THE SPHERE IFS AT WORK

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ABSTRACT

SPHERE is an extrasolar planet imager whose goal is to detect giant extrasolar planets in the vicinity of bright stars and to characterize them through spectroscopic and polarimetric observations. It is a complete system with a core made of an extreme-Adaptive Optics (AO) turbulence correction, a pupil tracker and NIR and Visible coronagraph devices. At its back end, a differential dual imaging camera and an integral field spectrograph (IFS) work in the Near Infrared (NIR) (0.95 $\leq\lambda\leq$2.32 μm) and a high resolution polarization camera covers the visible (0.6 $\leq\lambda\leq$0.9 μm). The IFS is a low resolution spectrograph (R~50) operates in the near IR (0.95$\leq\lambda\leq$1.6 μm), an ideal wavelength range for the detection of planetary features, over a field of view of about 1.7 x 1.7 square arcsecs. Form spectra it is possible to reconstruct monochromatic images with high contrast (10^{-7}) and high spatial resolution, well inside the star PSF. In this paper we describe the IFS, its calibration and the results of several performance which IFS underwent. Furthermore, using the IFS characteristics we give a forecast on the planetary detection rate.
Keywords: Instrumentation, Extrasolar Planets, High Contrast Imaging, Integral Field Spectrograph

1. INTRODUCTION

During the last few years, direct imaging of exoplanets from the ground has provided breakthrough results thanks to the commissioning of new-generation instruments. The SEEDS survey conducted with HiCIAO[1] on the Subaru telescope allowed the detection of two planetary-mass companions to κ And[2] and GJ 504[3]. For the latter, strong absorptions of methane were revealed[4]. Data analyses on the first years of this 5-year survey (120 nights) were published[(5,6,7)], which suggest that massive planets in debris disks similar to β Pictoris b[8] are rare and that the majority of the imaged planetary-mass companions formed in the same way as brown dwarfs. Project 1640[9] at Palomar Observatory started a survey of 99 nights over 3 years late 2012, and obtained near-infrared (~1-2 μm) photometric and spectroscopic measurements of young brown dwarfs and giant planets[(10,11)]. The adaptive optics facility of the Large Binocular Telescope[12] and the LMIRCam instrument[13] are employed for a survey of ~100 nights, which started in 2013 for a duration of 3--4 years[14] and allowed multi-wavelength photometry in the L band[(15,16)] (3-4 μm) of the four planets of HR 8799[(17,18)] and M-band photometry of κ And b[19]. The MagAO system on the Magellan telescope was commissioned late 2012[20]. This instrument feeds two science cameras, VisAO in the visible and Clio2 in the near-infrared. A planetary-mass companion to HD

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106906 was detected with the near-infrared camera[21]. Visible observations allowed the confirmation of the low-mass stellar companion discovered by Biller et al. (2012)[22] in the gap of the transitional disk of HD 142527[23] and provided the first ground-based visible ($\lambda \leq 0.985$ μm) image of an exoplanet[24]. A survey to search for giant accreting protoplanets in the gaps of transitional disks has recently started[23]. The Gemini Planet Imager saw its first light at the Gemini South telescope in November 2013 and achieved H-band Strehl ratios of ~0.9 and 5σ contrasts of 10^5—10^6 at separations of 0.35-0.75"[25]. Data analyses of commissioning observations of β Pictoris b[8] and HD 95086 b[26,27,28] were published[25,29].

Finally, after crossing the ocean in February 2014, SPHERE[30] (Spectro-Polarimetric High-contrast Exoplanets Research) was reintegrated and tested at Paranal and now is mounted at the nasmyth focus of UT3 where it had its first light in May 2014. SPHERE is made of four subsystems: the Common Path Optics and three science channels, a differential imaging camera (IRDIS)[31], an Integral Field Spectrograph (IFS), and a visible imaging polarimeter (ZIMPOL)[32]. The Common Path includes pupil stabilizing fore optics (tip-tilt and derotator), the SAXO[33] extreme adaptive optics system with a visible wavefront sensor, and NIR coronagraphic devices in order to feed IRDIS and IFS with highly stable coronagraphic images. IFS explores the stellar neighborhood in order to find planetary spectral features. This quest is conducted searching for strong CH_4 absorption bands in both the stellar light reflected by gaseous Jupiter-like planets and in thermal emission from young-warm planets. Moreover it will be possible to have a first order characterization of the low mass companion itself. Additional science topics addressed by SPHERE include the study of protoplanetary discs, brown dwarfs, evolved massive stars and Solar System and extragalactic science.

