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 science goal is the detection and characterization of giant planets, together with observation of circumstellar environment. The infrared differential imager and spectrograph (IRDIS), one of the three science instruments for SPHERE, provides simultaneous differential imaging in the near infrared, among with long slit spectroscopy, classical imaging and infrared polarimetry. IRDIS is designed to achieve very high contrast with the help of extreme-AO (Strehl > 90%), coronography, exceptional image quality (including non-common-path aberrations compensation), very accurate calibration strategies and very advanced data processing for speckle suppression. In this paper, we report on the latest experimental characterizations of IRDIS performed with SPHERE/SAXO before the preliminary acceptance in Europe.

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

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1. INTRODUCTION

The SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) instrument[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 0.1''. Similar instruments are currently being built for other telescopes, such as GPI[2] (Gemini Planet Imager) for Gemini South, HiCIAO[3] (High-contrast Coronographic Imager for Adaptive Optics) for Subaru. The SPHERE instrument is based on an extreme adaptive optics (AO) system (SAXO)[4] and employs chronographic devices[5] and differential imaging techniques for stellar diffraction suppression. It is equipped with three science channels: a differential imaging camera (IRDIS)[5], an integral field spectrograph (IFS)[7], and a rapid switching polarimeter (ZIMPOL)[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 5σ contrast of at least 5 10^{-5} at 0.1" and 5 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].

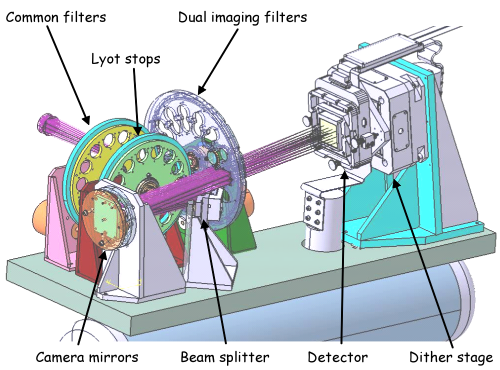
The main observing NIR survey mode, which, will be used for 80% of the guaranteed observing time, combines IRDIS dual imaging in H band with imaging spectroscopy using the IFS in the Y-J bands. This configuration permits to benefit simultaneously from the optimal capacities of both dual imaging over a large field with IRDIS 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 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 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.

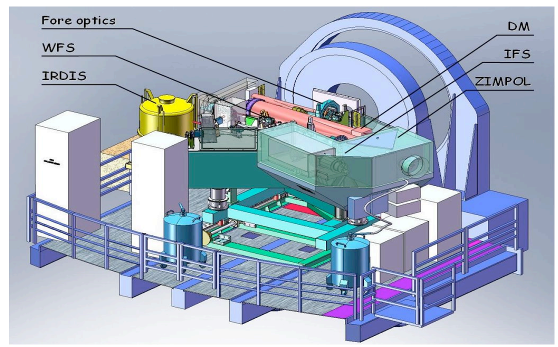
Mode	Use Science case	Wavelength Bands	Rotator mode	Filters, Resolution	Contrast Performance (1h, SNR=5, H<6)
Dual Band Imaging	Survey mode (H only) Characterization of cool outer companions	Y,J,H,Ks bands	Pupil or field stabilized	6 pairs R=20-30	~ 10^{-5} at 0.1” ~10^{-6} at 0.5”
Dual Polarimetry Imaging	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=35 MRS : R=350	~ 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. 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 35 and 323 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] .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 Ks are provided, as well as 10 narrow-band filters corresponding to molecular features and continuums. The IRDIS opto-mechanical implementation is shown on Figure 1.



(a)



(b)

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

4. LIMITATIONS FOR THE DETECTION 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 to 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 hour, leading a rotation of one pixel in few to several minutes at 0.5'' separation as shown on Figure 2.

