Calibration and data reduction for planet detection with SPHERE-IFS

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ABSTRACT

The 2nd generation VLT instrument SPHERE will include an integral field spectrograph to enhance the capabilities of detection of planetary companions close to bright stars. SPHERE-IFS is foreseen to work in near IR (0.95-1.65 micron) at low spectral resolution. This paper describes the observing strategies, the adopted hardware solutions for calibrating the instrument, and the data reduction procedures that are mandatory for the achievement of the extreme contrast performances for which the instrument is designed.

Keywords: Techniques: spectroscopic, Techniques: image processing, Techniques: high angular resolution, Methods: data analysis, Instrumentation: spectrographs, Instrumentation: high angular resolution, Instrumentation: detectors, Atmospheric effects

1. INTRODUCTION

The VLT Planet Finder SPHERE is designed with the primary science goal to image and characterize extra-solar planets around nearby stars.[1] In order to overcome the brightness contrast and the speckle noise, the instrument concept consists in a high-order AO+Coronagraph system[2,3] feeding three instruments optimized for Simultaneous Differential Imaging (SDI): an integral field spectrograph (IFS)[4,5,6] a differential imager (IRDIS),[7] and a differential polarimeter (ZIMPOL).[8]

Integral field spectroscopy is a very promising tool for the identification of high-contrast companions and can provide significant gain with respect to differential imagers equipped with narrow band filters, because the use of several wavelengths allows a better reconstruction and removal of the speckle pattern. IFS has also the additional advantage of working on several spectral features and in being sensitive to a variety of companions spectra. Furthermore, it might allow the reconstruction of the spectrum of a detected faint companions, then providing more physical information than simply a flux difference in two or three adiacent narrow bands.

Indeed first tests using SINFONI, an integral field spectrograph that is not optimized for high-contrast imaging, provided promising results.[9] Simulations of SPHERE IFS[10] confirm the detectability of faint companions close to bright stars, with contrast down to about 17 mag at 0.5 arcsec. For the achievement of such extreme performances, it is mandatory to keep errors due to instrumental effects at very low level. This can be achieved

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by optimizing the instrument design, by providing suitable tools to calibrate such effects and by developing adequate data reduction procedures.

The most relevant instrumental calibration issues for SPHERE-IFS are described in Sect. 2. Sect. 3 presents the adopted solution to ensure proper calibrations and Sect. 4 summarizes the calibration plan of SPHERE-IFS. Sect. 5 briefly describes the data reduction and analysis procedures to identify faint companions (planets) and characterize them. Sect. 6 summarizes our conclusion.

2. CALIBRATION ISSUES FOR SPHERE-IFS

2.1 Readout noise

The very high dynamic range between the central star and a planetary companion will force individual integration time to be rather short (few sesconds for a $J < 4$ star) to avoid detector saturation. On the other hand for faint stars ($J \sim 8$) 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 is expected to be about 18 e-; therefore with such a configuration readout noise might be the dominant source of error for single readout for faint stars. The solution adopted to reduce readout noise is that of Fowler readout, that should allow readout noise as low as for the single-read out mode, divided by the square root of the number of non destructive read outs.[11] This should allow to reduce read out noise to ~ 5 e-.

2.2 Flat fielding

An important possible limitation in high contrast imaging with SPHERE is the accuracy of flat fielding possible with Hawaii-II-RG detectors. To set appropriate values to the contribution of flat fielding to the total error budget, we analyzed real data. To this purpose, we have received from ESO (courtesy of G. Finger) two series, each one composed of 74 background subtracted flat field images taken with the HAWK-I IR mosaic. The Hawk-I mosaic is made of 4 2kx2k Hawaii-II-RG detectors, making up a total of 4kx4k. The first sequence of 74 DITs was taken between 19:37:22 and 19:42:01 of Dec. 12, 2006. The second sequence was taken between 7:02:25 and 7:07:12 of Dec 13, 2006. So the two sequences were taken at 11.5 hr difference, well matching beginning and end of a long observing night. Each series required about 5 minutes. Note that exposure level was rather low (< 0.1 times the saturation level of the detectors), so that a similar S/N could be obtained in a much shorter time or alternatively, a much higher S/N can be obtained within the same time. From these data, we made an analysis considering the 74 flat field images of 36 areas of 100x100 pixels close to the centers of each array of the mosaic.