The first commissioning run occurred mid May 2014.

2. IFS OVERVIEW

The heart of IFS[34] is a new kind of lens-based IFU called BIGRE[35] that is depicted in the inset of Figure 1. BIGRE is built as a double face lenselet array in which the second lenslet array allows formation of pseudo-slit images corresponding to very small portions of the field, which are then imaged on the detector after being dispersed. The array is made by 150 × 150 lenslets with 161.5 μm pitch allowing a FoV of 1.77" × 1.77". Specifically, BIGRE is placed at the interface of the IFS with the Common Path (CP) and it is optically conjugated with the telescope Focal Plane, that is re-imaged by an F/# = 316 beam. This allows to sample the diffractive PSF - arising from the AO compensation and the Coronagraphic spatial filtering, both working inside the CP optics - at the Nyquist's limit.

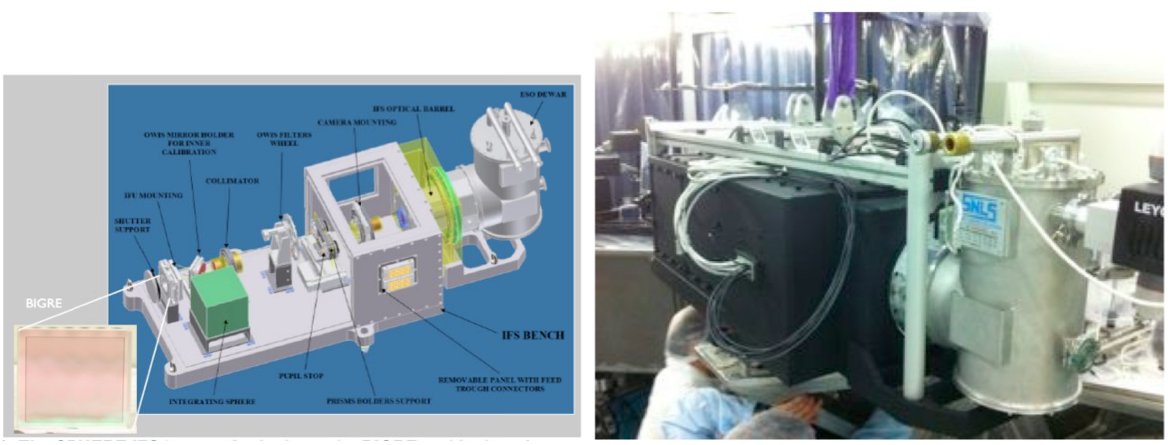

Figure 1: on the left the layout of the IFS is shown with the BIGRE array and its position indicated in the inset. In the right the IFS is mounted on the huge optical bench of SPHERE before its trip to Paranal.

The purpose of the IFS is thus to realize diffraction limit Integral Field Spectroscopy with the high contrast capabilities of the BIGRE device as IFU. To this scope, the whole IFS system, which is downstream the entrance lenslet array only re-images and disperses these slits with the highest optical stability and a good optical quality. The optimized IFS optical design is a fully dioptric concept design made by several optics located along a straight optical axis. The IFS is projected to work at different resolutions in two different wavelength ranges: R~50 in the 0.95 -1.35 μm (z-J mode) and R~30 in the wider wavelength range of 0.95 – 1.65 μm (z-J-H mode). The two resolutions are achieved by two different Amici prisms while the working wavelength ranges are defined by a combination of band pass, high- and low-pass filters mounted inside the dewar (low pass filter) and just in front of the prisms (band pass filter for the z-J mode and high pass filter for the z-J-H mode). The spectrograph is not cryogenic so a set of filters and baffles are used to minimize the thermal background noise. Most of the unwanted radiation is eliminated by the presence of a cold filter, about 40 mm before the detector and by two baffles, a cold absorbing baffle located inside the dewar, and a warm reflecting baffle located on the back of the IFS camera. The residual thermal background is mainly due to unavoidable thermal emission from the active IFS optical components.