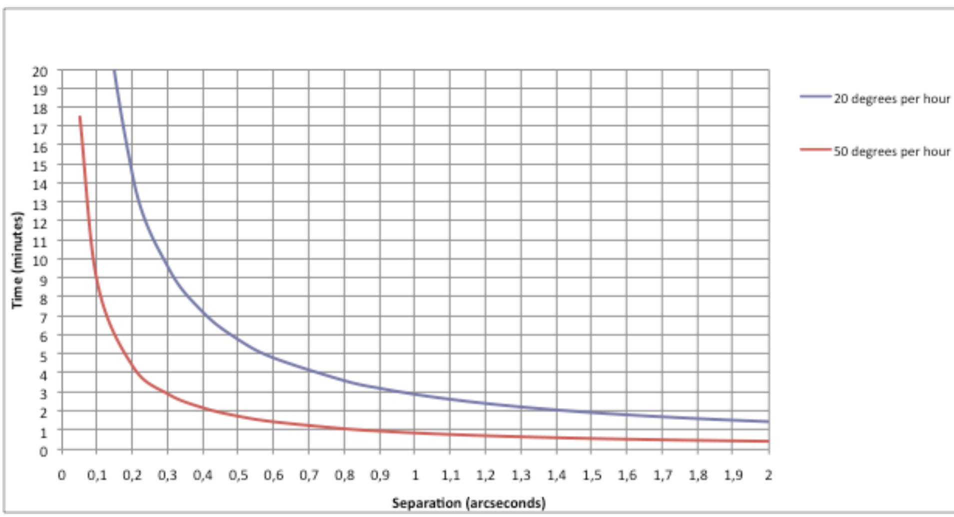


Figure 2: Time required to reach a field rotation of one pixel as function of the angular separation for 20 & 50 degree per hour field rotation rates.

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. The laboratory tests that have been performed with IRDIS in H-band without adaptive optics nor coronography show that the speckle residuals are at 1% level, leading to expected maximum speckle residuals when using coronograph <0.003. With adaptive optics and non common path (NCPA) aberration correction in addition, the speckle residuals will be even much lower. Further Tests will be performed including adaptive optics and coronography to determine the final level of performance expected when using ADI on sky but these preliminary results are already very encouraging.

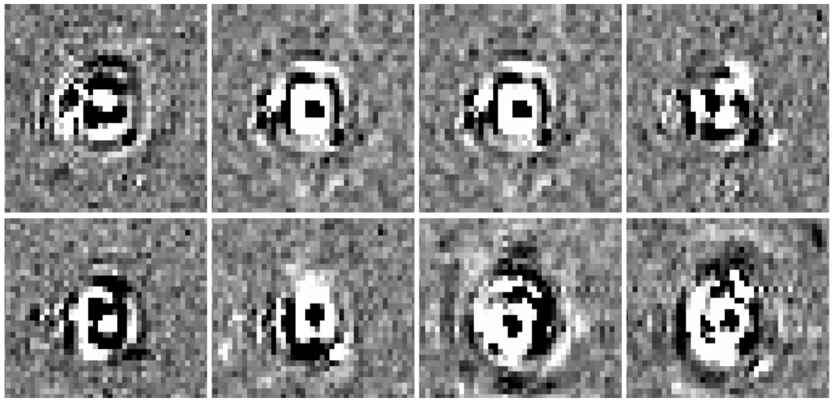


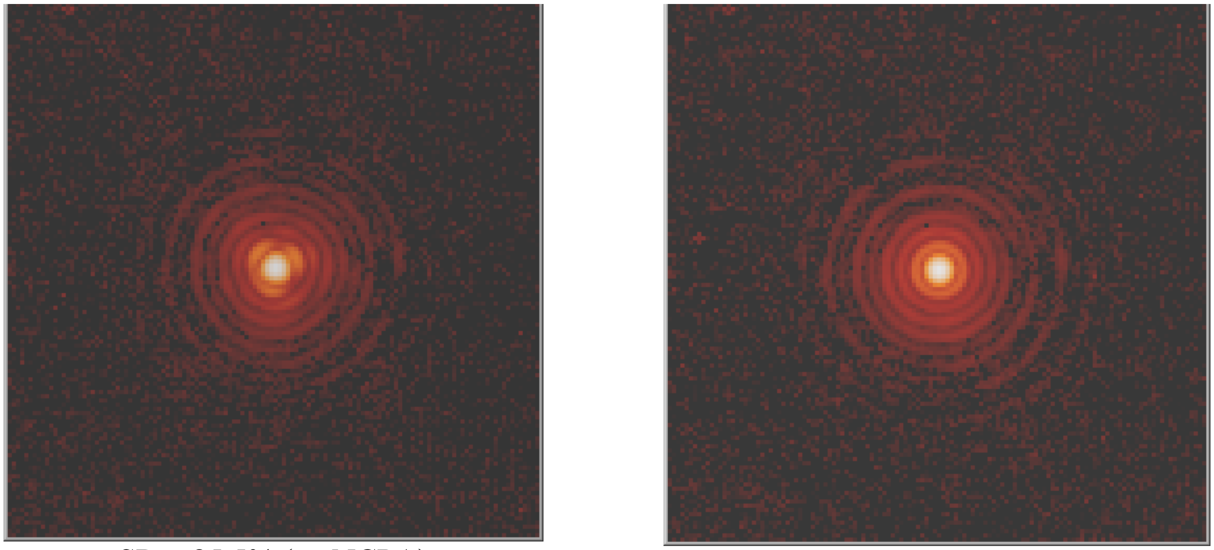
Figure 3: PSF speckle residual (taken for derotator positions ranging from 2 to 20 degrees) after subtracting the initial PSF (without derotation) at 1.6 microns.

