

Gearing up the SPHERE

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Direct imaging and spectral characterisation of exoplanets is one of the most exciting, but also one of the most challenging areas, in modern astronomy. The challenge is to overcome the very large contrast between the host star and its planet seen at very small angular separations. This article reports on the progress made in the construction of the second generation VLT instrument SPHERE, the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument. SPHERE is expected to be commissioned on the VLT in 2013.

Direct imaging is presently the most promising technique to efficiently reduce the photon noise generated by the host star, by suppressing its light

intensity while retaining the light from the exoplanet. It is mandatory to obtain spectral or polarimetric data of faint (contrast lower than about 10^{-6}) exoplanets. Direct imaging offers important complementary information to radial velocity studies of exoplanets, such as resolving the $\sin i$ ambiguity intrinsic to the radial velocity method, and allows for dynamic mass measurements of individual exoplanets. It can provide additional diagnostic data, e.g., through polarimetry, and greatly improves observing efficiency through the ability to confirm a detection in a couple of nights rather than following an orbit, which may take years.

In August 2007, the contract for the construction of SPHERE was signed with a consortium of 11 institutes from five European countries: IPAG (PI institute, Grenoble, France); MPIA (Co-PI institute, Heidelberg, Germany), LAM (Marseille, France), LESIA (Paris, France), Lagrange (Nice, France), Osservatorio Astronomico di Padova (Italy), Observatoire de Genève (Geneva, Switzerland), ETHZ (Zurich, Switzerland), University of Amsterdam (the Netherlands), ASTRON (Dwingeloo, the Netherlands), and ONERA (Châtillon, France). Signing the contract was quickly followed by the preliminary design review in September 2007 and the final design review in December 2008. The assembly, integration and testing of subsystems at the various integration sites took almost three years, ending in autumn 2011, and was concluded by a series of assembly readiness reviews. Since the end of 2011, SPHERE has been undergoing integration and testing at IPAG in Grenoble. The fully assembled instrument is now entering the final test phase and rapidly approaching Preliminary Acceptance Europe (PAE).

SPHERE (see Beuzit et al. [2006] for an overview) will provide high imaging contrast by combining extreme adaptive optics (XAO), coronagraphy, accurate calibration of non-common path instrumental aberrations and post-observational data calibration through various differential methods. The instrument is integrated on a large optical table which will occupy the Nasmyth platform A of the VLT Unit Telescope 3. The optical table

contains all the common-path optics including the XAO module and infrastructure such as the calibration source module. An enclosure will provide thermal inertia and stability and will also reduce local turbulence. Three scientific instruments are attached to this main bench: a differential near-infrared imaging camera and spectrograph (IRDIS, InfraRed Dual Imaging Spectrograph); a near-infrared low spectral resolution Integral Field Spectrograph (IFS); and a visible imaging differential polarimeter (ZIMPOL, Zurich Imaging Polarimeter).

Figure 1 illustrates the specified and simulated contrast performance of SPHERE for the different scientific instruments. The differential imaging methods rely either on spectroscopic features (IRDIS) or a certain degree of polarised flux (ZIMPOL) in order to provide the expected contrast performance. The simulations were performed for very bright stars, so the main limitations are residual differential aberrations rather than photon noise. The IFS data are assumed to be calibrated by spectral deconvolution (Mesa et al., 2011). Field rotation and potential further contrast improvements by angular differential imaging techniques were not taken into account. Such techniques are expected to make ZIMPOL compliant with its contrast requirements.

Concept and features

SPHERE is built around the XAO system, SAXO (SPHERE Adaptive optics for exo-planet Observation), which is designed as a standard single conjugate adaptive optics (AO) unit with many degrees of freedom. SAXO incorporates the high-order deformable mirror (HODM) with 1377 actuators on a 41×41 grid covering the aperture; a high temporal correction bandwidth of about 100 Hz is provided by ESO's deep depletion L3-CCD wavefront sensor camera and extremely low latency SPARTA real-time computer. As two of the dominant terms in the error budget (fitting error and temporal bandwidth error) are strongly reduced this way, SAXO provides a high Strehl ratio in the near-infrared (NIR) maximising the flux intensity in the point spread function (PSF) core and hence the exoplanet signal. The correction quality is still good

