14] are comforting towards full-expected performances but further tests with the complete SPHERE system at the telescope including are foreseen to predict even more accurately the level of contrast achievable on sky after the instrument is installed at the VLT.

Figure 4: 5-sigma detection limits for the spectral differential imaging (SDI) applied on H2H3 data without atmospheric turbulence and with apodized Lyot coronograph. The blue line shows the achievable contrast in SDI while the red line shows the H2 PSF with the coronograph.

7. Conclusion

The planet finding instrument SPHERE is been integrated for the ESO VLT observatory. It is currently tested by a consortium of French, German, Italian, Swiss and Dutch institutes in collaboration with ESO. We have described major results from the tests performed in the laboratory with adaptive optics and turbulence showing good agreement with expected performances. Extrapolation of the lab performance to on-sky performance lead to the conclusion that IRDIS will be able to reach, the technical specifications of \( 10^{-6} \) @ 0.2" and \( 10^{-7} \) @ 0.5" under conservative assumption on angular differential imaging thanks to very small temporal evolution of the aberration with the pupil or field derotation. These levels of performances rely upon a state-of-the-art extreme AO system and highly performing NIR focal plane unit as well as coronographs and optimized data-reduction pipeline including ADI, SDI, LOCI and Andromeda (reduced likelihood). Full instrument characterization has been performed as needed for preparing for sky observations.

Acknowledgements

SPHERE is an instrument designed and built by a consortium consisting of IPAG, MPIA, LAM, LESIA, Laboratoire Fizeau, INAF, Observatoire de Genève, ETH, NOVA, ONERA and ASTRON in collaboration with ESO. We are grateful to all the consortium members who contributed to build the IRDIS instrument and to the perform the laboratory test with the SPHERE system.
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