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 very important calibrations performed in the laboratory: the non common path aberrations calibration (and compensation) and the Flat field calibration.

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 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 4 shows that the correction of the non common path aberrations by the deformable mirror allows to achieve Strehl ration of 99%. These aberrations have been calibrated beforehand using phase diversity calibration using IRDIS with a point source 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.



SR = 85.5% (no NCPA) SR = 99.0% (with NCPA)

Figure 4: Both illustrations show the star PSF with and without non common path aberrations compensation

5.2. Flat Field

Another important limitation in high contrast imaging with IRDIS apart from speckle noise is the accuracy of flat fielding calibration with Hawaii-2-RG detectors. 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 during laboratory tests using both flat field observation, and object images. After flat field calibration, the average value for the flat field noise is 6.0×10^{-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 (using detector dithering and/or field rotation). In such case, the laboratory tests showed that the flat field noise is reduced to below 1.10^{-3} scaling down faster than the square root of the number of different pixels considered. 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. Large spatial scale flat field errors also have an impact on the achievable contrast. 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.

The contrast achievable with IRDIS when using SDI+ADI has been estimated by including the estimated speckle removal efficiency and all sources of noises based on the laboratory measurements (FF, readout, photon noise) to the instrument model as shown on Figure 5. On this figure we clearly see the increase of contrast with separation as well as the impact of readout noise for fainter magnitude targets.

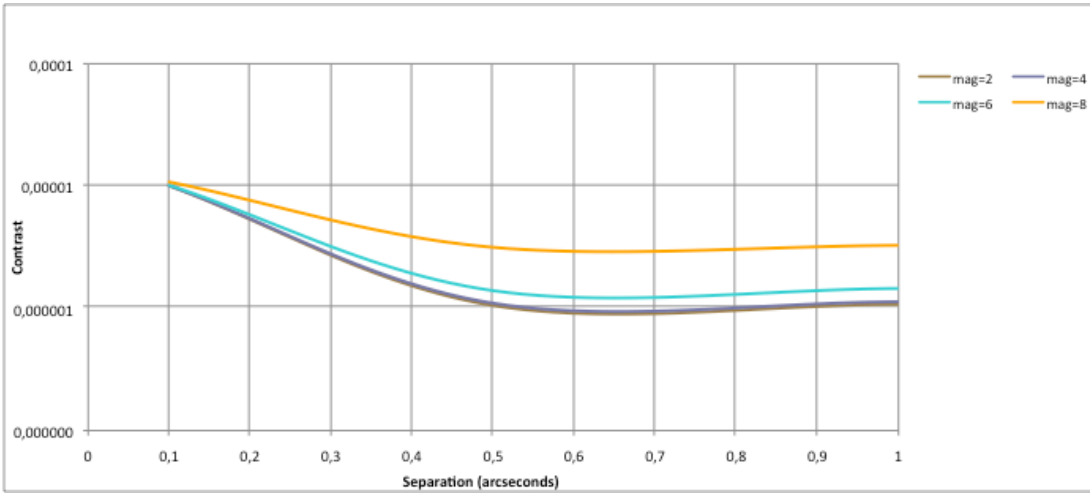


Figure 5: Expected contrast performance as function of stellar magnitude and angular separation

6. LABORATORY PERFORMANCES IN SDI FOR THE DETECTION OF EXOPLANETS WITHOUT CORONOGRAPH

During the laboratory tests we also acquired data (sequences from 10 to 20 minutes of exposure) to estimate the achievable contrast without coronograph. These images were first corrected using standard data reduction procedures: a background was subtracted from each image and these images were divided by a flat field. Both process were done using the data reduction pipeline developed for the SPHERE instrument[13]. After these steps, the frames were aligned by determining their individual center with a Gaussian fit on the peak of the PSF. Finally, the frames were combined using a median. The results are shown in Figure 6 for filters H2 (1.593 microns) and H3 (1.667 microns) (left and center). This Figure 6 also presents the result of the SDI procedure on both images (right). For SDI, 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 7 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 λ/D normalized to the maximum of the PSF (solid line). The contrast reached with the SDI procedure (dash line) is 10^{-3} at the center of the PSF and 10^{-4} at 0.15". Figure 7 also shows the result of SDI subtraction on simulated H2H3 data (dot line). We see that in the regions not limited by background noise the contrast reached with fairly long exposure time is compatible with the end to end simulation[14]. This first comparison is quite comforting towards full-expected performances but further tests with the complete SPHERE system including ADI and coronographs are foreseen to predict accurately the level of contrast achievable on sky before the instrument is shipped to the VLT.