It is expected that IFS will be mostly used together with IRDIS in the so-called NIRSUR (NIR survey) mode, developed for the large survey that will use about 80% of the GTO time. It 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" radius). In particular, it allows to reduce the number of false alarms and to confirm potential detections obtained in one channel by data from the other channel. This will be a definite advantage in case of detections very close to the limits of the system. Other two observing modes (NIROBS, IFS-H) will be briefly described in the following paragaraph.

3. IFS OPERATION AND DATA REDUCTION

The Instrumentation Software (INS) used in SPHERE follows the ESO standard partitioning: functions are subdivided among SW subsystems that either have been entirely provided by ESO, like the Detector Control Software, or have been developed by the Consortium by building on the base software provided by ESO. As part of a complex instrument, IFS has its own Observation Software, Instrument Control Software and Detector Control Software apart from modules that are specific to the subsystem.

The instrument operation consists of calibration and observation procedures. Three classes of calibrations are defined: science calibrations, technical calibrations and instrument monitoring. As IFS works in parallel with the differential imaging camera IRDIS, in the so-called IRDIFS mode, most of calibration procedures and all observations are performed simultaneously with the two instruments. The science calibration procedures determine:

- astrometry, plate scale and orientation of science frames;
- flux calibration to allow contrast estimate between the central star and a close companion;
- atmospheric calibration to remove telluric features from science spectra;
- PSF for extended object deconvolution;
- accuracy of IFS flat field made during daytime;
- sky background to remove sky signal from science images;
- wavelength calibration of the IFS spectra;
- star position on coronagraph images.

The technical calibrations allow to determine:

- zero level offset to remove the dark current and thermal background;
- detector flat field to calibrate the pixel-to-pixel response sensitivity;
- wavelength dependent transmission difference of individual lenslets and the spectra position on the detector;
- camera focus position.

The instrument monitoring includes:

- detector RON and gain factor;

- detector persistence after saturation;
- ghost positions and relative intensities;
- instrument background;
- dithering effects on wavelength calibration;
- distortions over the whole FoV;
- Pupil alignment.

In IRDIFS observing mode, three different sub-modes are available, according to the coronagraph setup and the spectral band:

- NIRSUR: extensively described in Sect. 2;
- NIROBS: to handle specific observation cases, when more flexibility is requested in instrument setup;
- IFS-H: to use IFS up to H band, sending K band toward IRDIS.

All the data taken through the INS templates are then reduced with the Data Reduction and Handling (DRH) software that, like INS, is composed by different procedures (called recipes) aimed to reduce each particular type of data. Currently, a number of IDL procedures have been implemented to cover that parts of the data reduction pipeline not yet fully implemented and tested in the DRH software.

4. AIT AT PARANAL

After the successful Preliminary Acceptance in Europe (PAE) at the end of 2013 SPHERE (and IFS) has been shipped to Paranal. Delivery at Paranal occurred on February 26th, 2014. Before the installation of the instrument at UT3 platform the system was reintegrated in the new integration hall (NIH) at Paranal basecamp. This facility permits to reintegrate instruments in a clean environment (10000 class, in the SPHERE case) before mounting them at the telescopes in a clean environment (in the SPHERE case 10000 class). Most of the operations performed at NIH were similar to those done in IPAG integration hall in Grenoble[35] after shipping IFS from the Padova Observatory. In particular:

- Dismounting and remounting of IFS from the CPI bench;
- Dismounting and remounting of Cryostat with the detector;
- Dismounting and remounting of collimator, camera and prisms;
- Check of alignment of the optics of IFS;
- Connecting cables and optical fibers of the instrument;
- Functional tests of servomechanisms;
- Functional tests of the detector.

The alignment of the IFS optics before mounting on the CPI bench have been conducted using a simulator that feed IFS in a similar way to the CPI. The photo shown in Figure 2 was obtained during this phase.