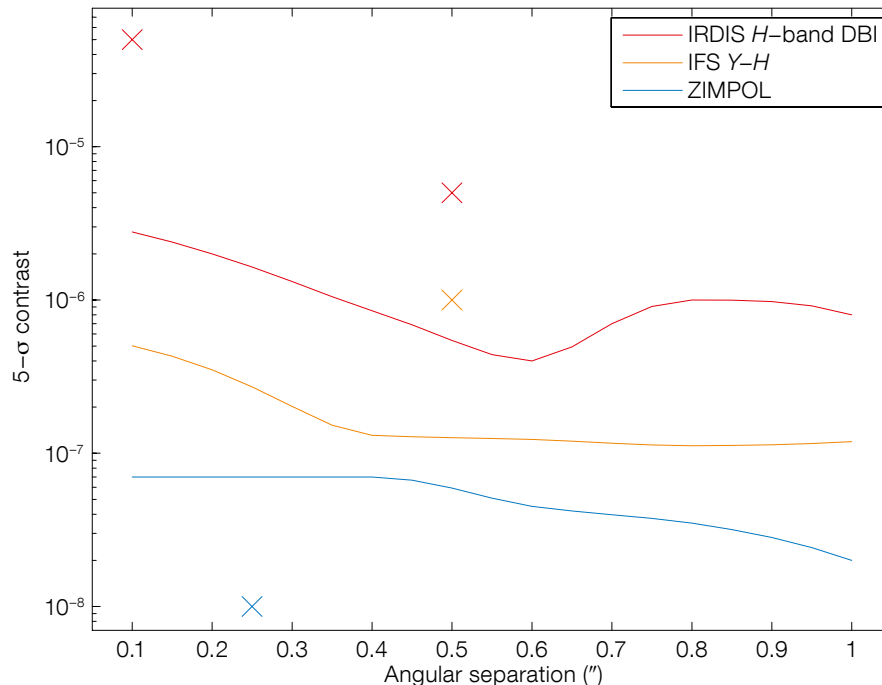


Figure 1. The contrast performance of SPHERE for its scientific instruments is shown as obtained from simulations (solid lines) before applying angular differential imaging techniques. The specified contrast performance of the different instruments is shown by crosses.

enough for diffraction-limited images in the optical part of the spectrum.

The HODM can suppress residual wavefront aberrations up to its correction radius θ_{AO} given by the ratio of the assumed wavelength of the observation divided by twice the inter-actuator spacing projected back to the telescope aperture ($\lambda/2D$). For a wavelength of $1.6 \mu\text{m}$ and an actuator spacing of 0.2 metres, $\theta_{AO} \approx 0.8$ arcseconds. The intensity of the stellar coronagraphic PSF halo is proportional to the power spectrum of residual aberrations, and their spatial frequency defines the angular separation from the PSF centre at which the light is scattered.

Since exoplanets are to be found at small angular separations, typically well below 0.5 arcseconds, a very efficient and precise correction of low spatial frequency aberrations, i.e., the low-order modes, is required to achieve a high-contrast (dark hole) close to the PSF centre, and is thus a prime objective of SAXO. Its spatially filtered Shack–Hartmann wavefront sensor (SHWFS) with 40×40 subapertures

of 6×6 pixels each is a suitable and well-established technology to achieve this goal. Very small low spatial frequency wavefront errors, even in the presence of vibrations, are achieved by efficient tip-tilt correction through linear quadratic Gaussian (LQG) control to a level of about one milliarcsecond root mean square (RMS). Figure 2 shows IRDIS images recorded in H -band without a coronagraph. The optically simulated seeing has a median value of 0.85 arcseconds, and the Strehl ratio derived from the corrected image was 94%.