From the observed rms pixel to pixel scatter within each 100x100 pixel area, we derived, taking into account photon noise and readout noise, the pixel-to-pixel response not uniformity (PRNU), which contribution is expected to be proportional to the signal. The contribution of PRNU was then obtained by the quadratic difference of the r.m.s. pixel-to-pixel scatter and the quadratic sum of photon noise and RON. The PRNU value was then obtained by dividing this contribution for the average signal. The average value of the PRNU (over 100x100 pixel areas) we obtained is 0.022. This is about twice the PRNU value between adjacent pixels obtained by[11] for Hawaii II-RG detectors: this difference can be attributed to the presence of large scale slopes with typical values of a few 10^{-4} pixel^{-1}.

2.2.1 Noise after flat fielding

In principle, pixel-to-pixel division for the flat field image should allow to eliminate, or at least reduce significantly the noise related to PRNU. To test the accuracy of this procedure we assumed that the first set of 74 images represented the flat field observation, and the second set represented the object image. We computed the two median images, and divided them for each other. We then assumed that the pixel-to-pixel scatter in the resulting (flat-fielded) images is due to quadratic sum of two terms:

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[*] Derotation within SPHERE instrument is possible but the best performances in term of contrast are expected to be achieved in pupil-stabilized mode.

1. The combination of photon and read out noise in the median images: we will assume that this is given by the noise due to these sources in each of the original images, divided by the square root of the number of exposures used.

2. The residual flat field noise, not properly corrected using our procedure.

The average value we obtain for the Flat Field Noise is 1.27×10^{-3}. This value of the Flat Field noise should be compared with the SPHERE Technical Specifications for IFS: FF accuracy: 5×10^{-4} (goal 10^{-4}). The average value we obtain for the Flat Field Noise is out of both Specification and Goal for IFS.

2.2.2 Noise after application of the dithering procedure

Since it was expected that the Flat Field Noise obtained by a simple flat fielding procedure should not be within specifications, IFS has been designed in order to overcome this problem (see Sect 3.3). In fact, we expect that if different detector pixels are used to observe the same sky area in different exposures (dithering), the contribution due to flat field noise to the total error should scale down roughly with the square root of the number of different pixels (exposures) considered. To simulate a dithering process in the analysis of the data provided by ESO, we averaged the images in 10x10 pixel bins. The bins were disjointed, to maintain statistic significance. We assumed that the pixel-to-pixel scatter in these binned images is due to quadratic sum of two terms: (i) The combination of photon and read out noise in the binned images: we will assume that this is given by the noise due to these sources in each of the original images, divided by the square root of the number of exposures used (that is 74), and further divided by the square root of the number of dithering step (i.e. 10x10=100). (ii) The residual flat field noise, not properly corrected using our procedure. Adopting the dithering procedure, the flat field noise can be reduced to values of about 2.6×10^{-4}. Even if the gain obtained by using the dithering procedure is actually less than the ideal square root of the number of dithering steps (about 5 rather than 10), it is still substantial. By adopting a similar dithering procedure, the Flat Field noise can be within the value given by the Technical Specifications, and actually midway between Top Level requirements and Goal for IFS.

2.2.3 Additional effects

Results presented in the previous subsection represent a lower limit to noise introduced by the flat fielding procedure. The value that will be actually achieved depends on the number of photons cumulated in the flat field observations, as well as on various second order effects not consider in these tests (chromaticity, not linearity, lack of reciprocity, persistence of images after saturation). These effects are taken into account in detail in the IFS calibration procedures.

2.3 Wavelength calibration

The requirement on the accuracy on wavelength calibration of the spectra is not highly demanding. Using dedicated simulations, we estimated that errors larger than 0.2 pixel on the detector, corresponding to about 0.002 μm, would cause a significant degradation of performances on speckle subtraction because of the errors on wavelength scaling. This requirement can be satified without the need of thermalizing the instrument and/or providing highly sophisticated devices for wavelength calibration and/or performing the wavelength calibration frequently during the night. However, emission-line lamp spectra usually adopted for wavelength calibration resulted not suitable for SPHERE IFS, because of line blending at the very low resolution of the instrument (34 for the YJH set-up, 54 for the YJ set-up). Therefore, the adopted solution for the wavelength calibration is a Fabry Perot etalon illuminated by a black body source. It provides 4 and 6 regularly spaced “lines” for the YJ and YJH set-up respectively.