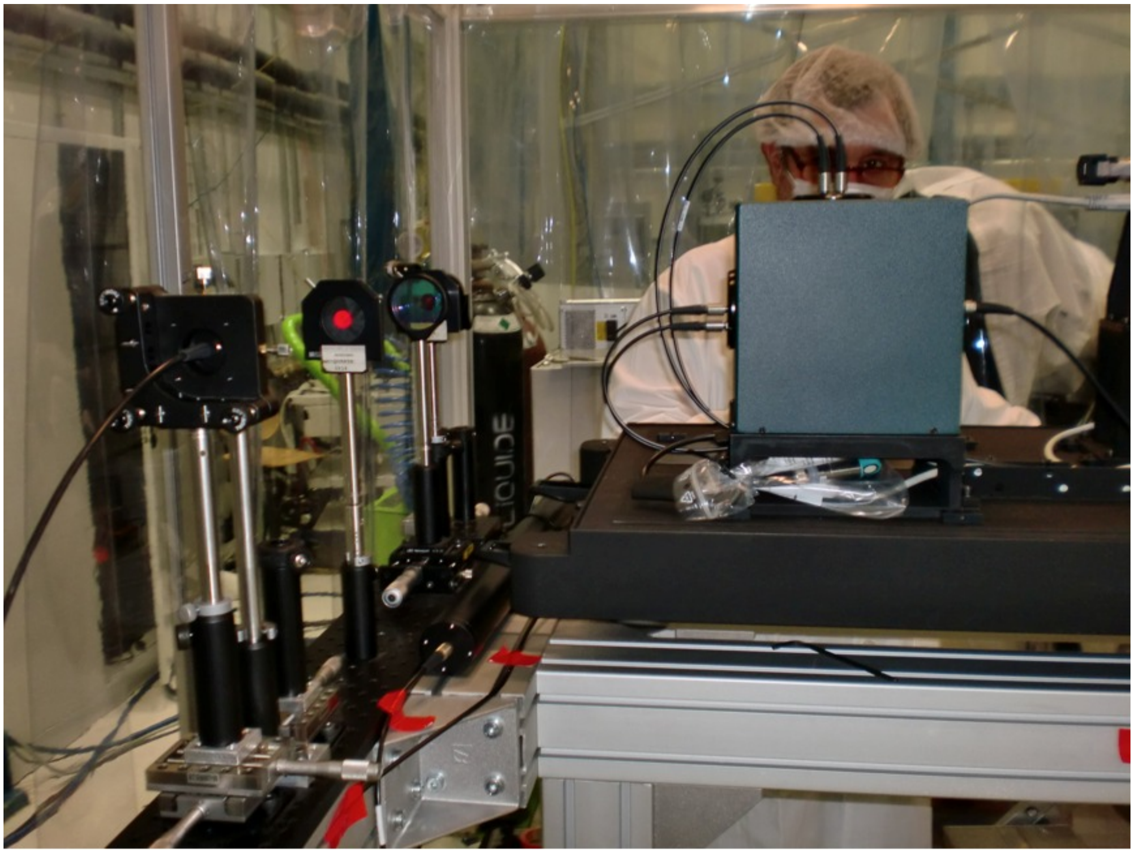

Figure 2: Alignment check of the optics IFS in NIH, before mounting on the CPI bench. The alignment was done using a CPI simulator (on the left).

After the successful checks of IFS, intensive tests were conducted to assure that the performances reproduced those obtained at IPAG. For instance, the focus procedure confirmed the optical performances obtained at IPAG (FWHM ~ 2 pixels).

In the first days of April SPHERE and IFS were packed and moved to the UT3 platform. The operation was similar to that performed at NIH but no dismounting and realignment of optics were required. Figure 3 shows IFS as it appeared at the telescope just before closing the SPHERE cover. Finally, after the last functional tests on the Nasmyth platform, IFS was ready for characterization tests and first light at the telescope.

Figure 3: IFS on CPI just before closing the SPHERE cover on the Nasmyth platform of UT3

5. TESTS AND CHARACTERIZATION

A series of data have been taken during the tests performed at Paranal both in the NIH and at the telescope. The data were reduced with the procedures described in Section 3. The results (displayed in Figure 4) confirmed the contrast values obtained in the labs in Europe.. A contrast better than 10^{-5} was obtained once the procedure for the speckle subtraction was applied.