The AO-corrected PSF is dominated by the Airy pattern of the telescope aperture and shows a ring structure modulated and sprinkled by quasi-static speckles from residual instrument aberrations with intensity up to 10^{-3} of the peak intensity at small angular separations. This Airy pattern is then removed by a coronagraph, and SPHERE provides a multitude of state-of-the-art coronagraphs such as the apodised Lyot coronagraph or the four-quadrant phase masks with inner working angles approaching the theoretical limit of one (λ/D), e.g., Martinez et al. (2010). Since stellar coronagraphy is a quickly evolving research field, future evolutions can be implemented through exchangeable masks both in the coronagraphic focus and in its entrance and

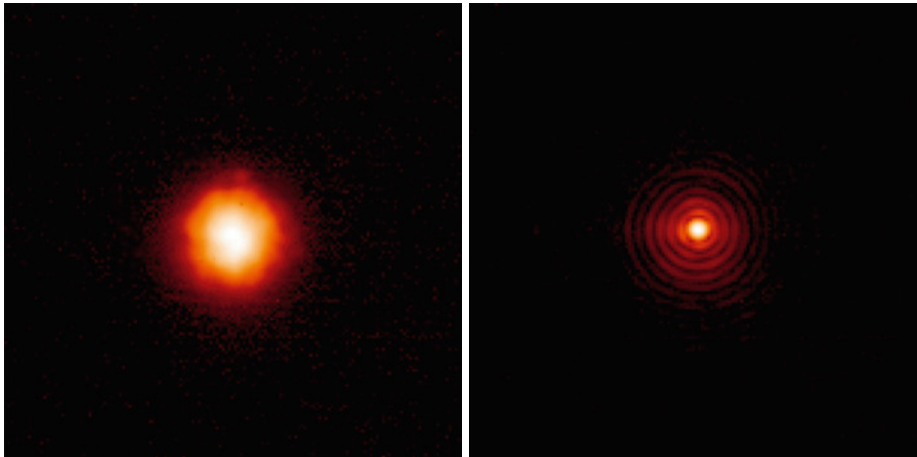


Figure 2. The SPHERE SAXO *H*-band point spread function is illustrated with the AO loop open (left, uncorrected image) and with the AO loop closed (right, corrected image).

exit pupil planes. Finally, residual instrumental aberrations will be measured by an evolved phase diversity technique and suppressed to a level of only a few nanometres rms by the deformable mirror (DM). Figure 3 shows an *H*-band PSF which has been corrected for the instrumental aberrations and has a derived Strehl ratio of 99%, consistent with a residual wavefront error of just a few tens of nanometres RMS.

The three scientific instruments will be fed by the XAO/coronagraphy system and implement the means for post-observational data calibration techniques. The main parameters of these instruments are summarised:

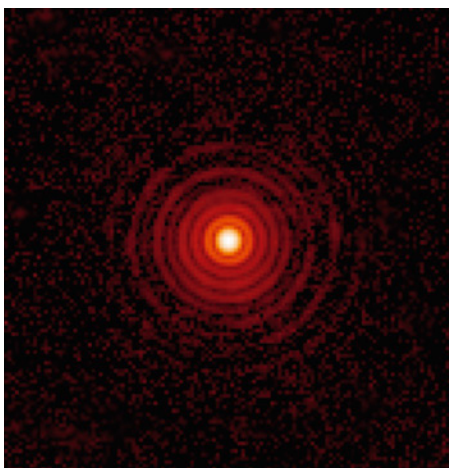


Figure 3. The SPHERE *H*-band point spread function, corrected from residual aberrations, is shown.

IRDIS covers a spectral range from 0.95–2.32 μm with an image scale of 12.25 milliarcseconds (mas) for Nyquist sampling at 950 nm. The field of view is permanently split into two channels of 11 by 12.5 arcseconds each, both for direct and dual imaging. The differential aberrations between the two channels, introduced by the beam splitter and the individual mirrors, focusing lenses and filters, have been carefully minimised to 7–10 nm rms total. Both channels are projected onto the same Hawaii 2RG NIR detector. Long-slit spectroscopy at resolving powers of 50 and 500 is provided, as well as a dual polarimetric imaging mode.

The IFS covers the spectral range 0.96–1.66 μm again with an image scale of 12.25 mas. The 1.73 by 1.73 arcsecond field of view is sampled by a two-sided

lenslet array, and each of the spatial pixels (spaxels) is dispersed by either one of two Amici prisms providing spectral resolutions of about 110 and 70 for the two bandpass modes *Y–J* and *Y–H* respectively.