2.4 Cross talk

Signal in one pixel depends on signal on close pixels due to cross talk. Cross Talk is caused by various mechanisms:

- Cross talk between adjacent pixels at the detector level, at the level of a few 10^{-2}.

- Incoherent cross talk: the instrumental PSF causes a broadening of the images. The effect is small (a few 10^{-4}), due to exceedingly good optical quality of IFS

- Coherent cross talk: in IFS, interference between adjacent lenses causes a coherent signal, of the order of a few 10^{-3}

In IFS the two first effects may be considered together, as a (very small) degradation of the PSF. Coherent cross talk is very difficult to handle properly, as it depends on illumination (i.e. speckles) and wavelength. Therefore the adopted choice was to optimize the IFS design to minimize the coherent cross-talk. An innovative design for integral field unit (IFU), called BIGRE, was developed for this purpose.[12] With this design, cross talk is expected to have a negligible effect. Therefore no dedicated calibration device and calibration procedure are foreseen to measure and correct it.

3. CALIBRATION DEVICES

The instrument design was performed taking into account the requirements for a proper calibration of the instrument. Two calibration arms are foreseen: a calibration arm internal to IFS, to provide illumination of the instrument after the lenslet array and a calibration arm on the SPHERE common path (CP), that provides illumination of the IFS through the lenslet array. This will also allow to take calibration frames simultaneously to IRDIS, saving a significant amount of time. Furthermore, there is possibility of moving part of the IFS camera to shift the spectra on the detector. This is required to reduce the FF errors and keep them within specifications, as discussed in Sect. 2.2. Finally, on-sky calibrations will also be performed for a few selected goals.

3.1 IFS internal calibration arm

Illumination of the whole IFS detector (to perform detector FF calibration) requires a dedicated source after the lenslet array or illumination from the common path moving the lenslet array out of the optical path. The first solution was adopted, avoiding the need of high-accuracy repositioning of the lenslet array.

The IFS internal calibration arm is composed of an integrating sphere, a flat folding mirror placed before the IFS collimator and mounted on a motorized slide (which allows to select light either from the lenslet array or from the integrating sphere), and a motorized wheel mounting a number of neutral density filters. Five lamp/filter combinations feed the integrating sphere, one white light and four narrow band (λ_c = 1.0, 1.2,1.3 and 1.5 μm, FWHM about 0.01-0.04 μm); these last will be used to properly calibrate the dependence of detector FF on wavelength.

3.2 CP calibration arm

The following calibration devices are located in the common path to serve IFS calibrations:

- FF lamp
- Point source lamp
- Fabry Perot etalon + black body lamp for wavelength calibration (see Sect. 2.3)
- Grid of holes for the calibration of astrometric distortions
- Laser source for the measurement of the spectral resolution (the line produced by the Fabry-Perot etalon are not fully adequate to this task)

Additional sources for calibrations of the CP, IRDIS and ZIMPOL are included in the design but not discussed here.

3.3 Dithering

Dithering of images on the IFS Detector is required to keep the noise below the Flat Fielding Technical Specification. From the opto-machanical point of view, the easiest solutions is obtained by moving the warm Camera optics. This is easier than to move the detector (which requires a cryo movement) and the whole dewar (that is much bigger and heavier than the camera optics). The needed amount of dithering on the Detector pixels is ± 90 μm; this quantity is reflected directly on the amount of Camera shifts along the XY plane, without any magnification/de-magnification factor.

In practice we foresee a fixed dithering pattern with 100 steps that shifts the spectra on the detector over a 10x10 pixel grid. Such a strategy applies to bright stars characterized by short integration time (less than a few sec.) and for which FF errors would exceed photon noise without a suitable dithering strategy. For fainter stars, for which longer integration time are foreseen, a pattern with a smaller number of dithering steps is considered, to keep the whole dithering cycle within 15 minutes.

4. CALIBRATION PROCEDURES

A detailed calibration plan is being prepared, including the definition of the various calibration procedures, the accuracy required, the frequency, the duration, the instrument set-up, and the related software (both at instrument control and data acquisition[13] and data handling and reduction level[14]). 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. All such calibrations should be available on the day following the science observation in order to allow data reduction to begin
- Instrument monitoring calibrations are carried out routinely at a lower rate (weekly to yearly) and are basically concerned with individual instrumental parts (e.g. detectors) whose performance and "health" is monitored hereby over long periods of time. They are useful for instrument monitoring, and not only for the science data reduction.
- 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.