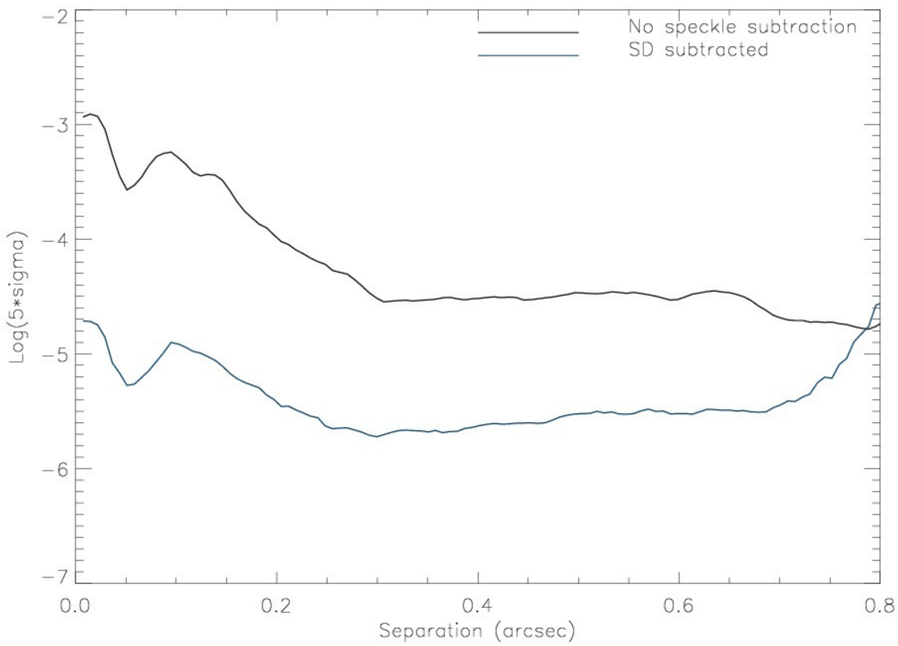

Figure 4 - 5σ contrast plot for the images taken during the NIH tests

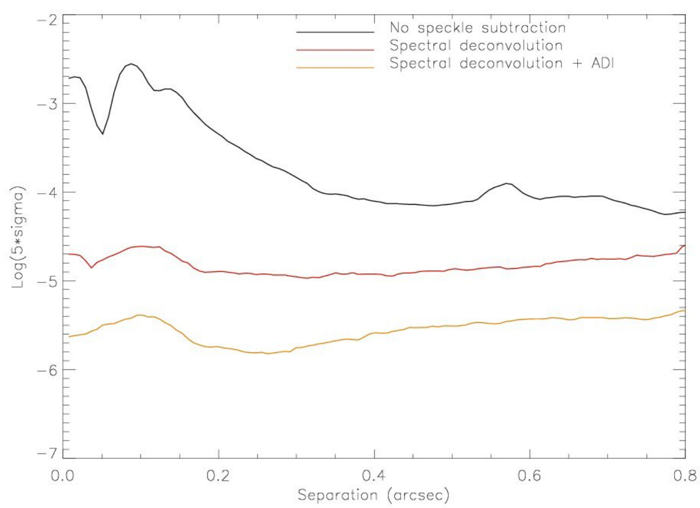

Figure 5 - 5σ contrast plot obtained from the on-sky observations of HD98281

6. FIRST LIGHT

The first part of the commissioning of the instrument started on mid May 2014. Various targets were observed to verify the capability of the instrument. The results obtained so far are very encouraging . The contrast showed in Figure 5 is similar to the ones obtained in laboratory but it is still limited by the background noise. Nonetheless, we were able to clearly image the white dwarf companion to HD114174 at a separation of 0.65 arcsec and a contrast of ~10.5 magnitudes with respect to the central star, as showed in Figure 6.

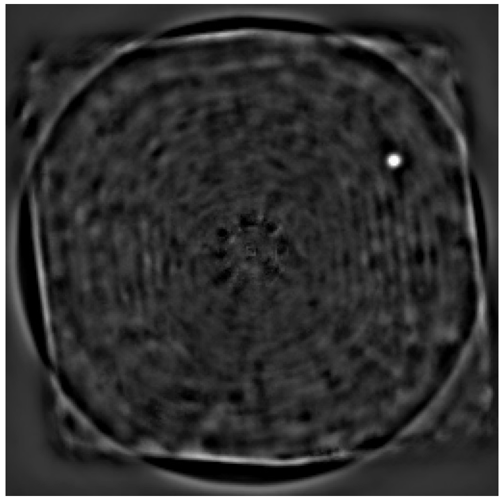

Figure 6 – Final image obtained for the star HD114147. The WD companion is clearly visible on the top right corner while the central star, more than 10^4 times brighter, has been well cancelled using the SPHERE subtraction procedures.