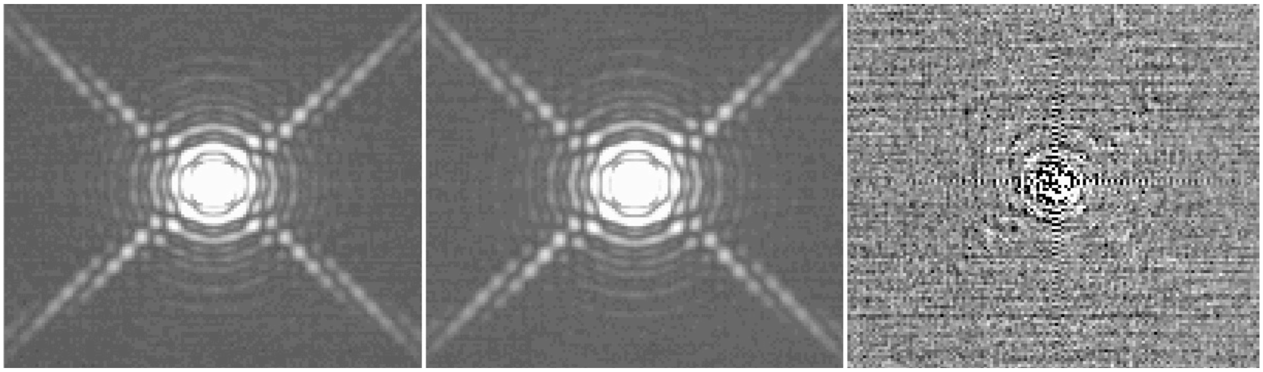


Figure 6: PSF obtained simultaneously thru H2 (Left) and H3 (Center) filters. The PSF residual (Right) obtained after spectral differential imaging.

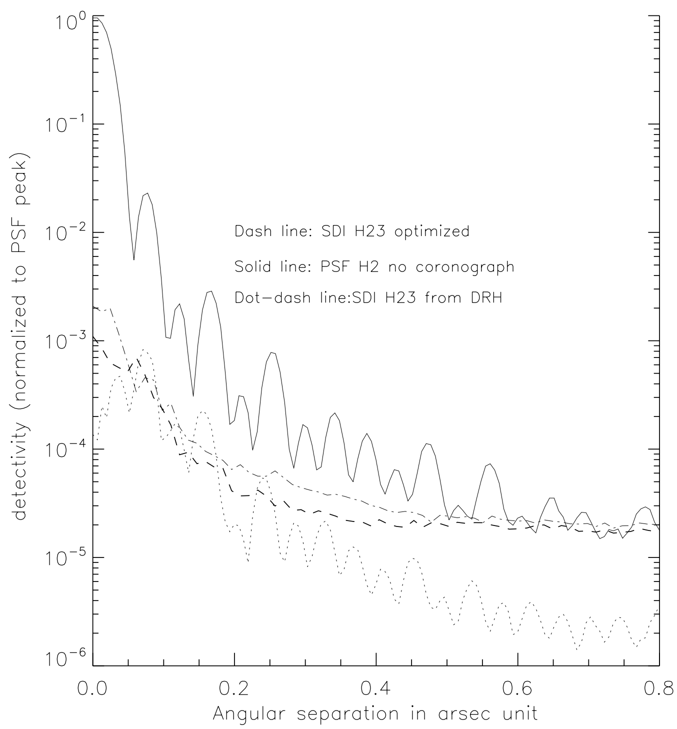


Figure 7: 5-sigma detection limits for the SDI applied on H2H3 data without coronograph. The Dash line shows the achievable contrast while the solid line shows the H2 PSF.

7. CONCLUSION

The planet finding instrument SPHERE been conceived for the ESO VLT observatory and is being tested since the beginning of 2012 in Grenoble. We have described here first laboratory test results of the IRDIS DBI mode in a non-coronagraphic setup in H-band. With this setup, we reach a SDI contrast of 10^{-4} at 0.15'' for a total exposure time of 15 minutes, showing good agreement with expected performances. The SDI procedure uses global optimization to reach optimal subtraction of the images taken in the two channels. We also showed that the temporal evolution of the aberration is small enough to allow very good ADI performances.
The final IRDIS performances will be soon tested with all its features together including state-of-the-art extreme AO system, highly performing NIR focal plane unit as well as optimized coronography and data-reduction pipeline including ADI, SDI, LOCI and Andromeda (reduced likelihood) in order to achieve the full instrument characterization needed for preparing on sky observations.

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