4.1 Science calibrations

Table 1 lists the foreseen science calibrations. The listed on-sky calibrations 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 spectrophotometric 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).

4.2 Technical calibrations

Table 2 lists the foreseen science 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 broad band sources of the IFS internal calibration arm to properly take into account the wavelength dependence 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 recostruction of the behaviour of the detector. A subset of the FF procedure is also planned to be performed in nighttime during telescope pointing, allowing us to take into account the short term (about 1 hour) temporal variations of detector FF. IFS FF will be obtained illuminating IFS with the CP FF lamp. This calibration will be used to

Table 1. Science calibrations for SPHERE-IFS

IFS Astrometry	Observe binaries or clusters
IFS Flux Calibration	Observe binaries
Instrument throughput	Observe spectrophotometric standards
Atmospheric calibration	Observe G or earlier type stars
PSF calibration	Observe PSF Reference star
Sky background	Observe a black field

define the location of the spectra on the detector and to remove the lenslet-to-lenslet sensitivity variations. The wavelength calibration will be obtained at beginning and end of the night to allow to take 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.

Table 2. Technical calibrations for SPHERE-IFS

Bias/Dark	Acquire dark/bias frames
Detector FF	Acquire detector FF frames
IFS FF	Acquire CP FF frames
Wavelength calibration	Acquire wavelength calibration frames
Field center	Acquire CP FF frames + dedicated device

4.3 Instrument monitoring

Table 3 lists the foreseen instrument monitoring calibrations. They are performed on regular basis (typically monthly) to check the proper working of the instrument and/or update suitable parameters (expected to change only slowly with time) to be used in the data reduction pipeline. Camera focus should be adjusted dayly; the calibration will be likely performed at lower rate once a suitable model of focus position vs temperature will be built.

Table 3. Instrument monitoring calibrations for SPHERE-IFS

Detector RON	Acquire bias frames
Detector gain and non linearity	Acquire detecor FF frames
Detector persistence	Acquire frames after saturation
Instrumental background	Acquire deep dark frames
Camera focus	Acquire frames with laser source
Dithering	Acquire wavelength calibration frames for all dithering positions
Ghost calibrations	Acquire deep frames with point source lamp
Distortion map	Acquire frames with dedicated grid
Pupil alignement	Acquire pupil images using dedicated CP lens
IFS sky flat	Acquire sky flats
IFS spectral resolution	Acquire spectra of the laser lamp

5. DATA PROCESSING

Data processing of the NIR SPHERE instruments (IFS and IRDIS) can be substantially divided in two parts:

1. Extraction of data cube ($x - y - \lambda$) from raw data (IRDIS: 2λ layers; IFS 25λ layers): this part basically includes removal of the instrument signature
2. Extraction of planet signal from the data cube

We define the first part as data reduction and the second one as data analysis. A general overview of the SPHERE data reduction and handling system is presented in.[14]

5.1 Data reduction

Schematically, the data reduction procedure on science images will exploits several calibration frames or calibration maps built from the calibration images taken as part of the calibration plan. These will be applied to the science frames. The following calibration maps are foreseen:

- **Masterdark/bias**
  A series of dark images characterized by different DITs and readout modes will be obtained.
- **Hot/bad pixel map**
  A map and hot and bad pixel will be build from dark and FF calibration frames
- **FF map**
  In IFS, accurate FF that takes into account the wavelength dependence can be obtained by comparing the signal on a pixel with that obtained by interpolating within a grid of 3-4 narrow-band signals for the same pixel obtained using the IFS internal FF lamp. This requires previous knowledge of the wavelength appropriate for that pixel. This is obtained from a map, which attributes to each pixel an index corresponding to the appropriate lenslet, and a wavelength. This map is the output of the wavelength calibration procedure. On the other hand, the building of the wavelength calibration map from the position of the "lines" on the detector requires a proper FF correction on the wavelength calibration frames. In practice, a short iterative procedure is required.
- **Wavelength calibration map**
  The spectra of the Fabry-Perot etalon produce a few (4-6 depending on the instrument set-up) isolated, rather narrow, "lines", that are suitable for the wavelength calibration. Polynomial fitting will be performed on wavelegth calibration images to derive the wavelength solution for each pixel (wavelength calibration map), iterating with the FF determination as discussed above.
- **IFU FF map**
  Lenslet-to-lenslet transmission variations (IFU FF map) will be obtained from images obtained using the CP white lamp.