In the first run of commissioning also the star ι Sgr (HR7581, J=2.29, K giant, D=55.7±0.6 pc) has been observed. The star was previously known as an astrometric binary[37] but the companion was never detected before. The IFS observing mode was Y-J. Once the IFS data cube was reduced with Spectra Deconvolution and ADI, the faint companion was clearly detected (S/N=50) at an angular separation of θ = 0.249 arcsec (see Figure 7) and a contrast of 9 mag. The object was simultaneously seen by IRDIS.

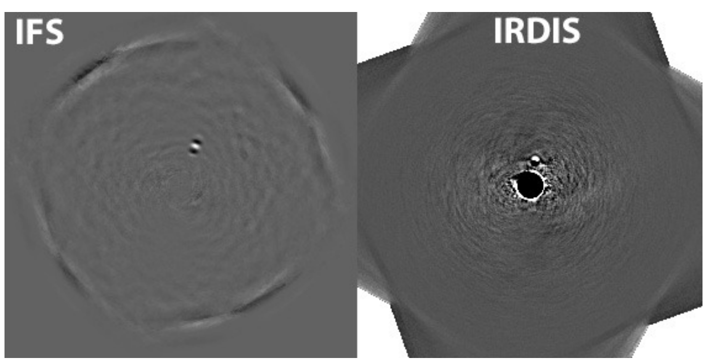

Figure 7: The companion of ι Sgr is clearly visible in the images taken with both IFS and IRDIS. The central star is $4x10^3$ times brighter than the M dwarf, but its image has been well cancelled by the subtraction procedures.

Using Δm=9 mag the calibration by Delfosse et al. (2000)[38], give a corresponding main sequence mass is 0.36 M_{Sun}. From the IFS and IRDIS data it is also possible to get the spectrum of the faint companion (see Figure 8) that results to be essentially flat, as expected for an early M-type star on IFS spectra.

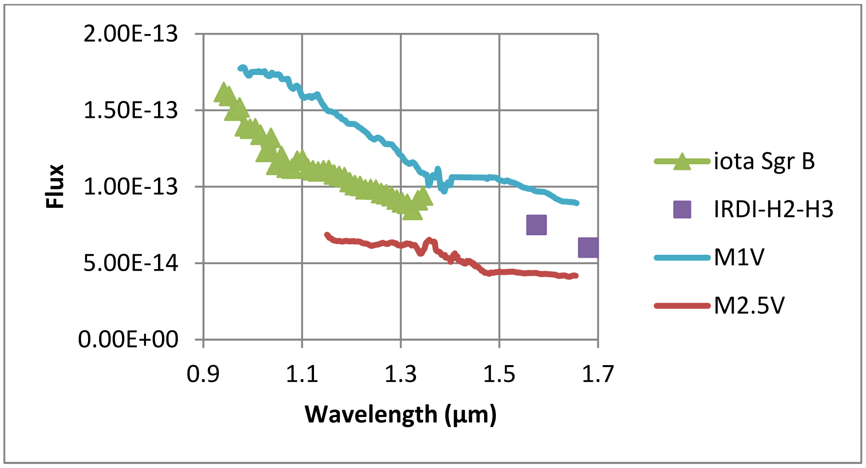

Figure 8: The spectrum (in W/m^2/µm) of ι Sgr B as obtained by the IFS data (green triangles) and IRDIS (violet squares) compared with those of two M stars of different spectral types, scaled at the distance of this system.

7. FUTURE WORKS

Following the general schedule, three additional commissioning runs of SPHERE are foreseen in the next months in order to fix remaining problems and provide functional and performance validation of the whole instrument and IFS in particular. The commissioning plan is described in details in the SPHERE document SPH656[39]. In the following a very brief summary is given.

1. Comm 1: The first run, already done, lasted 12 days and started at the mid May 2014. It was focussed on functional testing.
2. Comm 2: The second run will start in July 2014. It will be focused on full characterization of the performance in selected primary observing modes in NIR and Visible.
3. Comm 3: It will be devoted to characterize extensively the performances and calibrations of a larger set of observing modes and set-ups. This run will start in August 2014
4. Comm 4: The last commissioning period will be devoted to complete the remaining tests and characterization. The Comm is foreseen during October 2014.

8. CONCLUSION

The main characteristics of the integral field spectrograph (IFS) of SPHERE have been outlined together with a short report on the tests which the IFS underwent. Finally, after about ten years of efforts by a large team, the IFS and the whole SPHERE are now operational at UT3 of VLT. The first light data are very encouraging and give hope for a rich harvest of outstanding scientific results.

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