ZIMPOL covers the spectral range 600–900 nm with an image scale of 7 mas for correct sampling at 600 nm wavelength. The instantaneous field of view of 3.58 by 3.58 arcseconds is increased to almost 8 arcseconds in diameter through dithering by internal field selectors. The beam is split into two arms by a polarising beam splitter, each arm with its own detector. Differential polarimetry in each of the arms is implemented by a ferro-liquid crystal (FLC) modulator that is synchronised with a row modulation of the CCD (every second row is blind thanks to a lenslet array that is mounted directly onto the detector, see Figure 4), such that each CCD image contains interlaced images of perpendicular linear polarisation states. Filter sets common and separate to the two arms as well as a number of calibration devices complete the list of functions.

A set of three main observing modes defines how the light is split between the scientific instruments. IRDIFS is the survey mode which will be used for a large fraction of the time. In its main configuration, it combines IRDIS dual imaging in the *H*-band with IFS imaging spectroscopy in the *Y–J* bands with pupil stabilised coronagraphy. Other configurations

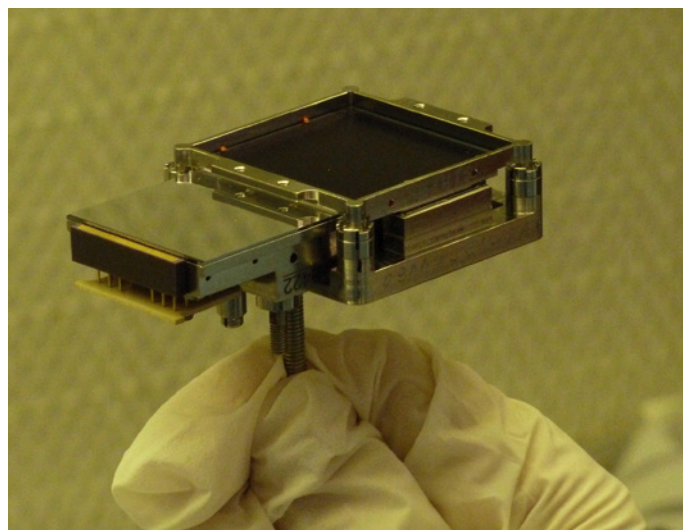


Figure 4. The SPHERE ZIMPOL CCD with the cylindrical lenslet array mounted on the detector is shown.

include *K*-band IRDIS and *Y-H* band IFS splitting as well as field stabilisation. IRDIS alone can be used to exploit its various modes for more generic NACO-like (*viz.* high resolution AO imaging) science, while ZIMPOL alone will provide high precision differential and absolute polarimetry as well as classical diffraction-limited imaging at optical wavelengths. No mode supports simultaneous NIR and optical observations.

Current status

SPHERE with all its subsystems has fully been integrated at IPAG in Grenoble. Figure 5 shows the status in early 2012, when the XAO wavefront sensor arm was still not populated, and the main bench was still exposed to the laboratory environment. In the meantime the main enclosure has been installed, and a thermal tent now surrounds SPHERE. Figure 6 shows a detailed view of the SPHERE optical bench with various subsystems and important components indicated. A detailed status update of the project has recently been presented by Beuzit et al. (2012).

The instrument software as well as data reduction and handling software are complete and are used for test data acquisition through template operation and for data analysis by the pipeline. Functional testing has been successful, and SPHERE is now entering the end-to-end performance evaluation with optically simulated turbulence. Major activities that are still to be completed are the thermal testing of the complete instrument over its specified temperature range between 0°C and 20°C, and the installation and testing of the vacuum cryogenic system, which has many similarities with the one that has been developed for MUSE.

There are, however, some pending issues which impact on the instrument performance and which will be resolved only in the longer term. The most prominent one is the HODM, which suffers from two main limitations: i) a strongly temperature-dependent shape-at-rest (about 1 μm peak-to-valley cylindrical wavefront deformation per degree Celsius); and ii) an electrical interface in compliance for