The processing on science images will include the following:

- **Removal of hot/bad pixel and cosmic ray hits**
  Removal of hot/bad pixel and cosmic ray hits will be performed using the maps derived from calibration frames and suitable frame-to-frame comperison
- **Subtraction of dark/bias**
  Subtraction of the dark/bias pattern will be performed taking into account the individual DIT and readout mode of the science frames.

- **Spectrum location**
  Each frame is acquired at a (pre-defined) dithering position. Therefore, spectra appear at different locations on the detector. The accuracy of the dithering position as derived from encoder positions (stored in the FITS header) is about 4 μm, i.e. 0.2 pixel. This is enough to avoid any ambiguity on the identification of the spectra (to which lenslet they belong) but much better sub-pixel accuracies can be derived by measuring the position of the spectra on the detector using e.g. cross-correlation. In this way it will be possible to build a "Spectrum Location Map", giving the location of the spectra provided by individual lenslet on the detector and associating each pixel to an individual lenslet

- **Applying detector FF correction**
  The FF map will be applied to each science frames taking into account the wavelength of individual pixels. When applying the FF map, shifts of spectra due to dithering must be taken into account. The coordinate offsets due to dithering should then be determined before FF calibration procedure.

- **IFS FF**
  Lenslet-to-lenslet transmission variations will then be removed by comparing the signal in each pixel with the relative efficiency of the corresponding lenslet. This is done exploiting the lenslet index appropriate to that pixel, produced by the wavelength calibration procedure, and the relative transmission value for that lenslet stored in the IFU FF map. When applying this step, shifts of spectra due to dithering must be taken into account.

- **Spectrum extraction**
  For each spectrum, data are summed over rows (if dispersion is along column), producing an uni-dimensional spectrum corresponding to each lenslet. We will call these spectra "raw spectra"

- **Wavelength calibration**
  Wavelength calibration will be applied to raw spectra obtaining wavelength calibrated spectra

- **Applying distortion maps**
  Distortion affects differential imaging in two ways:
  - Scaling of monochromatic images to a reference wavelength can be incorrect, resulting in not perfect speckle subtraction
  - Astrometric positions may be incorrect

  The first effect needs appropriate remapping of images to a linear scale. In IFS this should be done on the data-cube. This effect of distortion is expected to be small, but requires appropriate simulations. The second effect can be corrected a posteriori, on the extracted physical data.

- **Frame combination**
  In IFS, images are generally taken with the IFS fixed with respect to the pupil. Therefore, during an exposure, the sky field will rotate with respect to the IFS. To extract the planet signal, each monochromatic image (x-y slice of the data-cube) should be de-rotated, so that the planet signal should fall always on the same pixel, before individual DITs are combined. All monochromatic images (x-y slice of the data-cube) should be rotated by the same amount See[15] for additional details.

5.2 DATA ANALYSIS AND SEARCH FOR PLANETS

There are two main ways to examine the data cube for extracting planet signal:

1. Compare various $\rho-\theta$ slices of the data cube (at constant wavelength λ), in a way similar to that considered for standard differential imaging, but with multiple wavelength images (Planet detection)

2. Compare various $\rho - \lambda$ slices of the data cube (at constant θ), in a way similar to that considered by[9] (Spectrum determination, once the location of planet has been determined).

5.2.1 Planet detection

The basic concept of differential imaging is to exploit the fact that while the stellar spectrum is quite flat in the range of interest (and can however be determined accurately using all the spectra provided by those space pixels where there is no planetary signal), the planetary spectrum has a strong variation with wavelengths: these features are very strong in the near-IR spectrum of giant planets of the Solar system, as well as cool objects, where strong methane bands are present.

From the raw data we generate a set of monochromatic images, one for every pixel of every single spectra. These data can be used to implement a differential imaging procedure that allows detection of planets. The procedure we devise is as follows:

1. Images are divided into two groups: planetary images (that is images at wavelengths where the planet signal is present), and reference images (that is images at wavelengths where the planet signal is very weak or absent).
2. We may then distinguish two cases:
    - Single Differences
        - A reference image is assigned to each planetary image
        - For each pair, the reference image is spatially scaled according to the wavelength ratio between the wavelengths of planetary and reference image
        - The scaled reference image is subtracted from the planetary image
    - Double Differences
        - two reference images are assigned to each planetary image, one with wavelengths respectively shorter and longer than that of the planetary image.
        - For each tern, the reference images are spatially scaled according to the wavelength ratio between the wavelengths of planetary and reference images
        - The three images are combined according to the double difference formula of[16]
    - The procedure at step 2 should eliminate most of the speckle pattern. If the pairs are selected so that the planet image is present only in one of the two images, the planet image will not be canceled out
3. A weighted average of the cleaned differential images will provide the best final image to be used for planet search. Note that since the planetary images are not scaled, the planet position will not shift with wavelength.

There are two critical issues in this procedure:

- This procedure requires interpolations to be made, while scaling images. The number of interpolations to be made is effectively reduced to only one per pair (two per tern when using the double difference approach). These interpolations introduce some numerical noise (which should be reduced by the square root of the number of independent pairs that are created). Various interpolation routines may be tested; we have actually tried FREBIN, CONGRID, and a special routine written by us which performs cubic spline interpolation in two dimensions, based on the one-dimensional SPLINE IDL routine applied to the two dimensions consecutively. This last seems to produce best results.
- Pairing of monochromatic images, and the optimal weights should be given according to the noise model. If errors are dominated by photon noise, the best procedure should be to give the same weights to all pairs. In this case pairs should be selected in order to have similar (or even constant) wavelength separation. If errors are dominated by calibration errors (speckle residuals) the best procedure in single differential imaging is to create pairs having the smallest possible wavelength separation, compatible with the gradients present in the planetary spectra; in this case weights should be assigned according to the inverse of the square of wavelength separation

For what concern double differences, this last approach is limited by the intrinsic width of the emission peaks in the planetary spectrum. Practically, we expect very small advantage by creating terns with the smallest possible wavelength differences; it should then be more advantageous to have various terns with the same wavelength difference, and give the same weight to all of them.

5.2.2 Spectrum extraction

Spectra can be extracted from the data cube using e.g. the algorithm described by.[9] The principle of this method is that speckles are expected to change smoothly with wavelength. Speckle images at different wavelengths will essentially overlaps, after appropriate radial scaling of the monochromatic images proportionally to the wavelength λ. In first approximation this scaling produces a roughly constant speckle pattern as a function of wavelength, where the small residual variations with wavelength can be obtained by interpolation. The method to work properly, it should be possible to clean the image from the planet image. In the scaled images, the radial location of the planet images changes proportionally to wavelength. Outside the bifurcation point, speckle pattern at a given wavelength can be reconstructed (and eliminated) using regions unaffected by the planet image. Inside the bifurcation point a (less reliable) iterative procedure is required, which makes some assumption about the shape of the speckle pattern to be subtracted. The radial coordinate r of the bifurcation point is given by:

$$r = 2\epsilon 1.22(\lambda_0/D)\frac{\lambda_1}{\lambda_2 - \lambda_1} \tag{1}$$

where λ_1 and λ_2 are the minimum and maximum wavelength of the IFS spectra (0.95 and 1.35 μm), λ_0 an intermediate value, D the telescope diameter, and ϵ a suitable parameter related to the "inclination" of the spectra of the planet within the data cube in the scaled images: $\epsilon = 1$ corresponds to the situation in which at a given scaled radial distance, there is no spectral region clean from the planet image (but just so). If $\epsilon > 1$ there is some part of the scaled image free from the planet signature, that can be used to reconstruct the speckle profile. The bifurcation point for the SPHERE-IFS is at about 222 mas (for $\epsilon = 1.1$) or 242 mas (for $\epsilon = 1.2$). from field centre, which corresponds to about 7-8 λ/D. This is only slightly larger than the radius of the central mask of the Coronagraph. This procedure can then be safely applied over most of the field of view of the SPHERE-IFS.

6. SUMMARY

We have described the main instrumental calibration challenges to be addressed to achieve detectability of giant planets using a low-resolution near-infrared integral field spectrograph coupled with an exttrme AO system at a 8m-class telescope, the solution adopted in the instrument design to properly handle calibration issues, the calibration and data processing procedures. The design of SPHERE-IFS appear the capability to achieve the extreme contrast required for the detection and first physical characterization of giant planets around nearby stars.

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