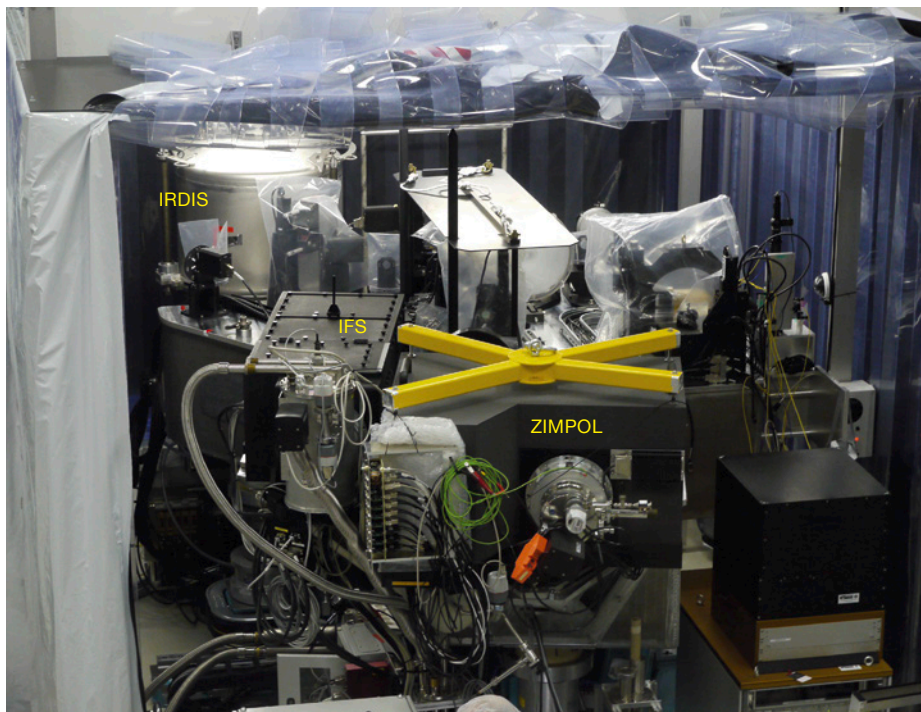


Figure 5. SPHERE in the assembly laboratory at IPAG with all instruments integrated into the common path.

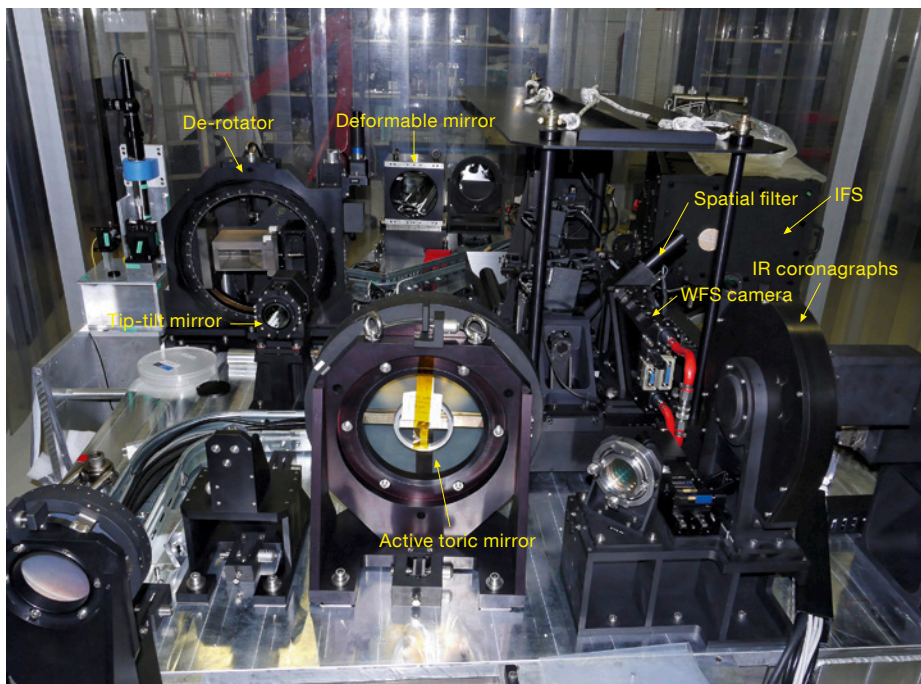


Figure 6. Detailed view of the SPHERE optical bench is shown with the main subsystems indicated. The active toric mirror, used to compensate for the HODM temperature-dependent shape-at-rest, is clearly visible in the centre foreground.

a number of actuators (currently four actuators are dead, and several tens of actuators respond more slowly than specified, but still on a timescale of a millisecond). In order to overcome these problems, the production of a replacement, HODM2, was launched in 2010. Several modifications to the design ensure that all SPHERE specifications are fulfilled. Unfortunately, a number of manufacturing problems have occurred that have delayed the delivery of HODM2 until October 2013. Because the cylindrical shape-at-rest of the HODM can be offloaded to a toric mirror (a mirror with a spherical surface with added astigmatism from Zernike terms of third and fifth order) in the common path, and the actuator deficiencies mainly introduce increased photon noise which can be mitigated by longer exposure times, SPHERE will use HODM1 for its acceptance and integration testing (AIT) and, depending on the achieved performance, even for installation and commissioning at the VLT.

Another concern is the degradation of the protected silver coatings of several common path and infrastructure (CPI) mirrors. These are being closely monitored and may require a re-coating at some stage, probably during the period of shipment to Paranal Observatory. Finally, the detector motion stage (DMS) of IRDIS has been

found to be out of specification, with one axis not working properly and not achieving the required amplitude. The DMS is supposed to move the detector by small amounts to cope with bad pixels and improve the flat field accuracy, which are both important, but, at least for AIT, not necessarily vital objectives. A replacement DMS is currently in production and should be ready for installation at the VLT.

Releasing SPHERE

The instrument's preliminary acceptance in Europe is planned for early spring 2013, immediately followed by shipment to the Paranal Observatory and on-site integration in late spring 2013. With this schedule, first light is expected in summer 2013 during the first commissioning period. Further commissioning periods will be carried out later in 2013 during which the instrument will be operated, characterised and validated in all possible observing modes. Further objectives of the commissioning period include instrument operation through the standard procedures and the implementation of the data reduction pipeline as well as the determination of operational efficiency. After the commissioning period, science verification will be carried out involving scientists from the ESO community to demonstrate SPHERE's scientific potential

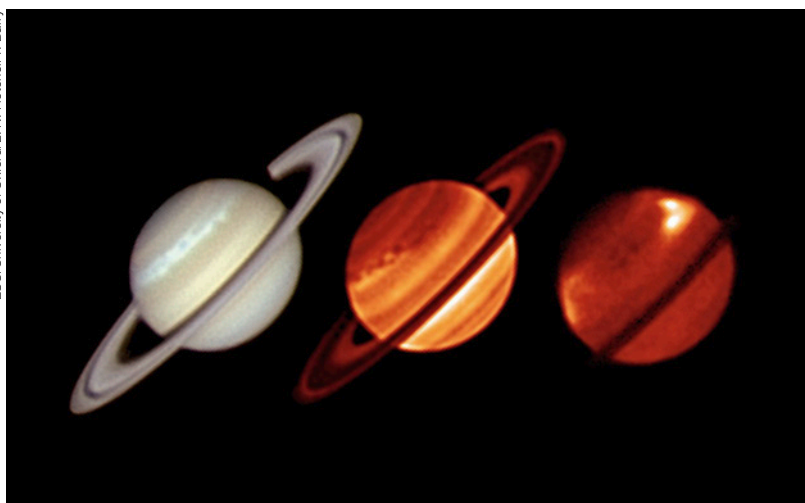
and to experiment with the data reduction tools available at this time.

A workshop dedicated to SPHERE and its future use is planned for late summer 2013; the date will be confirmed depending on a successful start of commissioning, possibly followed by a delta call for proposals. This workshop will include a dedicated session on ground-based high contrast imaging with SPHERE and cover observing proposal preparation and data reduction.

It is foreseen to release SPHERE to the community during Period 92, and to include SPHERE in the Period 93 (April–September 2014) regular call for proposals for the first time. Starting early 2014, European astronomers will be able to carry out spectacular programmes dedicated to the detection and characterisation of exoplanets with an unprecedented accuracy.

References

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Two thermal infrared images of Saturn (centre and right) taken with VISIR, and an amateur visible-light image (left) by Trevor Barry for orientation, are shown. The images were taken on 19 January 2011 and show the mature phase of the northern spring hemisphere storm. The centre image (18.7 μm) reveals the structures in Saturn's lower atmosphere including the storm clouds and its central cooler vortex; the right image (8.6 μm) is sensitive to much higher altitudes in the stratosphere, where emission flanking the central cool region over the storm is observed. See Release eso1116 for more details.